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Proceedings of
Third International Symposium on Alcohol Fuels Technology

May 29-31, 1979
Asilomar, California, U.S.A.

U.S. Department of Energy
Assistant Secretary for
Conservation and Solar Energy
Office of Transportation Programs

Published April 1980

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Proceedings of
Third International Symposium on Alcohol Fuels Technology

Master

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Organized by the
University of Santa Clara

U.S. Department of Energy
Assistant Secretary for
Conservation and Solar Energy
Office of Transportation Programs

Washington, D.C. 20585

Published April 1980

FOREWORD

Although a considerable number of preprints for the Third Symposium were available to meet the requests of those who could not attend the Symposium, the supply was exhausted within four months. Hence, it was concluded that the final papers would be published by the U.S. Department of Energy.

At the opening of the Symposium, Dr. Sharrah, Senior Vice President of Continental Oil Company, addressed the attendees, and his remarks are included in this volume.

The Symposium was concluded by workshops which addressed specific topics. The topical titles and the chairpersons are as follows:

Alcohol Uses	Philip S. Meyers
Production	T. A. J. Keefer
Environment and Safety	Britt Marie Bertilsson
Socio-Economic	Michael W. Grainey

The workshops reflected a growing confidence among the attendees that the alcohols from coal, remote natural gas and biomass do offer alternatives to petroleum fuels. Further, they may, in the long run, prove to be equal or superior to to the petroleum fuels when the aspects of performance, environment, health and safety are combined with the renewable aspect of the biomass derived alcohols.

Although considerable activity in the production and use of alcohols is now appearing in many parts of the world, the absence of strong, broad scale assessment and support for these fuels by the United States Federal Government was a noted point of concern by the attendees.

The environmental consequence of using alcohols continues to be more benign in general than the petroleum based fuels. The exception is the family of aldehydes. Although the aldehydes are easily suppressed by catalysts, it is important to understand their production in the combustion process. Progress is being made in this regard. Of course, the goal is to burn the alcohols so cleanly that catalytic equipment can be eliminated.

In conclusion, we want to thank the authors of the papers in this document for their contributions. We also want to thank Faye Guercio of the University of Santa Clara and Carol Check of the Department of Energy for their secretarial assistance.

E. Eugene Ecklund, Chief
Alternative Fuels Utilization Branch
Conservation and Solar Energy
Department of Energy

Richard Pefley
Symposium General Chairman
University of Santa Clara

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1980 Meeting in Brazil

At the conclusion of the Third International Symposium a decision was made to hold another meeting in Brazil. The meeting will be the:

IV International Symposium
on
Alcohol Fuels Technology
Guaruja, SP, Brazil
October 5-8, 1980
Conference Chairman: Prof. Eston de Eston
c/o Instituto de Pesquisas Technologicas
Caixa Postal 7141
01000 Sao Paulo, Brazil

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THIRD INTERNATIONAL SYMPOSIUM ALCOHOL FUELS TECHNOLOGY

HOSTED BY THE UNIVERSITY OF SANTA CLARA

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ALCOHOL FUELS TECHNOLOGY

THIRD INTERNATIONAL SYMPOSIUM

MAY 29, 1979

PRESENTATION BY

DR. M. L. SHARRAH

SR. V.P., RESEARCH & ENGINEERING,
CONTINENTAL OIL COMPANY

ASILOMAR, CALIFORNIA, MAY 28-31, 1979

IT IS WITH A GREAT DEAL OF PLEASURE THAT I RISE TO MAKE THIS KEYNOTE ADDRESS TO THE THIRD INTERNATIONAL SYMPOSIUM ON ALCOHOL FUELS TECHNOLOGY. TODAY, ENERGY COMPANIES TEND TO BE DENIGRATED RATHER THAN PRAISED FOR THEIR EFFORTS, AND I LOOK UPON IT AS AN HONOR TO HAVE BEEN ASKED TO START AND GIVE A LEAD TO THE DELIBERATIONS OF SUCH AN AUSPICIOUS GROUP.

SINCE THE FIRST SYMPOSIUM IN STOCKHOLM, THE SIZE OF THIS GROUP AND THE POLITICAL, PUBLIC, AND TECHNICAL INTEREST IN ALCOHOL HAVE GROWN CONSIDERABLY, GIVING PERHAPS A GOOD INDICATION OF THE VALUE OF ALCOHOL AS A FUEL.

BEFORE MAKING ANY FURTHER REMARKS ON ALCOHOL, HOWEVER, I WOULD LIKE TO DWELL FOR A FEW MINUTES ON THE ENERGY SUPPLY AND DEMAND SITUATION.

ENERGY CRISES ARE NOT NEW. PERHAPS THE FIRST, AND SURELY THE FIRST IMPORTANT ONE OCCURRED IN BRITAIN IN THE SIXTEENTH CENTURY WHEN THE TRADITIONAL BIOMASS FUEL - WOOD - BECAME SHORT IN SUPPY BECAUSE OF THE COMPETING DEMANDS OF URBAN DEVELOPMENT AND WORLD COMMERCE. THAT IS, PEOPLE INCREASINGLY WANTED TO LIVE IN CITIES WHERE THEY NEEDED WOOD FOR HOUSES; AND THE SEARCH FOR NEW LANDS AND RICHES, AND THE WARS WITH OTHER COUNTRIES, MEANT THAT MORE WOODEN SHIPS HAD TO BE BUILT.

AS A RESULT, COAL, WHICH HAD BEEN PREVIOUSLY BURNED IN ONLY SMALL QUANTITIES IN PARTS OF THE WORLD, BECAME A MAJOR SOURCE OF ENERGY. THIS LED TO NEW METHODS OF MANUFACTURING, TO THE EXPANSION OF INDUSTRY, TO THE EXPLOITATION OF UNTAPPED RESOURCES, AND INDIRECTLY TO THE INDUSTRIAL REVOLUTION.

THE SPECTACULAR DEVELOPMENT OF CIVILIZATION DURING THE THREE AND A HALF CENTURIES OF THE COAL AGE WAS REPEATED AGAIN THIS CENTURY FOLLOWING THE DISCOVERY OF OIL - A FUEL WHICH IS EASY TO PRODUCE, EASY TO PROCESS, EASY TO DISTRIBUTE, AND EASY TO USE. BECAUSE EVERYTHING WAS SO EASY, IT WAS ALSO VERY CHEAP WITH THE RESULT THAT THE INVENTIVE TECHNOLOGY OF THE COAL AGE WAS

RAPIDLY REPLACED BY THE CONSUMPTIVE TECHNOLOGY OF THE OIL AGE.

SOON, HOWEVER, THERE WERE WISE MEN WHO TRIED TO INDICATE THE NEED FOR SELF DISCIPLINE, AND FORECAST THE RAPID DEMISE OF OIL BECAUSE THE INSATIABLE DEMAND WAS FAR OUTSTRIPPING PROBABLE SUPPLY.

UNFORTUNATELY, ALTHOUGH THEY WERE UNDOUBTEDLY CORRECT THEIR STATEMENTS HAVE BEEN LOOKED UPON AS PRESENT DAY MALTHUSIANS, SO THAT NOW IT IS DIFFICULT TO PERSUADE MANY THAT THE "WOLF" IS REALLY AT THE DOOR.

IN GENERAL ENERGY CONSIDERATIONS HAVE BEEN NATIONAL RATHER THAN INTERNATIONAL AND HAVE BEEN MADE TO ENABLE THE GOVERNMENTS OF CONCERNED COUNTRIES TO EVALUATE THEIR POTENTIAL SOURCES OF FUTURE ENERGY SUPPLIES.

ONE SUCH STUDY WAS THAT MADE IN 1971 IN THE UNITED STATES AFTER THE U.S. DEPARTMENT OF THE INTERIOR, ASKED THE NATIONAL PETROLEUM COUNCIL TO UNDERTAKE A COMPREHENSIVE STUDY OF THE NATION'S ENERGY OUTLOOK. THE CHAIRMAN OF THE COMMITTEE SET UP TO DO THIS JOB WAS MR. JOHN MCLEAN, WHO WAS ALSO THEN CHAIRMAN OF THE BOARD OF CONOCO, AND I WOULD LIKE TO BRIEFLY QUOTE TO YOU SOME OF THE TESTIMONY HE GAVE TO THE HOUSE WAYS AND MEANS COMMITTEE IN FEBRUARY OF 1973.

"THE TREND OF RECENT EVENTS PROBIDES PERSUASIVE EVIDENCE THAT ENERGY PROBLEMS, IN ALL THEIR MANY RAMIFICATIONS, WILL RANK HIGH ON OUR LIST OF NATIONAL PRIORITIES FOR AT LEAST THE NEXT TWO DECADES".

"THE ESSENTIAL FACTS WITH REGARD TO THE U.S. ENERGY OUTLOOK MAY BE SUMMARIZED AS FOLLOWS:"

"<u>FIRST</u>, THE U.S. ENERGY PROBLEM IS A MEDIUM-TERM PROBLEM; IT NEED NOT BE A LONG-TERM PROBLEM. WE HAVE POTENTIALLY RECOVERABLE OIL, GAS, COAL, URANIUM, AND SHALE OIL SUFFICIENT TO MEET OUR ENERGY REQUIREMENTS FOR AT LEAST 200 YEARS, AT PRESENT CONSUMPTION RATES. OUR PROBLEM IS TO DEVELOP OUR POTENTIAL RESOURCES FAST ENOUGH TO MEET OUR GROWING REQUIREMTNTS IN THE

MEDIUM-TERM — THE 10-15 YEARS IMMEDIATELY AHEAD."

"SECOND, THE U.S. ENERGY REQUIREMENTS WILL APPROXIMATELY DOUBLE BETWEEN NOW AND THE MIDDLE 1980'S. ENERGY CONSERVATION PROGRAMS, VOLUNTARY OR MANDATORY, ARE NOT LIKELY TO ALTER THE GROWTH PATTERN IN ANY MAJOR DEGREE. THIS IS BOTH A POLITICAL AND AN ECONOMIC JUDGEMENT."

"THIRD, TO MEET AT LEAST 90 PERCENT OF THESE REQUIREMENTS, WE SHALL HAVE TO RELY UPON THE FOUR CONVENTIONAL FUELS -- OIL, GAS, COAL, AND NUCLEAR POWER -- WHICH TODAY SUPPLIES ABOUT 95 PER CENT OF OUR REQUIREMENTS. TECHNOLOGICAL PROBLEMS, TOGETHER WITH THE LONG LEAD TIMES AND MASSIVE CAPITAL INPUTS REQUIRED FOR NEW PLANT CONSTRUCTION, PRECLUDE ANY MAJOR CONTRIBUTION FROM THE NEWER ENERGY SOURCES BEFORE THE MIDDLE 1980'S."

"FOURTH, THE FOUR CONVENTIONAL FUELS ARE NOT LIKELY TO BE DEVELOPED FAST ENOUGH TO MEET OUR ENERGY NEEDS IN THE PERIOD IMMEDIATELY AHEAD. HENCE, WE SHALL HAVE TO IMPORT A GROWING VOLUME OF OIL AND GAS FROM OVERSEAS."

IN ANOTHER PORTION OF HIS TESTIMONY HE PROPHETICALLY STATED: "THE ECONOMIC AND POLITICAL IMPLICATIONS OF OUR FUTURE ENERGY OUTLOOK ARE STAGGERING."

"FIRST, AS OUR IMPORTS OF OIL AND GAS GROW, WE SHALL BECOME INCREASINGLY DEPENDENT UPON FOREIGN COUNTRIES FOR A VITAL PORTION OF OUR ENERGY SUPPLIES. OUR DEPENDENCE WILL NOT BE GEOGRAPHICALLY DISPERSED; IT WILL BE HIGHLY CONCENTRATED. MOST OF THE OIL WILL HAVE TO COME FROM THE 11 OPEC COUNTRIES."

"SECOND, OUR GROWING REQUIREMENTS FOR OIL AND GAS IMPORTS WILL PROVOKE A LARGE AND GROWING DEFICIT IN THE UNITED STATES BALANCE OF TRADE IN FUELS. IN 1970, THIS DEFICIT WAS ABOUT $2 BILLION; IN 1973, IT WILL BE OVER $4 BILLION, AND BY EARLY 1980'S IT COULD EXCEED $20 BILLION. OUR GOODS AND SERVICES ACCOUNT IN 1972 WAS FOR THE FIRST TIME IN DEFICIT BY ABOUT $5 BILLION. A FUEL DEFICIT OF SOME $20 BILLION WILL IMPOSE A WELL-NIGH IN-

TOLERABLE BURDEN ON OUR TRADE POSITION AND MAKE IT INCREASINGLY DIFFICULT TO MAINTAIN STABILITY OF THE DOLLAR IN THE WORLD FINANCIAL MARKETS.

"THIRD, OUR GROWING PURCHASES OF OIL AND GAS, COUPLED WITH THOSE OF WESTERN EUROPE AND JAPAN, WILL CREATE MAJOR NEW CENTERS OF FINANCIAL POWER. WE ARE ON THE BRINK OF THE MOST DRAMATIC EXPANSION OF WEALTH AND FINANCIAL POWER BY A SMALL GROUP OF COUNTRIES THAT THE WORLD HAS EVER KNOWN. BY 1985, THE OPEC COUNTRIES COULD BE COLLECTING OIL REVENUES AT AN ANNUAL RATE OF ALMOST $45 BILLION, EVEN WITHOUT ADDITIONAL PRICE INCREASES AFTER 1975."

"FOURTH, AS WE MOVE FROM A LONG PERIOD OF ABUNDANCE TO A TIME OF GROWING SCARCITY IN ENERGY MATERIALS, OUR ECONOMY WILL CERTAINLY EXPERIENCE RISING ENERGY COSTS. BY 1985, U.S. ENERGY COSTS COULD BE 100 PERCENT HIGHER THAN THEY ARE TODAY. THESE INCREASES CAN BE ABSORBED IN OUR ECONOMY WITHOUT SERIOUS DISRUPTIVE EFFECTS. OUR PROBLEM IS ONE OF ADEQUACY AND CONTINUITY OF ENERGY SUPPLIES - NOT ONE OF ENERGY COSTS."

THOSE STATEMENTS ARE AS RELEVANT TODAY AS THEY WERE WHEN THEY WERE MADE SIX YEARS AGO. UNFORTUNATELY, DURING THE INTERVENING YEARS THIS COUNTRY HAS MADE LITTLE PROGRESS TO AMELIORATE THE POSITION, AND INTERNATIONAL EVENTS HAVE AGGRAVATED THE SITUATION.

IN FACT, ALTHOUGH THERE HAS BEEN A GREAT AWARENESS OVER THE LAST DECADE OF THE ENERGY RESOURCE-DEMAND IMBALANCE, THE WORLD CONTINUES TO USE ABOUT SEVENTY PERCENT OF ITS ENERGY IN THE FORM OF OIL AND GAS. OIL AND GAS, HOWEVER, REPRESENT LESS THAN THIRTY PERCENT OF THE TOTAL RECOVERABLE FOSSIL FUEL RESOURCES, AND EVEN LESS WHEN NUCLEAR AND NATURAL RESOURCES SUCH AS HYDROELECTRICITY ARE COUNTED.

ALTHOUGH MOST GOVERNMENTS AND MANY PEOPLE ARE AWARE OF THESE FACTS, THE DEPENDENCE OF OUR WAY OF LIFE ON PETROLEUM MAKES IT DIFFICULT TO CHANGE -- BUT CHANGE WE MUST. IT SEEMS TO ME THAT THE TREMENDOUS INVESTMENT, BOTH IN

CAPITAL AND EQUIPMENT, AND THE HUGE INERTIA OF HABIT, MAKES IT DIFFICULT TO GRASP HOW WE CAN MANAGE WITH THE ALTERNATIVES.

THE EASY ALTERNATIVE, APART FROM USING ENERGY MORE EFFICIENTLY, IS SUBSTITUTION. WE SHOULD QUICKLY REVERSE THE TREND OF USING OIL AND OIL PRODUCTS WHERE COAL, OR NUCLEAR; OR NATURAL ENERGY FORMS SUCH AS HYDROPOWER CAN BE USED JUST AS WELL -- IN THE GENERATION OF ELECTRICITY, FOR INSTANCE. BY THIS MEANS WE WILL EXTEND THE LIFE OF OUR OIL AND GAS RESOURCES.

BUT, MOST OF THE SUPPLY PROBLEM WILL STILL REMAIN SO THAT IN SOME APPLICATIONS WE MUST EITHER ABANDON THE ENTRENCEHED METHOD OF USE, AS IN TRANSPORTATION, OR WE MUST FIND SOME ALTERNATIVE. SINCE ABANDONMENT SEEMS QUITE IMPOSSIBLE, CERTAINLY IN THE SHORT TERM WE NEED TO AGGRESSIVELY PURSUE OTHER ENERGY SUPPLY ALTERNATIVES.

CONOCO MANY YEARS AGO BECAME AWARE OF THE NEED TO CONSIDER NON-CONVENTIONAL ENERGY SOURCES, AND MORE THAN A QUARTER OF A CENTURY AGO BECAME INVOLVED IN THE DEVELOPMENT OF THE NOW WELL-ESTABLISHED, MOVEMENT OF NATURAL GAS FROM AREAS OF THE WORLD WHERE IT WAS BEING WASTED TO AREAS WHERE IT COULD BE USED. WE DID THIS BY PLAYING A MAJOR ROLE IN THE TECHNOLOGICAL DEVELOPMENT OF LARGE SCALE PRODUCTION AND MOVEMENT OF CRYOGENIC LIQUIDS.

ONE OF THE POSSIBLILITIES WE HAD TO CONSIDER AT THAT TIME WAS THAT OF MAKING THE GAS TRANSPORTABLE, NOT BY PHYSICALLY LIQUEFYING IT, BUT BY CHEMICALLY LIQUEFYING IT. THAT IS BY CONVERTING IT INTO METHANOL. AND SO, WE BECAME INTERESTED IN METHANOL.

WE ALSO HAD A BACKGROUND OF KNOWLEDGE ON THE PRODUCTION AND USE OF ENERGY FROM COAL RESULTING FROM THE RESEARCH EFFORTS OF OUR SUBSIDIARY, CONSOLIDATION COAL, AND WE WERE QUICKLY ABLE TO REALIZE THAT THE MOST FEASIBLE METHOD OF PRODUCING SUBSTITUTE FUELS WAS SYNTHESIS OF PRODUCTS MADE BY THE GASIFICATION OF COAL. TO SUBSTANTIATE THIS REALIZATION, BEGINNING

IN 1972, WE ORGANIZED AND MANAGED TWO PROGRAMS IN ASSOCIATION WITH THE BRITISH GAS CORPORATION, THE FIRST OF WHICH PROVED, IN 1974, THAT COMMERCIAL SCALE METHANATION OF COAL GAS WAS POSSIBLE. WE THERFORE, HAVE NO TECHNICAL RESERVATIONS WHAT-SO-EVER AS TO THE COMMERCIAL FEASIBILITY OF PRODUCTING LARGE QUANTITIES OF METHANE OR METHANOL FROM COAL. WITHIN THE SAME PERIOD WE BEGAN TO EVALUTATE THE POSSIBLILITY OF CONVERTING REMOTE GAS RESERVES INTO METHANOL.

WE SATISFIED OURSELVES ON THIS POSSIBLITY, AS YOU HEARD AT THE LAST CONFERENCE IN WOLFSBURG, BUT WE ALSO CONVINCED OURSELVES THAT IN PRINCIPLE, IF METHANOL WAS A WORTHWHILE PRODUCT OF REMOTE GAS, IT WAS ALSO A WORTHWHILE PRODUCT BY SYNTHESIS FROM COAL.

THUS, WE HAVE SUPPORTED THIS AND OTHER SERIES OF CONFERENCES AND SYMPOSIA, AND I AM HERE TODAY TO PROVIDE ENCOURAGEMENT IN THE RAPID DEVELOPMENT OF ALCOHOL AS AN ALTERNATIVE ENERGY FRORM.

THE STATEMENTS MR. MCLEAN MADE IN 1973 ABOUT U.S. ENERGY SUPPLIES ARE EQUALLY RELEVANT TO MANY OTHER COUNTRIES IN THE WORLD. IT WAS THE AWARENESS OF THE SAME FACTS BY THE SWEDISH GOVERNMENT WHICH LED TO THEIR SETTING UP, IN 1975, IN ASSOCIATION WITH THE VOLVO CAR CORPORATION, THE SWEDISH METHANOL COMPANY. THAT COMPANY HAD THE DUTY OF FINDING SOME INDEPENDENCE FROM IMPORTED OIL, AND LOOKED TOWARDS THE POSSIBILITY OF CONVERTING, INTO METHANOL, THE OIL SHALE AND PEAT WHICH EXIST IN LARGE QUANTITIES IN SWEDEN. THOSE ACTIONS ALSO LED TO THE CALLING OF THE FIRST INTERNATIONAL SYMPOSIUM ON ALCOHOL FUELS.

THE WEST GERMAN GOVERNMENT SUPPORTED IN 1974, A STUDY BY FIFTEEN COMPANIES ON ALTERNATIVE FUELS FOR MOTOR VEHICLES, WHICH CONCLUDED THAT METHANOL COULD PROVIDE, IN THE SHORT AND MEDIUM TERM, A FUEL WHICH COULD BE INDEPENDENT OF CRUDE OIL. FURTHER SUPPORT FOLLOWING THAT STUDY LED TO THE EXTENSIVE

ROAD TESTING PROGRAM ON METHANOL-GASOLINE BLENS, IN WHICH VOLKSWAGEN, DEUTSCHE-SHELL, AND OTHERS, HAVE PLAYED SUCH AN IMPORTANT PART AND, OF COURSE, MADE WEST GERMANY THE LOGICAL HOST FOR THE SECOND SYMPOSIUM.

FOLLOWING THAT LOGIC, BRAZIL, WHO HAS CERTAINLY MADE THE MOST PROGRESS IN THE USE OF ALCOHOLS AS A FUEL, SHOULD HAVE BEEN THE HOST FOR THIS THIRD SYMPOSIUM, BUT WHEN THE SELECTION WAS MADE THE INTERNATIONAL COMMITTEE WAS SUFFICIENTLY IMPRESSED WITH THE EFFORTS OF THE UNITED STATES TO INVITE THEM TO BE HOST. FOR MYSELF, I WOULD LIKE TODAY TO CONGRATULATE BRAZIL ON THE EFFORTS THEY ARE MAKING TO PROVIDE THEMSELVES WITH SOME DEGREE OF INDEPENDENCE FROM IMPORTED OIL.

AS THE CONFERENCE UNFOLDS, YOU WILL HEAR HOW NEW ZEALAND AND CANADA ARE ALSO MAKING PLANS TO USE INDIGENOUS NON-CRUDE OIL SOURCES, EITHER IN THE FORM OF BIOMASS OR NATURAL GAS, TO PROVIDE A RESOURCE FOR ALCOHOL MANUFACURE.

BECAUSE OF THIS WIDESPREAD INTEREST IT IS NOT SURPRISING THAT THIS SYMPOSIUM WILL PRESENT THE VIEWS OF AUTHORS OF 69 PAPERS FROM ELEVEN COUNTRIES. THE CONTENTS OF THOSE PAPERS WILL FIND YOU DISCUSSING A WIDE RANGE OF TOPICS ON ALCOHOL TECHNOLOGY.

FORTY-TWO OF THE PAPERS REFER TO ALCOHOL IN THE FORM OF METHANOL, AND SIXTEEN IN THE FORM OF ETHANOL, WHILE A FURTHER EVELEVEN REFER TO ALCOHOLS IN GENERAL.

THE SOURCE OF THE ALCOHOL IS USUALLY BY SYNTHESIS FROM SOME OTHER FOSSIL FUEL IN THE CASE OF METHANOL, AND BY FERMENTATION FROM AGRICULTURAL PRODUCTS IN THE CASE OF ETHANOL.

THE BALANCE OR EMPHASIS OF THESE PAPERS IS PERHAPS AS IT SHOULD BE BECAUSE THE POTENTIAL AVAILABILITY ON A WORLD-WIDE SCALE OF AGRICULTURAL PRODUCTS IS QUITE SMALL AFTER ALL FOOD DEMANDS HAVE BEEN SATISFIED. SOME

COUNTRIES LIKE BRAZIL ARE FORTUNATE IN HAVING LARGE UNCULTIVATED AREAS OF LAND IN A VERY GOOD CLIMATE, BUT OTHER COUNTRIES WITH ENERGY PROBLEMS ARE HARD PRESSED TO EVEN GROW THE FOOD THEY NEED FOR THEMSELVES--MUCH LESS GROWING THEIR ENERGY SUPPLY.

OUR ANALYSES HAVE SHOWN THAT THERE ARE, THROUGHOUT THE WORLD, EXTENSIVE RESOURCES OF RAW MATERIALS WHICH CAN BE CONVERTED INTO METHANOL ON A LARGE SCALE USING COMMERCIALLY PROVEN TECHNOLOGY. THE MAJOR RESOURCE IS COAL, BUT SOME COUNTRIES WITH LARGE AREAS CAN PRODUCE SIGNIFICANT QUANTITIES OF TIMBER, AND IN ALL COUNTRIES THERE ARE OPPORTUNITIES TO USE ORGANIC WASTES FROM LARGE URBAN AREAS.

ETHANOL ON THE OTHER HAND, USING EXISTING NORMAL TECHNOLOGY, IS PRODUCED BY THE FERMENTATION OF SEASONAL CROP MATERIAL, AND THEN ONLY ON A SMALL SCALE AS COMPARED TO METHANOL.

AS A "HAS BEEN" ORGANIC CHEMIST, I AM ALSO EXCITED BY THE UTILIZATION OF METHNAOL AS A FUEL IN THE FORM OF MTBE (METHYL TERTIARY BUTYL ETHER). THE REACTION OF METHANOL WITH ISOBUTYLINE CAN BE PERFORMED ALMOST QUANITIVELY IN ORDINARY EQUIPMENT EVEN IN THE PRESENCE OF OTHER C_4 OLEFINS -- IT IS ALMOST BEAUTIFUL IN ITS SIMPLICITY. THE RESULTING MTBE HAS AN ENERGY CONTENT ONLY SLIGHTLY LESS THAN GASOLINE, A BLENDING OCTANE NUMBER ABOUT 20 POINTS HIGHER THAN THAT OF THE NORMAL GASOLINE POOL, AND IS WIDELY MISCIBLE WITH GASOLINE REGARDLESS OF HUMIDITY CONDITIONS. I THINK IT REPRESENTS AN ELEGANT AND ECONOMICALLY VIABLE APPROACH TO BURNING METHANOL. AND, BEST OF ALL, THE ENVIRONMENTAL PROTECTION AGENCY HAS APPROVED THE USE OF UP TO 7% MTBE IN GASOLINE.

THUS, WE HAVE INEVITABLE COME TO THE CONCLUSION THAT ALCOHOL CANNOT HAVE ANY MAJOR IMPACT ON THE ENERGY SUPPLY SITUATION IN THE SHORT TERM, OTHER THAN IN EXCEPTIONAL CIRCUMSTANCES SUCH AS EXIST IN BRAZIL OR AS MTBE.

IN THE MEDIUM TERM WE BELIEVE ONLY METHANOL FROM COAL, OR REMOTE NATURAL GAS, CAN MAKE A SIGNIFICANT CONTRIBUTION, BUT WE ARE CONCERNED BECAUSE SOCIO-ECONOMIC FACTORS APPEAR TO BE OVERWHELMING ALL OUR EFFORTS TO DEVELOP METHANOL AS A FUEL.

THIS IS LARGELY DUE TO THE DIFFICULTY IN DEFINING THE VALUE OF METHANOL RELATIVE TO THE CONVENTIONAL LIQUID HYDROCARBON FUEL IT CAN REPLACE. METHANOL IS NO DOUBT CLEANER, CAN BE BURNED WITH A HIGHER EFFICIENCY, CAN BE WIDELY USED, AND CAN, IN ALMOST ANY COUNTRY, PROVIDE A MEASURE OF ENERGY INDEPENDENCE. THESE ATTRIBUTES, HOWEVER, MUST BE GIVEN A VALUE, AND I HOPE YOUR DELIBERATIONS THIS WEEK WILL GIVE SOME GUIDANCE, NOT ONLY TO ENERGY COMPANIES LIKE CONOCO, BUT ALSO TO LEGISLATORS AND THE CITIZENS THEY REPRESENT.

THE USE OF GOVERNMENT DIRECTIVES, SUBSIDIES, OR TAX RELIEF IS PROMOTING THE USE OF ETHANOL IN TRANSPORTATION IN THE UNITED STATES, BUT I BELIEVE YOUR DELIBERATIONS THIS WEEK WILL SHOW THIS USE TO BE TOO SMALL AND TOO UNECONOMIC TO HAVE A MAJOR IMPACT. IT IS HOWEVER APPARENT TO ME THAT THESE SAME INCENTIVES COULD BE USED MUCH MORE EFFECTIVELY TO ENCOURAGE METHANOL PRODUCTION.

THIS THIRD SYMPOSIUM ON ALCOHOL FUELS TECHNOLOGY IS BEING HELD AT A TIME WHEN THE WHOLE WORLD IS ACUTELY AWARE OF THE NEED FOR A CHANGE OF DIRECTION. THE GROWTH IN ATTENDANCE AND THE INCREASED INTEREST SHOWN IN ALCOHOL FUELS SINCE THE FIRST SYPOSIUM INDICATES THAT YOU HAVE AN OPPORTUNITY TO MAKE A POSITIVE CONTRIBUTION TO THAT CHANGE.

THE LAST SESSIONS OF YOUR CONFERENCE WILL BE DEVOTED TO TRANSITION SCENARIOS AND FORECASTS, AND SOCIO-ECONOMIC AND GOVERNMENTATL CONCERNS. I HOPE AND TRUST THAT YOU MAY COME OUT OF THESE LAST SESSIONS WITH CLEAR INDICATIONS OF HOW ALCOHOL CAN BECOME A VIABLE LIQUID FUEL IN THE NEXT DECADE AND EVEN RECOMMENDATIONS FOR SPECIFIC SIGNIFICANT PROJECTS. THE WHOLE WORLD NEES ALL THE ENRGY HELP IT CAN GET, AND IT NEEDS THAT HELP NOW!

GOOD LUCK TO ALL OF YOU.

ALCOHOL FUELS FROM BIOMASS IN NEW ZEALAND - THE ENERGETICS AND ECONOMICS OF PRODUCTION AND PROCESSING

by

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This paper summarises the current state of the on-going research programme on the economics and energy balance associated with the production and processing of alcohol fuels from biomass in New Zealand. Detailed analysis is given on three biomass alternatives, fodder beet (*Beta vulgaris*), straw residue and trees (*Pinus radiata*) - and two processing routes - ethanol by fermentation and methanol by gasification, since each highlights different and important aspects of the production and processing system framework from farm/forest to final product. Current indications are that alcohol fuels can be produced in New Zealand at a price close to that of imported, refined motor spirit, and future relative price movements will probably favour the indigenous alcohol fuel. The next stage in the New Zealand programme is pilot plant production systems, and this should commence within the next 2-3 years.

ENERGY SUPPLY AND DEMAND IN NEW ZEALAND

New Zealand is well endowed with most primary energy sources, having large reserves of coal, natural gas and hydro-electricity. It has, however, yet to discover any significant sources of indigenous liquid petroleum which means that in total, the country has a very high dependence on imported energy, all of which is petroleum. Table 1 shows the relative proportion of primary energy consumption in New Zealand compared with the U.S.A. and highlights the fact that in 1977, imported oil formed over 48 percent of all primary energy used in the country.

Table 1
Relative Proportion of Primary Energy Consumption

Energy Source	U.S.A. (1973)	N.Z. (1977)
	%	%
Coal	17.8	12.8
Petroleum	43.3	57.8 (48.8 imported (9.0 indigenous
Hydroelectricity	4.0	11.5
Natural gas	33.7	17.9
Nuclear	1.2	-

Source: References (1)*and (2).
*Numbers in brackets (1) designate References at end of paper.

The cost of this imported oil has escalated dramatically since 1970, when it required $75 million or eight percent of the value of all imports. Now the cost exceeds $500 million or over 15 percent of all import payments. For economic and strategic reasons, therefore, the Government is encouraging the development and use of indigenous alternatives(2). There is a rapid movement away from imported oil to gas and coal for non-transport uses but because over 90 percent of transport fuel is currently imported, it will require much time and effort to have a large impact on this sector - indeed, a 1977 scenario study by the New Zealand Energy Research and Development Committee(3) concluded that provision of transport fuels is by far the most significant energy problem faced by New Zealand. Total domestic transport fuel use in New Zealand approximates 100 PJ(4).

The large Maui natural gas field which is due to come on stream later this year has an estimated capacity of over 6000 PJ. This is capable of meeting all the expected non-transport demands and fifty percent of the transport demands for at least 40 years. The use of CNG (compressed natural gas) and LPG (liquified petroleum gas) in fleet vehicles appears economically attractive and very much in the nation's interest. Proposals are being investigated for the production of methanol from natural gas for blending with gasoline to about the 15 percent level. Trials have been underway in N.Z. for over five years(5). If these measures were used to the maximum extent with no insoluble problems arising, approximately 50 percent of the imported transport fuels could be replaced from indigenous sources. The life of the natural gas field is of course finite and it is expected that less than 50 percent of the field will remain at the turn of the century. In the longer term N.Z. could manufacture methanol or synthetic gasoline from coal for transport uses, and/or turn to biomass.

In 1977 the New Zealand Energy Research and Development Committee established the Energy Farming Research Group to examine the potential of N.Z. to produce transport fuels from specifically grown biomass. Three of the options discussed in their report(6) are summarised in this paper. As background, however, an overview of New Zealand agriculture and forestry is given in the next section.

AGRICULTURE & FORESTRY IN NEW ZEALAND

New Zealand has nearly 27 million hectares of land and a population of 3.1 million. Fifty percent of the land is classifiable as flat, rolling or moderately steep, and with mean temperatures of 15°C in the north to 9°C in the south and the majority of the country receiving an annual rainfall between 600-1500 mm, conditions for temperate zone agriculture are very favourable. In fact, agriculture is the industry in which New Zealand's prosperity depends.

There are 60,000 farm holdings in New Zealand covering 21.2 million ha. Individual ownership is the predominant organisation type. Crops grown in New Zealand are generally sufficient to meet domestic needs except for some overseas trade in specialist products, so it is the pastoral sector (meat, wool and dairy) whi dominates the agricultural scene. Exports of pastoral products contribute around 70 percent of total export receipts. In total, agriculture generates 10 percent of the national income and employs 11 percent of the work force.

The majority of the 7 million ha of forested land in New Zealand is unmerchantable because of topography or conservation reasons. Plantings of exotic pines totalling 0.7 million ha form the mainstay of the forest industry, and with a current rate of annual planting of 40,000 ha, this pattern will continue. The sector contributes around eight percent of export receipts, mainly in pulp and pulp products, and employs four percent of the work force.

New Zealand farming and foresty has established expertise in the production of low cost biomass. The next sections discuss the implication of diversification from traditional products to energy farming.

ETHANOL FROM FODDER BEET (*Beta vulgaris*)

Fodder beet is a very high yielding forage crop obtained by crossing two other beet species, sugar beet and mangolds. It combines the high yields and varied growth habit of mangolds with the high dry matter content of sugar beet. Susceptibility to beet cyst nematode (*Heterodera schachtii*) may restrict plantings to a one in five year rotation.

The attraction of fodder beet as a feedstock for energy farming is its high yield of fermentable sugars on a per hectare basis(7). Sugar yields of 64-70% root DM (dry matter) have been recorded, and with root yields of 15-20 ODT ha^{-1} (oven dry tonnes per hectare) dryland or up to 30 ODT ha^{-1} irrigated, sugar yields can be very high - for this analysis an irrigated root yield of 120 t ha^{-1} is assumed, equivalent to 15 t ha^{-1} sugar, or over 9000 litres ethanol ha^{-1}. This compares with yields of 4000 ℓ ha^{-1} from sugar cane and sugar beet, 2300 ℓ ha^{-1} from cassava and eucalyptus, and 1000 ℓ ha^{-1} from wheat(8).

Further trials are needed to isolate the growth, harvest and storage conditions that will maximise the yield of fermentable sugars on a per hectare basis. For instance, fodder beet storage may be much more flexible than for sugar beet since the creation of inert sugars and/or oligosaccharides does not impair the value of this feedstock for alcohol fermentation. Current indications are, however, that this species of beet will provide a high yielding feedstock which will be energetically and economically attractive for energy farming.

Feedstock Supply

It is envisaged that fodder beet grown specifically for energy processing would all be supplied in a free market situation with contracts between the factory and individual farmers. This contrasts with the situation where the processing factory owns the land used or biomass supply, but reflects the existing New Zealand farm land ownership pattern which is predominated by small-medium sized individual holdings. The raw material supply function would depend on the comparative profitability of fodder beet and traditional enterprises on particular farm types, but since irrigated Class 1 soils are preferred, proven relatively high net returns would be essential to guarantee concentrated planting densities. Beet production would integrate well with the existing rotational crop farming pattern on the better soils in New Zealand, and complement the current product mix. It is an already established crop and its incorporation into an energy cropping system would be an extension of existing expertise and technology. Plantings would probably vary between 10-40 ha per unit, with seeding in September-October and harvesting from May-August. Beet storage could extend the feedstock supply period for up to eight months.

Beet Processing

The processing scheme used for beet is relatively simple requiring no high pressure or high temperature technology. The beet, either from the storage heap or freshly delivered, starts its processing as does sugar beet for sugar production by being washed, sliced into cossettes, and the sugar extracted in a countercurrent cooker/extractor which produces an 8-10% sugar solution. The extracted beet can be either pressed and sold for stockfood, or sent to the methane digesters.

The continuous fermenters work on the sugar solution and produce a 4-5% alcohol solution which is centrifuged from the yeasts. The bulk of the yeast is recycled to the fermenters, and the alcohol distilled in a single still to produce 94.5% wt ethanol.

Evaporation to concentrate the sugar solution is not attractive energetically or economically. It also leads to some degradation of sugars and more importantly the degradation products inhibit fermentation. The stillage is mixed with any waste yeast or beet residues not used for stock food and anaerobically fermented to produce a CO_2, methane gas mixture used as boiler fuel.

All processing steps used in the costings are conventionally and well developed. The only movel features are in the integration of the individual steps to produce the overall package. When all residues are fed to the methane digesters the plant is self-sufficient in thermal energy. An overall energetics analysis of the plant shows that it is capable of yielding more than 54% of the energy contained in the beet fed as energy in the product ethanol.

Economics

Details of a hypothetical 200 ODTPD (oven dry tonne per day) beet ethanol processing factory are shown in Table 2. An average figure of \$40 ODT^{-1} for the delivered cost of beet is made up of net return to the farmer (35%), input costs (19%), harvesting (19%), and assembly 14 km to the plant (27%). This generates a final product price of \$6.80 GJ^{-1}. Since the delivered cost of feedstock represents approximately 70 percent of the final product price, the magnitude of this cost factor is very important. A low rate of farmer uptake, for instance, will increase assembly distance and markedly affect final product price. Fig. 1 graphically depicts this relationship, and shows that if uptake is only one percent (i.e. one ha in every 100 ha planted in beet), average assembly distances increase to 32 km and final product price to \$7.50 GJ^{-1}. Clearly there is a minimum cost tradeoff between the net return paid to the farmer and planting densities , since high returns will lead to concentrated planting and low assembly costs.

Table 2
Ethanol Plant Statistics

Feedstock:	Fodder beet
Plant size:	200 ODTPD (oven dry tonnes per day)
Capital Cost[a]:	\$6.3 million
Operating period[b]:	8000 hours year^{-1}
Raw material requirement:	370,500 t year^{-1} (66,700 ODT)
Crop yield:	120 t ha^{-1} @ 18% DM (irrigated)
Planted area:	3100 ha
Planting Density:	5% (5 ha in every 100 ha)
Collection Area:	From 14 km circular area adjacent to factory, or from 62,000 ha.
Conversion:	0.35 t ethanol per ODT beet
Production:	23,170 tonnes ethanol year^{-1} 29.6 x 10^{6} litres pure ethanol year^{-1}
Delivered cost of feedstock:	\$40 ODT^{-1}
Product Price: (ex factory 10% DCF 15 yrs)	\$6.80 GJ^{-1} \$184 tonne^{-1} 15¢/ℓ petrol equivalent in blend 19¢/ℓ petrol equivalent pure
Delivered cost of feedstock as a proportion of product price:	70 percent
Employment:	28 shift workers 5 permanent staff

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[a] At the time of writing, February 1979, NZ\$1.00 = US\$1.05

[b] Although costings assume an 8000 hour annual operating period, respiration of sugars with storage will probably restrict the operation to 6-8 months (4000-5000 hours). Since the raw material cost constitutes 70 percent of the final produce price however a reduced operating period does not change the product prices significantly.

Energetics

The energy balance associated with fodder beet-ethanol looks very attractive. The total direct and indirect energy requirements for delivery to the factory are estimated at 19.6 GJ ha^{-1} year^{-1}, or 0.91 GJ ODT^{-1}. With a plant yield of 21.6 ODT ha^{-1} and calorific values of 17.7 MJ kg^{-1}, the net energy yield into the factory is 362 GJ ha^{-1} year^{-1}, or an energy ratio of 19:1.

The overall energy ratio ex factory is estimated at 10:1*.

METHANOL FROM STRAW RESIDUE/WOOD

An alternative alcohol fueld option is the production of methanol from straw or wood. The next section discusses these two routes.

Straw Residue Feedstock

Straw residue as a feedstock for energy farming has formed the basis for much of the research in Europe, England, Canada, the U.S.A., and Australia. The main reason for this emphasis is the low opportunity costs associated with most straws because they have little alternative use. In addition since they are commonly regarded as a byproduct of grain production, the costs and energy requirement of production are totally attributed to the principal crop of grain, and therefore straw represents a cheap source of cellulose.

Approximately 210,000 ha of white straw crops (wheat, barley and oats) are grown in New Zealand, sufficient for domestic requirements only. The plantings are concentrated in the Canterbury region of the South Island, and since wheat and barley straw have little alternative use, they provide a readily available supply of biomass - indeed, it has been estimated that 99 percent of wheat straw and 90 percent of barley straw is either discarded or burnt.

Wheat and barley grain yields of 3.5 and 3.3 t ha^{-1} are estimated to yield 3.1 and 1.95 t ha^{-1} collectable straw residue respectively, or a total collectable biomass of 196,000 tonnes (at 85% DM) from a collection radius of 90 km within the Canterbury region(9).

Wood Feedstock

New Zealand exotic forestry is dominated by plantings of *Pinus radiata* (Monterey pine) which achieves growth rates of 11 ODT ha^{-1} year^{-1} on an 18 year rotation. The plantings have, however, been concentrated in the periods 1925-36 and 1965+, so there is a large imbalance in the age structure of the forest estabe. Current harvesting is largely from stands planted during the depression but timber supply is expected to increase dramatically after 1990 as the later plantings come on stream.

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* Defined as the ratio of energy in the product at the plant battery limits over the total energy in production, assembly and processing. Lower calorific values used.

State exotic forests are concentrated in the Rotorua region of the North Island which contains 332,000 ha of net productive stocked area, or over half of the New Zealand total. This includes the Kaingaroa State Forest of 108,950 ha, which produces an estimated 300-400 ODT day^{-1} of radiata pine residues from current clearfelling operations.

Research on wood as a source of biomass for energy farming has therefore initially concentrated on utilisation of the existing residue and the potential timber surplus from 1990, although more analysis is needed on the hardwood options, especially short rotation coppiced stands.

Processing of Straw or Wood

The most economical method of processing cellulose and lignin is gasification (12), which involves the construction of large plants incorporating high pressures (up to 10 MPa) and high temperatures (up to 1 000°C). The initial processing step involves gasification of the feedstock with oxygen. This process is commonly done with coal but is as yet unproven on a large scale with straw or wood. This produces a gas which is predominantly CO, H_2 and CO_2, but does contain four percent methane which justifies reforming to CO and H_2. The H_2 to CO ratio is too low for methanol manufacture. The H_2 to CO ratio at 1:3 is well below the stoichiometric requirements for methanol synthesis so that a significant CO shift is required, viz.

$$CO + H_2O \rightarrow CO_2 + H_2$$

to produce more H_2.

Most of the original CO_2 present plus the CO_2 produced in the shift reaction is then removed by absorbtion in propylene carbonate or N methyl pyrolidene before compression and methanol synthesis over a copper, chrome, zinc catalyst. The synthesis is done at between 5 MPa and 10 MPa depending on plant size at 260°C.

$$CO + 2H_2 \rightarrow CH_2OH$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

The methanol and water is condensed from the recycle gases from which the purge is taken for reforming of the methane.

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

Some of the purge gases are used to fire the reformer which runs at 920°C.

The gasification, clean up, shift, CO_2 removal and synthesis sections of the plant are overall self-sufficient in steam and it is only the oxygen plant which uses significant electrical energy for compression. Further engineering design optimisation could well produce much of this energy. The overall processing energy efficiency is about 48%; that is the energy in the product methanol is 48% of the total energy into the plant including the raw material.

Within the gasification technology used for the costing the only processing step which required proving on a large scale is that of the primary gasification of the raw material. Subsequent processing is conventional technology and well developed.

Economics

The data on methanol plants using alternative feedstocks is summarised in Table 3. Each of the alternatives is discussed below:-

Straw residue: It is estimated that the average cost of straw residue collected from the Canterbury region and delivered to a centrally located processing plant would be \$40 ODT^{-1}. This estimate is based on a Hesston 4800 Big Bale system, with farmers being paid \$18.40 ODT^{-1} for the straw and a roadside cost of \$28.50 ODT^{-1}. Although these costs are higher than U.S. estimates, they reflect relatively higher opportunity costs for the straw and smaller paddock sizes in the N.Z. situation. The final product price at \$9.60 GJ^{-1} is equivalent to the energy forest option where the higher delivered cost of the feedstock (\$55 ODT^{-1}) is matched by the scale economies in the larger processing plant (2500 ODTPD as against 500 ODTPD).

Forest residues*: Forest logging residues currently have no alternative use, and their opportunity cost is therefore minimal compared with other forestry options. The estimated cost of harvesting, chipping and transport vary widely however, mainly because of fluctuations in the moisture content of the residues (from 5% - 60%) depending on weather conditions at harvest and storage. The delivered feedstock cost of \$30 ODT^{-1} used here is made up from \$16 for recovery, \$6 for chipping and transport over 20 km at \$8. This could range in particular situations by up to \$7-8 ODT^{-1}, but the product price of \$8.60 GJ^{-1} indicates the need for further detailed research into this option.

Energy forests: There are five cost components in using exotic forest estate as a feedstock for an alcohol fuels programme - opportunity cost (net return foregone by diverting resources from alternative use), and the costs of production, harvesting, chipping and transport. Clearly, if the existing forest estate has potential use for log or chip export, or new energy forests are planned, all five costs are involved. At the other extreme however, if the wood is totally surplus to requirements, only the last three cost components are relevant. Delivered costs therefore

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* Data on the production economics and energetics of the forestry option is drawn from (10).

vary widely but the \$55 ODT^{-1} assumed here reflects the present value of all the costs and potential returns attributable to an 18 year rotation *P. radiata* forest, and is made up of opportunity cost (\$5), growing (\$20), harvesting (\$13), chipping (\$10) and transport (\$7). This assumes total harvesting of above ground biomass using a feller-buncher and fertiliser application to maintain nutrient balance. The costs are dominated by the growing component which represents 36 percent of the feedstock price, so it is clear why the forest residues option appears so comparatively attractive.

Indeed, the final product price of \$9.60 GJ^{-1} is significantly above that using a feedstock of logging residues, but if substantial substitution of methanol is required in the New Zealand vehicle fleet, large resource shifts to energy forests may be essential.

Table 3
Methanol Plant Statistics

Feedstock:	Wheat & Barley straw	Forest Residue	Energy Forest
Plant size:	500 ODTPD	500 ODTPD	2500 ODTPD
Operating period:		8000 hrs $year^{-1}$	
Capital cost:	\$NZ 35 million	\$NZ 35 million	\$NZ 110 million
Raw material requirement:	196,100 t yr^{-1}	166,700 ODT	833,300 ODT
Conversion:		0.47 t methanol per ODT wood	
Production:		78,767 t methanol 99.7 x 10^6 l pure methanol	
Delivered cost of raw material:	\$40 ODT^{-1}	\$30 ODT^{-1}	\$55 ODT^{-1}
Product price:			
$\$GJ^{-1}$	\$9.60	\$8.60	\$9.60
$\$tonne^{-1}$	\$192	\$172	\$192
Petrol equiv.			
¢/l blend	27	24	27
¢/l pure	17	15	17
Delivered cost of feedstock as a proportion of final product price:	40%	35%	50%
Employment:	40 shift 18 permanent	40 shift 18 permanent	60 shift 25 permanent

Energetics

The energetics of the straw and forest options are presented below.

Straw residues: All energy inputs associated with growing the grain crop are debited to the primary crop. The direct and indirect energy expended in windrowing, baling, loading and assembly is estimated at 1.8 GJ ha^{-1}, or 0.65 GJ t^{-1}. At an average weighted straw yield of 2.8 t ha^{-1}, and average calorific value of 17.8 MJ kg^{-1}, the net energy gain at the factory gate is estimated at 40 GJ ha^{-1}, or an energy ratio of 23:1. On an ex-factory basis, the energy ratio is 11:1.

Energy forest: The direct and indirect energy inputs to growing, management, harvesting, chipping and assembly of wood from an energy forest are estimated at 0.9 GJ $tonne^{-1}$. This assumes an 18 year rotation untended energy forest with total chipping of above ground biomass and fertiliser application for nutrient replacement. With an average yield of 10.6 ODT ha^{-1} $year^{-1}$, this implies a net energy gain of 18.2 GJ $tonne^{-1}$ of chips delivered to the mill (193 GJ ha^{-1}), or an energy ratio of 21:1. The overall energy ratio ex factory is 10:1.

IMPLICATIONS

1. The economics of alcohol fuel extenders at ethanol/methanol prices of 15-17 ¢/l petrol equivalent in blend compares well with the current prices of imported premium motor spirit of 14.7 ¢/l.

2. The net balance on foreign exchange indicates a substantial benefit in favour of ethanol from agricultural crops - import savings of \$1160 to \$1330 ha^{-1} - more than offset the lost export income from traditional exports of \$450 to \$660 ha^{-1}.

3. Energy farming could significantly affect regional development in N.Z.

4. The strategic implications of energy farming are significant. Currently N.Z. is reliant on overseas suppliers for 90 percent of her transport fuel requirements and recent events in Iran underscore the vulnerability of such a dependence.

SUMMARY

New Zealand has many similarities with Brazil when an alcohol fuels programme is considered - a large proportion of export earnings are currently allocated to the import of transport fuels, yet there is an abundance of temperate zone agricultural land for biomass production. The economics and energetics of both beet-ethanol fermentation and straw/wood-gasification look attractive with high alcohol yields and product prices comparable with imported refined motor spirit. Pilot plant production systems should commence within three years, and it is probable that alcohol fuels from biomass will contribute a significant proportion of the motor spirit pool by the end of this century.

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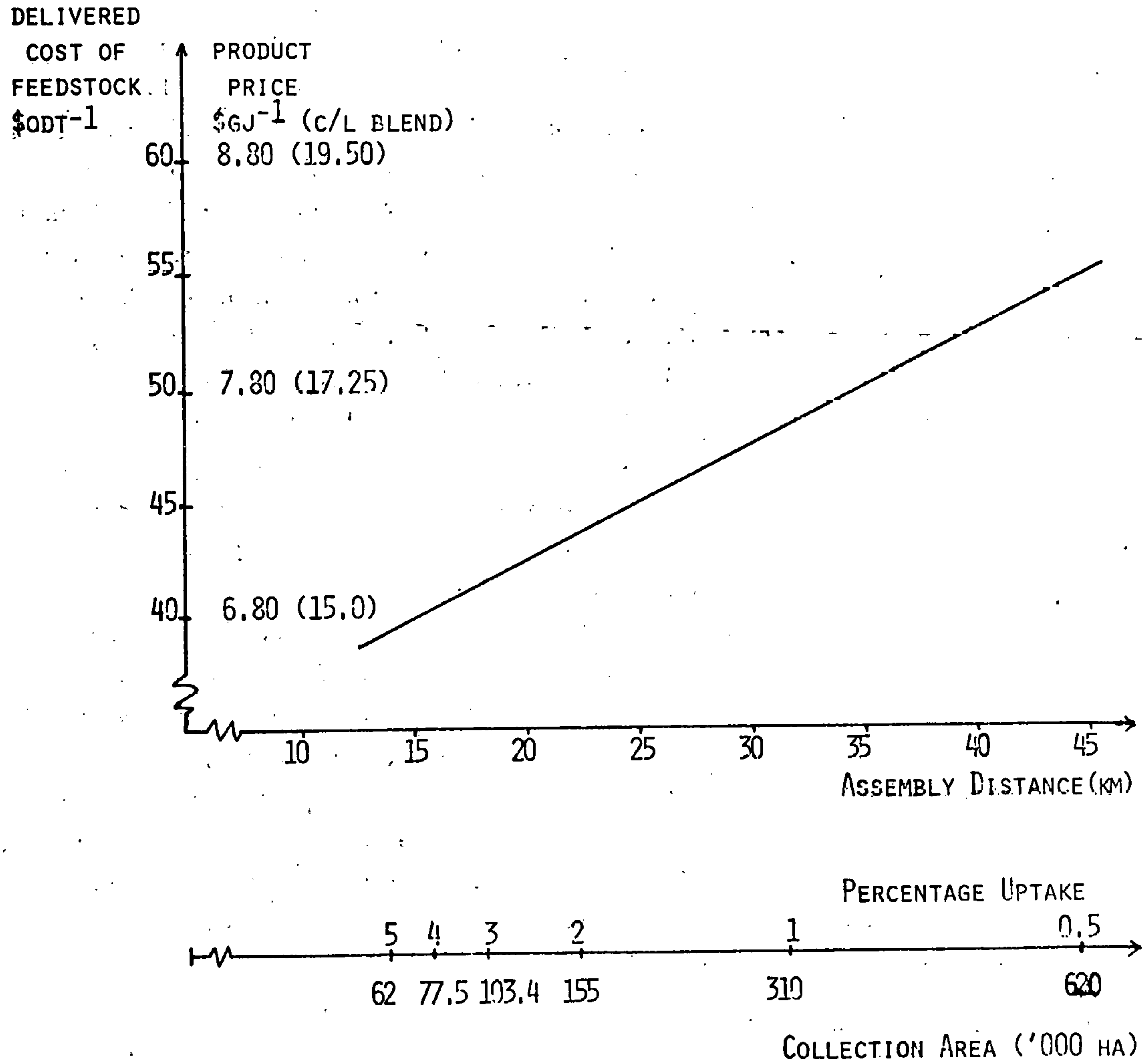
Fig. 1

FODDER BEET ASSEMBLY COSTS AND PRODUCT PRICES



THE GROWING OF SUGAR CANE FOR ENERGY

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INTRODUCTION

In April, 1975 Dr. Melvin Calvin, Nobel-prize winning chemist from the University of California, Berkeley and the author were invited to Brasil (PLANALSUCAR) to discuss with their technologists the potential of growing sugarcane for energy on a large scale. A green light was given to their programs. President Geisel announced on Oct. 9, 1975 that a National Alcohol Commission would be created permitting the use of alcohol as a fuel, with up to 20% mixtures with gasoline, to reduce costly petroleum imports. Their National Alcohol Commission was established in November, 1975. By July, 1976 they had 14 new distilleries in operation. By August, 1977 they had 51 new distilleries producing at an annual rate of 3.65 billion liters. By September, 1978 they had 74 new distilleries producing at an annual rate of 4.5 billion liters. Brasil has not achieved these annual goals, as many distilleries have not produced continuously at their rated capacities for entire seasons, but their production is climbing dramatically.

The author is a consultant to many Usinas in Brasil, increasing sugarcane production per hectare and thus lowering the cost per liter of alcohol produced. Brasil averages 50 tons cane/ha., while the Usinas in the State of Sao Paulo average 65 tons cane/ha. Usina da Barra, for example, now has 70% of their acreage averaging 90 tons cane/ha. They produce 3 million tons of cane per year, with one million tons cane processed directly into alcohol. All of the molasses produced from the two million tons cane for sugar is upgraded into alcohol. Usina da Barra is currently producing over 500,000 liters alcohol per day.

Doubling sugarcane production per hectare through improved cultural practices and varieties selected for their capabilities of "total sugars" production, rather than sucrose alone, result in approximately 30% reduction in costs per liter of alcohol produced. In this period of increasing costs of fossil fuels, sugarcane production for energy is certain to gain prominence in supplying a part of the energy needs of many developing countries of the Tropics that are now forced to import fossil fuels at ever-increasing prices.

VARIETIES SELECTED FOR TOTAL SUGARS PRODUCTION

Sugar cane varieties are being selected, not for their sucrose production, but for their "total sugars" production. Glucose and other reducing sugars are nearly equal to sucrose in fermentation into alcohols. In fact, sucrose reverts to glucose prior to its conversion into alcohol, as shown in the following formula:

$$C_{12}H_{22}O_{11} + H_2O \dashrightarrow 2\ C_6H_{12}O_6$$

Sucrose	Glucose

$$C_6H_{12}O_6 \dashrightarrow 2C_2H_5OH + 2CO_2$$

Glucose	Alcohol	Carbon dioxide
180 grams	92 grams	
672 KCal	655 KCal	

Varieties in order to be selected for alcohol production must have a high stalk population. High stooling varieties, such as NCo376 that have up to 160,000 stalks per hectare, are desirable. The variety must be fertilizer responsive and be able to use supplementary applications of fertilizer to continue its "boom stage" of growth until near harvest time. Variety L60-14, for example, in replicated variety trials at Hda. San Francisco, Tambo Valley, Peru produced 391 tons cane/ha. for alcohol in 26 months vs other varieties that produced as little as 128 TCH in the same period. Varieties are now available that can produce 200 TCH per year for alcohol!

The varieties selected for alcohol should be responsive to the chemical ripeners such as POLARIS and ETHREL, so that vegetative growth can be curtailed very quickly, and the sugars stored in the stalks--not used as energy for continued vegetative growth.

The varieties selected will have a full canopy of green leaves six weeks prior to harvest when the chemical ripeners are flown on. Desiccants such as Gramoxone (Paraquat) are then flown on ten days prior to harvest to improve the burns and reduce the trash-in-cane taken to the mill.

SUPPLEMENTARY APPLICATIONS OF FERTILIZER

Multiple supplementary applications of fertilizer, usually nitrogen (urea) and potash (muriate of potash) are applied at 5, 7, and 9 months of age to keep the cane growing at optimum rates. With 14 or 15 green leaves in the canopy, less than 5% of the foot candles of energy falling on the upper leaves ever reach the soil. With stalk populations up to 160,000 stalks/ha. there is no light at the base of the stools to encourage sucker growth, unless lodging has occurred.

Application rates range from 50 to 100kg/ha. of urea and 50 to 100 kg/ha. of muriate of potash per application. Heavy phosphate fertilization has been applied with the seed at planting time to encourage rapid root and shoot development. Total NPK application rates range from 200 to 300kg N/ha; P_2O_5 ranges from 100 to 200kg/ha; and K_2O ranges from 200 to 400kg/ha.

Continued feeding results in extended periods of "boom stage" of growth, in large diameter stalks with long internodes continuing until the chemical ripeners are applied. Balanced feeding is absolutely essential to keep the sugar cane plant growing at or near optimum rates. Table 1 shows data from Hawaii(5) stressing the fact that potassium deficiencies retard the conversion of reducing sugars into sucrose in the cane plant.

TABLE 1

PREHARVEST ANALYSES OF VARIETY H37-1933 AT LIHUE, HAWAII

Field Yields	%8-10 Stalk H_2O	%8-10 Stalk N	%8-10 Stalk K	% Reducing Sugars	% Sucrose	Tons Cane/ha.	Tons Cane/TS
17 TS/ha	80.7	0.42	0.68	11.8	37.5	178	10.62
17-25TSH	77.1	0.25	1.22	6.4	41.7	215	9.64
25-32TSH	75.3	0.19	1.47	5.7	46.2	197	7.13

These data show marked differences in sugar yields because of potassium deficiencies. The same cane produced for alcohol would show smaller differences, but still in favor of balanced nutrition for higher cane yields and higher total sugars production.

OPTIMUM MOISTURE CONDITIONS

The supplementary fertilizer applications are timed when optimum moisture conditions exist. Supplementary irrigations are applied to prevent moisture from becoming a limiting factor of growth. At Usina Sao Luiz (Didini, Brasil) large block tests with multiple applications of fertilizer by airplane, with a new variety Co775 and supplementary sprinkler irrigation, increased cane yields from 80 tons cane/ha. to 177 tons cane/ha. per year with significant reductions in costs per liter of alcohol produced.

The record yields of sugar cane production are now being produced where daily water balance charts are kept, considering the water storage capacities of the soils in the depth of rooting, pan evaporation from a free water surface, and water supplied either as rainfall or in irrigations. Tambankulu Estates in Swaziland, Africa grow up to 235 tons cane/ha. in 13 months of growth, which is 18 tons cane per hectare per month. During the "boom stage" of growth, after full canopy has developed, they apply 27mm of water every 3 days in solid set sprinkler irrigation. Their 1977 blocks treated with extra nitrogen and potash applications by airplane costing R157/ha. produced 27 tons cane/ha. extra, worth R280/ha. for a 78% profit.

RIPENING PRIOR TO HARVEST

In the growing of sugarcane for sugar, it has been necessary to precede harvest with a ripening period of several weeks to several months in order to dehydrate the reducing sugars to recoverable sucrose. The formula is as follows:

$$\underset{\text{Glucose}}{2\ C_6H_{12}O_6} - H_2O \dashrightarrow \underset{\text{Sucrose}}{C_{12}H_{22}O_{11}}$$

In the growing of sugarcane for alcohols and cellulose it is not necessary to ripen the cane and convert most of the sugars to sucrose. The reducing sugars are equally as important as sucrose in the fermentation processes.

Chemical ripeners and plant growth regulators are now being used commercially to convert the cane growing luxuriently to a cycle of sugar storage. In 1977, seventy-five percent of the acreage of cane harvested in Hawaii used POLARIS to reduce the time required for ripening from as long as 7 months to 8 weeks, with approximately two tons sugar/ha. more "in the bag".

POLARIS is being used commercially in some 15 countries, with consistently good results, now that the varieties have been identified that respond to POLARIS. ETHREL is being used commercially in four countries on sugarcane, largely in Southern Africa. Other chemical ripeners have not given consistently good results in replicated trials with POLARIS and ETHREL in many countries.

USE OF VINACA FOR SOIL IMPROVEMENT

The remainder of the fermented juice after alcohols have been distilled off, vinaca, is hauled or pumped back on the fields near the mill. Vinaca is acid and corrosive, so is usually hauled back to nearby fields in stainless steel tank trucks and trailers. Where irrigation is practiced, the vinaca is applied in the mill water to fields below the mill. If necessary, the vinaca and mill water are pumped to higher elevations to spread the large quantities of vinaca over larger areas so as not to build up excessively high levels of potash in the soils. Vinaca is usually applied at rates of 30 to $50m^3$/ha. Vinaca is high in organic matter, and high in potash, particularly if molasses from sugar production is upgraded into alcohol along with juice from cane. Typical formulas of vinaca are shown in Table 2.

TABLE 2

CHEMICAL COMPOSITION OF "VINACA" (BRASIL)

	From Molasses %	From Cane Juice %
Total Solids	6.4 - 6.7	6.5 - 6.7
Organic Matter	4.6 - 5.0	4.8 - 5.2
Mineral Matter	1.9 - 2.1	1.4 - 1.6
N	0.04 - 0.05	0.01 - 0.02
P	0.01 - 0.02	0.01 - 0.02
K	0.4 - 0.7	0.1 - 0.2
Ca	0.07 - 0.10	0.04 - 0.06
Mg	0.02 - 0.03	0.01 - 0.02
pH	4.2 - 4.8	4.2 - 4.6

In Hawaii, with continuous applications of irrigation water high in potassium, 1,000kg/ha. K_2O were applied per year, causing KCl to crystalize out in the cane juice. Application rates of $50m^3$/ha. of vinaca means up to 350kg/ha. K_2O applied with the vinaca comes from molasses, per application.

As cane yields are increased, potassium removed from the soils will mean higher potash fertilization requirements on 80 to 90% of the acreage in cane. Two million acres per year are now being planted to cane in Brasil for alcohol and cellulose production. A 100 ton crop of cane removes about 250kg K_2O, which must be replaced in fertilizers if continued high yields are expected. The 10 to 20% of the area that receives vinaca will receive no potash fertilizers. In the 80 to 90% of the acreage producing heavy cane tonnages (120-200TC/ha./year) fertilizer formulas ranging from 2-1-2 to 2-1-4 are expected to be used in the future.

ENERGY OUTPUT/ENERGY INPUT FOR SUGARCANE

Sugar cane is the world's most efficient plant, on an annual basis, in the converting of sunlight energy into stored energy. Many plants actually have a negative energy balance of inputs to energy output. Detailed studies by the author have shown up to five times the energy stored as the total of energy inputs in seedbed preparation, fertilization, cultivation and herbicide usage, harvesting and cane transport. A part of the favorable energy balance is due to the long cycle of plant and many ratoon crops where high energy costs of planting occur only once in ten or more years. The ratoon crops have a much higher energy stored/energy inputs ratio than plant cane. They start faster, develop a full canopy of green leaves sooner, and store more total sugars per hectare per annum than plant cane.

Since energy is such an important factor in food, fiber and energy production, it is interesting to compare the energy expended to produce different crops. Table 3 compares the energy produced vs input energy for many crops.

TABLE 3

ENERGY CONTENT VS ENERGY INPUTS FOR FOOD CROPS

Food Crop		Calorie Content per Calorie Input
Barley		6.6
Wheat		5.4
Sugarcane		5.0
Sweet sorghum:	Grain & Stems	3.39
	Stems only	2.27
Corn		3.3
Rice		2.6
Potatoes		2.1
Cassava		1.7
Apples		1.3
Dry beans		1.2
Grapes		1.1
Tomatoes		0.76
Peaches		0.73
Green beans		0.55
Oranges		0.43
Lettuce		0.34
Cauliflower		0.25

Even though barley and wheat have a higher energy output vs input ratio, the much higher total energy production per hectare per year for sugarcane places this crop in a class by itself. The harvesting of sugarcane can be completely mechanized at a cost often lower than manual operations.

VALUE OF SUGAR CANE BAGASSE CLIMBING

Sugarcane bagasse, the fibrous material from which the juices and sugars have been extracted, is rapidly becoming as valuable as sugar or alcohol. Thirty-three countries now have cellulose plants using bagasse as the raw material, from which many pulp and paper products are produced. Cellulose from bagasse now has a value of US $270 per metric ton, and is climbing steadily. Brasil, for example, now imports 300,000 tons of pulp and paper products per year. By the mid 1980's they expect to export 2,000,000 tons of cellulose from sugarcane bagasse, eucalyptus and pine fibers to Europe and the United States. In processing sugarcane for alcohol, approximately 40% excess bagasse is not needed for processing the cane and for alcohol production, and can be used in cellulose plants.

FUTURE FOR ALCOHOL FUELS FROM SUGAR CANE BRIGHT

All sugarcane growing, petroleum importing countries in the Tropics have a potential of producing a part of their energy needs as alcohols from cane. Equipment costs are relatively cheap, when compared to the costs of sugar mills. Smaller sugar mills, no longer economic for sugar production, can be economic for alcohol production. 100,000 liters/day distilleries require only 60 tons cane per hour, or a relatively low milling capacity.

Since the juices are not converted into sugar, the power and energy requirements of the alcohol plants are far less than that for sugar mills. Consequently, capital investments are far less than those for sugar mills.

The costs of anhydrous alcohol production in a number of consulting mills of the author in Brasil average in a range of US $0.21 to $0.24 per liter. Average cane yields per hectare in Brasil are only 50 tons/ha., with the Sao Paulo mills averaging 65 tons cane/ha. As yields climb, first to 100 TCH and later to 150 and even 200 TCH, costs per liter of alcohol produced will decline. This will be in a period of ever-increasing costs of fossil fuels, so alcohol production for fuel from sugarcane has a bright future!!!

ECONOMIC FEASIBILITY STUDIES

Economic feasibility studies have been completed by your author for private sectors in Panama, South Africa, Costa Rica and The Philippines in the growing of sugarcane for energy--alcohol, cellulose, and animal feeds. Contracts have already been signed for Brazilian distilleries in Costa Rica. Other contracts are certain to be signed in the near future.

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ASPECTS OF ENERGY CONVERSION IN THE PRODUCTION OF METHANOL FROM COAL

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METHANOL PRODUCTION METHODS

In the methanol plants constructed in recent years with a capacity of 1.000 t/day and more, natural gas is used exclusively as feedstock for synthesis gas production.

The energy requirement for the production of one ton of methanol on the basis of natural gas is at present approx. 32 - 34 GJ. The net calorific value of methanol being 20 GJ/t, this corresponds to an efficiency of about 60 %. At present, methanol plants are designed for the production of high-purity methanol. When producing methanol for use as a fuel, the purity requirements may be reduced, thus resulting in savings in the synthesis and distillation units.

A methanol plant on the basis of natural gas comprises relatively few plant sections. Synthesis gas is supplied from the steam reforming plant at required composition and can be fed directly to the methanol synthesis unit after intermediate compression without any other treatment.

The production of methanol from coal requires an extensive plant complex, see Fig. 1. The energy conversion rate in the individual process stages is of considerable importance for assessing the feasibility of the process.

ENERGY CONVERSION IN THE PRODUCTION OF METHANOL FROM COAL

PRELIMINARY REMARKS

The energy yield in the individual process stages in the production of methanol from coal has been examined and its effect on the overall efficiency, which is found by multiplying the partial efficiencies of the individual steps, will be discussed.

Autothermic gasification of coal has been taken as a basis, that is, gasification with the aid of oxygen, to which steam is added, depending on the special conditions of the process.

The coal gasification process is assumed to operate in co-current or quasi co-current (fluidized bed). The characteristics of such a coal gasification process are of minor importance for the efficiency of coal gasification. In coal gasification, the gas composition will in any case be such as to necessitate gas treatment (CO shift conversion, CO2/H2S removal).

The question as to whether the coal requires special preparation, particularly drying, as is usually the case with lignite, is of great significance for the energy balance. This has several interesting effects on the process configuration.

INFLUENCE OF INDIVIDUAL PROCESS STEPS ON THE ENERGY CONVERSION

Gasification unit

Coal is gasified with steam and oxygen in the gasifier under adiabatic conditions.

The energy of the feedstock coal is found again in the chemical energy and sensible heat of the raw gas produced. The sensible heat can be utilized in the waste heat boiler downstream of the gasifier. Energy losses in the gasifier are therefore restricted to heat losses due to radiation, losses to cooling water and the energy content of dust and ash. Heat losses due to radiation can be minimized by the appropriate selection and sizing of the brick-lining. The cooling of items that are sensitive to heat, such as nozzles, is reduced as much as possible and thus kept to a minimum by using high-temperature and corrosion-resistant materials. Energy losses through the ash or slag discharge are more serious, as this can also entail the loss of unconverted carbon. However, efforts are being made to achieve a high coal conversion rate by selecting the appropriate process conditions (temperature or retention time) or by choosing a process configuration such that the carbon-rich ash fraction can be returned to the process or used as an energy carrier at another point (steam generator).

Synthesis gas compression

The synthesis gas must be pressurized before it is fed to the methanol synthesis unit.

The specific compression energy requirement per ton of methanol calculated for a final synthesis pressure of approx. 60 bar is shown in fig. 2. It should be noted that the specific figures given in this paper for the compression energy requirement refer to a methanol plant with a capacity of 2.000 t.p.d.

When gasifying at atmospheric pressure the raw gas has to be cooled before being fed to the compression unit. Heat is dissipated to the cooling water, because its temperature level is too low to be utilized, in other words, it is lost. At the same time, process condensate must be withdrawn. Consequently the gas must be humidified before entering the CO shift conversion unit.

If gasification is effected under pressure, compression prior to conversion can be dispensed with and the CO shift conversion can be coupled with the gasification. The consequences of this will be dealt with later. When compressing the gas to the final pressure of the methanol synthesis, a higher initial pressure can be used and the energy required for the compression decreases accordingly (fig. 2). The necessity to compress the oxygen partly off-sets the saving in the synthesis gas compression unit.

It should also be pointed out that, if the gasification pressure is increased, the CH4 content in the process gas also increases, and this may involve disadvantages in the downstream process steps.

CO shift conversion

Due to the elemental analysis of the feedstock, coal, the CO/H2 ratio in the synthesis gas is usually greater than 1, whereas the methanol synthesis process requires a CO/H2 ratio of approx. 0.5.

Excess CO can be converted to hydrogen by means of the water gas shift reaction. The reaction is exothermic and proceeds at a temperature between 200 and 500 oC, i.e. it is possible to utilize the liberated heat.

The incoming process gas must contain a certain amount of steam, the amount being greater than that calculated from the stoichiometric ratio. The steam excess prior to the CO shift conversion should be kept as low as possible. This is because the energy required for producing the excess steam is available again downstream of the conversion unit, but at a low temperature level, so that recovery and utilization, particularly at moderate operating pressure, requires considerable effort.

If the CO shift conversion unit is directly coupled with the gas generation unit, this water vapour can be introduced into the gas by the evaporation of quench water. The temperature conditions of the quench should be selected such that the required water quantity will evaporate. Particulate impurities are removed from the gas in the quench stage by the scrubbing effect, but gaseous impurities, particularly hydrogen sulphide, remain in the gas. When using this scheme, the conversion catalyst employed must be sulphur-resistant.

The sulphur content of the coal is usually high enough for the minimum H2S content required for these catalysts. Another advantage of this design principle is that gas impurities, such as COS and HCN, are converted or decomposed in the CO shift conversion unit, which might result in a simplified design of gas purification process with lower heat consumption.

Gas purification (CO2/H2S removal)

The gas purification unit operates at a relatively low temperature and, consequently, utilization of the heat fed to the CO2/H2S removal unit and which is obtained again in the form of waste heat, is only possible to a limited extent. The heat produced in the CO2 vapour cooler and in the liquor coolers is either dissipated to the air or the cooling water and is thus lost. The energy requirement for the scrubbing process is determined by three factors:

- quantity of matter to be removed
- pressure of the gas to be treated
- required final purity.

In the case of gasification at medium pressure and gasification at atmospheric pressure with upstream intermediate compression, it would be desirable to perform the gas purification at as low a pressure as possible in order to save compression energy that would otherwise be required for the carbon dioxide. On the other hand, at a higher pressure level in the CO2/H2S removal unit, the regeneration energy is lower because of the higher partial pressure of the CO2. The liquor cycle in the CO2/H2S removal unit can also be reduced. The increased consumption of compression energy (electric power or high-pressure steam) should be compared with the decreased consumption of regeneration energy, while the overall energy balance of the plant might also have to be taken into consideration.

No high demands are made on the gas purity with regard to the CO2 content, as it is permissible for a certain residual CO2 content to remain in the synthesis gas. The regeneration requirement is determined more by the specified max. H2S content, particularly when absorption takes place at relatively low pressure.

To operate a chemical CO2/H2S scrubbing unit (e.g. Benfield), low-pressure steam will be sufficient, the temperature of which is adequate for liquor regeneration. In the case of a physical process (e.g. Rectisol), the process gas must be cooled down. The refrigeration unit required for this purpose is driven by high-pressure steam or electric power, whereas high-purity nitrogen, for example, is used for regenerating the liquor because of the low temperature. The consumption figures depend to a certain extent on the pressure of the CO2/H2S removal unit.

Which type of scrubbing and which process are finally selected greatly depends on the process parameters in the plant. Here, the treatment of the sour gas obtained must also be considered. Since the H2S/CO2 ratio is low in coal gasification selective removal of the H2S is not to be recommended at this stage. The use of a Claus plant for treating the sour gas would result - at least in theory - in utilization of the chemical energy present in the hydrogen sulphide. This only seems to be feasible in the case of a relatively high sulphur content in the coal. The separation of H2S from CO2 by means of downstream scrubbing facilities in order to obtain an enriched sour gas has hardly any advantages with regard to the energy balance, because the energy required for the separation process is higher than the benefit obtained in the Claus plant.

Methanol synthesis unit

The methanol synthesis reaction is an exothermic process. The heat of reaction is generated at a medium temperature level and can be used for generating steam or preheating the boiler feedwater.

Methanol synthesis is a recycle process. In order to limit the inerts in the cycle, a certain amount of purge gas must be removed. The recycle rate and the purge gas rate depend on the inerts content in the feed gas as well as on the reaction pressure (see fig. 3). The inerts content in the coal gasification process is determined in particular by the residual methane content. The energy required for the recycle compressor must be considered as lost energy within the synthesis gas unit. The purge gas would not figure as a loss in the balance for the synthesis unit as its energy content would appear on the credit side.

However, the purge gas should not be used for underfiring purposes, but returned to the gasification process at a suitable point or further processed to SNG.

Methanol distillation unit

The water formed during the synthesis process as well as the by-products must be removed by distillation in order to obtain the required product specification. Similar to the CO2 removal process, the energy fed to the distillation unit is obtained again at a low temperature level and it usually cannot be utilized. One possibility of utilizing this heat is to use an absorber type refrigeration unit which provides the cold requirement for a physical removal process and thus enables HP steam to be saved. The high capital expenditure is only justified if the ratio of energy costs to capital investment costs is appropriate.

The energy consumption depends on the selectivity of the distillation process. If a higher content of other impurities in the product methanol is permissible, as is the case when using methanol as a carburettor fuel, a lower energy consumption can be expected (see fig. 4). In the Mobil process, which is based on crude methanol, the distillation unit can be omitted. The energy otherwise necessary for distillation can be credited to the Mobil plant.

Coal preparation

In many cases the coal must be prepared, for example, dried and ground. The energy requirement for the grinding unit is relatively low. The energy requirement for the drying unit is significant if moist raw materials such as raw lignite, peat or wood are to be gasified.

In relation to the utilizable synthesis gas quantity (H2 and CO), larger quantities of oxygen as gasification agent and more feedstocks are required when moist material is used. More energy is then needed for the production and compression of the oxygen.

On the other hand, a higher moisture content also means a higher raw gas rate, in other words more utilizable steam can be produced in the waste heat section which fact can be regarded as a credit. The resulting consumption of high-pressure steam only increases relatively slowly with the moisture content (see fig. 5).

If back-pressure turbines are used for driving the compressors in the plant, back-pressure steam can be used as the source of heat for the drying process.

The following consideration shows in simplified from what aspects are to be borne in mind for the optimization of plant sections and of the entire process. To simplify matters, it was assumed that high-pressure steam is only required in the air separation unit and as process steam in the gasification unit, and low-pressure steam is only required in the drying unit. (In fact, high-pressure and low-pressure steam are also required for other plant sections.)

Based on this assumption, the drying steam requirement and production of back-pressure steam was plotted against the moisture content of the feedstock (fig. 5). It was assumed that the initial moisture content is approx. 60 % by weight. The comparison of the drying steam and back-pressure steam shows that for a certain operating point (at approx. 35 % moisture by weight) the steam production and consumption are balanced.

ENERGY SUPPLY FOR THE PLANT

If it is assumed that the only energy supplied to the plant is the feedstock, all the other energy required (electric power and driving steam) must be generated in the plant itself. In accordance with common practice in commercial plants, all large compressors and also pumps, if appropriate, are driven by steam turbines.

The following major items of equipment require driving energy:
- air separation unit
- synthesis gas compression unit

- recycle compressor for the methanol synthesis unit
- boiler feedwater pump
- electricity generator for supplying minor consumers within the complex

LP steam is mainly required by:
- gas purification unit
- methanol distillation unit
- coal drying unit (if any)
- boiler feedwater deaeration section

Process heat is used in various parts of the plant for generating steam or preheating the boiler feedwater. This mainly applies to the following plant sections:
- waste-heat boiler downstream of the gasification
- CO shift conversion unit
- methanol synthesis unit

Another possible steam consumer is the gasifier (process steam).

The overall balance shows that make-up steam must be generated in a separate steam boiler in order to cover the energy balance.

In the process units, only high-pressure saturated steam is generated and must be superheated in the steam boiler. The pressure and the superheating temperature of the high-pressure steam should be selected such that the amount of HP steam required for the driving turbines corresponds to the total amount of LP steam required (back-pressure steam).

Fig. 6 shows the water and steam balance of the plant as designed on such a basis. Thus, when such a scheme is put into practice, there will be an interrelationship between the power and the heat required, which is a prerequisite for a high energy efficiency of the steam system, as no heat of condensation has to be dissipated to the environment.

By-products which cannot be used directly in the process are incinerated in the steam generator in order to recover energy.

OVERALL ENERGY BALANCE FOR THE PLANT

The energy losses in a plant for the production of methanol from coal are tabulated in fig. 7 and 8. Fig. 7 shows how the lost energy is dissipated to the environment. In fig. 8, the energy loss is broken down by individual plant sections. The efficiency for the entire plant is over 50 %.

The tables show that the main sources of loss are the plant sections in which mixtures are separated into their components, namely the gas purification unit, the methanol distillation unit and the coal drying unit.

The use of dry feedstock, which means that the drying unit can be dispensed with, increases the efficiency. However, the increase in efficiency in this case would not correspond to the loss shown in fig. 8 for the coal drying unit, as the LP steam used for the drying process is of relatively low quality. If the drying unit were to be omitted, the plant's LP steam demand would decrease considerably, so that, instead of back-pressure turbines, condensation turbines would have to be used in some cases and with these, the heat of condensation of the steam is dissipated to the environment as lost heat.

The conditions are similar in the CO2/H2S removal unit if a scrubbing process with a lower total energy demand is used, for example if a physical removal process is used instead of chemical scrubbing. In view of the fact that a chemical scrubbing process primarily requires low-grade LP steam only and a physical scrubbing process requires higher-grade energy, the same considerations apply here as for the drying process. Moreover, the different capital investment costs for a physical and chemical scrubbing processes including the necessary auxiliary facilities must be taken into account.

Finally, the question raises how the thermal efficiency can be raised further. The points already mentioned regarding the raising of the gasification pressure, the improvement of the gas quality and the treatment of purge gas are important. Another point worth considering is an increased utilization of the waste heat, particularly the vapours from the CO2 removal unit and the methanol distillation unit.

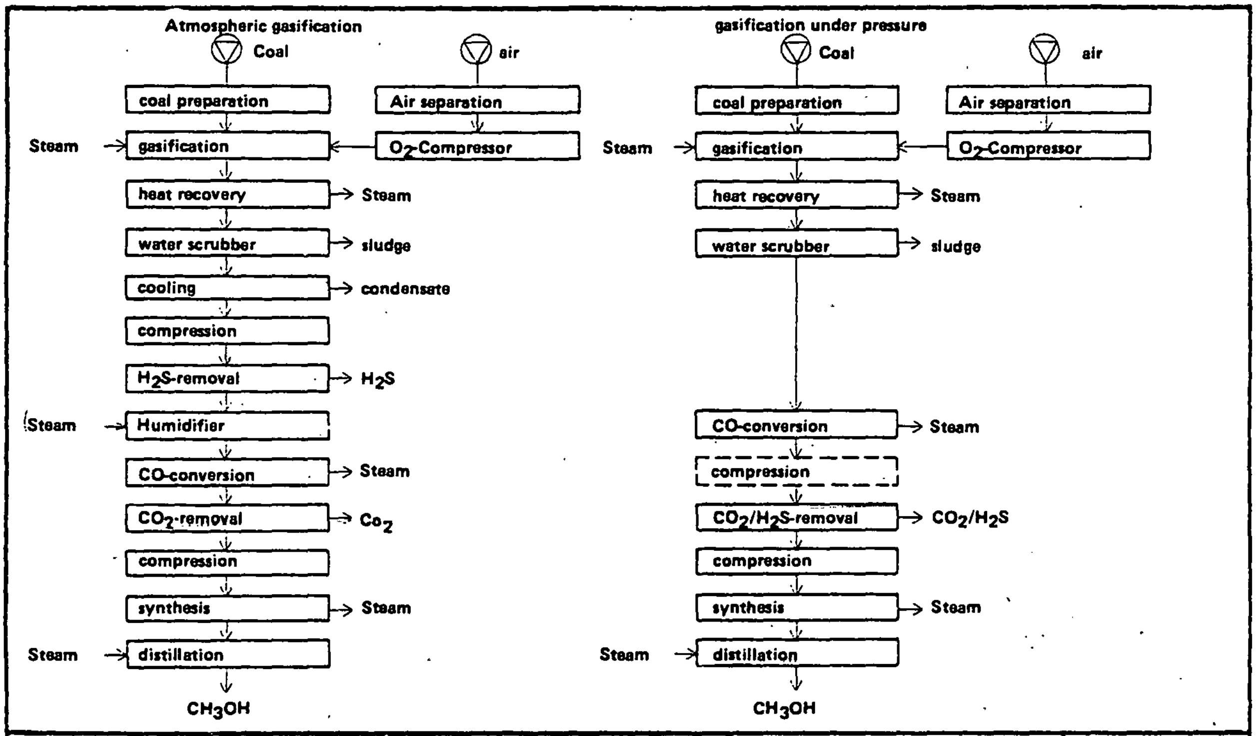
CONCLUSION

The energy conversion rate attained in a process, and which is characterized by the total efficiency, is an essential criterion for assessing the feasibility. However, it is not only the energy conversion rate or efficiency that is decisive for the feasibility of the process, but the capital investment costs are also important.

This aspect is emphasized by the compilation of the methanol price on the basis of individual cost factors. A plant for the production of 2.000 tpd methanol from lignite in the Federal Republic of Germany was taken as a basis. The individual cost factors account for the following percentages of the total methanol price:

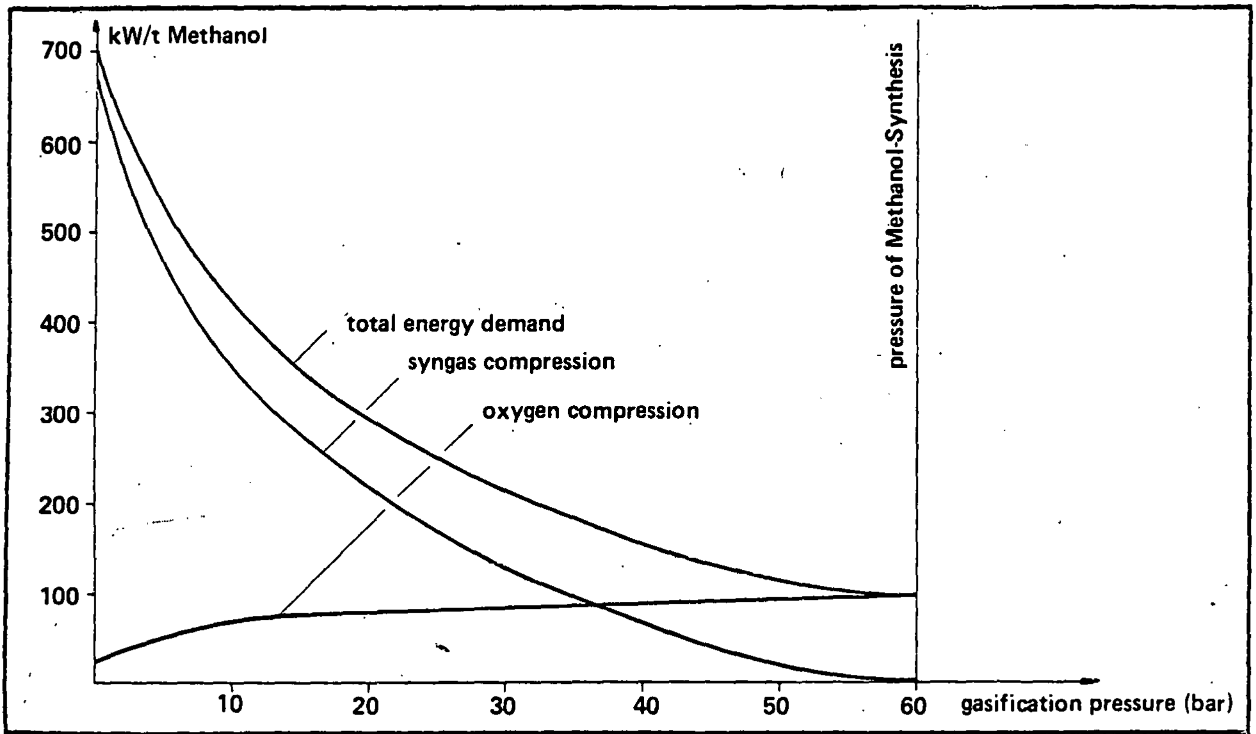
cost of coal and other utilities	approx. 35 %
capital-related costs	approx. 55 %
personnel costs	approx. 10 %

Factors such as local conditions or statutory requirements may also have an influence on the process configuration.



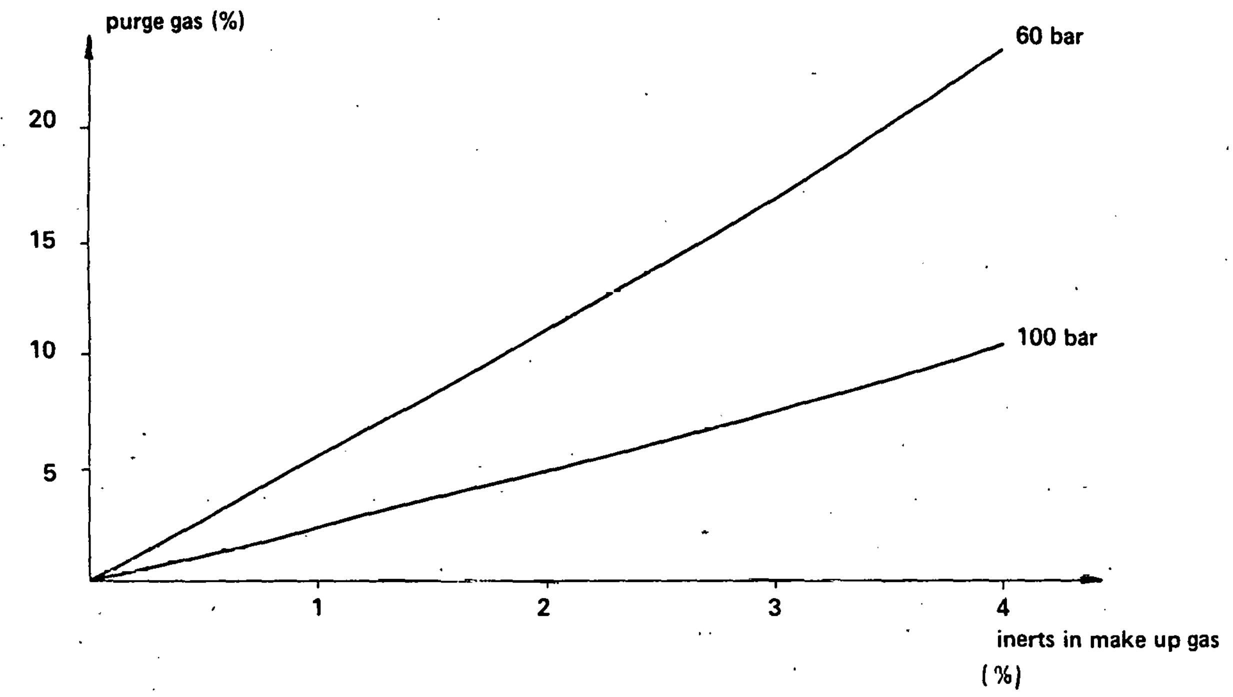
METHANOL FROM COAL
Block flow diagram

Fig 1



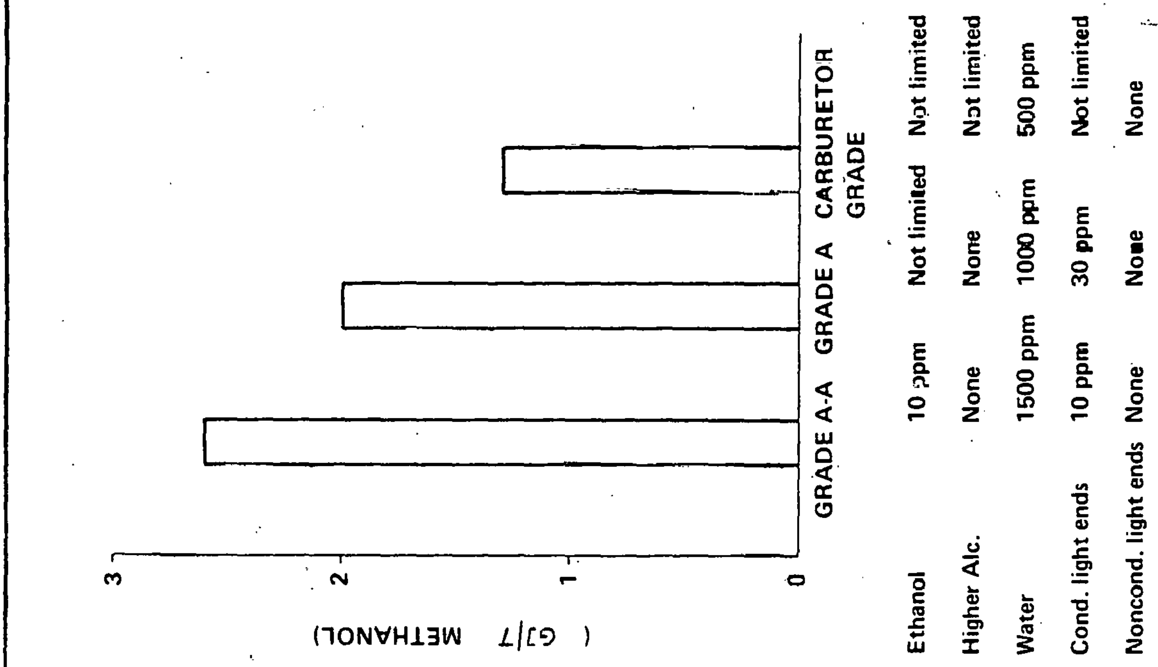
METHANOL FROM COAL
Compression energy at different gasification pressures

Fig. 2



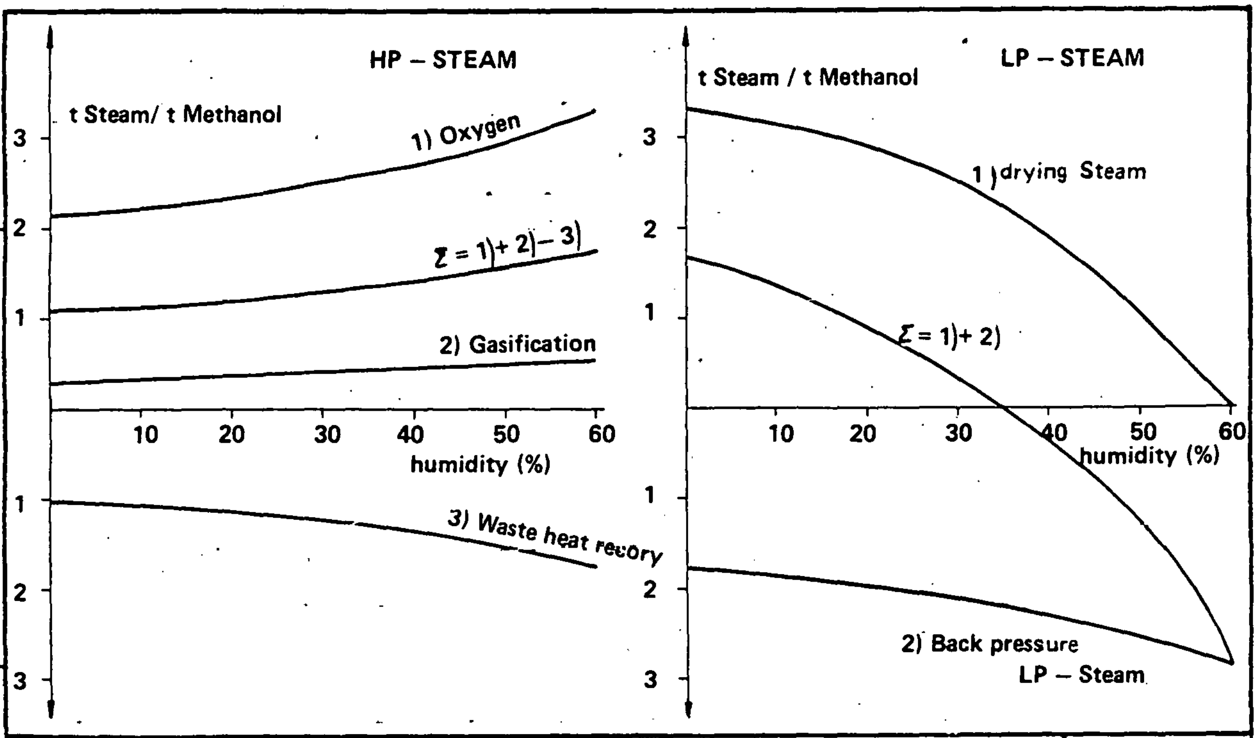
METHANOL FROM COAL
Purge Gas/Inert Gas Relation in Methanol-Synthesis

Fig 3



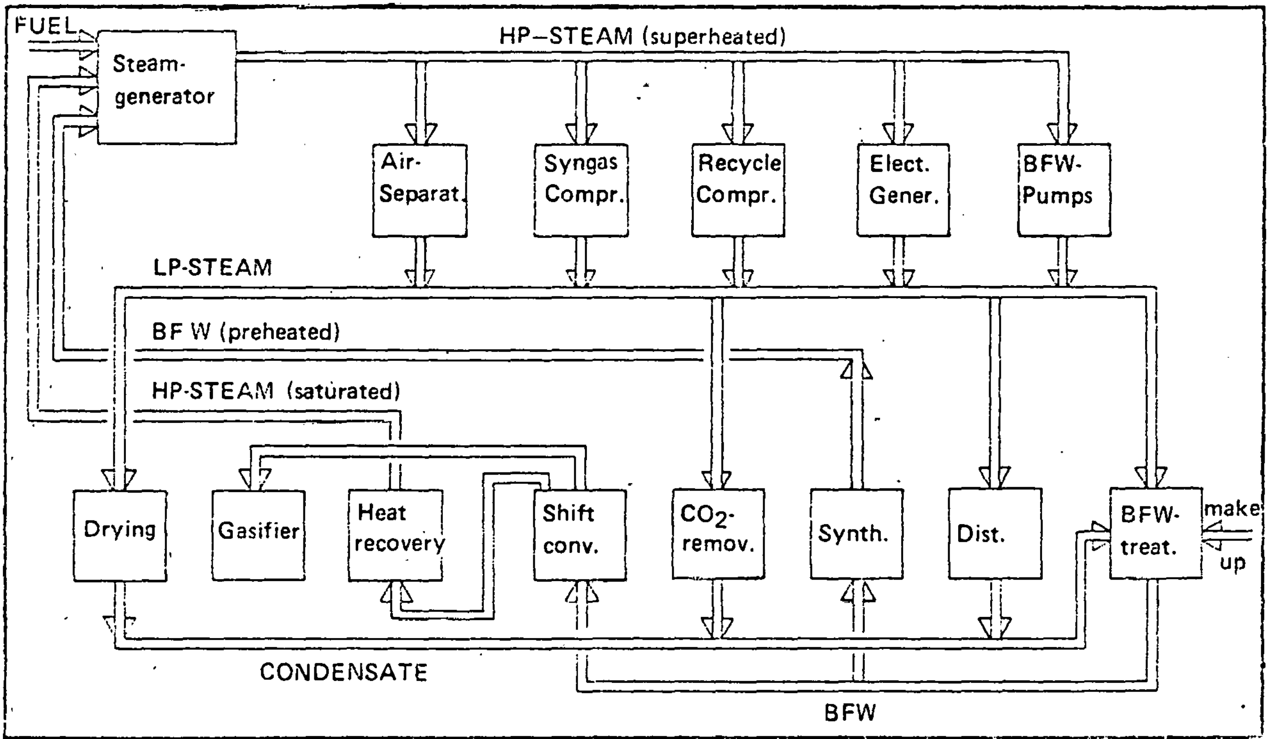
METHANOL FROM COAL
Reboilor heat demand of methanol distillation

Fig. 4



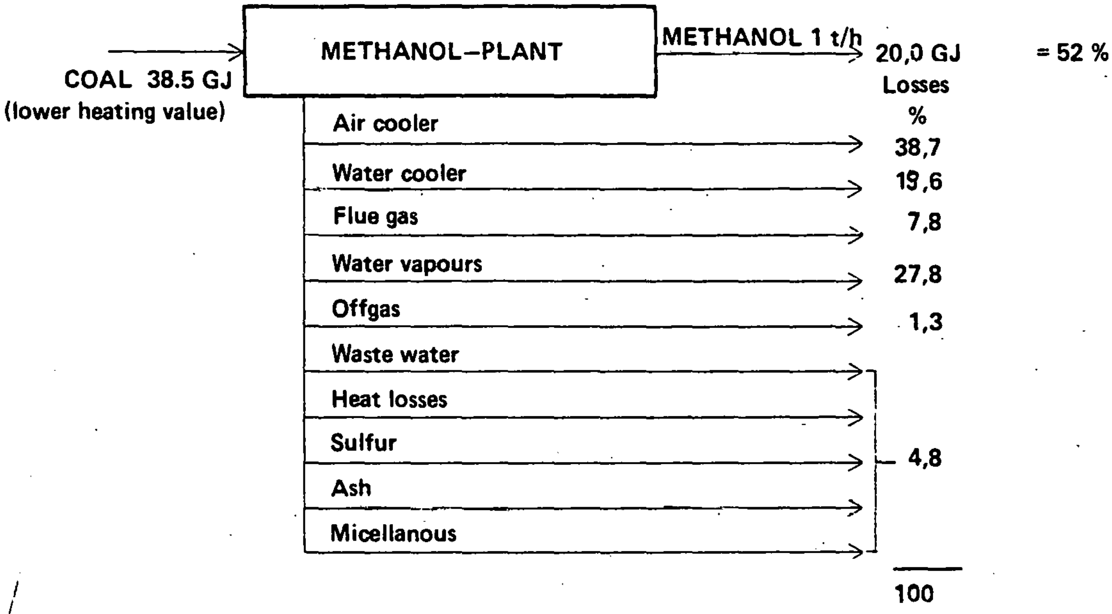
METHANOL FROM COAL
Steam balance of gasification and drying

Fig 5



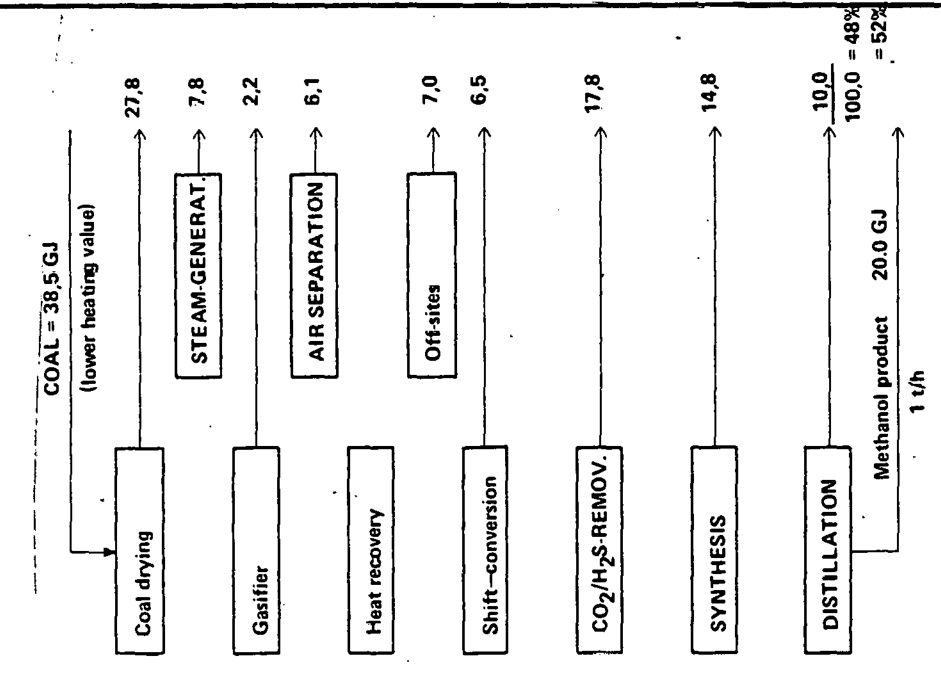
METHANOL FROM COAL
STEAM AND WATER BALANCE

Fig. 6



METHANOL FROM COAL
Distribution of Energy Losses

Fig. 7



METHANOL FROM COAL
Energy dissipation

Fig. 8

ALCOHOL FUEL TECHNOLOGY AND THE NATIONAL ENERGY ACT

by

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I. Introduction:

Alcohol fuels, as alternatives to or as supplements to petroleum fuels, offer many potential benefits. These include economic, environmental (both in terms of auto emissions and in recycling farm or wood waste for the production of alcohol) and energy policy benefits. To the extent that alcohol fuel, either in pure form or as a mixture with gasoline (gasohol) replaces petroleum fuel, it constitutes a contribution to the goals of the nation's energy policy as formulated in the National Energy Act.

The Carter Administration, recognizing the importance of gasohol in particular, provided some significant incentives in the National Energy Act to encourage its widespread use in transportation and other sectors. This paper will examine these incentives and their relationship to the entire energy pricing scheme established by the National Energy Act. In particular, the interplay of the gasohol incentives with the competing pricing systems for oil and natural gas will be examined.

II. The National Energy Act -- An Overview:

President Carter made the establishment of a coherent, systematic, national energy policy one of the earliest and highest priorities of his Administration. The formation of a cabinet level Department of Energy, which consolidated all or part of more than ten previous federal energy agencies, symbolized the Carter Administration's commitment to one federal focus for a unified energy policy. The Department of Energy Organization Act passed Congress fairly rapidly and was operational on October 1, 1977, the target date established by President Carter.

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While the Department of Energy would be the primary implementer of federal policy, what that policy would be was contained in the National Energy Act. Whereas the Department of Energy Organization Act received quick Congressional action, the fate of the National Energy Act was a different story. The National Energy Act was offered to Congress on April 20, 1977 but did not pass until a year and a half later, on October 15, 1978.

Unlike the Department of Energy Organization Act which passed Congress in substantially the same form in which it was introduced, the National Energy Act underwent substantial and drastic revisions before final passage. Whereas the National Energy Act as introduced was estimated to result in savings of from 4.5 million to 6 million barrels of oil per day (42 gallon barrels), the estimate of oil savings from the bill enacted by Congress is only 2.5 million barrels per day. Major programs for fuel pricing were substantially altered or omitted entirely by Congress. The most important of these were: (a) the mandatory provisions which required state public utility commissions to impose certain rate formulas on electric and gas utilities in order to conserve energy were modified to require the commissions to merely consider such rate proposals and (b) the entire petroleum taxing-pricing program was omitted. The omission of the petroleum pricing system, in particular, may have significant impact on the effectiveness of the alcohol fuel incentives contained in other provisions of the Act.

III. Summary of the Act:

The program as designed by President Carter to create an effective energy policy contained three major objectives:

a. As an immediate objective that would become even more important in the future, to reduce dependence on foreign oil and vulnerability to supply interruptions;

b. In the medium term, to keep U.S. imports sufficiently low to weather the period when world oil production approaches its capacity limitation; and

c. In the long term, to have renewable and essentially inexhaustible sources of energy for sustained economic growth.

The importance of reducing oil consumption in the President's energy program is graphically illustrated by the following statistics:

a. Oil constituted 27% of American energy consumption in 1976;

b. At the time of the 1973-74 oil embargo, the United States imported 37% of the total oil consumed.

c. Total U.S. imports of oil had risen by February 1977 to nine million barrels per day, half of total American consumption.

The Act as proposed by President Carter set a target of reducing oil imports to 6.5 million barrels per day by 1985. The goal is not to achieve total energy independence through a crash program. Rather, the President's program attempts to reduce oil imports to a manageable level and thereby reduce the United States' vulnerability to supply interruptions and to achieve a state of relative invulnerability. In order to not deplete America's own resources, the program includes the continued importation of foreign oil for a number of years though at a reduced level. To accomplish this goal, the Act contains a series of tax credits, penalties, incentives and prohibitions to encourage conservation of energy generally (the program calls for a reduced annual energy growth rate of no more than 2% per year) and to encourage the replacement of petroleum-based energy sources by other resources. The National Energy Act, as passed by Congress, consisted of five separate acts which are summarized briefly below.

A. Energy Tax Act of 1978 -- HR 5263:
This act contains tax credits for residential installation of insulation and other weatherization materials (15% of all expenditures up to $2,000 for a maximum credit of $300) and for renewable resource equipment (solar, wind, or geothermal energy -- the tax credit is 30% of the first $2,000 expended and 20% of the next $8,000 for a total credit of $2,200). The act also contains tax incentives to encourage the use of buses, vanpooling, and recycling of lubricating oil.

This bill contains additional tax incentives for industry and business to finance equipment in order to minimize or replace petroleum fuels with geothermal, solar, wind, farm waste and other non-petroleum fuels. The oil depletion allowance and similar tax advantages previously afforded to the petroleum industry are now also available to geothermal energy and natural gas developed from geopressurized gas.

Of particular interest to the Alcohol Fuels Technology Symposium are the following provisions:

1. The elimination of the federal excise tax on the sale of gasoline which is a mixture containing at least 10% alcohol;

2. The U.S. Department of Energy must provide an annual report to Congress on the use of alcohol in fuel.

3. Business and industry are provided an additional investment tax credit of 10% for equipment which uses a fuel or feedstock (including alcohol) other than oil or gas.

The Energy Tax Act also contains the "gas guzzler tax" which taxes inefficient automobiles. The tax is a sliding scale, with a gradually increasing tax and gradually decreasing miles per gallon target for each model year. For example, the tax in 1980 ranges from $200 for cars with less than 15 miles per gallon to $550 for cars with less than 13 miles per gallon, while the 1986 tax is $500 for cars with less than 22.5 miles per gallon and $3,850 for cars with less than 12.5 miles per gallon. This was the only major oil tax to survive. The petroleum pricing scheme was omitted in its entirety.

The Energy Tax Act is as interesting for what it excludes as for what is contained in the bill. The House version of the bill contained numerous other provisions, many of which were major components of the President's original program, which did not survive the joint Senate-House conference. These included:

1. Repeal of personal income tax deduction for state and local taxes on gasoline,
2. Crude oil equalization tax,
3. Natural gas liquids equalization tax,
4. Heating oil refund and other home heating tax credits,
5. Crude oil equalization tax rebates,
6. Energy cost credit for the elderly,
7. Expanding the definition of stripper wells which are exempt from price controls,
8. The establishment of an energy production, conservation and conversion trust fund from the revenues generated from new taxes imposed by this bill,
9. Payments to states up to $400 million each year for 1978-1981 for repair of federal aid highways, with payment derived from the crude oil equalization tax,
10. Excise tax on business and industrial use of oil and natural gas with a system of offsetting tax credit for certain energy equipment expenditures,
11. Investment tax credit for business insulation,
12. Exemption from federal taxation for the interest on certain industrial development bonds used for coal gasification, liquefaction, bioconversion and for certain state and local bonds to provide electricity which are not now exempt,
13. Percentage depletion allowance for peat,
14. Tax credits for the production of non-conventional oil and gas, such as shale oil, tar sands, geopressured natural gas and tight rock formation gas,

15. Presidential authority to adjust petroleum imports, import quotas, duties, and tariffs,

16. A refundable tax credit for the purchase of petroleum products for use in tax exempt residences, hospitals, churches and schools,

17. Suspension of import duties on insulation materials,

18. A low-income energy stamp program similar to the food stamp program,

19. Expedited consideration of federal authorizations for proposed U.S. pipeline systems to carry crude oil supplies inland from the West Coast.

B. Power Plant and Industrial Fuel Use Act of 1978 -- HR 5146:
The purpose of this bill is to encourage the use of coal and (for electric generation) nuclear fuel for future large baseload generating plants and large industrial users instead of oil or natural gas. The bill prohibits the use of oil or natural gas in new electric generating stations and industrial facilities, and prohibits the use of oil or gas in existing facilities after January 1, 1990. Exemptions may be granted by the Secretary of Energy on a case-by-case basis. One of the exemptions explicitly available is for a fuel mixture containing oil or natural gas with another substance (such as alcohol), so long as only the minimum percentage of oil or gas necessary to maintain efficient operation is used. This may result in a substantial incentive to spur the use of alcohol both as a direct fuel and in combination with oil for fuel.

C. Public Utility Regulatory Policy Act of 1978 -- HR 5037:
This bill requires that each state utility commission consider the imposition of certain rate standards for electric and gas utilities in order to conserve energy. Among others, the standards include cost-of-service declining block, time-of-day, and lifeline rates.

The bill also provides the Federal Energy Regulatory Commission with broad authority to order interconnections, wheeling, and pooling in order to promote energy conservation or promote the efficient use of energy resources. The Commission also has authority to facilitate the development and sale of electricity from small (less than 30 megawatts) power production facilities. (If alcohol is used to fuel small electric generating facilities, this bill could provide significant incentives for its development.) The Commission must issue rules which require electric utilities to sell to and pourchase electric energy from small power production facilities at "just and reasonable rates". The Commission may also exempt small power production facilities in whole or in part from various federal and state regulatory requirements, including the Federal Power Act, the Public Utility Holding Company Act, state laws and regulations respecting the rates or the financial or organizational structure of electric utilities, if necessary to encourage small power production.

D. National Energy Conservation Policy Act -- HR 5037:
This bill, building upon existing legislation, expands the state conservation programs into the following areas:

1. Residential weatherization programs with certain assistance provided by the utilities,

2. Weatherization grants for low income families,

3. Weatherization programs for schools, hospitals, and local government buildings.

In addition, federal secondary financing and loan insurance are available for energy conserving improvements and solar energy systems. The Secretary of Energy must also issue energy efficiency standards for automobiles and other products.

E. The Natural Gas Policy Act of 1978 -- HR 5289:
This bill, along with the petroleum pricing provisions which were not enacted, was the most controversial aspect of the entire National Energy Act and was primarily responsible for the lengthy period required for its enactment. The Natural Gas Policy Act is a complex bill which allows the price of natural gas to rise substantially over that authorized by existing law, and eventually results in the decontrol of natural gas pricing entirely. The bill was heavily criticized both at its introduction and in its final amended form by two opposing groups: producer interests who thought that decontrol was coming too slowly and consumer groups who thought the bill went too far in dramatically raising prices and increasing producer profits.

The bill raises the price of natural gas to accomplish three purposes: (1) to dissuade its use when more plentiful fuels are available, (2) to spur further exploration and development of natural gas, and (3) provide price incentives for intrastate natural gas (which is sold at a much higher price than interstate gas) to enter the interstate market. To accomplish this, the bill contains the following provisions:

1. Pricing formulas with escalator clauses for a number of different categories of natural gas -- of principal importance is that new natural gas (produced from new reservoirs after April 20, 1977) may be sold at a maximum price of $1.75 per million Btus.

2. On January 1, 1985, all new natural gas and existing gas previously sold by intrastate will no longer be subject to price controls.

3. Existing interstate gas may be sold at a maximum price of $1.45 per million Btus (with escalator clauses), but only subject to Federal Energy Regulatory Commission approval under the "just and reasonable" standard of the existing Natural Gas Act. Existing interstate gas prices will not be decontrolled.

4. The President is given broad emergency powers to declare a natural gas supply emergency and to order allocations. The emergency period expires after 120 days unless extended by the President.

IV. The Petroleum Pricing Formula that was Omitted from the National Energy Act:

The taxing scheme proposed by the Carter Administration for petroleum pricing was perhaps the single most important factor for directly reducing petroleum imports. The petroleum taxes alone were estimated to result in a savings of 2 to 3 million barrels of oil per day. The importance of the petroleum pricing formula, however, is not limited to its direct savings of oil. The absence of such a formula for oil but the inclusion of a comparable formula for natural gas affects the demand for petroleum versus natural gas and other fuels which compete with petroleum. That impact is sufficiently important to merit a brief outline of what the proposed petroleum pricing formula contained.

Under existing law, domestic oil producers are subject to a price ceiling of $11.28 per barrel for "new" oil and $5.25 per barrel for "old" oil compared to the world price in 1977 of $13.50 per barrel. A major assumption underlying the President's proposed energy policy was that federal pricing policy encourages over-consumption of the scarcest fuels by artificially holding down prices, and that the pricing of oil and natural gas should reflect the economic fact that the true value of a depletable resource is the cost of replacing it, i.e. the new free market price (subject to certain restrictions).

This rationale, along with the desire to spur the production of new natural gas, was the basis for the Administration's natural gas pricing scheme (although the eventual decontrol enacted by Congress was different from the price-raising formula proposed by the President). A similar rationale existed with respect to the proposed crude equalization tax on petroleum.

Under the Administration's proposal, the price of newly discovered oil would be allowed to rise over a three-year period to the 1977 world oil price, with subsequent adjustments based upon inflation, providing a domestic incentive price for new oil. The ceiling on old oil would rise with inflation. In order to ensure that the market decisions made by consumers are based on the real value of oil, all domestic oil would be subject at the wellhead to the crude oil equalization tax equal to the difference between its controlled price and the world price. The tax would be added in three steps between 1978 and 1980 and would subsequently increase with world price. Net reserves from this tax would be returned to the consumers through a per capita energy credit against other taxes or through other refund mechanisms. The proposed tax attempted to both establish a more realistic energy pricing system and to prevent windfall profits to the oil producers.

The Administration's proposal also included other petroleum taxes, including a standby gasoline tax on excess fuel consumption. The heart of the petroleum pricing proposal, however, was the crude oil equalization tax.

V. Impact of the Natural Gas Pricing Scheme and Lack of a Petroleum Pricing Scheme on Other Energy Sources:

The petroleum pricing scheme and the natural gas pricing formulas were an integral part of the entire energy plan prepared by the President. As noted above, the two were somewhat parallel in approach, although for different reasons. The absence of a petroleum pricing scheme may undermine the goals of the National Energy Act in more ways than simply the loss of 2-3 million barrels of oil per day which might have been saved.

One of the controls by which the Administration's energy plan proposes to emphasize the replacement of petroleum with other energy sources is by placing these other resources on a relatively equal competitive level with oil and natural gas. This would be accomplished in a number of ways, principally including the following:

a. Extending the depletion allowance currently allowed for oil and natural gas to geothermal development and to the development of natural gas from geopressurized brine; similarly intangible drilling costs and other deductible expenses would be made equally available to geothermal development as they are to oil and natural gas.

b. The series of tax incentives, including personal income tax credits and investment tax credits for weatherization, solar, geothermal, wind, and other non-petroleum energy sources (including alcohol-gaohol) were designed not only to ease the economic cost of the major capital expenditures often required for these resources but also to make the cost-comparison more favorable when compared to continued use of petroleum or natural gas.

c. The petroleum and natural gas pricing schemes would have removed many of the existing governmental pricing policies which maintain oil and natural gas prices below the current world market (and perhaps free market) costs.

Absent an absolute prohibition of the use of oil and natural gas (which is the approach of the Power Plant and Industrial Fuel Use Act of 1978), American dependence on petroleum fuels will only be reduced most directly when other competing energy resources are either cost-competitive or very nearly so. The tax incentives provided in the Energy Tax Act of 1978 attempt to bridge the economic gap between non-petroleum replacements and the established oil and natural gas markets. The proposed oil and natural gas pricing schemes would have done that further, by removing the previous government policies which kept oil and gas prices lower than the market would bear, policies which resulted in both excessive use by consumers and the resulting possibility of shortages.

(As the crude oil equalization tax provisions recognized, however, we are not in a strictly free market situation, but are subject to foreign cartels and other pricing policies on the international level which can defeat free market supply-demand equations and unjustly enrich energy suppliers. The crude oil equalization tax provisions recognized this fact and included refunds to consumers. The natural gas pricing scheme included no such refund, which resulted in major consumer opposition to the bill.)

The inclusion of a pricing formula for natural gas but the lack of one for petroleum means that, at least with regard to economic incentives and the stimulus of the marketplace, the replacement of petroleum by other sources will be retarded. Given the pervasive nature of the use of petroleum in the American economy, both as a direct fuel and as converted to other energy forms, other energy sources must inevitably be compared by consumers with petroleum prices as the choices of energy sources are individually made.

To the extent that alcohol fuels, or for that matter, solar, wind, or geothermal energy sources reflect incremental replacement pricing, while petroleum does not, the Administration's energy policy of reducing reliance on petroleum imports and encouraging replacement of petroleum by other energy sources will be frustrated. The carefully balanced scheme developed by the Administration in its original energy proposal has been tilted by the inclusion of natural gas pricing and the exclusion of petroleum pricing from the National Energy Act. It is unclear how much this balance has been tilted, but until an oil pricing program is included in subsequent amendments to the National Energy Act, the effectiveness of the economic incentives contained in the Act will be hindered.

Alcohol fuels, as well as other fuel technologies, are fast becoming viable alternatives and, perhaps, necessary alternatives, to petroleum and natural gas. Programs in the states, as well as by the federal government, are hastening this day. For example, in my own State of Oregon the 1977 Legislature pased one of the most comprehensive legislative packages in the nation to encourage both energy conservation and renewable resource development through the use of tax incentives, low-interest loans, grants, and other incentives. The Chairman of the House Energy and Environment Committee has continued this trend by introducing a package of six bills in the 1979 Legislature to encourage widespread alcohol fuel use in Oregon. These bills include tax and loan financing incentives for alcohol producing facilities, state motor pool requirements for gasohol use, and other state actions to generate alcohol fuel use. The package emphasizes the derivation of alcohol from farm and wood waste, thereby assisting a pollution problem as well as an energy problem. While it is not clear how many of these bills on alcohol will be passed, it is likely that some legislation will emerge from the Oregon Legislature this session to encourage alcohol fuel use.

The activities that the State of Oregon and other states and industries are undertaking to promote alcohol fuels and other petroleum replacements are vitally important, and the federal government took a major step twoard establishing a rational nationwide energy policy with the passage of the National Energy Act. Yet so long as no modern oil pricing formula exists, the work of the National Energy Act is incomplete, and the activities of both the federal government and the states to promote oil replacement energy sources will continue to face a major roadblock.

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THE SWEDISH OIL AND FUEL POLICY IN THE 1980´s

by

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In March 1979 the Swedish government presented a bill concerning the Swedish energy policy for the 1980´s. In this context I will touch upon the proposed oil policy and give a more detailed statement on the policy on alternative fuels for transports.

The main goals for the Swedish energy policy is to establish a good supply security, minimize the effects on the environment and maximize the freedom of action in the future.

Despite the fact that large investments are already being made or planned in Sweden in order to lessen the increase in energy requirements as well as develop new sources of energy, crude mineral oil will still at the end of the century be the dominating source of energy. It can at the same time be stated that mineral oil is an exhaustable raw material. In order to avoid a more or less permanent shortage towards the end of this century it is of utmost importance for Sweden to develop additional and alternative forms of energy. Already before an exhaustion of the world´s mineral oil resources starts to cause obvious shortage, disturbances caused by for example international political crises or decided limitations of production will at least temporarily create problems for Sweden´s supply of oils and motor fuels. Thus the most important goal for Sweden is to reduce the dependence on mineral oil. Sweden is more dependent on mineral oil for its supply of energy than most other industrialized states. Furthermore, as Sweden completely lacks own sources of mineral oil, as well as natural gas and coal, it is natural for us to concentrate on different alternative sources of energy in order to reach our goal to reduce the dependence on oil. The supply of motor fuels is probably the sector of the energy field which in the long run is mot vulnerable due to the extreme dependence on oil. In view of both the long-term general development and for emergency reasons it is then of great importance to Sweden to find alternatives to the present suppply of motor fuels. These alternative motor fuels should be possible to manufacture from domestic, replenishable raw materials.

ALTERNATIVE MOTOR FUELS

The Swedish policy on alternative motor fuels in the future can be summarized as follows. Our transport systems is- except trackbound vehicles - at present essentially dependent on imported crude oil or imported petroleum products. Gasoline as well as diesel powered vehicles utilize the light petroleum fractions which are in particular demand. Due to this, it is essential to create conditions in order to utilize alternative motor fuels within the transport sector. Fuels produced synthetically, primarily methanol and ethanol or synthetic fluid hydrocarbons are of interest in this context. Also gaseous fuels, primarily liquified petroleum gas, LPG, obtained from petroleum have been discussed. LPG is suitable where environmental aspects are concerned. The introduction of motor gas fuel contributes to a widening of the fuel base, but does not lessen the dependance on oil. With regard to long-term energy policies the introduction of gas is a measure active in a relatively short-term view and only for limited car fleets. Measures should be taken as early as possible to create conditions for other alternative motor fuels, and these measures should be taken successively. A guiding aspect should then be to avoid unnecessary unilateral Swedish measures in the form of extensive special provisions, design criteria and similar requirements resulting in the isolation of Sweden from the transport systems and energy supply of its neighbors where the motor market, the use of fuel as well as supply of fuel raw materials during emergencies are concerned.

A governmental energy commission emphasizes that continued research and development work should be performed in order to find a suitable technology for gasification of domestic fuels particularly as a raw material for a domestic production of synthetic motor fuels. The Commission also regards it as desirable that such a production during the 1980's and -90's from coal and vacuum residual oils of high sulphur content should be prepared, and also that the possibilities for the import of motor fuels not based on crude oil as well as fuel components should be studied.

Advisory bodies, to whome the matter has been referred, consider it of considerable importance that various kinds of measures are taken now in order to make possible an introduction of synthetic motor fuels. Individual bodies are however sceptical of the possibilities to accomplish about 1990 the introduction and domestic production of methanol to the extent the energy commission has proposed.

Svensk Metanolutveckling AB (SMAB) was formed in 1975 as a development company jointly owned by the government owned company Berol Kemi AB and AB Volvo. The purpose of the company was to investigate the possibilities to utilize methanol as a motor fuel during normal conditions as well as during supply emergencies in the motor fuel field. During the years 1975-1978 the company has performed development and investigation work for the Swedish government concerning the utilization of methanol as a motor fuel, primarily by mixing it into gasoline free of lead additives, but also for operation on pure methanol in otto engines as well as diesel engines. The work has been financed primarily by the governmental Energy Research Programme and by AB Volvo.

In the 1978 Annual Report of SMAB to the government reporting on efforts during the years 1975-1978, it is stated that the company's investigation and development work up to now has indicated that future liberty of action in the motor fuel field can be created by measures aiming at adaptation of the fuel distribution system and the fleet of vehicles to the use of alcohols as well as fuels containing alcohol. We state that proposals should be prepared for specifications for new vehicles as well as regulations for the conversion of older vehicles for the operation on such fuels. Furthermore, we state that the work involving the development and selection of a suitable gasification technology where domestic raw materials are concerned should be given high priority in the Energy Research Programme. We also emphasize the need of stimulating an early conversion to alternative fuels within individual fleets of vehicles. To this purpose, abolished or reduced taxation on alcohol-based fuels is proposed.

SMAB, at present owned to 80 per cent by Studsvik Energiteknik AB, has in January 1979 submitted a proposal to the Ministry of Industry for the activities during 1979-1981. The plan includes basic activities as well as considerable project activities. After receipt of replies from consulted bodies, the Government on March 1, 1979 approved of a budget for the basic activities during the three-year period. A minor part of the work will be financed to equal shares by AB Volvo and Statsföretag AB (the government companies group), which own 10 per cent each of the company.

In accordance with indications in the Government's proposition to Parliament regarding energy research etc SMAB's activities will be aimed at research and development of long-term supply of motor fuels utilizing primarily domestic raw materials, the intention being to comprise both research and development concerning production and distribution of synthetic motor fuels in the form of alcohols or synthetic gasoline as well as efforts clarifying the conditions required for the adaptation of otto and diesel engines to alternative motor fuels. Such research and development including studies of environmental effects required as a base for decisions on production and distribution of synthetic motor fuels based primarily on domestic raw materials will also be included in our activities. An important aspect in this connection is that this work will also be of benefit to the planning of the supply preparedness in case of an international crisis, blockade or war.

Where the production of synthetic motor fuels are concerned considerable efforts are being made within the Energy Research Programme. It can be anticipated that the construction of a larger test and demonstration plant will be required in order to carry out tests concerning the production of synthesis gas based on domestic raw materials.

A delegation for solar energy and oil substitute fuel, which has been appointed by the Government, has been assigned the task to study questions of control measures, provisions and introductory strategies for the introduction of synthetic motor fuels further to the work financed by the Energy Research Programme.

Furthermore, it is important to establish as soon as possible comparatively large-scale test and demonstration activities concerning synthetic fuel operation in various forms. Such tests will also provide opportunities to study and possibly take measures where components of the fuel or the exhaust gases harmful to the environment are concerned. In order to simplify introduction of methanol on the motor fuel market motor fuel taxes on methanol and other motor alcohols will be reduced with 50 per cent.

Negotiations are in progress concerning the utilization of the car fleets of some national authorities in order to try to create further possibilities to carry out operational tests as well as obtain a base for the increased use of primarily methanol, and in this way successively build up a market for synthetic motor fuels. The Telegraph Board has in its reply to the report of the energy commission stated that the Board to a certain extent is prepared to participate in practical tests of alternative motor fuels.

It is of great importance that activities of this kind can commence and provide further information as a base for a decision in the beginning of the 1980's on the strategy for the introduction of synthetic motor fuels. It is then of great importance that interested parties within the chemical and petrochemical industries as well as future producers of raw materials within e.g. the forest industry are also committed at an early stage.

The work carried out by SMAB has proven that the use of gasoline with methanol additives cannot be assumed to require any more important modifications of present otto engines and fuel systems of the vehicles. It is thus desirable that the manufacturers of cars as soon as possible try to fit out new cars for operation on gasoline having alcoholic additives. The Swedish Minister of Agriculture has appointed a special working group assigned to propose measures to simplify the introduction of motor fuels free of lead additives etc. One of the tasks of the group is then to submit proposals for regulations that new cars shall be designed in such a way that they without the risk of damages to engines and fuel systems can be operated on gasoline free of lead additives as well as fuel containing methanol or some other alcohol.

The international development, where synthetic motor fuels are concerned, has been much faster than expected. Therefore, it is also possible that opportunities will appear fairly soon where several countries co-ordinate their work in this respect.

SOME IMPLICATIONS OF LARGE-SCALE METHANOL PRODUCTION FROM CANADIAN FOREST BIOMASS*

by

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THE CANADIAN LIQUID FUEL PICTURE

Crude Oil Imports

Canada is highly dependent on imported crude oil, and has recently moved from being a net exporter of oil to a net importer. In early 1977, the National Energy Board forecast an expected shortfall of domestic oil supply relative to requirements of more than a million barrels per day in 1985, although later forecasts present a somewhat more optimistic picture.

In February 1978, the Government of Canada and the provincial governments agreed to a 1985 target for crude oil imports of 800,000 barrels/day, or one-third of consumption, whichever is less. Achieving this target requires continued conservation to keep a low growth of energy demand; in addition, expectations of new supplies from frontier areas, and increased production of synthetic crude oil from tar sands and heavy oil deposits, must materialize.

Even with these measures pursued, a requirement to import up to 800,000 barrels/day has continuing implications for Canada's strategic security of supply, balance of payments, and domestic inflation, all of which are matters of considerable concern. To illustrate: the expected annual import liability for 800,000 barrels/day in 1985 would be $5-7 billion (in 1977 Canadian dollars), depending upon future world oil prices. This is comparable to the export earnings of the forest products industry, Canada's largest export sector. As it will be difficult to increase exports dramatically, with other countries also trying to do the same, import substitution possibilities become particularly significant.

Alternatives

Fortunately, Canada is reasonably well-endowed with alternative energy sources. As world oil prices escalate, conservation, interfuel substitution and increased efficiency in fuel use

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* The opinions expressed in this paper are those of the author, and do not necessarily represent those of the Government of Canada or the Department of the Environment.

become increasingly attractive, as do development of alternative energy sources such as tar sands, heavy oils and frontier reserves. In addition, new types of fuels derived from non-petroleum feedstocks can become economically justifiable.

In the transportation sector, interfuel substitution possibilities are very limited. Only liquid fuels presently exhibit the mobility and storability features required in many transportation applications. Alcohols in particular stand out as versatile and clean-burning alternative liquid fuels which could be brought on stream in significant quantities in the near to medium term future.

METHANOL AS AN ALTERNATIVE LIQUID FUEL

Recognizing the advantages of alcohols, several comprehensive government-sponsored studies have been undertaken in Canada during the past eighteen months, to consider the technical and economic feasibility of large-scale alcohol production and use in Canada. The studies focussed on the production of methanol from renewable resources, and its use in the transportation sector. As feasibility studies, they did not really address the major energy policy issues involved.

This paper highlights the findings of a consultant study recently undertaken for Canada's Departments of the Environment; Energy, Mines and Resources; and Agriculture (1). The major conclusions of this and another recent Canadian study (2) are summarized, along with some of their implications.

Economic Feasibility of Methanol

The feasibility studies incorporated the following basic elements:

a) Calculations were in constant 1977 Canadian dollars (i.e. considering increasing real oil prices);

b) Opportunity values in direct combustion (which generally rise as oil prices increase) were used for feedstocks;

c) Production plants were assumed to be large-scale for coal and natural gas feedstocks, smaller for biomass:

d) 10% real (net of inflation) rate of return over a 20 year plant life was used;

e) Allowances were included for both the advantages (eg. increased fuel efficiencies in straight methanol engines) and disadvantages (eg. vehicle adjustment and fuel distribution costs) of methanol;

f) Customers were assumed to pay costs equivalent to those for petroleum products; and

g) The same general levels of tax receipts were assumed for government.

Using these assumptions, the conclusions of the feasibility studies were generally as follows:

a) Although a number of technical problems relating to methanol production and use were identified, these are expected to be relatively straightforwardly solvable. Methanol could be an attractive substitute for gasoline and diesel fuel in Canadian transport sector applications, and would become competitive with petroleum products as world oil prices rise. Methanol could have high values, in blend uses, because of its octane boost characteristic. However, with the relatively low volumes of methanol involved, blend use is only seen as one possible transition phase towards methanol use as a straight transportation fuel. Methanol would be less competitive in stationary applications, such as home heating or electricity peak load shaving.

b) Methanol produced using combined feedstocks (the methane in natural gas as the primary feedstock; with forest biomass, straw, or municipal solid waste as the secondary feedstock) could be economical as a straight transportation fuel when oil prices reach about $20/barrel. The relatively low production cost results from efficient balancing of the different H_2:CO ratios of the synthesis gas streams involved. This combined feedstock production process is very sensitive to the cost of natural gas, but relatively insensitive to the cost of the secondary feedstock. If sufficient natural gas were available, very large-scale production of methanol could result; this possibility raises significant energy policy questions.

c) Methanol produced from western Canadian coal could be economical as a straight transportation fuel when oil prices reach about $22/barrel. Use of coal is, however, likely to be limited by environmental considerations, including water supply availability.

d) Methanol produced using forest biomass alone as the feedstock could be economical as a straight transportation fuel when oil prices reach about $25/barrel and higher. The feasibility of using biomass as the feedstock is highly dependent upon its cost, which is generally expressed in $/oven dry ton (ODT). The price of oil at which methanol from forest biomass would become competitive rises approximately as follows:

Feedstock price	:	$10/ODT	$20/ODT	$30/ODT	$40/ODT
Methanol competitive at oil price of	:	$24/bbl	$28/bbl	$32/bbl	$36/bbl

As world oil prices increase in real terms, methanol could be produced from a variety of feedstocks in different regions of Canada, these feedstocks changing with time. Initially, methanol production would probably be from the combined feedstock process and from coal. As oil prices rise, the cost advantages of these feedstocks in comparison with forest biomass would diminish, and might eventually disappear. Thus, while it is unlikely that forest biomass alone would initially be used in any large scale production of methanol, it could have a major role if world oil prices escalate dramatically. Use of forest biomass as a feedstock would be especially promising wherever large quantities of low-cost biomass are available, and in the combined feedstock process.

Canadian Markets for Methanol

The potential markets for methanol in Canada are large. While various assumptions can be made about market growth and penetration rates, it is significant that if the Canadian road transportation market were to be fully penetrated by methanol as a straight transportation fuel by 2005, displacing gasoline and diesel fuel, it would require about 11 billion Imperial gallons of methanol per year. This amount of methanol is roughly equivalent to the displacement of 600,000 barrels of oil per day. (The question of displacing the various fractions produced from crude oil is not addressed here.)

Such a large-scale development of methanol as a fuel for the transportation sector could offer Canada significant industrial and regional development benefits, employment and environmental benefits, in addition to the benefits of security of supply and improved balance of payments which would result from any domestically produced alternative liquid fuel.

Department of the Environment Interests

The Department of the Environment has several specific interests in possible large-scale methanol use in the transportation sector. As nearly half of Canada's air pollution problems come from vehicle emissions, our interest in potentially lower emissions from methanol-fueled vehicles is obvious. And the environmental effects of alcohol fuel spills and leaks are likely to be less severe than those resulting from oil spills or leaks.

With this Department including the Canadian Forestry Service, we are particularly excited by the possible new opportunities for further development of the forest industry, which could be associated with large-scale methanol production from forest biomass.

USE OF FOREST BIOMASS FEEDSTOCKS

What then is the potential for forest biomass in methanol production? Forest biomass represents the major renewable feedstock capable of supporting very large-scale methanol production in Canada. Considerable debate is, however, underway regarding how much forest biomass could actually be made available, and at what price. As indicated above, this is key to determining when methanol production from forest biomass could develop in Canada. There are also some concerns that a methanol industry might displace traditional sources of wood supply to the forest industry.

The sources of forest biomass envisaged for methanol production are:

- surplus mill residues (bark, sawdust, shavings, chips) which in some areas now constitute a disposal problem;
- logging residuals (branches, twigs, slash) presently left scattered at harvesting sites;
- economically accessible surplus stands, especially hardwoods;
- degraded, infested, diseased or over-mature stands;
- surplus reserves economically inaccessible for conventional forest products alone; and
- energy plantations (of short and mini-rotation hybrids).

Use of these sources of biomass would mean that methanol production would not have to displace any traditional sources of wood supply to the forest industry. Indeed, this use would be highly compatible with the movement towards more intensive management of Canadian forests.

The Canadian forest sector now harvests about 60 million ODT each year, and leaves a similar amount of biomass behind as logging residuals. Moveover, this 60 million ODT harvest includes what normally ends up as mill residues. The Canadian forest sector harvest is expected to rise to some 100 million ODT per year by the end of the century. Major reforestation and silviculture programs are currently underway to ensure that Canada's forests can supply this fibre demand by the traditional forest sector.

The volumes of forest biomass that could potentially be involved in large-scale methanol production are significant in comparison with these present and forecast harvests. For example, production of 11 billion Imperial gallons of methanol per year from forest biomass would require about 100 million ODT of wood feedstock per year. Even using natural gas and biomass as combined feedstocks, 11 billion Imperial gallons of methanol would require at least 16 million ODT of wood biomass, plus one Tcf of natural gas - about one-half of Canada's current domestic consumption.

The following biomass supplies are forecast to be available after meeting the fibre demands of the forest sector. At $20/ODT and below, some 8 million ODT of mill residues and logging residuals will be available in 1985, largely in interior British Columbia. At $30/ODT, over 30 million ODT of these residues and residuals could be available annually from 1985 to 2025 throughout Canada. However, there is likely to be considerable competition for these residues, as lumber and pulp and paper mills turn to burning them for on-site steam and heat generation to replace increasingly expensive oil and gas. At higher prices, up to $40/ODT, volumes of over 100 million ODT per year could become available annually from 1985 to 2025 throughout Canada, from all of the forest biomass sources listed above.

While Canadian forest products companies do not presently think of themselves as potential liquid fuel energy producers, development of a methanol industry could offer major opportunities involving: new markets for forest biomass, more efficient utilization of the forest resource, manufacturing of new harvesting equipment, and employment generation across the country. The latter would be particularly significant, as this new employment would largely be in Canada's slow-growth areas.

INSTITUTIONAL SITUATION

There is, of course, considerable interest in using coal, biomass or other feedstocks to produce a synthetic gasoline directly, rather than methanol, for use in existing vehicle fleets and fuel distribution systems. Unless a technological breakthrough emerges, however, methanol used as a straight transportation fuel currently appears more economic than synthetic gasoline.

The "chicken and egg" problem remains: fuel companies are reluctant to produce new fuels until the engines exist to use them, just as engine manufacturers are reluctant to develop and produce new engines until appropriate fuels are widely available. A related institutional problem for Canada is the pan-continental nature of the North American fuel and vehicle markets, although this could be overcome by flexible-fuel or dual-fuel vehicles. Moreover, the Canadian market is about the same size as California's, for which special vehicles are presently manufactured.

COMPARISON WITH TAR SANDS DEVELOPMENT

An interesting comparison can be made between large-scale methanol development and tar sands development in Canada. It is important to recognize that these are not currently competing alternatives. The forecast shortfalls in liquid fuel supplies relative to domestic consumption already assume maximum development of tar sands plants. To increase its energy self-sufficiency, Canada thus needs to explore all opportunities based on domestic resources.

For roughly equivalent output energy, 11 billion Imperial gallons of methanol per year or 600,000 barrels of oil per day, the following table shows that capital costs are estimated to be of the same order of magnitude. The continuing employment in forest-based methanol production would, however, be about three times that of tar sands, and could be throughout Canada (rather than in only one province) in areas characterized by slower economic growth. This raises the difficult policy issue for government: more jobs in less developed regions, versus the institutional difficulties associated with introducing a new fuel.

Comparison of Methanol Development and Tar Sands Development

	Methanol Plants and Biomass Harvesting	Tar Sands Plants
Number of Plants	up to 120 (depending on scale)	5
Output energy	11 billion gallons methanol/year	600,000 barrels crude oil/day
Capital cost	$11*-22 billion	about $15 billion
Construction employment	82*-165,000 man-years	100,000 man-years
Continuing employment	50-60,000 man-years annually	15-20,000 man-years annually

* The lower end of these ranges assume use of the combined feedstock process (natural gas and forest biomass), rather than forest biomass used alone as the feedstock.

STATE OF METHANOL DEVELOPMENT IN CANADA

Technical Questions

A number of technical questions still remain to be resolved, relating to biomass production and harvesting, gasification technology and methanol production, and end use performance of methanol.

While the overall volumes of available forest biomass appear adequate to support large-scale use of forest biomass for methanol production, regional and site-specific work is needed to establish precise amounts, locations and delivered prices. The technologies of collecting residuals from logging sites, optimized harvesting systems, and energy plantation operation, have yet to be determined. Detailed analysis is also required of the on-site environmental effects of more extensive biomass removal.

Although the various technologies involved in methanol production from both coal and biomass feedstocks are reasonably well understood, extensive operational experience is lacking and optimal processes are not yet clearly defined, particularly for large-scale medium-BTU wood gasification. The use of natural gas and biomass as combined feedstocks, which is expected to produce cost savings, has not yet been tested.

At the user end, there are environmental and engineering questions regarding the effects of methanol spills and leaks, engine emissions, fuel performance under Canadian driving conditions, handling procedures and distribution costs, and the costs of modifying vehicles to run on methanol fuels.

Work Underway in Canada

Investigation into several of these matters is currently underway in Canada, partly under a research, development and demonstration program on energy from the forests (the ENFOR Program) launched by the Canadian Forestry Service. This $30 million, 6-year program broadly addresses the contribution that forests can make to Canada's overall energy picture, by examining the areas of biomass growth and production, biomass harvesting, and subsequent conversion and gasification.

The possibility of large-scale methanol production and use in Canada raises a number of important issues of energy policy, relating to both feedstocks and displacement of present fuels. In light of these issues, the technical questions outstanding, the economics of methanol production from biomass, and the variety of other alternatives open to Canada, there is a clear need to proceed with our investigations on a number of fronts. Thus the Government of Canada is also studying the full range of alternatives, including other fuel options, appropriate for the latter part of this century and beyond.

References

(1) Intergroup Consulting Economists Ltd., Liquid Fuels from Renewable Resources: Feasibility Study (prepared for the Government of Canada), Department of the Environment, Ottawa, Ontario, Canada, May 1978. This report consists of the following volumes:

- Summary and Conclusions
- Volume A: Demand Studies
- Volume B: Conversion Studies
- Volume C: Forest Studies
- Volume D: Agricultural Studies
- Volume E: Municipal Waste Studies

(2) Advisory Group on Synthetic Liquid Fuels, Liquid Fuels in Ontario's Future, Ministry of Energy, Government of Ontario, Toronto, Ontario, Canada, 1978.

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ETHANOL/GASOLINE BLENDS AS AUTOMOTIVE FUELS

by

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ABSTRACT

An experimental study of gasoline and 10% ethanol/90% gasoline blends was made using five late-model vehicles operated on a climate-controlled chassis dynamometer. Data were obtained to permit comparisons of fuel economy, emissions, and other significant operational characteristics observed in tests with the two fuels.

Volumetric fuel economy was shown to be slightly decreased while energy economy was slightly increased using the ethanol/gasoline blend.

Compared with the results using base gasoline, the use of the ethanol/gasoline blend had no adverse effect upon regulated emissions at test temperatures within the range 20° to 75° F; at 100° F there were minor increases in emissions using the ethanol/gasoline blends.

Addition of ethanol at 10% concentration generally either had no effect or only slight effect on unburned hydrocarbon; an exception was noted for 100° F at which temperature unburned hydrocarbon from the blend was increased significantly over that found with the base fuel.

Road octane quality of the ethanol/gasoline blend was increased by about 3.5 numbers over the base fuel.

INTRODUCTION

Ethanol has been used in internal combustion engines for many years both in pure form and mixed with gasoline. Both beneficial and detrimental characteristics of ethanol as motor fuel have long been noted and widely recognized. The present situation is complex, however, and there are many factors that should be considered before ethanol/gasoline blends are widely marketed in the United States. Some of the questions that should be answered before such a move is made are: (1) What effect will the use of ethanol have on exhaust emissions of current and future production vehicles which must meet governmentally-improved emissions standards?, (2) What effect will the use of ethanol have on meeting federally-mandated fuel economy standards of present and future vehicles?, (3) What effect will ethanol have on life expectancy of current and future emission control systems which are currently mandated to control emissions for 50,000 miles?, and finally, (4) What are the economics of ethanol compared with other attractive alternative fuel options?

In an effort to provide information concerning some of the above questions, the Bartlesville (Okla.) Energy Technology Center, in cooperation with the Division of Transportation Energy Conservation of the Department of Energy, undertook a program of research to investigate the effect of using a 10% ethanol/90% gasoline fuel mixture on vehicle emissions and fuel economy using late-model vehicles with current and advanced emission control systems.

EQUIPMENT AND PROCEDURES

Emission and fuel economy data were generated on a chassis dynamometer in an enclosed facility capable of maintaining ambient temperature from 20° to 100° F. The chassis dynamometer, constant volume sampling (CVS) system, and emission measuring equipment are those specified in the federal emission test procedure [1]*. In addition to "bag measurements" as specified by the federal test procedure (FTP), the regulated emissions plus carbon dioxide (CO_2) and exhaust flow and dilution air flow were measured continuously. The real time measurement provided an internal check of the bag measurements and aided in detailed modal analysis during and subsequent to the test.

In addition to the regulated emissions measurements, aldehyde and alcohol content of the exhaust were also measured. Aldehydes were measured by the 3-methylbenzothiazolone hydrazone (MBTH) method [2]. A procedure utilizing gas chromatography for determining unburned ethanol was developed as part of the overall project and is described in a separate publication [3]. Hydrocarbon character of the exhaust was determined by gas chromatography [4].

The five vehicles used in the test are described in table 1. Two of the vehicles utilized 3-way catalyst systems for emission control with closed loop feedback from exhaust oxygen sensors for air-fuel (A/F) mixture control. The vehicles had accumulated 3,000 to 10,000 miles using unleaded gasolines prior to tests conducted with the alcohol-blended fuels.

The vehicle's engines were adjusted to manufacturers' specifications at the start of the test and not readjusted during the program.

Emissions and fuel economy were measured at ambient temperatures of 20°, 45°, 75°, and 100° F to determine influence of temperature on exhaust characteristics. At each temperature condition, emissions were measured using a base gasoline and a blend of 90 vol-pct gasoline base/10 vol-pct anhydrous ethanol. In the following discussion the latter fuel will be referred to as "ethanol blend". Analyses of the test fuels are reported in table 2. Triplicate tests were conducted at each temperature/ test fuel condition and results averaged to insure data reliability. Exhaust hydrocarbon (HC) composition was determined in only two of the triplicate tests (for four of the vehicles).

The evaporative emissions were not determined on the vehicle tests and the vehicles were not subjected to a "heat build" soak period prior to emissions testing. The vehicles were conditioned by operation through an LA-4 cycle with the test fuel in the vehicle's fuel tank and allowed to

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*Numbers in brackets designate References at the end of paper.

soak at the specified test temperature for 12 to 18 hours prior to emissions testing. Ambient temperature was maintained in the test facility within ±2° F at 45°, 75°, and 100° F. While at the 20° F test condition, the tests were started at about 18° F with the temperature rising to about 30° F during the highway fuel economy portion of the test cycle.

EMISSIONS/FUEL ECONOMY

A comparison of exhaust emission data between the base gasoline and the ethanol blend at 75° F ambient temperature is presented in Fig. 1. The results indicate reductions in all regulated emissions using the ethanol blend compared to gasoline. Carbon monoxide (CO) emissions were reduced approximately 25%, unburned hydrocarbons approximately 14%, and oxides of nitrogen (NO_X) were decreased approximately 6% by the use of the ethanol blend compared to the base fuel. However, aldehyde emissions were increased by approximately 25% Fuel economy results (Fig. 2) show that at 75° F, base gasoline attained slightly greater volumetric fuel economy (mpg), and the ethanol blend attained slightly greater fuel energy economy (mi/10^5 Btu). However, the differences in fuel economy between the two fuels are less than 2.5% expressed either on a volumetric or an energy basis. Therefore, a much larger sampling of vehicles is necessary before a statistically meaningful number can be attributed to the fuel economy effect of large-scale usage of ethanol blended with gasoline.

Temperature Effect

Alcohols, when added to gasoline, have been shown by other researchers to sometimes markedly affect the fuel's vapor pressure and distillation characteristics [5] which may, depending upon ambient temperatures, affect engine operation. Some researchers have also suggested significant fuel economy differences exist between using gasoline and gasoline/alcohol mixtures at ambient temperatures lower than the federal test specifications [6]. Therefore, in addition to testing the vehicles at the federal specified temperature of 68° to 86° F, the vehicles were also tested for exhaust emissions and fuel economy at 20°, 45°, and 100° F.

Emissions data show minimum CO emissions (Fig. 3) occur at 75° F using both fuels; however, the ethanol blend generally produced less CO than the base gasoline. For example, at the 20°, 45°, and 75° F test conditions, the use of the ethanol blend produced about 20% less CO than the base fuel; however, at the 100° F condition, CO emissions were essentially equivalent for both fuels.

Modal analyses suggest that a large part of the CO differences between the two fuels occur during cold engine operation in which A/F mixture is generally rich. However, at the 100° F condition the "hot start" CO emissions are higher with the ethanol blend compared to gasoline.

Hydrocarbon emissions trends (Fig. 4) are very similiar to CO emissions described above in that hydrocarbons are essentially doubled by operation at 20° F compared to 75° F using either fuel. Between fuels, however, the ethanol blend showed HC reduced approximately 10% at 20°, 45°, and 75° F; at the 100° F condition, hydrocarbons were increased about 15% with the use of the ethanol blend as compared to gasoline.

Oxides of nitrogen emissions (Fig. 5) were only slightly affected by temperature. An NO_X reduction of about 7 percent was apparent at the 20° and 45° F condition by the use of the ethanol blend compared to the base gasoline; however, at 75° F the difference is essentially nil, and at 100° F the use of ethanol blend produced about 5% more NO_X than using the base fuel.

Exhaust aldehydes (Fig. 6) were also only moderately affected by ambient temperature. The use of the ethanol blend fuel produced approximately 25% more aldehydes than the base fuel at all temperatures except at 45° F where the emissions levels from both fuels are similar.

The unburned ethanol level (Fig. 7) was shown to be dependent upon ambient temperature with the minimum levels occurring at 75° F. The amount of ethanol in the exhaust using the ethanol blend fuel ranged from 2.5 to 3% of the amount of total unburned hydrocarbons in the exhaust at each test temperature. Essentially no ethanol was detected in the exhaust of the vehicles operating on the base fuel.

Fuel economy was affected by ambient temperature using both fuels with approximately 2 miles/gallon improved fuel economy attained by operation at 100° F compared to 20° F. In comparing fuels, volumetric fuel economy (Fig. 8) for both urban and highway portions of the test cycle was shown to be decreased using the ethanol blend at all temperature conditions. A comparison of the difference in composite fuel economy (weighted urban/highway) between the base and ethanol blend fuel is shown in Fig. 9. The data show the volumetric fuel economy of the ethanol blend fuel to be about 2.5% lower than the base fuel which closely corresponds to the 3.4% lower energy content of the ethanol blend fuel.

Advanced Emission Control Systems

Some advanced emission control systems utilize exhaust oxygen sensors to feed back a signal to the fuel induction system for precise A/F mixture control. The system's primary function is to maintain the A/F ratio near stoichiometric conditions, which is necessary for 3-way catalyst operation for effective control of CO, HC, and NO_X. A side bonus from the exhaust feedback systems is the potential of the hardware to maintain the same stoichiometric A/F ratio while using either straight gasoline or alcohol/gasoline blends.

Two vehicles in the test fleet utilized 3-way catalysts with closed loop A/F control systems. Test data from these systems and comparable data from systems utilizing straight oxidation catalyst suggest the following:

The influence of temperature (Figs. 10 and 11) in CO and HC emissions shows similiar effects and trends for 3-way and for oxidation catalyst; these effects and trends are essentially alike for the base gasoline and ethanol blend.

Carbon monoxide emissions are primarily a function of A/F; therefore, any emission control system that allows fuel rich operation is expected to produce significant CO emissions, and fuels that effectively "lean" A/F mixtures condition are expected to reduce CO emissions. The majority of CO and HC emissions from the 3-way catalyst systems is produced during cold start (rich A/F) operation in which the exhaust oxygen sensor signal is overridden. As a result, lower CO and HC emissions can be expected from ethanol blends compared to gasoline using both 3-way and oxidation catalyst systems provided a significant portion of the emissions is produced during cold start (rich A/F) operation. Unburned HC emissions are significantly lower from the 3-way catalyst systems at all temperatures and both fuels compared to the oxidation catalyst systems.

Oxides of nitrogen emissions from the vehicles equipped with 3-way catalysts were significantly reduced compared to the other systems, using both test fuels and at all temperatures (Fig. 12). Oxides of nitrogen emissions were essentially unaffected by the use of the ethanol blend in the vehicles equipped with 3-way catalyst systems.

Exhaust aldehydes were found to be lower (by a factor of approximately 4) from the vehicles with the 3-way catalyst systems compared to the vehicles with oxidation catalyst systems (Fig. 13) at all temperatures and with both test fuels. However, aldehydes were generally increased by use of the ethanol blend fuel compared to the base gasoline in both types of catalyst systems.

In using the ethanol blend fuel, the 3-way catalyst equipped vehicles produced about one-half the amount of unburned ethanol in the exhaust as vehicles equipped with oxidation catalysts.

Hydrocarbon Characterization

Detailed exhaust hydrocarbon analyses were conducted to determine the effect of using the ethanol blend fuel on the exhaust hydrocarbon composition. These data were obtained for four of the test vehicles (two vehicles with oxidation catalyst and two vehicles with 3-way catalyst) at 20°, 45°, 75°, and 100° F ambient temperatures using both fuels.

Hydrocarbon compositional data are presented by classes of hydrocarbons calculated on a mass basis (gm/mile) considering the weighted contribution of the three phases of the test cycle. The data are presented in Fig. 14 through 17. Fig. 14 presents the total paraffins, aromatics, and olefins at the various temperatures. The results suggest the ethanol blend fuel produces either the same as, or slightly less, total paraffins, aromatics, and olefins than the base fuel at all temperatures using both catalyst systems--a single exception being at 100° F in which the 3-way catalyst system produced more paraffins using the ethanol blend fuel than the base fuel. Closer examination of the exhaust paraffins at 100° F test temperature with the 3-way catalyst system (Fig. 15) suggests also that the amount of normal, iso, and C_{4+} paraffins are all increased using the ethanol blend fuel compared to base fuel. At all other test conditions the ethanol blend fuel produced the same or lower levels of paraffins than did the base fuel.

The amount of benzene as well as C_{7+} aromatics (Fig. 16) in the exhaust of the oxidation catalyst vehicles was reduced by the use of the ethanol blend compared to the base fuel; however, using the 3-way catalyst systems, the exhaust aromatics were essentially unaffected by the ethanol blend fuel. The amount of acetylene (Fig. 16) in the exhaust is essentially unaffected by use of the ethanol blend fuel.

Examination of the olefin classes in the exhaust (figure 17) suggests reductions of ethylene and alkenes due to the use of the ethanol blend fuel compared to the base fuel in the oxidation-catalyst-equipped vehicles at all test temperatures except 100° F. The internal alkenes and diolefins in the exhaust are unaffected by the ethanol blend fuel at all temperatures using both catalyst systems.

The hydrocarbon characterization results show that (a) ambient test temperature and type of emission control system affects the hydrocarbon distribution to a much greater extent than does using the ethanol blend fuel compared to the base gasoline, and (b) the use of the ethanol blend generally had either no effect on or reduced the exhaust HC components except at the higher temperature test condition.

ROAD OCTANE RESPONSE

The road octane rating of ethanol/gasoline mixtures was determined on four of the test vehicles. Octane determinations were not conducted on the Volvo due to inability to change fuels quickly while using the fuel-injection system. Road octane determinations were conducted using three base fuels of 81, 86, and 91 research octane number (RON), each with 0, 5, and 10% anhydrous ethanol added. A modified Uniontown road octane technique was used, except the tests were conducted on a chassis dynamometer. Relatively constant ambient temperature conditions were attained by operation only during morning hours. A single test consisted of comparing the reference fuels and all test fuels in one vehicle without interruptions. Triplicate tests were conducted for each vehicle/fuel combination.

The data (Fig. 18) show that addition of 10% ethanol increases the road octane value of an 81 RON base fuel by about 4.5 numbers and a 91 RON base fuel by about 3 octane numbers. The octane increase due to ethanol was found to be relatively linear within the range tested.

The average road octane blending value of ethanol ranged from 122 for the 81 RON fuel to 117 for the 91 RON base fuel.

SUMMARY

Vehicle tests were conducted to determine the effects on fuel economy and emissions in adding 10 vol-pct ethanol to a base gasoline. Comparative road octane values were also determined for the base fuel and blend. Results show that compared to the base gasoline the addition of ethanol at 10% concentration results in the following:

- Decreased volumetric fuel economy.
- Increased fuel energy economy.
- Reduced CO, HC, and NO_X emissions at 20°, 45°, and 75° F.
- Increased HC and NO_X emissions at 100° F.
- Aldehyde emissions increased by about 25% at 20°, 75°, and 100° F.
- Exhaust HC distribution not materially affected.
- Road octane quality of an 81 RON fuel increased by 4.5 numbers and a 91 RON fuel by 3 numbers.

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TABLE 1. - Description of test vehicles

Year Make/Model	Engine, cu-in. displacement	Transmission	Type emission control
1975 Dodge Colt	98	Auto/3-speed	Air injection/EGR
1976 Chevrolet Impala	350	Auto/3-speed	Oxidation catalyst/EGR
1977 Pontiac Astre	151	Manual/5-speed	Oxidation catalyst/EGR
1977 Volvo 242	130	Auto/3-speed	3-way catalyst[1]
1978 Ford Pinto	140	Auto/3-speed	3-way catalyst/EGR[1]

[1] Systems include closed loop feedback for A/F control.

TABLE 2. - Fuel specifications

	Base fuel	Base fuel + 10 pct ethanol
FIA, analysis pct:		
Aromatic	28	-
Olefin	8	-
Saturates	64	-
Distillation, ASTM D86:		
IBP	90	90
Pct evaporated:		
5	111	108
10	124	118
20	151	135
30	184	148
40	210	162
50	233	217
60	256	244
70	282	272
80	312	301
90	347	338
95	480	373
EP	416	410
Specific gravity	0.746	0.751
Reid vapor pressure, psi	9.7	10.9

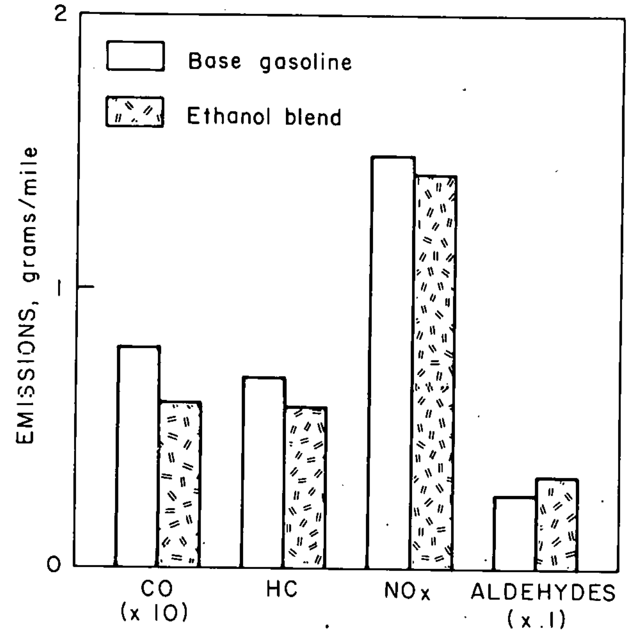

Fig. 1. - Influence of Fuels on Exhaust Emissions, 75°F

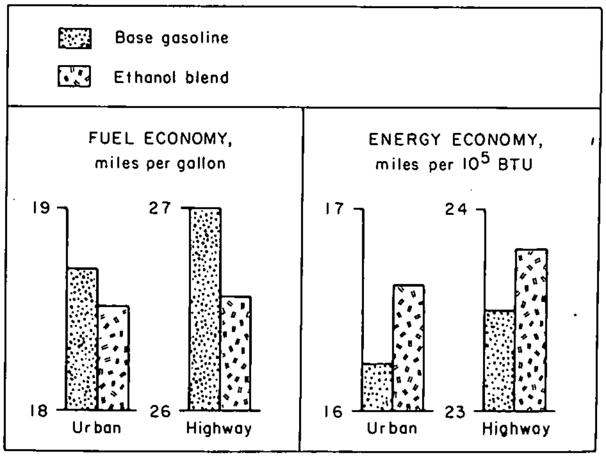

Fig. 2. - Influence of Fuels on Fuel Economy, 75°F

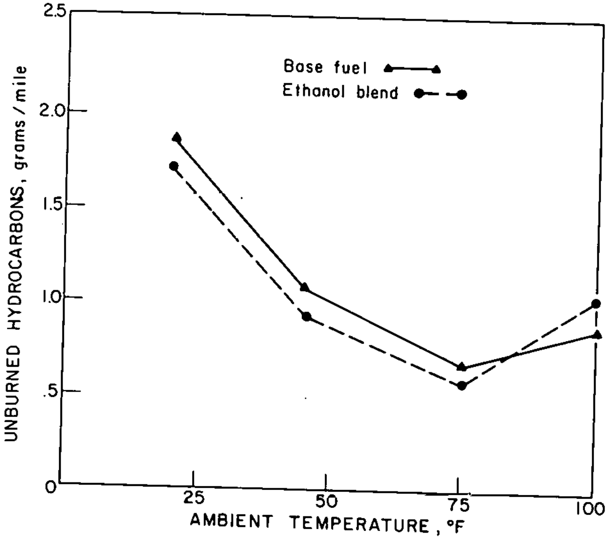

Fig. 4. - Influence of Ambient Temperature on HC Emissions

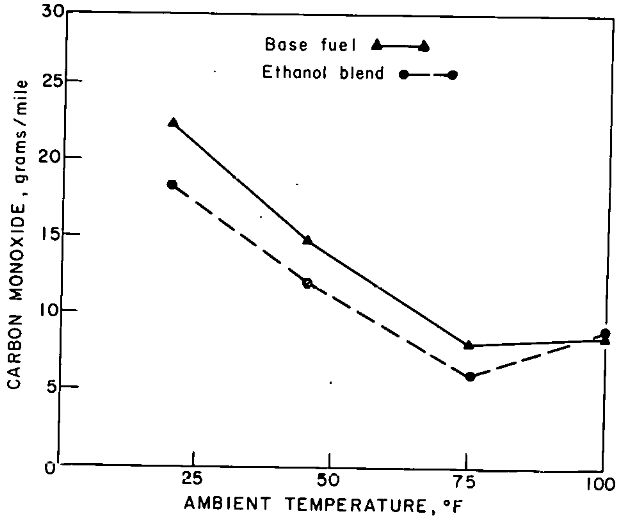

Fig. 3. - Influence of Ambient Temperature on CO Emissions

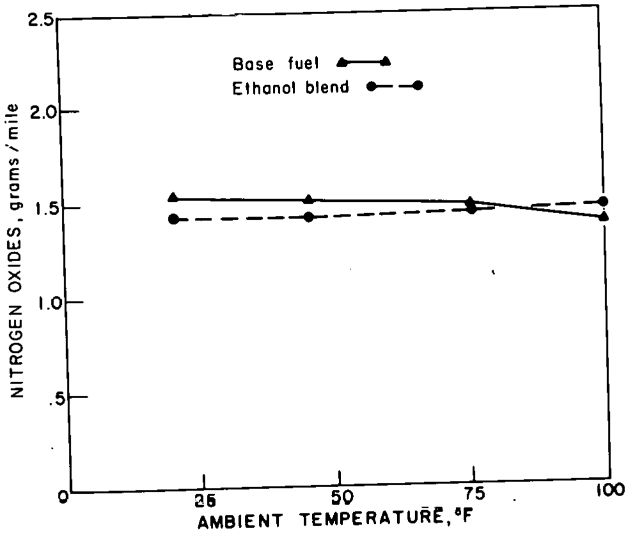

Fig. 5. - Influence of Ambient Temperature on NO_x Emissions

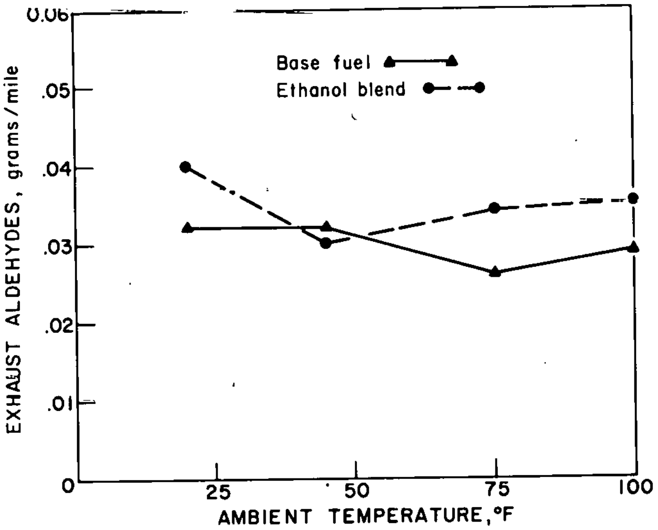

Fig. 6. - Influence of Ambient Temperature on Aldehyde Emissions

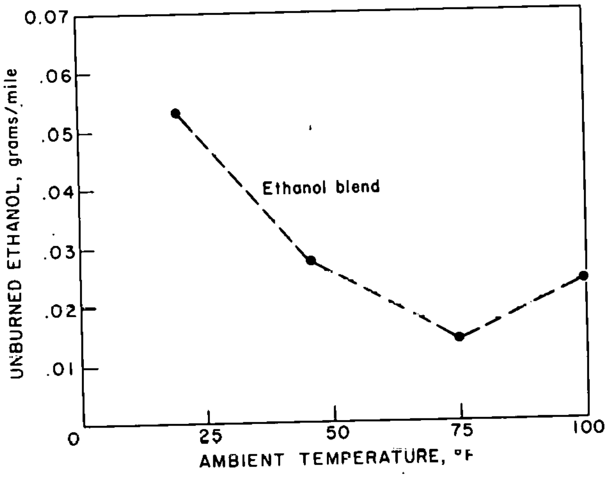

Fig. 7. - Influence of Ambient Temperature on Ethanol Emissions

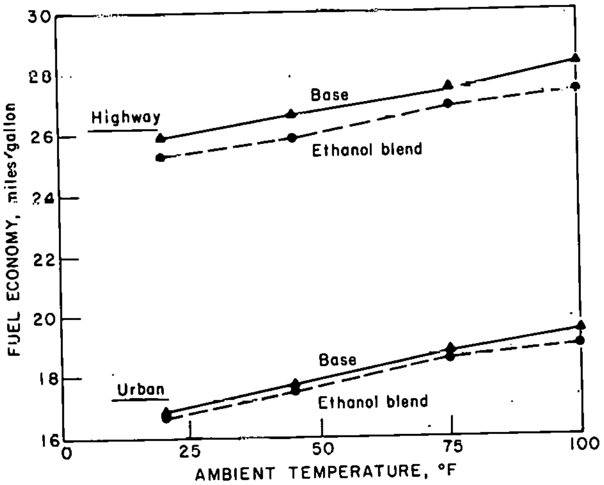

Fig. 8. - Influence of Ambient Temperature on Fuel Economy

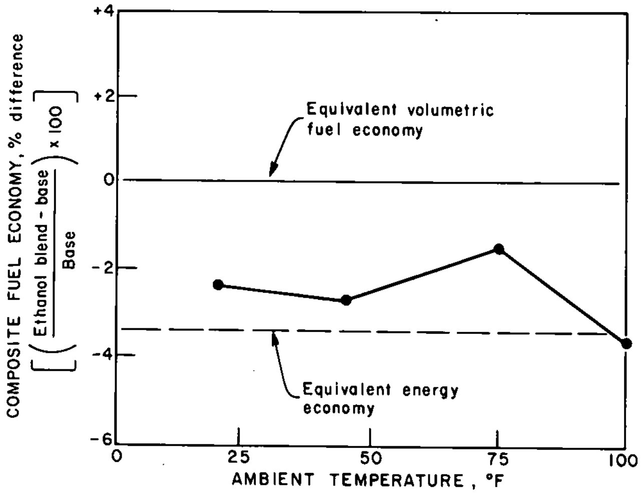

Fig. 9. - Influence of Fuel and Ambient Temperature on Fuel Economy

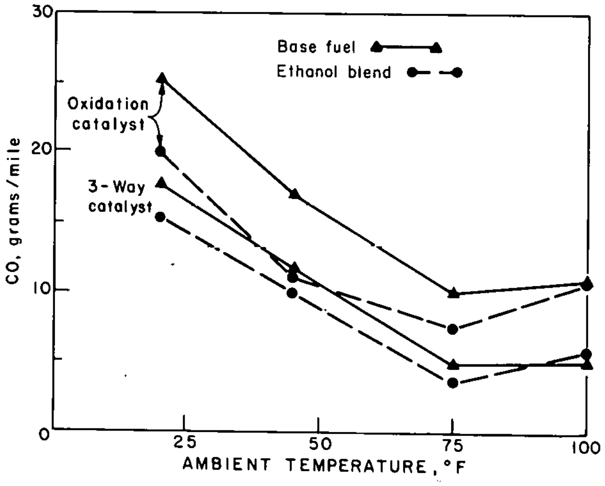

Fig. 10. - Influence of Ambient Temperature and Catalysts on CO Emissions

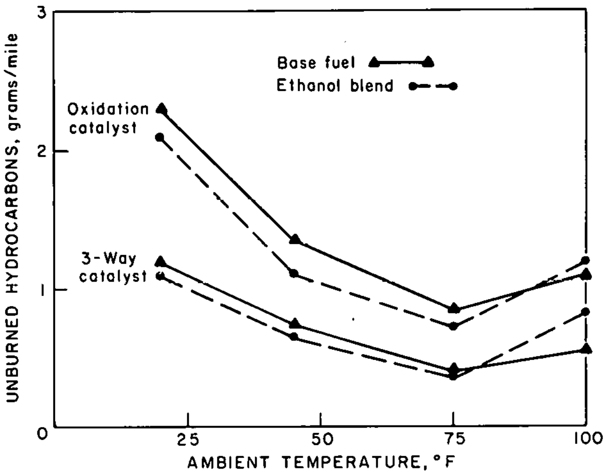

Fig. 11. - Influence of Ambient Temperature and Catalysts on HC Emissions

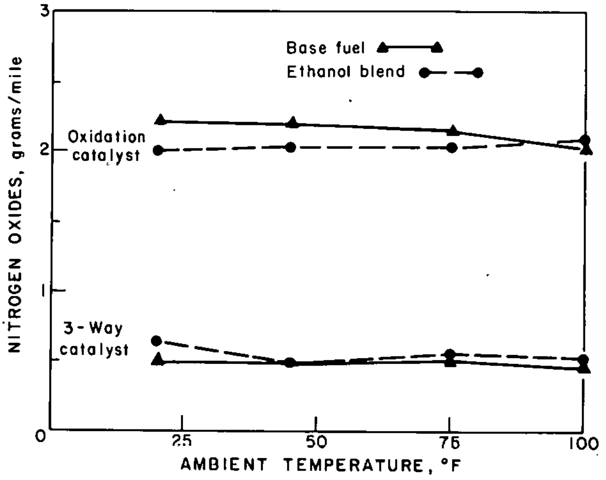

Fig. 12. - Influence of Ambient Temperature and Catalysts on NO_X Emissions

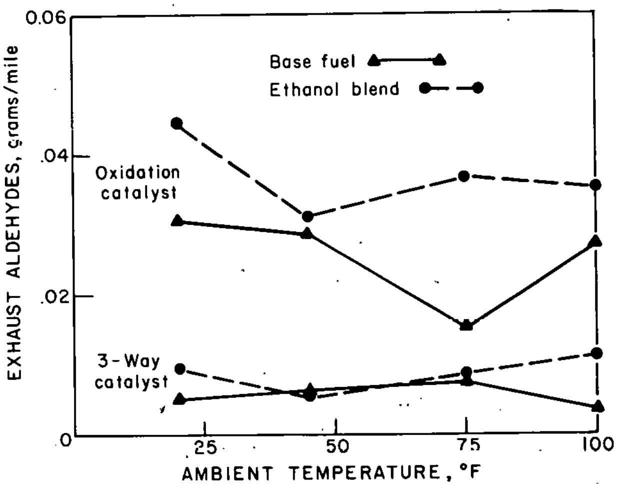

Fig. 13. - Influence of Ambient Temperature and Catalysts on Aldehyde Emissions

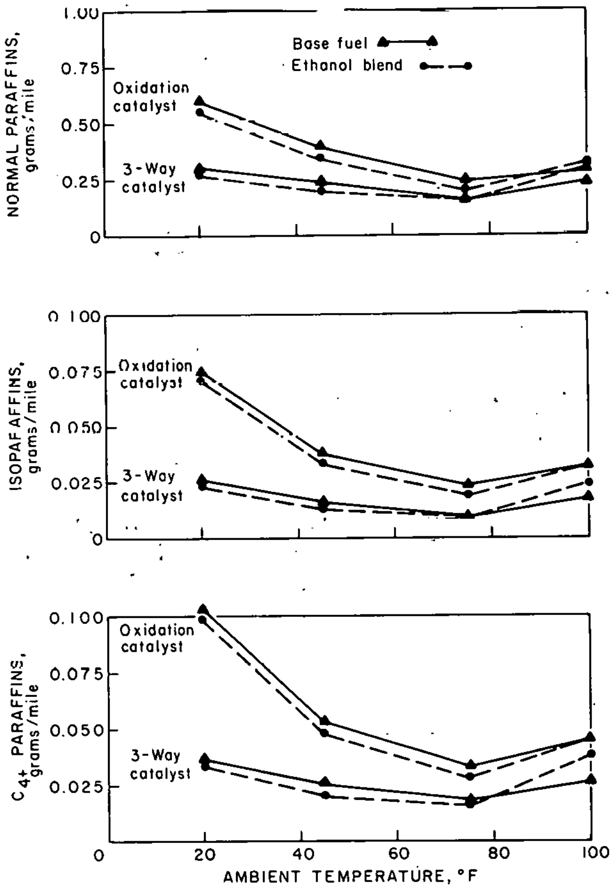

Fig. 15. - Influence of Ambient Temperature on Exhaust Paraffins

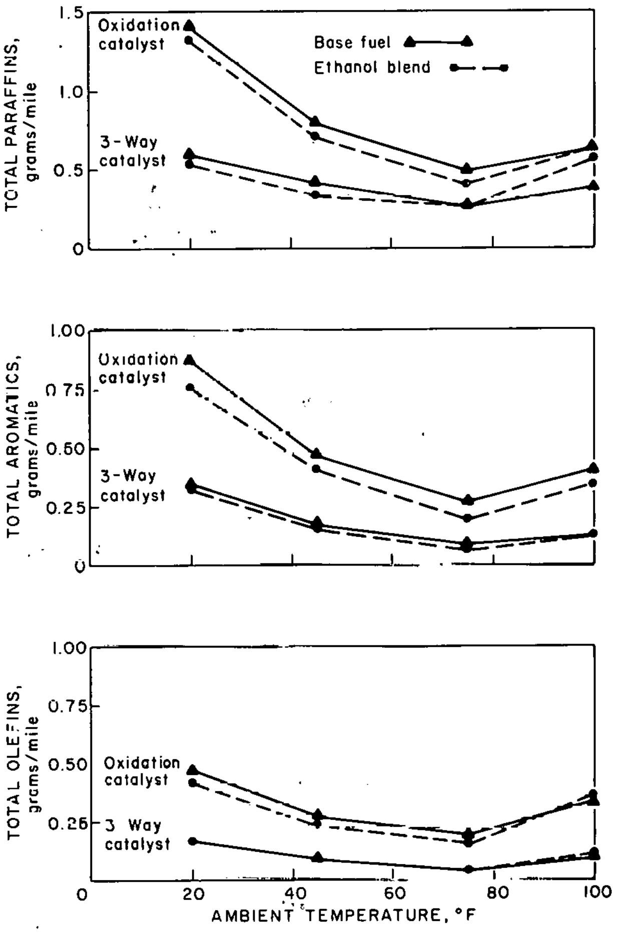

Fig. 14. - Influence of Ambient Temperature on HC Composition

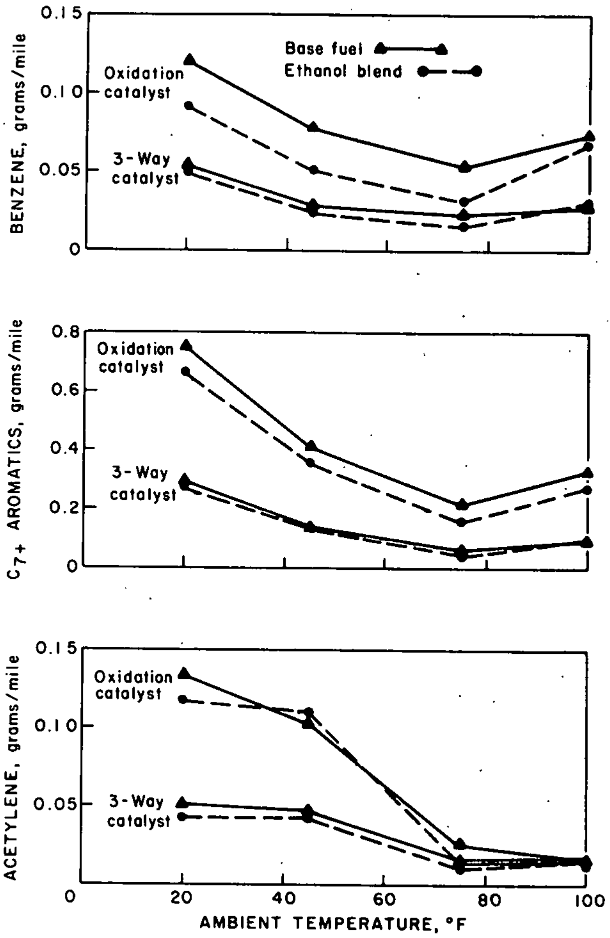

Fig. 16. - Influence of Ambient Temperature on Exhaust Aromatics and Acetylene.

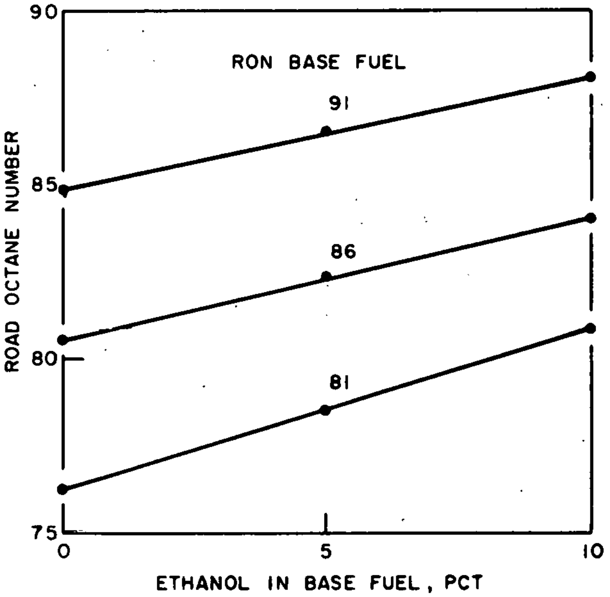

Fig. 18. - Influence of Ethanol on Road Octane

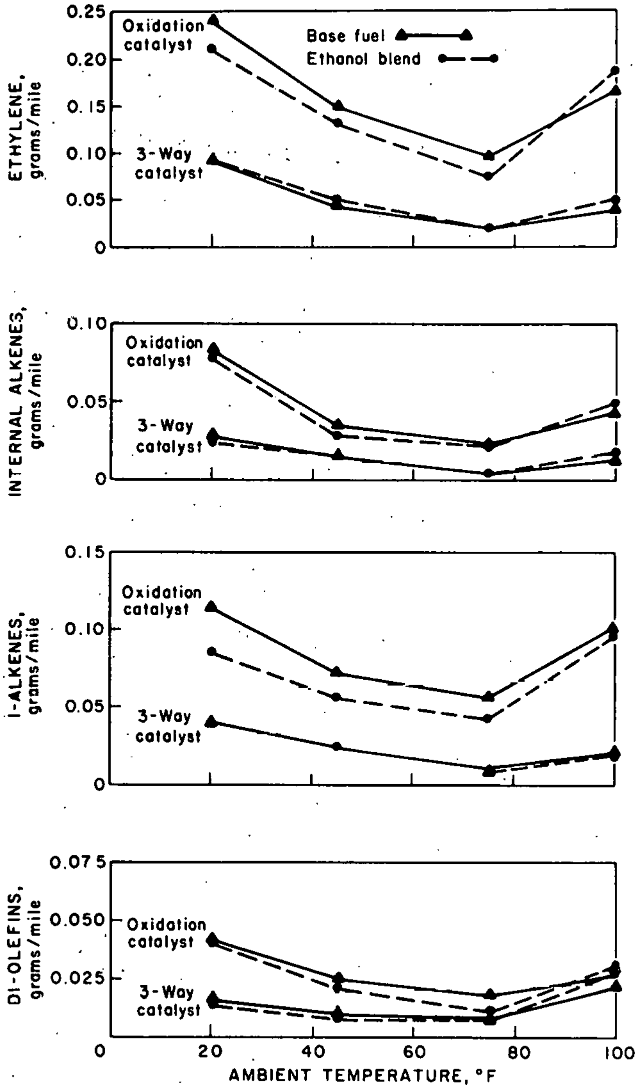

Fig. 17. - Influence of Ambient Temperature on Exhaust Olefins

EXPERIENCES WITH THE UTILIZATION OF ETHANOL/GASOLINE AND PURE ETHANOL IN BRAZILIAN PASSENGER CARS

by

G. Pischinger - VWB
N.L.M. Pinto - VWB

PREFACE:

For the better understanding of Brazil's energy problems, we feel it convenient to go into some preliminary explanations.

Brazil currently imports about 80% of its petroleum needs, at prices five times as high as those before the 1973 crisis. The outgo of US $ 4 billion a year for oil imports, 50% of which for use in vehicles, has rendered necessary revision to the country's energy policies, some of the steps taken being as follows:

a) Incentives to prospecting for oil
b) Limiting of highway speeds to 80 km/h (50 mph)
c) Closing of gas stations on Sundays and Holidays
d) Raising of the prices of petroleum products and of highway toll charges
e) Development of a NATIONAL ALCOHOL PROGRAMME.

In Figure 1, it will be seen that although the country's development results in a continuing growth in the consumption of petroleum products, the rate of growth for gasoline has dropped. On the other hand, the rate of growth for diesel oil has risen. The desired over-all reduction - or, rather, limitation - has not been obtained, but the general public has been rendered conscious of the problem.

EARLIER APPLICATIONS OF ALCOHOL AS AN AUTOMOTIVE FUEL:

In Brazil, the addition of alcohol to gasoline - and even the use of straight alcohol - for vehicle use goes back to 1923. It was only from 1967 on, however, that alcohol-gasoline mixtures came into relatively general use and, even then, the purpose of such additions was not the saving of petroleum but rather the using up of excess alcohol from sugar mills. This rendered the problem both regional and seasonal, and alcohol percentagens in the mixtured varied all the way from 0 to 30%.

NATIONAL ALCOHOL PROGRAMME:

This programme was brought into being to help meet the petroleum crisis, and ethyl alcohol was chosen as the country's best option for the following reasons:

- Previous experience of its application to vehicles.
- Production technology already available.
- Favorable climate and terrain for growing the raw materials.

It could also be mentioned that any biomass-based fuel will provide a very welcome number of jobs on the land and thus contribute to stemming the tide towards the cities.
With this plan, the country's agricultural frontiers are being pushed out and there is a corresponding expansion of existing alcohol plants and installation of new distilleries. Such activities are being financed by the Federal Government at low rates of interest and over periods of 15 years.

The plan itself was divided into two distinct phases. The first phase aims at providing enough alcohol to garantee a nation-wide and constant-percentage mix of 20% by volume. Begining in 1974 and on a regional basis, increasing proportions of alcohol have been mixed into the gasoline and the forecast is that 1979 will see the attainment of the 20% target. This, be it said, is to a great extent the result of sugar being available because of a 90% drop in world sugar prices.
At present, use of alcohol-gasoline mixture is limited to the larger consumer centers, but it is planned to make such usage uniform across the nation by 1980 or 1981. This initial availability of the alcohol mix on a regional basis was adopted for three reasons:

1 - Use of existing blending facilities during build-up of nation-wide facilities.

2 - Concentration of blend-using vehicles in areas accesible for observation and action.

3 - Ouicker reduction of automotive pollution in the larger cities.

The picture of alcohol additions is given in Figure 2.

Regional availability, however, has worked against the introduction by VWB of engine modifications (higher compression-ratio) to offset the fuel consumption increase (4 to 6%) resulting from alcohol's lower heat content. But at least reason 3, above, is valid. Figure 3 shows how alcohol mixes reduce the majority of vehicle pollutants. The aldehyde emissions are being studied by VWB and PETROBRÁS together.

The second phase of the programme consists of the development and production of cars and utilities running on ethyl alcohol hydrated to 4 or 5%. Production of such vehicles is scheduled to start in 1981. Reporting of results thus far obtained by VWB with alcohol-fueled vehicles will be undertaken in the second half of this paper.

As for methyl alcohol, its production in Brazil is still limited, although there are several projects under way for producing it from eucalyptus trees, which do well in poor soil or from local coal.

Nevertheless, we are investigating its mixture with gasoline (15%) and also gasoline-ethanol-methanol mixes. These three-way mixes are still under study, but it is interesting to note that methanol-gasoline mixes are satisfactory up to 6% of methanol; above this, separation occurs unless prevented by the addition of 2% anhydrous ethanol.

Another point worthy of note is the addition of ethyl alcohol to diesel oil. The Government has decided that, before end of 1979, diesel fuels shall have a 4%-by-volume mix of ethanol. The specific object of this decision is to offset the unbalance between diesel oil and gasoline from local refining operations.

ALCOHOL PRODUCTION:

It is undeniable that Brazil is in a privileged position to substitute alcohol for gasoline and diesel oil. To satisfy 1985 fuel needs, it would be enough to plant 2% of its land area in sugar-cane and cassava. See Figure 4.

TECHNICAL ASPECTS

In Brazil, alcohol-gasoline blends are a familiar matter, with no major effects on the functioning of the existing cars For this reason, we would like, in the technical part of our paper, to step right into our experiences with straight alcohol as a fuel. We want to describe the work we have done and some of the experiences and results obtained with the 4-cylinder in-line engine of the Passat (Dasher, in the US) which, in Brazil, has a displacement of 1500 cc.

CONCEPT:

The usual steps, such as compression-raising and carburettor and ingnition adjustments, were taken. In the interest of fuel economy, the leanest possible mixture was sought. In gasoline engines, this trend is well established, but in alcohol-burning versions serious difficulties are encountered.

A relatively high boiling point together with vaporization heat 3.5 times higher than for gasoline render the attaining of a lean-mixture engine extremely difficult. The mixture formation along the way to the combustion chamber is hampered by these characteristics, even in warmed-up alcohol-engines, in the same way that it is affected in gasoline engines under cold running conditions. This means that the alcohol engine never warms up properly in the carburation area, so that the operation of a car so equipped always requires a rich mixture, as is the case with gasoline engines during the warm-up period. As a result, both the fuel consumption and the emissions of CO and unburnt fractions become completely unacceptable.
To get the required "warm" operation of alcohol engines, it is necessary to take all the steps that would be taken to improve consumption, emissions and driveability in the gasoline engines during their warm-up periods.

At VW Brazil we have effected substantial pre-heating of the air (to 90ºC) as well as heating of the walls of the inlet manifold, to which engine heat radiation contributes. Fortunately, this heating not only can, but must be, continuous, so there is no need for complicated controls to interrupt it. An additional advantage of this is that the possibility of overcooling the mixture-conducting parts is eliminated during the periods when the heating would be disconnected, e.g. under conditions of full load. On the other hand maintaining the heat makes it necessary to keep the compression ratio a little lower in order to avoid knocking. Our alcohol engine has a compression ratio of 10.5, which has proved to be a good compromise for all factors including durability. The power output of 53 kW thus reached is actually 10% higher than the 48 kW produced by the equivalent gasoline engine.

CARRYING-OUT OF ADJUSTMENTS

As is well known, only a few optimizations of the gasoline engine under cold-running conditions can be carried out satisfactorily on a test bench:
much more important is the adjustment of the engine, after installation in the vehicle, aiming at driveability. This is obviously true for alcohol engines too. Back on the dynamometer you can then perform the finer adjustments based on the application of heat to the intake manifold and stream. With this in mind, we developed, in vehicle operation, the combined heating and leaning-out of the mixture. A closer look at the results obtained by each step was given by measurements of the emissions and consumption in the CVS cycle and other simulations on the chassis dynamometer.

CONSUMPTION RESULTS

At VW Brazil, we carry out a consumption test on the chassis dynamometer which assumably corresponds to the average traffic conditions in the most densely populated areas of Brazil. It combines the City-Driving Cycle (CDC), but starting with a warm engine, and the Highway-Driving Cycle (HDC). The overall fuel consumption is calculated by the formula:

$$0.7\ \mathrm{CDC} + 0.3\ \mathrm{HDC}$$

The load on the rollers is adjusted to the actual rolling-resistance curve obtained by means of the torque observed on the road. The following is a comparison between the alcohol and gasoline engines in the Passat:

	CDC			HDC	Total
	consumption 1/100 km	CO g/mi	NOx g/mi	consumption 1/100 km	consumption 1/100 km
gasoline	11,33	44,9	2,1	8,13	10,37
ethanol	13,82	9,0	3,2	10,01	12,68
percentage based on gasoline	22% more	80% less	52% more	23% more	22,3% more

We believe that these results are very positive and show that the theoretically higher consumption of roughly 45%,stemming from the properties of the fuels under consideration, can be substantially diminished. We also find that the results in CO emissions show that we could well achieve a lean operation still using a simple single-stage carburettor. The NOx-emissions reflect the fact that we both operate the engine with a higher compression ratio and also introduce additional heat into the charge.

TEST RESULTS

In extremely severe road-tests covering more than 100,000 km, no damage whatsoever was observed in the engines that could be blamed on the use of alcohol. In cooperation with Texaco, the quality of the HD-30 engine oil was checked constantly and it was established that, at least under these conditions, the oil-change intervals could have been raised, from the 7,500 km now in force for the gasoline-engined cars, to 10,000 km. Other tests are still being carried out on the vehicles in the factory fleet, in ordinary every-day use.

There could, however, be considerable surprises in the possibly critical reactions of some materials on coming into contact with ethanol. All vehicles are subject to the need for changes in some materials used in them. As an example, PVC will, in time, be rendered brittle by ethanol, so it should be substituted. Also, we had inconvenient deposits, formed in the carburettor, of an ochre-colored powder which resulted from an acid reaction with the epoxy coating of the fuel tank.

QUALITY OF THE ALCOHOL

Close attention should be paid to the quality of the alcohol, especially its acid content. Up till now, ethanol has been a by-product of the sugar refineries. Its quality can vary considerably, from batch to batch, because of inadequate control during the manufacturing process. There should be closer control of the temperature during the fermentation, so as to obtain a low acid content. Care should also be taken in stocking and distribution. In this area, there is a great need for research and development aimed at obtaining a fuel of constant quality. The substantial investments required should not be underestimated.

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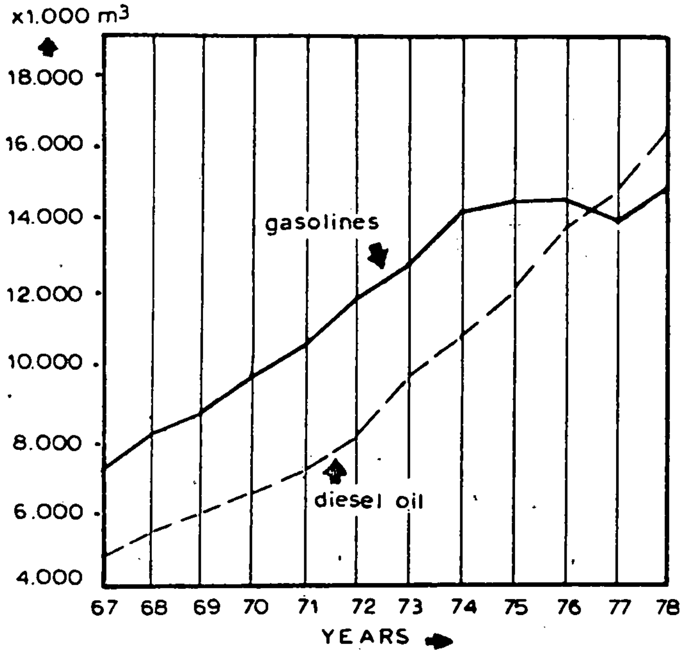


unit: 1.000 m³

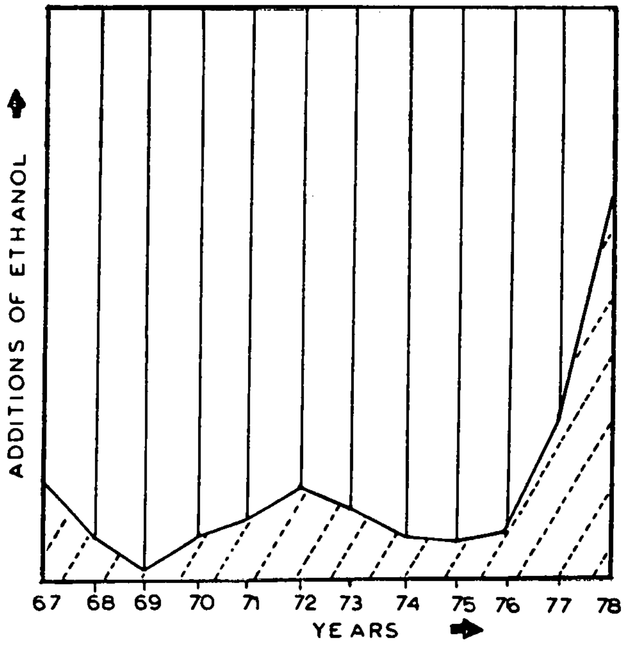
Consumption of automotive fuels		
years	gasolines	diesel oil
1967	7,247	4,898
1968	8,216	5,534
1969	8,748	5,932
1970	9,705	6,515
1971	10,617	7,158
1972	12,004	8,178
1973	13,929	9,712
1974	14,322	10,749
1975	14,619	11,996
1976	14,724	13,797
1977	14,103	14,807
1978	15,100	16,444

note: gasolines without ethanol

source: CNP/Petrobrás

CONSUMPTION OF AUTOMOTIVE FUELS IN BRAZIL

FIGURE Nº 1

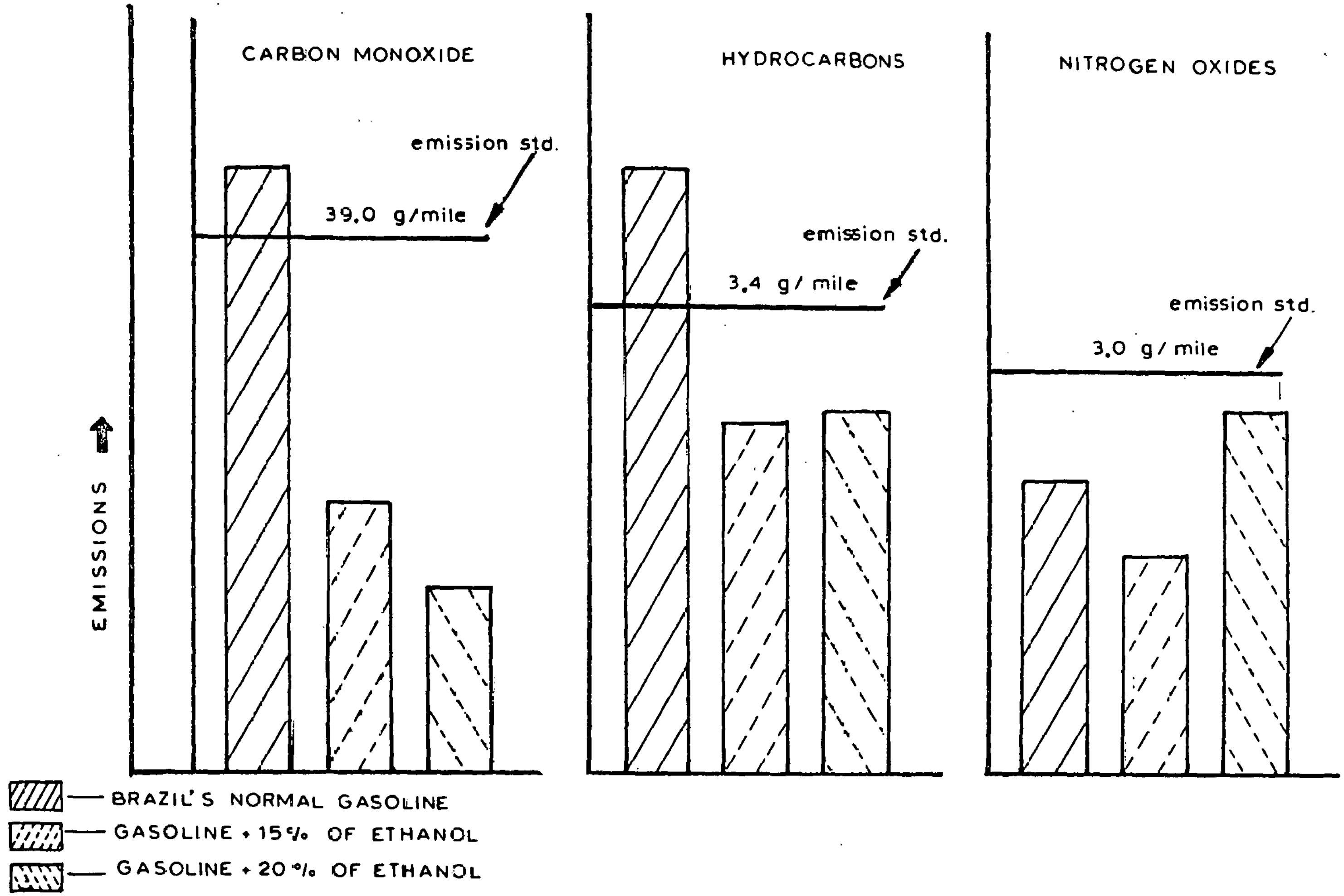


YEARS	QUANTATIES OF ETHANOL ADDED TO THE GASOLINE x1,000m³	% OF ETHANOL IN THE GASOLINE
1967	437	6.0
1968	191	2.3
1969	32	0.4
1970	184	1.9
1971	254	2.4
1972	391	3.3
1973	309	2.2
1974	190	1.3
1975	162	1.1
1976	171	1.2
1977	639	4.5
1978	1,600	10.5

source: MME/Petrobras

VOLUME AND PERCENTAGE ADDITIONS OF ETHANOL IN GASOLINE-ETHANOL BLENDS

FIGURE Nº 2



EMISSIONS FROM NON-EMISSION-CONTROLLED VEHICLES USING GASOLINE AND DIFFERENT GASOLINE-ETHANOL BLENDS

FIGURE N° 3

Brazil currently consumes 32,000,000 m^3 a year of gasoline and diesel oil. Allowing 30 % more to cover its lower heat content, 42,000,000 m^3 of ethanol would be needed to substitute the petroleum fuels.

Assuming that the consumption of vehicle fuels will rise by 10 % a year, we would need about 75,000,000 m^3 of alcohol in 1985.

Based on the production of 72.5 liters of alcohol per ton of sugar-cane, requirements would be:

$$\frac{75{,}000{,}000{,}000}{72.5} = 1.03 \text{ billion tons of cane}$$

With cane production of 60 tons per hectare, we would need:

$$\frac{1.03 \text{ billion}}{60} = 17.2 \text{ million hectares} = 172{,}000 \text{ km}^2$$

Brazil's land area being 8,511,965 km^2, we would have to cultivate about 2 % of it to produce sufficient alcohol to cover automotive needs in 1985.

ALCOHOL PRODUCTION

FIGURE 4

Dup

50,000 MILE METHANOL/GASOLINE BLEND FLEET STUDY
--A PROGRESS REPORT--

by

Ken R. Stamper, U.S. Department of Energy, USA

ABSTRACT

Seven current production automobiles are being used in a fleet study to obtain operational experience in using 10% methanol/90% gasoline blends as an automotive fuel. Data from chassis dynamometer tests (run according to the 1975-78 Federal test procedure) have been obtained, showing fuel economy and exhaust emissions of carbon monoxide, oxides of nitrogen, unburned fuel, methanol, and aldehydes. These data are shown for each of the vehicles when operated on the 10% methanol blend, and on unleaded low octane Indolene. Chassis dynamometer tests were run at 5,000-mile intervals during the 35,000 miles accumulated on each of the four 1977 model-year vehicles and at 5,000 and 10,000 mile accumulation levels for each of the three 1978 model-year vehicles. These data show an average decrease in volumetric fuel economy (≅ 5%) and a reduction in carbon monoxide emissions associated with the use of the 10% methanol blend. Exhaust emission deterioration factors are projected from the Federal test procedure urban cycle data. The most severe driveability problems that have been encountered thus far into the program are related to operating on a phase separated fuel and materials compatibility problems with an elastomer in the air-fuel control hardware of one vehicle.

INTRODUCTION

In an effort to provide information concerning the use of methanol/gasoline blends as a fuel for the transporation sector, a fleet study is being conducted at the Department of Energy's Bartlesville (Okla.) Energy Technology Center. The study involves seven 1977 and 1978 model-year (MY) automobiles operating on a 10% methanol/90% gasoline blend. The objective of this investigation is to provide information on the driveability, fuel economy, exhaust emissions, and component deterioration associated with the long-term use of methanol/gasoline blends in current-production automobiles. Vehicles in this study are not altered, inasmuch as one objective of the study is to determine the nature and severity of any problems that might arise should alcohol fuels be used as a direct replacement for, or supplement to, traditional fuels, with no opportunity to modify the vehicles.

FLEET OPERATION

The seven vehicles involved in the fleet study are described in Table 1. The four 1977 MY vehicles have been used in the fleet study since its beginning in July, 1977, and have accumulated over 35,000 miles on a 10% methanol/90% gasoline blend. The 1977 MY vehicles are forty-nine states production automobiles and are equipped with oxidation catalysts. The three 1978 MY vehicles entered the program at a later date and each has accumulated 10,000 to 15,000 miles on the methanol blend. The Volvo and

Ford Pinto are equipped with three-way catalytic converters and closed-loop air-fuel (A/F) control systems. Each of the 1978 MY vehicles are California production automobiles.

The vehicles in the fleet are operated for approximately three hours each day over a fixed route covering approximately 100 miles. The route is comprised of approximately a 30% city/70% highway-type driving mixture. The automobiles are operated by non-professional drivers six days/week, road conditions permitting. During each mileage accumulation cycle the driver evaluates the vehicle's performance during cold and hot-start operations as well as routine urban and highway operation on the 10% methanol blend.

Chassis dynamometer tests are made at 5,000-mile intervals to acquire fuel economy and exhaust emissions data. The tests are run according to the 1975-78 Federal test procedure (FTP) for the urban cycle and highway fuel economy test (HFET). Duplicate runs are made for each vehicle operating both on the 10% methanol blend and an unleaded low octane Indolene.

The 10% methanol blend is batch mixed and stored in an underground tank having a 4,000 gallon capacity. Water concentration in the underground tank has ranged from 229 to 1040 ppm in the four batches of blend used to date. The base gasoline used for the blend is made from hydrocarbon stocks so that the vapor pressure, aromatic content, and octane number of the alcohol/gasoline blend approximate an unleaded regular grade gasoline. Analyses of the test fuels used in this program are shown in Table 2.

The vehicles in the fleet study are not protected from weather extremes. Temperatures encountered thus far in the test program have ranged from -5° to 107° F. Temperatures during the mileage accumulation cycles have ranged from 4° to 105° F.

1975-78 FEDERAL TEST PROCEDURE RESULTS

Fuel Economy

The fuel economy data for the fleet (from chassis dynamometer tests run over the 1975-78 FTP urban and HFET cycles using unleaded Indolene and the 10% methanol/90% gasoline blend) are shown in Fig. 1. The results from the urban cycle tests show an average volumetric fuel economy penalty of about 5% associated with the fleet operating on the methanol blend compared to results from the fleet operating on Indolene for both the 1977 and 1978 MY vehicles. The HFET test results show an average 6% and 4.5% decrease in volumetric fuel economy associated with operating on the 10% methanol blend for the 1977 and 1978 MY vehicles, respectively. The energy economy (mi/100,000 Btu) of both sets of vehicles in the fleet is roughly equivalent for the two fuels.

Regulated Emissions

The emission rate of carbon monoxide (CO) from the 1975-78 FTP chassis dynamometer tests shows consistent reduction with the methanol blend compared to test results from operating on Indolene (Fig. 2). This reduction in the CO emission rate is believed to result from the methanol blend's leaning effect on the stoichiometry of the air-fuel mixture. The overall reduction on the CO emissions achieved by the methanol blend is not as great with the 1978 MY vehicles as with the 1977 MY vehicles. This would appear to be due primarily to the dominance in the 1978 MY fleet of vehicles using closed-loop A/F control systems which function to maintain a constant oxygen concentration in the exhaust gas stream by adjusting A/F.

The emission rates of oxides of nitrogen (NO_X) from the test fleet are shown in Fig. 3 as a function of mileage accumulation. The individual test vehicles do not show a consistent effect of operating on the 10% methanol blend compared to results from operating on Indolene. However, the leaning effect of the blend on A/F (for those vehicles not equipped with closed-loop A/F control) could be expected to increase or decrease the NO_X emission rate, depending upon the original A/F adjustment of a particular vehicle. On the average, the 10% methanol blend shows slight reductions in NO_X for the 1977 MY fleet and slight increases for the 1978 MY fleets, compared to test results from operating on Indolene.

The emission rates of unburned fuel (UBF) from the test fleet show slight increases associated with the use of the 10% methanol blend over the test results from the fleet operating on Indolene (Fig. 4). The UBF emissions from the tests using the 10% blend are not corrected for the low flame ionization detector response for methanol (response factor ≅ 0.73) [1]*; correction would still further increase the measured UBF emissions for the blend. Some of the increase in UBF emissions could be attributed to the fact that the vapor pressure of the blend ranges from 1 to 3.5 psi higher than that of Indolene. Generally, UBF emissions during the cold transient and stabilized phases of the FTP urban cycle are lower when operating on the methanol blend. During the hot transient phase, however, the vehicles operating on the methanol blend show a marked increase over UBF emissions measured when operating on Indolene. Similar observations were made in a previous study [2] with the suggestion that the UBF emissions increase in the hot transient phase was a result of the higher volatility of the blend. The only notable exception to this trend was found in vehicle #176, which showed comparable but slightly lower UBF emissions for all three phases when operating on the methanol blend. This fuel-volatility explanation would tend to be supported by the fact that vehicle #176 is the only fuel injected vehicle in either fleet.

Unregulated Exhaust Emissions

In addition to the regulated exhaust emissions, measurements of exhaust emission rates of methanol and aldehyde were made for each dynamometer test.

The methanol exhaust emissions were measured by taking a constant volume sample and determining the methanol content using gas chromatography [1]. The emission rates of methanol from the individual vehicles equipped with an oxidation catalyst and operating on the methanol blend ranged from 0.013 to 0.106 gm/mile over the 1975-78 FTP urban cycle (Fig. 5). The average methanol emission rate from the vehicles equipped with three-way

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*Numbers in brackets designate References at end of paper.

catalysts was 0.023 gm/mile when operating on the methanol blend. The emission rates of methanol from 1977 and 1978 MY vehicles operating on Indolene was an order of magnitude lower than when operating on the blend.

Aldehydes were measured using the methyl benzothiazolone hydrozone (MBTH) technique for measuring total aldehydes [3]. Previous studies have suggested that the predominant aldehyde specie associated with the combustion of methanol in spark-ignition engines is formaldehyde [4]. The emission rates of aldehydes are expressed as formaldehyde. The 1977 MY fleet operating on the 10% methanol blend shows aldehyde emission rates to increase an average of 75% over the results from tests of the same vehicles operating on Indolene (Fig. 6). Aldehyde emissions from the individual vehicles in the 1978 MY fleet operating on the 10% methanol blend are considerably lower than the emission rates from the 1977 MY fleet operating on Indolene. The 10% methanol content of the blend does not appear to have any significant impact on the emission rates of aldehydes from the vehicles in the 1978 MY fleet.

Deterioration Factors

Generally, as the emission control components and engines age they might be expected to lose their capacity to control exhaust emissions. The Environmental Protection Agency (EPA) requires that each automobile manufacturer establish the durability of the emission control components for each engine family used in new motor vehicles to establish their conformity to exhaust emission standards. These durability data are generated in a well established and controlled series of fleet tests [5] in which the vehicles are driven for 50,000 miles and tested at 5,000-mile accumulation intervals.

The deterioration factor is determined for each regulated exhaust emission by using a least-squares linear regression fit to the FTP data generated at each 5,000 mile interval, from the 5,000 mile through to the 50,000 mile test points. The equation of this line is used to interpolate values at 50,000 miles and 4,000 miles; the deterioration factor is then computed by dividing the 50,000-mile data point by the 4,000 mile data point. These data have been published by EPA [6,7] for the engine families represented in the 1977 and 1978 MY fleets.

Although the EPA certification data are generated on prototype vehicles operating under tightly controlled maintenance and mileage accumulation schedules, it is assumed that vehicles of the same engine family can be expected to exhibit "similar emissions characteristics throughout their useful life" [5]. Based on this assumption, a comparison was made of durability data reported on vehicles representing the same engine families as those vehicles that are being used in the methanol blend fleet study. The results of the least squares fit applied to data from the individual test vehicles are shown in Table 3, with the corresponding values of interpolated and projected emissions results at the 4,000 and 50,000-mile test points. Deterioration factors projected from the 1977 MY fleet vehicle tests and deterioration factors from the EPA certification tests show the greatest disparity when the deterioration factors associated with CO emissions are compared. Yet when the deterioration factors are applied to the mass pollutant emission data from the 1977 MY fleet vehicles and from the EPA certification vehicles [8] the projection suggests that while the deterioration rate of CO emissions from the 1977 MY methanol fleet is greater, the overall effects show the CO emission rates from this fleet to be comparable to those projected from EPA certification vehicles (Fig. 7). The deterioration factors from the 1977 MY methanol fleet and the corresponding EPA certification vehicles for UBF and NO_X are comparable, but there is some disparity in the levels of pollutant emissions at any one point in the life of the fleet. The difference in the projected levels of NO_X emissions (0.3 gm/mile) is apparently associated with the difference in original calibration of vehicle #163 between the certification vehicle and the corresponding vehicle in the fleet study. The UBF emission rates appear to be on the order of 0.35 gm/ mile higher in the fleet than projected from EPA certification data. A portion of this difference can be attributed to the higher vapor pressure of the methanol blend used in the fleet study as was described earlier in this report.

The 1978 MY fleet deterioraiton factors were computed based on information from 5,000 and 10,000 mile runs--considerably less than was used in the 1977 MY fleet and EPA certification computations; and, therefore, has a more limited statistical credibility. The average fleet test results show UBF deterioration factors to be comparable; but this is not the case with NO_X and CO emissions (Fig. 8). The average CO emissions from the fleet at any particular point in the life of this fleet is estimated to be considerably lower when operating on the methanol blend. The deterioration factor for NO_X emissions for the methanol blend fleet, shows a much more rapid increase in mass emissions with fleet life, due primarily to the influence of car #176. The rate of increase in NO_X emissions and the higher base in NO_X emissions from this particular vehicle deviates significantly from the levels projected by EPA [7,9]. A component failure in the fuel injection distributor of vehicle #176 is associated with (but not totally responsible for) an NO_X increase from 0.40 gm/mile NO_X to 1.10 gm/ mile NO_X, over a period of 8,000 miles of operation.

DRIVEABILITY

The term of this project provided an opportunity to develop in-use driveability data on the 10% methanol/90% gasoline blends. As the vehicles are operated over the 100-mile mileage-accumulation route the driver evaluates the vehicle's performance on the blend by responding to a series of questions. These questions are separated into three parts; the first series is concerned with identifying cold-start difficulties, the second concerns operating malfunctions associated with vehicle operation with a fully-warmed engine, and the third with hot-start difficulties. Each malfunction that the driver identifies is assigned a demerit value; the frequency with which the malfunction occurs determines the weighting factor. The weighting factor is multiplied by the demerit, and the sum of the weighted demerits for each 100-mile run gives the driveability demerits that are associated with that particular run.

The time required to start the vehicle in both the cold and hot-start operations is also a factor in determining driveability. In order to account for this factor, a starting time of 2 seconds received no demerits; a starting time of 2 to 10 seconds received 6 demerits; and a starting time for over 10 seconds received 11 demerits. The driveability demerit system used in this series of tests is illustrated in Table 4.

This driveability rating system bears some resemblance to the driveability system adopted by the Coordinating Research Council (CRC) and the general definition of the malfunctions described by CRC do apply. However, due to the difference in the driving cycle, driveability demerits developed in this series of tests are not comparable to those from CRC driveability tests.

The average driveability demerits generated by the fleet of seven vehicles as of January 31, 1979 are shown in Fig. 9 along with the average driveability demerits generated for the month of January, 1979. The most pronounced driveability problems associated with operating these vehicles on a 10% methanol blend have developed in car #164. The majority of these problems are associated with the vehicle hesitating on accelerations and stalling before the engine is fully warmed. These problems seem to be related to a materials compatibility problem with the accelerator pump cup in the carburetor; this will be discussed more fully later in this report. Vehicle #176 shows the smallest effect of the blend on driveability. This is probably due to the action of the closed-loop A/F system maintaining a stoichiometric A/F mixture in the engine and thus minimizing the blend leaning effect. This vehicle was not operating the month of January 1979.

During the month of January 1979, the National Weather Service recorded a high temperature of 47° F in the Bartlesville area. The water concentration in the fuel stored in the underground tank was approximately 740 ppm, which caused the fuel to separate into two phases at 50.5° F. Thus, the driveability data for the month of January represent data from the fleet operating on a phase separated fuel. Comparing these data to the average driveability demerits generated on each of the vehicles over their entire life in the project as of January 31, 1979, gives an indication of the relative difficulty of operating the vehicles on a separated fuel. Four of the six vehicles operated during this month showed an increase in driveability demerits over their average. Of these four vehicles only car #164 showed an increase in driveability demerits beyond one standard deviation from the average driveability demerits generated as of January 31, 1979.

Operating the vehicles on the phase separated fuel was probably not as difficult as one would have expected due in part to the properties of the lower phase. The vapor pressure of the lower phase was only one psi lower than that of the blend (methanol blend #4). Gasoline components comprised about 45% (liquid volume) of the lower phase.

MATERIAL COMPATIBILITY

Since the beginning of the fleet operation in July, 1977, two vehicles have developed materials compatibility problems. The accelerator pump cup in the carburetor of car #164, originally a Buna-N material, was the subject of a recall and was replaced with a Viton pump cup. The Buna-N material was replaced because the manufacturer found that the material, when exposed to gasolines with an aromatic content on the order of 30% or more, hardened and became embrittled when the plasticizers in the material were removed by the gasoline. The black pump cup (Buna-N) shown in Fig. 10 failed while in service. The lighter colored pump cups (shown in the upper portion of the figure) are the Viton replacements. The Viton pump cup on the right was exposed to the 10% methanol blend; the Viton pump cup on the left was exposed to the base fuel used in the blend. The resulting increase (≅ 8%) in the outside diameter of the pump cup when exposed to the methanol blend is believed to have resulted in continued driveability problems (discussed in the previous section). The pump cup tended to stick or hang to the cylinder wall. Based on our experience with this vehicle, neither pump cup would give acceptable driveability on the long-term with a methanol/gasoline blend.

The second materials compatibility problem was also associated with a Viton elastomer. The o-ring used in the line pressure regulator of vehicle #176 (illustrated in Fig. 11) is made of Viton. The o-ring on the left failed in service while the vehicle was operating on the 10% methanol blend; the o-ring on the right was used as the replacement for the failed o-ring and had not been exposed to any fuel at the time this photograph was taken. The increase in outside diameter (≅ 10%, half of which is a result of exposure to the methanol in the blend) is believed to have contributed to the o-ring failure, although the manufacturer indicates that similar failures have occurred in the field with the vehicles operating on gasoline. There are a number of Viton o-rings located in the fuel distributor. Other instances of inspecting the line pressure regulator (located in the fuel distributor) have led to the discovery that while other o-rings are not cut, they do tend to slip out of place. These o-rings seal against pressures in the fuel metering system which control A/F, which in turn influences both the production of NO_X and the efficiency of the three-way catalyst in reducing NO_X. The change in the fuel pressure control characteristics of the line pressure regulator is believed to have been partially responsible for the high NO_X deterioration factor of car #176 described in the previous section of this report. However, this materials problem cannot account fully for 0.7 gm/mile NO_X emission increase in car #176.

SUMMARY AND CONCLUSIONS

Based on the information generated thus far into the project, it appears that long term use of methanol/gasoline blend will reduce volumetric fuel economy on the order of 5%. Provided the manufacturer's A/F adjustment remains unchanged from that of the vehicles used in this study, emissions rates of CO can be expected to decrease substantially due to the blend leaning effect on fuel/engine systems that are not equipped with closed-loop A/F feedback control. Smaller reductions in CO emissions can be expected from those vehicles equipped with closed loop A/F control systems. The UBF emissions will change in character, in that ≅ 7% of the pollutant will be unburned methanol. Aldehyde emissions are shown to increase over those generated from operating on straight gasoline in vehicles with conventional carburetor/oxidation catalyst systems; however, no significant increase in aldehyde emissions is expected from vehicles with closed-loop A/F control/ three-way catalyst systems.

Projections based on deterioration factors suggest, that long-term use of 10% methanol blends will not adversely affect emission rates of CO and NO_X, barring complications resulting from materials compatibility problems. Increases of UBF emissions can be expected if the vapor pressure of the blend cannot be limited to levels comparable to those found in commercial gasolines.

The vehicles used in this study will start and operate in cold weather on phase separated fuel due in part to the properties of the lower phase. However, most of the vehicles show an increase in driveability problems associated with operating on a phase separated fuel. Materials compatibility problems can have a serious adverse impact on driveability, whether operating on a separated fuel or on a single phase 10% methanol blend.

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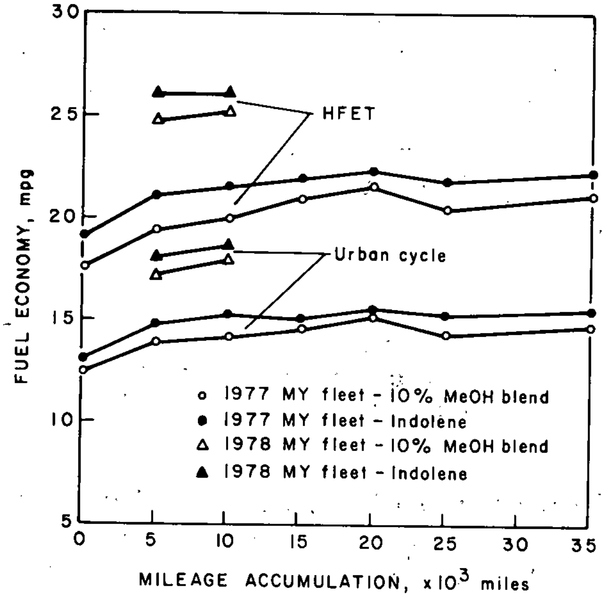


Fig. 1. - 1975-78 FTP and HFET Results for 1977 and 1978 MY Vehicles at Various Mileage Accumulation Intervals

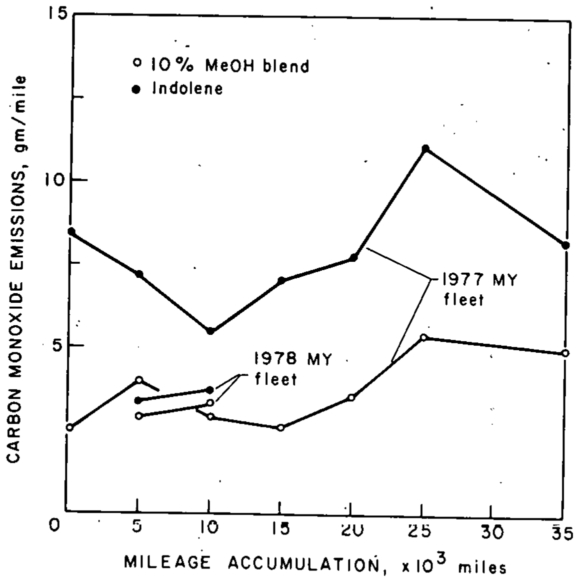


Fig. 2. - Carbon Monoxide Emission Rates from the 1975-78 FTP Cycle, 1977 and 1978 MY Vehicles

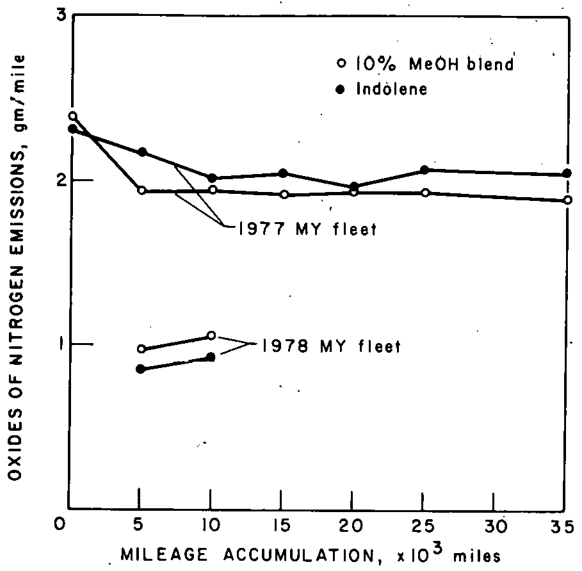


Fig. 3. - Oxides of Nitrogen Emission Rates from the 1975-78 FTP Cycle, 1977 and 1978 MY Vehicles

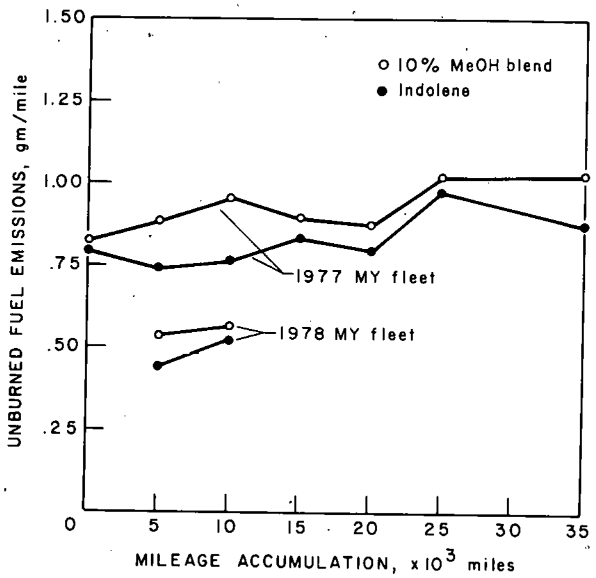


Fig. 4. - Unburned Fuel Emission Rates from the 1975-78 FTP Cycle, 1977 and 1978 MY Vehicles

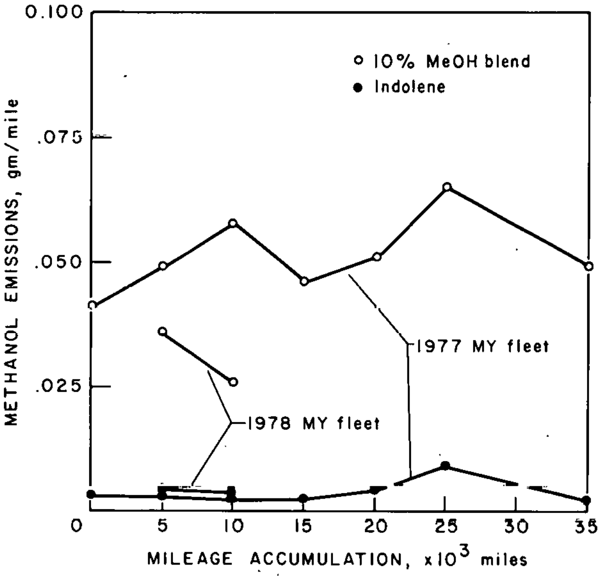


Fig. 5. - Methanol Emission Rates from the 1975-78 FTP Cycle, 1977 and 1978 MY Vehicles

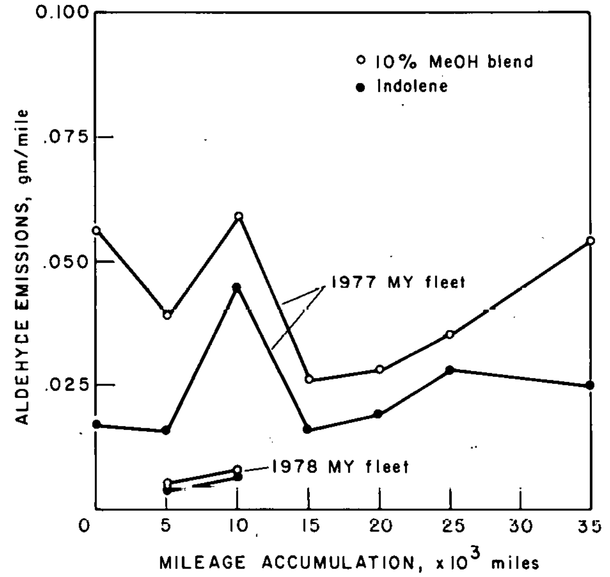


Fig. 6. - Aldehyde Emission Rates from 1977 and 1978 MY Vehicles Operated over the 1975-78 FTP Cycle

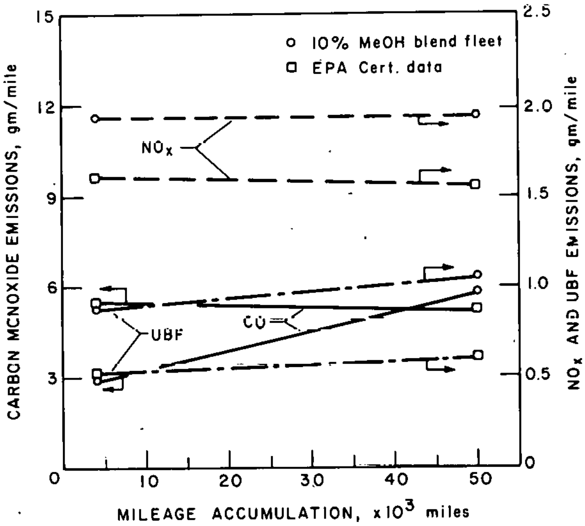


Fig. 7. - Comparison of Deterioration Factors Projected from 1977 MY Vehicles Operating on 10% Methanol Blend and from Certification Tests (References 6 and 8)

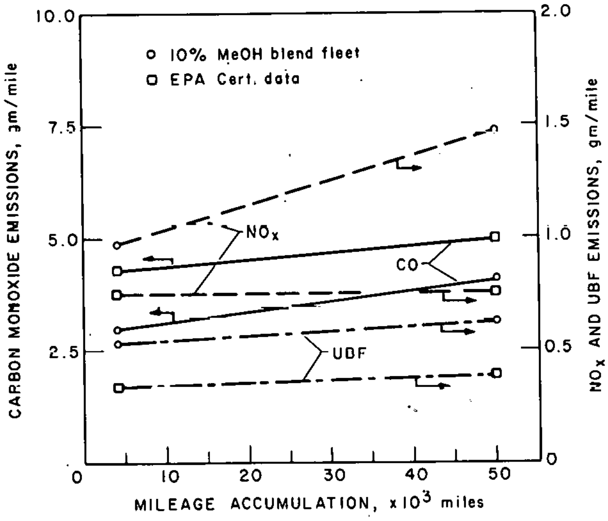


Fig. 8. - Comparison of Deterioration Factors Projected from 1978 MY Vehicles Operating on 10% Methanol Blend and from Certification Tests (References 7 and 9)

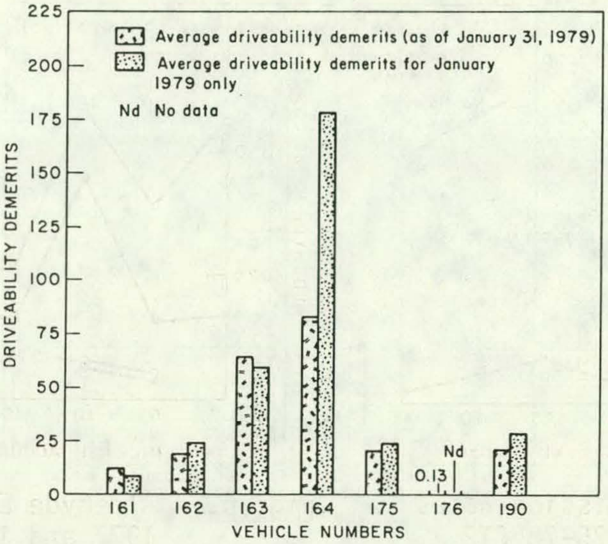
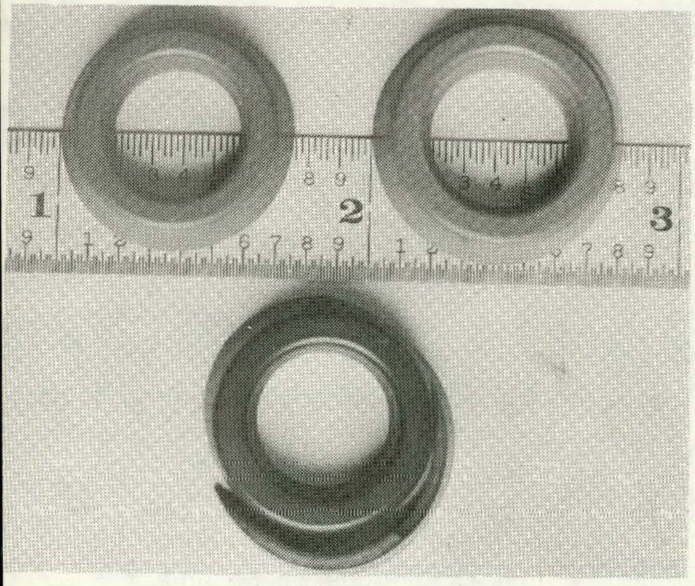


Fig. 9. - Driveability Demerits for Methanol/Gasoline Blend Fleet (Average Demerits for All Runs and Average Demerits for Runs Made in January 1979)



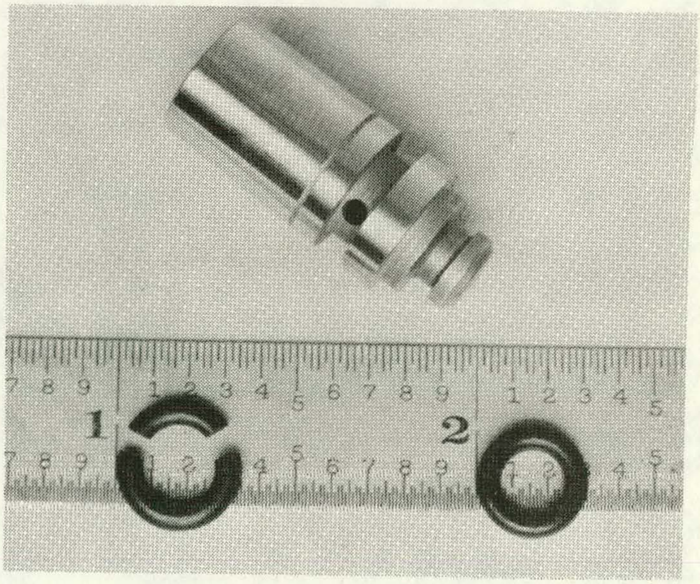


Fig. 10. - Accelerator Pump Cups from Car No. 164

Fig. 11. - Line Pressure Regulator o-Rings from Car No. 176

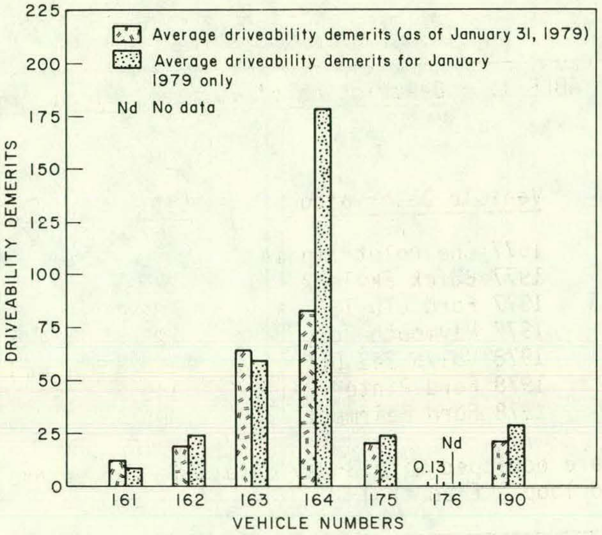


Fig. 9. - Driveability Demerits for Methanol/Gasoline Blend Fleet (Average Demerits for All Runs and Average Demerits for Runs Made in January 1979)

Fig. 10. - Accelerator Pump Cups from Car No. 164

Fig. 11. - Line Pressure Regulator o-Rings from Car No. 176

TABLE 1. - Description of methanol blend fleet

Vehicle #	Vehicle Description	Engine Disp., CID	Carb.	Test I.W., lb
161	1977 Chevrolet Impala	305	2V	4,000
162	1977 Buick Skylark	231	2V	3,500
163	1977 Ford LTD II	302	2V	4,500
164	1977 Plymouth Fury	225	2V	4,000
176	1978 Volvo 242 DL*	130	FI	3,000
175	1978 Ford Pinto*	140	2V	2,750
190	1978 Ford Fairmont	200	1V	3,000

*Vehicles are equipped with 3-way catalytic converters and closed-loop A/F control.

TABLE 2. - Analyses of fuels used in methanol fleet studies

	Indolene #1	Indolene #2	Methanol Blend #1	Methanol Blend #2	Methanol Blend #3	Methanol Blend #4
FIA analysis, %:						
Aromatics	22	28	26	14	14	20
Olefins	11	8	2	9	9	8
Saturates	67	64	72	77	77	72
Distillation, ASTM D86, °F:						
IBP	89	88	102	96	98	92
Pct evaporated:						
5	116	112	114	108	108	102
10	129	126	117	112	112	108
20	155	154	122	118	116	116
30	182	181	128	124	123	124
40	206	208	148	131	129	129
50	225	233	203	187	189	130
60	243	256	224	207	210	215
70	265	282	228	224	226	236
80	294	309	256	244	246	264
90	338	346	300	292	296	313
95	376	380	362	351	350	355
EP	411	418	371	404	398	394
Specific gravity	0.734	0.749	0.736	0.728	0.730	0.730
Equivalent Reid vapor pressure psi*	10.1	9.5	10.6	12.2	11.7	13.2

Note: Fuel numbers 1, 2, 3, and 4 indicate the chronological order in which the fuels were used. Thus far into the program two batches of Indolene and four batches of the methanol blend have been used in the fleet operation and testing.

*Reid vapor pressure from micro vapor pressure test.

TABLE 3. - Deterioration factors and projected emission levels

Vehicle #	Projected emissions levels, gm/mile*		Deterioration factor from MeOH fleet	Projected emission levels, gm/mile from Ref. 8 and 9		Deterioration factor from Ref. 6 and 7
	4,000 Miles	50,000 Miles		4,000 Miles	50,000 Miles	
Car 161:						
CO........	5.12	5.57	1.089	3.3	1.50	.455
HC........	.71	.99	1.395	.35	.30	.871
NO_X.......	1.78	1.74	.978	1.63	1.38	.845
Car 162:						
CO........	1.93	8.66	4.483	3.7	5.32	1.440
HC........	.41	1.09	2.690	.35	.65	1.853
NO_X.......	1.47	1.79	1.220	1.76	1.81	1.028
Car 163:						
CO........	1.26	2.57	2.04	6.1	5.03	.824
HC........	1.50	1.16	.776	.68	.79	1.168
NO_X.......	2.38	2.47	1.037	1.70	1.55	.912
Car 164:						
CO........	3.40	6.47	1.902	8.7	9.03	1.038
HC........	.89	.96	1.078	.69	.69	1.005
NO_X.......	2.08	1.72	.826	1.33	1.45	1.092
1977 Fleet average:						
CO.......	2.93	5.82		5.45	5.22	
HC.......	.88	1.05		.52	.61	
NO_X......	1.93	1.93		1.61	1.55	
Car 175:						
CO.......	4.50	6.89	1.532	2.4	2.81	1.171
HC.......	.40	1.08	2.769	.17	.18	1.060
NO_X......	.69	1.38	1.996	.75	.85	1.134
Car 176:						
CO.......	1.70	1.15	.676	6.9	6.18	.896
HC.......	.17	.08	.465	.49	.40	.824
NO_X......	1.07	2.73	2.542	.22	.25	1.138
Car 190:						
CO........	2.63	4.20	1.594	3.5	4.96	1.418
HC.......	1.04	.72	.690	.34	.46	1.347
NO_X......	1.14	.31	.270	1.27	1.26	.990
1978 Fleet average:						
CO.......	2.94	4.08		4.27	4.98	
HC.......	.53	.63		.33	.35	
NO_X......	.97	1.47		.75	.79	

*The emission levels are projected from a least squares linear regression of 1975-78 FTP test results from vehicles operating on the 10% methanol blend.

TABLE 4. - Driveability demerit system

Phase of operation	Malfunction	Demerit value	Weighting factor					Weighted Demerit*
			Frequency over the cycle No.		Starting time, seconds			
			1 - 3	over 3	0 - 2	2 - 10	over 10	
Cold-start	Starting time	1	-	-	0	6	11	
	Stall	20	2	4	-	-	-	
Fully-warmed operation	Stall	32	2	4	-	-	-	
	Hesitation	6	2	4	-	-	-	
	Surge	4	2	4	-	-	-	
Hot-start	Starting time	1	-	-	0	6	11	
	Stall	32	2	4	-	-	-	

Total demerits = Σ of Weighted Demerits = ______

*The weighted demerits are computed by multiplying the demerit value by the appropriate weighting factor.

METHANOL/GASOLINE MIXTURES IN FOUR STROKE OTTO ENGINES

by

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Company, Sweden.

INTRODUCTION

The Swedish Methanol Development Company (SMAB) has since its establishment in March 1975 done development work on mixed fuels applications in four stroke otto engines.

The application studies have been aimed at carrying out the technological and economical consequences of introducing a grade of gasoline on the Swedish market with a 15-20% methanol content. A number of technical problems were identified before the start of our tests:

- Methanol/gasoline mixtures are sensitive to water, with risk for phase separation.
- Methanol in gasoline reduces the energy content by volume of the fuel due to the lower thermal value of methanol.
- Materials used today in the fuel distribution network as well as in the fuel systems of automobiles are not sufficiently resistant to methanol.
- A content of methanol in the fuel alters the distillation curve and vapour pressure of the fuel, with risk of starting difficulties and running difficulties.
- Methanol has an influence on the octane properties of the mixture.
- The engine lubricating oils of today are not formulated for fuels containing methanol.

From the analyses made by the company´s own research and other published research it was evident that the composition of the base gasoline with regard to the various hydrocarbons has a very significant importance for the possibilities of solving a number of problems. We have therefore made great efforts in defining a gasoline base which will reduce the technical problems. In addition it must be economically feasible to achieve during the 1980s and 1990s.

FUEL FORMULATION

Forecasts for the refinery configuration in Sweden and West Europe in the 1980s and 1990s as well as for the product mix and the availability of hydrocarbons for gasoline production have been analysed.

The refinery configuration and choice of crude oil control the product division, and together with the demand of the market those components are controlled which will be available for the production of gasoline. Sweden imports large quantities of gasoline from Western Europe, which also results in dependance on the Western European refining industry.

The product division in Western European refineries differs from that of the American ones. Most American refineries convert heavy oils by cracking them into light gasoline components, and in this way they produce large quantities of gasoline and small quantities of heavy oils in comparison with the Western European refineries, see table 1.

The conversion capacity of Europe and Sweden is low in comparison with USA which is illustrated in table 2.

The present lack of balance between European demand for heavy oil middle distillates and gasoline points to continued low demand for heavy oils and increased demand for naphta and gasoline, which fits the prognosis made for the future. A prognosis for 1990 compared with 1976 in Western Europe indicates that the trend in Western Europe will be towards adoption of the American production division up to 1990 resulting in increased output of light products at the expense of the heavier products. Increased conversion capacity from heavy to light products will be required, see table 3.

The various conversion methods provide different hydrocarbon combinations in the gasoline pool. In this way, the gasoline properties are influenced as well as the portion of the components that can be used for gasoline and the need of additives.

The average gasoline produced in Sweden today has a high content of aromatics and a low content of olefins, while the average W. European gasoline has a somewhat lower content of aromatics and higher content of olefins.

In the future we have to expect an extension of the European converting plants in the form of cracking and isomerization plants. This will result in an average increase in olefine and isoparaffine contents as well as an average decrease of aromatic contents. A decrease of the latter will be accentuated as demand from the chemical industry for these will increase.

Various fuel formulations have been studied in SMAB´s laboratory tests and field tests, but for the extensive field test in operation since the company was formed in 1975 fuels have been formulated from components typical of present Swedish refinery products. Table 4 illustrates the specifications for these fuels, designated M1 and M2 respectively.

FUEL PROPERTIES OF METHANOL/GASOLINE MIXTURES

The fuel properties are related to:

- Phase separation and water tolerance
- Knocking properties
- Driveability
  In general
  In cold climate, with cold starts and warming up period
  In warm climate, vapour lock
- Fuel consumption
- Power output
- Emissions
- Materials
- Engine lubricating oils

Phase separation and water tolerance

Gasoline containing methanol is subject to risk of phase separation between gasoline base and methanol/water due to infiltrated water during distribution or consumption of the fuel. The formulation must be carried out in such a way that a safe water tolerance is obtained.

Water tolerance increases with

- increased temperature
- increased content of methanol
- increased content of aromatics
- additives of higher alcohols

Laboratory test have been executed at BP Research Centre, Sunbury and at Berol Kemi, Stenungsund in order to survey at which contents of water and at which temperatures various mixtures of methanol/gasoline are subject to phase separation.

Aromatic content

Table 5 illustrates how water tolerance improves with increased content of aromatics in the fuel.

Admixture of higher alcohols

Fuel water tolerance can be improved by addition of higher alcohols. Investigations carried out by us indicate that several admixtures provide a good result, but the best results were obtained from isobutanol. The field test fuels, M1 and M2 respectively, that was used, can manage 0,3% and 0,2% respectively of water at a temperature of -15°C (+5°F). Table 6 illustrates at which content of water fuels having a content of 20 per cent of alcohol are subject to phase separation at 0°C, -15°C and -30°C (32°F, 5°F and -22°F).

Knocking properties

In co-operation with BP Research Centre, Sunbury a number of fuel formulations with and without methanol having different contents of lead (from 0 to 0,4 grammes per litre) have been investigated. If methanol is added to the gasoline, the octane number improves, this particularly applies to the research and front octane numbers, while the motor octane number is less influenced. The octane improving properties of the methanol varies with the hydrocarbon combinations of the basic fuel. The methanol together with high contents of olefins and/or isoparaffins, which also have high research and front octane numbers, means risk of overestimation for these while the motor octane number remains low. For the typical present Swedish gasoline, however, where the front octane number is the most critical, an addition of methanol is of great importance. The decrease of lead content from 0,4 g/l to 0,15 g/l decided on in Sweden will also increase the mix-in value of methanol, and this will be even more accentuated when the decision is taken to completely abolish lead as an additive to gasoline.

The methods of measuring the octane number are adapted to petroleum products, and due to this they are not quite reliable when methanol is added. The method of measuring the research octane number, where the temperature of the intake air is determined to +20°C (68°F), results in an octane number that is too high where methanol is present. We consider, however, that methanol as an octane number improving agent is of great importance, but the method of measuring the research octane number should be modified when testing methanol/gasoline mixtures in order to avoid overestimation of the octane number improving effect of methanol.

In order to investigate possible differences in octane number variations with methanol/gasoline mixtures and gasoline, tests have been run at BP Research Centre at Sunbury. The results of these tests - where six Volvo cars were tested -do not indicate any significant differences for methanol/gasoline mixtures in comparison with pure gasoline.

As the research and motor octane numbers are determined in a one-cylinder engine in a laboratory (CFR-motor), they cannot easily be correlated to the performance of gasoline in a multicylinder engine under road conditions.

A study to obtain the road octane number according to "Modified uniontown road rating test" has been performed with Gulf Technology Europe in Rotterdam using four cars of different makes in order to study the road octane number for a methanol/gasoline mixture without lead additives, methanol/gasoline mixtures having various lead additives as well as compare these results with a premium gasoline having lead additives and a series of reference fuels.

The results of the road octane number tests indicate that the methanol/gasoline mixture has lower interpolated road octane numbers than those of conventional gasolines. When lead (0,15 g/l) was added to methanol/gasoline mixtures, the road octane numbers were improved - particularly with TEL. The investigation, which had a limited extent, indicates however that further investigations are required in order to make possible optimization of methanol/gasoline mixtures which do not cause knocking and at the same time do not provide unnecessarily high anti-knock properties.

DRIVEABILITY

In general

Fuel density, distillation curve, octane number, vapour pressure, vaporization heat and formulation as well as additive of methanol all have influence on the driveability performance.

From SMAB's long-term test, which has been in operation for 4 years using about 50 cars with a total of more than 1,5 million kilometres, certain driveability problems have been reported as a result of the methanol additive. The field test has mainly proved, however, that if the carburetter or injection system is adjusted in order to partly equalize the leaning effect, it is at normal driving in the Swedish climate hardly possible to observe any difference when switching over to the methanol/gasoline mixture. The fact that almost only Volvo cars have been used for the tests executed by SMAB means, however, a certain limitation.

Cold climate and cold starts

Road and chassis dynamometer tests have been carried out, in cooperation with Deutsche Shell AG, in order to determine the cold start and driveability performance of gasoline/methyl fuel blends in passenger cars under extreme winter conditions.

Conventional gasolines, covering a wide range of volatility, and blends of these gasolines together with metyl fuel (9:1 methanol: isobutanol) up to 20% by volume were used in the test programme. These fuels were evaluated in six cars with carburetter engines of various makes representing the majority of the current Swedish car population.

The test criteria were cold starting, driveability and warm-up performance of the cold engine. The environmental conditions (very low ambient temperatures) and the test procedure made the test programme severe.

The following conclusion can be summarized from the results of the test programme:

In most of the cars the addition of methyl fuel causes deterioration in the cold start, driveability and warm-up performances compared with conventional gasolines. The extent of deterioration varies from very small to very large in the car fleet used and the size of deterioration tends to vary exponentially with increasing amounts of methyl fuel.

Generally the test programme showed that with the current car population and the current emission legislation the use of methyl fuel as a fuel component at concentrations of 10% and above will cause unacceptable cold weather driving at low ambient temperatures (below -15°C). However, the large variation in driveability performance between engine types suggest that improvements can be achieved by modification to engine hardware.

The great differences between different types of cars and results of tested motor adjustments indicate that problems with methanol fuels can be solved using simple adaption measures.

Warm climate, vapour lock

Two summer tests have been performed:

- 1976 in the Swiss Alps and on Corsica, where we used 3 Volvo cars fitted with injection engines. The results indicate that the methanol/gasoline mixture is more liable to cause vapour locks than pure gasoline, but this will not cause any great problem to these cars in the Swedish climate.

- 1978 in Sierra Nevada, Spain, in co-operation with Volkswagen Research, Aral, Veba Chemie, and Deutsche Shell a test was executed in order to test driveability in a warm climate using different kinds of gasoline as well as gasolines containing various proportions of methanol. Seven cars were included in this test. Volkswagen provided one VW Golf and one VW Rabbit, Aral one Opel Ascona and one Mercedes Benz 280. Veba Chemie one Opel Manta, and SMAB one Volvo 244 and one Saab 99.
  This test has not yet been evaluated.

Fuel consumption

SMAB´s comparisons are based on engines where the fuel and air intake systems have been adapted to the fuel mix.

The decrease of temperature caused in the intake mixture due to the high vapourization heat has a tendency to improve the volumetric efficiency of the engine. Furthermore, with some engines a decreased formation of nitrous oxide should provide a more favourable point of ignition as well as possibly lessen the need for exhaust recycle(EGR).

These factors improve engine efficiency. It might, however, be more difficult when using mixed fuels to obtain optimal distribution of the fuel to the individual engine cylinders. This has influence on deterioration of fuel economy if compensation in the form of "richer" adjustment must be applied.

It is obvious that some modifications should be expected where the Swedish car population is concerned. Based on our own experience and results reported, SMAB considers it reasonable to reckon with an average unchanged fuel consumption in the beginning as measured on an energy basis at a switch-over to mixed fuels. As the engine manufacturers will have the opportunity to carefully adapt and optimize their products to the new fuel, it should be possible to anticipate a small efficiency improvement.

Power output

The specific energy content of a mixture of air/mixed fuel and air/gasoline respectively have only marginal differences at suitable air ratios. As the differences in efficiency furthermore are small at the methanol contents in question, the differences in specified maximum power output should be insignificant, which is also confirmed in the report documentation available.

Emissions

Fuels containing methanol have been considered as being positive for the environment due to the content of harmful components of the exhaust gases being much less than for pure gasoline operation. The observations are usually based on tests of older cars, where the engines have been adjusted for a rich air/fuel mixture to provide good driveability at the most differing operational conditions and where very little consideration was taken to exhaust gas emissions or fuel costs. Due to the leaning effect of the mixed fuel, considerable reductions primarily of CO and HC emissions have been achieved under these conditions.

As a result of stringent legislation regarding exhaust gases from newer cars these are, however, adjusted to such lean mixtures that they need adjustment to richer mixtures at a switch-over to mixed fuel if an acceptable driveability is to be maintained. Thus the greater portion of the reported improvement fails to appear.

The great advantage of fuels containing methanol is that the octane number improving properties of methanol provide a possibility to abolish octane improving lead and so called scavengers in the fuel. Further conditions are created, when required, to accomplish considerable reductions of harmful emissions by aid of exhaust purification equipment.

Materials

Those cars that have participated in SMAB´s field tests have been entirely of standard type where materials in fuel system components are concerned.

At the contemporary laboratory tests of corresponding material qualities (polymer materials) increased or heavily increased swelling due to the methanol content of the test fuel has been determined. Despite the increased tendency for swelling only a few cases of leakage have occurred and then to a small extent, in the fuel systems of the test cars.

No problems due to deteriorated durability have been determined. The cases of leakage refer to the fuel pump in the carburetter engines where a deformed gasket has been the faulty detail. Incidentally, the fuel pumps together with the fuel filters of the injection systems have formed the most faulty components of the test.

Where the pumps are concerned, deteriorated function of valves due to fuel contamination has dominated as type of failure, while with the filters a sealing and fixing adhesive has been influenced in such a way that fuel has by-passed the filter insert (however, without leaking). Contamination in the fuel system has, however, been present in the test cars to a greater extent than usual. Partly, this has probably been due to the fact that only one filling station has been available and that filling up from cans has been common. A problem concerning materials determined during the winding-up of the field test is that lead has been released out of the fuel tank coating in cars fitted with injection engines, and deposited elsewhere in the fuel system. This problem should be further investigated.

Supported by results obtained up to the present date it can be stated that:

- modification will be required for most cars
- the extent of this varies between the car models
- measures required should not necessarily be technically difficult or economically unacceptable.

Engine lubricating oils

No lubricating problems have occurred during the tests, which indicates that no essentially different properties are required for methanol/gasoline mixtures than those for pure gasoline.
The last field test certainly have not yet been fully evaluated, but analyses of lubricating oils and the absence of engine damages as well as the results of the first field test confirm this conclusion.

The motor oils subjected to testing have been partly specially formulated, and partly such oils at present available on the market. As only certain oils have been tested, it cannot be excluded that commercial oils do exist which would create difficult problems where deposits, wear or chemical corrosion are concerned.

SMAB´s judgement is that motor oils can be produced meeting the requirements for operation on methanol/gasoline mixtures. Further to the tests being executed at present on the commercial motor oils, tests must be performed concerning the properties of lubricating oils when used with methanol/gasoline mixtures.

GENERAL CONCLUSIONS

Five areas of problems have been identified by our own test activities and various external information. These are:

- water tolerance problems
- material problems
- cold start problems

- vapour lock problems
- driveability problems

The conclusion of SMAB´s work is that all problems can be solved at a cost that is not too deterrent.

The water tolerance problems can be solved by adding e.g. isobutanol to the fuel in combination with certain measures to lessen the risk of water infiltration into the distribution system. The extent of the measures that must be taken will finally be determined by another distribution field test using a suitable methanol/gasoline mixture. In the light of experience gained at present it can, however, be determined that possible problems can be solved without economically unacceptable modification of the distribution network.

Problems concerning materials occurring because of the fuel can be solved by adapting the vehicles.

Testing of the cold start performance of various cars indicates that the differences between individual cars of the same type and different types of cars often are greater than the differences between various fuels, with or without methanol. The cold start problems are, however, generally more accentuated when fuel containing methanol is used. The great difference between different types of cars and the results of minor engine adjustments have indicated that cold start problems when using methanol fuel can be solved by fairly simple measures concerning adaption of the vehicles. The aim should, however, be to maintain the light gasoline components present in conventional gasolines in the methanol/gasoline mixtures.

Increased tendencies of vapour lock have appeared when testing methanol/gasoline mixtures under extreme conditions (high altitudes and high temperatures). Great differences between individual cars and types of vehicles indicates, however, that the problem is related to the vehicles. The conclusion from the performed tests is that vapour locks will not create any problem when using methanol/gasoline mixtures in the Swedish climate.

Driveability problems at operation on methanol/gasoline mixtures registered or reported from other tests are mainly of the same pattern as the cold start and vapour lock problems. Variations between various individual vehicles and types of vehicles are greater than the differences between tested fuels. Problems registered when using methanol fuels depend on the leaning effect of methanol. The problems can usually be solved by simple adaption of the cars´air/fuel ratio.

No problems as regards meeting emission legislation in Sweden have been identified. The addition of methanol makes possible a trouble-free switch-over to gasoline free of lead, which in its turn opens the possibility to introduce considerably more stringent emission legislation by utilizing catalytic exhaust gas purification.

Where octane number properties and other quality specifications are concerned, these should be subject of more penetrating studies aiming at proposals for new norms and quality specifications as a preparation for an introduction on the market.

TABLE 1

Product division for petroleum products in W. Europe and USA 1976

Division	W. Europe 1976	USA 1976
Naphta + gasoline	19,6%	52,7%
Middle distillate	36,8%	27,0%
Fuel Oils	37,7%	9,8%
All others	5,9%	10,5%

TABLE 2

Conversion capacity in USA, W. Europe and Sweden 1978

Refinery units	USA	W.Europe	Sweden
Distillation capacity %	100	100	100
Conversion in % by volume of distillation capacity			
Reforming	18,0	10,8	14,3
Catalytic cracking	27,0	5,3	-
Hydrocracking	5,1	0,7	-
Thermal cracking, visbreaking	8,7	3,8	7,6
Alkylation, polymerization, isomerization	5,1	0,7	-

TABLE 3

Division of petroleum products in W. Europe 1976 and 1990

Division	W. Europe 1976	W. Europe 1990
Naphta + gasoline	19,6%	22,6%
Middle distillate	36,8%	35,9%
Fuel Oil	37,7%	34,5%
All others	5,9%	7,0%

TABLE 4

Fuel specification of the methanol/gasoline mixtures M1 and M2

Determination		Denomination	Value		Method
			M1	M2	
Octane number	RON		min 97	97-100	ASTM D 2698
	MON		min 87	85-89	ASTM D 2700
	RON 100°C				ASTM D 2699
Vapour pressure		kp/cm^2	max 0,90	max 0,90	ASTM D 323
V/L ratio (36/1)		°C	50		estimated
Total lead alkyl		PPM	max 2	max 2	
Total sulphur		% wt	max 0,10	max 0,10	SIS 150216
Distillation test	IBP	°C	35	max 35	
	10% evaporated	°C	70	max 70	
	50% evaporated	°C	110	max 110	
	90% evaporated	°C	max 180	max 180	
	FBP	°C	205	max 205	
	Residue	%vol	max 2	max 2	
Composition	aromatics	%vol	25-40	25-35	ASTM D 1319
	bensene	%vol	max 5	max 5	
	olefins	%vol	max 5	max 10	ASTM D 1319
	methanol	%vol	16	18	
	isobutanol	%vol	4	2	

TABLE 5

Water tolerance on gasoline basis W75/1902, W76/182A and W75/2005

Gasoline base n:o		W75/1902	W76/182A	W75/2005
Catalytic reform 97 ON	%	100		
" " 95 ON	%		72	
Straight run gasoline	%		28	
Fullrange catalytically cracked gasoline W75/2005	%			100
Aromatics % by volume		54,6	35,2	15,5
Olefins " "		-	-	46,0
Naphtenes and paraffins % by volume		45,4	64,8	38,5
Water tolerance at 0°C %		0,03	0,02	0,01

TABLE 6

Water tolerance % by weight for fuels containing 20% alcohol

Percentage Methanol/isobutanol	FM 6			Heavy gasoline base		
	0°C	-15°C	-30°C	0°C	-15°C	-30°C
16/4 field test fuel M1	0,50	0,30	0,30	0,40	0,40	0,20
18/2 field test fuel M2	0,40	0,20	0,10	0,30	0,20	0,10
19/1	0,30	0,10	0,10	0,20	0,10	0,10
19,5/0,5	0,20	0,10	0,10	0,20	0,10	0,10

FM 6 = 85% 96 RON catalytically reformed
15% straight run gasoline

Heavy gasoline base = 75% 98 RON catalytically reformed
25% 40 RON SRB

IMPROVEMENT OF THE WATER TOLERABILITY OF METHANOL-GASOLINE BLENDS

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ABSTRACT

The study reported in this paper is part of a project on energy saving sponsored by the Italian State Research Council.
The behaviour of blends of hydrocarbons and Methanol has been examined at different temperatures, with and without water in the system. The solubilizing efficiency of oxygenated compounds has been evaluated, with special regard to the C_2-C_8 alcohols.

PHASE SEPARATION OF METHANOL CONTAINING FUELS

The use of Methanol in gasoline blends can raise phase separation problems which, in dry conditions, are due to its partial solubility in saturated hydrocarbons, while, in the presence of water, depend on the unfavourable distribution factor between the aqueous and the hydrocarbon phase. In a previous paper (1)* we have reported the results of a study on the solubility of Methanol in hydrocarbon fuels, which was based on the simplified experimental approach of considering the phase equilibrium of the Methanol-Isooctane-Toluene-Water systems. The simplification applied, together with the disregard of the effects of the naphtenes and olefins, certainly limit the validity of the quantitative results obtained from such a model. The comparison with the solubility data of blends of Methanol in non-olefinic refinery streams has shown that, in dry conditions, our model differs to a certain extent from that based on the behaviour of commercial fuels; conversely, our model gives a satisfactory match of the experimental data obtained with commercial fuels in the presence of water (2).
In spite of the limitations outlined, our model is a valuable tool for homogeneously exploring a complete range of concentrations to identify the most critical areas. The complete illustration of the solubility limits is given in the ternary diagrams in Fig. 1, in which four isowater tolerance lines are reported at three temperatures: the tolerance line corresponding to a water content of less than 0.02 wt% represents the dry condition. The area on the right of the isowater tolerance lines defines

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*Numbers in brackets (1) designate References at end of paper.

the partial solubility conditions, while on the left there is the total solubility area. The diagrams in Fig.1 show that, in the dry condition, the aromatic hydrocarbons act as a solvent of the Methanol-saturated hydrocarbons system; as a consequence, the limited solubility of Methanol in fuel should not create any problem, because the aromatic content of the commercial fuels is such as to allow the addition of up to 15 to 20 wt% of Methanol without incurring in phase separation down to -10°C (2). When water is present, the two phase areas open and increase with an increase in water concentration. For a given Methanol content, an increase in aromatics enhances the water tolerability, however this positive effect, which is very sensible at low aromatic concentrations, decreases at higher levels. Fig.1 shows that at 0°C phase separation occurs in fuels containing 10 wt% of Methanol in presence of 0.5 wt% water whatever the hydrocarbon composition is, while, with 0.3 wt% water present, it only occurs when the aromatic content of the hydrocarbon phase is lower than 70 wt%. The dependance of the water tolerability on the Methanol concentration is also illustrated in Fig.1: starting from high aromatic gasolines (e.g. 50 wt%) the water tolerability monotonically rises with an increase in Methanol concentration, whilst starting from low aromatic gasolines (e.g. 30 wt% at -18°C) an increase in Methanol concentration reduces the water tolerance to zero when the compositions reach the miscibility line of the anhydrous condition. Besides the water tolerability, it is interesting to investigate the behaviour of Methanol containing gasolines when the amount of water present exceeds the tolerance limits. Table 1 shows the phase partition when two compounded fuels, containing about 10 wt% of Methanol, are treated at -18°C with an excess of water. The Methanol losses rise with an increase of the excess water; however, an increase in the aromatic content seems to reduce these losses. The fuel type B in the right column gives a homogeneous blend at 0°C with 0.3 wt% water present; when lowering the temperature down to -18°C, phase separation occurs and the loss of Methanol can be estimated to be 27 wt%.

SOLUBILIZING EFFECT OF HIGHER ALCOHOLS

Instability towards water negatively affects the performance of Methanol containing gasolines; the addition of suitable solubilizing agents seems to be the most appropriate approach to this problem. Previous work (3-4) has indicated that none of the various compounds examined appeared to be more effective than higher alcohols in the range C_3-C_8. However, there are very few detailed studies available on the dependance of the required amount of solubilizing agent on the concentration of Methanol and aromatics, the temperature and the water level. In an effort to gain more knowledge in this area we have examined the solubilizing effect of several alcohols following a simple experimental design based on the determination of the minimum amount of the agent required to homogenize a Methanol-Isooctane-Toluene blend at a given water content and test temperature. A modified Aniline Point apparatus (IP 2/61, method D) was used: the temperature, measured by means of a resistance thermometer, was kept constant in a thermostatic bath within ± 0.1°C and recorded. A weighed amount of hazy Methanol-Hydrocarbons-Water blend is introduced in the glass U-tube and the solubilizing agent is added, under stirring, from an automatic microburette until the turbidity disappears. In order to avoid a decrease of the water concentration during the addition, solubilizing agents containing the same water concentration as the hazy blend were employed. The results are reported on the ternary diagrams Methanol-Isooctane-Toluene showing the cosolvent isocontent lines, which indicate the minimum amount of solubilizing agent required to obtain homogeneous blends in the presence of the given amount of water at the test temperature. The Fig. 2-3-4 show the behaviour of Isobutanol at three temperatures and three water levels. Other alcohols have been tested in the same way at 20°C and in the presence of 0.5 wt% water, these being Ethanol, n-Propanol, n-sec-iso and ter-Butanol, n-Amyl, n-Hexyl and n-Octyl alcohols. Other different functional compounds, such as Methyl-ter-Butyl Ether (MTBE), Methyl Acetate and Monoethylene Glycol Mono-ter-Butyl Ether (MEGTBE) have also been tested. The qualitative behaviour of the various alcohols is the same, but quantitatively they differ to a certain extent. The efficiency of the various compounds tested was evaluated by comparing the amounts of the different solubilizing agents required to homogenize a blend of Methanol (15 wt%) Isooctane (63.7 wt%) Toluene (21.3 wt%), at 20°C and in the presence of 0.5 wt% water. The results are reported in Fig.6 as grams of solubilizing agent for 100 grams of initial blend versus the number of carbon atoms: the linear alcohols show a higher solubilizing efficiency compared to the branched ones. The efficiency of Butanols, for instance follows the order: n-Butanol > Isobutanol $\cong$ sec-Butanol > ter-Butanol. The chain length improves the solubilizing efficiency of the linear alcohols up to five carbon atoms, while a very small effect is shown in the range C_5-C_8. The comparison between alcohols and other functional compounds confirms the findings of previous researchers (3-4) relative to the higher efficiency of the hydroxylic function compared to the ethereal and the estereal ones, as shown in table 2. The ternary diagrams in Fig. 2-3-4 show that the required Isobutanol concentration increases with decreasing temperature and increasing water content and that at higher tem peratures (20°C) the quantity of solubilizing agent required decreases with increasing Methanol and aromatics content. These diagrams also show that at lower temperatures (-18°C) there is a more complex relationship between the relative amounts of solubilizing agent and Methanol; as a matter of fact with increasing Methanol content the required amount of solubilizing agent reaches a minimum value. The fairly comprehensive picture offered by the results of our experimental model enables to understand some aspects not yet clarified, like the different requirements posed by the Methanol content and the hydrocarbon phase composition. At low Methanol content (up to about 10 wt%) the required amount of solubilizing agent strongly depends on the Methanol concentration, whilst at high concentration it is almost independent of it. For a Methanol content lower than 5-7 wt%, the required amount of solubilizing agent is almost independent of the hydrocarbon composition which, on the contrary, plays an important role when the Methanol content is high (> 20 wt%). Before examining the practical implications of our results, consideration should be given to the solubilizing effect offered by Isobutanol towards the Methanol-Isooctane-Toluene and the Methanol-Aromatics-Saturated hydrocarbons systems, with the hydrocarbon compositions in the last system being obtained by blending two refinery streams (alkylate and reformate). The results, reported in Fig.5, show that there are no major differences among the two systems, however our model could be too optimistic.

PRACTICAL IMPLICATIONS SUGGESTED BY THE RESULTS

The results of our study suggest that the phase separation problems in Methanol containing blends can be minimized by the use of higher alcohols; this can be accomplished in practice by using the so called Methyl Fuel, which is a blend of higher alcohols (mainly Isobutanol) and Methanol obtained in the production of Methanol with a low selectivity process (5-6). Another feasible solution envisaged is the addition to the blend of sec-Butanol obtained by hydration of linear olefins. It has already been shown that Isobutanol and sec-Butanol have almost the same solubilizing efficiency (Fig.6). The results of this work help to optimize the alcoholic mixture with regard to temperature, water content, hydrocarbon phase composition and ratio between alcoholic and hydrocarbon phase. Fig.7 shows the minimum Isobutanol concentration required in the alcoholic blend versus the total amount of alcoholic components added to the hydrocarbon phase. The diagrams in Fig.7 clearly indicate that the Isobutanol concentration is higher the lower is the alcoholic content of the fuel and that this quantity is strongly influenced by the temperature, the water level and the hydrocarbon phase composition. According to literature, the maximum concentration of higher alcohols in the Methyl Fuel does not exceed 20 wt%, because higher concentrations would induce difficulties in the production process (5). Supposing optimistically that the total higher alcohol content of the Methyl Fuel consists of Isobutanol, the data in Fig. 7 show the applicability limits of a Methyl Fuel with that composition. As an example, for a minimum attainable temperature of 0°C and a maximum water content of 0.3 wt%, the Methyl Fuel must be blended with the hydrocarbon phase in an amount not lower than 19.5 g/100g of hydrocarbons with an aromatic content of 35 wt%, and not lower than 23.5 g/100g of hydrocarbons with an aromatic content of 30 wt%. For lower temperatures and/or higher water levels, the Methyl Fuel to hydrocarbon ratios required are bigger. At -18°C and 0.5 wt% water content, the use of Methyl Fuel does not solve the solubility problems any more.

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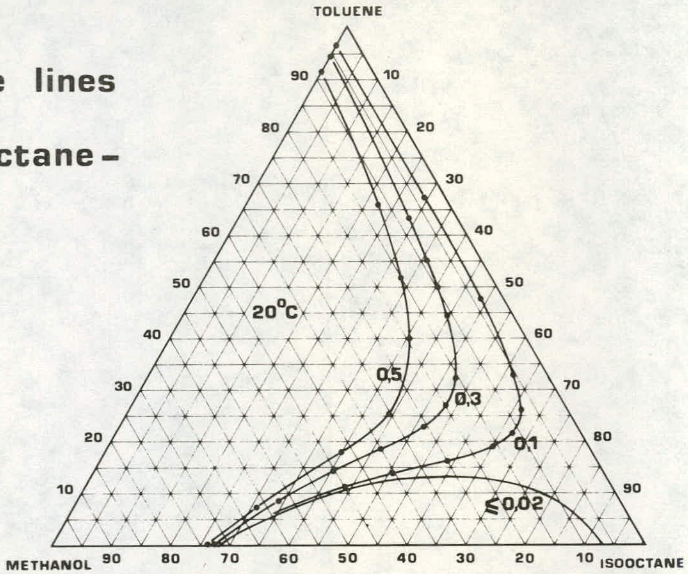
TABLE 1

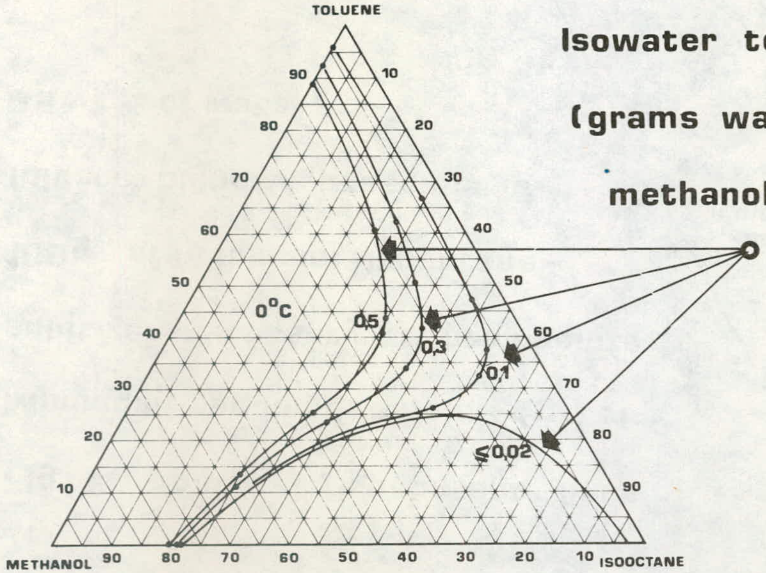
	Fuel Composition							
	A				B			
Isooctane wt%	54.0				44.6			
Toluene "	36.3				44.5			
Methanol "	9.7				10.9			
Calculated water tolerability g/100g	≃ 0.08				≃0.11			
	Phase Separation							
Water added g/100g	0.10		0.48		0.14		0.63	
Phase partition g	Upper 96.0	Lower 4.0	Upper 89.0	Lower 11.0	Upper 98.5	Lower 1.5	Upper 89.3	Lower 10.7
Phase composition								
Isooctane wt%	55.4	23.3	59.6	6.7	45.0	21.3	48.7	7.0
Toluene "	36.6	27.7	38.6	15.6	44.3	33.5	47.3	20.5
Methanol "	8.0	48.2	1.7	73.9	10.6	44.2	4.0	67.1
Water "	0.07	0.82	0.06	3.81	0.13	1.00	0.06	5.38
	Losses in the lower phase							
Isooctane wt%	1.7		1.4		0.7		1.7	
Toluene "	3.1		4.7		1.1		4.9	
Methanol "	20.0		83.7		6.1		65.8	

TABLE 2

Compounds	Carbon Atoms number	Required amount of solubilizing agent to homogenize the blend reported in Fig.6
n-Propanol	3	4.9
Methyl Acetate	3	10.8
n-Amyl alcohol	5	3.9
MTBE	5	10.3
n-Hexyl alcohol	6	4.1
MEGTBE	6	7.5

Fig : 1 – Isowater tolerance lines for system : Methanol – Isooctane – Toluene (wt %)





Isowater tolerance lines (grams water in 100g of methanol–hydrocarbon blend)

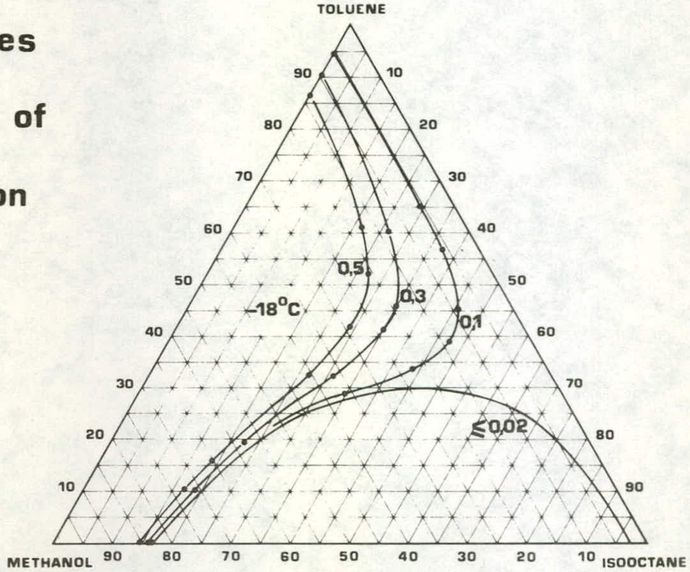
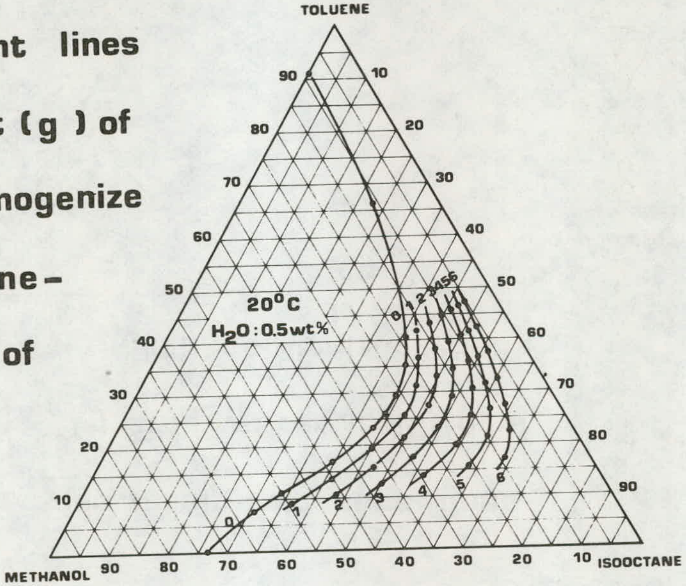
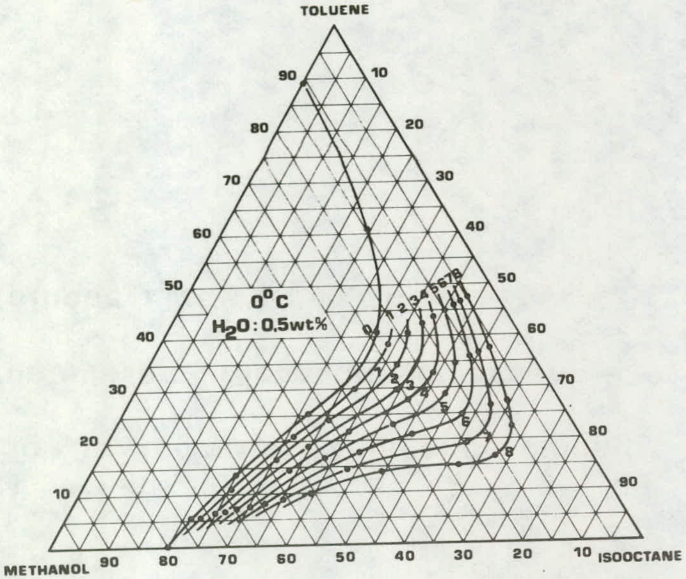


Fig : 2 Solutizer isocontent lines

Minimum required amount (g) of solutizer necessary to homogenize 100g of Methanol – Isooctane – Toluene blend in presence of 0.5wt % of water.





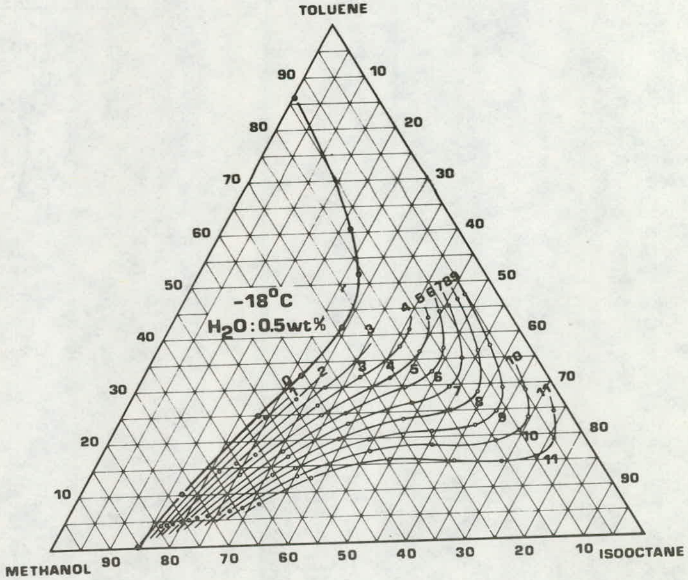
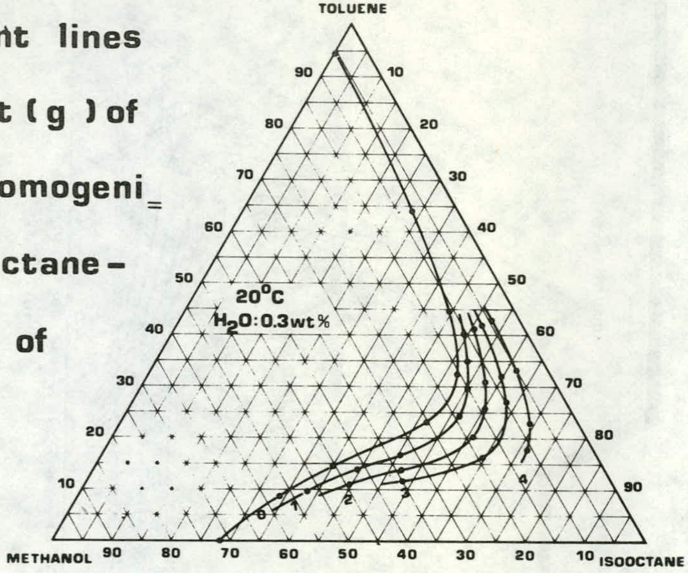
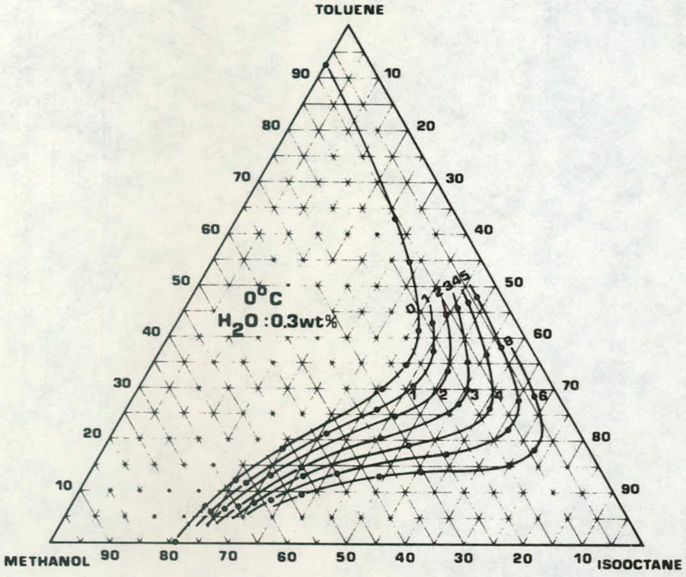
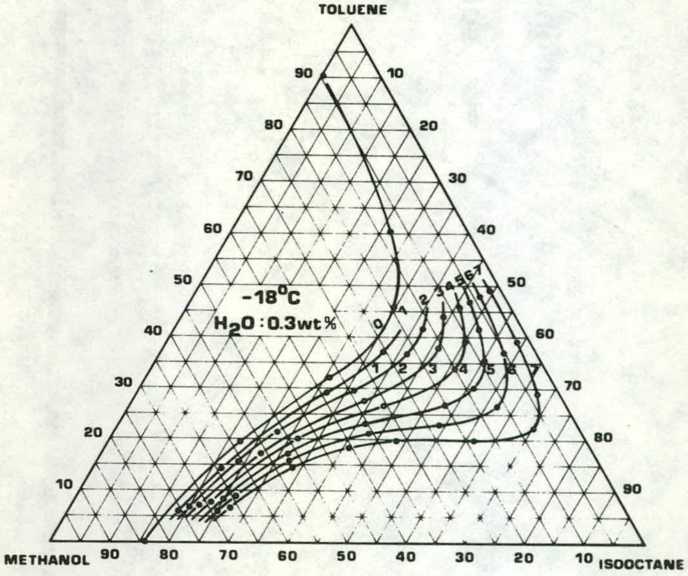


Fig: 3 Solutizer isocontent lines Minimum required amount (g) of solutizer necessary to homogenize 100 g of Methanol-Isooctane-Toluene blend in presence of 0.3 wt% of water.







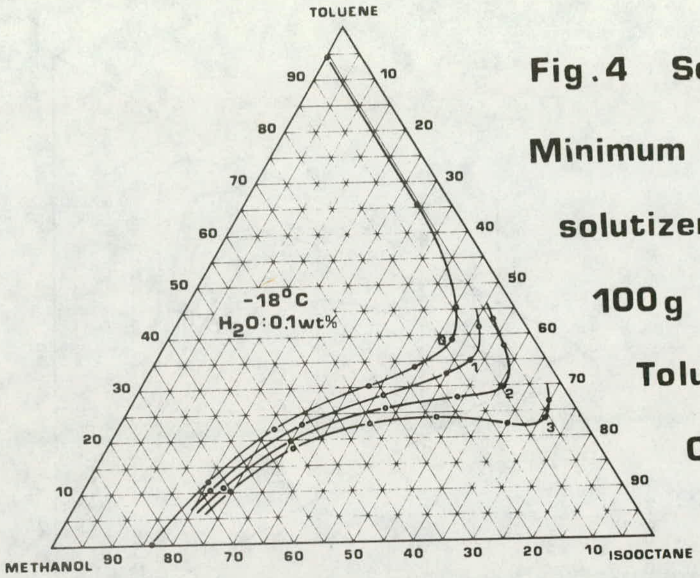


Fig.4 Solutizer isocontent lines Minimum required amount (g) of solutizer necessary to homogenize 100 g of Methanol-Isooctane-Toluene blend in presence of 0.1 wt % of water.

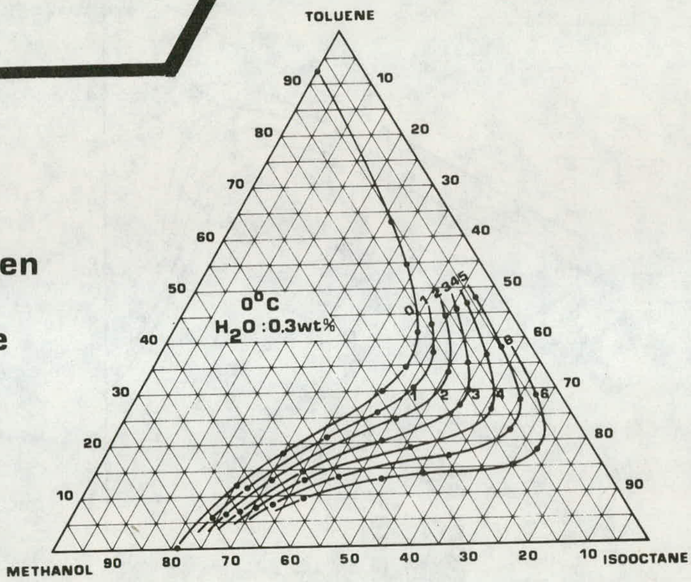
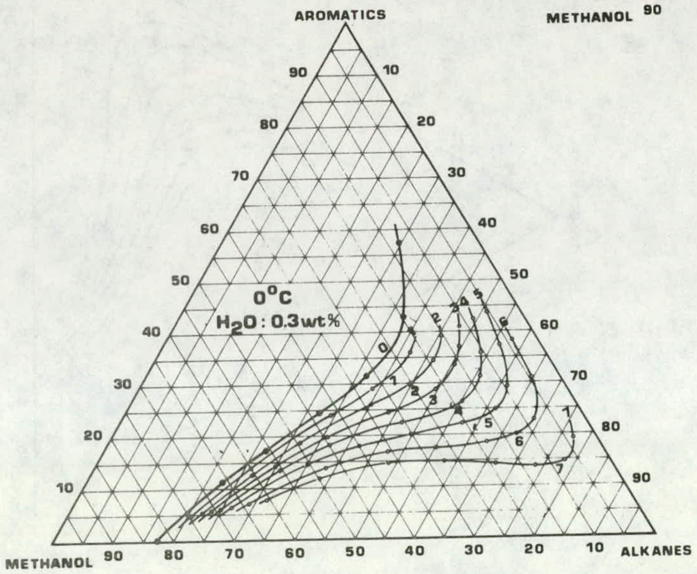


Fig: 5 Comparison between Methanol-Isooctane-Toluene and Methanol-Commercial fuel sistems (wt %)



Solutizer power VS length of the chain

blend wt% (Toluene 21.25 - Isoctane 63.75 - Methanol 15.0) water wt% 0.5 temperature : 20°C fig. 6

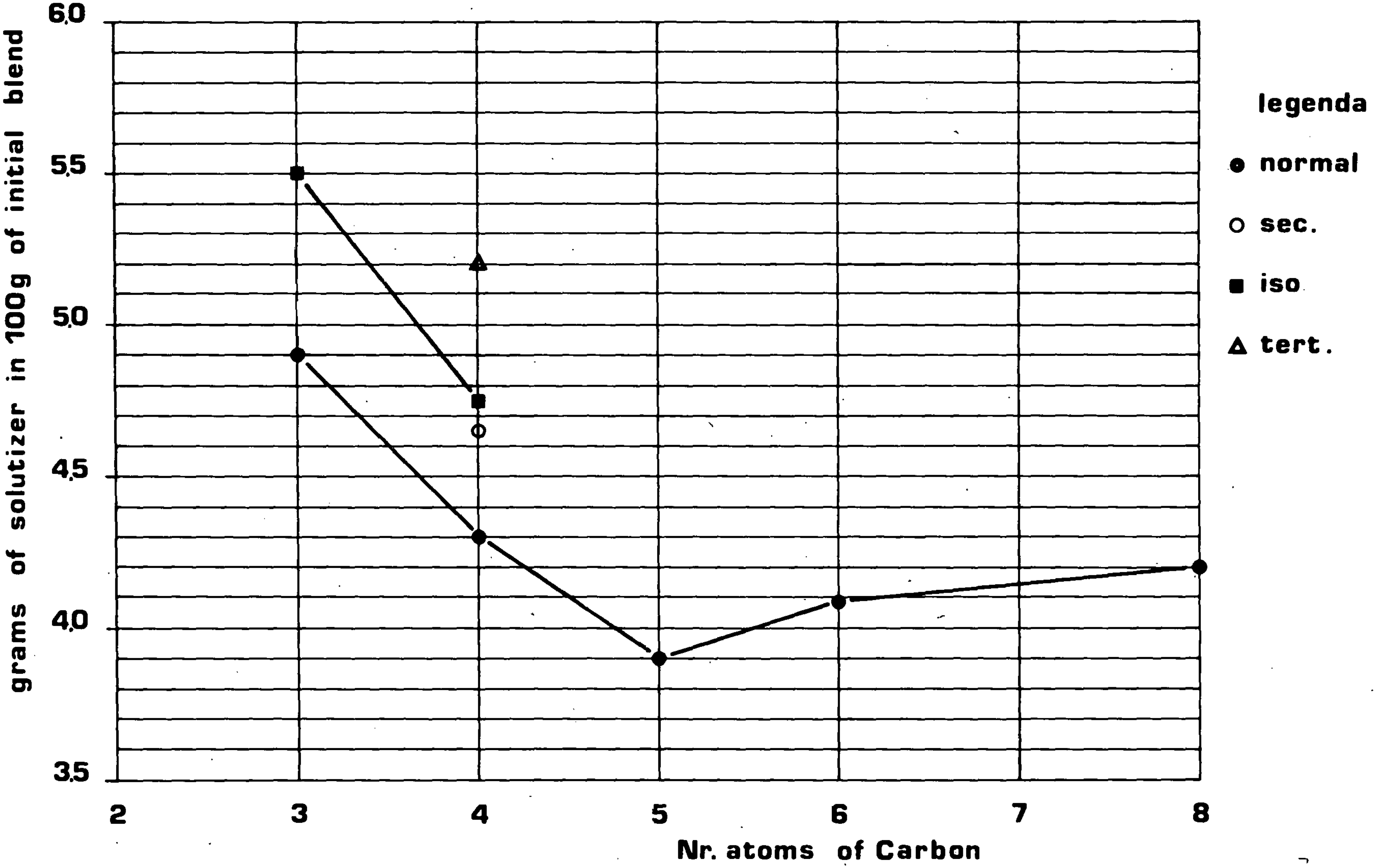
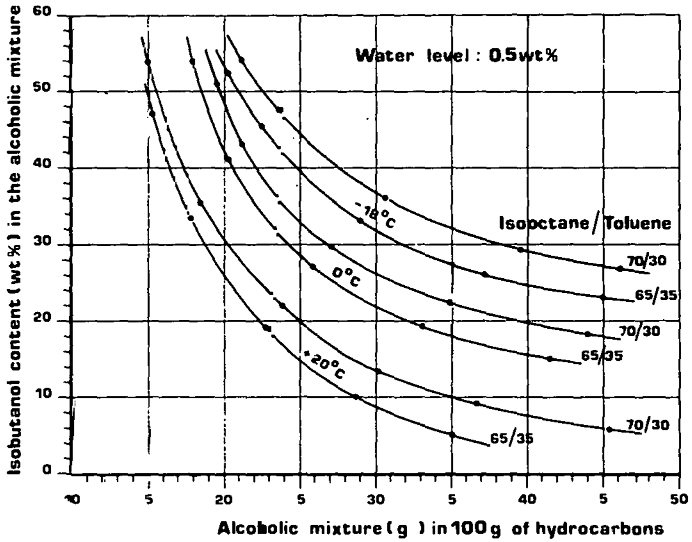
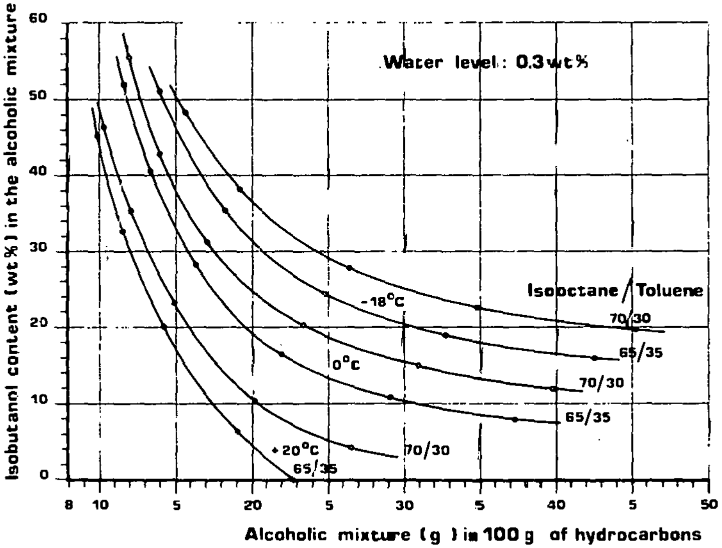
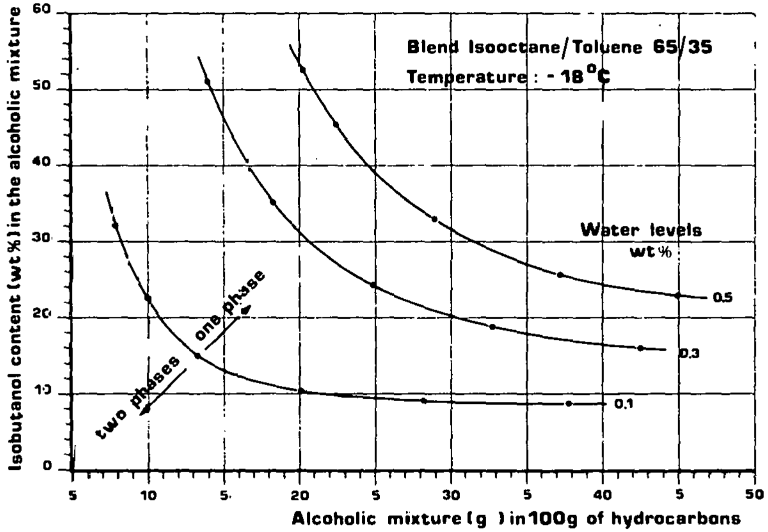


Fig: 7 Relationship between added Methyl fuel amount (g/100g Hyd.) and its compositions (Isobutanol wt %) at various water levels, hydrocarbons content and temperatures.







Dup

MODELING OF FLAME PROPERTIES OF METHANOL

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INTRODUCTION

Methanol is considered to be a more practical transport fuel than methane for large scale uses, yet in comparison with methane little is known about its fundamental flame properties. Several experimental studies have been made of the flame speed of stoichiometric methanol-air mixtures at atmospheric pressure and unburned gas temperature (T_u) of 298 K [1,2,3]*. In addition, deWilde and van Tiggelen [4] have examined the variation of the laminar flame speed in methanol-air over a range of equivalence ratios at somewhat elevated initial temperatures ($T_u \geq 390$ K), and Metghalchi and Keck [3] have briefly examined some of the effects of unburned gas temperature, equivalence ratio, and pressure on flame speed.

Laminar flame speed data are extremely useful tools for studying such fundamental processes as ignition, NO_x formation, and flame quenching. In addition, many turbulent flame models prescribe the turbulent flame speed as a function of the laminar parameters. Thus, detailed information describing the dependence of flame speed on various flame parameters can be a valuable diagnostic and design aid. However, even for methane, a fuel for which considerable theoretical and experimental work has been done, there is a considerable disparity among the values quoted for the laminar flame properties. For example, in a recent review paper Andrews and Bradley [5] determined the flame speed for stoichiometric methane-air at atmospheric pressure, with T_u=298 K, as 43 cm/sec, while under identical physical conditions Garforth and Rallis [6] found a value of 34 cm/sec. The magnitude of this discrepancy gives an indication of the difficulties and uncertainties of experimental determinations of flame properties. The

* Numbers in brackets [1] designate References at end of paper.

use of computer modeling techniques provides an alternative method of obtaining this type of information. A recent paper by Tsatsaronis [7] has used this approach for studying methane-air flames, and in this paper we apply the same type of modeling technique to the prediction of properties of methanol-air flames.

In a recent study of the detailed chemical kinetic reaction mechanism for methanol oxidation, the authors [8] included initial computational results for the flame properties of a stoichiometric methanol-air mixture at atmospheric pressure and 298 K. Those model calculations predict a value for the laminar flame speed S_u of 44 cm/sec, in excellent agreement with experimental measurements. In the present paper additional computations are reported which describe the dependence of flame speed on pressure (P), unburned gas temperature (T_u), and equivalence ratio (ϕ). In addition, the mechanistic details which are responsible for these effects are identified and discussed.

REACTION MECHANISM AND NUMERICAL MODEL

The detailed reaction mechanism reported in Reference [8] has been used in this study without modification, and the reader is referred to that paper for the reaction rate coefficients and further details on the elementary reactions involved. The model was composed of 84 elementary forward and reverse reactions between 26 different chemical species. Reactions involving NO_x species are not included in the present results. The detailed kinetic model was validated by comparison with a variety of different experimental results, covering wide ranges in operating conditions. The final mechanism, used in this paper, reproduced experimental data for methanol oxidation in reflected shock waves and in the turbulent flow reactor, over a combined temperature range of 1000-2180 K, for equivalence ratios between 0.05 and 3.0 and for pressures between 1 and 5 atmospheres.

The key reactions involving CH_3OH consumption in most flames include

$$CH_3OH + OH = CH_2OH + H_2O \qquad (3)$$

$$CH_3OH + H = CH_2OH + H_2 \qquad (5)$$

$$CH_3OH + H = CH_3 + H_2O \qquad (6)$$

with a considerably smaller contribution from

$$CH_3OH + O = CH_2OH + OH \quad . \qquad (4)$$

Reaction numbers refer to the reaction mechanism, Table I in Reference [8]. The hydroxymethyl radical (CH_2OH) is then consumed by

$$CH_2OH + M = CH_2O + H + M \qquad (9)$$

$$CH_2OH + O_2 = CH_2O + HO_2 \quad . \qquad (10)$$

Many of the properties of methanol oxidation are the result of the varying contributions of these reactions. Under fuel-lean conditions, Reactions 3 and 10 dominate, while Reactions 5, 6, and 9 are most important in rich conditions. Each elementary reaction has a distinct temperature dependence, so that different reactions dominate in different regions of the same flame. The flame models predict that relatively few methyl radicals (CH_3) are produced in methanol oxidation, so only small quantities of methane, ethane, and ethylene are formed. Most of the fuel consumption occurs by way of the hydroxymethyl radical and then formaldehyde, consistent with experimental observations [2,4,9].

Using a numerical approach developed by Lund [10], three series of flame models were computed, and the results of these calculations are summarized in Table I. The unburned gas temperature T_u, the pressure P, the initial fuel-air equivalence ratio ϕ, and the computed laminar flame speed S_u are shown. In addition the peak species concentrations, expressed as mole fractions, of many of the species in the flame region itself are also given. Finally, the flame thickness δ is shown. The flame thickness has been defined here as the region over which the total energy release rate due to chemical reactions is at least 1% of the peak value. This peak value occurs in each flame model near a temperature of 1700 K, and the flame thickness typically includes the temperature range 900-2000 K, although in the low pressure and non-stoichiometric flames the upper temperature limit is closer to 1900 K. The flame thicknesses defined in this manner are somewhat larger than those derived from other definitions, but almost any definition of flame thickness is somewhat arbitrary, and the values in Table I should be viewed as indications of trends.

EFFECT OF UNBURNED GAS TEMPERATURE

The dependence of S_u on unburned gas temperature was determined for stoichiometric methanol-air at atmospheric pressure, based on calculations for T_u= 300, 400, and 600 K. The results are shown graphically in Figure 1a and are well represented by the expression

$$S_u = 12.3 + 0.000352\ T_u^2 \quad \text{cm/sec.}$$

The quadratic dependence on T_u agrees well with measurements of Metghalchi and Keck [3], and a similar temperature exponent has been reported for methane-air mixtures [5,6]. The large effect of variation in T_u is due to two principal effects. The thermal conductivity and species transport coefficients are proportional to $T^{0.5}$, so the unburned fuel in the induction region ahead of the flame is heated more rapidly as T_u increases. In addition, the overall fuel reaction time depends strongly on the initial fuel-air temperature [8,11,12]. Nearly all of the elementary reaction rates increase with temperature, accelerating the fuel consumption and thermal energy release. Species concentrations in Table I for Models A, B, and C show a consistent trend as T_u increases, with the radical species mole fractions increasing monotonically. The mole fractions of the relatively stable intermediate species (CH_2O, H_2, CH_4, C_2H_6), and the flame thickness show very little variation with T_u. Increasing the unburned gas temperature allows the flame to maintain higher radical concentrations which are then responsible for the higher rate of fuel consumption and flame propagation.

EFFECT OF PRESSURE

Models A, D, and E were computed with T_u=300 K, ϕ=1.0, and pressures of 1, 10, and 1/10 atmospheres respectively. The low pressure flame conditions are very close to those considered by Akrich et al. [13], and the computed results for Model E agree very well with the measured data of Akrich et al. The computed values for the flame speed are plotted in Figure 1b, showing that a single expression of the form S_u= 44 P^{-x} cannot be fit to the results. The same qualitative dependence of flame speed on pressure has been observed many times for methane-air flames [5,6,14]. Both computed and experimental results suggest that the pressure variation of flame speed for both methane and methanol at elevated ($P > 1$ atm) pressures is essentially different from its dependence at lower pressures. The computed models indicate strongly that there are in fact two distinct factors which are determining this behavior. The first of these involves the variation of thermal and molecular diffusivity with density. As discussed in previous work [8], the numerical model assumes that these transport coefficients are inversely proportional to density. As a result, the low pressure Model E, with a correspondingly lower density, has a higher rate of heat and species diffusion, leading to a higher flame speed that the reference Model A at atmospheric pressure. The lower density and higher diffusivities also produce a considerably greater flame thickness for Model E as noted in Table I. The high pressure Model D has a conversely thinner flame and lower flame speed than the reference Model A.

Analysis of the kinetic details in each of these flames provides additional information on the pressure dependence of flame speed. The same elementary reactions are important, at about the same relative locations in the flame, in the low pressure and atmospheric pressure flames. The effect of changes in thermal diffusivity are reasonable small, resulting in the computed change in S_u from 50 cm/sec to 44 cm/sec with a pressure increase of an order of magnitude. However, the calculations indicate that as the pressure is further increased, the effects of certain radical recombination reactions become much more pronounced. The rates of these recombination reactions are pressure dependent, and pressure increases eventually cause a qualitative change in the structure of the laminar flame. Radical species, particularly the lighter species H, O, and OH diffuse out of the main flame zone into the induction region ahead of the flame. At lower pressures these species react primarily with fuel and oxygen molecules. In contrast, at high pressures a larger fraction of these radicals recombine. Reaction 46 is particularly effective in reducing the flame speed

$$H + O_2 + M = HO_2 + M \qquad (46)$$

since it competes with one of the key chain branching reactions, Reaction 40.

$$H + O_2 = O + OH \qquad (40)$$

The authors have previously discussed [15] the importance of pressure variation on the competition between Reactions 40 and 46 in detailed reaction mechanisms. In the present flame models the radical recombination reactions, primarily Reaction 46, affect the flame speed and structure very little for pressures at or below atmospheric pressure, and Reaction 46 is nearly unimportant in Models A and E. The gradual increase in the rate of Reaction 46 with increasing pressure becomes significant above atmospheric pressure and is responsible for the qualitatively different pressure dependence of the laminar flame speed in the two pressure regimes. The same competition between Reactions 40 and 46 is also responsible for the observed [5,6,14] and computed [7] dependence of flame speed on pressure for methane-air flames.

EFFECT OF EQUIVALENCE RATIO

Variation of fuel/air equivalence ratio in Models A, F, G, and H predicted the flame speeds summarized in Figure 1c. The shape of the curve, with the peak near $\phi = 1.1$, is similar to those for methane-air [5,7], and the numerical values at $\phi = 0.8$ and $\phi = 1.0$ agree well with those reported by Metghalchi and Keck [3]. Values at $\phi = 1.2$ and $\phi = 1.5$ are slightly higher than those reported by Metghalchi and Keck. Examination of species concentrations in Table I indicates that levels of CH_4 and C_2 species (C_2H_2, C_2H_4, C_2H_6) are considerably higher in Model H ($\phi = 1.5$) than in the stoichiometric Model A, by factors of between 3 and 15. Methane in particular exceeds 1200 ppm in the richest flame. The importance of C_2H_6 (300 ppm), C_2H_4 (250 ppm), and C_2H_2 (600 ppm) in the richest case indicates that the detailed reaction mechanism must accurately describe the oxidation of C_2 species as well as the oxidation of methanol. The authors have noted previously [8] that the present mechanism eventually becomes inaccurate for very rich methanol oxidation ($\phi > 3.0$) in shock tube simulations, also due to the difficulties associated with modeling C_2 species oxidation. Further mechanism development is needed in this area, and detailed measurements for rich methanol-air flames would also be extremely useful.

SUMMARY

The detailed reaction mechanism and flame model have been used to predict various properties of methanol-air laminar flames. The predicted values agree well with experimentally determined properties in those cases where data are available, and the predicted trends are consistent with measured data for other fuels in those cases where methanol-air flame data are not available. It is important to emphasize that this is a purely predictive study, with no adjustments made to reaction rate data or transport properties to improve agreement with experiment.

The model prediction of the pressure dependence of flame speed and structure has shown that the increased dependence of flame speed on pressure above 1 atmosphere is due to competition between radical recombination reactions and chain branching reactions. This result provides a detailed interpretation of a great deal of experimental flame speed data for methanol-air flames and for methane-air flames as well.

Fromthe point of view of practical applications for the model, the excellent agreement between these calculated flame parameters and previously measured data indicate that the model is correctly predicting most of the significant properties of these flames. As a result it should be expected that the model could be used reliably in the interpretation of most methanol-air experimental data and as a practical aid in a design capacity

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Figure 1a. Predicted laminar flame velocities for stoichiometric mixtures of methanol and air at one atmosphere pressure, as a function of unburned gas temperature. Open circles represent results for Models A, B, and C.

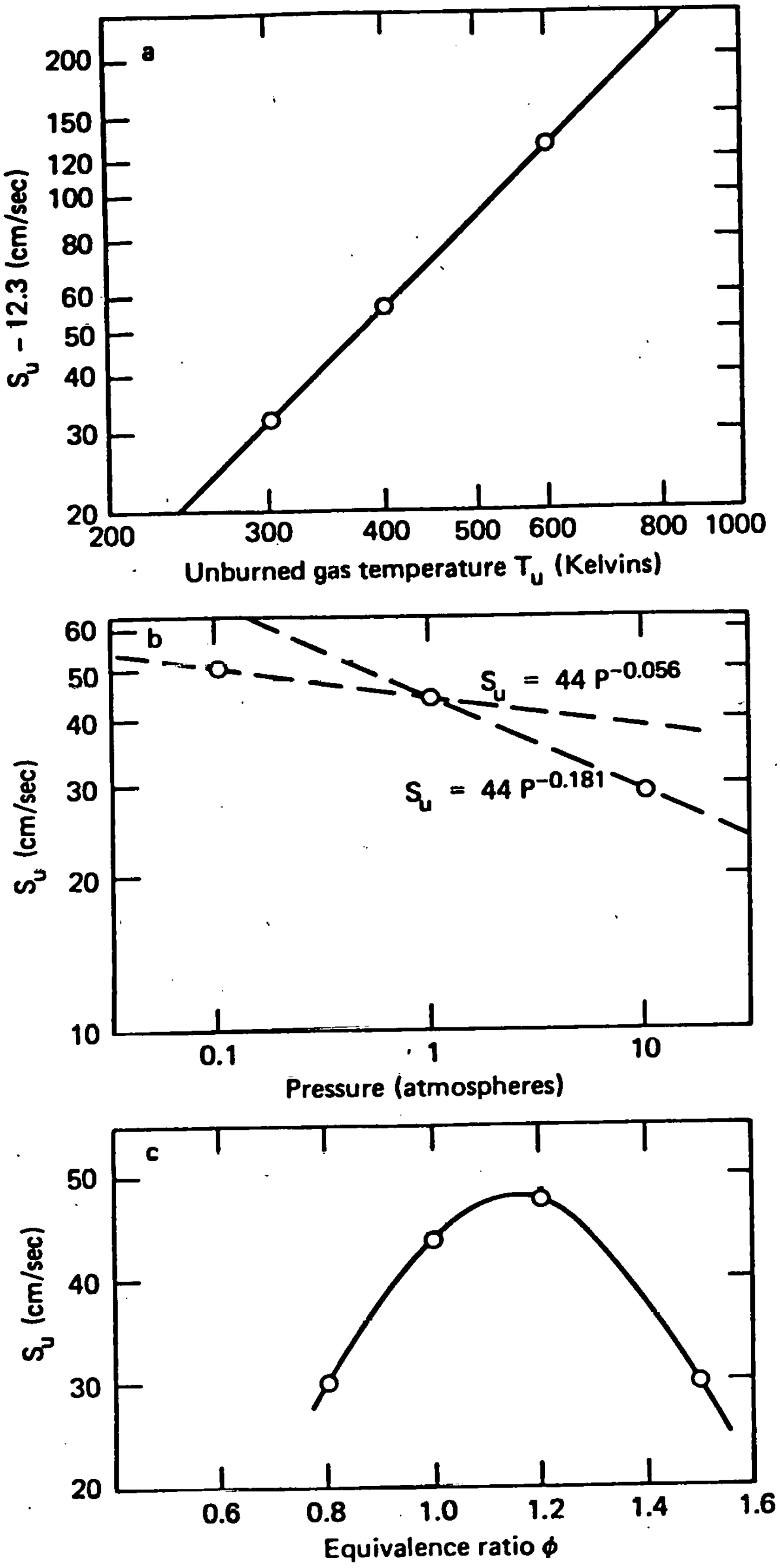
Figure 1b. Predicted laminar flame velocities for stoichiometric mixtures of methanol and air, with unburned gas temperature of 300 K, as a function of pressure. Open circles represent results for Models E, A, and D. Dashed lines represent linear fits to adjacent data points, attempting to fit $S_u = 44 P^{-x}$ cm/sec.

Figure 1c. Predicted laminar flame velocities for mixtures of methanol and air at one atmosphere pressure and T_u=300 K, as a function of equivalence ratio. Open circles represent results for Models F, A, G, and H.

Model	T_u	ϕ	P	S_u	δ	H	H_2	O	OH	CO	HCO
A	300	1.0	1.0	44	3.40	5.73-3	1.31-2	2.65-3	7.34-3	5.14-2	1.57-4
B	400	1.0	1.0	68	2.90	6.38-3	1.37-2	3.00-3	8.18-3	5.26-2	1.66-4
C	600	1.0	1.0	139	2.85	7.81-3	1.49-2	3.88-3	1.02-2	5.63-2	2.17-4
D	300	1.0	10.0	29	0.43	2.29-3	9.55-3	1.34-3	5.57-3	4.40-2	8.92-5
E	300	1.0	0.1	50	15.30	8.27-3	1.49-2	3.33-3	7.98-3	5.33-2	1.78-4
F	300	0.8	1.0	30	4.36	2.55-3	6.27-3	2.46-3	5.88-3	3.27-2	9.45-5
G	300	1.2	1.0	48	2.47	7.63-3	2.56-2	1.51-3	5.68-3	6.73-2	1.83-4
H	300	1.5	1.0	30	2.36	3.75-3	6.00-2	1.79-4	1.11-3	9.35-2	9.64-5

Model	CH_3	CH_4	HO_2	H_2O_2	CH_2O	C_2H_6	C_2H_4	C_2H_2	CH_2OH
A	2.61-4	2.28-4	5.70-4	1.23-3	4.36-3	8.99-5	4.21-5	3.80-5	5.66-3
B	2.66-4	2.34-4	6.22-4	1.22-3	4.46-3	9.17-5	3.86-5	4.04-5	6.34-3
C	3.76-4	2.37-4	8.04-4	1.16-3	4.44-3	8.83-5	3.93-5	4.80-5	7.83-3
D	1.24-4	1.48-4	5.74-4	1.02-3	3.46-3	3.49-5	1.51-5	1.59-5	3.78-3
E	3.09-4	2.56-4	6.12-4	1.26-3	4.61-3	1.09-4	5.02-5	3.93-5	6.42-3
F	1.46-4	1.30-4	4.32-4	9.91-4	2.93-3	4.64-5	2.13-5	2.34-5	2.26-3
G	4.74-4	4.27-4	7.02-4	1.43-3	5.63-3	1.49-4	1.03-4	1.31-4	6.89-3
H	6.88-4	1.28-3	5.05-4	1.30-3	6.20-3	3.05-4	2.59-4	6.12-4	5.15-3

Table I Summary of flame properties. T_u is in Kelvins, 0 is equivalence ratio, pressure P is in atmospheres, flame speed S_u is in cm/sec, flame thickness δ is in mm. Species represent peak mole fractions in the flame zone with the number after the (-) giving the power of 10.


a
$S_u - 12.3$ (cm/sec)
200
150
120
100
80
60
50
40
30
20
200
300
400
500
600
800
1000
Unburned gas temperature T_u (Kelvins)
b
S_u (cm/sec)
60
50
40
30
20
10
$S_u = 44\ P^{-0.056}$
$S_u = 44\ P^{-0.181}$
0.1
1
10
Pressure (atmospheres)
c
S_u (cm/sec)
50
40
30
20
0.6
0.8
1.0
1.2
1.4
1.6
Equivalence ratio ϕ

FLAME QUENCHING AND EXHAUST HYDROCARBONS IN A COMBUSTION BOMB AS A FUNCTION OF PRESSURE, TEMPERATURE AND EQUIVALENCE RATIO FOR METHANOL AND OTHER ALCOHOLS[+]

by

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ABSTRACT

The influence of pressure, temperature and air/fuel ratio on the content of unburnt hydrocarbons in flame gases has been investigated in a combustion bomb. Fuels have been propane, methanol and ethanol. The results show very small HC-concentrations in contrast to previous investigations, a temperature dependence proportional $T^{-1.3}$, a linear pressure dependence with 1/p, and a dependence of the air/fuel ratio proportional $1/\lambda$. In addition the composition of the exhaust gases has been investigated and the interaction wall-flame, especially the behaviour of an artificial crevice at various pressures.

INTRODUCTION

Considerations about new fuels for automobiles nowadays include not only price, availability, and economy but also the problems of air pollution which arises by the combustion of new fuels as well as by the combustion of the traditional gasolines. From the exhaust gases not only the pollutants CO and NO_x but also considerable amounts of unburnt fuel and partially burnt fuel enter the atmosphere. In addition to the hydrocarbons in the exhaust gases the fuel tank and the crankcase contribute to the hydrocarbon emission. In the latter cases, the source can be localized and reduced rather well by special constructions. In the case of the exhaust hydrocarbons the different sources are not completely clear and consequently there is no direct way to attack the problem. Daniel [1] [++] showed, that one of the numerous sources of the hydrocarbons in the exhaust gases is the incomplete combustion of the fuel/air mixture in the combustion boundary layer near to the walls. A second source is the flame quenching in crevices and small orifices [2]. Wentworth for example showed

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[+] This work is part of a research project of the DAIMLER-BENZ AG, Stuttgart, with the DFVLR concerning the reduction of hydrocarbon-emissions of spark-ignition engines.

[++] Number in brackets designate References at end of paper.

the importance of the crevice between the piston and the cylinder [3]. There are also investigations of the hydrocarbon contents in the burnt gases of a combustion bomb [4,5].

The aim of the present work is to investigate, how far these results can be transferred from one combustion bomb to another, what is the influence of walls, of the pressure, the temperature and the equivalence ratio on the hydrocarbon emission of a combustion bomb. To begin with these problems have been investigated with a constant volume bomb for pure hydrocarbons [6]. In further measurements the influence of wall structures and dead volumes will be investigated and at which time scale the combustion boundary layer will be reduced. There should also be a detailed analysis of the hydrocarbons contained in the burnt gas. These considerations apply also to alcohols as fuel and should also be investigated. Additionally there may arise problems specific to alcohols due to condensation, quench distances and pollutions.

EXPERIMENTAL WORK

The design of the combustion vessel was guided by two considerations: The vessel should be geometrically similar to an engine cylinder but without the typical shortcomings of a conventional cylinder such as leakages etc. The other strong constraint was to minimize crevices and deadspaces of sealings and valves as much as possible. The result was a cylindrical combustion bomb of 6 cm diameter and variable length. For the present investigations the length was 14,3 cm corresponding to a volume of 400 cm^3. The bottom and the top flange were sealed with gold wire gaskets in order to obtain a minimum of deadspace. The valve for charging and decharging the bomb was also vacuum tight and had no deadspace. The bomb was designed for pressures up to 200 bar at temperatures up to 700 K, which allowed initial pressures up to 20 bar. The temperature across the vessel could be kept uniform within 10 K and constant within 1 K.

The fuel/air mixture was ignited by a spark between a needle and a small plate in the middle of the bomb. The ifniter system was a Bosch HKZ type. The gap between the electrodes must be varied between 0.4 and 2.0 mm in order to get ignition at the different pressures.

The air/fuel mixtures were prepared in a mixing vessel of 3.5 l volume. Propane and air were measured manometrically. The mixtures with liquid fuels were prepared by injecting a known volume of the fuel into the heated vessel, which was then pressurised with the air. The methanol and the ethanol were of analytical grade, the air was synthetic air with a hydrocarbon content of less than 1 ppm.

The exhaust gases were analyzed gaschromatographically. Two instruments were used, a BeckmanGC4 with a Porapak Q column and a Perkin Elmer 3920 with a Marlophen 87 column. Both instruments were equipped with a thermal conductivity (TCD) and a flame ionization detector (FID). The tubings and valves between the combustion bomb and the gaschromatograph were kept at 150 C and could be evacuated to a pressure of less than 10^{-3} torr.

After the desired fuel/air mixture had been prepared in the mixing vessel, the previously evacuated bomb was charged with the fuel/air mixture. Then the valves of the bomb and of the mixing vessel were closed and the interface system evacuated to a pressure of less than 10^{-3} torr in order to avoid contamination of the tubes with residual unburnt gases. The mixture in the bomb was then ignited and the burnt gases were expanded into a heated storage vessel. A membrane vacuum pump evacuated the bomb down to a pressure of several torr in order to sample the whole gas of the bomb volume. For the experiments with pure hydrocarbons the burnt gases were fed directly to the FID measuring the total hydrocarbon emission. The signal of the FID was then calibrated against a hexane standard. In the experiments with alcohols the gas samples were fed to the columns mentioned above and the signals of the alcohols (and also of the other components) were calibrated against the appropriate standards. Thus the two values are not exactly comparable, but the discrepancy was normally within 15 percent and could be specified, as the other hydrocarbons were also measured besides the alcohols. The only species neglected is the formaldehyde due to the insensitivities of the FID and TCD. The concentrations in the burnt gases are expressed in parts per million as carbon (ppm).

Besides the previous experiments with propane and gasoline as fuels [6] most experiments were made with methanol as fuel. At an initial pressure of 2 bar the temperature was varied between 350 K and 600 K at air/fuel ratios of $\lambda = 0.8$; 1.0 and 1.2. Further the initial pressure was varied between 1 and 3 bar at an initial temperature of 350 K and at $\lambda = 1.0$. Further experiments were made with an artificial crevice 0.2 mm thick, 40 mm in height and 70.4 mm in length which was inserted into the bomb. With this setup measurements were made at pressures P_O between 2 bar and 9 bar at $T_O = 400$ K and $\lambda = 1,2$. These latter experiments were repeated with ethanol as fuel ($\lambda = 1.0$). The experiments with higher alcohols have been omitted, as the higher alcohols are rather similar to the paraffinic fuels and thus no greater deviations in their behaviour are to be expected.

RESULTS

Variation of Pressure, Temperature and Equivalence Ratio

Figure 1 shows the variation of the methanol concentrations as a function of the initial pressure in the combustion bomb for an air/fuel ratio $\lambda = 1$ at the initial temperature $T_O = 350$ K at initial pressures up to 3 bar. The appropriate values for propane/air mixtures are also shown for comparison, which show a similar behaviour as the m ethanol values. The propane values are total hydrocarbon values as seen by the FID. They contain not only the unburnt fuel but also the small amounts of intermediate products as CH_4 e.g., which give an increase of a few percent. The total concentrations of the residual hydrocarbons (including also oxygen containing compounds but not formaldehyde in the exhaust gases are found to be very small and are in the order of only 100 to 300 ppm as carbon. This is more than one order of magnitude lower than concentrations measured by Panduranga [4], which means that the deadspaces of the combustion bomb are very small. Thus the contributions of the walls to the hydrocarbon emission seem to be very small. If the measured hydrocarbons would be attributed to a combustion boundary layer a quench distance of only about 0.001 mm would be calculated. At pressures above 5 bar only a small decrease with pressure is found. If the amount of unburnt hydrocarbons at high pressures is considered as a constant contribution the additional amount at pressures P_O below 5 bar is proportional to $1/P_O$. In the case of the methanol, the residual methanol $[Meth]_r$ can be expressed as $[Meth]_r = a/P_O + b$, $a = 164 [ppm \cdot bar]$, $b = [64]$ ppm , as represented by the dotted line. This also applies rather well to the propane. It should be noted, that the methanol measurements were made at pressures up to 3 bar and that at higher pressures effects could accur due to condensation e.g. which are not found for propane.

Figure 2 shows the temperature dependence of the residual fuel between 350 K and 600 K. The emission decreases with increasing temperature and is approximately proportional to $T^{-1.3}$.

Figure 3 shows the dependence of the hydrocarbon emission from the air/fuel ratio λ for propane as fuel. As for the methanol experiments the scatter of the concentrations is larger than the changes with λ these values have been omitted. Near $\lambda = 1$ the concentration of the hydrocarbons are proportional to $1/\lambda$ (dotted line).

Crevices

For a series of experiments an artificial crevice of 0.2 mm width, 40 mm height and 70.4 mm length with a volume of 0.56 cm^3 has been incorporated into the combustion bomb, which has a volume of 400 cm^3. Figure 4 shows the results for propane/air mixtures for various pressures at $\lambda = 1.0$ and the initial temperature of 300 K. First consider the pressure regime below 4 bar. The exhaust hydrocarbon concentrations are higher due to the contribution of the crevice, which contains the unburnt gas at a pressure P_1 somewhat higher than the initial pressure P_O. P_1 is about the pressure in the bomb at the time where the flame front passes the crevice. At increasing initial pressure the quench distance reduces and at a pressure of about 5 bar flame can enter into the crevice, thus reducing the hydrocarbon emission. A comparison of fig.1 and fig. 4 shows that the crevice was not completely "cleaned" by the flame, possibly a consequence of the nonuniform seize of the crevice.

The experiments with methanol ($\lambda = 1.2$, $T_O = 400$ K) show similar results, figure 5. Thus as some corrosion occurred in the bomb at the end of the experiments especially at high pressure runs the effect is somewhat masked due to detoriation of the wall which gives larger contributions of the walls to the exhaust fuel concentration. In contrast to the propane results an increase of the exhaust methanol concentrations is found at the higher pressures. This result is surprising at the first glance, but it could be interpreted as condensation effect. Due to the increasing pressure during combustion, the partial pressure of the methanol in the not yet burnt gas can exceed the local boiling pressure and condensation can occur, predominantly near the wall. Two consequences are possible: The methanol condenses on the surface of the wall and evaporates with a time delay, which results in an increase of the unburnt fuel. The other consequence is, that the mixture become leaner with increasing condensations, and this in turn increases the thickness of the combustion boundary layer and in the same manner the unburnt fuel concentration. Yet as the repeatibility of the alcohol measurements is not as high as that of the propane measurements the correctness of these considerations should be confirmed by further experiments. Figure 5 shows also some results for ethanol which are of similar magnitude as the methanol values. It should be noted that the ethanol experiments were made at $\lambda = 1.0$ and the methanol experiments at $\lambda = 1.2$.

Exhaust Hydrocarbons

The major part of the total hydrocarbons in the exhaust gases is the fuel itself at least in the experiments with the artificial crevice. Formaldehyde has not been measured in these experiments and shall not be discussed now. This problem will be in vestigated in later experiments. Previous measurements in methanol flames showed a formaldehyde concentration in the exhaust gases of less than 1 ppm [7]. Measurements in the exhaust gases of a methanol fueled engine showed in accordance with the results of Bernhardt and Lee [8] formaldehyde concentrations of 200 ppm. In this regime one would expect these formaldehyde concentrations. Acetaldehyde was found in the order of 1 ppm either for the methanol and the ethanol experiment with respect to total hydrocarbons emission.

In the methanol experiments the main portion of the hydrocarbons as measured by the FID was about 90% methanol besides about 2% methane and ethylene together and 5% of a compound which is probably dimethylether. Trace compounds were acetyldehyde, formic acide, acetone and ethanol. the latter due to impurities of the methanol.

In the ethanol experiments 80 - 95% of the total hydrocarbons measured by the FID were ethanol, besides 1 - 5% methanol, 1% acetone and 2% methane, ethylene, acetylene together.

CONCLUSIONS

The following conclusions may be drawn from the present results:

1. Polished walls of a combustion bomb give only a small contribution to the unburnt fuel in the exhaust gases. A small roughness of the surface increases the emission.

2. The hydrocarbon emissions normally decrease with increasing pressure and temperature (but see also top 5).

3. Crevices may enclose unburnt gas. At sufficient high pressures the flame can penetrate into the crevice and burn the gas. Thus the crevice should be very small or of such a magnitude, that the flame can burn into the crevice.

4. The contribution of crevices can be reduced in some cases by increasing the pressure.

5. Alcohols show emissions similar to those of pure hydrocarbons. Problems may arise at high pressure and low wall temperatures, where condensation may occur.

6. It would be desirable to investigate the time dependence of the residual hydrocarbons in a combustion bomb in order to get some information about the time in which the combustion boundary layer decreases.

ACKNOWLEDGEMENTS

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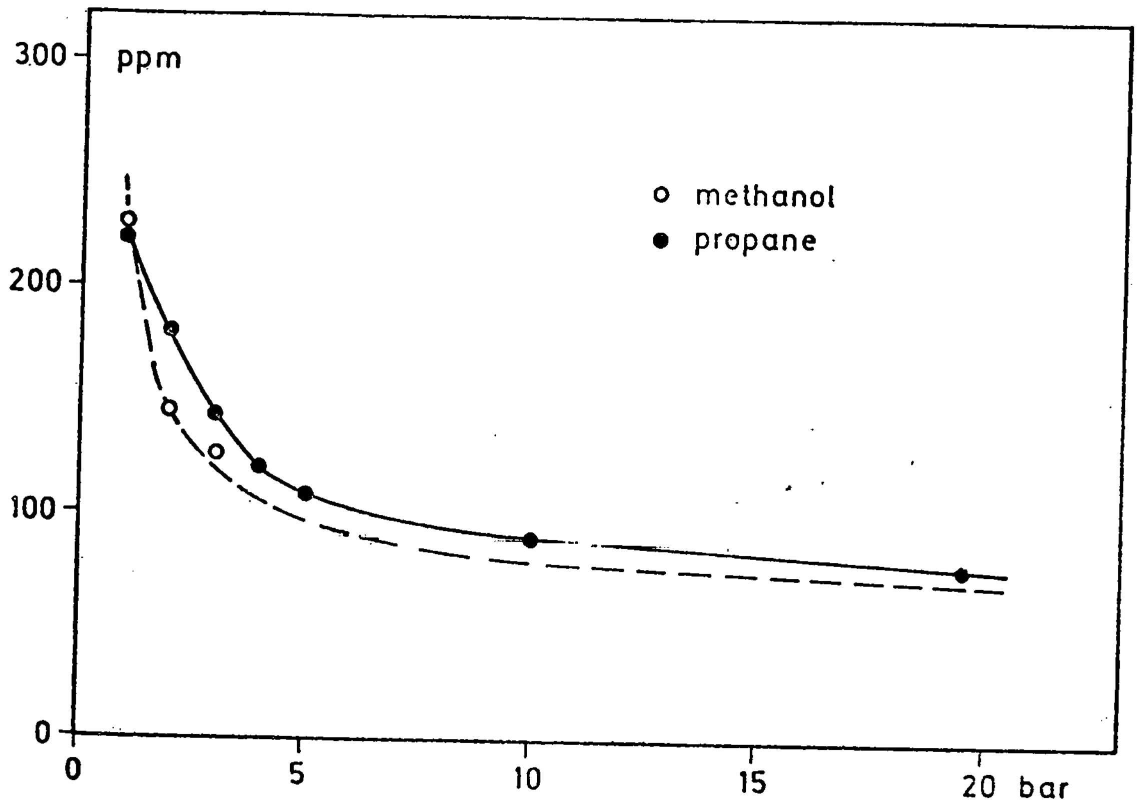

Figure 1: Unburnt fuel in the exhaust gases as a function of the initial pressure P_O for propane/air and methanol/air mixtures. Concentrations are expressed in parts per million as carbon. The propane values represent total hydrocarbon concentrations, the methanol values are the methanol concentrations in the exhaust gases. $T_O = 350$ K, $\lambda = 1,0$ for methanol. T = 300 K, $\lambda = 1,0$ for propane. The dotted line respresents the $1/P_O$ dependence.

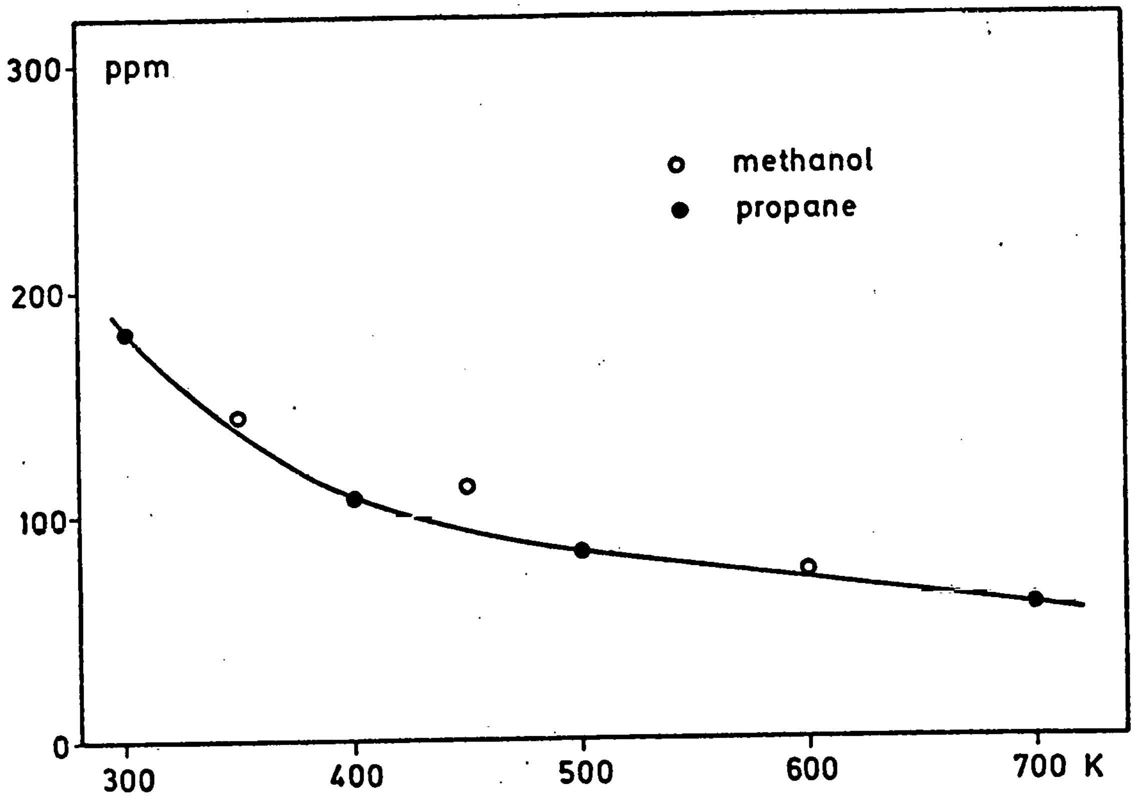

Figure 2: Unburnt fuel (specified as in fig. 1) in the exhaust gases as a function of the initial temperature T_0 for propane/air and methanol/air mixtures. Initial pressure = 2 bar, air/fuel ratio λ = 1,0.

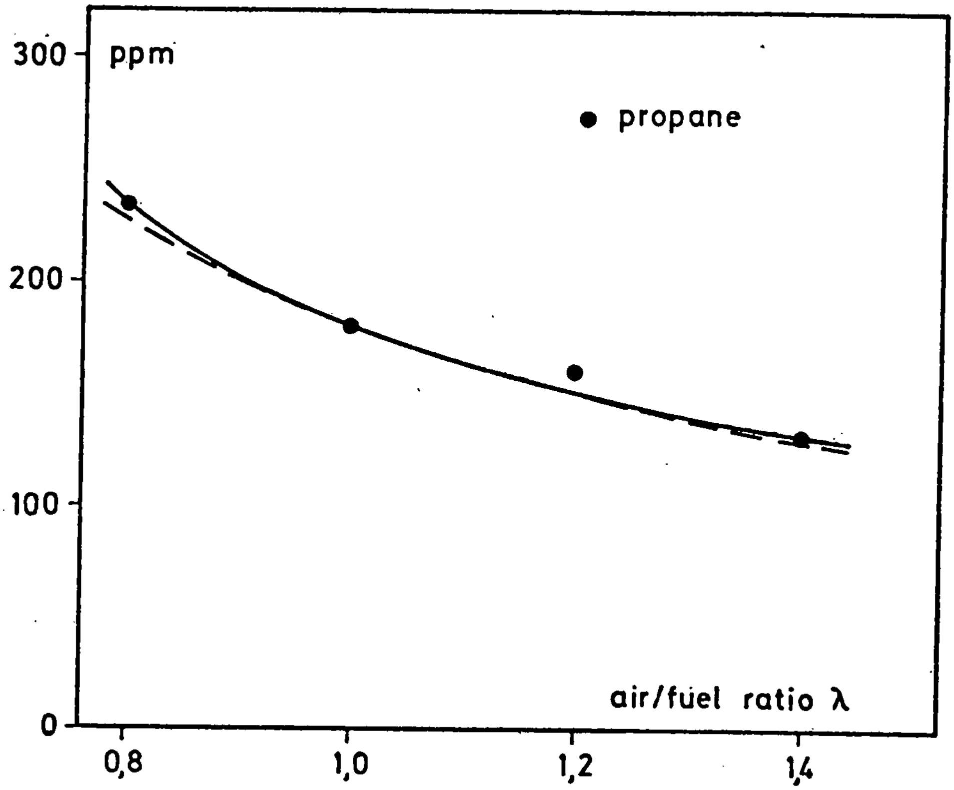

Figure 3: Unburnt fuel (specified as in fig. 1) in the exhaust gases as a function of the air/fuel ratio λ. λ is referred to the stochiometric mixture (λ =1). Fuel = propane. Initial pressure p_o = 2 bar, initial Temperature T_o = 300 K. The dotted line represents a dependence proportional to 1/λ.

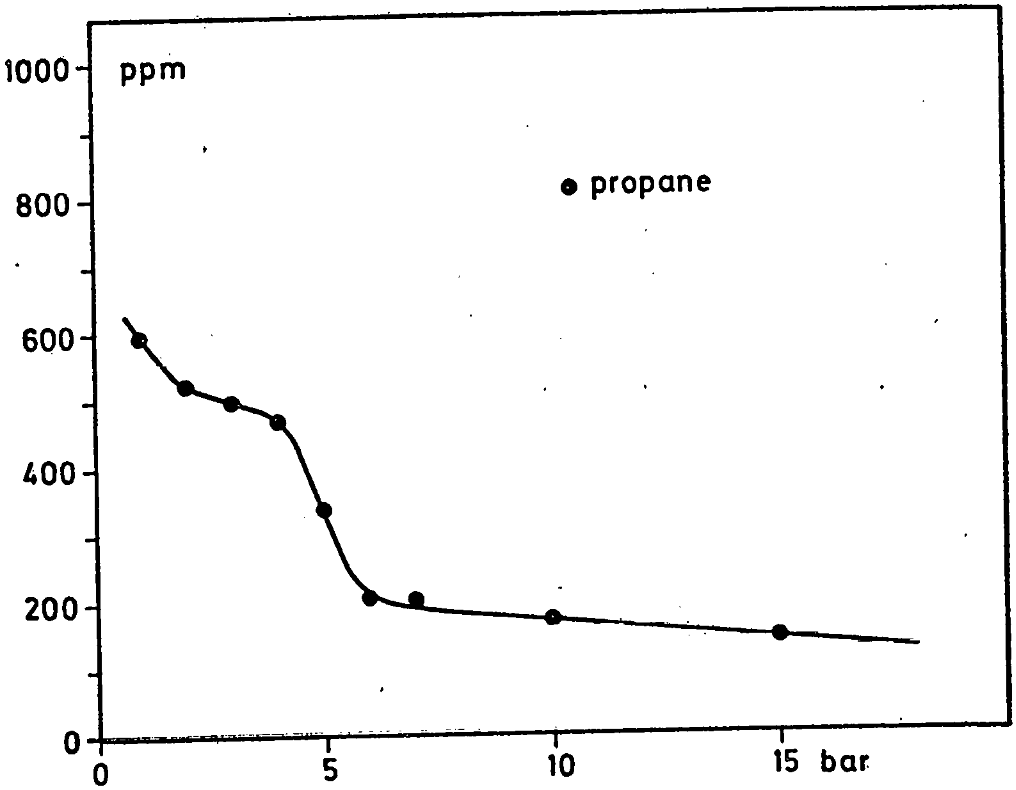

Figure 4: Unburnt hydrocarbons (specified as in fig. 1) in the exhaust gases as a function of the initial pressure p_o for propane as fuel. T_o = 300 K, λ = 1.0. Volume of the artificial crevice 0.56 cm^4. Volume of the bomb 400 cm^3.

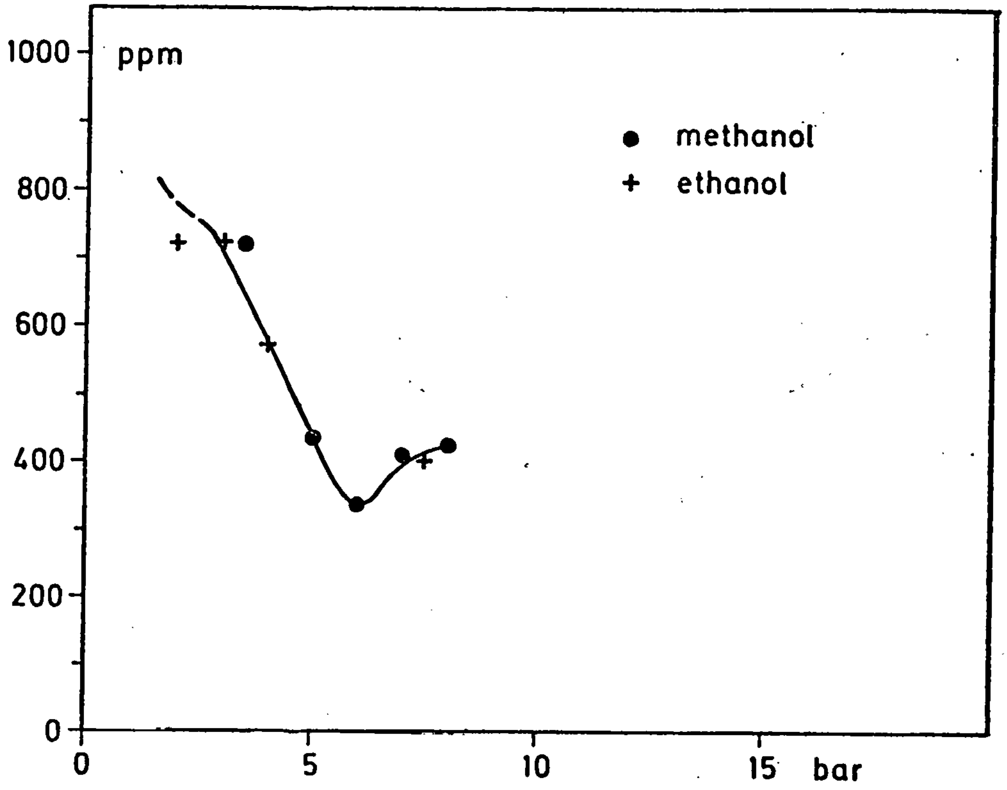

Figure 5: Unburnt alcohol in the exhaust gases as a function of the initial pressure p_o. Volume of the artificial crevice 0.56 cm^3 . T_o = 400 K. λ = 1.2 for methanol, λ = 1.0 for ethanol.

FACTORS INFLUENCING COLD STARTING OF ENGINES OPERATING ON ALCOHOL FUEL

by
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ABSTRACT

A common difficulty experienced with the use of pure alcohols or alcohol-gasoline blends in engines is their poor cold starting and warm up driveability characteristics. This paper examines the various fuel, engine and ignition system parameters that influence the problem. In particular, the cold starting problem with alcohol fuel is investigated using a theoretical approach, by examining the sequence of events taking place in a closed volume from the instant of deposition of a given quantity of ignition energy to the establishment of a stable flame.

INTRODUCTION

The use of ethanol and methanol either blended with gasoline or by themselves in automotive engines for transportation purposes appears attractive at the present time for a variety of reasons, some of which are:

1. feasibility of operating current automotive engines on alcohol fuels with a minimum of design modifications
2. possibility of attaining modest improvements in engine performance and exhaust emissions
3. capability of manufacture from replenishable raw material such as coal or agricultural feedstocks.

However, the most frequently encountered difficulty associated with the use of alcohol fuels and alcohol-gasoline blends, for which no satisfactory solutions exist at the current time, is their poor cold starting and warm up driveability performance [1]. This problem is particularly severe at or below temperatures of 50°F. or 10°C. The same fuel characteristics that contribute to the severe cold starting difficulties are also responsible for the high value of the total weighted demerits assigned to engines running on these fuels during warm up and driveability tests. With the use of alcohol-gasoline blends, as with straight alcohol fuels, the unsatisfactory cold start, warm up and driveability trends are present in various degrees of severity depending on the blend level.

FACTORS INFLUENCING COLD START AND WARM UP PERFORMANCE

Fuel Characteristics

The two most significant fuel properties that strongly influence the cold start and warm up driveability characteristics of alcohols and alcohol-gasoline blends are the fuel volatility and heat release. The common practice with present day gasoline engines is to supply an excess quantity of fuel via the carburettor, such that at colder ambient and engine temperatures, enough fuel will vaporize to give the proper air-fuel vapor mixture conducive to cold starting. For engines operating on pure gasoline the air-vapor ratio for cold starting is about 13:1. The cold start problem introduced with alcohol fuels is in part the outcome of the high vapor pressure exerted by these fuels [2,3]. With carburettors unmodified for alcohol operation, this leads to a larger percentage of alcohol vapor present in the fuel-air mixture entering the engine. The ignition and heat release characteristics of this fuel-air mixture with a higher concentration of alcohol vapor than gasoline vapor are markedly different than the pure gasoline-air mixture because of the lower heat of combustion of the alcohol fuel. Hence there are two combining factors which aggravate the cold start problem with stock carburettors - the blend leaning effect and the lower heat release effect, volume for volume of fuel. This is demonstrated in tests by Brinkman [4] where the total weighted demerits for cold start driveability increased with leaner mixtures. The problem is alleviated by using injection systems where the fuel volatility effects are not encountered [5]. That the poor cold start and warm up driveability characteristics of alcohol fuels is not solely the result of their higher volatility is shown from the fact that the addition of butane and pentane to an alcohol-gasoline mixture improves cold starting. These additives are also highly volatile, however they have high heats of combustion. This indicates that the cold starting difficulties with alcohol fuels are intimately connected with the ignition, heat release and flame propagations characteristics of these fuels, and are closely allied to the misfire phenomenon encountered with lean limit operation with gasoline.

Engine Charateristics

Among the engine variables that bear upon the cold start and warm up driveability performance of alcohol fuels are the metering and induction system characteristics, engine compression ratio and the ignition system.

Preheating the incoming fresh charge, either by directly heating the combustion air or by utilizing the exhaust gases to heat the induction gases is shown to improve the cold start and warm up driveability characteristics[4]. The effects of incoming charge preheat are two fold: greater vaporization of the relatively low volatile (compared to the alcohol fuel) gasoline and higher compressed charge temperature leading to better ignition and flame propagation characteristics. Similarly higher compression ratios should give better cold start and warm up characteristics with alcohol fuels, because of better ignition and flame propagation.

That the ignition system plays an important role in the cold start and warm up characteristics is indicated by the improved cold start and warm up driveability performance obtained by using higher ignition voltages and longer spark duration [6]. Thus studies in a four stroke ASTM-CFR engine by Topham, Smy and Clements [12] have shown that the use of a coaxial spark igniter producing a small jet of plasma extends the lean limit of operation and enhances engine performance with gasoline fuels. As mentioned before the cold start problems with alcohol fuels is similar to lean limit operation with gasoline insofar as the initial ignition and flame propagation phenomenon occur under similar conditions. In the case of lean limit operation with gasoline, the ignition and flame propagation is influenced by the low heat release rates because of the low stoichiometric ratio; in the case of cold starting with alcohols the combined effects of blend leaning and high concentrations of low heating value alcohol fuel render the initiation and stable propagation of a flame with the requisite burning velocity quite difficult.

Thus the failure to obtain satisfactory cold start performance is influenced by a combination of fuel and engine characteristics which are not adequately understood at the present time. The work reported in this paper is the first phase of a combined theoretical-experimental investigation of the cold start problem with alcohol fuels. This first phase takes a close look at the factors controlling the initial ignition and flame propagation sequence with alcohol fuel. Based on the results of the first phase of the work, the second phase experimentally investigates the different combinations of fuel and engine parameters which will provide satisfactory cold start and warm up performance. Initial results of the first phase are reported here.

IGNITION CHARACTERISTICS OF ALCOHOL FUEL

The failure of engines operating on alcohol fuels to start under cold ambient conditions is a direct consequence of the inability of the initial spark ignition energy to produce a self propagating flame with the required mass burning velocity. For a given alcohol fuel, this ignition process is influenced by:

1. the delivery of a suitable combustible mixture to the engine cylinder by the metering carburetor/injector via the intake manifold system,
2. the rate and strength of discharge of spark energy into an initiating kernel of gas, with temperatures in the kernel reaching values of the order of 2×10^3 to 10^4 °K,
3. the transport of energy from the initial kernel to the combustible mixture, which is affected by the heat conduction to the electrodes, and to the adjacent fuel-air mixture, as well as diffusion and convection process [7], and
4. the initiation of exothermic kinetic processes in the combustible gas, and the establishment of a flame kernel of critical volume.

These four related steps determine whether the fuel-air mixture burns properly and the engine starts, or if the flame dies out. Thus a knowledge of the different engine, fuel and igniter characteristics which would ensure the propagation of a stable flame would be of assistance in providing the proper conditions for cold starting.

To best investigate the above combination of relevant criteria, a numerical modeling approach is adopted similar to that employed by Dixon-Lewis and Shepard [8]. The study follows the individual combustion events of the ignition - flame propagation process from the initial deposition of spark energy till the establishment of a self propagating flame. This is done by the formulation of appropriate non-steady partial differential equations describing the various physical - chemical processes occuring in the engine cylinder. The fuel used in the present study is methanol, since its kinetic combustion characteristics are well known [9].

THE MODEL

The model used to study the ignition characteristics of methanol is shown conceptually in Figure 1. The initiation of combustion and the development of a flame is examined from the deposition of a specified quantity of ignition energy into a central kernel of gas. The rate of deposition of this ignition energy is controlled by varying the rate of specified temperature rise in the hot ignition core. This simplified approach is adopted in order to keep the calculation time within reasonable limits.

The physical processes taking place during ignition are illustrated in Figure 1. As energy is deposited into the hot central core, reaction occurs releasing additional amounts of heat in this region. This energy is transported by conduction and diffusion to the gas in the neighborhood of the ignition core. This adjacent gas then begins to react and further release heat energy. If this rate of heat release is higher than the losses by conduction and convection to the neighboring gases, then a stable flame is established. If the losses are greater than the chemical energy release, the flame is extinguished and a misfire results. The laws governing the physical processes occuring during the ignition process are the conservation equations for mass, momentum and energy and the species continuity equations and are given in reference 10. Diffusion and thermal conduction processes are estimated on the basis of the Chapman-Enskog theory. A simplified reaction scheme for methanol oxidation is employed to calculate the effects of chemical reaction and is given in Table 1. The ignition process is studied using a Lax-Wendroff finite difference technique with the appropriate boundary conditions as given in [10].

RESULTS AND DISCUSSION

The details of the ignition process occuring when the temperature of the central ignition core is raised rapidly to 3000 °K in 0.1 microseconds has been investigated for a methanol-air mixture in stoichiometric proportions. The initial pressure and temperature for this case are one atmosphere and 298 °K respectively. The container is taken to be a cylindrical vessel with a maximum radius of three cm. The ignition core radius is 0.4 cm. Using a finite difference numerical technique marching forward in time the processes occuring during the ignition sequence are investigated.

Figure 2 shows the temperature profiles existing in the combustion volume as a function of cylinder radius. The temperature profile existing at $t = 0.1 \times 10^{-6}$ seconds is the initial profile. The temperature profiles at 0.723×10^{-6} seconds and 0.196×10^{-5} seconds are also shown in the figure. Since the temperatures at increasing radii continue to increase with time, this is a case of successful ignition with flame establishment. Successful ignition occurs when the losses by conduction and convection can be adequately compensated by the chemical energy release through combustion. This is an important criterion especially in the ignition core. When the temperature in the ignition kernel is raised by the introduction of ignition or spark energy, a consequent pressure increase occurs in this region as seen in Figure 3, establishing steep pressure gradients in the immediate viscinity of the core. This leads to fairly high gas flow velocities of the order of 10,000 cm/sec or more. Hence convection losses from the ignition kernel are especially steep in the early part of the ignition process as seen from Figure 4. When turbulence and swirl are present, as in the engine cylinder, these losses increase further, increasing the value of the requisite minimum ignition energy.

The velocity profiles presented in Figure 4 indicate the possibility of steep gradients existing in the flow. These steep gradients often lead to the formation of shock waves which can develop into detonation waves if the conditions are suitable. Because of the lower heating value of methanol as compared to gasoline, the heat release rates during combustion are lower and the tendency for extremely steep gradients to develop in the flow is not present. Hence the higher octane rating of methanol and methanol gasoline blends. On the other hand, with hydrogen fuel, the fast burning velocities and high heat release rates increase the possibility of detonative combustion as shown by similar calculations on the hydrogen-air system [10].

Figure 5 shows the variation of temperature with time at two locations in the cylinder. The temperature at a point of radius 0.2 cm lying within the ignition core is assumed to be raised rapidly to 1700 °K in 0.1 micro seconds by the input ignition source such as a spark. It is seen that immediately following the cut off of external ignition energy, the heat losses are quite predominant and for a short period of time of about 3 microseconds chemical heat release and thermal losses are almost balanced. With higher convective, conductive and diffusional losses, the flame can be quenched. That this is not the case is shown by the steady increase in the temperature profile at 0.5 cm radius.

The computed mass fraction of methanol in the mixture at times of 0.723×10^{-6} seconds and 0.195×10^{-5} seconds are shown in Figure 6. As the flame propagates, the methanol is consumed as shown by the steadily increasing methanol mass fraction with increasing radius. On the other hand the mass fraction of the specie CH_2OH exhibits a peak whose maximum value is dependent on the temperature history of the specie. A similar peak is exhibited by the formaldehyde mass fraction shown in Figure 7. Here it is seen that the peak formaldehyde concentration at 0.723×10^{-6} seconds is higher than the peak value at 0.195×10^{-5} seconds. This is again a function of local time variant conditions. Studies such as the present one will help us to find the proper ignition conditions for minimum production of formaldehyde consistent with engine operation criteria such as cold starting and road load performance.

CONCLUSIONS

This preliminary investigation of the details of the ignition of a stoichiometric methanol-air mixture shows that the initiation and propagation of stable combustion is dependent on a combination of the chemical reaction characteristics of the fuel interacting with the conduction, convection and diffusional processes produced as a result of the deposition of the ignition energy into the mixture. The study leads to investigation of the synergistic effects of fuel and engine variables during the ignition process. Further study of this ignition phenomenon is being conducted to determine the best combination of fuel, ignition energy and engine characteristics which will lead to satisfactory cold starting and road load operating performance.

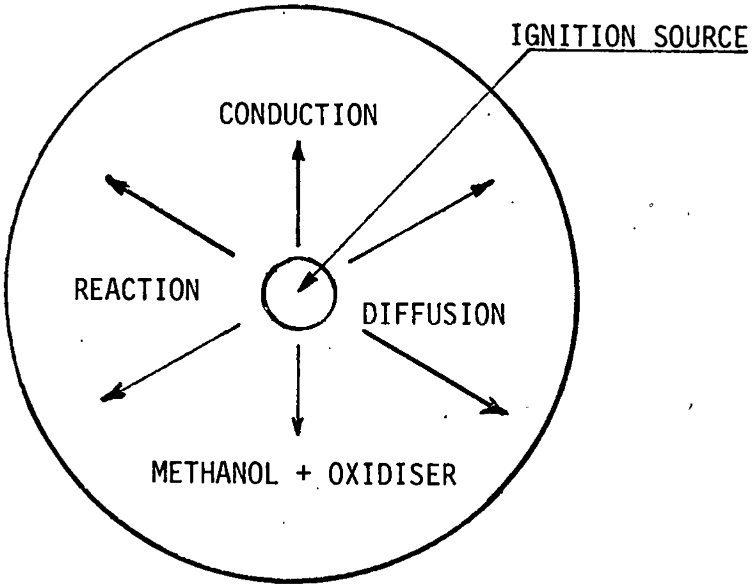

FIGURE 1

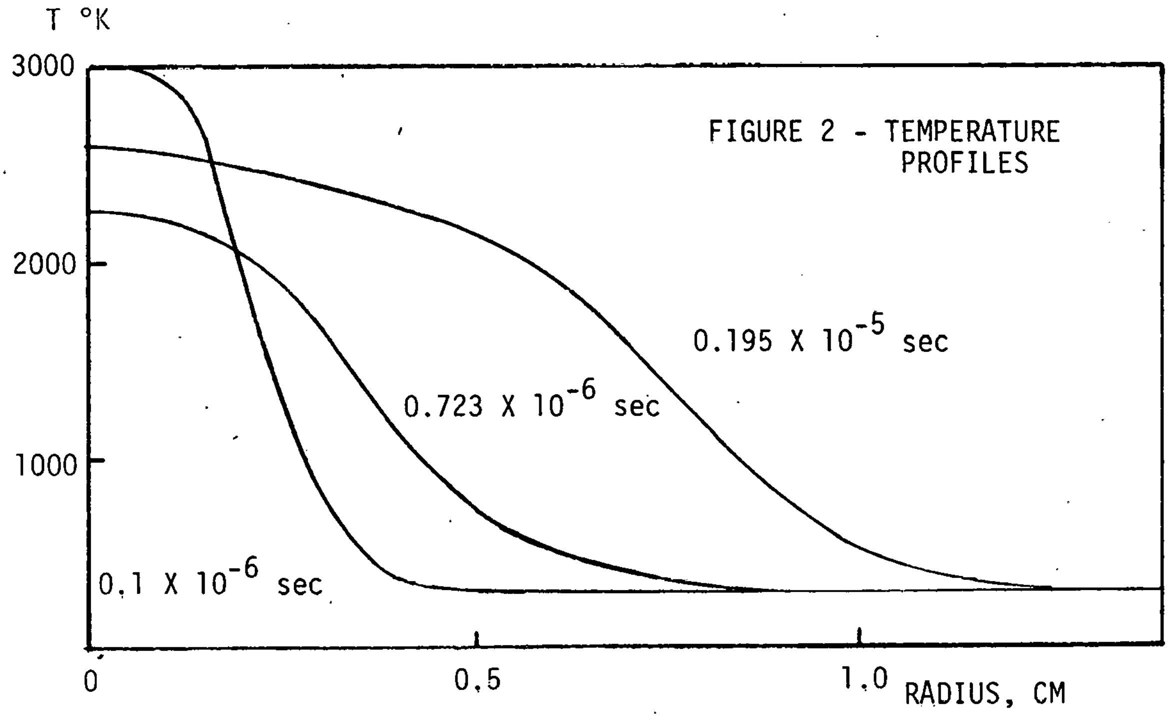

FIGURE 2 - TEMPERATURE PROFILES

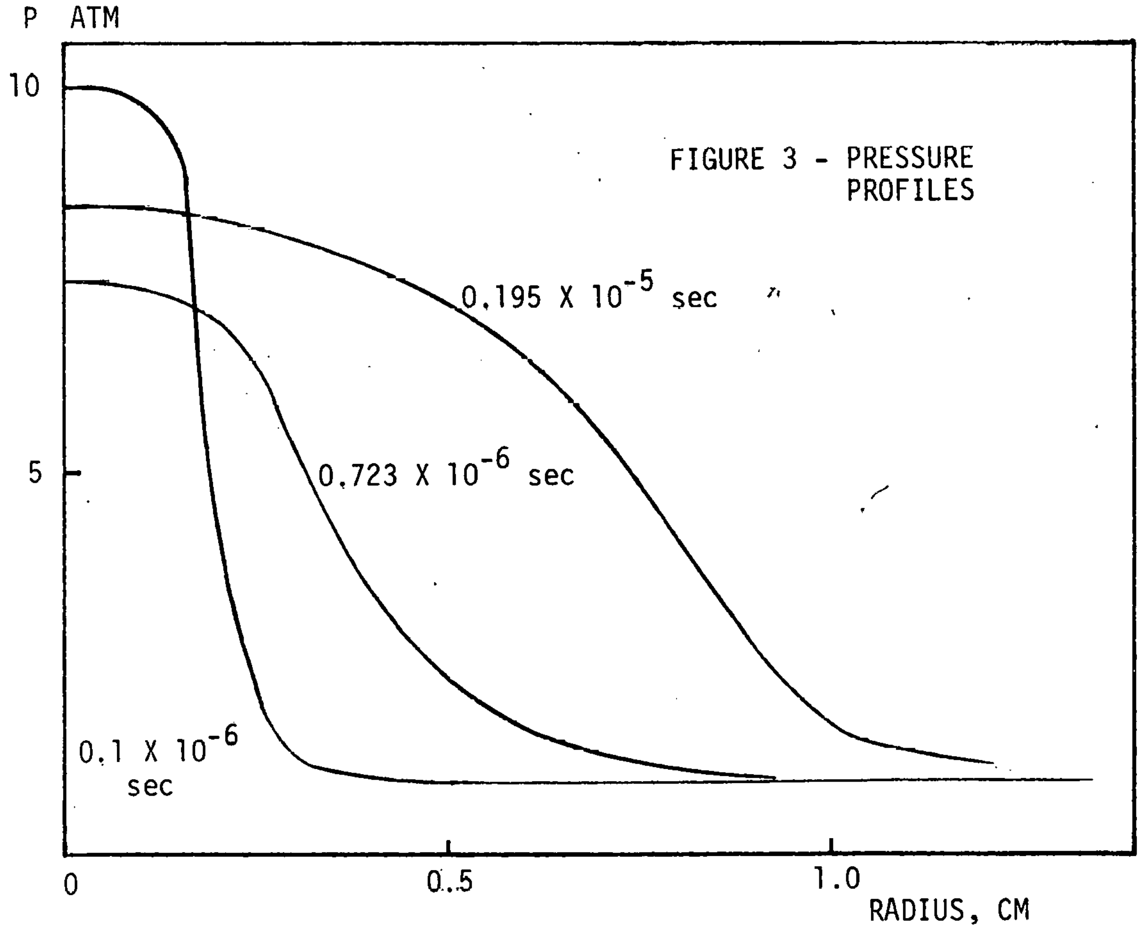

FIGURE 3 - PRESSURE PROFILES

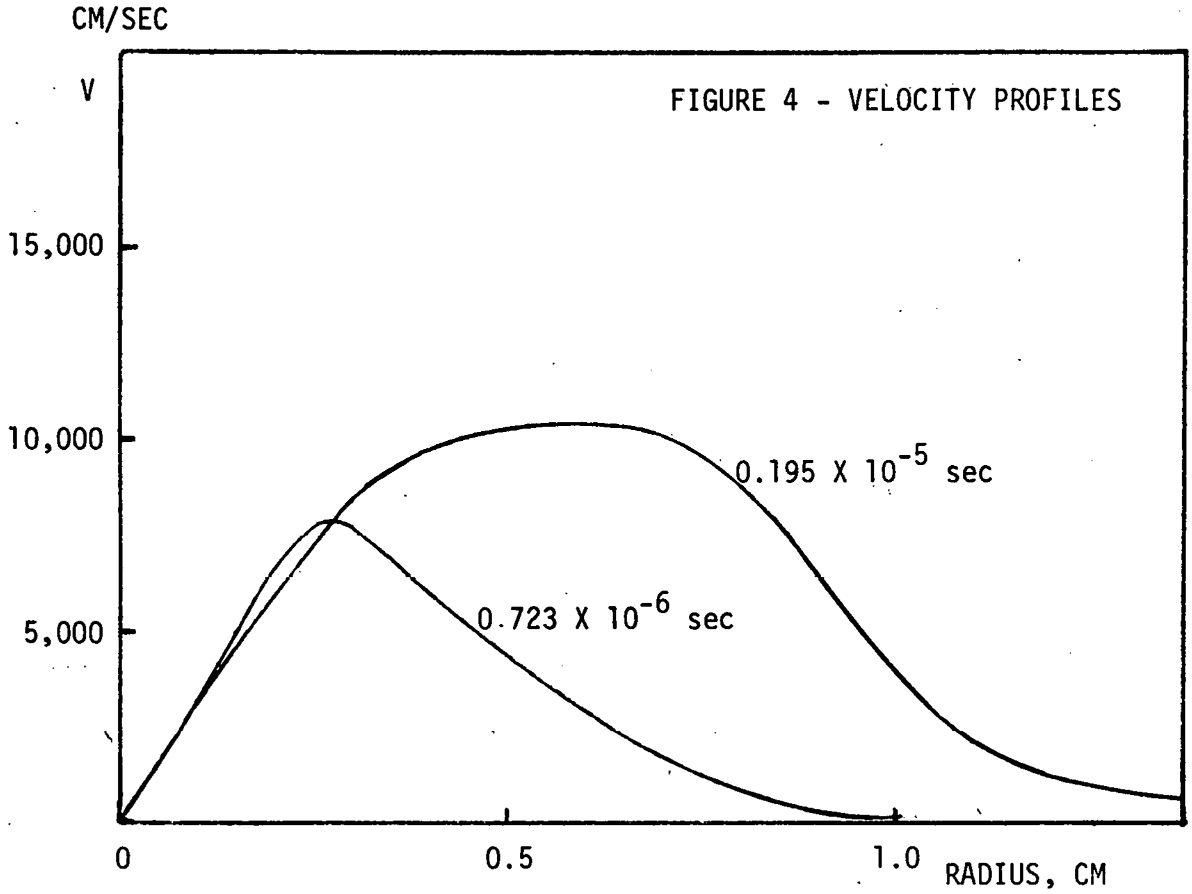

FIGURE 4 - VELOCITY PROFILES

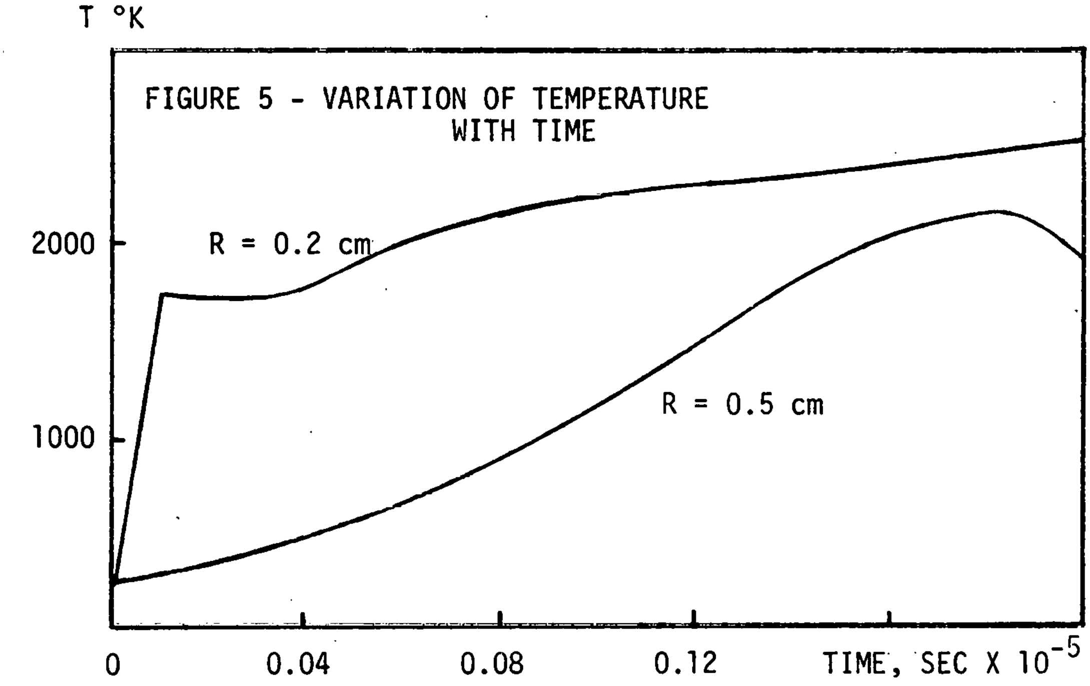

FIGURE 5 - VARIATION OF TEMPERATURE WITH TIME

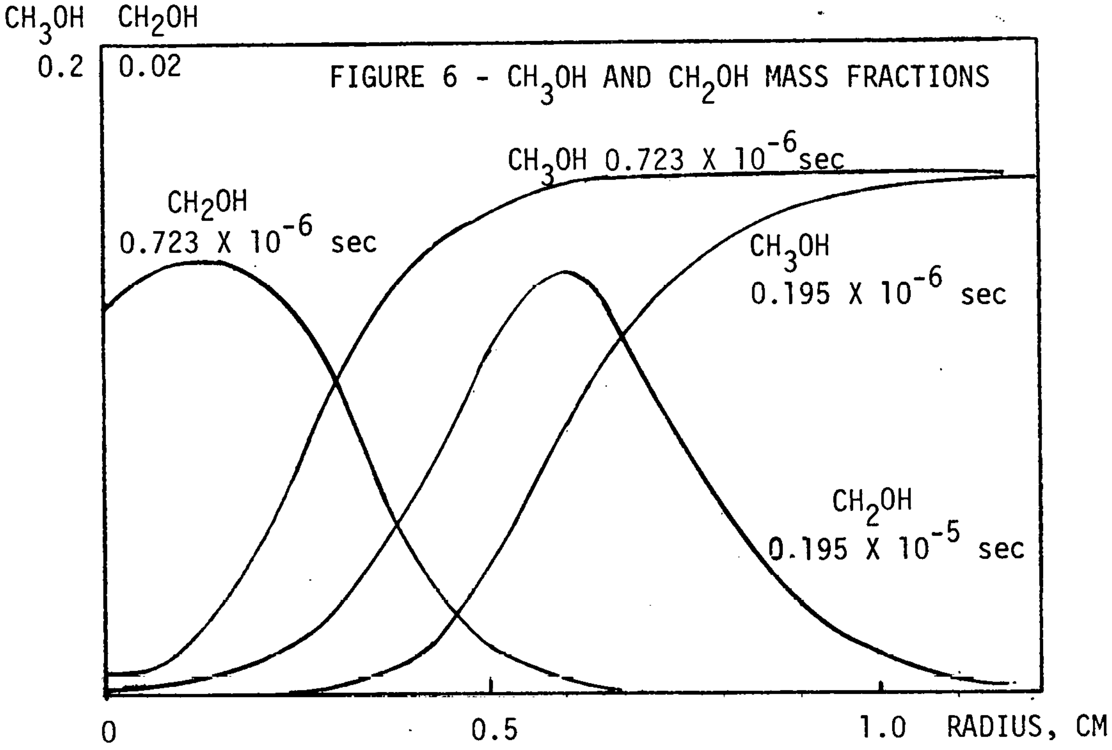
FIGURE 6 - CH_3OH AND CH_2OH MASS FRACTIONS

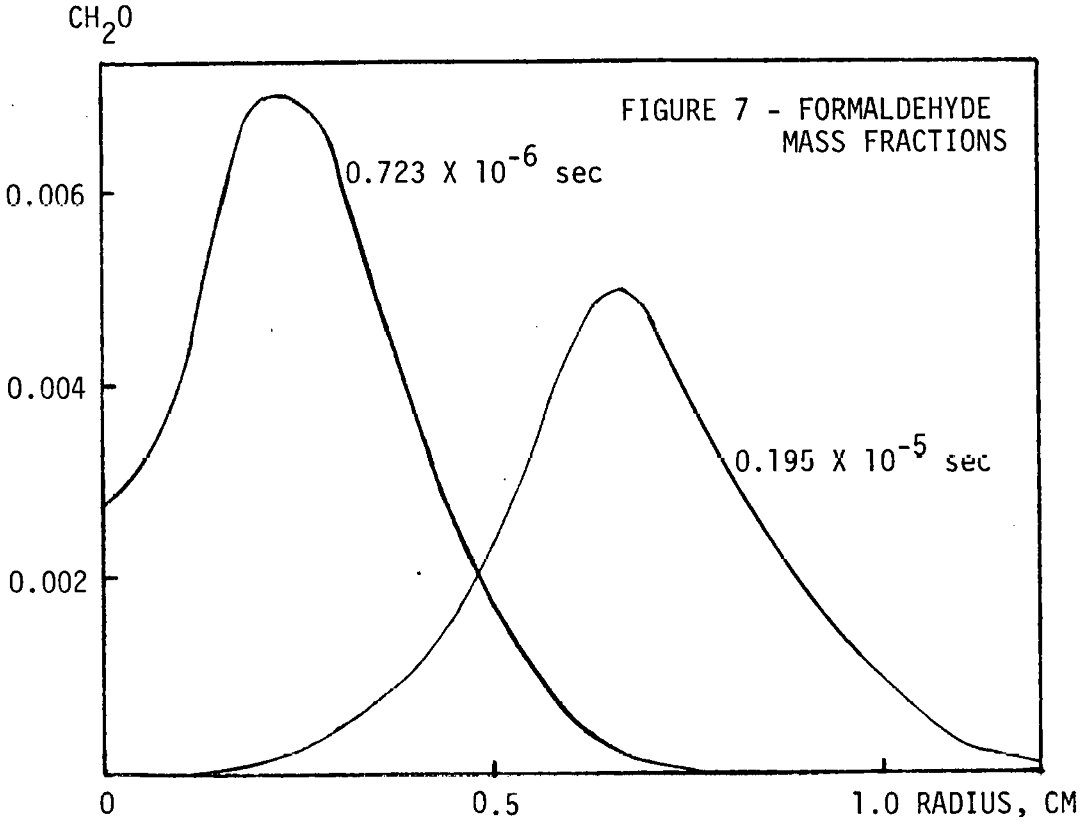
FIGURE 7 - FORMALDEHYDE MASS FRACTIONS

TABLE 1

	REACTION	RATE COEFFICIENT
1.	$H_2 + OH \rightarrow H_2O + H$	$11.4434 \times 10^{8} T^{1.3} \exp(-1825/T)$
2.	$O + H_2 \rightarrow OH + H$	$1.807 \times 10^{10} T \exp(-4480/T)$
3.	$H + O_2 \rightarrow OH + O$	$14.45 \times 10^{13} \exp(-8250/T)$
4.	$OH + OH \rightarrow H_2O + O$	$6.023 \times 10^{12} \exp(-550/T)$
5.	$H + HO_2 \rightarrow OH + OH$	$2.4092 \times 10^{14} \exp(-950/T)$
6.	$H + O_2 + M \rightarrow HO_2 + M$	$7.2545 \times 10^{15} \exp(-500/T)$
7.	$NO + NO \rightarrow N_2O + O$	$13.2506 \times 10^{11} \exp(-32100/T)$
8.	$N_2O + H \rightarrow N_2 + OH$	$7.83 \times 10^{13} \exp(-7600/T)$
9.	$N_2 + O \rightarrow NO + N$	$1.3 \times 10^{13} \exp(-38000/T)$
10.	$N + O_2 \rightarrow NO + O$	$6.6253 \times 10^{9} T \exp(-3150/T)$
11.	$CO + OH \rightarrow CO_2 + H$	$1.6864 \times 10^{7} T^{1.3} \exp(330/T)$
12.	$CHO + OH \rightarrow CO + H_2O$	6.023×10^{12}
13.	$CH_2O + OH \rightarrow CHO + H_2O$	$6.023 \times 10^{13} \exp(-500/T)$
14.	$CH_3 + O \rightarrow CH_2O + H$	$6.023 \times 10^{13} \exp(-500/T)$
15.	$CH_4 + OH \rightarrow CH_3 + H_2O$	$3.0115 \times 10^{13} \exp(-2500/T)$
16.	$CH_2O + M \rightarrow CHO + H + M$	$1.0 \times 10^{14} \exp(-18500/T)$
17.	$CH_2OH \rightarrow CH_2O + H$	$3 \times 10^{9} \exp(-14600/T)$
18.	$OH + CH_3OH \rightarrow CH_2OH + H_2O$	$3.0 \times 10^{13} \exp(-3000/T)$
19.	$H + CH_3OH \rightarrow CH_3 + H_2O$	$1.3 \times 10^{13} \exp(-2670/T)$
20.	$O + CH_3OH \rightarrow CH_2OH + OH$	$1.7 \times 10^{12} \exp(-1150/T)$
21.	$CH_3OH + M \rightarrow CH_3 + OH + M$	$4.0 \times 10^{15} \exp(-34200/T)$
22.	$CHO + M \rightarrow CO + H + M$	$5 \times 10^{14} \exp(-9570/T)$

Units: cc, mole, sec

Rate coefficients for equations 1-15 are from [11] and those for equations 16-22 are from [9].

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MODIFICATION OF A FORD PINTO FOR OPERATION ON METHANOL

by

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INTRODUCTION

In January of 1978 a program was initiated by the Legislature of the State of California to demonstrate that a conventional automobile can be operated on 100 percent synthetic fuel and synthetic lubricating oils. Methanol was the synthetic fuel of choice since it is well-established as an internal combustion (IC) engine fuel in high performance applications, and it has the potential of being manufactured from a wide variety of renewable resources which are totally independent of the availability of petroleum crude oil and natural gas. Methanol has also shown the potential for low emission levels of pollutants and high engine efficiency, both of which result in additional energy savings. Finally, substitution of a liquid synthetic fuel in energy systems presently dependent on liquid fossil fuels, such as the IC engine, offers minimal disruption of the distribution network and transportation sector.

Since technology presently exists for the synthesis of methanol from coal, and recognizing the favorable economics if the small percentage of higher order alcohols produced in this synthesis process do not need to be removed, an alcohol mixture that was primarily methanol (90%) was used as the engine fuel in this program. It is referred to as methanol-X.

VEHICLE SELECTION/SPECIFICATIONS

A 1978 Ford Pinto was chosen for this demonstration program because it is considered to be a typical example of a high-volume production, low-priced, American-made vehicle, and representative of the car and engine of the near future as each year's models shrink in size. The reliability of its 2.3-liter engine had been well demonstrated by virtue of the number in service for several years already. Confidence in its ruggedness was further reinforced when it was learned that this engine was soon to be available in a turbocharged version. The selection was further biased by the fact that researchers at the University of Santa Clara were also working with this engine, and some of the design modifications and components selected could be shared.

The station wagon model was selected, primarily because it provided additional space for carrying test equipment. The vehicle was ordered fully equipped, with air-conditioning and automatic transmission, even though such options tend to lower performance. These options are very popular with the car-buying public, and one of the goals of the program was to demonstrate that a methanol-fueled vehicle would have better driveability than the equivalent gasoline version while still meeting the emission and fuel economy requirements. To better illustrate this point, two identical vehicles were ordered, with one modified to operate on methanol, while the other one remained as delivered from the factory.

Because less than two months was allowed between date of delivery of the new vehicles and the date specified for delivery of a fully-operational methanol version back to Sacramento (June 1, 1978), a short block and complete cylinder head were ordered from the factory also. This shortened the "down-time" of the vehicle considerably. Some of the major component changes were made to this short/block cylinder head assembly prior to dismantling the vehicle. The vehicle engine was then removed and replaced with the previously prepared assembly, along with the necessary accessories such as starter, distributor, etc. from the original engine.

MAJOR ENGINE CHANGES

Three major engine changes were made: the compression ratio was increased, the peak engine torque was shifted, and the fuel feed system was optimized for use with methanol.

Compression Ratio Increase

Since the efficiency of an engine increases with increase in compression ratio, and methanol has a high octane rating, being about 109 (1)*, which allows knock-free operation even at high compression pressures, the compression ratio (CR) of the engine was increased from its stock configuration of 9:1 to almost 14:1, which theoretically yields an efficiency increase of about 7% based on CR changes alone.

Some consideration was given to milling the cylinder head in order to increase the compression ratio, but the most that could be taken off without compromising the structural integrity was about 0.060 inches, which only increases the CR to 10:1. Also, at high CR, valve to piston clearance becomes a problem and Ford engineers did not recommend "pocketing" the production pistons to provide valve relief as they felt it could impair the dome thickness.

Previous studies have shown that increases in NO_x emissions with increase in CR can be avoided if the proper surface to volume ratio (S/V) of the combustion chamber is maintained(2). Therefore, it was decided to increase the CR with a piston change, where the S/V ratio could be controlled and valve clearance provided for by having the pistons custom-made. The specifications for the piston design were provided by the University of Santa Clara based on their engine modeling studies, and the camshaft timing and lift. The maximum CR that could be achieved, based on these specifications, was 13.9:1.

The pistons were made by a company that specializes in high performance racing pistons and therefore they were designed

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*Numbers in brackets (1) designate References at end of paper.

to accommodate a full floating wrist pin. The stock Ford configuration for the rod placement on the pin was maintained, however. Also, the pistons do not have an off-set pin, since racers are not concerned with piston "slap". The aluminum alloy used to make the forging required a piston to cylinder wall clearance of 0.005 inches, which is more than the production piston requirement, but neither of these deviations caused any discernible problems.

The pistons as delivered by the manufacturer were considered to have too many sharp edges from the extensive machining required to produce them, so they were smoothed with a grinder. Otherwise these would have been ideal sites for the inducement of pre-ignition. The amount of material that had to be removed was not sufficient to have any real effect on the CR, however.

The piston rings used included a "gapless" ring in the second compression groove. This ring is really a two-piece ring; one ring is machined with a step to accommodate a thin "rail" whose gap is placed 180 degrees from that of the primary ring. Unfortunately, no quantitative data are available showing the increase, if any, in compression pressure since these pistons have not been used with conventional rings. In fact, it proved to be impossible to measure the compression pressure at all because the highest available compression gage had a maximum reading of 300 psi and it showed that the final engine configuration had a compression pressure higher than this. A diesel engine compression gage could be used, however, if the engine/gage coupling were properly modified.

At the same time that the short block was fitted with the new pistons and rings, it was completely "blueprinted"* and balanced by a shop specializing in machining for racing applications. This brings everything within much closer tolerances than a production item can be. This was done primarily to insure that if any problems developed at a later time, they could be identified as attributable to the modifications made and not production deviations.

The stock head gasket (0.043 in.) was replaced with a custom-made, high-performance, copper gasket (0.030 in.). The cylinder head bolts were torqued to 105 lb-ft.

Engine Peak Torque Shift

A camshaft was installed which had a profile that shifted the peak torque of the engine to a lower engine speed (~2300 rpm) which falls on the torque converter stall curve. The net torque increase (at the flywheel) resulting from the change in CR and shift in peak torque to the stall curve was estimated to be about 18%. These changes resulted in an increase in performance at low speed without sacrificing top end power. Figure 1 shows the estimated change in torque due to the increase in CR

Check and adjustment if required of all clearances for bearings, crankshaft, rods, pistons, etc.

and change in camshaft.

The net valve lift of the camshaft is 0.386 inches, the valve duration is 280° (crank angle) and the valve overlap is 60°. The camshaft was timed with solid lifters in #1 cylinder, using a dial indicator to measure the lift, as shown in Figure 2(a). A specially-manufactured, multiple-piece cam sprochet was used, which provided infinitely variable camshaft timing by the use of slotted holes and set screws, as shown in Figure 2(b). The final cam timing was just slightly in advance of the manufacturer's specifications. For example, at 0.005 inches of lift on the intake valve, the crank angle was 9.5°BTC instead of 8°. At 59°BBC, the exhaust valve lift was measured to be 0.0016 inches instead of the 0.001 inches specified in the cam profile data. Table I gives the lift as a function of crank angle, as measured with the dial indicator, for both the intake and exhaust valve.

TABLE I

Valve Lift as a Function of Crank Angle

Crank Angle (°BTC)	Intake Valve Lift (inches)	Crank Angle (°BBC)	Exhaust Valve Lift (inches)
29	0	62	0.0004
24	0.0002	59	0.0016
15	0.0030	19	0.0744
12	0.0040		
9.5	0.0050		
TDC	0.0126		

Fuel Feed System

Methanol has a high latent heat of vaporization which makes it more difficult to vaporize in an engine than gasoline. Therefore, it was decided to use a fuel injection system which provides fine atomization of the fuel. A six-cylinder, in-line fuel injection pump (Robert Bosch) was modified to four-cylinder operation by installation of a custom-made injection pump camshaft with four lobes, instead of six, with the two center elements inoperative. The camshaft timing in the pump is 1-2-4-3, while the engine firing order is 1-3-4-2. The pump elements were changed from 7 mm to 9 mm units in order to provide the volume of flow required for operation on methanol.

This is a timed fuel injection system with the pump timing set at 60°ATC on the intake stroke; i.e., the fuel flow shuts off at 60°ATC. The pump is synchronized with the crankshaft and camshaft by driving it off the engine with a timing belt (345L075).

An intake manifold was fabricated to accommodate the injection of fuel at the valve. The basic design of the manifold is a large plenum chamber, or log, common to four individual pipes leading to the intake ports. The injection nozzles were positioned in the pipes to spray on the valves. The nozzle opening pressure is 250 psi which results in fine atomization of the fuel.

The air intake is through a filter at the opening of the mixture controller (which houses the throttle plate), which is fitted to one end of the intake manifold log. These components can be partially seen in Figure 2(a). The jets in the mixture controller are changeable for both the idle and partial load, while full load is controlled by the setting of the fuel injection pump "rack". Calibration of the pump was accomplished on a Bosch test bench, which can be seen in Figure 2(c). Note the caps on the two center elements that are inoperative.

Initially, the jets in the mixture controller were 240 and 260 for idle and partial load, respectively, but they have since been changed several times to progressively leaner mixtures in order to bring the hydrocarbons (HC) and carbon monoxide (CO) emissions into the desired range, and to improve fuel consumption. The current configuration is operating successfully with jets of 100 and 130 for idle and partial load, respectively.

In order to calibrate the fuel injection pump for the modified engine configuration, an engine map of intake manifold pressure versus engine speed and load was required. Therefore, when all of the hardware changes had been made, except for the fuel system, the engine was refitted with the stock intake manifold and carburetor and the vehicle was operated on methanol while taking manifold pressure readings at different engine speeds and loads. The loads were varied by driving up and down hills, or on level road. The approach was rather "crude", but the data thus obtained were sufficient for pump calibration.

The carburetor was modified to operate on methanol by changing the jets to larger sizes. Table II gives the jet sizes used for methanol operation.

TABLE II

Jets for Methanol Operation of Pinto with OEM Carburetor

Circuit	Primary (inches)	Secondary (inches)
Main	0.074	0.066
Idle	0.070	0.041
Air Bleed	blocked off	0.066

After calibration of the pump, the fuel injection system was installed. The fuel pump opening at the engine block was closed with a plate. An electric fuel pump was installed at the tank, with a fuel filter placed between the electric pump and the injection pump. The line that originally had been used to return the vapors from the carburetor to the fuel tank was used for the fuel injection system return line.

OTHER HARDWARE MODIFICATIONS/INSTRUMENTATION

Spark plugs with a colder heat range (Champion BN-6Y) were installed. The vacuum advance on the distributor was disconnected and the ignition timing set at 25°BTC maximum. Initially, the ignition timing was set at 30°, but this resulted in engine knock under load. The distributor was determined to have 19 degrees of centrifugal advance so the idle setting is 6°BTC.

The alternator had to be moved to the right side of the engine in order to make room for the fuel injection pump on the left side. Brackets to mount the alternator were bolted to the engine block at the air conditioning unit. The modified position requires an alternator belt 47-3/4 inches in length. The completed engine installation can be seen from both sides in Figures 2(d) and 2(e).

The stock exhaust manifold was replaced with four exhaust pipes leading to one collector. Thermocouples were installed in each exhaust pipe, with four pyrometers installed in the dash for exhaust temperature readout. (Pyrometer #2 was observed to read 50°F higher at ambient temperature than the other three.) The bosses used for the thermocouples can also be used for exhaust emission probes if readings from each cylinder are desired.

Other instrumentation included an electric tachometer and an onboard exhaust gas analyzer for CO and HC. A locking gas cap completed the initial hardware changes.

PERFORMANCE

Driveability

The overall performance of the methanol car has been rated as excellent, with smooth idle and quick throttle response in comparison to the gasoline version. The increase in horsepower is quite evident, with a marked difference in the acceleration rate between the two vehicles. The methanol car did develop a problem almost immediately, however, where periodically it would act as if the fuel pump were failing. Investigation revealed that the terne plate from the fuel tank was dissolving and clogging up the filter screen in the tank, the internal filter in the electric pump and the primary in-line fuel filter. In fact, the pump had to be replaced when the key for the pump impeller sheared because of the heavy "lead" build-up in the pump which caused a great deal of "drag". Eventually the problem resolved itself when the terne plating was in essence gone.

Since the lubrication quality of methanol is poor, even though the fuel injection pump has its own oil sump, there was a noticeable "tappet-like" noise emitted by the injection pump. Therefore, one percent of diesel fuel was added to the methanol-X in order to protect the fuel injection pump. It subsequently operated much quieter.

For engine break-in and seating of the rings, a non-detergent lubricating oil was used in the engine. After delivery of the vehicle to Sacramento (~500 miles), it was drained and replaced with a synthetic motor oil.

Cold Start

The initial testing of the vehicle began in June of 1978 so no cold start problems were encountered until the following winter. Between temperatures of 40°F to 110°F, cold start would require about 10 to 20 seconds. Once the engine had been started, restart only required 1 to 2 seconds. These cold start tests were conducted from sea level to 8,000 feet. When winter arrived, however, the time required for cold start when the temperature was below freezing was considered unacceptable, so a small propane tank was added to the system. A small amount of propane could be released into the manifold with a switch installed in the driver's compartment. With this system the engine fires easily. In fact, the starting time is actually less than that of the gasoline-burning vehicle at the same ambient temperature.

Fuel Economy

The initial fuel consumption was quite high since the mixture controller was jetted for a fuel-rich mixture. With the 240 and 260 jets, the mileage was slightly less than 9 mpg. The fuel consumption was reduced considerably when smaller jets were installed, and yet there was no noticeable loss in performance. The present air-fuel ratio gives excellent fuel economy, ranging between 14 and 15 mpg, which is about 28 to 30 mpg gasoline equivalent. The fuel economy of the gasoline version is quite a bit lower, being about 21 mpg. To date, no FTP mileage figures are available.

Emissions

The methanol vehicle was tested for emissions at the University of Santa Clara shortly after delivery to Sacramento. Since the air-fuel ratio was quite fuel-rich, the HC and CO were much higher than desirable, being 1.03 and 25 gms/mi, respectively, but the oxides of nitrogen were extremely low, at 0.28 gms/mi. These initial emission tests showed that some compromises in performance and NO$_x$ emission levels would have to be made in order to bring the HC and CO within the 1980 standards. The NO$_x$ emissions were so low, however, that large changes in the air-fuel ratio could be made, to leaner mixtures, without exceeding the 1980 NO$_x$ standard.

Since the initial testing at the University of Santa Clara, the emission levels have been measured with the onboard exhaust gas analyzer. Some typical emission levels for CO and HC obtained while driving down the road are given in Table III.

TABLE III

Emission Levels for Methanol Vehicle

Driving Mode	CO (%)	HC (ppm)
acceleration	0.1-0.4	0-200
cruise	0.2	150-500
50-60 mph cruise	0-0.01	50

While these results cannot be considered to be very precise, they do show that the emissions from methanol combustion in an IC engine can be quite low, even without any external control devices. The high compression ratio, combined with the ability of methanol to burn successfully at an equivalence ratio leaner than that of gasoline, results in low emission levels for the CO quite analogous to those found in diesel engines. The HC emissions are the most difficult to control when operating on methanol. If a catalytic converter were used, however, the HC emissions would be quite low also. The NO_x emissions from methanol combustion are well-known to be low (3).

10,000 MILE ENGINE INSPECTION

At about 10,000 miles, a coolant hose burst and the engine was severely overheated when driven for about 20 minutes without any coolant. This resulted in some problems that would not have occurred otherwise, but the same conditions probably would have completely destroyed a gasoline-burning engine. Fortunately, methanol engines tend to operate cooler, so that the resulting damage was really quite minimal.

The extreme heat caused the head gasket to leak, allowing coolant to pass into the cylinders. This resulted in hydraulic hammering on the tops of the pistons. The high temperature and hammering made the pistons start to "sag". #1 cylinder was the worse, with the top ring land collapsed on the ring in two places. There was some deposition of piston material on the cylinder wall at these locations, but no actual scoring of the cylinder wall was found. There was some piston skirt scuffing, but it was quite minimal.

All of the bearings were still in excellent condition in spite of the fact that the engine oil seemed to be diluted with coolant and/or fuel, and was severely "burnt". It was quite thin and had an odor like gun cleaner. It has been sent out to be analyzed. The degradation in the quality of the lubricant was most evident on the camshaft lobes and bearings, but not severe enough to require replacement of these parts.

The pistons and rings were the only components replaced, primarily because of the collapsed ring land and the water hammer marks. The latter had sharp edges which could have resulte in pre-ignition problems.

The thin copper head gasket was replaced with a stock Ford head gasket produced for the turbocharged version of the 2.3-liter engine, since it is designed for high cylinder pressures also.

It is believed that if the engine had not lost its coolant, it would have been found to be in excellent condition. Performance had been extremely good and consistent up to this point. Hopefully, the next inspection will be made under more favorable conditions so that a proper evaluation can be made.

POSSIBLE DESIGN CHANGES FOR THE FUTURE

Vehicles modified to operate on methanol in the future should have their fuel tank removed and stripped of the terne plating. There are alternative coatings for protecting the inside of the tank, such as epoxies, which would not be dissolved by the methanol. Or the tank itself could be fabricated out of a material impervious to methanol.

The fuel injection system used for this demonstration vehicle provided excellent performance and low emissions, but it is no longer in production and has a relatively high cost. Therefore, the next fuel injection system will be a current production model. Since today's systems all inject at relatively low pressures, some loss in performance may result, especially for cold start, although other researchers have not found marked improvements in cold start behaviour with fully atomized fuel(4). Since the cold start problem has to be addressed for temperatures below freezing regardless, lower pressure injection should not be a serious compromise. The need for adding one percent diesel fuel would be eliminated also.

Rather than using a propane system for cold start, it is proposed to use heaters to evaporate a small quantity of the methanol instead. For extremely cold climates, a block heater is available for this engine.

While the internal parts of the electric fuel pump that were aluminum showed only slight corrosion after several thousand miles of operation, it is believed that the lifetime of this pump would be increased if the aluminum parts were anodized.

Further evaluation of the suitability of synthetic oil for use with methanol is being made. With some injection systems, dilution of the oil with fuel could exclude the advantage of increased mileage between oil drains. While methanol is not supposed to be miscible with engine oil, there is some evidence that it does mix with synthetic oil, at least under high temperature conditions.

Several different mixtures of methanol-X were tested, using ethanol, iso-butanol and n-propanol in varying amounts, but in all cases the methanol content was at least 90% by volume. No problems were observed with these various fuel formulations, so it was concluded that fuel-grade methanol is a ractical fuel for IC engines of the future.

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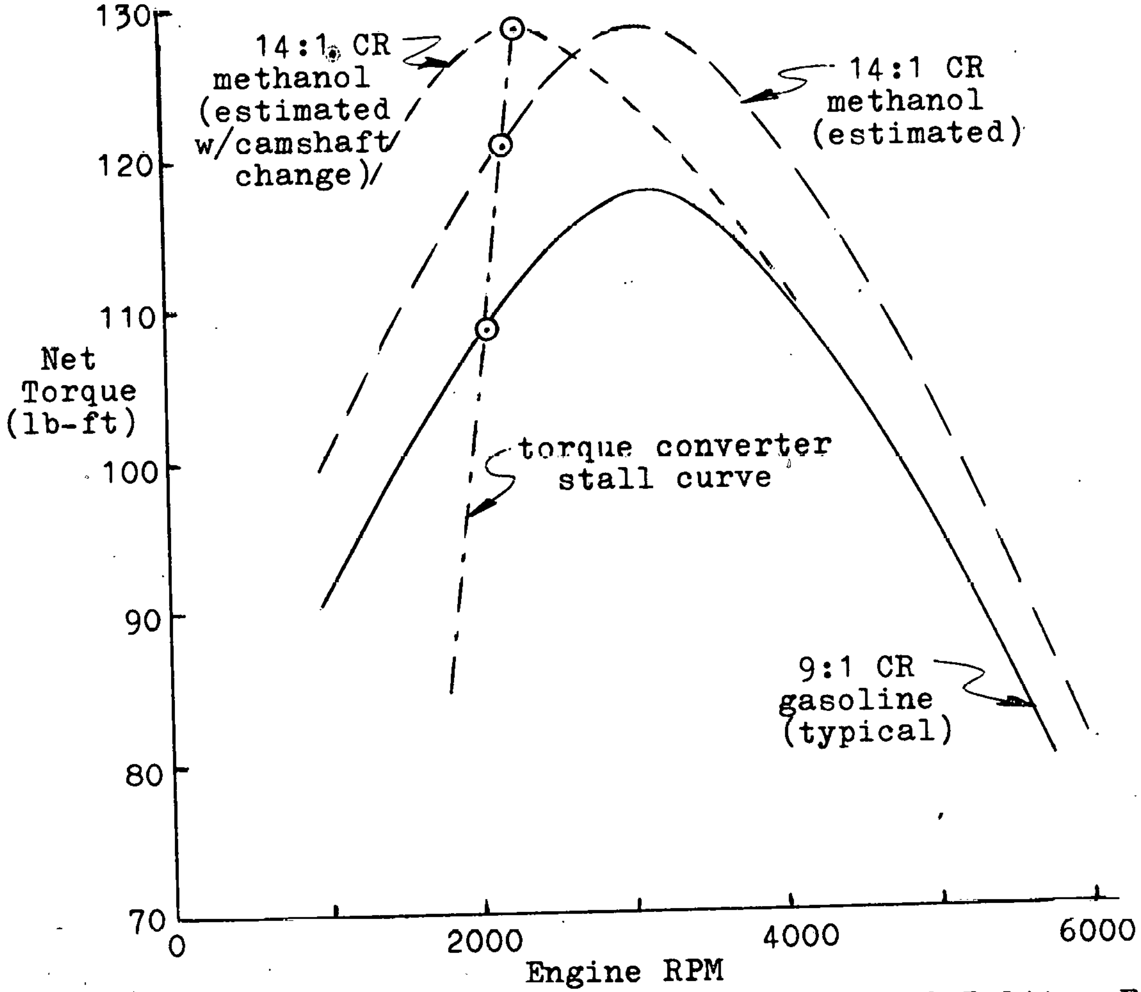

FIGURE 1. Increase and Shift in Peak Torque for 2.3-liter Engi

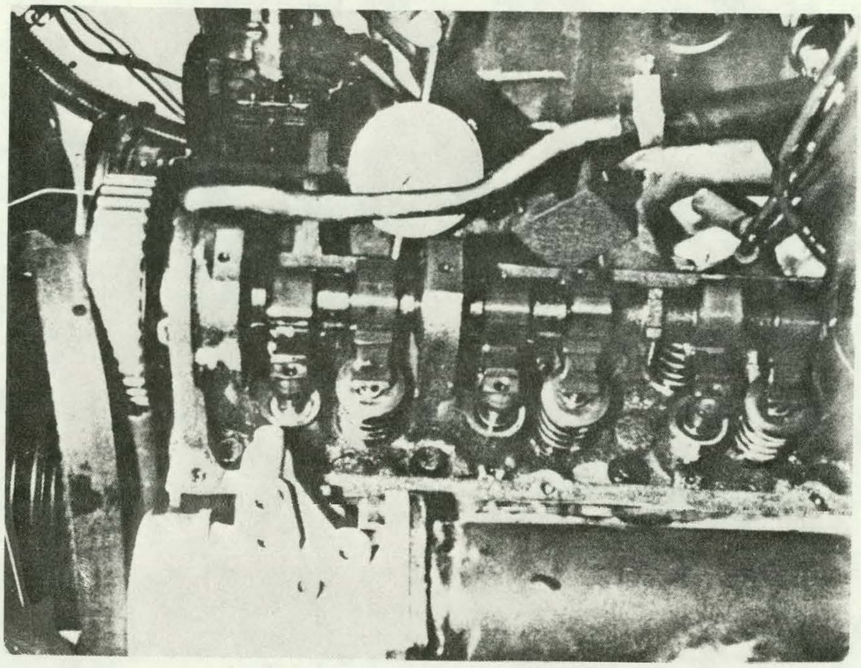

FIGURE 2(a). Timing the Camshaft by Measuring Valve Lift as Function of Crank Angle

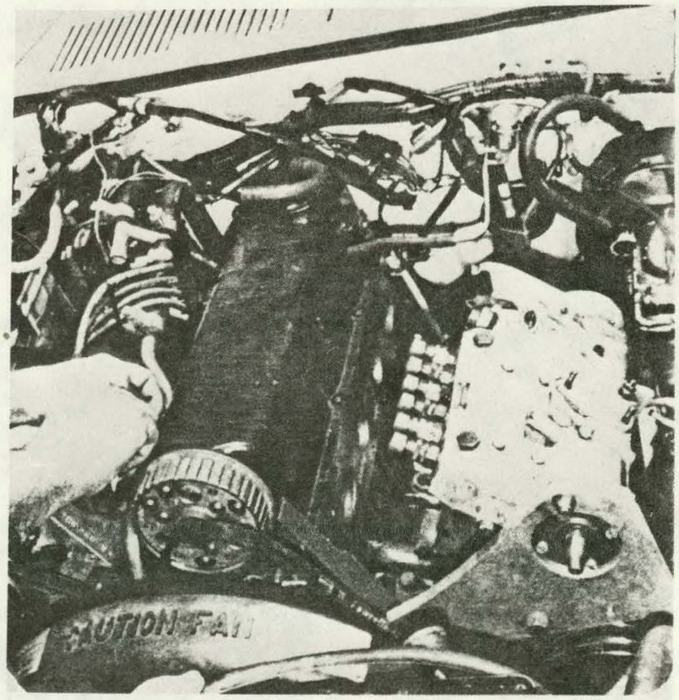

FIGURE 2(b). Cam Sprochet with Infinitely Variable Timing

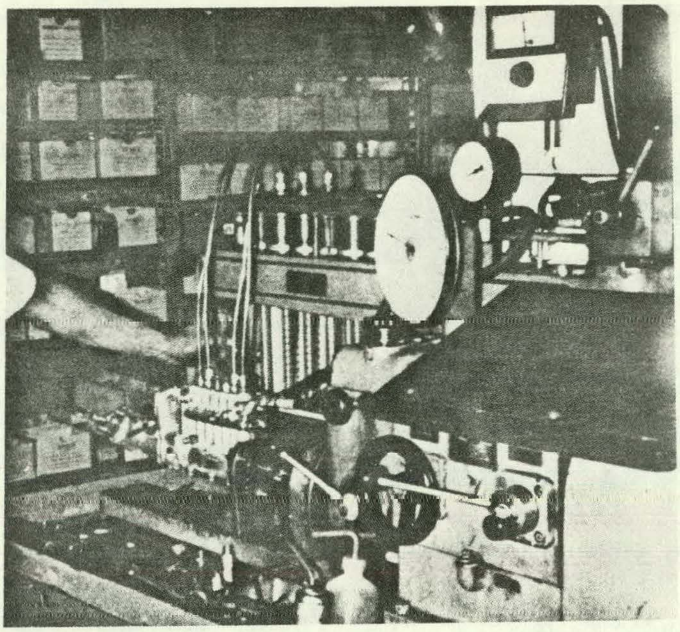

FIGURE 2(c). Calibration of Injection Pump

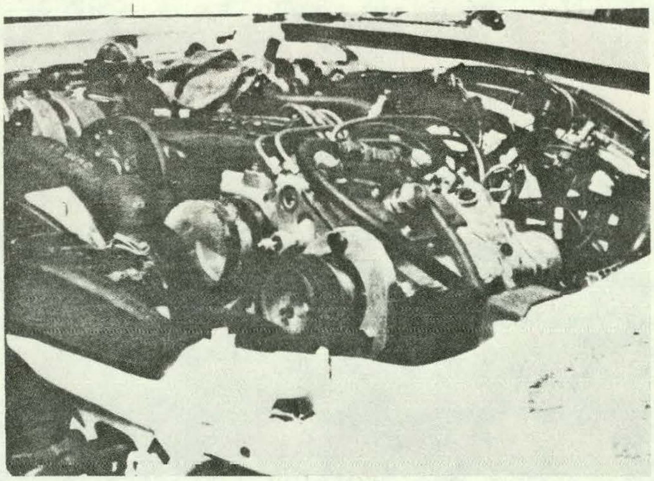

FIGURE 2(d). Completed Engine Installation; Left

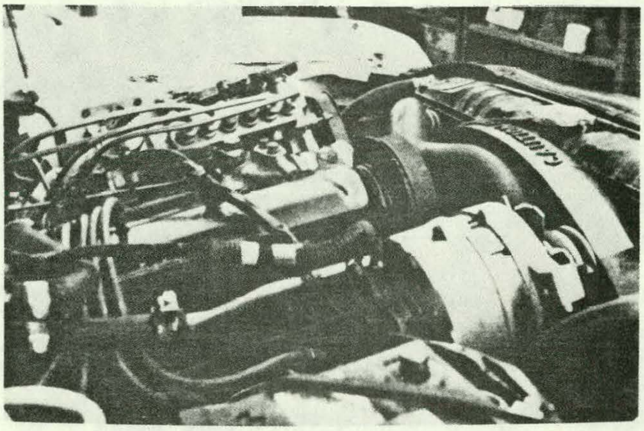

FIGURE 2(e). Completed Engine Installation; Right

THERMOKINETIC MODELING OF METHANOL COMBUSTION PHENOMENA WITH APPLICATION TO SPARK IGNITION ENGINES

by

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ABSTRACT

Two variations of a thermokinetic computer model were used to investigate the flame quenching and surface ignition phenomena occurring in methanol fueled SI engines. Both model variations produce reasonable trends when compared to the literature. Use of a detailed reaction mechanism in the quench zone model has shown aldehydes to increase an order of magnitude over bulk gas concentrations as the flame quenches, but this concentration is insufficient to account for measured exhaust aldehydes. A flow reactor study has shown additional aldehydes being formed from the unburned quench layer when it mixes with the hot exhaust gases during the expansion and exhaust strokes.

Quenching distance was found to decrease for increasing pressure and increasing wall temperature, while it increased for lean and very rich equivalence ratios and increasing EGR. Water addition showed only a slight increase in quenching distance for up to 30% of the fuel by volume.

Use of the detailed kinetic mechanism in the surface ignition model showed that methanol is dissociated at hot surfaces through formaldehyde to carbon monoxide and hydrogen. The hydrogen then dissociates into various radical species which trigger preignition and early combustion. Sensitivity studies show that hot surface temperature, assumed to be at the spark plug center electrode, is the most dominant physical parameter in the surface ignition process, while cylinder pressure and spark plug tip cooling played somewhat weaker roles. Equivalence ratio and use of diluents such as EGR and water addition had only slight effects on the likelihood of surface ignition.

INTRODUCTION

Methanol has been shown to increase thermal efficiency and power while reducing harmful exhaust emissions, with the exception of aldehydes, in spark ignition (SI) engines [1,2]*. Although aldehydes are classed as unregulated emissions, methanol fueled SI engines produce 2 to 10 times higher aldehyde emissions than a gasoline fueled SI engine [1]. Hence it is desirable to suppress their output from an otherwise relatively clean exhaust.

Earlier computer studies [3,4] have shown practically no formaldehyde present in the bulk combusted gases. Since formaldehyde is a product of slow oxidation of methanol, it is expected that formaldehyde

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*Numbers in brackets designate References at end of paper.

emissions are formed as the flame extinguishes against the cool cylinder walls and from the unburned quench gases as they are removed from the cylinder walls and mixed with the hot exhaust gases during the expansion and exhaust strokes. Study of aldehyde formation and flame quenching processes in methanol fueled SI engines is accomplished through the use of a detailed kinetic reaction mechanism and quench zone conservation equations. The concept and results are summerized in this paper.

Anothercombustion phenomenon summerized in this paper is the ignition of methanol-air mixtures at hot surfaces. While methanol has a high octane rating making it applicable to high compression ratio engines, high load conditions may heat the center electrode of the spark plug sufficiently to cause preignition (ignition of the unburned mixture prior to spark firing). Experimental engine studies in our laboratory have shown methanol to be more resistant than gasoline to knocking, yet it has preignited by what arebelieved to be lower surface temperatures than gasoline. Literature sources also show methanol to have a comparatively lower surface ignition temperature than gasoline [5,6]. While methanol's relatively longer ignition delay, lower flame temperature and faster burning velocity [6] are known to reduce the probability of autoignition (knocking), the details of surface ignition of methanol are not as well understood. In order to study the surface ignition process for methanol and find methods of controlling it, a detailed chemical reaction mechanism has been coupled with the surface ignition conservation equations.

I. QUENCH ZONE MODEL

The quench zone model, described in detail in Reference 7, consists of a quasi-one-dimensional flame propagation model in the presence of a cold wall. In the model, a reaction zone of finite mass moves through the unburned gas towards the cold wall at a calculated flame speed. Species concentrations within this reaction zone are determined by a detailed chemical kinetics reaction mechanism consisting of 94 reaction rate equations describing methanol-air combustion [7].

Heat loss to the cold wall is calculated as pure conductive heat transfer. The wall is considered to be chemically inert and at constant temperature. The initial conditions are set at the adiabatic stabilized conditions 1 cm from the cold wall. The reaction zone then moves towards the wall at finite but small and adjustable spatial increments until the calculated flame speed drops to zero. A schematic of this quench zone model is shown in Figure 1.

The model's conductive heat transfer coefficient in the heat loss equation was tuned to match experimental quenching distances at 1 and 27 atmospheres. It was found to closely approximate the thermal conductivity of the unburned gases. Experimental quenching distances used in this paper were taken from a study by Ishikawa and Branch [8]. All two-plate quenching distances were transformed to head-on quenching distances by using a multiplying factor of 0.4 which is consistent with experimental evidence [9]. As can be seen in Figures 2 and 3, the computer predicted quenching distances match the experimental data for both pressure and equivalence ratio variations.

Typical quench zone model runs show that both hydrocarbons and aldehydes increase an order of magnitude as the flame quenches. Table 1 summerizes the species concentrations in terms of four adjacent zones for stoichiometric mixtures at 1 and 27 atmospheres.

Using the thermodynamic Otto cycle calculations from Reference 4 and the quench zone results presented in this paper, the calculated quench hydrocarbons exceed experimental exhaust concentrations by over 10 times while the calculated flame out zone aldehydes plus the bulk gas aldehydes are approximately 1/12 of the experimental exhaust concentrations as shown in Table 2 for the conditions listed. This tends to support the concept that the hydrocarbons are oxidized as they are removed from the quenching surfaces, forming aldehydes as the oxidation reactions freeze due to rapid expansion through the exhaust valve.

Using a generalized adiabatic flow reactor program [10], the unburned fuel and air from the quench layers were mixed with the bulk combustion gases at 1100°K and 2.5 atmospheres with a gas velocity of 200 cm/sec. At these conditions the unburned methanol is oxidized forming formaldehyde in quantities measured in SI engine exhaust in a flow length easily encountered in an engine cylinder.

Results

Referring back to Figure 2, the quenching distance is seen to decrease as pressure is increased. However, the mass of unburned methanol in the quench zone (plotted in Figures 2-6 as milligrams of methanol per 100 cm^2 surface area) increases as the pressure is increased. These results support the experimental evidence that raising compression ratio results in higher hydrocarbon emissions [11]. Since surface-to-volume ratio increases and the exhaust temperature decreases as compression ratio is raised, the resulting aldehydes are also predicted to increase with increasing compression ratios.

Figure 3 shows the effect of equivalence ratio Φ on quenching distance. Minimum quenching distance occurs at an equivalence ratio of about 1.13 while minimum quench hydrocarbons occur at about 1.02. Measured exhaust hydrocarbons, however are found to continue to decrease reaching a minimum in the lean region [1]. This discrepancy can be explained as follows. Excess oxygen available in both the bulk and quench gases on the lean side, and the higher exhaust temperatures characteristic of lean engine operation, further oxidize the unburned hydrocarbons as the quench layer is removed from the quenching surfaces and mixed with the hot bulk gas. On the rich side, however, very little oxygen is available and exhaust temperatures are lower; therefore, further oxidation of the unburned quench layer is minimal.

This exhaust hydrocarbon trend, however, is modified for exhaust aldehydes. Since aldehydes are intermediate species in methanol oxidation, the excess oxygen and higher exhaust temperatures on the lean side result in high aldehyde exhaust emissions while the lack of oxygen and lower exhaust temperatures on the rich side result in low aldehyde emissions. This predicted trend is supported by experimental findings [1].

Wall temperature, as expected, is seen to have a strong effect on quenching distance and resulting hydrocarbon emissions in Figure 4. As the wall temperature is increased, quenching distance and resulting hydrocarbons decrease. Aldehyde emissions would also tend to decrease as the hydrocarbons decrease, resulting in lower aldehyde emissions for higher wall temperatures.

Use of exhaust gas recirculation (EGR) is a well-known method of reducing NO_x emissions [12]. However, as the amount of recirculation is increased, the quenching distance and resulting hydrocarbons also increase as shown in Figure 5. Because increased EGR decreases overall flame temperatures while increasing burning time, it is anticipated that increased EGR will result in higher aldehyde emissions unless the reduced oxygen concentrations offset these factors.

Water addition is another method of controlling NO_x emissions. Figure 6 shows that quenching distance increases only slightly as water addition is raised to 30% of the fuel volume. Since water addition reduces overall flame temperature without significantly reducing burning velocity it is anticipated that aldehydes will increase only slightly for increasing amounts of water addition.

II. SURFACE IGNITION MODEL

In the introduction it was pointed out that surface ignition must be understood and controlled if high compression alcohol fueled vehicles are to perform successfully. The surface ignition model, described in detail in Reference 13, is a simple thermal ignition model with detailed chemical kinetics. Since methanol is a clean burning fuel, combustion chamber deposits are not present to cause preignition, leaving the center electrode of the spark plug as the most likely cause. The model, shown in schematic form in Figure 7, describes the thermal and chemical behavior of a thin gas sleeve surrounding the hot center electrode of the spark plug. The model assumes that the electrode tip and gas sleeve are at the same temperature, with conductive heat transfer to the surrounding bulk gas only. The chemical composition of the gas sleeve is governed by the methanol oxidation reaction set [7]. Combustion of the gas sleeve, which would lead to preignition, is considered to be when the chemical energy release rate is greater than the heat loss rate to the bulk gas.

While published surface ignition temperatures have ignition delays (time until ignition) of up to 2 minutes or more, a more realistic ignition delay time limit for preignition to occur in an SI engine was estimated to be 10 milliseconds. Thus if the chemical energy release rate exceeds the heat loss rate within 10 msec, preignition is assumed to follow.

There are several factors which influence surface ignition in addition to the surface temperature. They are thought to be compression ratio, equivalence ratio, mixture density and temperature, and diluents. These have been studied parametrically and their effects are summerized in the following section.

Results

In order to understand the preignition process with methanol, one must look at the main reaction intermediates. As shown in Figure 8 for a stoichiometric mixture at 10 atmospheres and an initial center electrode temperature of 1200°K, the methanol dissociates through formaldehyde to carbon monoxide and hydrogen. The hydrogen then breaks down into various atomic and molecular radicals which trigger preigntion and early combustion. Since the heat of dissociation of methanol to carbon monoxide and hydrogen is only 13% of methanol's lower heat of combustion [6] and equilibrium studies show complete dissociation at 600°K and 10 atmospheres [14] it is easily seen why methanol has a comparatively low minimum surface ignition temperature. Note that the primary effect of raising the surface temperature is a shortening of the time scale of Figure 8.

The initial center electrode temperature is found to have an almost hyperbolic effect on ignition delay as shown in Figure 9. This behavior is typical of other fuels [15]. While adiabatic compression studies show methanol to have a significantly longer ignition delay than gasoline at the same conditions, hot plate surface ignition studies show methanol to ignite at a lower surface temperature [6].

Cylinder pressure also has a strong effect on minimum ignition temperature and ignition delay. As shown in Figure 10, as pressure is increased, minimum ignition temperature and ignition delay decrease. This pressure effect on minimum ignition temperature and ignition delay predicted by the model is similar to the experimental effects found for other fuels including gasoline [15]. Therefore, it is easily seen why preignition is more likely to occur in high compression ratio SI engines at high loads.

Equivalence ratio effects on minimum ignition temperature and ignition delay are shown in Figure 11. As the fuel-air mixture is leaned, the minimum ignition temperature and ignition delay increase weakly. This behavior is similar to paraffin hydrocarbons and gasoline, however, methane shows an opposite trend [15]. This opposite trend is also expected to actually occur for liquid methanol. With methanol's relatively high heat of vaporization, the additional fuel vaporization on the rich side of stoichiometric would lower bulk cylinder temperatures and pressures which would more than offset the minimal effect of equivalence ratio only.

Lowering the bulk gas temperature surrounding the gas sleeve increases the heat loss rate and thereby causes an increase in minimum ignition temperature and ignition delay as shown in Figure 12. Therefore, increasing the heat transfer away from the center electrode tip minimizes the occurrence of preignition.

Use of EGR causes a small increase in the minimum ignition temperature and ignition delay as shown in Figure 13. By adding EGR, the oxygen concentration is reduced thereby increasing minimum ignition temperature and ignition delay. This trend is also seen for water vapor addition in Figure 14.

Other physical parameters that effect preignition of methanol which were not studied in this paper include electrode surface area, surface condition and composition, and gas turbulence. A detailed discussion of the effects of these variables on minimum ignition temperature and ignition delay for other fuels can be found in Reference 15.

Conclusions

Two areas of concern dealing with methanol usage in spark ignition engines were studied using different variations of a thermokinetic computer model. The quench zone model variation predicts quench distances which match very well with experimental data. However, calculated SI engine hydrocarbon exhaust emissions are over 10 times higher than those found experimentally while calculated aldehydes are approximately 12 times lower than experimental exhaust concentrations. A flow reactor study shows aldehydes being formed from the unburned quench hydrocarbons when mixed with the hot bulk cylinder exhaust gases. The actual process of quench layer mixing with the bulk combustion gases and resultant oxidation and aldehyde formation during the expansion and exhaust strokes requires further study.

Calculated quench distances were found to increase with decreasing pressure, lean and very rich equivalence ratios, decreasing wall temperatures and increasing EGR. Water addition showed only a slight increase in quenching distance for up to 30% of the fuel by volume.

The surface ignition model variation produced reasonable trends which agreed with the literature for other fuels. The kinetic reaction mechanism showed that methanol is dissociated through formaldehyde to carbon monoxide and hydrogen at a hot surface. Breakdown of the hydrogen forms radical species which then trigger preignition of the bulk gas. Sensitivity studies show hot surface temperature as the most dominant parameter in the surface ignition process, while pressure and heat loss play somewhat weaker roles. Equivalence ratio, EGR and water addition were shown to have only weak effects on minimum ignition temperature.

With the evidence produced in these studies, some conjecture can be made about methanol fueled SI engine design. Engines should be designed with high compression ratios and combustion chamber shapes which minimize quenching surface area to reduce aldehyde and hydrocarbon emissions. Since no fouling is expected, spark plugs can be accurately designed to aid cold starting and minimize the possibility of preignition. Water addition also reduces the possibility of preignition while greatly reducing NOx emissions without loss of power or thermal efficiency [4], and without significantly increasing quenching distances. Thus, methanol-water mixtures need to be studied further as fuels for high compression ratio SI engines.

ACKNOWLEDGEMENTS

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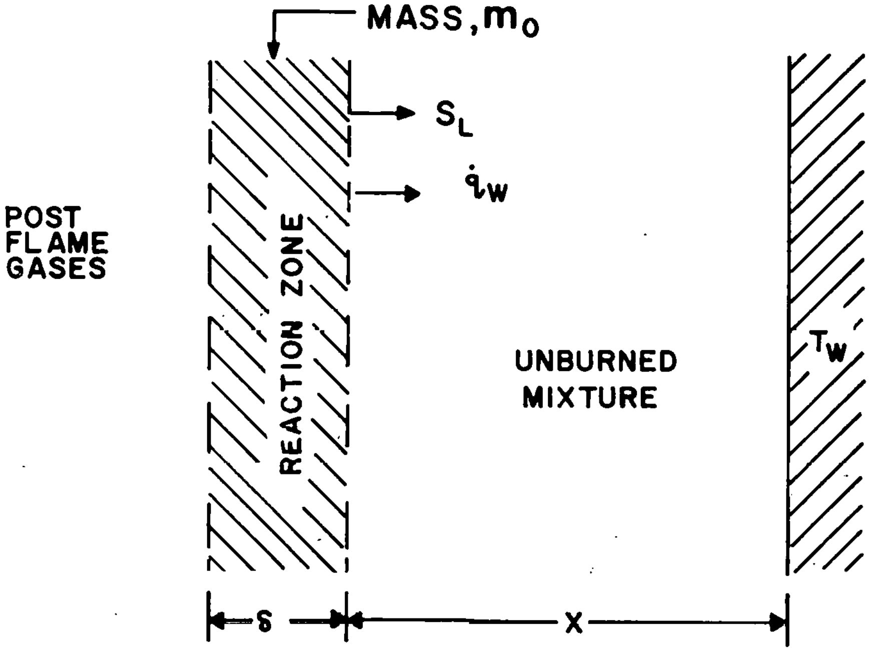

FIGURE 1: QUENCH ZONE MODEL SCHEMATIC

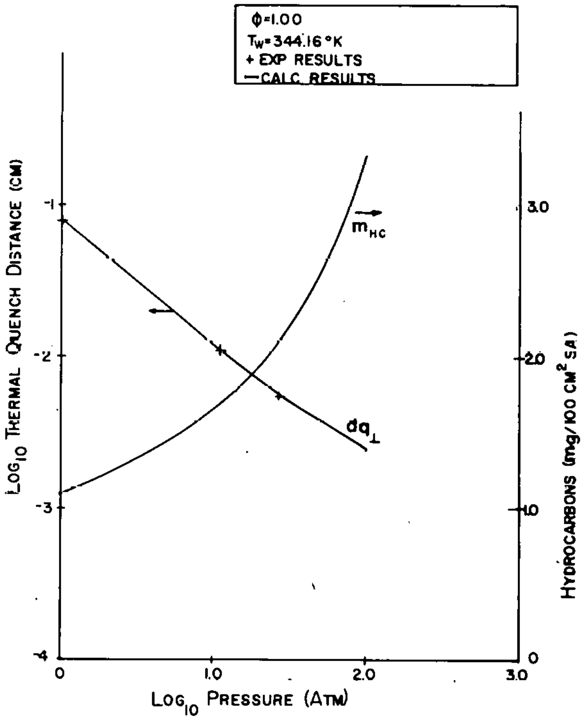

FIGURE 2: PRESSURE EFFECTS ON LAMINAR QUENCH DISTANCE

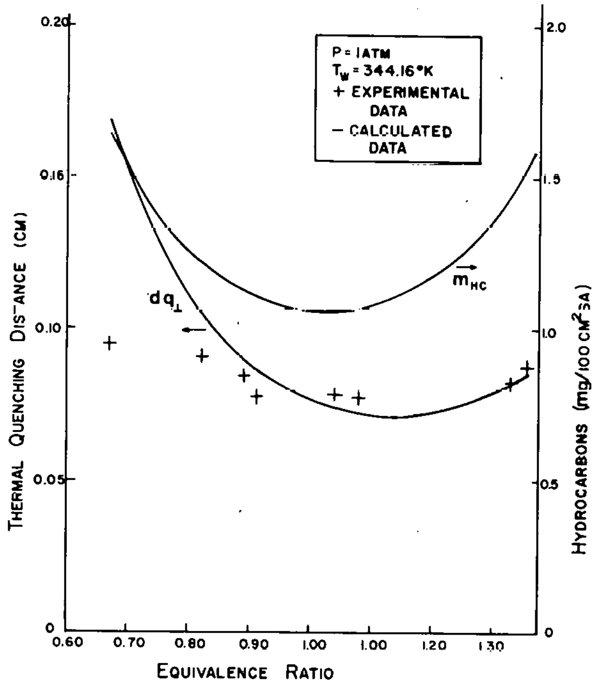

FIGURE 3: EQUIVALENCE RATIO EFFECTS ON LAMINAR QUENCH DISTANCE

TABLE 1: QUENCH ZONE SPECIES CONCENTRATIONS*

	POST FLAME	ADIABATIC REACTION ZONE	FLAME OUT REACTION ZONE	QUENCH ZONE
T, ^oK	2205	1978	344.16	344.16
mo, μg	1000	12.87	12.87	80.8
δ, cm	6.66	0.078	0.013	0.078
Hydrocarbons	(ppm)			
CH_3OH	22.0	1004.	6199.	12.28%
CH_4	2.4	5.0	132.	--
C_2H_6	--	0.01	7.6	--
C_2H_4	--	0.02	6.4	--
C_2H_2	--	0.09	8.2	--
Aldehydes	(ppm)			
CH_3O	--	0.03	--	--
CH_2O	1.8	52.5	602.7	--
HCO·	0.5	14.4	--	--
Nitric Oxides	(ppm)			
NO	52.1	3.6	0.3	--
NO_2	0.2	--	--	--
N_2O	0.3	0.7	0.4	--

*P=1 atm, ϕ = 1.00, T_w = 344.16°K

	POST FLAME	ADIABATIC REACTION ZONE	FLAME OUT REACTION ZONE	QUENCH ZONE
T, ^oK	2297	2082	344.16	344.16
mo, μg	1000	23.7	23.7	155.2
δ, cm	0.255	0.0056	$9.12X10^{-4}$	0.0056
Hydrocarbons	(ppm)			
CH_3OH	55.5	2095.	1.53%	12.28%
CH_4	34.7	70.3	227.	--
C_2H_6	0.05	1.0	1.0	--
C_2H_4	0.04	1.1	4.0	--
C_2H_2	0.01	9.7	3.0	
Aldehydes	(ppm)			
CH_3O	--	0.34	--	--
CH_2O	4.6	84.4	639.7	--
HCO	0.7	19.0	--	--
Nitric Oxides	(ppm)			
NO	62.5	4.3	0.5	--
NO_2	0.09	--	--	--
N_2O	1.0	5.4	2.6	--

*P = 27 atm, ϕ = 1.00, T_w = 344.16°K

TABLE 2: CALCULATED HYDROCARBON AND ALDEHYDE CONCENTRATIONS

ENGINE CONDITIONS

2.3 Liter Ford Pinto Engine Fueled on Methanol at WOT, ϕ=0.900, MBT Spark at 2000 RPM.

PERTINENT EXHAUST DATA

	Measured Engine Exhaust Data	Calculated Data
Hydrocarbons (PPM)	429	5080
Aldehydes (PPM)	177	15

CALCULATED QUENCH HYDROCARBON BREAKDOWN

Head Quench	2660 PPM
Cylinder Wall Quench	280 PPM
Piston Crown Quench	1331 PPM
Ring Crevice Quench	466 PPM
TOTAL QUENCH	4737 PPM

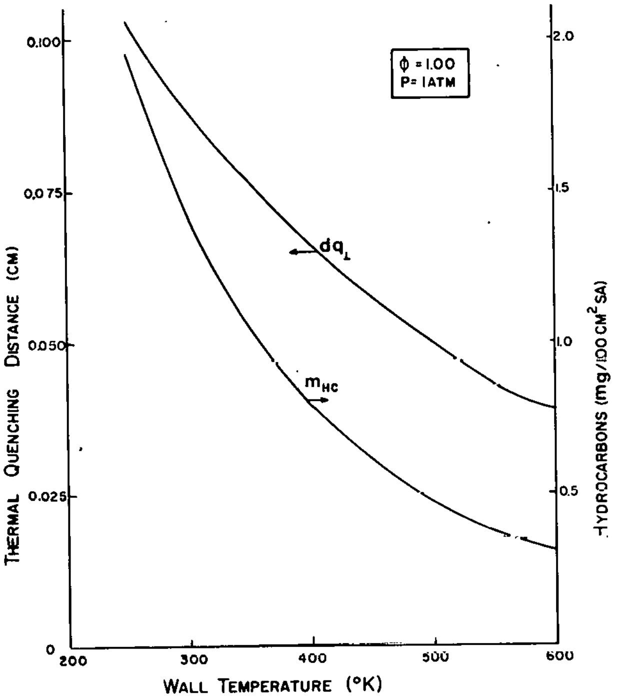

FIGURE 4: WALL TEMPERATURE EFFECTS ON LAMINAR QUENCH DISTANCE

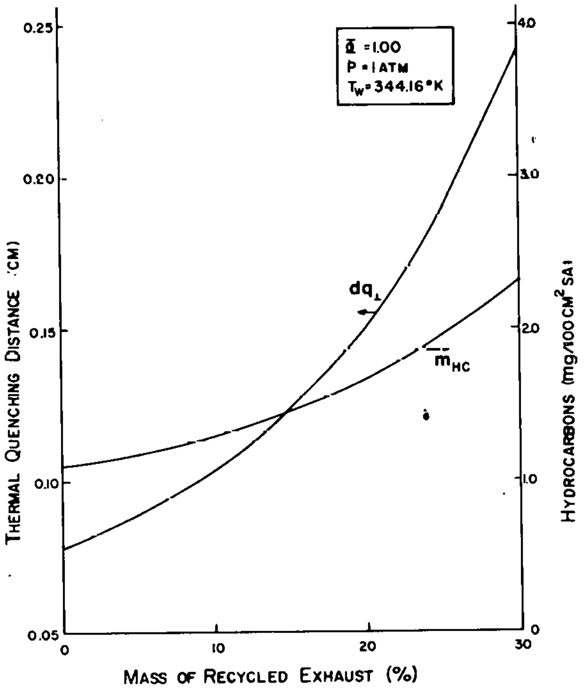

FIGURE 5: EXHAUST RECYCLE EFFECTS ON LAMINAR QUENCH DISTANCE

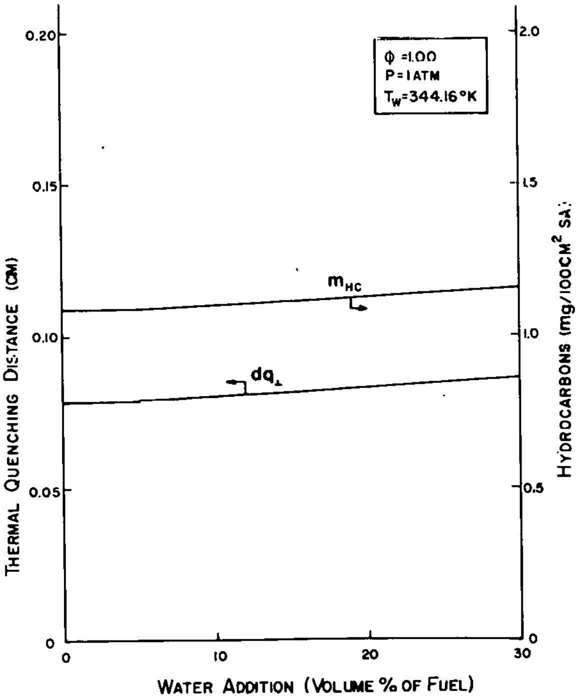

FIGURE 6: WATER ADDITION EFFECTS ON LAMINAR QUENCH DISTANCE

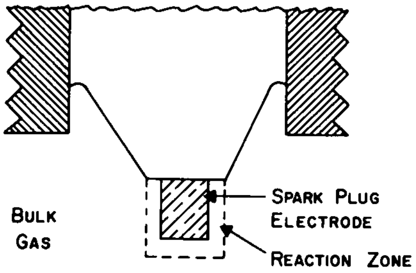

Figure 7: Surface Ignition Model Schematic

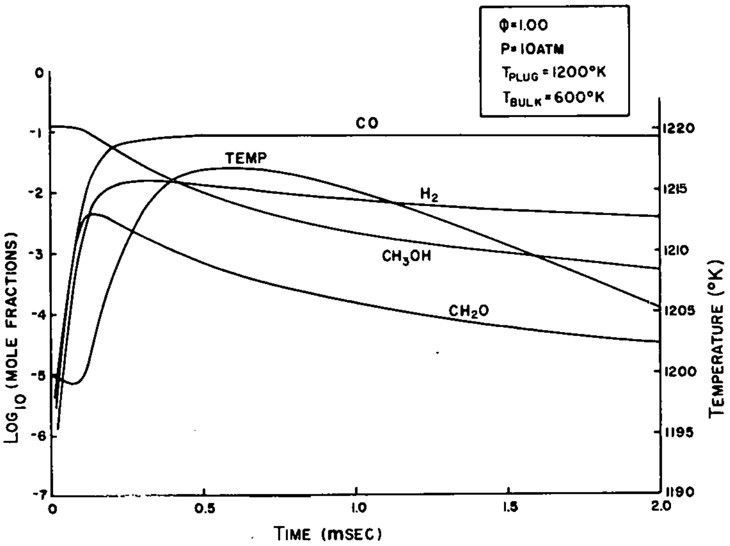

Figure 8: Surface Ignition Species Concentrations

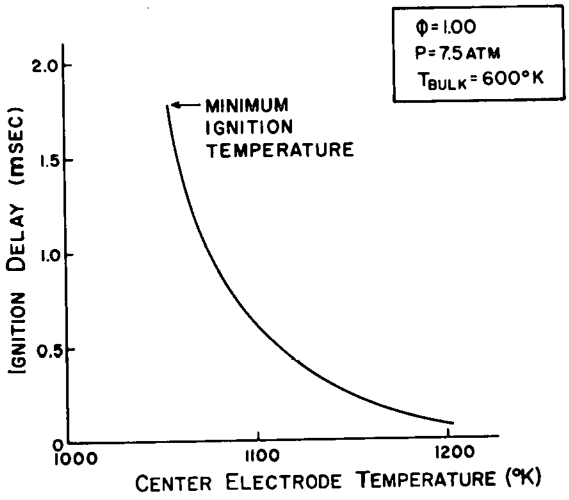

Figure 9: Electrode Temperature Effect on Ignition Delay

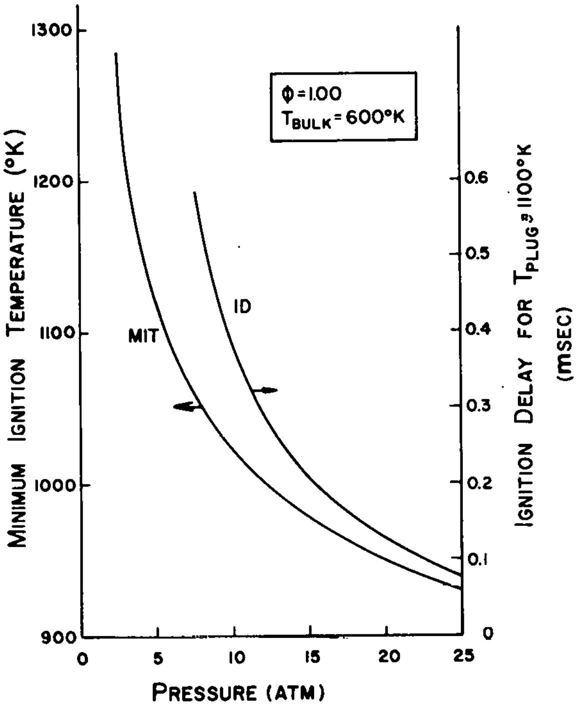

Figure 10: Pressure Effects on Minimum Ignition Temperature and Ignition Delay

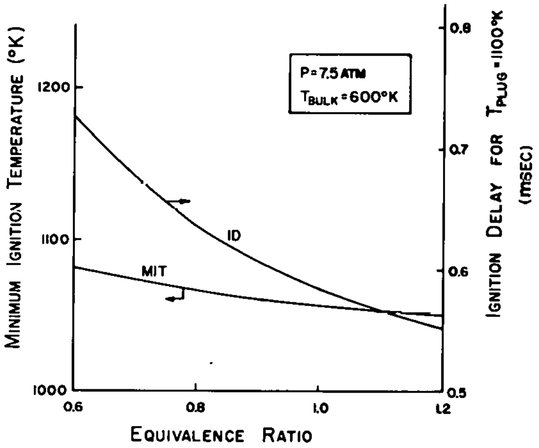

FIGURE 11 : EQUIVALENCE RATIO EFFECTS ON MINIMUM IGNITION TEMPERATURE AND IGNITION DELAY

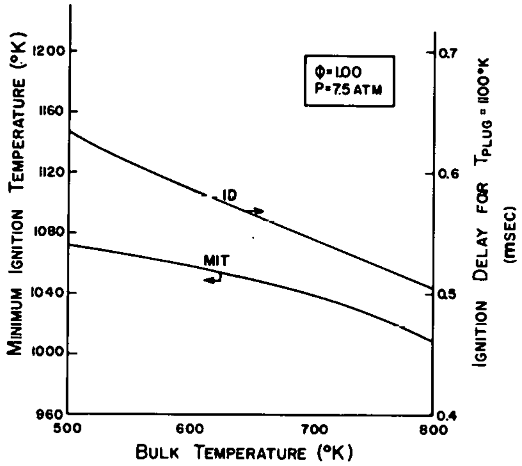

FIGURE 12: BULK TEMPERATURE EFFECTS ON MINIMUM IGNITION TEMPERATURE AND IGNITION DELAY

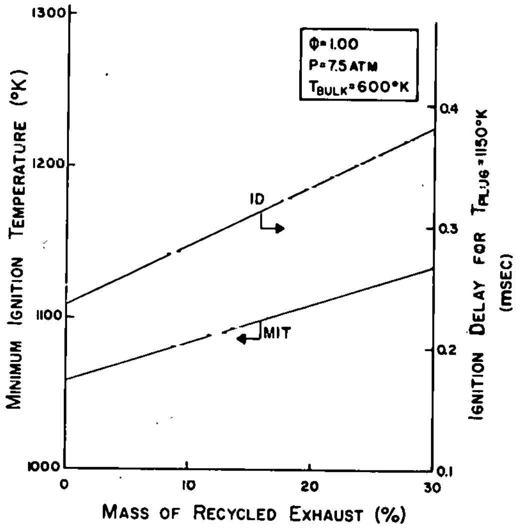

FIGURE 13: EXHAUST RECYCLE EFFECTS ON MINIMUM IGNITION TEMPERATURE AND IGNITION DELAY

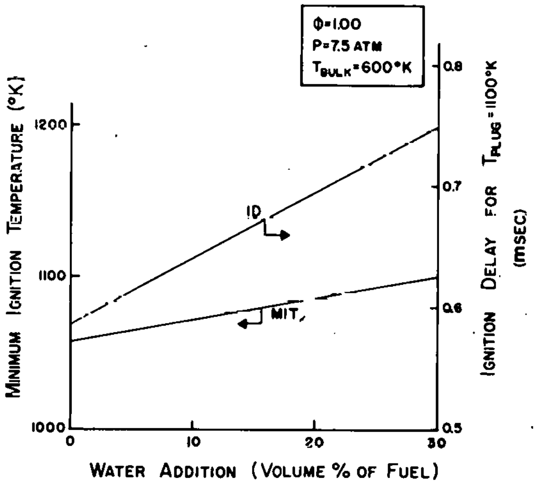

FIGURE 14: WATER ADDITION EFFECTS ON MINIMUM IGNITION TEMPERATURE AND IGNITION DELAY

EMISSIONS FROM GASOHOL FUELED VEHICLES

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INTRODUCTION

A waiver request from Gas Plus, Inc., and the Illinois Department of Agriculture, to permit use of 10% ethanol in gasoline was submitted to EPA on June 19, 1978. The Emission Control Technology Division (ECTD) in Ann Arbor, Michigan, was requested to assist in evaluation of this waiver request by testing ten vehicles on two gasoline fuels and three gasohol fuels. In addition, Southwest Research Institute (an EPA contractor laboratory), EPA-Office of Research and Development in Research Triangle Park, North Carolina, and the Department of Energy, Bartlesville Energy Technology Center, all participated in the test program. Only the EPA-Ann Arbor data is included in this report.

In accordance with section 211 f(4) of the Clean Air Act, the Administrator's decision in response to a request for a waiver to permit use of a fuel additive must be made within 180 days of receipt of the application for the waiver, otherwise the waiver is automatically granted. In this instance, the Administrator's decision on the gasohol waiver request was to not act. Therefore, the waiver was automatically granted. The use of 10% ethanol in gasoline is now permitted, but restrictions on its use could be undertaken later under section 211 (c) of the Clean Air Act should this be necessary. This section provides for periodic evaluation of in-use fuels.

SUMMARY

In the EPA test program four three-way and seven oxidation catalyst vehicles were tested using the U.S. Federal Test Procedure. Five fuels were used including two gasolines and three gasohols. All gasohol fuels in this program contained 10% ethyl alcohol by volume. The exhaust emissions, evaporative emissions, and canister weights were measured.

The data showed that gasohol:

1. Increased evaporative emissions by about 50%.
2. Decreased exhaust HC about 9%.
3. Resulted in a net increase of exhaust plus evaporative HC emissions.
4. Increased NOx emissions by about 7%.
5. Decreased CO about 35%.
6. Decreased fuel economy (carbon balance method) by about 2%.

FUELS

Five fuels were chosen:

Fuel 1 - Indolene
Fuel 2 - 90% Indolene plus 10% Ethanol
Fuel 3 - Typical summer grade gasoline
Fuel 4 - 90% Fuel 3 plus 10% Ethanol
Fuel 5 - Blended gasohol containing 10% Ethanol and approximating the Reid vapor pressure and distillation characteristics of Fuel 3
Fuel 6 - A re-blend of Fuel 5.

Fuel 5 did not meet EPA specifications when received and was replaced with Fuel 6. It was later determined that Fuel 6 was not as close in distillation characteristics to Fuel 3 as was desired. The back-end volatility of Fuel 6 (50, 70, and 90% points) is a little high and might be expected to adversely affect driveability (Table 1). Fuel 6 did result in an increase in driveability complaints. Because of the driveability problems encountered this fuel was not considered representative of a blended gasohol and emissions results from it did not influence the waiver decision. The distillation curves for these five fuels shows the marked effect that the addition of ethanol has on the front end volatility (Figure 1).

VEHICLES

Eleven 1977 through 1979 catalyst equipped vehicles were tested. Four of these were equipped with three-way catalysts and seven with oxidation catalysts. Some of the vehicles were preproduction prototypes. All were supplied by the manufacturers (Table 2).

TEST PROCEDURE

The vehicles were delivered to the EPA Motor Vehicle Emission Laboratory by the manufacturers. Each vehicle was checked to see that it was tuned to manufacturer's specifications. The evaporative emission canisters were loosened from their brackets so that the canisters could be easily removed for weighing.

Each vehicle was tested on each of the five test fuels in accordance with the U.S. Federal Test Procedure (40 CFR part 86) as modified to allow the canister to be weighed before and after the diurnal test and after the hot soak test. In addition, the soak period was restricted to 12-24 hours (FTP allows 12-36 hours). Replicate tests were planned on a time available basis and most vehicles received replicate tests on all five fuels. The test sequence (Table 3) shows the order the fuels were run in addition to the step by step sequence.

RESULTS

Gasohol fuels cause enleanment which should result in decreased HC and CO emissions. These effects were seen here. Exhaust emission results indicate that the two "mixed" gasohol fuels made by adding ethanol to a base fuel resulted in (Figure 2):

1. A substantial increase in evaporative emissions and in total HC emissions (evaporative plus exhaust).

2. A slight increase in NOx emissions.

3. A slight decrease in exhaust HC and in fuel economy (by carbon balance method).

4. A substantial decrease in CO.

The blended gasohol (Fuel 6) showed similar results with the exception of three-way catalyst vehicles where CO was higher than on the base fuel. Driveability complaints were more numerous with Fuel 6.

Fuel economy on the two "mixed" gasohol fuels was slightly lower than on the respective base fuels. The effect was fairly consistent across all eleven vehicles tested and amounted to from 0 to 2% decrease. The blended gasohol fuel resulted in a larger decrease in fuel economy of about 5%.

Average canister weights for the eleven vehicles before the diurnal breathing loss tests (BDBL), after the diurnal tests (ADBL), and after the hot soak test (AHS) are shown on Table 4. Also shown is the difference between the before and after diurnal tests (DDBL) and the change in weight from before diurnal to after hot soak tests (DTEST). This table also shows the emissions results and fuel economy for the eleven vehicles.

Evaporative emissions appear to correlate well with canister weights after each test (Figure 3). The canister weights after the hot soak test were always lower than after the diurnal test. This means that the FTP and one hour hot soak were a net purging operation and that canister capacity was available for the hot soak test, but was not used. Thus, it appears that hot soak emissions (which account for most of the evaporative emission on a 3.3 trips per day basis) from gasoline or gasohol fueled vehicles could be reduced by better design of the evaporative emission control system as it pertains to hot soak losses.

ETHANOL EVAPORATIVE EMISSIONS

Ethanol concentration in the SHED was determined on 12 diurnal and 10 hot soak tests for Fuels 4 and 6. A Perkin-Elmer model 3920 chromatograph with TRIS (Cyano Ethoxy) propane columns - 15% on chromasorb P was used.

Diurnal breathing losses averaged .26 grams ethanol and hot soak losses averaged .33 grams ethanol with a range of .1 to .6 grams per test.

OTHER CONSIDERATIONS

The EPA study was constrained to evaluating the effect of a 10% ethanol-90% gasoline blend on emissions. Some other factors which were not addressed here, but warrant careful consideration are:

1. Motor vehicle fuel may not be the best place to use ethanol. Properly adjusted engines such as turbine engines in power plants might be better able to efficiently use this fuel.
2. There is a net energy deficit associated with the production of ethanol from field crops.
3. The use of a potential food source as fuel raises questions. During periods of world wide grain shortages this practice may be difficult to defend.

CONCLUSION

The purpose of this program was to evaluate the effects on emissions that the use of gasoline containing 10% ethanol would have. It was determined that gasohol has a strong effect on some emissions.

* Evaporative emissions increased substantially.

* Exhaust HC and CO emissions decreased.

* NOx increased.

* Fuel economy decreased slightly.

It is possible that a gasohol fuel properly blended to meet market requirements would not cause the substantial increase in evaporative emissions seen in this program.

- Appendix Follows -

TABLE 1

Typical Fuel Inspection Data

ITEM	Analyzed by 1/	Fuel 1 EPA	Fuel 2 EPA	Fuel 3 Howell	Fuel 4 Howell	Fuel 5 Howell	Fuel 6 Howell	Nat'l. Avg. 2/	Calif. 2/
1. API Gravity	H-3,4,5,6	-	-	57.5	56.5	61.0	52.6	59.3	57.7
2. Sp. Gr.	C	-	-	0.749	0.753	0.735	0.769	.742	.748
3. R.O.N.	E-1,2,3,4 H-5,6	98.0	100.5	92.0	95.4	95.5	96.4	92.9	93.2
4. M.O.N.	H-3,4,5,6	-	-	82.6	84.2	88.1	88.6	83.9	84.7
5. Ole. %	E-1 H-3,4,5,6	2.5	-	16.5	16.6	0.4	17.6	7.2 4/	-
6. Aro. %	E-1 H-3,4,5,6	24.0	-	28.5	28.9	23.0	34.6	30.8 4/	-
7. RVP, PSI	M-1-6	9.0	9.2	10.0	10.7	7.9	10.0	9.8	8.4
8. Dist., F, 3/									
	IBP	87	94	89	86	107	94	89	94
	10%	128	130	119	118	126	126	121	126
	20%	162	147	142	132	136	139	146	147
	30%	194	156	167	144	145	150	171	168
	40%	215	179	196	154	152	162	-	-
	50%	229	220	227	201	205	242	221	216
	60%	240	234	255	243	232	280	-	-
	70%	253	245	287	272	260	311	266	275
	80%	274	265	321	314	295	335	-	-
	90%	313	309	360	355	321	370	333	344
	EP	383	386	417	413	337	408	410	413

1/ H = Howell Hydrocarbons, Ethyl = Ethyl Cord, M = EPA-MVEL, D = D.O.E. Fuel Survey, C = Calculated value.

2/ D.O.E. Fuel Survey, Summer, 1977.

3/ Fuels 1-6 were analyzed by EPA.

4/ MVMA Fuel Survey, Summer, 1977.

Table 2
Vehicles used in EPA Gasohol Test Program

Manufacturer	Model	Year	Engine	Catalyst	V.I.D.
Ford	T-Bird	1979	351-V8	TWC	71S42
Ford	Bobcat	1978	140-I4	TWC	8Y2-2.3-C-122
General Motors	Sunbird	1978	151-I4	TWC	80153
General Motors	Regal	1978	231-V6	TWC	48257
Ford	Maverick	1978	302-V8	OXID	8B1-302-F-97
Ford	Pinto	1979	140-I4	OXID	9#2-2.3-F-85
General Motors	Impala	1977	350-V8	OXID	8B042
General Motors	Regal	1978	231-V6	OXID	5944
Chrysler	Omni	1978	105-I4	OXID	ZL44A8D159064
Chrysler	Salon	1978	318-V8	OXID	RH41G8A206799
Toyota	Corolla	1979	97-I4	OXID	79-FE-3

TABLE 3

Gasohol Test Sequence

1. Drain and refuel to 20% tank capacity.
2. Run 1 LA-4 cycle.
    a. Check idle CO and RPM first time on each fuel.
3. Hot soak one hour (key off to key on).
4. Drain and refuel to 40% tank capacity.
5. Run 1 LA-4 cycle.
6. Soak 12-24 hours @ 68-86F (key off to key on).
7. Run 1 FTP with SHED:
    a. Drain and refuel to 40% tank capacity (leave fuel cap off).
    b. Move vehicle to SHED.
    c. Weigh cannister.
    d. Check cannister lines.
    e. Perform 1 hour diurnal heat build. (Fuel cap on @ 60°F.)
    f. Immediately after heat build:
        -Remove heat blanket
        -Weigh cannister
        -Reinstall cannister & check cannister lines.
    g. Run 3 bag FTP emissions test within 15-60 minutes of end of diurnal test.
    h. Run 1 hour hot soak immediately following emissions test.
    i. Weigh cannister immediately following hot soak test.
8. Precondition for next test:
    a. If within 24 hours of FTP key off go to step 4.
    b. If longer than 24 hours since FTP key off go to step 1.
    c. If changing fuel type go to step 1.
9. Two tests for each fuel type with following sequence:
        1,2,3,4,6,3 for group 1 vehicles.
        3,4,6,3,1,2 for group 2 vehicles.
        (6 fuel runs X 2 tests each X 11 vehicles = 132 tests)

TABLE 4

ENVIRONMENTAL PROTECTION AGENCY
MOTOR VEHICLE EMISSION LABORATORY
ANN ARBOR, MICHIGAN

GASOHOL PROGRAM DATA SUMMARY

PROCESSED: DEC 15, 1978
(REVISION A: DEC. 27, 1978)

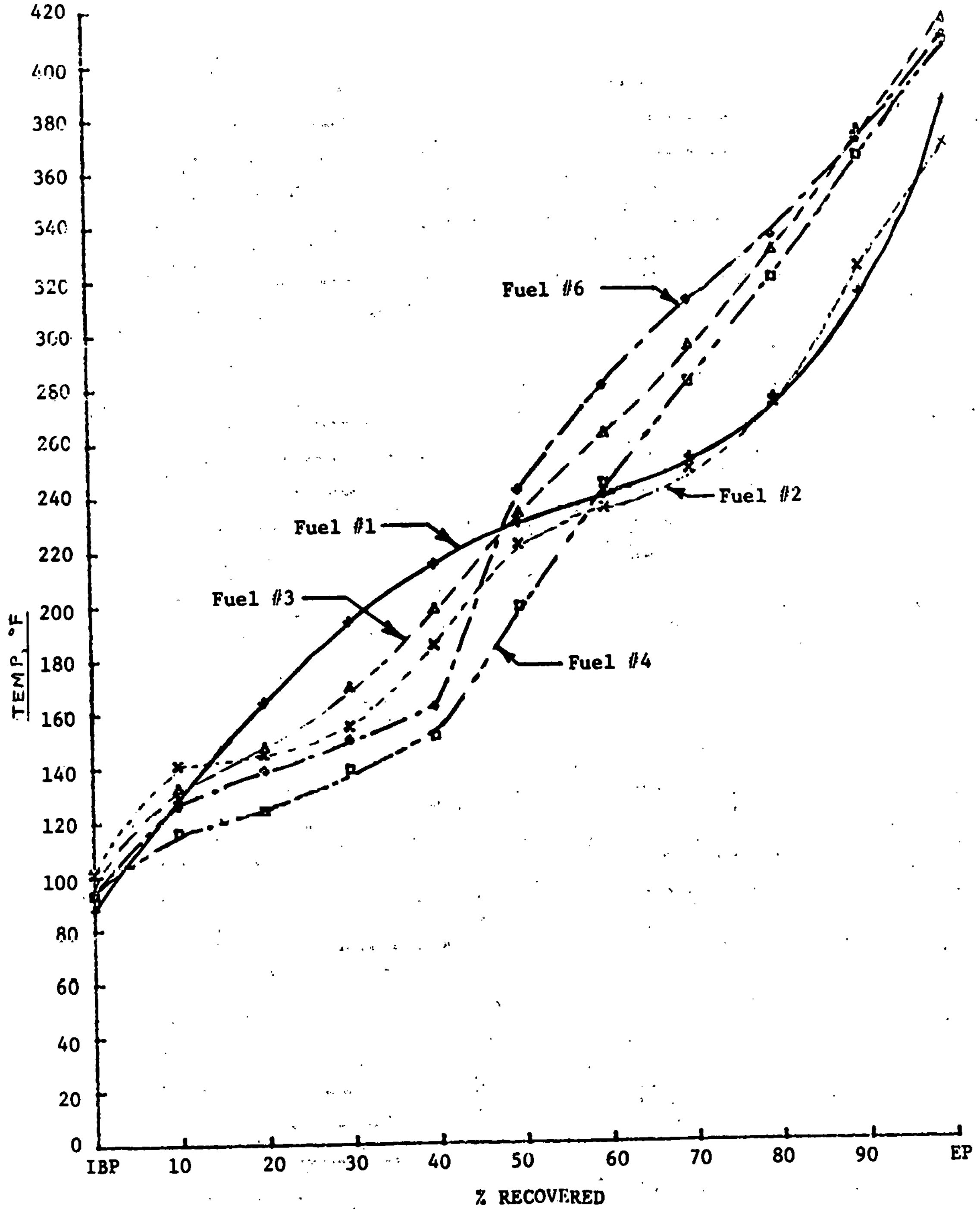
CATALYST TYPES: 3-WAYS AND OX-CATS
NUMBER OF VEHICLES: 11

MEANS OF ALL TESTS		HC	CO	NOX	CO2	FE	DBL	HSL	TLOSS	TOTHC	BDBL	ADBL	AHSL	DDBL	DTEST
		(GRAMS/MILE)				(MPG)	(GRAMS)								
FUEL	N														
FUEL 1	(19)	0.451	6.61	1.16	470.	19.3	1.12	1.02	2.14	15.60	890.	904.	885.	13.3	-4.9
FUEL 2	(21)	0.410	4.39	1.26	467.	19.0	1.45	1.75	3.20	17.35	891.	907.	892.	16.3	1.1
FUEL 3	(41)	0.535	8.20	1.25	472.	19.1	2.51	1.63	4.15	21.11	900.	919.	898.	19.4	-2.1
FUEL 4	(21)	0.490	5.51	1.33	468.	18.8	4.04	2.68	6.72	24.97	905.	927.	908.	21.5	2.7
FUEL 6	(25)	0.665	6.57	1.38	482.	18.2	3.93	2.24	6.17	27.76	905.	924.	905.	19.3	0.6
DIFFERENCES BETWEEN MEANS															
FUEL 2 - FUEL 1		-.041	-2.23	0.09	-3.	-0.4	0.33	0.73	1.06	1.76	1.	4.	7.	3.0	6.0
FUEL 3 - FUEL 1		0.084	1.59	0.08	2.	-0.2	1.39	0.61	2.00	5.52	10.	16.	12.	6.1	2.9
FUEL 4 - FUEL 3		-.045	-2.69	0.08	-4.	-0.3	1.53	1.04	2.57	3.86	5.	8.	10.	2.1	4.8
FUEL 6 - FUEL 3		0.130	-1.63	0.13	10.	-0.9	1.41	0.61	2.02	6.65	5.	5.	7.	-0.1	2.7
RATIOS OF MEANS (%)															
FUEL 2 / FUEL 1		91.	66.	108.	99.	98.	129.	171.	149.	111.	100.	100.	101.	122.	-23.
FUEL 3 / FUEL 1		119.	124.	107.	100.	99.	224.	160.	193.	135.	101.	102.	101.	145.	42.
FUEL 4 / FUEL 3		92.	67.	106.	99.	99.	161.	164.	162.	118.	101.	101.	101.	111.	-131.
FUEL 6 / FUEL 3		124.	80.	111.	102.	95.	156.	137.	149.	132.	101.	101.	101.	100.	-29.

NOTES: 1. TOTHC IS TOTAL HC EMISSIONS (EXHAUST + EVAPORATIVE) FOR 3.3 TRIPS PER DAY.

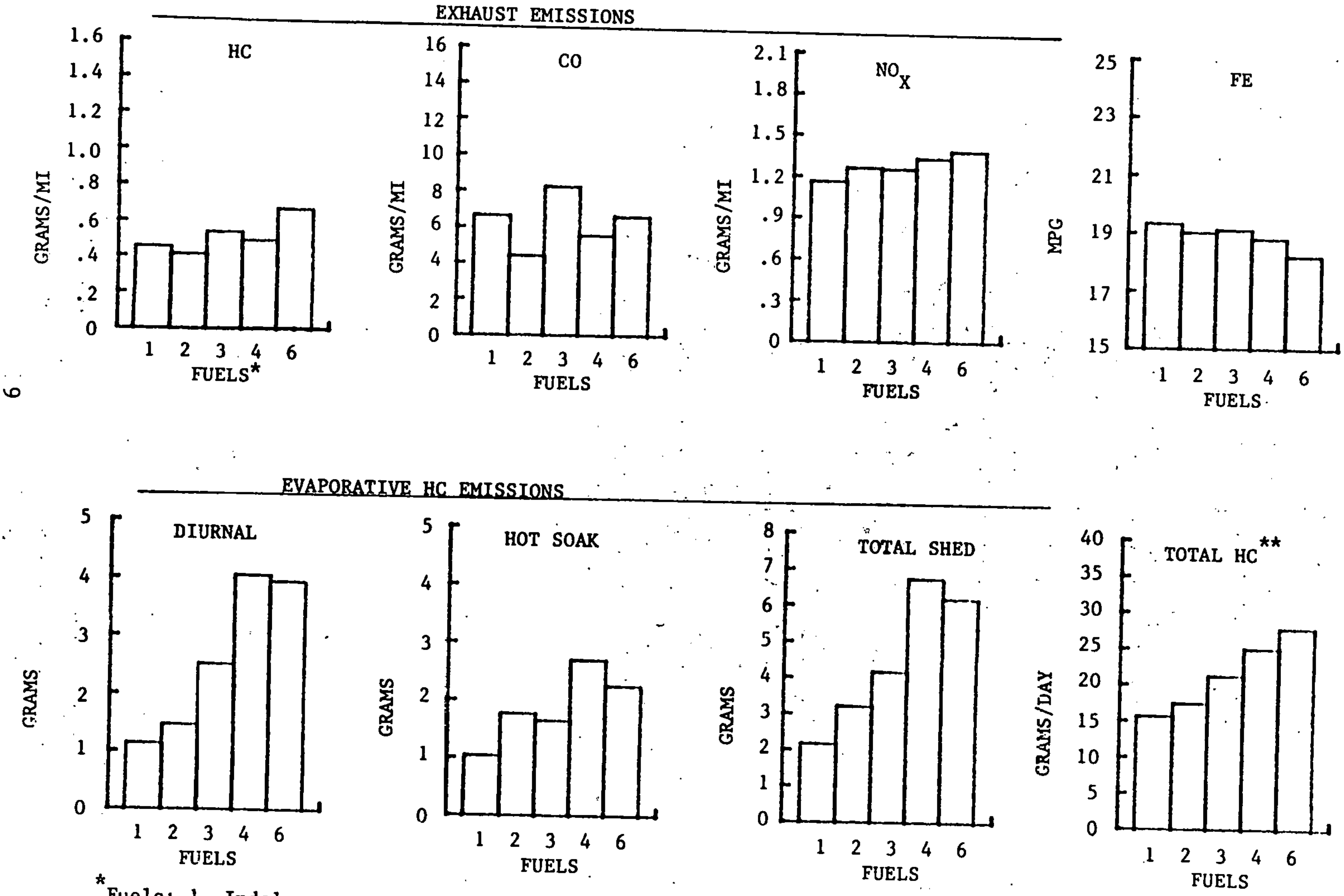
2. FUEL DESCRIPTIONS-
   1. INDOLENE (RVP=9.0). SOURCE: EPA MVEL LAB FUEL IN USE FOR CERTIFICATION TESTING.
   2. 90% INDOLENE + 10% ETHANOL (RVP=9.3). SOURCE: BLENDED USING FUEL NO. 1 AND 200 PROOF ETHANOL AT EPA MVEL
   3. COMMERCIAL GASOLINE (RVP=10.0). SOURCE: HOWELL HYDROCARBONS (MSED ORDER).
   4. 90% FUEL NO. 3 + 10% ETHANOL (RVP=10.7). SOURCE: HOWELL HYDROCARBONS (MSED ORDER).
   6. BLENDED GASOHOL CONTAINING 10% ETHANOL (RVP=10.0). SOURCE: HOWELL HYDROCARBONS (MSED ORDER).

FIGURE 1. COMPARISIONS OF DISTILLATION CURVES OF TEST FUELS



Fuels: 1. Indolene (RVP=9.0)
2. Indolene + 10% Ethanol (RVP=9.2)
3. Commercial Gasoline (RVP=10.0)
4. 90% Fuel 3 + 10% Ethanol (RVP=10.7)
6. Blended Gasohol containing 10% Ethanol (RVP=10.0)

FIGURE 2. AVERAGE EMISSIONS OF 11 1978-79 CATALYST VEHICLES.



*Fuels:
1. Indolene
2. Indolene plus 10% Ethanol
3. Commercial Gasoline
4. 90% Fuel 3 + 10% Ethanol
6. Blended Gasohol containing 10% Ethanol

**Exhaust plus Evaporative Emissions for 3.3 trips per day.

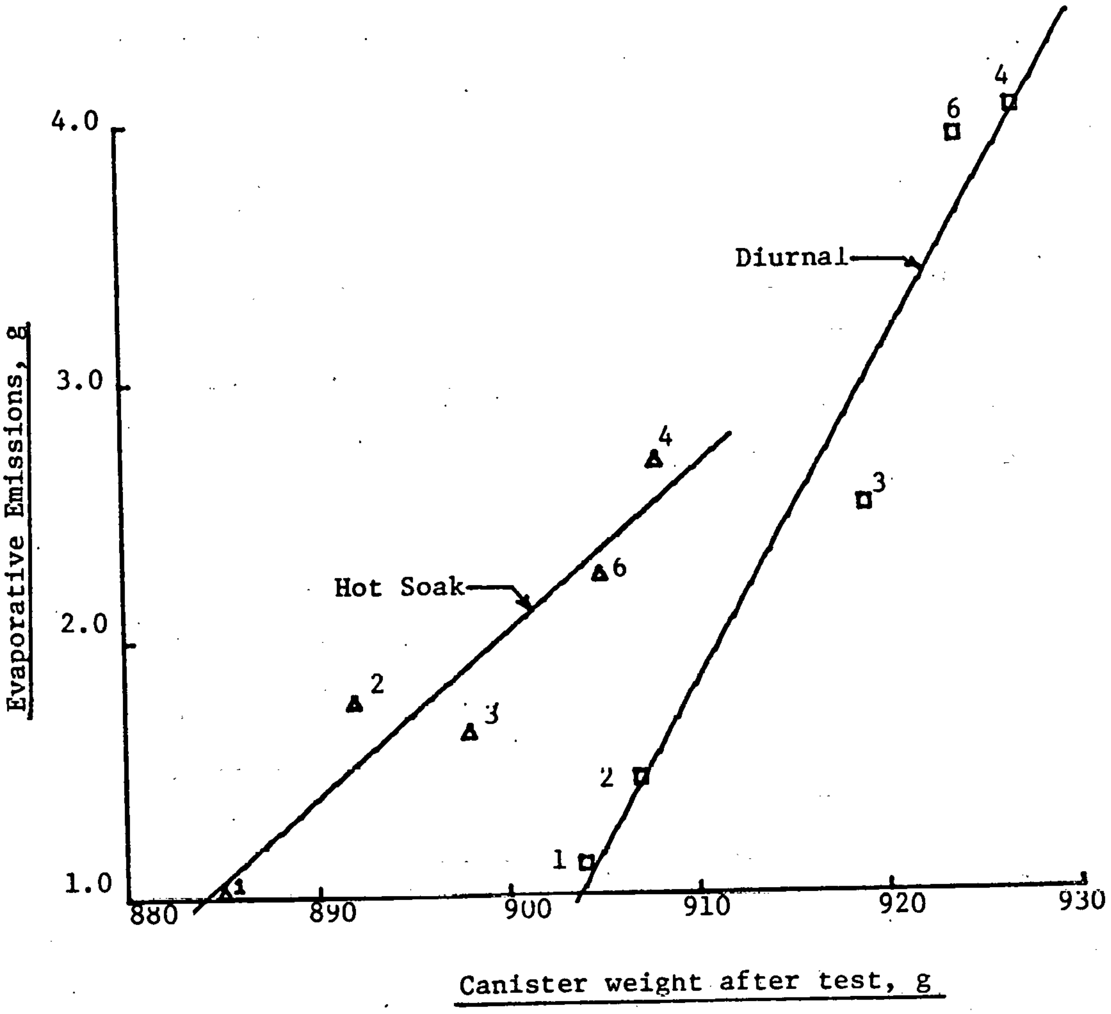


Figure 3 - Average evaporative emission for eleven vehicles. Fuel number is indicated by data point.

BRAZILIAN VEHICLE CALIBRATION FOR ETHANOL FUELS

by

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ABSTRACT

This paper discusses calibration development for 20% and 100% ethanol fuels in two current Brazilian engines. The development was limited to external adjustments. Engine design revisions to resolve problems such as cold start or materials compatibility, or revisions to take advantage of the higher fuel octane were not included in this study.

Vehicle tests were conducted on the 1.4L engine in a 1976 and a 1978 vehicle to determine the effects of a 20% ethanol/80% Brazilian gasoline blend as a direct substitute for Brazilian gasoline with no carburetor adjustments. Vehicle performance, fuel economy, driveability and emissions tests were conducted. Carburetor adjustments were then made to obtain an operable equivalence ratio range for neat ethanol and the hot CVS portions of the vehicle tests were repeated. Tests were also conducted with 10-20% gasoline added to the neat ethanol to improve low temperature volatility. Neat ethanol significantly increased the unburned ethanol and aldehydes in the exhaust gas. The analytical methods used to measure these exhaust constituents are described.

Engine dynamometer tests were conducted on a 2.3L light truck engine to develop best fuel economy and best power calibrations for neat ethanol. Automatic carburetor and distributor calibrations were developed and compared with the manual calibrations. The engine was installed in a vehicle and confirmation tests were conducted on gasoline, on the 20% blend with no adjustments and on neat ethanol with the developed automatic calibrations.

The results of these test programs on the 1.4L and 2.3L engines are presented and discussed. Improvements in efficiency and power were due primarily to differences in equivalence ratio and fuel octane.

INTRODUCTION

Recent energy shortages have demonstrated the need for decreasing dependence upon petroleum as an automotive fuel source. In Brazil, 70% of the petroleum used for processing fuels and lubricants is imported, generating a negative effect on the balance of trade. To alleviate the situation, the Brazilian government has initiated a national program to supplement gasoline with ethanol. At the present time a blend of 20% ethyl alcohol and 80% gasoline is being used in the areas close to the alcohol production centers and the current plan is to have this blend available nationwide by 1981. In addition, several fleets are already operating on ethanol alone. The government plans to make available neat ethanol at gas stations in selected areas by 1981 so that customers can buy vehicles for ethanol or gasoline. It is the ~overnment objective to have 20% of the 1982 automobile production volume unning on neat ethanol fuel.

Some modifications of engines and vehicles are necessary to use ethanol and ethanol-gasoline blends (1,2). These modifications are similar, although somewhat less extensive, to those for methanol and methanol-gasoline blends (3-10). A test program was conducted to determine the extent to which ethanol and ethanol blends could be accommodated by engine calibration adjustments with minimal hardware modifications. Three Brazilian vehicles were used in this program: a 1976 1.4L sedan, a 1978 1.4L sedan and a 1977 2.3L light truck, Table 1.

FUEL PROPERTIES

The base gasoline used in this study was blended from U.S. stocks to match properties of regular grade gasoline in Brazil and is referred to as Brazilian gasoline hereafter. Relevant properties are listed in Table 2 for this Brazilian gasoline and for the U.S. emissions test fuel Indolene. The ethanol and blends of 20% ethanol in Brazilian gasoline used in this study are also described in Table 2. The ethanol was denatured and was commercially available. While this specific composition may not match Brazilian fermentation ethanol precisely, it was believed to be adequate for this engine test program. Properties which depend more upon chemical composition, such as material compatibility or phase stability, could not be evaluated with this ethanol formulation.

Properties which make ethanol distinct from gasoline as a liquid fuel include lower heat of combustion, different stoichiometric air-fuel ratio, higher heat of vaporization and a single boiling point rather than a full distillation range. The low heat of combustion implies that a larger amount of fuel must be used to provide the same total energy in the combustion chamber. If driving range must be maintained, an ethanol fueled vehicle will require a larger fuel tank to accommodate this difference in heat of combustion. Substituting ethanol for gasoline without carburetor adjustments does not change the metered air-fuel ratio a great deal since the densities are similar. However, since the stoichiometric air-fuel ratio is considerably lower for ethanol than for gasoline, the equivalence ratio is very different. Adding ethanol to gasoline causes the equivalence ratio to become progressively leaner. Many of the effects observed with blends or neat ethanol can be attributed to this change in equivalence ratio. Fuel supply and metering systems must be increased in capacity and throughput when alcohols are used in order to maintain equivalent engine operation. Liquid fuels having high heats of vaporization, such as ethanol, may not be completely vaporized in the intake system unless additional heat is supplied from external sources. Liquid fuel in the intake system and in the combustion chamber can create air fuel distribution and combustion problems. This is perceived as poor driveability, particularly in cold weather.

The single boiling point characteristic of ethanol aggravates the problem of mixture preparation. Gasoline contains components with a wide range of volatility so that an acceptable amount of vaporization for combustion can be obtained over all operating conditions without creating unmanageable amounts of vapor in the liquid handling systems. In contrast, ethanol is difficult to evaporate in sufficient quantities at low temperature, but once high temperatures are achieved, it may produce too much vapor in the

*Number in brackets ( ) designate References at the end of paper.

liquid system, causing fuel pump vapor lock. Such problems often can be resolved by appropriate design revisions to accommodate unique fuel properties. Differences in test fuel volatility are shown by the distillation curves in Figure 1. The vapor pressure of neat ethanol is very low compared with gasoline. However, when blended with gasoline up to about 25%, the more polar ethanol decreases the solubility of light hydrocarbons and thus increases the vapor pressure of the blend.

The intake heat requirement to vaporize ethanol is compounded by its lower heating value. Five times more heat to the intake air-fuel mixture is required to provide the same mixture quality with neat ethanol as with gasoline. This includes a factor of 3.3 for heat of vaporization and a factor of 1.6 for the additional fuel required to provide the same amount of energy. Heat requirements for equivalent mixtures using blends fall between those of gasoline and neat ethanol. Substantial revisions to the intake mixture heat supply are required to achieve equivalent mixture quality using fuels which contain large amounts of alcohol.

MEASUREMENT OF UNBURNED FUEL EMISSIONS

Vehicle emission tests were conducted on chassis dynamometers using the U.S. Federal emission test proceudres, which were developed for use with gasoline as the fuel. With ethanol, the exhaust gas of an engine contains unburned ethanol and partial oxidation products of ethanol such as aldehydes. Additional instrumentation was needed to measure these exhaust gas constituents. The flame ionization detector (FID) commonly used for exhaust hydrocarbons does not respond fully to either alcohols or aldehydes. A correction can be applied only if the relative amounts of the unburned fuel constituents and their FID response are known. Data in the following sections reported as exhaust HC were obtained with an FID and no corrections were applied. Therefore, these values must be used with caution since the discrepancy increases with ethanol fuel content. FID HC are an adequate representation of total unburned fuel emissions for gasoline and a 20% ethanol blend. At an ethanol content of 80% or higher in the fuel, a significant amount of unburned fuel was not measured by the FID.

Measurements were made of unburned ethanol and aldehydes to determine the magnitude of the underestimation by the FID and to examine the impact of ethanol fuel on air quality. Samples from tests on the 1976 1.4L vehicle with Brazilian gasoline, low and high content blends and neat ethanol were collected proportionately from the dilute stream during cruises and CVS-H tests. The ethanol samples were obtained from a cold trap and on a polymer adsorbent. The ethanol was detected with a computer controlled gas chromatograph/mass spectrometer (GC/MS). Aldehydes were collected in dual impingers and analyzed by the 3-methyl 2-benzothiazolone hydrazone (MBTH) method for total aliphatic aldehydes. The aldehydes resulting from ethanol combustion were expected to be primarily aliphatic.

A simplified procedure was available for analysis of the 1978 1.4L and 2.3L vehicle tests. A Fourier transform infrared spectroscopy method (FTIRS) (11) had been developed to identify and quantify light hydrocarbons and other emission species. Using computer data reduction, the complete IR spectrum an be traversed and quantified readily. An example is given in Table 3 for exhaust composition from the 2.3L vehicle using neat ethanol. A variety of hydrocarbons are identified along with water, CO, CO_2 and NOx. Methanol, ethanol, formaldehyde and acetaldehyde are also identified. One source for the methanol is the denaturent. Species with more than five carbon atoms tend to be lost in the C-H stretching absorption when gasoline is present, so the FTIRS is not suitable, in general, to determine total aldehydes. Total aliphatic aldehydes were also measured by MBTH from the same sample. The FTIRS recorded 80% of the total aldehydes in this case.

The FTIRS measurements agree adequately with the CVS bag concentrations of CO and CO_2 by NDIR and of NOx by chemiluminescence. Assuming no loss of sample in the bag, the comparison of unburned fuel concentration is a measure of the FID response. After adjusting the FTIRS total unburned fuel upward to account for the additional aldehydes observed by MBTH, the FID response was determined to be 0.71 for this test. This is consistent with the published response value for ethanol. The specific amount varies somewhat within the CVS-H tests conducted, and a correction upward of 20-40% appears necessary to obtain the total unburned fuel concentration from an FID measurement. The calculation of unburned fuel mass flow requires an additional correction since the average molecular composition is not $CH_{1.85}$ as in gasoline, but about $CH_3O_{0.5}$, i.e. primarily ethanol and aldhydes. This, together with the adjustment for FID response, requires that unburned fuel mass emissions from a vehicle using neat ethanol, but measured and calculated as for gasoline, must be multiplied by a factor of 2.0-2.3 to obtain correct mass emissions. The FID HC data reported in the following sections do not include these adjustments. Sufficient information was not available in all cases and the value measured by the current test procedure was considered useful. However, for quantitative comparison of mass unburned fuel emissions, the adjustments described above are necessary.

The FTIRS is a laboratory instrument and samples must be transported to it from the vehicle test location. CVS sample bags made of Tedlar ^{R} were used since previous tests had shown these were equivalent to direct sampling from a dilute stream. Significant loss of aldehyde or alcohol sample occurred only when sample undiluted exhaust which resulted in condensate formation in the bag.

Table 3 shows an analysis of a sample extracted from the same bag after overnight storage. Formaldehyde dropped 12%, acetaldehyde 3%, methanol 16% and ethanol 14%. This provided reassurance that substantial quantities of the unburned fuel species were not being lost during transport from the test location to the instrument. Total NOx and water vapor dropped to half the earlier values.

MINIMAL ADJUSTMENT TO ACCEPT ETHANOL

To fully take advantage of ethanol as fuel, one has to redesign the engine to utilize its high octane and extended lean limit properties. Such redesign should provide for higher compression ratios and the optimization of ignition timing and air-fuel mixtures. The objective of this study was to determine the extent to which the advantages could be realized by calibration adjustments on current engines with no major hardware revisions. Vehicle tests were conducted with minimal changes necessary to accept ethanol fuels and engine tests were run to develop optimum calibrations.

Direct Substitution of Ethanol Blend

Brazilian vehicles are calibrated to accept either gasoline or a 20% ethanol blend with no adjustments since both are available. Since the stoichiometric air-fuel ratio of ethanol is less than that of gasoline, a direct substitution of an ethanol blend gives a leaner mixture for combustion which, in turn, leads to changes of fuel economy, emissions and vehicle behavior. The effects of replacing Brazilian gasoline with a 20% ethanol blend in the same gasoline were consistent for all three Brazilian vehicles used in this study.

Table 4 presents results for the 1978 1.4L sedan. Leaning-out of the air-fuel mixture is indicated by a reduction of more than 10% in the fuel-air equivalence ratio, ϕ_{FA}. This change was observed at idle and steady speeds as well as in the acceleration modes of the CVS driving cycles. The leaning effects were also reflected in the improvement of energy economy both in the CVS cycle and on the road. Based upon energy consumed per unit distance traveled, the direct substitution of a 20% ethanol blend gave a 6% improvement. On the basis of volume per unit distance, results for the blend were slightly worse than those for gasoline because of the lower energy content in the ethanol.

Emissions from the vehicle also followed the trend of the equivalence ratio. With the 20% ethanol blend, both HC and CO were reduced substantially while NOx was increased. As shown in Table 4, FTIRS aldehydes in the exhaust with the 20% ethanol blend as fuel were slightly higher than with Brazilian gasoline. Unburned ethanol was the more significant of the unregulated emissions when the 20% blend was used.

Performance, as measured by acceleration capability, was improved by direct substitution of gasoline by the 20% ethanol blend. The time needed to accelerate from 0 to 97 km/h was reduced by 1.1 seconds. As no hardware adjustment was made in the vehicle, the improvement could have been due to an overly rich calibration on gasoline and improved volumetric efficiency from the larger heat of vaporization of ethanol.

While the energy economy and power were improved, the driveability of the vehicle deteriorated. Slight surging and hestitation of the vehicle were observed during hot operation. This was probably due to the leaner equivalence ratio. A subsequent slight reduction in carburetor main jet size caused a severe loss in driveability, indicating high sensitivity to equivalence ratio in this range.

Operation on Neat Ethanol

The 1978 1.4L test vehicle could be operated on neat ethanol only after the metering jets in the carburetor were enlarged to provide a comparable equivalence ratio. Measurements of intake mixture temperature, A/F distribution and calibration settings helped to define the hardware revisions necessary to best utilize ethanol. The carburetor was adjusted for best economy using neat ethanol through a CVS-H driving cycle. Cold start CVS tests were not attempted, since substantial intake manifold revisions were necessary before such tests would have been meaningful. While making the carburetor adjustments, comparable driveability was maintained on the chassis dynamometer throughout the emission test driving cycle. A few additional driving modes were added to simulate sensitive operating conditions for driveability. The equivalence ratio at idle was adjusted to match a 20% ethanol blend to compare economy and emissions. Results in Table 4 show that even though the equivalence ratios at all operating conditions were not precisely the same, the CVS-H fuel economy of the two cases were equal on an energy basis but not on a volumetric basis. Data on regulated emissions showed small increases in HC and CO and a significant decrease in NOx comparing the 20% blend results to neat ethanol. Total aldehydes, as measured by FTIRS, almost doubled while unburned ethanol increased more than ten-fold.

The idle air-fuel mixture misfire limit was leaner with ethanol than with gasoline. A CVS-H test was conducted with an equivalence ratio, ϕ_{FA}, at idle equal to 0.67, Table 4, which is well below the misfire limit for an engine operated on gasoline. No driveability problems were experienced by the driver through the CVS cycle. The energy economy was improved by 8% while all emissions were reduced except acetaldehyde, which was increased by 50%. If acetaldehyde is of less concern than other emissions, these results illustrate the advantages of the lean burn characteristics of ethanol to the extent they can be realized without intake system modifications to increase mixture heat and improve air-fuel distribution.

Cold start, driveaway evaluations demonstrated high sensitivity to ambient temperature. A cold start was not possible with neat ethanol when the ambient temperature was below 5°C. 10% gasoline added to the fuel bowl extended cold start capability downward to 0°C, and larger quantities were needed at lower ambients. The warmup period was prolonged compared with gasoline operation, and the choke was required indefinitely to enrich the ethanol/air mixture when the ambient temperature was below 5°C.

Difficulties with operating the ethanol fueled vehicle in cold weather were caused by the high heat of vaporization of ethanol. The only external heat source to the air fuel mixture on the 1.4L engine was from a small contact area between the intake and exhaust manifolds directly under the carburetor. This was insufficient to compensate for the large amount of heat extracted from the intake air to vaporize the ethanol. Intake mixture temperature was depressed resulting in incomplete vaporization.

The temperature depression of the intake mixture is illustrated in Figure 2, which shows the temperature change of the air-fuel mixture relative to the carburetor inlet, at several locations and at different vehicle cruise speeds. For neat ethanol, the mixture dropped to the lowest observed temperature across the carburetor. The idle fuel flow was sufficiently low and the residence time sufficiently high so that the mixture recovered more than its loss before entering the cylinders. As the air and fuel flow increased, the supply of external heat became inadequate and the temperature recovery was less. At 48 km/h and above, the initial temperature depression was more than 30°C. With the intake air at about 38°C, icing could occur in the carburetor and temperature recovery of the mixture in the manifold was negligible. In contrast, temperatures of the air fuel mixtures of both the Brazilian gasoline and the 20% ethanol blend were seldom colder than the intake air. Enough external heat was received to fully recover before entering the cylinders.

The problem of vaporization of ethanol also resulted in a more uneven distribution of equivalence ratio among cylinders. Emission samples from cylinders showed the maldistribution increased with vehicle cruise speed from an equivalence ratio spread of .06 idle to .20 at cruise 80 km/h. This could be attributed to the increase in air and fuel flow rates and the resultant temperature depressions. The distribution is expected to become worse at cold ambient temperatures. The drop in intake mixture temperature and the poor air-fuel distribution limit the extent to which the lean limit properties of ethanol can be utilized in existing engines.

High Ethanol Content Blends

A series of tests were conducted on a 1976 1.4L vehicle, to examine the effects of blends with ethanol as the primary component. Blends of 80% and 90% ethanol were compared with a 20% blend and with Brazilian gasoline and neat ethanol. Carburetor adjustments were made to match the equivalence ratio of the 80% blend to the 20% blend. Results of steady-state and CVS-H tests, Table 5, were similar to those obtained on the 1978 vehicle, Table 4. The 80% and 90% blends were similar to neat ethanol regarding emissions of MBTH aldehydes and unburned ethanol. The presence of gasoline in the fuel improved driveability, especially during warm-up.

Equivalence ratio measurements made during the CVS-H tests explain some of the driveability problems experienced on neat ethanol. The equivalence ratio, $\emptyset_{FA}$, was much leaner than expected at high mass flow rates, causing a significant increase in necessary throttle opening. This might have been due to the formation of vapor in the fuel metering passages. An equivalence ratio of 0.63 was observed with no misfire.

CALIBRATION DEVELOPMENT FOR NEAT ETHANOL

Results discussed previously deal with the effects of carburetor adjustments with no attempt to change the spark timing. In a separate study, the 2.3L engine from a 1977 truck was installed on an engine dynamometer to calibrate spark timing and carburetion simultaneously for best power and best efficiency. Automatic calibrations were then developed and evaluated in the test vehicle.

Engine Calibrations

Engine dynamometer tests were conducted on the 1977 2.3L engine for maximum torque to determine the increase possible with ethanol. Spark timing on the production engine must be retarded from MBT because of the low octane of Brazilian gasoline. Figure 3 shows knock-limited (KL) torque and thermal efficiency of the engine using Brazilian gasoline and the improvements possible with best fuel and spark timing settings for a 20% blend and for neat ethanol. The 20% blend was also knock limited, requiring some spark retard, while MBT was readily obtained with neat ethanol. The torque and efficiency improvements are due primarily to the higher fuel octane. Since the blend included a leaded octane improver at the same level as in the Brazilian test gasoline, removal of lead from the blend will decrease the knock-limited torque.

Maximum part thorttle efficiency was determined at several speed/load combinations. Figure 4 shows the dependence of efficiency on equivalence ratio with MBT spark timing for an intermediate torque level over a range of engine speeds. Best efficiency was typically between 0.8-0.9 ϕ_{FA} with enrichment for maximum torque.

Automatic calibrations were developed from the best economy and best torque spark timing and carburetor settings. Figure 5 shows centrifugal and vacuum advance curves which closely match most of the points. However, the hardware to implement this calibration was not available for the vehicle test program. The production curves shown in Figure 5 were used in the vehicle tests. Compromises were also made in the carburetor settings. Interaction among the idle, main and power enrichment systems prevented matching the desired equivalence ratios under all conditions; light loads were richer than desired and WOT was somewhat leaner, causing some torque loss, Figure 6. Further carburetor modifications could have reduced the compromise, but were not available for the vehicle tests.

Vehicle Tests

CVS-H tests were conducted on the 2.3L engine in a truck test vehicle using Brazilian gasoline with production carburetor and distributor settings, followed by tests with direct substitution of a 20% ethanol blend, Table 6. The carburetor developed for neat ethanol was then installed and the CVS-H tests were repeated. Idle and light load equivalence ratio were found to be much richer than expected, as can be seen from the CO results. Carburetor settings were then restored to the best economy values and the idle was set leaner, providing the final data in Table 6. While vehicle performance could be improved by further carburetor and distributor hardware improvements, this fuel economy is believed to be representative of the possible improvements with ethanol. The CVS-H thermal efficiency was improved by 10%, bringing the volumetric fuel economy to within 70% of the base gasoline economy from 65%, as expected from the ratio of the fuel heating values.

SUMMARY AND CONCLUSIONS

The major effects on engine operation from the use of ethanol fuels can be anticipated from the properties of the fuels. The difference in stoichiometric air-fuel ratio has the effect of shifting the equivalence ratio towards the lean side. Exhaust emissions, fuel economy and driveability reflect this shift. The heating value of the fuel is reduced also, decreasing driving range. The larger heat of vaporization provides some NOx and octane advantage but it also delays warm up and can drop the intake temperature so low that poor mixture quality and air-fuel distribution cause driveability problems. Volatility characteristics of ethanol are not well suited to current vehicles. However, these problems can be overcome with revisions to the engine and modifications of the fuel.

Most Brazilian vehicles are calibrated to accept either gasoline or a 20% ethanol blend. This calibration must be a compromise between the two fuels and is not optimum for either; operation on gasoline is too rich for best economy and operation on the blend is close to driveability limits.

Operation on neat ethanol was possible after the carburetor metering jets were enlarged to provide a comparable equivalence ratio. Increased power and thermal efficiency were obtained by taking advantage of the higher octane and lean limit properties of ethanol. Lean operation was limited by the depressed intake temperatures, the low vapor/liquid ratio and poor air-fuel distribution. Further improvements obtained by hardware changes to increase compression ratio and improve air-fuel mixture preparation and distribution were beyond the scope of this study.

Optimum calibrations developed on an engine dynamometer were not fully realized in the vehicle due to compromises made by implementing automatic calibrations in the production carburetor and distributor.

Cold start was not possible on neat ethanol at ambient temperatures below 5°C. Even at stabilized engine temperatures, enrichment was required for acceptable driveability at ambient temperatures below 5°C to compensate for the inadequate heat provided by the production manifold. The addition of 10% gasoline to the ethanol extended cold start ability down to 0°C and improved cold driveability.

The use of ethanol fuel decreases NOx and increases unburned fuel exhaust emissions when compared with gasoline at the same equivalence ratio. CO emissions were similar unless increased by poor air-fuel distribution. The most significant differences in the unburned fuel emissions are the presence of unburned ethanol and substantial amounts of aldehydes, principally acetaldehyde. The impact of these emissions on Brazilian air quality must be determined.

ACKNOWLEDGMENT

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TABLE 1

Descriptions of Brazilian Test Vehicles

Vehicle	1978 Sedan	1976 Sedan	1977 Truck
Vehicle weight (lb.)	2300	2300	3400
Test Inertia Weight Class (lb.)	2500	2000	3500
Transmission	4m	4m	4m
Axle	4.13:1	4.13:1	5.38:1
Engine	1.4L	1.4L	2.3L
Compression Ratio	8.0:1	8.0:1	7.8:1

TABLE 2

Fuel Properties

	Gasoline		Ethanol	20% Ethanol 80% Br. Gas.
	Brazil	Indolene		
Spec. Grav. 60°/60°F	.747	.743	.795	.754
RVP (100°F) psi	6.1	8.8	2.5	6.5
Distillation °C				
IBP	38	32	78	42
10%	62	57		58
50%	107	107		74
90%	179	155		176
EP	218	196		207
RON	75	97	∿110	87
MON	71	88	89	77
FIA % vol.				
Aromatics	25	30		20
Olefins	8	7		7
Saturates	67	63		53
OH			100*	20
Lead, g/ℓ	.129	.004		.103
Sulfur, wt%	.105	.02		.084
H/C	1.87	1.86	3.0	2.00
O/C			0.5	.05
Heat of Combustion LHV, KJ/kg	∿44,100	∿44,100	∿26,950	
Heat of Vaporization KJ/kg	∿280	∿280	∿920	
Stoichiometric A/F	14.57	14.6	8.98	13.76

*Fuel grade ethanol composition

Ethanol	93%
Methanol	4%
Ethyl Acetate	1%
Gasoline	1%
Methyl Isobutyl Ketone	1%

TABLE 3

Exhaust Composition from Neat Ethanol by FTIRS

pound		Amount at 4 hours		Error	Amount at 26 hours
Water	H_2O	1.10%		0.2	0.52
Carbon Dioxide	CO_2	1.08%		0.2	1.07
Carbon Monoxide	CO	488.	ppm	18.4	490.
Heavy Hydrocarbons	HC_6^+	0.3	ppmc	14.7	0
Nitric Oxide	NO	14.4	ppm	0.6	4.0
Nitrogen Dioxide	NO_2	46.9	ppm	0.6	31.5
Nitrous Oxide	N_2O	0.4	ppm	0.2	0.4
Nitrous Acid	HONO	2.4	ppm	0.2	2.2
Hydrogen Cyanide	HCN	0.1	ppm	0.4	0
Ammonia	NH_3	0	ppm	0.2	0.1
Sulfur Dioxide	SO_2	0.3	ppm	0.4	0.2
Methane	CH_4	8.7	ppmc*	0.2	8.8
Acetylene	C_2H_2	4.6	ppmc	0.4	4.5
Ethylene	C_2H_4	26.0	ppmc	0.9	26.0
Ethane	C_2H_6	1.8	ppmc	0.4	1.7
Propylene	C_3H_6	0.5	ppmc	1.8	0.6
Isobutane	C_4H_8	3.0	ppmc	1.8	3.5
Formaldehyde	CH_2O	8.8	ppmc	0.2	7.8
Acetaldehyde	CH_3CHO	57.4	ppmc	1.6	55.6
Formic Acid	HCOOH	0.6	ppmc	0.2	0.2
Methanol	CH_3OH	7.6	ppmc	0.2	6.4
Ethanol	C_2H_3OH	194.	ppmc	0.2	168.
Total NOx		63.7	ppm		37.6
Total HC		313.3	ppmc		280.0
CVS BAG					
FID HC		240.6	ppmc		
NDIR CO		463	ppm		
Chemi NOx		64.6	ppm		
NDIR CO_2		1.04	%		
MBTH Aldehydes		46.4	ppm		

*ppmc = ppm carbon

TABLE 4

1978 1.4L Sedan

	Brazilian Gasoline	20% Ethanol 80% Brazilian Gasoline	100% Ethanol $Ø_{FA}$ Idle Match 20%	100% Ethanol Lean Idle
Equivalence Ratio, $Ø_{FA}$				
Idle	.98	.86	.84	.67
48 km/h	1.07	.90	1.01	.92
CVS-H 1st acc	.97	.92	.97	.92
2nd acc	1.00	.96	.94	.91
Fuel Economy				
MJ/km basis				
CVS-H	3.12	2.93	2.90	2.69
Road: City	3.70	3.49		
Suburb	2.60	2.43		
ℓ/100 km basis				
CVS-H	9.5	9.6	13.6	12.6
Road: City	11.3	11.4		
Suburb	7.9	7.9		
Emissions CVS-H (gm/mi)				
HC	3.32	2.44	2.53	2.50
CO	49.37	20.62	27.50	17.00
NO_x	1.86	2.86	1.86	1.66
Formaldehyde	.05	.07	.07	.04
Acetaldehyde	.05	.16	.34	.52
Methanol	.02	.03	.14	.08
Ethanol		.19	2.98	1.19
Performance (sec)				
0-96 km/h	18.0	16.9		
Driveability (Scale 1-10)				
Crowds/cruises	7	5		
/PT accel.	7	6		

TABLE 5

1976 1.4L Sedan

Cruise Tailpipe Emissions (48 km/h)

	Brazilian Gasoline	.20 ETOH .80 Br. Gas.	.80 ETOH .20 Br. Gas.	.90 ETOH .10 Br. Gas.	100% ETOH
FID					
HC ppmc	3105	1890	1552	1215	675
CO %	2.74	0.67	1.98	1.50	0.98
NOx ppm					
O_2 %	0.8	1.2	0.85	1.1	1.5
CO_2 %	12.0	13.52	12.88	12.88	12.88
MBTH Aldehyde ppm	41.9	47.2	115.8	119.5	128.0
ETOH ppm		32	136		168
A/F	13.58	14.06	9.95	9.71	9.27
$Ø_{FA}$	1.07	0.98	1.04	1.01	0.97
STOIC	14.57	13.76	10.33	9.80	8.98

CVS-H EMISSIONS

Fuel	Test	HC (gm/mi)	CO (gm/mi)	Economy $\frac{ℓ}{100 km}$	Economy $\frac{MJ}{km}$	MBTH Aldehydes as Formaldehyde (gm/mi)
Brazilian Gasoline	-1	2.43	60.1	8.74	2.85	.06
	-2	2.37	57.6	8.43	2.75	.06
	-3	1.79	45.9	9.08	2.97	
	-4	1.84	49.5	8.91	2.90	
Indolene Clear	-1	1.75	42.3	8.88	2.99	
	-2	1.75	52.1	9.01	2.94	
20% ETOH 80% Br. Gas.	-1	1.84	32.5	8.84	2.69	.06
	-2	1.75	32.3	8.78	2.66	.06
80% ETOH 20% Br. Gas.		1.69	34.0	12.38	2.91	.24
100% ETOH	-1	1.87	20.1	13.75	2.93	.26
	-2	1.64	17.9	13.68	2.91	.25

TABLE 6

2.3L Truck CVS-H Tests

	Brazilian Gasoline	20% Ethanol Blend Substitution	100% Ethanol Automatic Calibration Power	100% Ethanol Automatic Calibration Economy
Fuel Economy				
MJ/km	5.27	4.78	5.30	4.80
ℓ/100 km	16.01	15.68	24.83	22.48
Emissions (gm/mi)				
HC	5.44	4.65	3.56	3.67
CO	94.47	63.51	89.25	15.14
NOx	2.72	3.01	1.59	2.85
Formaldehyde	.87	.13	.16	.31
Acetaldehyde	0	.10	.85	1.49
Methanol	0	.03	.20	.29
Ethanol	0	.11	4.20	5.24

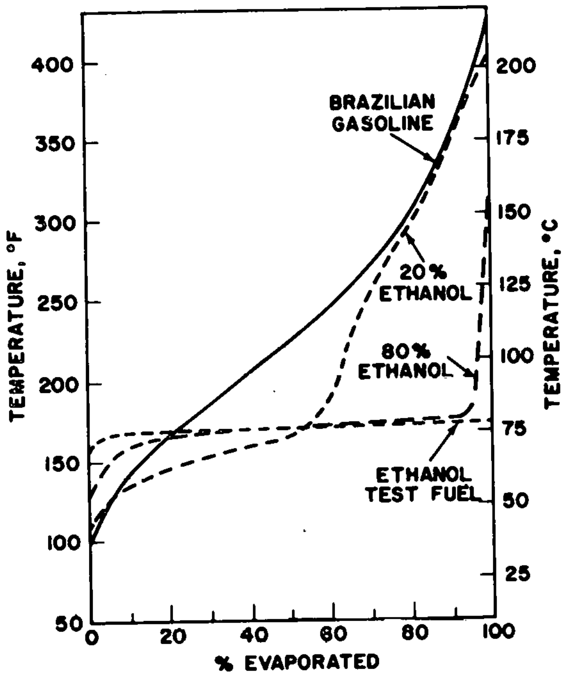

Figure 1 - Distillation of Brazilian gasoline and blends with ethanol

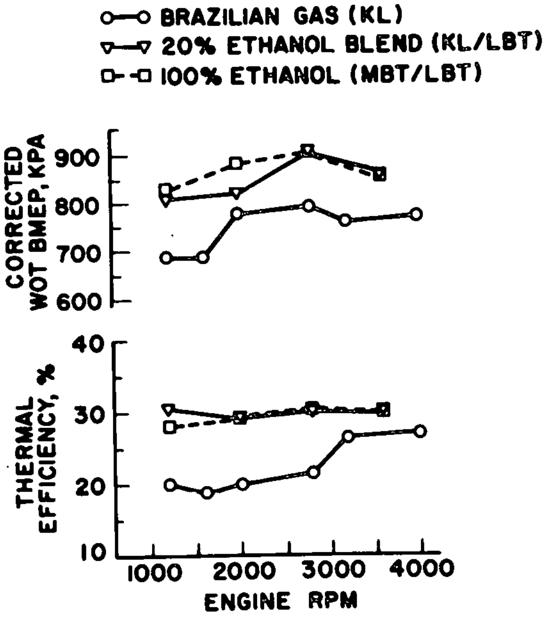

Figure 3 - Best torques and efficiencies with different fuels at WOT, 2.3L engine

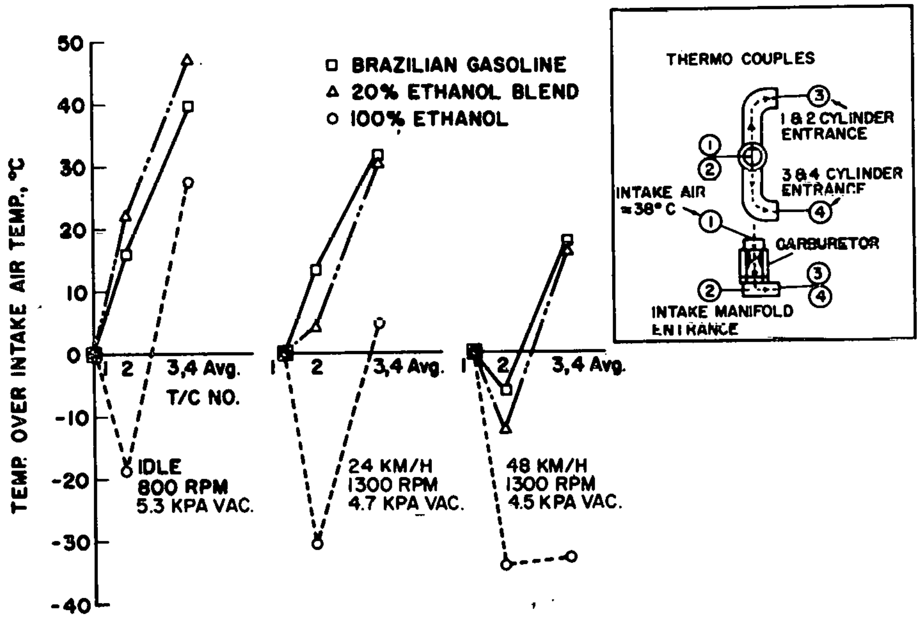

Figure 2 - Temperature change of air-fuel mixture in intake manifold, 1.4L 1978 sedan

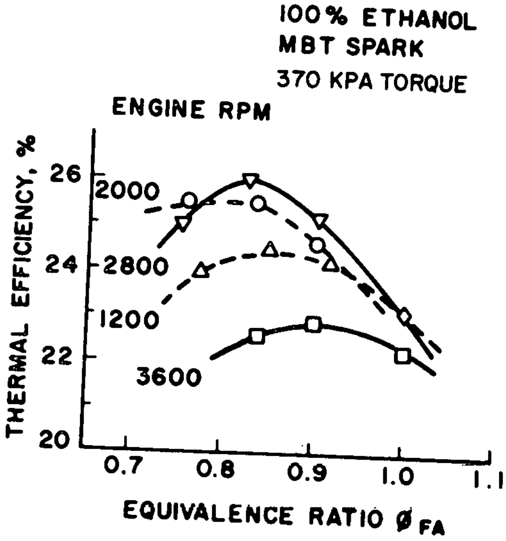

Figure 4 - Change of thermal efficiency with equivalence ratio at part throttle, MBT spark, 2.3L engine

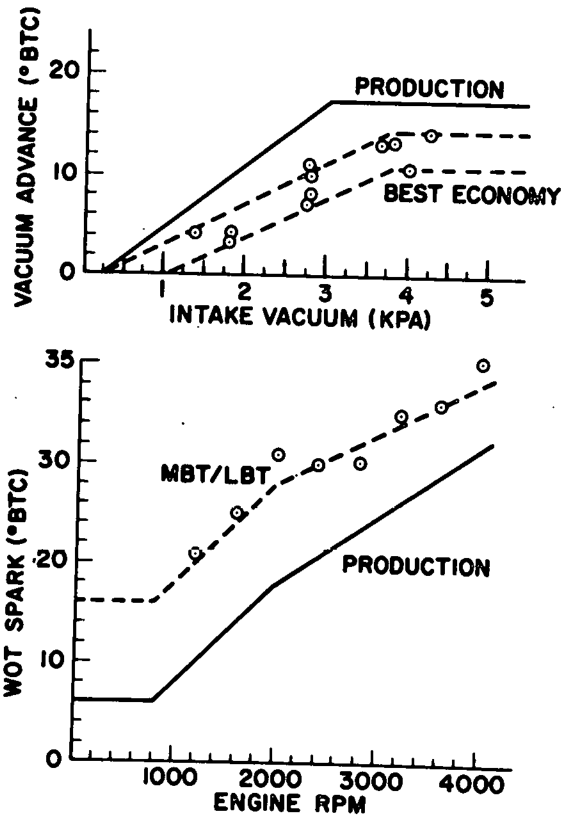

Figure 5 - Best economy spark timing, 100% ethanol, 2.3L engine

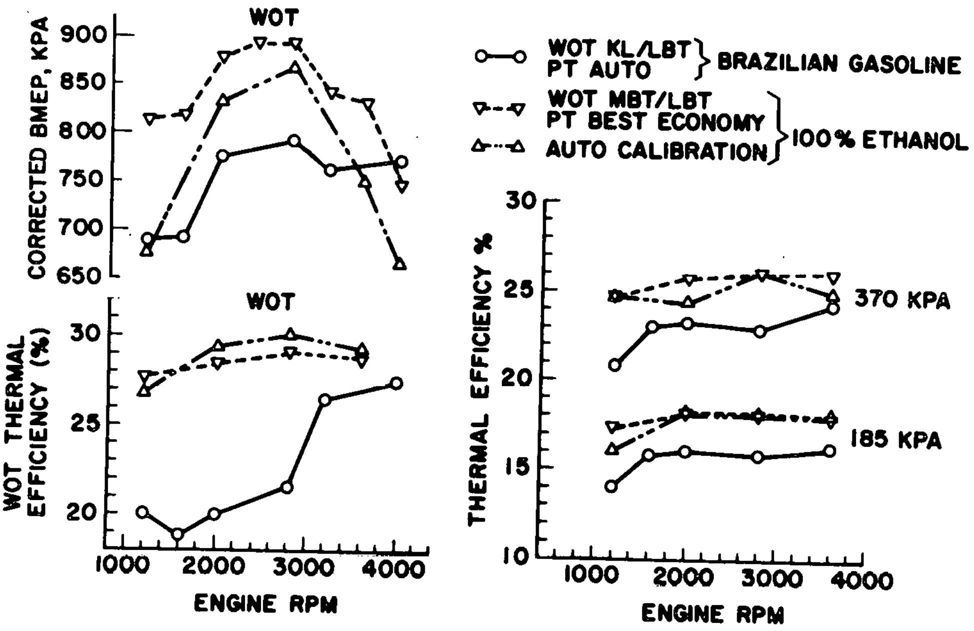

Figure 6 - Comparison of auto and best economy operations using 100% ethanol and operations using Brazilian gasoline

BP NEW ZEALAND EXPERIENCE WITH METHANOL/GASOLINE BLENDS

by

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INTRODUCTION

The Middle East crisis of 1973 highlighted the vulnerability of all oil importing nations like New Zealand, to disruption of normal supplies, rising prices, and the ultimate physical depletion of a resource formerly taken for granted. New Zealand has a special problem in that of the 52% of its primary energy requirement which is currently met by imported oil, 69% is used in the transport sector (1)*.

New Zealand is well endowed with energy resources, particularly large coal and natural gas fields. To date little indigenous oil has been located, but this, and the condensate from the gas fields represent about 17% of the refinery's intake.

The development of alternative transport fuels has been studied in New Zealand for several years (2), and possibilities such as liquified petroleum gas or compressed natural gas are being actively developed. Methanol is seen as an attractive liquid fuel for use as a gasoline extender, particularly as it could be produced economically from natural gas drawn from the very large Maui gas field.

Following research here and in the UK, BP New Zealand concluded that the local production of methanol for use as a gasoline extender was a technically feasible option capable of early implementation. Further, it could be adopted without requiring substantial investment to modify existing vehicles or fuel distribution systems, and one which provided for a substantial reduction in energy related foreign expenditure. In 1977 therefore, the company embarked on an extensive test programme designed to develop economic solutions to known problem areas, and extend its experience in the blending, distribution and use of a 15% vol methanol/85% vol gasoline blend (M15)**.

New Zealand premium grade gasoline has been used as the hydrocarbon component in preparing the M15 blends used in these trials, but a properly designed methanol/hydrocarbon blend would be more suitable for vehicle use than the M15 blend employed. Should methanol/gasoline blends be adopted for general use in New Zealand, it is likely that the optimised hydrocarbon blending component would be produced at the New Zealand refinery in place of premium grade gasoline.

Notes:- *Numbers in brackets (1) designate References at end of paper

**In this paper M15 is used to describe only the 15% vol methanol/85% vol gasoline blend used in the trials, rather than a specially blended 15% vol methanol/85% vol hydrocarbon motor fuel designed to meet currently accepted gasoline quality

PROPERTIES OF METHANOL/GASOLINE BLENDS

The differences in composition between methanol and gasoline, and the effect of methanol addition on the properties of gasoline have been well documented (3, 4, 5, 6, 7). Specific aspects which are considered in these trials are compatibility with distribution and vehicle fuel system components, blend stability under practical conditions, and the need for additives (isobutanol) to improve water tolerance.

The typical characteristics of the fuels are shown in Table 1.

TRIAL RESULTS

Methanol/Gasoline Fuel

(a) Blend Preparation

The gasoline/alcohol blends used for retail tank preparation, and the M15 test fuel, were all prepared in road tank wagons of 8500 litre capacity. The quantities blended ranged from 1300 to 8350 litres.

The method of blending was to add gasoline to the tank wagon to 20% of the total blend volume. The alcohol was then added, followed by the balance of the gasoline and the product circulated. Samples were checked for homogeneity and circulation continued until this was achieved. The temperature, density, and water tolerance of the blend was then determined. Typical water tolerances of the blends prepared were 1600 ppm at 22°C.

(b) Retail Tank Preparation

In New Zealand, the age, size and condition of underground tankage varies widely, some tanks being over 30 years old (with a typical age being 10 years) and sizes range from 2 000 to 50 000 litres. Approximately 60% of these underground tanks do not have manholes and thus access to such tanks for sampling or introducing an auxiliary suction pump is restricted, usually to the tank contents dip pipe.

None of the underground tanks used in the trials had manholes and despite the limited access the development of techniques for tank cleaning and reducing water content to a level low enough to ensure phase stability was pursued. For these BP trials all but two of the prepared tanks were used to supply the M15 fuel to the test vehicles, the remaining two being employed for static tests.

(c) Blend Monitoring

Regular monitoring of blends at retail outlets has been an important feature of these trials. Immediately a tank was converted, the contents were checked daily for a few days to determine water content. Following this initial period the tank contents were sampled weekly and the blend quantity, water tolerance and alcohol content checked. The change in water content of the blend in one underground tank is demonstrated in Figure 1.

In general, blends have remained stable, in some cases over many months. One tank charged with 3500 litres of blend and with negligible drawings over seven months showed an increase in water content of only 200 ppm. The tank vent was of the standard open type, without a dessicator, indicating that no special venting equipment would be required.

(d) Tank Cleaning Test Rig

Although preparation of these tanks provided a reasonable basis for developing a tank commissioning procedure, further refinement was considered necessary to improve the efficiency and reduce the cost of water removal. To achieve this a 13 500 litre tank was set up as a test rig which would enable samples to be taken from 17 positions within the tank and tested for water content. Details of the tank dimensions and sampling points are shown in Figure 2.

Using this tank a programme of trials was instigated to evaluate existing and new tank cleaning techniques. In all cases the tank was emptied prior to each test run, and then 15 litres of water added, as previous experience had shown that underground tanks retained about 15 litres of water which could not be removed by a thief pump. Tests carried out to date include:-

1. 418 litres neat isopropanol - static test.

2. 418 litres neat isopropanol - circulating test.

Comparison of the samples taken in Tests 1 and 2 indicate that circulation reduced the time for reasonably stable water contents to be achieved from 96 hours (Test 1) to 4½ hours (Test 2).

3. 8500 litres of an 11.5% vol methanol, 3.5% vol isobutanol and 85% vol gasoline - static test.

Figure 3 shows the results of this test. The water content at the bottom of the tank (positions 1C, 3C, 5C - dotted lines) is shown to decrease steadily but after 250 hours is still considerably above the water content higher in the tank (positions 2B, 5B, 2A - solid lines). These latter indicate a gradual increase in water content as water was picked up from the bottom, but a completely homogeneous blend was not achieved.

4. Repeat of Test 3 circulating the blend through a 12 mm nozzle inserted down the dip pipe and directed towards the suction end. Circulation rate was 180 ± 10 litres a minute.

Table 2 presents the results of this test, indicating that water contents stabilised after 30 minutes circulation, at about 2200 ppm. The contents of the tank were clearly homogeneous.

These results have shown the need for circulation and that the alcohol/gasoline tank cleaning blend was more efficient than the neat isopropanol.

Further work is now concentrating on optimising the nozzle configuration and flow rate.

Based on the initial results of this test rig, and the tank monitoring programme, we believe that conversion of the retail underground tank network will not pose any significant problems.

Vehicle Tests

(a) General

New Zealand currently has in excess of 1.2 million petrol engined vehicles of which well over 1 million are passenger cars (human population is about 3.25 million) (8). Annual new car registrations, which averaged in excess of 81 000 from 1970 to 1976, have been only about 60 000 cars per year over the last two years (8). Whilst a wide range of makes (40) and models (99) are available (9), most are of Japanese, British or Australian origin, assembled locally from CKD (completely knocked down) packs.

No formal exhaust emission control legislation currently exists, but increasing numbers of new vehicles are fitted with some form of emission control system, depending upon their country of origin.

To expand our practical experience with the use of methanol/gasoline blends, the Wellington regional fleet of BP and its associates has operated on M15 since December 1977. Most of these vehicles are used by company field staff, but several are basically private vehicles and are operated as such.

(b) Fleet Trials

The test vehicles commenced using M15 progressively from December 1977. At the time of their being brought into the trial the vehicles ranged from brand new, to four years old with up to 177 000 km of use. The fleet includes vehicles of 20 different model types, which together represent approximately 40% of 1978 new car registrations.

The distance travelled by the BP test fleet is approximately 500 000 km. This has all been on M15, with the exception of isolated instances of some vehicles using gasoline when operating outside the Wellington area, where M15 was unavailable. Normal vehicle maintenance has been carried out according to manufacturers recommendations, but the vehicles were not retuned at the time of being brought into the trial.

Initially, vehicles had their fuel tanks fully drained before filling with the M15 blend. This procedure was considered unnecessary after the first five vehicles and was discontinued. All subsequent vehicles were filled with M15 without any fuel tank preparation.

The drivers, who have received no instructions regarding driving procedure, recorded their comments on the vehicles operation on a weekly log. Several drivers complained at first of difficult starting, cold stalling, and the need to use more choke on M15 than on gasoline. On investigation, it was found that generally the vehicles concerned were in a poor state of tune, and that driveability of the vehicle, even on gasoline, was poor. Once carburettor and ignition settings were returned to manufacturer's settings, acceptable driveability was restored and the operating complaints ceased.

One driver has reported continued hot starting problems at ambient temperatures above about 27°C. Considering that the front end volatility of the M15 used in the trials consistently exceeded that of premium gasoline by as much as 50%, it is most surprising that only one vehicle has experienced hot fuel handling problems.

The fuel consumption of the trial vehicles on M15 is being monitored, and compared with the consumption for the vehicle on gasoline where this information is available. Where comparisons can be made the vehicles on M15 have given a mean increase in volumetric fuel consumption of 3.7%, which corresponds to a reduction in total energy consumption of 4.1%.

(c) Test Track

Twelve vehicles have been tested using a modified SAE J1082 (10) interstate cycle procedure to obtain accurate fuel consumption comparisons between M15 and gasoline. Prior to the tests the ignition systems were set at manufacturer's recommendations, but carburettor settings were left as received.

The tests were carried out on a motor racing circuit approximately 3 km long, using ten laps for each test. To maintain objectivity, the two test fuels (gasoline and M15) were identified by a code unknown to the drivers. Fuel consumption was determined by measuring the weight of fuel consumed in each test. Each vehicle was driven on each test fuel by two drivers, and at each of two engine speeds (2000 rpm in top gear, and 3000 rpm in the next intermediate gear), to provide comparative data on the effect of engine/vehicle speed on fuel consumption.

The fuel consumption results are shown in Table 3. The mean change in fuel consumption for all vehicle/driver/speed combinations shows that the volumetric consumption of the M15 blend is some 3% greater than gasoline. Since the volumetric calorific value (nett) of the M15 is only 91.8% of that of gasoline (Table 1) an 8.2% volumetric consumption penalty might be expected. From the results obtained it is clear that the lower calorific value of M15 has been offset by improved engine efficiency. On an energy basis the change in fuel consumption equates to a reduction in specific energy consumption of 4.8%.

Component Compatibility

(a) Distribution System Components

Five different makes of kerbside pump have been used to dispense fuel to the test vehicles since the trials began. To date only three "in service" breakdowns have occurred as a result of material incompatibility with M15. The problems recorded were saturation of a cork float in the air eliminator, disintegration of a microfilter allowing dirt to enter the meter, and swelling of an O ring in a meter by-pass. In each case these components were replaced with readily available units known to be compatible with methanol gasoline blends, and the pumps have since operated satisfactorily.

(b) Vehicle System Components

Five of the test vehicles have experienced compatibility problems.

On one vehicle, the flexible fuel line (polyurethane) from the fuel pump to the carburettor collapsed twice within three weeks of operation on M15. This fuel line passed over and was clamped to the rocker cover, and this was the point of failure on both occasions. Replacement of this fuel line with one compatible with M15 (neoprene), and re-routing the line away from the rocker cover has enabled this vehicle to operate satisfactorily for a further 12 months without problem.

On a second vehicle the fuel line collapsed after one week on M15, where it passed through the body moulding, and it was replaced with neoprene. Examination of the failed line indicated that mechanical abrasion may have been more significant in its failure than incompatibility with the blended fuel. Certainly, the fuel line on a further example of this model has shown no signs of deterioration despite being operated on M15 for nearly 20 000 km. On this third vehicle, the carburettor float needle valve collapsed four days after it was brought into the trial. A replacement unit, and that in the first vehicle, have operated quite satisfactorily for over 12 months, suggesting the initial failure was due to mechanical collapse of the body rather than incompatability with M15.

A fourth vehicle suffered repeated swelling of the carburettor float after about ten days operation on M15, leading to severe carburettor flooding or complete fuel blockage. A float made of compatible material was not available for this vehicle. Low cost methods of treating conventional floats are being investigated.

On the fifth vehicle, the driver complained of a significant deterioration in performance. Examination showed that the accelerator pump seal had collapsed and upon replacement the vehicle has continued to operate satisfactorily. As the accelerator pump had been in use for over 177 000 km, it was concluded that mechanical degradation was the most significant factor causing the failure, rather than incompatibility with the blend.

On a number of other vehicles of the same model type, the fuel lines elongated. This has not caused any driveability problems, nor does the fuel line appear to have been affected in any other way by the blended fuel. Comparison of these vehicles with similar ones operating only on gasoline indicates that fuel line elongation can also occur, but to a lesser degree than with the M15 blend.

CONTINUING DEVELOPMENT

Although our current field experience now covers more than 12 months operation with M15, additional work is being carried out, or planned. This includes:-

(a) Compatibility testing of distribution and vehicle system components, in a dynamic test rig.

(b) Development of the most cost effective tank preparation procedure using the tank cleaning test rig.

(c) Erection of tank blending facilities at the installation to gain additional data on the blending and storage of M15 prior to distribution.

(d) Development of suitable techniques for the recovery and re-use of separated blend components.

(e) Continuing vehicle trial fleet monitoring.

(f) Monitoring used lubricating oil degradation in several test vehicles.

(g) Carrying out hot fuel handling, cold start and warm up vehicle dynamometer trials to determine the most satisfactory fuel specification for New Zealand in the event that methanol/hydrocarbon fuels are adopted. This work is being undertaken by the BP Research Centre in the UK, and supported by field trials carried out in New Zealand.

(h) Development of a fuel for further distribution/vehicle test work which most closely approximates the anticipated compositional and physical characteristics of the fuel which would be made available throughout New Zealand if the methanol extension programme were adopted.

(i) Development of tankship discharge procedures, and product handling techniques to minimise water pick up in methanol and gasoline.

(j) Implementation of a large scale distribution trial to several areas throughout New Zealand.

STUDY OF FULL SCALE PRODUCT DISTRIBUTION

Geographical

New Zealand is a long narrow country stretching 1500 km from latitude 34°S to 47°S. More than half of the population lives in the upper half of the North Island. Typical annual rain fall in inhabited areas ranges from 200 to 2000 mm, whilst temperatures vary from an infrequent extreme low of around minus 17°C to plus 38.4°C.

Gasoline Distribution

Six petroleum marketing companies supply the retail sector. 75% of the gasoline demand is produced at a single refinery located at the north of the North Island, from whence it is distributed by coastal tanker to strategically located ocean installations. The remaining 25% is currently imported. Inland depots are maintained for distribution to non-coastal points. Geographical aspects and coastal distribution patterns are shown in Figure 4.

The retail gasoline distribution system in New Zealand comprises about 3800 individual retail outlets, having approximately 10 000 underground tanks.

Ocean Terminal Discharge and Storage

Established operating procedures for discharging gasoline from tankships use sea water line cleaning after product discharge and the lines are left water filled when not in use. In storage, water will separate from gasoline quite rapidly and water contents of 100 ppm within a few hours of tank filling are achieveable.

Some ports also have chemical discharge facilities available, which are being assessed to ensure that in-tank methanol water contents can be maintained as low as possible. Procedures for dry storage of methanol, including the use of dessicator breathers are well established, although additional investment may be required to ensure tank suitability.

At this stage, the need for the addition of higher alcohols to improve blend water tolerance appears to be marginal but studies, using isobutanol, are continuing.

After a careful study of alternative distribution possibilities, it is envisaged that bulk storage of blend components would be maintained at ocean installations and in-line blending would occur immediately prior to distribution of product. This system of product blending/distribution is considered to be the best compromise in terms of distribution costs consistent with least exposure to blend contamination and possible phase separation by water.

Retail Storage

From a survey of existing retail tanks having no direct access water contents up to 0.1% of the tank volume have been measured. Other tanks removed for replacement have revealed iron oxide over the whole interior surface, while in some tanks a heavy sludge similar to alluvial mud occurs on the tank bottoms. This can be up to 20 mm thick with heaviest deposits away from areas of product movement.

Techniques for cleaning tanks containing these contaminants will be developed using the tank cleaning test rig.

CONCLUSIONS

1. During the last 12 months some 90 000 litres of M15 has been blended and stored in underground tanks at service stations in the Wellington area of New Zealand, where it has been used by a fleet of test vehicles.

2. The blend has been monitored constantly and once stabilised, no instance of phase separation has occurred.

3. Test vehicles were not tuned initially for operation on M15. In most instances there have been no adverse driver reactions to the test fuel. Where complaints have been made the main areas have concerned cold starting, warm up and some aspects of driveability. Following mixture adjustments during the trials these criticisms generally ceased.

4. Measurements of fuel consumption showed an average volumetric increase of 3%, and a decrease on an energy used basis of approximately 5%, when compared with gasoline operation.

5. Laboratory studies of the compatibility of the fuel distribution system and vehicle component materials in the presence of the methanol/gasoline blend indicated potential problems which, in general, have not occurred, or have been readily solved at low cost.

6. A study of the country's distribution system leads to the conclusion that, should a methanol blend be introduced on a national basis, storage and in-line blending of the methanol and gasoline at ocean terminals could be achieved satisfactorily.

Onward distribution and storage at the retail outlets could be accomplished with little chance of phase separation occurring due to the presence of water if relatively simple precautions, additional to those required for gasoline handling, were taken.

7. Simple techniques can be developed to clean and remove water from underground retail tanks in preparation for methanol/gasoline blends.

ACKNOWLEDGEMENTS

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The authors wish to thank their colleagues and vehicle drivers in New Zealand, and personnel in the United Kingdom all of whose assistance was of great value in preparing this paper.

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TABLE 1

TYPICAL FUEL CHARACTERISTICS

Inspection Data		Premium Gasoline ex New Zealand Refining	M15 Blend	Methanol
Density at 15°C	kg/litre	0.739	0.744	0.794
Research octane number		96	102	110
Motor octane number		89	91	86
Lead content	g Pb/litre	0.83	0.71	Nil
Distillation				
IBP	°C	30	30	65
10% volume recovered at	°C	55	50	
20% " " "	°C	67	57	
30% " " "	°C	80	65	
40% " " "	°C	90	70	
50% " " "	°C	102	96	
60% " " "	°C	114	111	
70% " " "	°C	120	117	
80% " " "	°C	140	137	
90% " " "	°C	160	158	
FBP	°C	190	190	65
Reid vapour pressure at 37.8°C	kPa	70	90	
Latent heat of vapourisation	kJ/kg	354	484	1 170
Stoichiometric air to fuel ratio		14.7	13.4	6.5
Calorific value, gross	kJ/kg	47 098	43 557	23 492
nett	kJ/kg	43 729	40 160	19 934

TABLE 2

TANK CLEANING TEST RIG

Water content of 8500 litres of a 3.5% vol isobutanol, 11.5% vol methanol, 85% gasoline blend on top of 15 litres water, circulated through a 12 mm nozzle at 180 ± 10 litres/minute (Test 4)

Sampling Position (see Figure 2)	Circulation Time min			
	0	10	20	30
	Water Content, ppm, unless % Indicated			
1C	3738	90 000	3400	2241
3C	77.5%	4 246	2242	2208
4C	89%	2 563	2241	2291
5C	90.8%	2 454	2283	2247
1B	360	2 225	2279	2225
2B	326	3 204	2221	2233
4B	432	2 217	2254	2332
5B	613	2 213	2212	2247
2A	327	2 234	2250	2233
5A	315	2 213	2212	2255

TABLE 3

TRACK FUEL CONSUMPTION TESTS
COMPARISON BETWEEN M15 AND GASOLINE

Vehicle	Year	Engine Size cc/cylinders	Average Road Speed km/h		% Change using M15 Compared with Gasoline	
			2000 rpm in Top	3000 rpm Gear below Top	Volumetric Consumption	Total Energy Consumption
1. Ford Cortina	1977	1593/4	54.6	59.1	+3.0	-4.8
2. Morris Marina	1976	1798/4	57.3	56.8	+0.1	-7.4
3. Mazda 808	1977	1272/4	48.8	56.0	+4.9	-3.0
4. Holden Kingswood	1974	3310/6	62.8	56.3	+1.8	-5.9
5. Holden Torana	1976	1897/4	55.5	59.9	+5.6	-2.4
6. Ford Cortina	1974	1998/4	58.6	62.5	+3.0	-4.8
7. Vauxhall Chevette	1977	1256/4	52.2	55.2	+7.2	-0.9
8. Ford Escort	1978	1298/4	50.6	52.4	+4.3	-3.6
9. Mitsubishi Lancer	1977	1238/4	43.6	44.7	+1.7	-6.0
10. Datsun 180B	1977	1770/4	58.9	63.8	+2.4	-5.3
11. Chrysler Avenger	1978	1599/4	54.8	57.9	-2.0	-9.4
12. Toyota Corona	1977	1587/4	54.4	54.6	+4.4	-3.5
				Mean % change	+3.0	-4.8

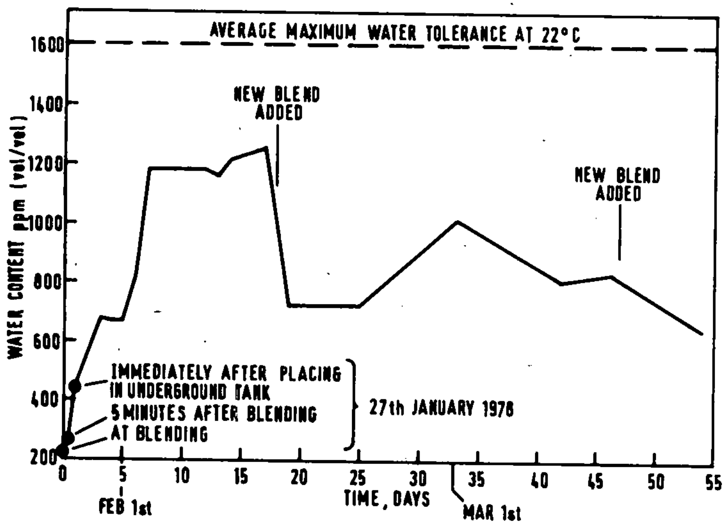


FIG 1 WATER CONTENT OF M15 IN AN 8 YEAR OLD 2200 LITRE CAPACITY UNDERGROUND TANK

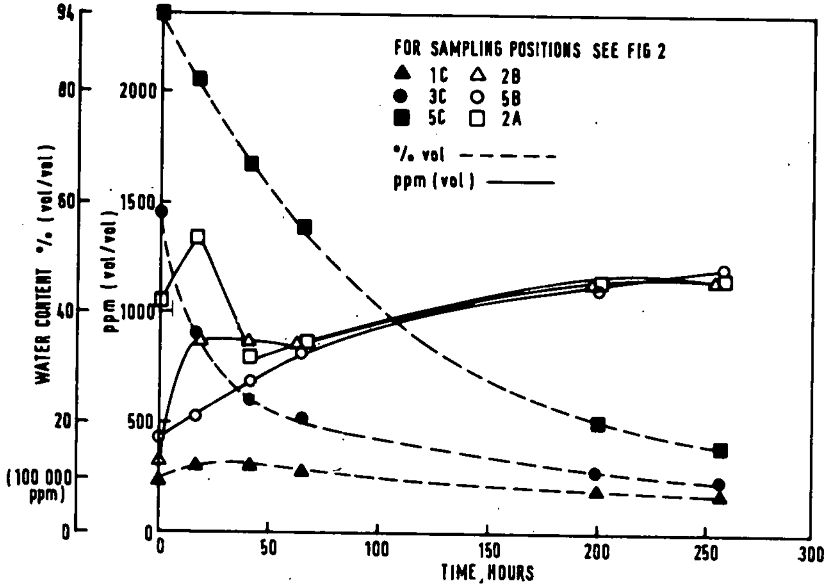
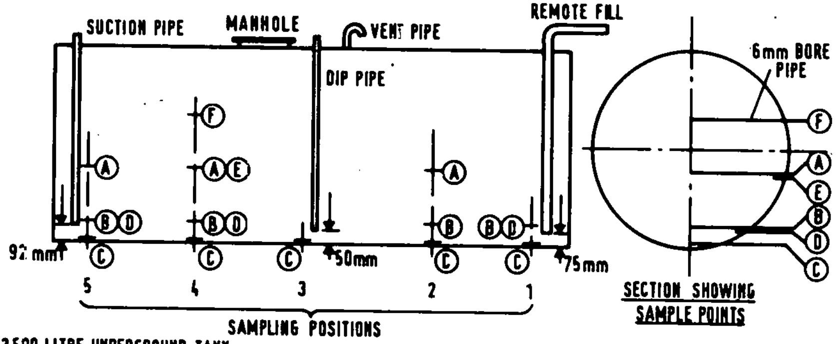
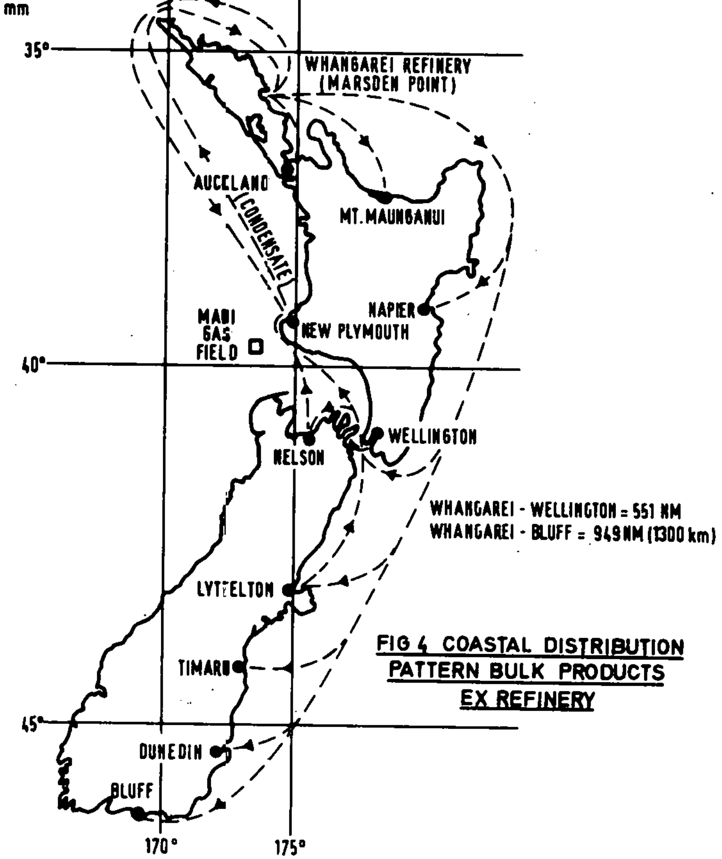


FIG 3 TANK CLEANING TEST RIG. VARIATION OF WATER CONTENT WITH TIME (TEST 3, STATIC)



13500 LITRE UNDERGROUND TANK
1800 mm dia x 5500 mm LONG
NOTE
TANK INSTALLED WITH 30 mm FALL TO SUCTION PIPE.

FIG 2 TANK CLEANING TEST RIG



WHANGAREI - WELLINGTON = 551 NM
WHANGAREI - BLUFF = 949 NM (1300 km)

FIG 4 COASTAL DISTRIBUTION PATTERN BULK PRODUCTS EX REFINERY

ALCOHOL/GASOLINE RELIABILITY FLEET TESTS:
A U.S. FEDERAL PROJECT

by

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ABSTRACT

Investigation of alcohol fuels for the past several years has provided a sufficient data base to enable systems engineering to identify optimum fuel/engine/vehicle combinations suitable for large scale proof-of-performance field tests of alcohol/gasoline blends. Stimulated by Congressional funding for planning and initiating alcohol/gasoline fleet tests in Government vehicles, the Alternative Fuels Utilization Program (AFUP) is proceeding to conduct these systems and reliability tests in parallel, with the goal of achieving utilization readiness for commercial adoption cica 1982-83. Formulated fuels and appropriate engines have been specified for comparative testing under the systems-oriented Controlled Fleet Test phase. Based on the results of these tests, two fuels will be selected for the Reliability Fleet Test phase. One fuel will be an ethanol/gasoline blend, and the other will be either a methanol/gasoline blend or a methanol/ethanol/gasoline blend. All fuels involve 10-volume percent alcohol. Fuels and vehicles will be representative of anticipated commercial products. Field tests will involve a variety of climatic conditions over a minimum of two annual cycles.

BACKGROUND

Ethanol and methanol are among the nonpetroleum fuel options which can be derived from resources available in abundance in the U.S. to replace current liquid fuels. The Alternative Fuels Utilization Program (AFUP) of the Office of Transportation Programs (TP), Department of Energy (DOE), therefore includes an alcohol fuels program for highway vehicles(1)*. While the longer-term objective regarding alcohol fuels is the optimization of resource/engine/fuel systems based on neat alcohols, the near-term goal is to test and evaluate alcohol/gasoline blends in commercial and government fleets in order to prove the practicability and reliability of blends as a transition strategy to alcohol fuels or as a progenitor of alcohol/synfuel blends(2). Assessment and evaluation studies of alcohol/gasoline blends in spark ignition internal combustion engines were initiated in 1977, with problem solving on these fuels to be completed in 1979.

*Numbers in parenthesis ( ) indicate references listed at the end of the paper.

In developing an alternative fuel/engine system, the time-phased activity flow follows the same general logic regardless of fuel, shown in Fig. 1. First, the candidate fuel is characterized and operational tests are made in appropriate engines to identify and understand the problems in the fuel/engine/vehicle system. Next, a broad spectrum of candidate solutions are examined and developed. Then the best combination of solutions is used in a system design aimed at optimum results, and this is tested and evaluated. Now, several vehicles embodying the selected design are tested in controlled fleet tests and deficiencies are corrected, thus finalizing the design. At this point, the program will have progressed to where performance and socioeconomic viability of alcohol/gasoline blends will have been established. The next sequential step is the demonstration of commercial readiness for the fuel/engine system from the end-use standpoint (including distribution) through the successful accomplishment of large-scale reliability fleet testing and associated statistical proof of performance.

Because the problems associated with the utilization of alcohol/gasoline blends, as well as their potential solutions, are not complex, it appears feasible to conduct these latter test phases concurrently with minimum risk and thereby shorten the overall schedule. Using this approach, it is planned that reliability fleet testing be initiated on a limited scale by the end of 1979, scaled up as soon as practicable, and completed in 1982 or 1983, thereby saving about two years(3). This approach meets the desires of the Congress which added funds to the AFUP FY 1979 budget for planning and initiating fleet tests of alcohol/gasoline blends in Government vehicles. Thus, this project is a combination of Controlled Fleet Tests and Reliability Fleet Tests, with the activities scheduled such that pertinent information from the first appropriately feeds the second in a timely fashion.

TEST ADMINISTRATION

Activities will involve two complementary operations. An Industry Group will consist of representatives of vehicle and fuel suppliers to provide technical expertise and guidance during the course of the project. An Operating Group, comprising governmental activities and private business enterprises, will provide the vehicles and fuels as well as conduct the field operations. Thus, the approach involves parties that would and/or could serve as major initial customers.

Unlike many other fleet test exercises that are conducted to determine the performance and compatibility of new products, this program is characterized by the added constraint of limited availability of the test product itself, viz., the alcohol/gasoline blend. Furthermore, there is no distribution experience on a national or regional basis, nor dedicated equipment in place to handle these fuels. From the vehicle standpoint, it will be necessary to insure that those to be used in the program are suitably modified/designed as necessary to accommodate the blends.

Thus, it is evident that both of these technical groups must be involved in the project at an early stage. The Industry Group will be responsible for a wide variety of activities including, but not limited to, reviewing and recommending:

1. Fuel specifications and test methods,
2. Alcohol and gasoline suppliers,
3. Alcohol/gasoline mixing and transport methods,
4. Facilities for wholesole/retail storage,
5. Fuel surveillance procedures (sampling and test),
6. Vehicle modifications,
7. Special vehicle maintenance and inspection procedures,
8. Special parts support (as required),
9. Recordkeeping for all supply activities,
10. Statistical analysis methodology,
11. Vehicle and fuel test data.

An eminent choice to coordinate the industry activities is the Coordinating Research Council (CRC). As an independent organization with a membership of over a thousand drawn from the petroleum and automotive industries, and with long involvement in fuel research and testing, CRC appears to be unique as a means of providing this service.

An independent organization with extensive experience in fuel, lubricant, engine, and vehicle testing will be selected to manage the Operating Group program. The list of activities for which the Operating Group manager will be responsible includes:

1. Detailed test planning and overall management of fleet operations,
2. Selection of the reliability fleets and test facilities,
3. Establishment of operating and maintenance procedures, including fuel economy and emissions tests,
4. Selection of (modified) vehicle suppliers and procurement of required vehicles,
5. Selection of fuel suppliers, fuel procurement, distribution, and storage,
6. Definition of reporting requirements and forms, to include driver surveys, and
7. Compilation of test results, data assessment, economic analysis, and preparation of final report.

With a nationwide project of the scope envisioned herein, and the two major participating groups described above, it is clear that detailed planning and close coordination of all facets are mandatory. This will be achieved by use of the organization shown in Fig. 2. The Aerospace Corporation, a Federal Contract Research Center, has been assigned the following functions by DOE:

1. Integrate the activities of the Industry and Operating Groups to assure compatability and achievement of objectives within financial constraints.
2. Provide overall project management under the supervision of the DOE Project Manager.
3. Conduct related special studies and tasks as requested.

CONTROLLED FLEET TESTS

The purpose of this activity is to assure the technical participants and stakeholder community that suitable solutions to problems are incorporated in the fuels and vehicles used and that the fuel/engine/vehicle design is optimized for commercial applications. To achieve this goal, the Controlled Fleet Test activity will be conducted by the Industry Group.

Most of the test fuels will be formulated to meet appropriate specifications reflecting consideration of both operational performance and supply capabilities. While they will consist of 10-volume-percent alcohol (made up primarily of ethanol and/or methanol) in gasoline, the alcohol portion will not be restricted to pure products. Depending on the results of ongoing testing to establish blend requirements, the alcohol phase may contain higher alcohols and ethers, and in the case of ethanol, unpotable impurities and various denaturant constituents. However, it is expected that the alcohol portion in all cases will have to be essentially anhydrous, this requirement being of particular importance for the methanol blends. The gasoline component of these formulated fuels will be unleaded, regular grade, generally conventional types for which some basic properties may be modified or uniquely specified, for example, Reid Vapor Pressure. A typical gasoline will be used as a control, and Gasohol* will be included since it is in commercial trade.

Fuels and engine/emission control system packages have been identified for the Controlled Fleet Tests.' Sixteen engine/emission suste, combinations will be used which are representative of anticipated automobile production in the 1982-85 and beyond time period. Vehicles using these engines have yet to be selected. A base gasoline, Gasohol and three other formulated ethanol/gasoline blends have been specified. Each fuel will be tested in all vehicles for driveability, fuel economy, evaporative emissions, regulated exhaust emissions (HC, CO and NO_x), unburned alcohol and aldehydes. About five methanol fuels will be similarly tested in the vehicles, but bench tests will first be run on about 24 compositions before final selection is made. Other fuel/engine/vehicle tests, not yet specified, will also be conducted as part of the Controlled Fleet Tests.

*Gasohol is a registered trademark of the Nebraska Agricultural Products Industrial Utilization Committee. It is a fuel currently marketed in the Midwest, consisting of 10-volume-percent ethanol in conventional regular grade unleaded gasoline. Inasmuch as it is not formulated to meet a standard specification, samples of commercial Gasohol may differ considerably in volatility from the base gasoline and exhibit variations among themselves in composition and other properties.

RELIABILITY FLEET ACTIVITIES

The principal goal of the reliability fleet testing program is to successfully demonstrate, under a variety of operational conditions, the supply, distribution, and utilization of 10-volume-percent alcohol/gasoline blends**, including both methanol- and/or ethanol-based alcohols. Fuels for this program will consist of a formulated ethanol blend and either a formulated methanol or a composite ethanol/methanol blend.** Specific fuels and formulations will be determined on the basis of results from the Controlled Fleet Tests. Some of the expected ancillary outputs from the program include:

1. Establishment of a performance and reliability data base for in-service operation under a wide spectrum of conditions,
2. Accumulation of fuel supply system experience to guide subsequent design of commercial facilities,
3. Definition of requirements and procedures for maintenance support, and
4. Development of more precise impact and market assessment data.

The minimum evidence of test program success will be achievement of commercial readiness for the fuel blends. If the blends are economically competitive at the time of test completion, it is likely that commercialization will be initiated. If the economics are marginal, local or Federal organizations may continue commercial operations on the basis of local, state, regional, or Federal subsidies and/or incentives.

Reliability Fleet Tests will be conducted by the Operating Group, which will be composed primarily of government activities and private companies who operate vehicle fleets in various parts of the country. On the government side, representation may be at the Federal level, e.g., DOE, GSA, DOD, EPA, DOT, and the Postal Service.*** States may participate on an individual basis and possibly tie-in through regional organizations, such as the National Gasohol Commission.

At the local level, both city and county governments often operate pools for official cars and also attendant maintenance facilities. In addition, they may also have cognizance of trucks and buses that would be suitable for participation in the project.

There are many opportunities for fleet participation in the private sector, ranging from taxicabs and delivery vehicles to executive cars. However, an important business consideration is that little interruption of normal operations can be tolerated.

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*As used in this document, the term "blends" includes fuel mixtures such as Gasohol and formulated blends which must meet certain specifications for composition, volatility, octane number, etc.

**In addition to these formulated fuels, some early fleet tests may utilize commercially available Gasohol in unmodified used vehicles.

***Interest has also been expressed by the Canadian Government in some type of joint fleet test participation.

Three categories of fleets are envisioned for the reliability program: Participating, Affiliated, and Cooperative Fleets. The first type will most closely adhere to program parameters and controls, receive primary funding consideration, and provide the primary data base. The Affiliated Fleets will operate essentially in accordance with Participating Fleet procedures but may not be able to provide all of the services and controls required of the Participating Fleets. Fleet operations differing substantially from those for the other two categories will be included in the Cooperative Fleet category. Data from these fleets are expected to be mainly of qualitative value. The degree of Federal funding, if any, for the latter categories is at present undetermined.

RELIABILITY FLEET SELECTION

Program emphasis will be on conventional spark-ignited internal combustion (Otto cycle) engines.

In order to achieve the most information of broadest possible application to the gasoline-powered highway vehicle population, care is required in selecting the test fleets to be used in the program. It is clear that the selection process will require an iteration of numerous factors, particularly those associated with climatic conditions, available vehicles, and fuel logistics.

Although tests of Gasohol have been conducted by some states in the Midwest and these states do experience a wide temperature swing between summer and winter, they do not encounter the extreme temperature and humidity limits within the contiguous U.S. In addition, they have not necessarily had much experience in, for example, bumper-to-bumper freeway traffic at temperatures of 100°F or more. It is, therefore, incumbent in selecting geographical sites for the test fleets that at least the following factors be considered, separately and in combination:

1. Temperature--high and low extremes,
2. Altitude--sea level to high altitude,
3. Moisture--dry to high humidity, snow and rain,
4. Terrain--flat to mountainous, and
5. Traffic--open to heavy congestion.

Year-round operation will be the general rule, particularly in areas that experience significant seasonal variations. Also, exposure to some of these extremes will be more critical for methanol/gasoline blends than for ethanol/gasoline.

The important factors to consider in the selection of the fleet operators, in addition to location which has been covered above, include the following:

1. Size of fleet and types of vehicles, including gasoline-fueled control groups;
2. Vehicle duty cycle--day operation only, all year, mileage per year, continuous cruise or stop-and-go;
3. Support facilities--in-house fueling, maintenance capability, parking accommodations;
4. Recordkeeping--existing procedures and forms; and
5. Financial responsibility--interest in cost-sharing or required incentives.

In keeping with the basic premise that the reliability tests should encompass as wide a variety of vehicle applications as possible, candidate operators should include taxi fleets, delivery services, trucking companies (gasoline-powered trucks), government car pools and Postal Service vehicles. Selection must keep in mind the overall objective of proving the commercial viability of engine/vehicle systems that utilize formulated alcohol/gasoline fuels. Consequently, the vehicles must be as close as possible to what the auto industry will provide to the general public; thus, there is a probability that all vehicles specifically modified by the manufacturer to be compatible with alcohol/fuel blends may have to be new. To reduce costs, such vehicles may be obtained through purchasing pools. In the case of Gasohol, it will be expeditious and appropriate to use unmodified cars in the test fleet to duplicate present, albeit limited, consumer usage.

Where possible, fleets will be selected in proximity to existing laboratories or testing facilities in order to obtain emission levels and other controlled test data at selected time periods over the duration of each fleet test.

At this time the number of fleets and the number of vehicles have not been determined. The minimum number needs to be sufficient to satisfy the stakeholder industries and assure statistically significant data.

FUEL SUPPLY FOR RELIABILITY FLEETS

Supplying the ethanol/gasoline and methanol/gasoline blends for the fleet tests will be a major part of this program. Demonstration of the effectiveness of the fuel distribution system is, in fact, an important project goal. The exact nature of the requisite system is not defined at this time, but of overriding importance will be the location and size of the test fleets since this will dictate the volume of fuel to be delivered and its destination.

It is not expected that methanol from coal or biomass will be available in required quantities for this program, although some might be produced during the later portion of the project. However, specifications for the methanol fuel phase is expected to take into consideration subsequent products derived from coal or biomass. Ethanol is available either from natural sources via fermentation or synthetically from petroleum. Fermentation ethanol will be given preference.

Regardless of the alcohol or its source, it must be mixed with gasoline at some point in the distribution system. There are a number of options for this operation, and the methods used need to be determined. To a considerable extent this is dependent on the number and location of the vehicle fleets.

An attempt to locate fleets in proximity to fuel suppliers will be made to avoid the high cost of fuel transportation. Samples of fuel from each supplier will be placed in a limited storage stability test. Also, additional fuel sampling/analysis will be undertaken by qualified laboratories to ensure fuel property consistency and purchase description compliance.

It is anticipated that if any problems in supply or vehicle operations occur, the fuel or vehicle supplier will be apprised of the difficulties and expected to provide field fixes or correct future deliveries. In addition, the Industry Group will monitor and assess test data and advise the Operating Group Manager regarding any desired changes or adjustments in field activities. Through these mechanisms the appropriate degree of reliability will be achieved to assure success.

SUMMARY

Parallel Controlled Fleet Tests and Reliability Fleet Tests, addressing fuel/engine/vehicle systems solutions and field proof-of-performance, respectively, will be initiated later this calendar year. Fuels and engine/emission system configurations for the former have been identified by the fuels and automotive industries. The tests will gather data on driveability, fuel economy and emissions. Based on the results of these tests, two fuels will be specified for use in the Reliability Fleet Tests, which will provide statistical proof of performance. One fuel will have ethanol as the primary alcohol component, while the other will be based on methanol or a methanol/ethanol combination. All fuels are nominally 10-volume percent alcohol. Organizational details have been established, as have criteria for selection of operating fleets. Tests will involve operating in a variety of climatic conditions, over at least a 2-year period. Successful completion of the tests will result in achieving utilization readiness of alcohol/gasoline blends for commercial implementation in the U.S.

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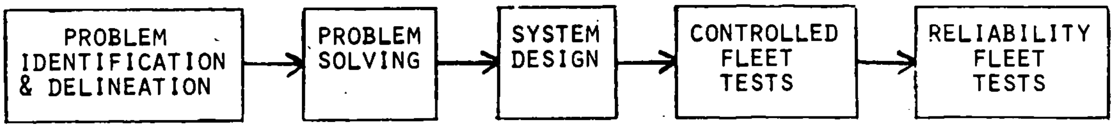
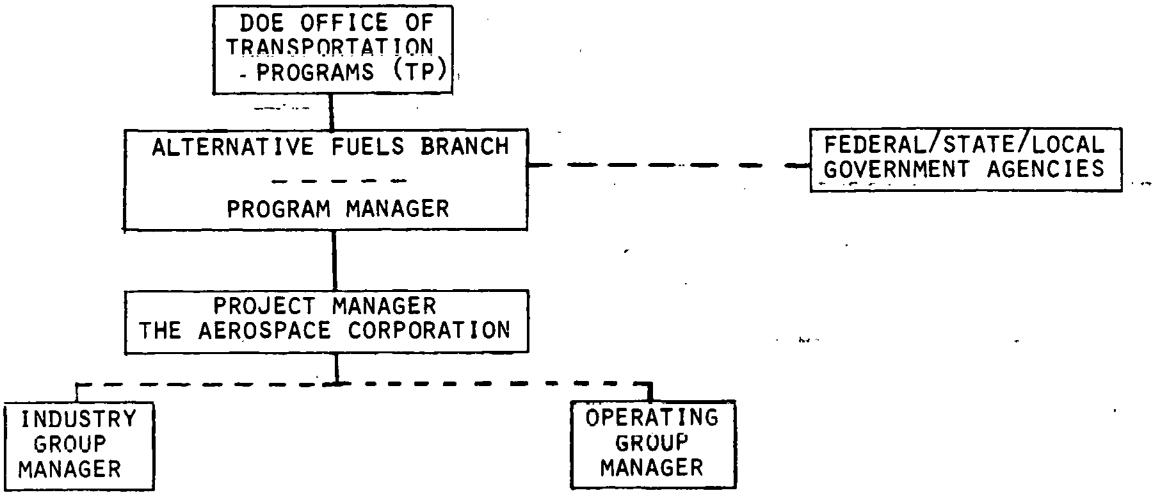
SEQUENCE OF FUEL/ENGINE DEVELOPMENT FOR ALTERNATIVE FUELS

FIGURE 1



MANAGEMENT ORGANIZATION STRUCTURE

FIGURE 2



- GOVERNMENT FLEETS
- PRIVATE BUSINESS FLEETS
- AUTOMOTIVE COMPANIES
- FUEL SUPPLIERS

MID-TERM PROSPECTS FOR THE USE OF ALCOHOLS AS MOTOR VEHICLE FUELS

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ABSTRACT

The paper presents a brief discussion of the world energy resource situation and concludes that non-petroleum based substitute fuels will be needed for automobiles in the foreseeable future. Volkswagenwerk feels that practical substitutes for fossil fuels include methanol that can be obtained from coal, natural gas, and municipal waste; and ethanol from biomass, such as sugar cane, cassave, sweet sorghum, or other plants.

The paper reviews various approaches to the production of alcohols and their application in motor-vehicle diesel and spark-ignition engines. The diesel engine development work focused on dual-fuel operation with alcohol and diesel oil and on the use of ignition-improving additives. A variety of spark-ignition engines (S.I.E.) concepts was found to be feasible for operation on methanol, ethanol, alcohol/gasoline blends, and other alcohols. A description is presented on the extent and current status of Volkswagenwerk's research and development activities in the area of various S.I. alcohol-powered engines. It was found that fuel blends consisting of gasoline and more than 15 - 20% methanol or 20% ethanol require redesign and modifications to the base engine concepts because of the properties of alcohols which differ from those of today's automobile fuels.

It was found the alcohol fuels are the most readily obtainable alternatives of all substitutes and that they might be made available in substantial quantities within the foreseeable future.

INTRODUCTION

The primary energy resource situation (reserves, availability, prices) recently has come into the focus of attention throughout the industrialized countries of the world as it had during the peak of the 1973/74 energy crisis (1,2,3)*. The most significant reasons are the dwindling primary energy reserves, especially crude oil and natural gas, and the political instability of some oil-producing countries. Even though the world's motor-vehicle population of 330-million units (1978) uses a mere approximately 11% of all crude oil (see Fig. 1), it may be stated that automobile operation fully depends on fossil fuels. This, then, is the reason why the automobile industry must at this time research into possible alternatives for non-fossil fuels that can be obtained from other primary energy sources such as coal, natural gas, nuclear energy, oil shale, tar sands, and biomass. It appears that methanol and ethanol offer the greatest potential of all alternative fuels under discussion.

The paper discusses the possible application of these alcohol fuels in automobiles as seen by the automobile industry, and especially by Volkswagenwerk AG.

THE WORLD ENERGY RESERVES

Future automobile fuels will be of significance only if they are produced at reasonable cost (4) from primary energy sources that are either available in large quantities or can be renewed continuously. Figure 2 is an overview of the world's energy potential and shows the geographic distribution of the non-regenerative fossil energy sources (petroleum, natural gas, coal), of the non-regenerative sources of nuclear energy (uranium for nuclear fission processes), and of the regenerative energy source biomass. It may be seen that today's exploitable energy reserves are as follows:

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*The numbers in brackets designate references at the end of the paper.

Petroleum	145-billion tons SKE
Natural Gas	743-billion tons SKE
Coal	591-billion tons SKE
Uranium	153-billion tons SKE

(1 ton SKE = $3 \cdot 10^7$ BTU)

The graph in Figure 2 also shows that the potential of the world's present biomass roughly equals 1000-billion tons SKE. This is more than 100 times the world's primary energy consumption in 1978. It should be borne in mind, though, that only the net primary productivity of the photosynthetically active organisms in the biomass are of interest because it constitutes the ceiling of the bioconversion potential. The net primary energy production of the biomass is estimated at roughly 40-billion tons SKE (5) and thus equals an average of.2% of the sun's radiated energy received on Earth. The technically exploitable biomass production could approximately satisfy the present energy demand of the world if large-scale biotechnological processes are employed at a conversion rate of 25%.

It is concluded, therefore, that after the foreseeable exhaustion of petroleum (see Fig. 3) and natural gas, coal and nuclear energy carriers are the only non-regenerative sources that will have a future because of the more favorable reserve situation and the more evenly spread geographic distribution. This especially applies to the area of motor-vehicle technology. In addition to that, biomass will become increasingly important as a source of automotive fuel and as a base material for the chemical industry despite the present high cost of the conversion of biomass to secondary energy (6). While petroleum will continue to be available for more than two decades (Fig. 3), petroleum prices will continue to rise (Fig. 4). Consequently, the coal- and biotechnologies will be able to compete with the present petroleum technologies in the next five or ten years.

ALTERNATIVE AUTOMOTIVE FUELS

Economic Considerations

Figure 5 is a comparison between the potential energy carriers and the most important alternative fuels for automotive application. A comparison between the energy prices of some selected fuels (3,7) with the price of gasoline (distilled from crude bought at $16/bbl), see Figure 6, shows that in addition to coal-derived methane, coal-derived methanol and biomass-derived ethanol may be produced at low cost. Methane application in motor vehicles is limited because it must be liquefied and requires special tanks. Alcohols, however, normally are liquid substances and thus can be distributed, stored and used like any other present motor-vehicle fuel.

Alternative fuels and energies will differ among different geographical regions. This distribution is assumed to be as shown below:

Brazil	Ethanol from sugar cane, maniok, and sweet sorghum; perhaps methanol from wood (eucalyptus).
South Africa	Fischer-Tropsch gasoline and diesel fuel from coal, ethanol from sugar cane.
New Zealand	Methanol from natural gas
Germany, Poland, Soviet Union	Methanol from coal
Sweden, Canada	Methanol from wood, peat, oil shale, and municipal waste
Phillipines, Thailand, Hawaii	Ethanol from sugar cane
U.S. Midwest	Ethanol from various agricultural production (corn, milo, etc.);
California	methanol from various sources.

In view of the possibly different alternative fuels developments in certain regions (especially in regard to alcohol), the automobile industry not only is interested in the levels of production cost but also in the effectiveness of energy conversion in the engine/vehicle system in order to be able to determine the cost of operation. Figure 7 shows the energy consumption data determined in the Europe Test on a vehicle the size of a VW Rabbit (8). Diesel oil and alcohol fuels (methanol/gasoline blend M15, pure methanol, and pure ethanol) produced very good results. The comparatively low electricity consumption is due to the energy regeneration during deceleration phases.

Figure 8 shows the operating cost based on the energy consumption in the Europe Test (ECE Test) for the alternative fuels listed in Fig. 7.

Figure 9 shows the energy operating cost including the possible extra cost for the powerplant or the energy storage unit (batteries and cryogen tank) and the assumptions submitted in Table 1. The energy cost of alcohol-fueled powerplants are comparatively low when compared with the anticipated cost of gasoline-powered units in the foreseeable future.

APPLICATION OF ALCOHOL FUELS

Possible Application in Gasoline and Diesel Engines

It was shown earlier that the economic use of alternative fuels primarily depends on the availability and price of the raw materials required and also on the process of converting the source energy into fuel and the fuel into power on board the vehicle.

On the basis of the present state-of-the-art there are the following possible applications for methanol, which can be derived from coal, natural gas, residual oil, wood, municipal waste, and biomass (see Fig. 10):

1. Gasoline Engine

1.1 Methanol/gasoline blends with a methanol content of up to 20% (e.g. M 15), depending on the quality of blend preparation. Requires only minor engine and vehicle modifications.

1.2 Dual-fuel operation methanol/gasoline with a methanol content of up to 30%. Disadvantage: vehicle needs two tanks and two fuel systems.

1.3 Pure methanol operation (M 100) or a blend of up to 90% methanol and high alcohols, ethers, etc. for increased volatility and better cold-start behavior. High compression ratio. Special spark plug design required in order to avoid pre-ignition. This type of operation requires a special intake system and a distributor and fuel preparation system calibrated for methanol.

2. Diesel Engine

2.1 Dual-fuel operation on methanol/diesel (engine requires modification for methanol operation). The substitution percentage is limited by quench and knock behavior requirements and varies between 35 and 80%. Manifold or direct injection.

2.2 Base diesel engine converted to a high-compression methanol engine.

2.3 Diesel engine operated on methanol with the aid of ignition-improving additives (adaptation of the methanol fuel to the diesel engine requirements).

Ethanol can be made from the so-called energy plants, such as sugar cane, sugar beet, sorghum, and maniok as well as wood and coal (see Fig. 11). Ethanol can be used for the following applications:

3. Gasoline Engine

3.1 Operation on ethanol/gasoline blends that contain up to 25% ethanol (e.g. "Gasohol", E 20). This type of operation requires only minor modifications to the engine and vehicle. The ethanol component must satisfy certain specifications in regard to acid and water content.

3.2 Dual-fuel operation on ethanol/gasoline (see 1.2 above).

3.3 Operation on pure ethanol (E 100) or ethanol fuel. The ethanol fuel must have a higher content of volatile components than the methanol fuel. The required engine modifications are outlined in 1.3 above.

4. Diesel Engine

4.1 Dual-fuel operation on ethanol/diesel fuel (see 2.1 above).

4.2 Ethanol operation with ignition-improving additives, ethanol/diesel fuel mixtures, and ethanol/diesel fuel emulsions.

Work is being done throughout the world in the area of possible applications of future alcohol fuels (3, 8 - 12). Major efforts in alcohol fuel technology (production, distribution, application) have been made in Germany (Federal Republic) since 1975 within the framework of research and demonstration programs that were supported by the German Federal Ministry for Research and Technology. In Germany, Sweden, Canada, New Zealand and recently, California, alcohol fuel work is focused on methanol fuels (blends and pure) (3). Volkswagenwerk found that methanol/gasoline fuel blends such as M 15 can be made at lesser cost than gasoline because of the octane-boosting effect, which in turn results in lower energy operating cost. It is entirely feasible, therefore, that M 15 fuels will be available soon in Europe, Canada, New Zealand, and California.

The situation is similar for ethanol/gasoline fuel blends. "Gasohol" (E 10) is on the market in the U.S. Midwest, and E 20 in the Brazilian states of Sao Paulo and Rio.

Vehicle-Related Measures for Alcohol Fuel Operation

Measures related to the vehicle must be prepared in addition to the diesel or gasoline engine modifications required for alcohol fuel operation. These measures would be related to the following aspects:

- Economy
- Vehicle safety (e.g. in regard to the different flashpoint temperature and ignition limits of alcohol fuel versus gasoline)
- Space availability (larger fuel tank)
- Material selection
- Driveability (especially cold-start driveability)
- Behavior at extreme temperatures (cold start, hot start, vapor lock)
- Durability (e.g. corrosion problems, lubricant behavior)
- Exhaust gas emissions.

The following advantages and problems emerge for alcohol-operated vehicles versus present cars:

Gasoline/methanol- and gasoline/ethanol-blend fueled vehicles:

- slightly improved economy and at times significantly improved exhaust-gas emission behavior after adaption of the carburetion or injection system to the fuel blend.

- fuel supply system components must be compatible with alcohols.

- Larger tank is not required.

- Driveability problems are posed during engine warm-up; vapor lock and durability problems may occur.

Vehicles powered with pure-alcohol fueled SI engines (see Figure 12):

- Substantially improved economy. Substantial reduction of NOx and unburned fuel component emissions.

- Fuel tank must be enlarged by 40% (ethanol) up to 95% (methanol) for the same operating range.

- Cold-start aid or addition of highly volatile additives to alcohol.

- Suitable materials should be subjected for the intake and exhaust systems in order to eliminate possible corrosion.

Alcohol-fueled diesel engines:

- The simultaneous combustion of alcohol and diesel oil in the engine reduces the emission of soot, NOx and PNA and does not affect the economic operation.

- The preparation and injection of a homogeneous mixture of alcohol and diesel oil is technically feasible but requires a comparatively high engineering outlay. Its disadvantage is demulsification of the mixture when the engine is not running or during cold start. The pilot injection process, i.e. the separate injection of alcohol and diesel oil by separate injection systems, permits the processing of large portions of alcohol. The process appears to be economical, does not produce any soot, and keeps the noise level low.

- The alcohol/diesel fuel dual-fuel operation improves fuel economy and reduces soot formation. Its disadvantage is the comparatively small portion of the diesel fuel that is replaced by alcohol.

SUMMARY AND CONCLUSIONS

In conclusion, it may be stated that alcohol fuels from available resources such as coal, natural gas, biomass, waste, etc., are the most readily obtained of all alternative fuels for automobiles during the coming decades. This especially applies to methanol and ethanol fuels and blends which could be made available in substantial quantities in a mid-term approach. Other mid-term candidates may be alcohol/gasoline blends.

The alcohol-fueled automobile engine is a feasible powerplant for the intermediate term because alcohol can be produced by today's technology. The powerplant can be based on the current spark ignition gasoline engine and would require comparatively few and simple modifications. Automobile makers such as Volkswagen can produce vehicles for operation on either pure alcohol or alcohol/gasoline blends.

Regardless of what alternative fuels there will be, Volkswagenwerk AG is undertaking every effort to make sure that the proper technology is available.

This is one of the reasons for the deep involvement of Volkswagenwerk's Research Division in the 4-year program of the German Federal Department of Research and Technology, under which large-scale alternative fuel tests are performed, especially on alcohol-fuel-powered vehicles. Many problems remain to be solved in the area of the economic use of alcohols in diesel engines.

Table 1: Assumptions for the Computation of Consumers' Energy Costs

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- Vehicle: VW Rabbit (passenger car)
- Compared with the current gasoline vehicle no additional cost to the consumer for
    - M 15
    - Methanol fueled vehicle
    - Ethanol fueled vehicle
- Lifetime of the vehicle 10 years; mileage 8,000 miles per year (13,000 km per year)
- Additional cost for

- Diesel engine	$600
- Electric-battery-powered vehicle	$500 for one battery set (lifetime 450 ... 700 cycles, 50 km/cycle)
- Methane-fueled vehicle for the cryogenic tank (LNG)	$1100

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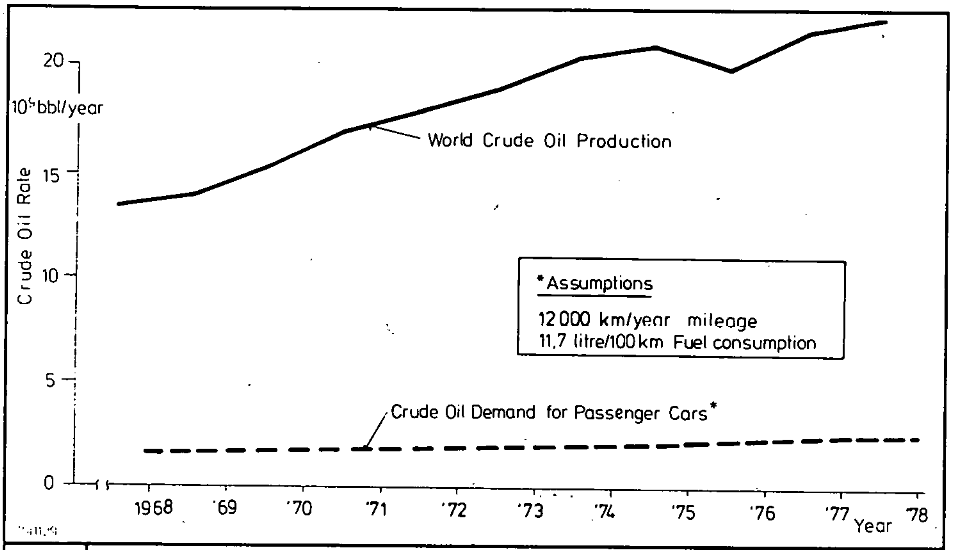
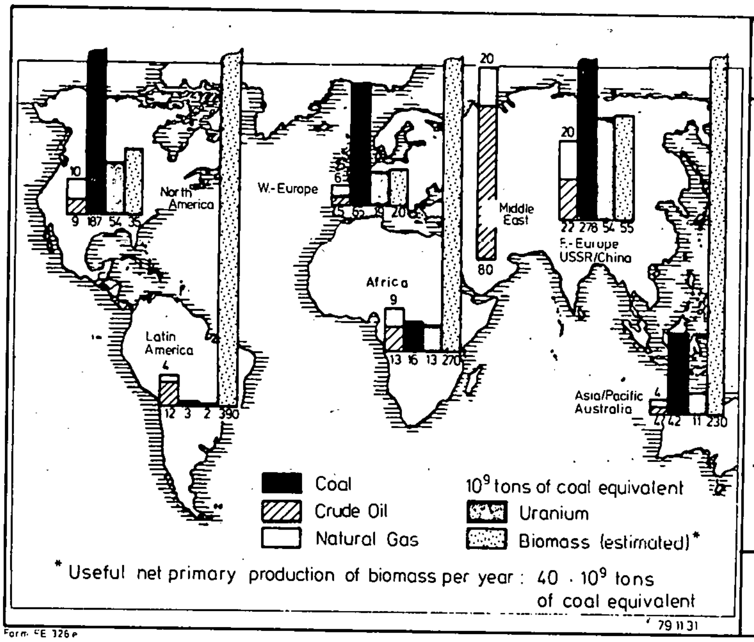


*Assumptions
12 000 km/year mileage
11,7 litre/100 km Fuel consumption

World Crude Oil Production and Crude Demand for Passenger Cars

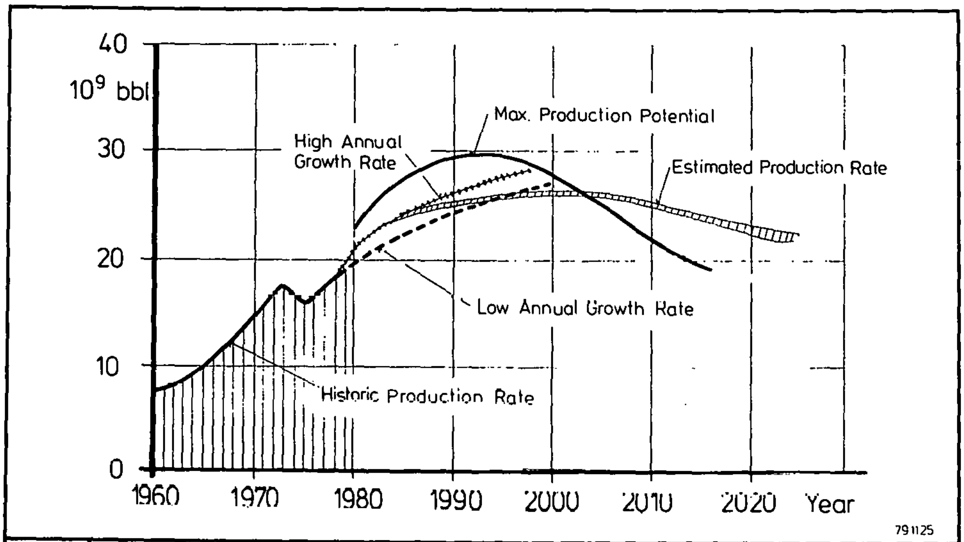
Fig. 1



* Useful net primary production of biomass per year: 40 · 10^9 tons of coal equivalent

Proved World Primary Energy Reserves

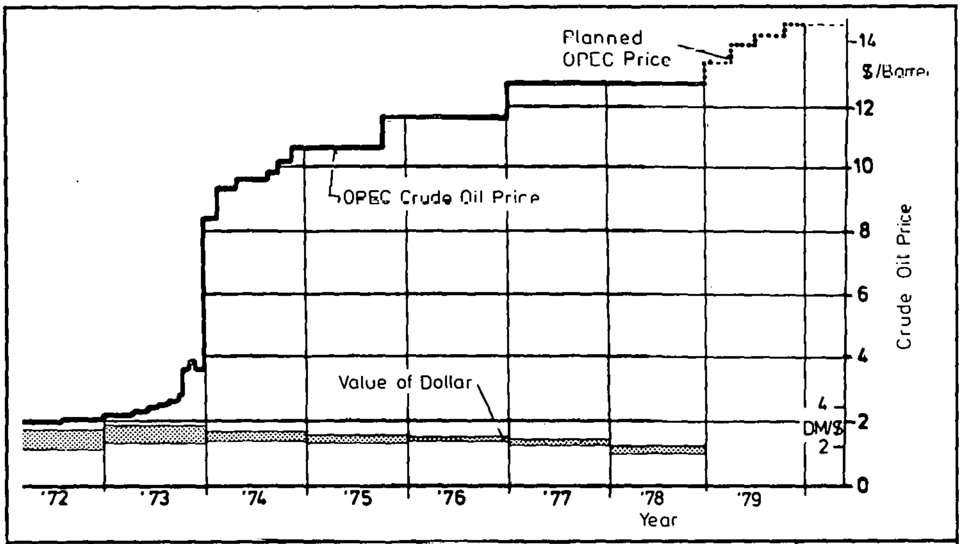
Fig. 2



Crude Oil Production Rate
(World outside Communist Areas)

Fig. 3

Source: Shell 1978



Average Selling Price
(Arabian Light)

Fig. 4

Form FE 326c

Primary energy

- Oil shale and tar sands
- Natural gas
- Coal
- Wastes (municipal and agricultural)
- Nuclear energy
- Solar energy

Alternate automotive fuels

- Synthetic gasoline
- Synthetic diesel oil
- Methanol
- Ethanol
- LPG
- Methane (LNG, CNG)
- Hydrogen
- Electrical energy

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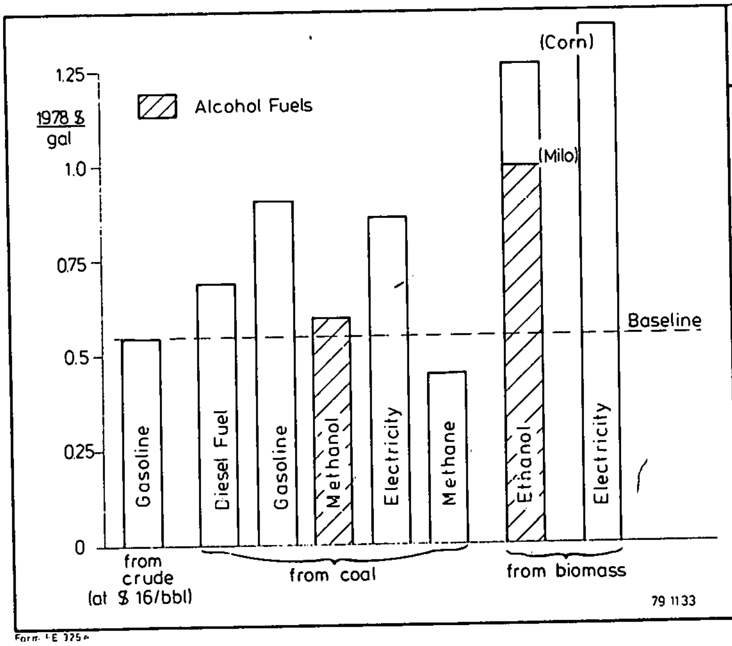
Alternate primary energy sources and forms of secondary energy for motor cars

Fig. 5

Form FE 376c

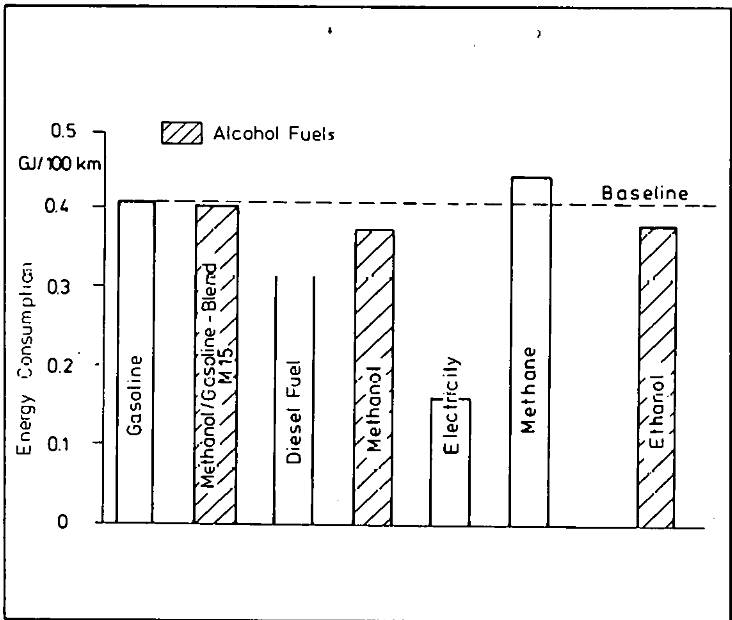


Energy Cost of Fuels in 1978 $/Gallon Gasoline Equivalent for Large Scale Production

Figure 6

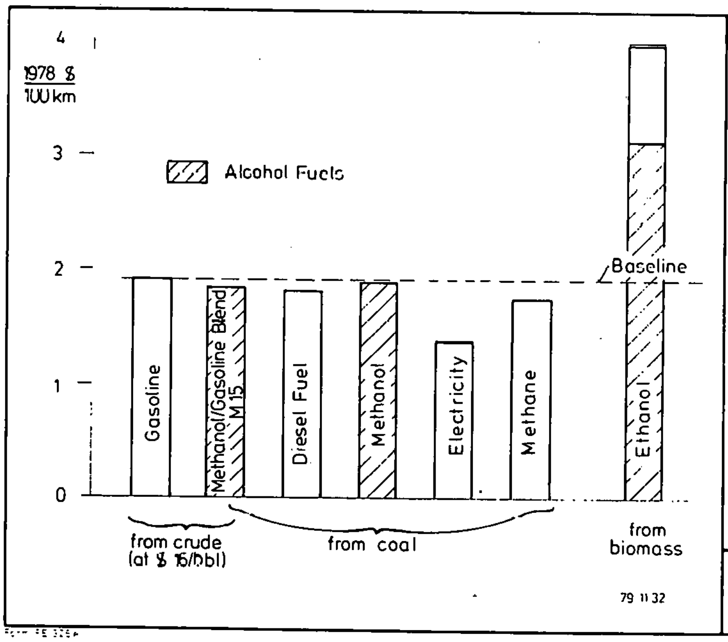
Form FE 375c

(w/o distribution cost)



Energy Consumption pro 100 Kilometers During ECE Test Procedure·

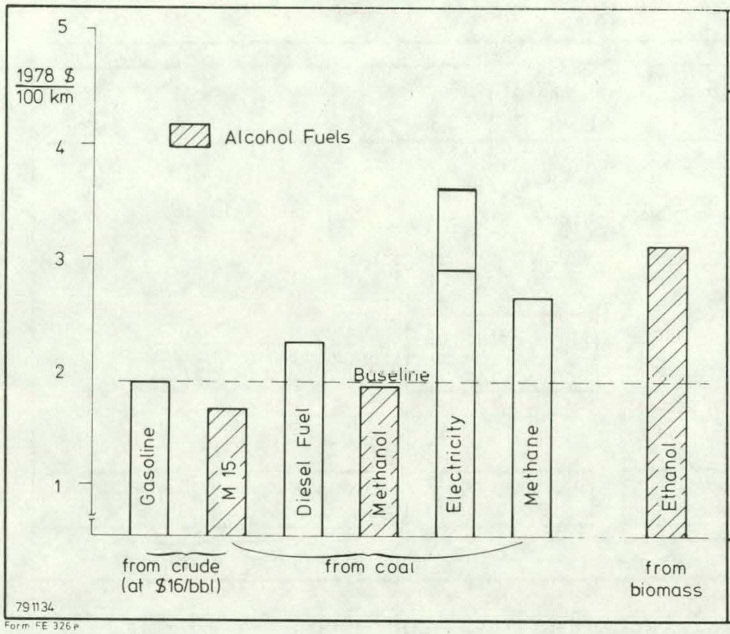
Figure 7



Energy Cost for Travelling 100 Kilometres (Based on ECE Test Procedure)

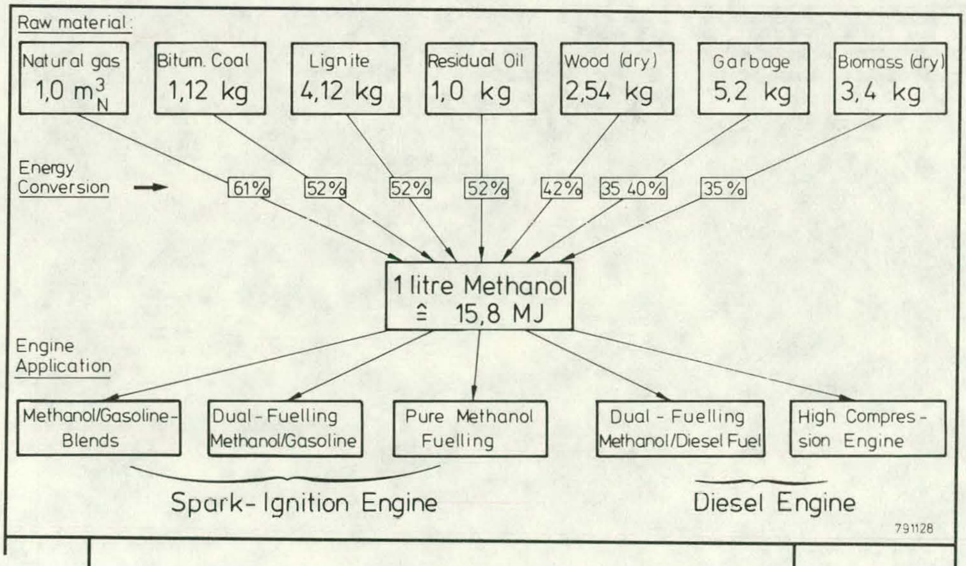
Figure 8

(w/o taxation)



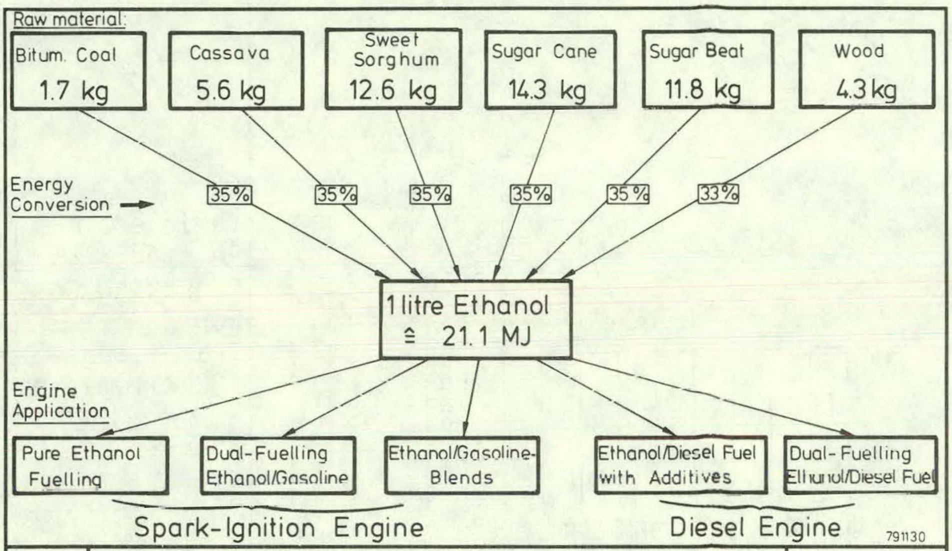
Vehicle Related Operating Cost For Travelling 100 Kilometres (w/o Taxes)

Figure 9



Methanol Production and Application

Fig. 10



Ethanol Production and Application | Fig. 11

Form FE 326c

VW Rabbit operated by alcohol engine | Fig. 12

Dup

THE PHYSICAL PROPERTIES OF GASOLINE/ALCOHOL AUTOMOTIVE FUELS

by

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ABSTRACT

Non-petroleum derived alcohols are likely candidates for near-future use as alternative automotive fuels. Low molecular weight alcohols may be used alone or in combination with gasoline, but either usage presents its own unique set of advantages and disadvantages. This report addresses the physical property changes (both beneficial and detrimental) which occur when alcohols are added to gasoline as fuel extenders.

The experimental data and discussion of results cover four physical property areas: water tolerance, vapor pressure, distillation characteristics, and octane quality. The alcohols include methanol, ethanol, n-propanol, i-butanol, and synthetic "methyl fuel."** Several additional alcohols were tested, but only as gasoline/methanol cosolvents. The major objective of the physical properties study was to determine the interdependency among the variables which are responsible for the significant property changes so that, where possible, gasoline/alcohol properties can be estimated from blend composition. Trends are also discussed in terms of the general influences of system variables.

INTRODUCTION

Petroleum shortages and recognition of limited reserves have prompted many recent studies of alternate automotive fuels which can be obtained from non-petroleum sources [1].*** The ultimate goal of alternate fuel studies is to replace petroleum as the major source of automotive fuels, but this would require rather extensive and costly changes in current methods and equipment for fuel processing and distribution. A near-term practical approach involves supplementation of petroleum reserves by incorporating non-petroleum-derived fuels directly into the petroleum-derived fuel supply.

The technology already exists to manufacture methanol, ethanol, and methyl fuel from a variety of non-petroleum sources, and these alcohols can be added to gasolines as fuel extenders. Structural differences between the alcohols and hydrocarbons,

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** Methyl fuel is a trade name given to crude methanol which has been manufactured under conditions which produce substantial quantities of higher molecular weight alcohols.

** Numbers in brackets [1] designate References at end of paper.

however, are sufficient to produce nonideal gasoline/alcohol solutions. Low molecular weight alcohols apparently have a synergistic effect upon the octane quality of gasolines; miscibility is incomplete at sufficiently low temperatures and/or in the presence of contaminant water; and alcohol/hydrocarbon azeotropes produce nonideal vapor pressure and distillation behavior.

A knowledge of the physical properties of gasoline/alcohol blends is necessary in order to fully assess the potential of the alcohols as fuel extenders. Experimental work was done at BETC to supplement the existing physical properties data base. The information contained in this report was derived from these experiments.

PHYSICAL PROPERTIES MEASUREMENTS

Octane number, micro vapor pressure, and distillation characteristics were measured by standard ASTM methods [2] with the exception of a slight modification to the micro vapor pressure (MVP) procedure. To minimize the possibility of phase separation, the MVP samples were air saturated at 50° F and maintained at that temperature in the charging bulb.

The water tolerances (miscibilities of gasoline/alcohol/water mixtures) were determined using cloud point temperature as a function of water concentration which allowed the miscibility of each gasoline/alcohol mixture to be viewed as the water tolerance of the mixture at a particular temperature. Incremental water additions were made to establish data points over the temperature range. Initial water content was determined using a coulometric Karl Fischer procedure [3].

RESULTS AND DISCUSSION

Water Tolerance of Gasoline/Alcohol Solutions

The fraction of water that can be tolerated in a single-phase gasoline/alcohol solution is largely dependent upon four variables:

1. solution temperature,
2. gasoline composition,
3. alcohol structure, and
4. alcohol concentration.

It is convenient to determine water tolerance from the relationship between cloud point temperature in °F (T) and water concentration in weight percent (W) because the water concentration at the cloud point is, by definition, the water tolerance and the relationship over the experimental temperature range (≃-10 to 75° F) is quadratic.

$$T - K_2W^2 + K_1W + K_0 \qquad (1)$$

A typical family of water tolerance curves is shown in figure 1 for various methanol concentrations in a single gasoline. The water tolerance for these gasoline/methanol solutions is mid-range, and from the figure it can be seen that below ≈0.04 wt-pct water, water tolerance is inversely related to methanol level and above ≈0.08 wt-pct water, the relationship is direct. In the experimental temperature range, low water tolerance solutions exhibit only the inverse relationship and high water tolerance solutions only the direct relationship.

A rather extensive study of hydrocarbon/methanol water tolerance [4] revealed that water tolerance is related to the boiling point (T_0) of the hydrocarbons within each of the classes; paraffinic, olefinic, and aromatic. These relationships are illustrated in figure 2. The vertical lines on each curve show the approximate ranges for the average (weighted) boiling point ($\overline{T}_0$) of each class within typical gasolines. From these relationships at various solution temperatures (T_1), expressions were empirically derived for the water tolerance of each of the three classes of hydrocarbons. For example:

$$W = (K_5 + K_4\overline{T}_0)T_1^2 + (K_3 + K_2\overline{T}_0)T_1 + K_1\overline{T}_0 + K_0 \qquad (2)$$

The water tolerance of each class was adjusted for the mole fraction of the class within the gasoline, and the adjusted values were summed to give a water tolerance value for the solution. Using this method, water tolerance estimates for several refinery stocks and gasolines containing methanol at 5, 10, 15, and 20 wt-pct gave precisions of ±0.005, 0.015, 0.021, and 0.034 wt-pct water, respectively.

The solubility properties of the alcohols depend upon the relative influences of the hydrocarbon and hydroxyl groups. The influence of each of the groups in a monohydric alkanol is determined by molecular configuration as well as size, but in a homologous series, adding CH_2 groups will decrease solubility in water and increase solubility in gasoline. A greater solubility in gasoline and lesser solubility in water should shift the partitioning of the alcohol in favor of the upper (gasoline) layer of a separated gasoline/alcohol/water mixture. To test the validity of this assumption, water was added to 5 and 20 vol-pct n-propanol in a gasoline in proportions analogous to the gasoline/ alcohol solutions coming into contact with a 4 vol-pct storage tank water bottom. Each phase of the two two-phase mixtures was analyzed for water content and, from this information and the total water volume, the maximum propanol in the lower (water) phase and minimum propanol in the upper (gasoline) phase were calculated by assuming no gasoline in the water phase and no water in the gasoline phase. Test results are given in table 1 and compared to similar data for methanol taken from a previous report [5].

When the water contamination of the gasoline/methanol solutions is lowered to 0.5 vol-pct, methanol partitions to the water phase at 60 to 64 vol-pct of the total methanol volume. Reduction of the water contamination in gasoline/n-propanol solutions would undoubtedly produce similar results and relatively small amounts of the alcohol would be lost to the water phase. This leads to the conclusion that separated mixtures of gasoline and alcohols consisting of three carbons or more are comparable to water contamination of gasoline alone, and with the possible exception of i-propanol, little is to be gained from water tolerance measurements of the solutions unless the formulation of a water-containing fuel is desired.

Water tolerance measurements were made for ethanol and two methyl fuels in gasoline at 5, 10, and 15 wt-pct [6]. Measurements with a high (no. 3) and a low (no. 4) water tolerance gasoline indicate that the water tolerance differences between the gasoline/alcohol and comparable gasoline/methanol solutions are nearly constant over the experimental temperature range and with most (if not all) gasolines. The mean and standard deviation of the water tolerance difference from 0° to 70° F have been calculated for each alcohol at each concentration. These values are given in table 2. Table 2 shows that the gasoline has little effect upon the water tolerance difference and that combining the values for the two gasolines introduces little variability above that produced by water tolerance curve slope differences (indicated by the magnitudes of the standard deviations for each gasoline). The combined mean values for the two gasolines represent the weight percent of water that a gasoline/alcohol solution will tolerate above that of an equivalent gasoline/methanol solution. The standard deviation indicates that the estimate holds within 8.0 percent or 0.005 absolute water tolerance increase over the temperature range, 0° to 70° F.

Cosolvents for Water Tolerance Enhancement

The effectiveness of several materials as cosolvents for gasoline/methanol solutions has been investigated [7]. Material types included surfactants, alcohols, and alcohol mixes. Cosolvent effectiveness was determined on the basis of water tolerance increase (ΔW) when a fraction of the solution methanol was replaced by the cosolvent. Table 3 lists the types of surfactants tested and the largest ΔW for each group. The best surfactant tested was only about 50 percent as effective as 1-hexanol (table 3-no. 11). On a weight basis, surfactant molecular size is apparently too great a disadvantage. Compared to hexanol, for instance, a C_{18} surfactant would require approximately three times the weight concentration to obtain an equivalent molar concentration.

Ormandy, et. al. [8], reported synergistic water tolerance effects for some alcohol pairs in gasolines and hydrocarbons. One of the larger effects was for ethanol/i-butanol in cyclohexane. A solution of cyclohexane/methanol/ethanol/i-butanol in the proportions 70/6/12/12 would dissolve 17-29 wt-pct more water than the mean water tolerance of ethanol and i-butanol individually in cyclohexane/methanol at 24 percent, but this is an unrealistically high cosolvent level. The water tolerance of the same components in the proportions 70/18/6/6 was additive, and from this it was concluded that alcohol cosolvent pairs at realistic cosolvent concentrations are not likely to give synergistic water toleranc

The monohydric alkanols in the carbon range, C_3 to C_6, were the best gasoline/methanol cosolvents found. Initial experiments [9] involved adding 5 wt-pct cosolvent to a 90/10 gasoline/methanol solution. Thirteen higher alcohols (C_2 to C_8 excluding C_6) were tested, and of this group, 1-pentanol was found to be most effective at this concentration (1-hexanol was later found to be more effective than 1-pentanol at comparable concentrations). The results of these experiments are summarized in figure 3 with all C_3 to C_5 alcohol cosolvent solutions within the 2-propanol to 1-pentanol limits. Water tolerances for a C_7 and a C_8 alcohol cosolvent solution were below that of 1-pentanol. Within a homologous alcohol series, water tolerances generally increased from C_3 to C_5, tertiary to primary, and branched to normal.

Several gasolines and other hydrocarbon mixtures were tested at 5 to 30 wt-pct methanol and with 0 to 40 wt-pct of the methanol replaced by cosolvent. Under these conditions, the total alcohol content of the cosolvent solutions corresponded to the total alcohol content of the gasoline/methanol solutions. Table 4 gives the results of these experiments in terms of cosolvent effectiveness. The interesting aspect of the table is the relative positions of the cosolvents at the different alcohol levels. Although comparison is made at 30 wt-pct methanol replaced by cosolvent, ΔW vs cosolvent is nearly linear from 5 to 30 wt-pct methanol replacement.

Experimentation with 1-hexanol was relatively complete, and the effectiveness of this cosolvent can be estimated for all but exceptionally high water tolerance hydrocarbon solutions where ΔW becomes much smaller than the expected values. The estimate, however, is valid for most, if not all, gasoline type hydrocarbon mixtures. The following equation gives values which generally agree with the experimental values by within 10 percent or 0.02 absolute:

$$\Delta W = (0.379A + 1.58)AB \times 10^{-4} \qquad (3)$$

where A is the total alcohol concentration in weight percent and B is the weight percent of methanol replaced by 1-hexanol.

Two-Phase Gasoline/Methanol Mixtures

The terminology normally used to describe two-phase systems can be misleading. Referring to the conjugate phases by the names of the nonconsolutes (for instance, "gasoline" phase and "water" phase for a gasoline/methanol/water mixture) implies that these phases are rich in the compounds for which they are named. When the two-phase area is large and when the solvent (gasoline)/solute (methanol) pair is caused to separate by relatively small quantities of diluent (water), as is the case for gasoline/methanol fuels, the diluent phase is likely to be rich in solvent or solute.

A relatively high water tolerance gasoline/methanol solution containing 10 volume percent methanol was made to separate at 64° F by adding 0.3 vol-pct water. The lower (water) phase composition was 29.4/67.4/3.2 gasoline/methanol/water, on a volume basis. Even at 0.5 vol-pct water, the lower phase contained 22.8 vol-pct gasoline. Gasoline content is important because high vapor pressure hydrocarbon/methanol azeotropes are hydrocarbon rich, and vaporization would tend to deplete the lower phase of these components with a relatively small portion of the total lower phase volume vaporized.

Apparently, enough gasoline is present in the lower phase of some separated gasoline/methanol fuels to allow some automobiles to be operated when ambient temperatures are sufficiently low to close the choke. At BETC, a fleet of six automobiles was operated successfully at temperatures down to 0° F using a 90/10 gasoline/methanol fuel. The phase separation temperature of the fuel was 50.5° F. The automobiles were soaked overnight at ambient temperatures, normally with the fuel tanks at 60 to 70 percent of capacity. None of the automobiles failed to start and problems were encountered with only one automobile which would not idle after the choke released. In addition, the low-temperature driveability of this vehicle was substandard. Satisfactory performance of the remaining five automobiles after choke release implies that by this time either mixing had occurred or the volume of the lower phase was sufficiently small to allow delivery of the upper phase to the engine.

Vapor Pressure of Gasoline/Alcohol Solutions

Monohydric alkanols form minimum boiling azeotropes with hydrocarbons [10]. In general, the lower boiling alcohols form azeotropes with lower boiling hydrocarbons, and as the boiling point of the alcohol is increased, the boiling point of the lowest boiling azeotropic hydrocarbon also increases. In addition, the azeotrope of a particular hydrocarbon with a higher boiling alcohol will have a boiling point nearer to that of the pure hydrocarbon (less azeotropic boiling point depression). The relationships between the boiling points of the hydrocarbons and their alcohol azeotropes are illustrated in figure 4.

The vapor pressures of the neat alcohols are considerably less than gasolines. The neat alcohols included in this study were measured at 100° F by the micromethod [2], the values adjusted for air saturation, and the adjusted values compared to the literature values. Agreement was within 4 mm Hg. The measured values in mm Hg were: methanol = 267, ethanol = 149, n-propanol = 74, and i-butanol = 53. Air saturation at 50° F accounted for 25, 27, 24, and 25 mm Hg, respectively.

The behavior of the various alcohols in forming azeotropes with the hydrocarbons (figure 4) serves well to explain the relative vapor pressures among the various gasoline/alcohol solutions. The vapor pressure data for the alcohols in two gasolines have been plotted versus alcohol concentration in figures 5 and 6. When added to gasoline at 5 to 15 wt-pct, methanol and ethanol (which form azeotropes with low boiling hydrocarbons) give gasoline/

alcohol vapor pressures higher than the gasoline. Hydrocarbon boiling point depression is greater with methanol resulting in a greater vapor pressure increase. In addition, a greater positive deviation from Raoult's Law coincides with a lesser solubility for methanol in gasoline. The deviation decreases from methanol to i-butanol in order of molecular size.

The vapor pressure increase for methanol in nine gasolines was found to range from 176 to 182 mm Hg. The vapor pressure range in mm Hg for the gasolines was 424 to 586. For gasolines in this vapor pressure range, 180 mm Hg appears to be a good estimate for 5 to 15 wt-pct methanol solutions. In a gasoline which has an exceptionally high vapor pressure (678 mm Hg), methanol produced an increase of only 155 mm Hg ($\simeq$ 0.5 psi less than the low vapor pressure gasoline). The remaining gasoline/alcohol solutions were prepared with the 678 mm Hg gasoline and a 495 mm Hg gasoline. They also produced smaller increases (or larger decreases) in the high vapor pressure gasoline. This is reasonable since, at the higher pressure, a greater proportion of each of the components common to both gasolines will be condensed in the liquid phase.

The effect of hydrocarbon azeotrope formation with n-propanol and i-butanol is offset by the low vapor pressures of the alcohols, and it appears that a very low vapor pressure hydrocarbon mixture (probably below the limit for gasolines) would be required for these alcohols to produce a significant vapor pressure increase. The synthetic methyl fuel curves are located about as they should be, though they do not conform exactly to positions calculated from the positions of the four component alcohols.

Distillation Characteristics of Gasoline/Alcohol Solutions

Before discussing distillation characteristics, clarification concerning one aspect of comparison should be beneficial. That is, comparing the distillation curve (temperature versus vol-pct distilled) of a base fuel to that of a solution of a foreign material blended with that fuel. Adding a foreign material diminishes the volume fraction of base fuel in the starting material by the volume fraction added. For an ideal distillation and a given temperature, the fraction of blended fuel recovered will be less than that of the base fuel until the boiling point of the blended material is reached. At higher temperatures, the fraction of blended fuel recovered will be greater. Below the boiling point of the blended material, the distillation temperature of the blended fuel will be higher; and above the boiling point of the blended material, the distillation temperature of the blended fuel will be lower.

The differences between the distillation curves of gasolines and their alcohol solutions will be the combined results of (1) adding the foreign material (alcohol) to the base gasoline, and (2) hydrocarbon/alcohol azeotropism; the first tending to raise front-end distillation temperatures and the second tending to lower them.

The portion of the distillation curve altered significantly and the extent to which it is altered is dependent upon:

1. alcohol concentration,
2. the shape and position of the gasoline curve, and
3. the structure of the alcohol.

The effects of different alcohol concentrations and the shape and position of the gasoline curve were discussed in some detail in two previous reports [4,6]. It should be stated here, however, that increasing the alcohol concentration will:

1. cause the curve to be displaced farther to the left at temperatures below the alcohol boiling point and farther to the right at higher temperatures,
2. require that a greater portion of the solution be distilled before alcohol depletion,
3. shift the point of maximum temperature depression to larger fractions of recovered distillate, and
4. increase the maximum temperature depression.

Gasolines which distill at higher temperatures will:

1. give larger temperature depressions with a given alcohol and
2. deplete the alcohol at a lower fraction of recovered distillate.

The distillation of methanol, ethanol, n-propanol, and i-butanol at 15 wt-pct in gasoline is shown in figure 7. Figure 4 provides a convenient guide for explanation of the differences among the four alcohols which were tested. Methanol and ethanol form azeotropes with hydrocarbons boiling below the initial distillation temperature. This tends to lower front-end distillation temperatures. Azeotropic temperature depression is greater for methanol than it is for ethanol, and the temperature is lowered from the beginning of the distillation. Ethanol azeotropic temperature depression is smaller, and at higher ethanol levels, the dilution effect is predominant for the first 5 to 10 percent of the solution distilled. Propanol and i-butanol do not form azeotropes with low boiling hydrocarbons, and the differences between the front-end of the gasoline and gasoline/alcohol curves is largely the result of base gasoline dilution.

Considering the alcohols in order from C_1 to C_4, the increasing boiling point of the lowest boiling azeotropic hydrocarbon causes the point of maximum temperature depression to appear at successively larger fractions of collected distillate. Higher distillation temperatures must be reached before azeotropic distillation begins. The azeotropic temperature depression for a particular hydrocarbon decreases as the boiling point of the alcohol increases. Therefore, as the alcohol boiling point is increased, the temperature depression for the gasoline/alcohol solutions is decreased.

Curve shapes for the synthetic methyl fuels (not shown in figure 7) are about what one would expect. The methanol depresses the front-end distillation temperatures, but the presence of the higher alcohols tends to decrease the severity. Compared to methanol at a particular alcohol level, the distillation temperature breaks upward at a lower fraction of recovered distillate (the combined effect of lower methanol concentration and the presence of the higher alcohols), but the higher alcohols tend to spread the temperature depression over a larger portion of the curve.

Antiknock Quality of Gasoline/Alcohol Solutions

Octane numbers reported in the literature [11,12] vary as much as 10 for a single neat alcohol. One problem encountered in rating alcohols stems from the difference between their combustion stoichiometry and that of the reference gasolines. This difference prevents strict application of the gasoline rating procedure to the alcohols and may be one reason for the spread in reported values.

When considering the properties of solutions, however, the effect of the minor component (alcohol) upon the major component (gasoline) is of prime interest. If the property values of the individual components of a solution are not additive, the error can be assigned to the minor component. Practical (as opposed to theoretical) property values for the minor component can then be calculated from solution composition and experimental values for the solution and the major component measured individually. In this manner, the actual behavior of the minor component in solution is determined. The minor component value is referred to as a "blending" value to distinguish it as a practical unit. Blending octane numbers for the alcohols (BON_2) can be calculated from the following equation:

$$BON_2 = \frac{ON_3 - ON_1(F_1)}{F_2} \qquad (4)$$

where F is the fraction of component in solution (weight fraction is used in this report) and the subscripts, 1, 2, and 3 designate gasoline, alcohol, and solution respectively.

The octane values for the alcohols in two gasolines are given in table 5. The relationship between octane number and 0 to 15 wt-pct alcohol is very nearly linear,and the slope and intercept values for the linear regression analysis of octane number versus weight fraction of alcohol are given in table 6. The blending octane numbers of the alcohols are also given in this table.

The BON_2 values in table 6 clearly show that n-propanol and i-butanol give smaller octane increases than methanol and ethanol; and for both gasolines and test methods, n-propanol appears to be a slightly better octane improver than i-butanol. Uncertainty in the analytical precision and the lack of a repeated trend allows only the observation that the differences among methanol, ethanol, and the methyl fuels (if differences actually exist) are probably insignificant. Mean BON_2 values for gasoline blends of the two alcohols and two alcohol mixtures give calculated ON_3 values that isagree with the experimental values no more than 0.6. On the other hand, the BON_2 values taken at face value indicate that methanol is a slightly better octane booster according to the research measurement method; ethanol is slightly better according to the motor method; and the presence of n-propanol and i-butanol in the solution diminishes the octane improvement effect of methanol and ethanol.

Within the experimental matrix of this study, the magnitudes of the apparent octane numbers of the alcohols (BON_2) are nearly independent of ON_1 when ON_3 is measured by the research method. When ON_3 is measured by the motor method, however, the alcohols are considerably more effective octane improvers in blends with low octane gasolines as compared to high octane gasolines. This is reflected in the larger BON_2 values for the low octane gasoline. In table 6, slope (m) magnitudes of the linear equations show that, as expected, the absolute ON_3 increase is greater for the lower octane gasoline regardless of the measurement method.

The synthetic methyl fuels were included in the study primarily to determine if the properties of the alcohol solutions (more than one alcohol) are additive when blended with gasoline. Blending octane numbers were calculated for the gasoline/methyl fuel blends from the BON_2 values of the four alcohol components and the fraction of each in the methyl fuels. These values (table 6) are not significantly different from those generated by regression analysis of the gasoline/methyl fuel blends. Although the levels of the higher alcohols in the gasoline blends are too low to definitely establish octane number additivity, agreement of the BON_2 values indicates that, under conditions similar to those of this study, the octane values of the individual alcohols in gasoline can be considered to be additive in alcohol solutions blended with gasoline.

SUMMARY

Methanol is not completely miscible with gasolines at sufficiently low temperatures and/or in the presence of contaminant water and methanol partitioning favors the water (lower) phase of a separated mixture. As the molecular weight of the alcohol is increased, gasoline solubility and blend water tolerance increases and smaller fractions of alcohol partition to the water phase of separated mixtures. Higher molecular weight alcohols are effective cosolvents for increasing the water tolerance of gasoline/methanol blends, but separation of gasoline/methanol in the gas tank does not necessarily disable the vehicle.

Nonideally high vapor pressures and low boiling points for gasoline/alcohol solutions result from alcohol/hydrocarbon azeotrope formation. The magnitude of deviation from ideality generally decreases with higher boiling alcohols.

Low molecular weight alcohols are good gasoline octane improvers. Octane improvement diminishes as the molecular weight of the alcohol is increased (not considering configuration) and as the octane quality of the base gasoline is increased.

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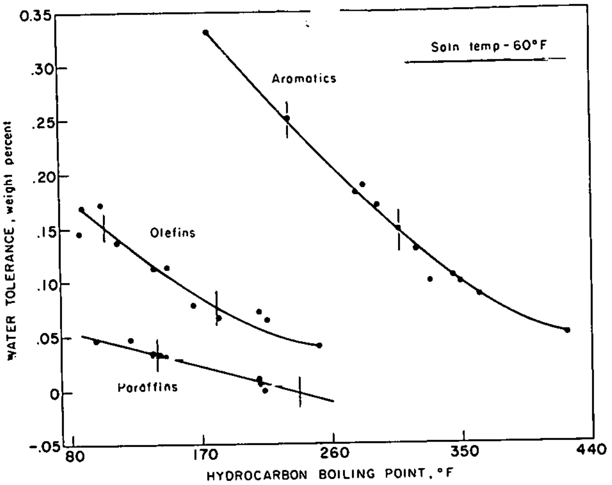

Fig. 2. - Relationship of Water Tolerance to Hydrocarbon Boiling Point

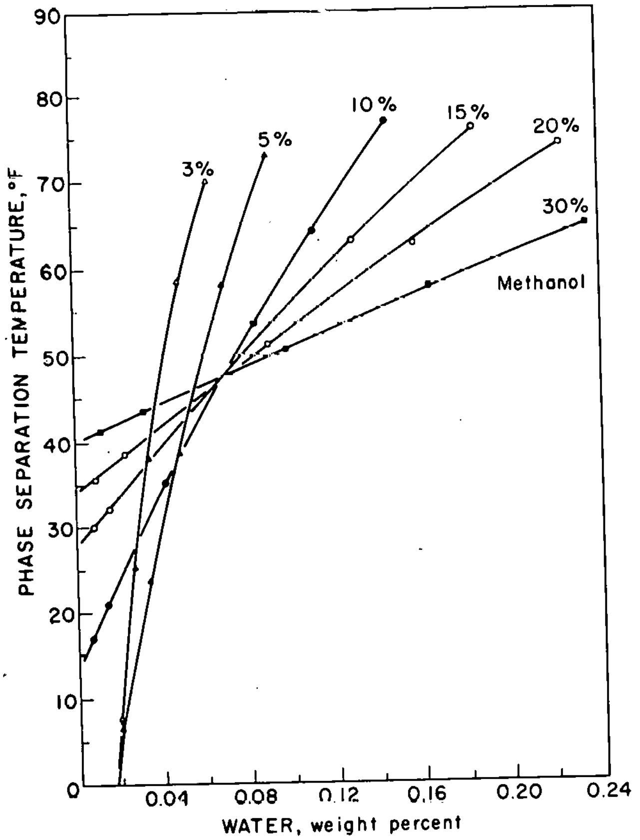

Fig. 1. - Water Tolerance of a Gasoline Containing Various Concentrations of Methanol

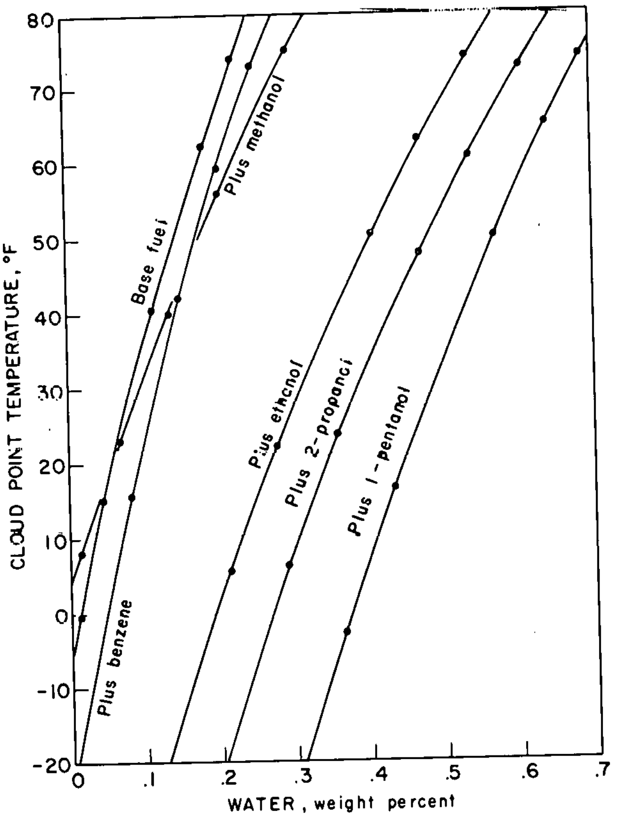

Fig. 3. - Effect of 5 Wt-pct Alcohols Added to 90/10 Gasoline/ Methanol

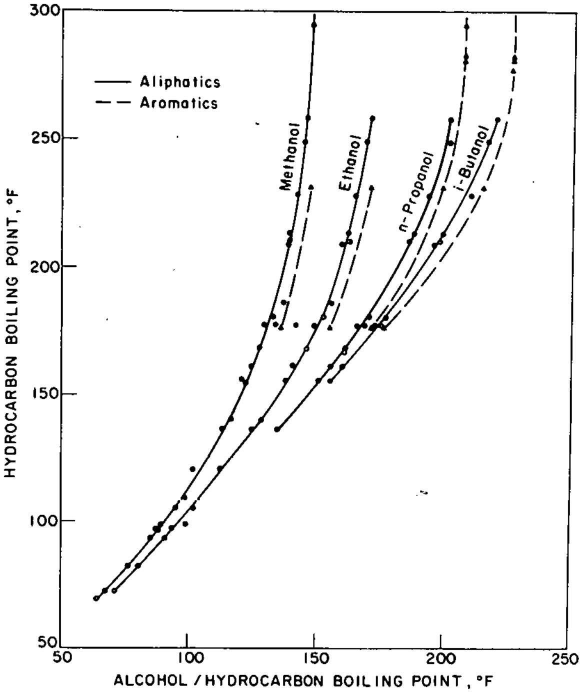

Fig. 4. - Boiling Point Relationships of Hydrocarbon/Alcohol Azeotropes

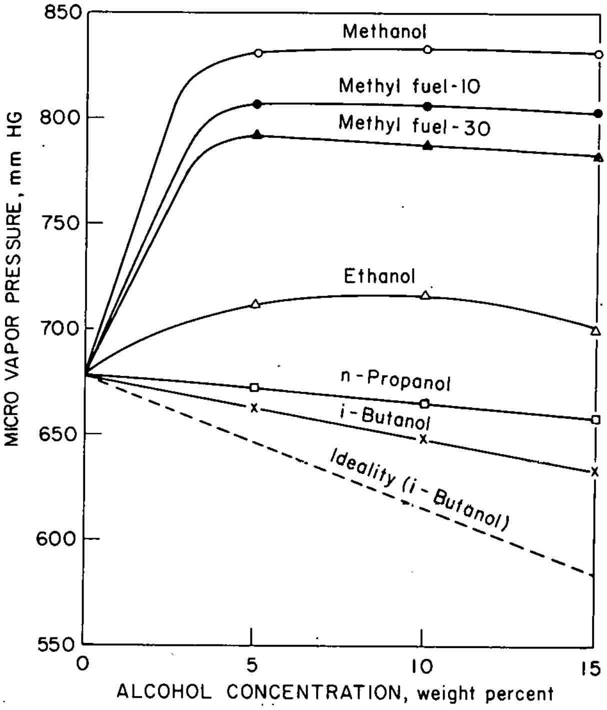

Fig. 5. - Effect of Alcohol Upon the Vapor Pressure of Gasoline No. 3

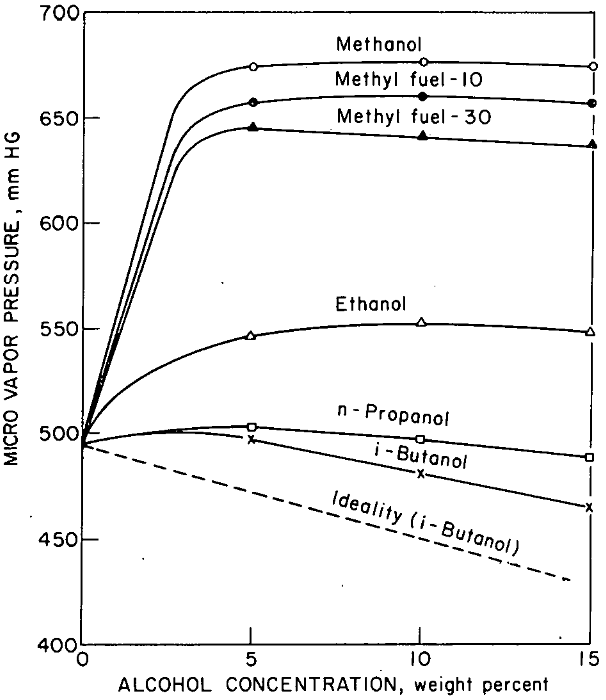

Fig. 6. - Effect of Alcohol Upon the Vapor Pressure of Gasoline No. 4

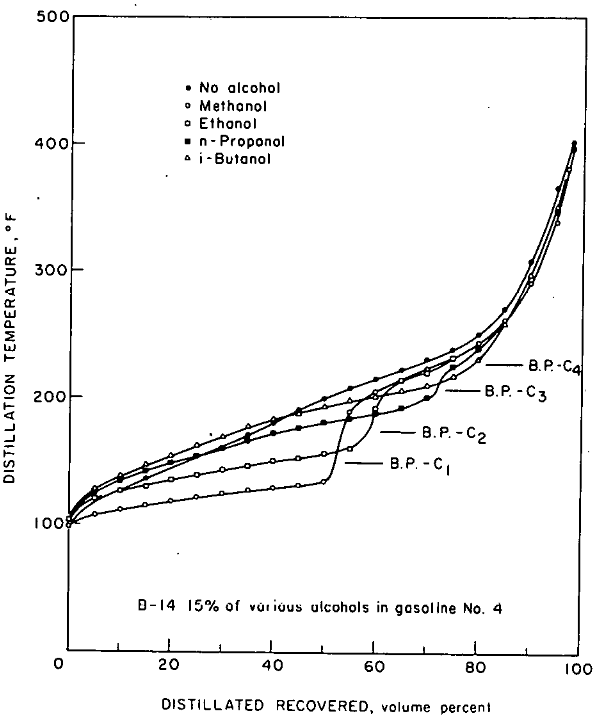

Fig. 7. - Distillation Characteristics at 15 Wt-pct Alcohol

TABLE 1. - Loss of methanol and n-propanol to the water phase of separated gasoline/alcohol mixtures

Alcohol name	Alcohol in gasoline/alcohol solution	Vol-pct of total alcohol	
		In upper (gasoline) phase	In lower (water) phase
n-Propanol	5.0 vol-pct	>79	<21
Methanol	5.2 vol-pct	≈7	≈93
n-Propanol	20.0 vol-pct	>96	<4
Methanol	20.8 vol-pct	≈5	≈95

TABLE 3. - Surfactants as cosolvents for gasoline/methanol solutions (gasoline/methanol = 80/20, 0.2 fraction of methanol replaced)

Class		Number of compounds tested	Largest ΔW[3]		HLB range
No.	Type		at 70° F	at 0° F	
1	POE[1] alkylaryl ethers	7	0.169	0.220	3.4-13.0
2	POE alkyl ethers	3	0.190	0.271	4.9- 5.3
3	PEG[2] alkyl esters	5	0.049	0.128	3.5- 8.0
4	Glycol and glycerol alkyl esters	9	0.143	0.201	0.8- 6.8
5	Sorbitan alkyl esters	5	0.013	0.096	1.8- 8.6
6	POE sorbitan alkyl esters	4	0.032	0.097	9.6-15.0
7	High molecular weight esters	3	-0.008	insol	?
8	Lanolin derivatives	3	-0.013	0.087	?
9	Soaps	2	insol	insol	?
10	Miscellaneous	5	0.194	0.209	?
11	1-Hexanol	-	0.378	0.390	≈6.0

[1] Polyoxyethylene.

[2] Polyethyleneglycol.

[3] Water tolerance with cosolvent minus water tolerance without cosolvent.

TABLE 5. - Octane data on gasoline/alcohol blends[1]

Alcohol		Octane number			
		Gasoline No. 1		Gasoline No. 2	
Name	Concen., wt-pct	Research	Motor	Research	Motor
None............	None	78.5	72.0	90.1	83.5
Methyl fuel--10.	5	80.6	74.2	93.0	84.0
	10	83.3	75.8	94.8	84.5
	15	87.0	78.7	97.0	85.0
Methyl fuel--30.	5	80.8	74.2	92.5	84.0
	10	83.5	76.0	94.5	84.4
	15	86.1	77.8	96.4	85.0
Methanol........	5	80.9	74.2	92.8	84.0
	10	84.1	76.4	95.1	84.5
	15	87.1	78.0	97.2	85.0
Ethanol.........	5	81.6	74.4	92.8	84.2
	10	83.9	76.7	94.7	84.8
	15	86.7	78.7	96.5	85.3
Propanol........	5	80.5	73.8	91.9	83.9
	10	82.8	75.1	93.4	84.2
	15	84.5	76.7	94.8	84.5
i-Butanol.......	5	80.4	73.5	91.4	83.7
	10	81.7	74.7	92.9	84.0
	15	83.6	75.8	94.0	84.2

[1] Gasoline No. 1 - CRC octane requirement fuel number CRC-RMFD286
Gasoline No. 2 - CRC octane requirement fuel number CRC-RMFD287

TABLE 2. - Estimate of water tolerance difference between the alcohols and methanol

Alcohol		Mean and standard deviation of water tolerance difference		
Name	Concen., wt-pct	Gasoline No. 3	Gasoline No. 4	Gasoline Nos. 3 & 4
Methyl fuel--10[1]	5	0.010 ± 0.003	0.019 ± 0.002	0.014 ± 0.005
	10	.050 ± .003	.057 ± .001	.054 ± .004
	15	.101 ± .006	.098 ± .005	.099 ± .006
Methyl fuel--30[2]	5	.053 ± .002	.057 ± .004	.055 ± .004
	10	.145 ± .004	.155 ± .003	.150 ± .006
	15	.314 ± .012	.305 ± .014	.309 ± .013
Ethanol	5	.187 ± .006	.200 ± .017	.194 ± .014
	10	.479 ± .031	.475 ± .034	.477 ± .032
	15	.846 ± .058	.826 ± .066	.836 ± .061

[1] Ethanol/propanol/i-butanol = 2/3/5.
Methanol/higher alcohols = 90/10.

[2] Ethanol/propanol/i-butanol = 2/3/5.
Methanol/higher alcohols = 70/30.

TABLE 4. - Alcohol cosolvent relative effectiveness

increasingly effective

Total alcohol concentration, wt-pct							
5		10		15		30	
Alcohol name	ΔW[1]	Alcohol name	ΔW	Alcohol name	ΔW	Alcohol name	ΔW
1-Propanol	0.050	1-Hexanol	0.164	1-Hexanol	0.363	1-Hexanol	1.162
2-Butanol	.048	2-Butanol	.158	1-Pentanol	.318	1-Pentanol	1.133
1-Pentanol	.046	1-Pentanol	.154	2-Butanol	.299	2-Butanol	.951
2-Propanol	.042					t-Butanol	.893
1-Hexanol	.039					1-Propanol	.882
t-Butanol	.038					2-Propanol	.779
Ethanol	.032					Ethanol	.534

increasingly effective

[1] ΔW is given for replacement of 30 wt-pct of methanol with cosolvent.

TABLE 6. - Correlation of solution octane number and alcohol level

Alcohol name	$ON_3 = mF_2 + b$			Alcohol in gasoline, wt-pct				BON_2, m + b	BON_2,[1] calc.
				0	5	10	15		
	m	b (AVG.)	r	Back calculation error					
GASOLINE NO. 1--78.5 RON (EXP.)									
Methyl fuel--10..	55.3	78.3	0.9962	0	+0.4	+0.5	-0.4	134	135
Methyl fuel--30..	52.2	78.3	.9998	0	+0.1	0	0	131	132
Methanol.........	58.4	78.3	.9993	0	+0.3	0	-0.1	137	
Ethanol..........	56.3	78.3	.9986	0	-0.4	+0.1	+0.1	135	
n-Propanol.......	42.3	78.3	.9986	0	0	-0.2	-0.2	121	
i-Butanol........	35.1	78.3	.9977	0	-0.3	+0.1	0	113	
GASOLINE NO. 1--72.0 MON (EXP.)									
Methyl fuel--10..	40.5	72.3	0.9948	0	+0.1	+0.5	-0.4	113	110
Methyl fuel--30..	36.6	72.3	.9999	0	0	0	0	109	108
Methanol.........	38.6	72.3	.9983	0	+0.1	-0.2	+0.1	111	
Ethanol..........	43.0	72.3	.9996	0	0	-0.1	0	115	
n-Propanol.......	29.0	72.3	.9992	0	0	+0.1	0	101	
i-Butanol........	23.4	72.3	.9997	0	0	0	0	96	
GASOLINE NO. 2--90.1 RON (EXP.)									
Methyl fuel--10..	42.5	90.6	0.9990	0	-0.2	+0.1	0	133	133
Methyl fuel--30..	38.8	90.6	.9999	0	0	0	0	129	130
Methanol.........	44.2	90.6	.9998	0	0	-0.1	0	135	
Ethanol..........	39.8	90.6	.9991	0	-0.2	-0.1	+0.1	130	
n-Propanol.......	28.2	90.6	.9996	0	+0.1	0	0	119	
i-Butanol........	22.6	90.6	.9956	0	+0.3	-0.1	0	113	
GASOLINE NO. 2--83.5 MON (EXP.)									
Methyl fuel--10..	10.0	83.5	1.0000	0	0	0	0	94	94
Methyl fuel--30..	9.8	83.5	.9970	0	0	+0.1	0	93	93
Methanol.........	10.0	83.5	1.0000	0	0	0	0	94	
Ethanol..........	12.2	83.5	.9977	0	+0.1	-0.1	+0.1	96	
n-Propanol.......	6.6	83.5	.9972	0	0	0	0	90	
i-Butanol........	4.8	83.5	.9965	0	0	0	0	88	

[1] Calculated from weighted individual alcohol BON_2 values.

DEVELOPMENT OF AN ON-BOARD MECHANICAL FUEL EMULSIFIER FOR UTILIZATION OF DIESEL/METHANOL AND METHANOL/GASOLINE FUEL EMULSIONS IN TRANSPORTATION

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INTRODUCTION

A shortfall in Canada's liquid fuel supply is expected by the mid-1980's. Acceleration of production from oil sands and heavy oil deposits can only alleviate, not avert this tightness of supply. Accelerated R & D effort into liquid fuel substitution is clearly in demand, particularly in regard to resolving the uncertainties surrounding the application of alternate liquid fuel options for transportation.

There are many options open, one of which is the utilization of alcohol fuels. The key to alcohol fuels lies in their flexibility, both for production and utilization. They can be made from a variety of energy sources, some of them renewable, and it is important to see that they can be applied to both gasoline and diesel powered vehicles as full extenders. It would also be desirable if vehicles could operate either on blended or non-blended fuels, so that flexibility of vehicle movement is maintained outside of areas where alcohol fuels may be available.

Ontario Research Foundation is addressing a number of problems related to the development of vehicle capability in this regard. Two programs are underway, one to examine methanol as a fuel extender for diesel engines, and the other to address the problems of applying methanol blended gasolines under Canadian climatic conditions where phase separation of the blends will be prevalent during cold weather operations. The key to both programs lies in the application of an in-fuel-line mechanical emulsification device to engine fuel management systems so that diesel engines can be fueled with methanol/diesel fuel emulsions, and phase separation problems of methanol/gasoline blends can be overcome by fueling spark ignition engines with a fuel emulsion of the two phases. The mechanical emulsification device, which has been developed at ORF (the ORF HydroShear) has design features compatible with installation in the fuel line of both diesel and spark ignition engines.

HYDROSHEAR DEVELOPMENT

Development of the vortex principle from the original concept of Ranque, and later Vonnegut[1], has taken place at ORF over the last few years. The configuration of the original vortex whistle has changed but the mode of operation is the same albeit much more efficient.

The basic shape of the HydroShear can be seen in Figure 1. The tangentially introduced liquid accelerates in the inlet and converts part of the driving pressure into kinetic energy. In the large chamber the rotating liquid is gradually forced towards the centre and during the inward motion the tangential velocity continuously changes under the influence of the various forces acting on it. The liquid forms essentially concentric layers which rotate at different velocities and hence form shear stresses between them. On reaching the discharge nozzle, the liquid attains a certain axial velocity and is discharged. Because of the tangential velocity in a properly designed nozzle, a central hollow core is formed where there is no liquid and where the pressure is significantly below the ambient level and hence filled with the gases separated from the liquid and with vapour from the liquid itself. Both the shear forces and the instability of flow in the exit nozzle contribute to the mixing and emulsification of liquids to a significant degree.

For a specific liquid and pressure drop there is an "ideal" HydroShear capacity. Capacity is defined as the flowrate through the HydroShear and since this system may be designed for more than one pass, it does not necessarily equal the production rate.

HydroShears designed for a 250 psi pressure drop have an "ideal" capacity for light fuels, such as diesel, of 0.6 to 0.9 U.S. Gpm, however because of the wall friction, which is less pronounced in the HydroShears made for diesel fuel rather than a more viscous oil, capacities as low as 0.15 U.S. Gpm and as high as 2.4 U.S. Gpm can be designed with only a moderate loss of efficiency.

The HydroShear emulsification systems for both methanol/diesel and methanol/gasoline are recirculating loop systems which pump a 5 to 10 times greater quantity of fuel through the HydroShear than the demand of the engine. Enough emulsion stability is attained between the HydroShear discharge and the injectors to provide an adequately dispersed feed for the engine.

It has been calculated that if the emulsification system is matched to the demand of the diesel engine in the recirculation loop, the actual power consumption of the HydroShear and associated piping amounts to between 0.35 and 0.45 HP. This is less than half percent of a typical rated full load engine power of 125 HP. The system is run at a uniform rate at all engine loads so that the power demand remains constant. However, the advantage of methanol at low loads is problematical and it is likely that, at start up and idling, methanol would not be used. The pump used for the HydroShear doubles as the normal recirculating pump and there is enough pressure remaining after the HydroShear for the injector to operate normally.

It has been found that stability, in the absence of chemical emulsifiers, is enhanced by the addition of small amounts of water into the methanol in the ratios of approximately 1:6 to 1:20 water to methanol. The stability is enhanced from seconds in the case of straight methanol/diesel emulsions to minutes in the case of methanol-water solution/diesel emulsions as determined by settling tests. This is a sufficient length of time to ensure a homogeneous mixture entering the fuel injectors.

ENGINE TEST PROGRAMS

Methanol/Diesel Fuel Emulsions

Studies on methanol as a fuel extender for diesel engines are being carried out by other workers using dual fuel injection devices[2] or by adding methanol via the combustion air[3]. The ORF approach employs methanol/diesel fuel emulsions and has as objectives:

1. To design a mechanical emulsifier processing system compatible with installation in the fuel system of a Detroit Diesel 8V 71N diesel engine to fuel the engine with methanol/diesel emulsions.

2. To carry out engine dynamometer tests with this system to determine performance relative to stability of the emulsion and methanol content.
3. To design and install on a heavy duty diesel powered truck, an on-board emulsification test rig, which will allow this truck to be operated on the road fueled with methanol/diesel emulsions.
4. To demonstrate the performance of this truck with fuel emulsion by subjective assessment of driveability, and by examination of fuel efficiency, diesel oil savings, and engine power output, together with limited analysis of exhaust emission characteristics, sufficient to determine whether obvious benefits or constraints exist.

Preliminary engine dynamometer tests have been carried out feeding 20% methanol/diesel fuel emulsions, prepared with the ORF HydroShear, to a Deutz F6L 714 V-6 precombustion chamber diesel engine, with a maximum continuous rating of 130 BHP on neat diesel oil. The fuel emulsion also contained 0.6% water to improve stability. A typical emulsification test rig used in engine dynamometer tests is shown in Fig. 2. The rig can be used to prepare either water/diesel emulsions, as indicated, or methanol/diesel emulsions, and has been used on both Detroit Diesel 8V 71N and Deutz F6L 714 engines. The engine is normally started on neat diesel fuel, and during the warm-up period, the emulsion is prepared. The Magikist pump is started in order to flush the system with a fresh emulsion. To do this, the emulsion dump/sampling valve and rotameter valves are opened fully with the rotameter bypass valve closed. Diesel fuel and methanol are thereby drawn into the system from the small tanks to replace the dumped volume of emulsion. The proportion of methanol in the emulsion is determined by the relative restriction in each pick-up line, and is controlled with the rotameter valves. After having been pumped through the engine mounted HydroShears, the emulsion is returned, via a 25 psi pressure relief valve, to the cooling coil and pump. The dump/sample valve is closed when the system is flushed and the mixture is recycled for a period of time at 400 psi to ensure delivery of a homogeneous emulsion. The engine is switched to operate on emulsion from neat fuel in such a way that neither system becomes contaminated. The neat fuel bypass is opened, allowing the lift pump to continue to operate on neat fuel, thereby maintaining self lubrication. As the engine consumes emulsion, it is replaced constantly with methanol and diesel oil, in the correct proportion, from the small tanks. In this way the same emulsion composition is maintained in the system independently of fuel consumption. Methanol and diesel fuel consumptions are monitored gravimetrically using two digital balances. At the end of the test period, the engine is switched back to neat diesel oil and flushed for several minutes to ensure removal of traces of methanol from the engine fuel system.

Engine performance data obtained with the Deutz engine operated at full load and two speeds of 2200 and 1600 RPM with neat fuel and about 20% methanol/diesel fuel emulsion is shown in Table I and Figure 3. It is important to recognize that at off full load condition, governor compensation occurred with the Deutz engine when the lower BTU content emulsion fuel was used, so that when fuels were switched from neat to emulsion fuel at off full load condition there was little change in RPM or load due to increase in fuel rate caused by governor compensation. At full load condition the governor would not compensate for the reduced BTU value of the emulsion fuel and the full load condition was reduced by about 5-10% as is evident by referring to Figure 3. At the same time, partial governor compensation occurred to increase the total fuel consumption rate of emulsion fuel, as is apparent from the fuel consumption data shown in Table I. The fuel consumption rate of the diesel component of the emulsion measured in lbs/hour was reduced 11-18% for the 18% emulsion and brake specific diesel fuel consumption was reduced by up to 13%. Also shown in Table I is the brake specific fuel consumption measured on a BTU basis. At the rated speed of 2200 RPM the total fuel consumption measured on this basis is reduced by about 5% for a 6% decrease in power, and the engine efficiency increases. At 1600 RPM, the reverse is true, and engine efficiency decreases. The data is, as yet, limited, but it appears the engine will operate satisfactorily with about 20% emulsion fuel with a decrease in power small enough that it may not be noticed by the operator. At rated speed, about the expected savings in diesel fuel occurs when the emulsion is employed. At idle speed, no significant benefits of using the emulsion are observed, and it would be better if the engine were operated only on diesel fuel at idle.

Particulate emission rates from the engine with neat and emulsion fuels are shown in Table 2 and plotted in Figure 4 on a g/1000 BTU basis. Significant particulate emission reduction occurs when methanol/diesel fuel emulsion is employed, which is believed to be greater than could be accounted for by change in fuel/air ratio. Further data is required to determine the true magnitude of this reduction at the same fuel/air ratios. Table 3 shows the gaseous emission rates with neat and emulsion fuels. Nitrogen oxides are increased with emulsion fuel, which might be expected from the change in fuel/air ratio.

It is hoped that current data obtained with the Detroit Diesel engine can be presented at the meeting.

Methanol/Gasoline Emulsions

This program addresses problems related to Canadian utilization of methanol/gasoline blends. These are:

1) Cold weather operation

2) Water sensitivity to phase separation in winter

3) Vehicle compatibility
   - materials
   - fuel/air ratio control
   - flexibility for vehicle movement outside of areas where methanol might be available

Use of an ORF HydroShear in a vehicle's fuel management system would reduce the sensitivity of water for creating phase separation in winter. If satisfactory engine performance can be obtained by emulsifying the two phases, then it would be unncessary to add blending agents such as higher alcohols, or control the water content of the blended fuel, the latter being a controversial issue regarding practicality of application during production and distribution. Vehicle movement flexibility is enhanced if an oxygen sensor, located in the exhaust, could control the fuel/air ratio via closed loop feedback so that stoichiometric fuel/air ratios were maintained independent of whether the fuel was gasoline or a methanol/gasoline blend.

The ORF program, sponsored by Transport Canada, has three phases identified with objectives:

Phase I - Feasibility study - engine dynamometer tests at ambient temperature.

Phase II - Climate controlled engine dynamometer tests

Phase III - On-board testing
- road tests
- chassis dynamometer tests

Phase I objectives are:

1) Feasibility study of ORF HydroShear emulsifier capability to overcome phase separation problems in winter
   - induced phase separation with water
   - phase diagrams
   - fuel management design
   - carburetted and fuel injected vehicles

2) Fuel mapping with blends of 15%, 25%, 35%, 45%, 55%, and 80% methanol

3) Fuel/air ratio control
   - closed loop feedback system
   - lean burn conditions

An attempt will be made to operate the engines under lean burn conditions, but it is expected that the oxygen sensor may be limited in its ability to control the fuel/air ratio much outside stoichiometric because of the voltage-exhaust gas composition relationship. A study conducted by Engelhard Industries [4], has shown that stoichiometric fuel/air ratio control can be maintained with an oxygen sensor when the engine is fueled with 0-50% ethanol/gasoline blends and 0-20% methanol/gasoline blends, and this lends encouragement to the ORF study.

Two base gasolines are being selected, representative of low and high aromatic content, and two vehicles have been selected and purchased for engine testing. These are:

1) 1978 Volvo 244DL equipped with λ-Sond emission control system.
2) 1979 Chevrolet Monza equipped with 3-way catalyst closed loop feedback emission control system.

The latter vehicle will allow testing of a carburetted engine, and the former, a fuel injected engine. Current test data available will be presented at the meeting.

It is hoped, therefore, that programs of this nature will improve the degree of flexibility of vehicles, to allow operation on methanol containing fuels as required.

ACKNOWLEDGEMENTS

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TABLE I

ENGINE PERFORMANCE DATA AT FULL LOAD

SPEED RPM	LOAD BHP	% METHANOL IN DIESEL FUEL	INJ. TIM. % BTDC	EXHAUST TEMP. °C	FUEL CONSUMPTION RATE						HEAT VALUE BTU/MIN.	ENGINE EFFICIENCY %	% CHANGE IN TOTAL FUEL CONSUMPTION AS BTU.BHP.Hr	% CHANGE IN MAX. LOAD
					TOTAL FUEL		DIESEL COMPONENT		METHANOL COMPONENT					
					LBS./BHP.Hr	BTU/BHP.Hr	LBS./BHP.Hr	BTU/BHP.Hr	LBS./BHP.Hr	BTU/BHP.Hr				
2200	130	0	25	471	0.462	9066	0.462	9066	-	-	19,623*	28.1		
	122	17.8	25	404	0.489	8576	0.402	7888	0.087	688	17,450	29.7	-5.4	-6.2
1600	105	0	25	482	0.395	7751	0.395	7751	-	-	13,559	32.9		
	93	17.8	25	371	0.480	8423	0.395	7751	0.085	672	13,053	30.2	+8.6	-11.4
	105	0	30	483	0.421	8261	0.421	8261	-	-	14,443	30.9		
	97	20.8	30	360	0.502	8620	0.397	7790	0.105	830	13,934	29.5	+4.3	-7.6

* Based on a typical constant volume heat of combustion for No. 2 oil, Gulf Diesel 25, API = 33 of 19623 BTU/LB. fuel

TABLE 2

PARTICULATE EMISSION RATES

SPEED RPM	LOAD BHP	FUEL	INJ. TIMING °BTDC	g/BHP-hr	g/hr	g/lb. FUEL	g/1000 BTU
2200	130	D25	25	0.237	30.79	0.513	0.025
1600	105	D25	25	0.445	46.75	1.128	0.055
2200	122	EMUL	25	0.089	10.88	0.182	0.010
1600	93	EMUL	25	0.116	10.74	0.241	0.013
2200	125	EMUL	30	0.140	17.54	0.532	0.020
1600	97	EMUL	30	0.167	1.620	0.333	0.019
2200	125	D25	30	0.401	50.07	1.070	0.052
1600	105	D25	30	0.855	89.73	2.032	0.099

TABLE 3

GASEOUS EMISSION RATES AT FULL LOAD
INJECTION TIMING AT 25° BTDC

SPEED RPM	LOAD BHP	FUEL	CO_2			CO			SO_2			THC as C_1		
			%	g/BHP-hr	g/1000 BTU	ppm	g/BHP-hr	g/1000 BTU	ppm	g/BHP-hr	g/1000 BTU	ppm	g/BHP-hr	g/1000 BTU
2200	130	D25	9.9	657	69.1	300	1.27	0.133	52	0.502	0.053	53	0.139	0.015
2200	122	EMUL	8.1	666	74.2	230	1.20	0.134	45	0.539	0.060	62	0.201	0.022
1600	105	D25	9.4	562	69.2	260	0.990	0.122	48	0.418	0.051	24	0.057	0.007
1600	93	EMUL	8.0	643	73.0	160	0.818	0.093	41	0.480	0.054	35	0.111	0.013

SPEED RPM	LOAD BHP	FUEL	NO_x			NO			NO_2		
			ppm	g/BHP-hr	g/1000 BTU	ppm	g/BHP-hr	g/1000 BTU	ppm	g/BHP-hr	g/1000 BTU
2200	130	D25	480	2.17	0.229	480	2.17	0.229	-	-	-
2200	122	EMUL	560	3.17	0.353	550	3.09	0.344	10	0.086	0.010
1600	105	D25	435	1.77	0.218	435	1.77	0.218	-	-	-
1600	93	EMUL	510	2.82	0.321	500	2.74	0.311	10	0.084	0.010

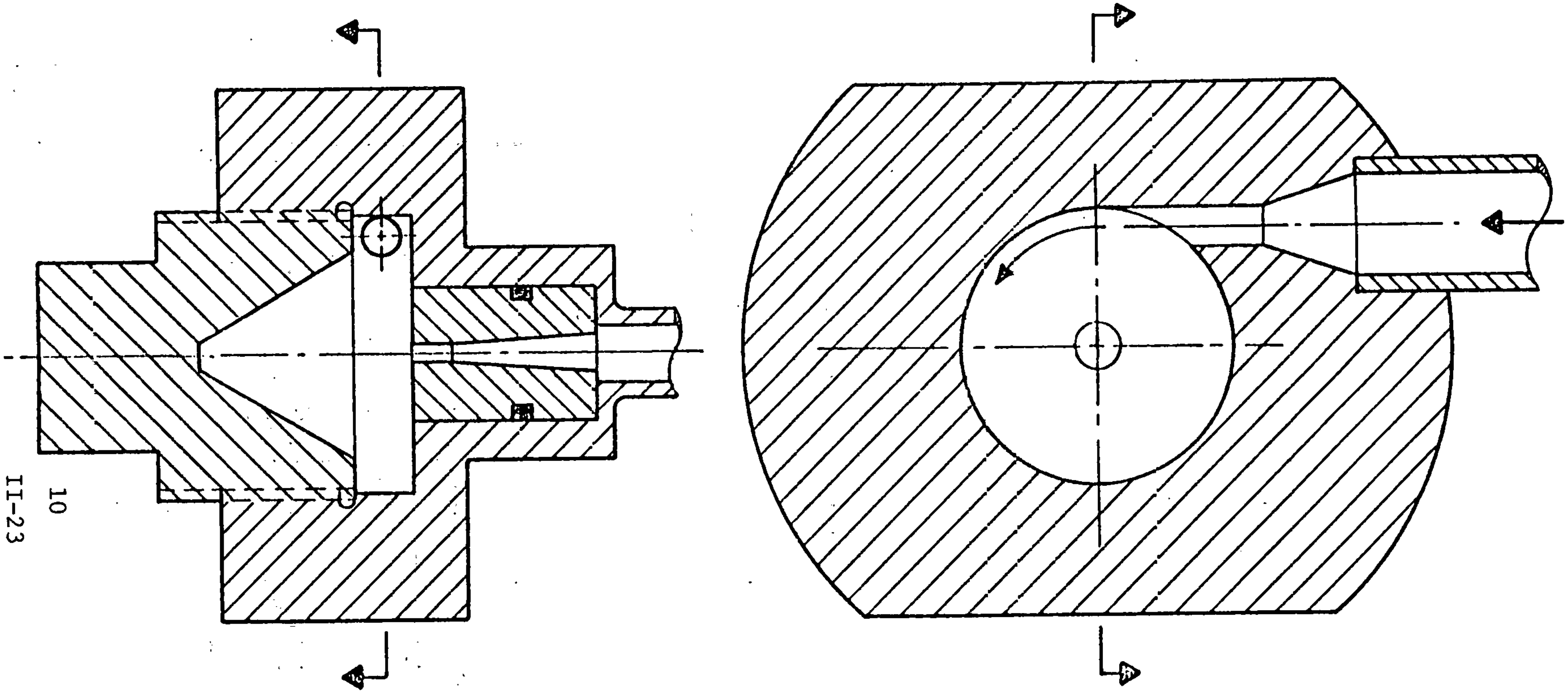
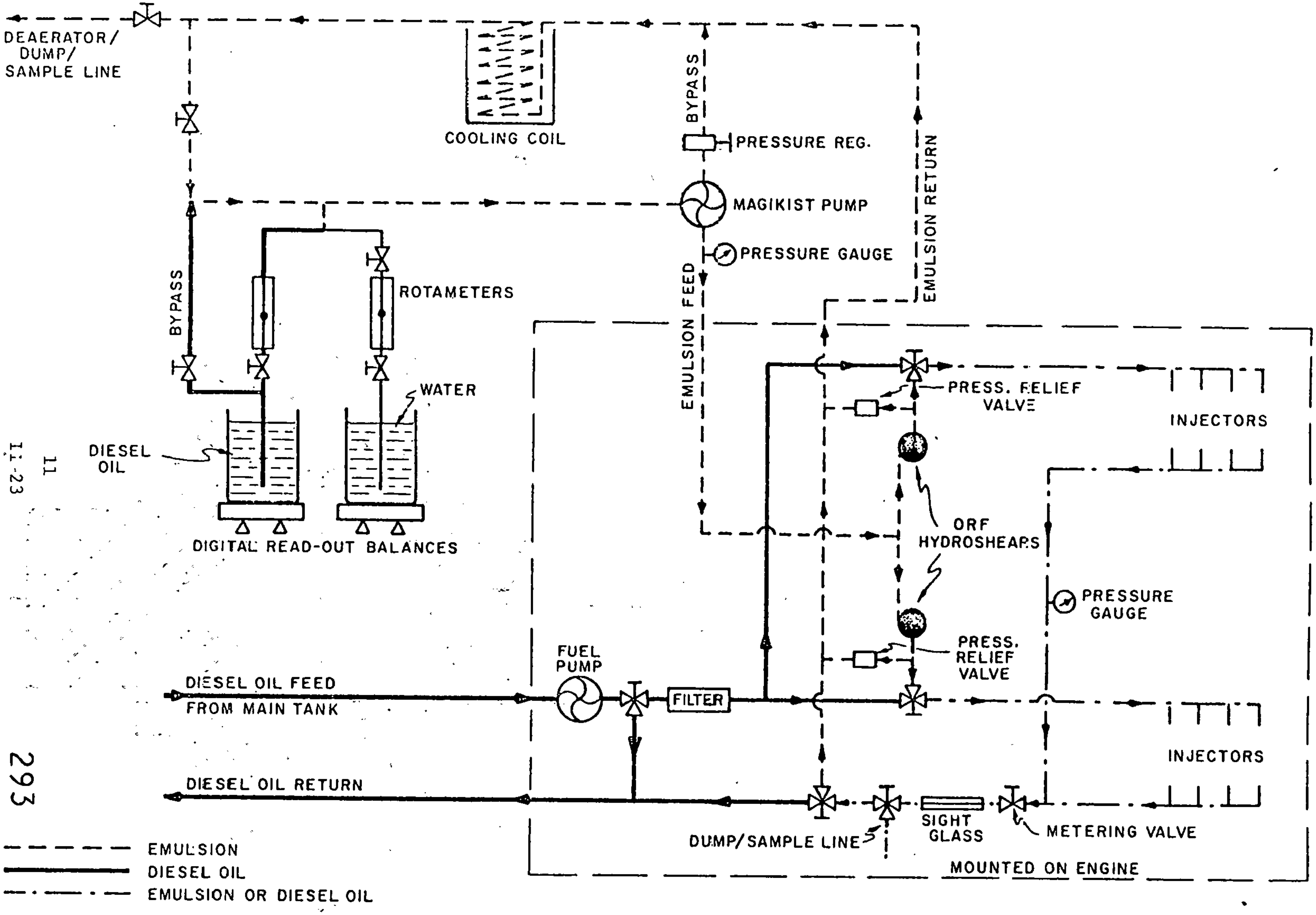


FIGURE 1

TYPICAL HYDROSHEAR

APPROX. 2x FULL SCALE

FIGURE 2



SCHEMATIC OF THE MODIFIED DETROIT 8V71N DIESEL ENGINE FUEL SYSTEM WHICH ALLOWS OPERATION ON CONTINUOUS FEED EMULSION OR NEAT FUEL.

FIGURE 3

COMPARISON OF MAXIMUM LOAD OBTAINED FOR 25° and 30° BTDC USING DIESEL 25 AND EMULSION

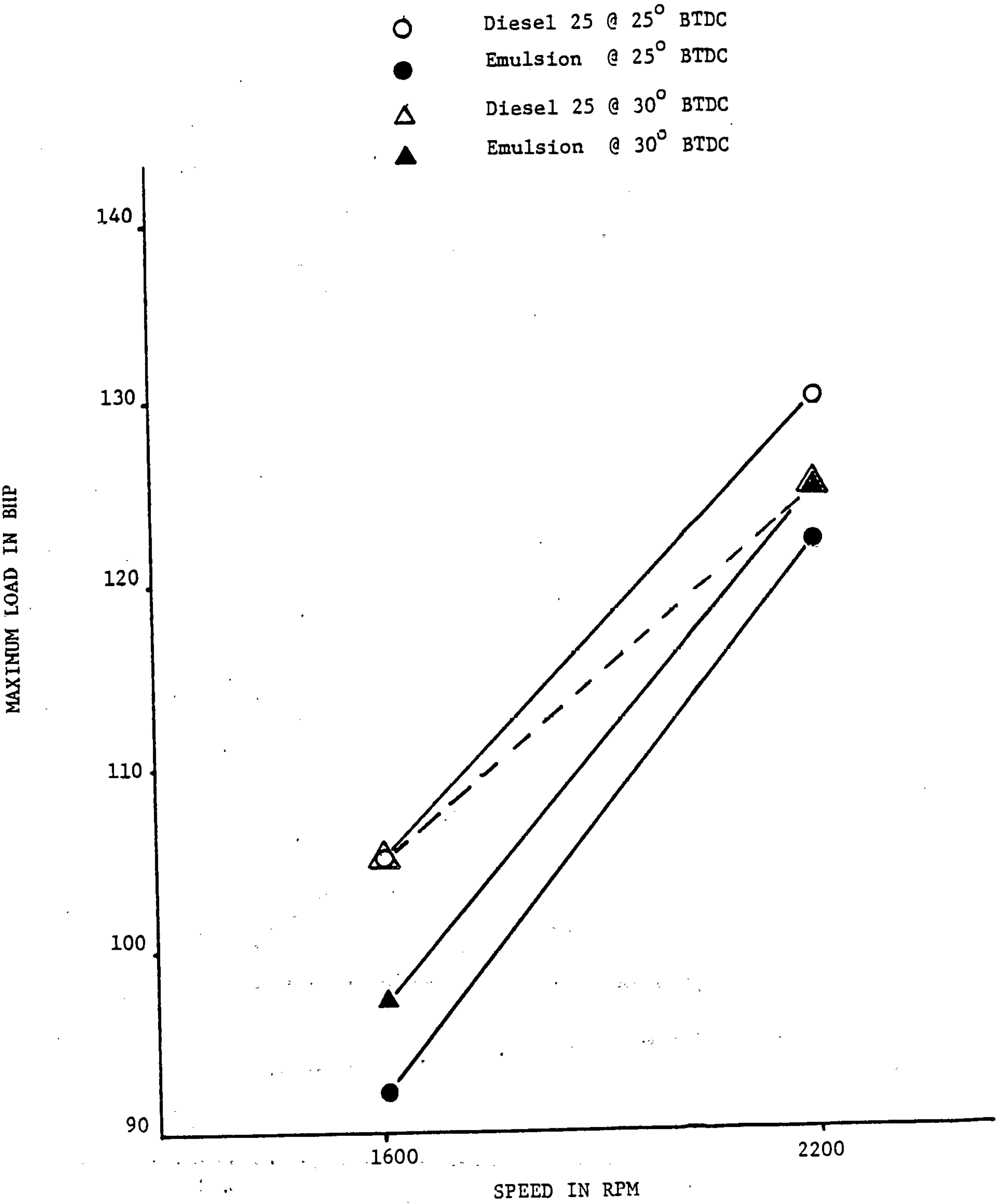
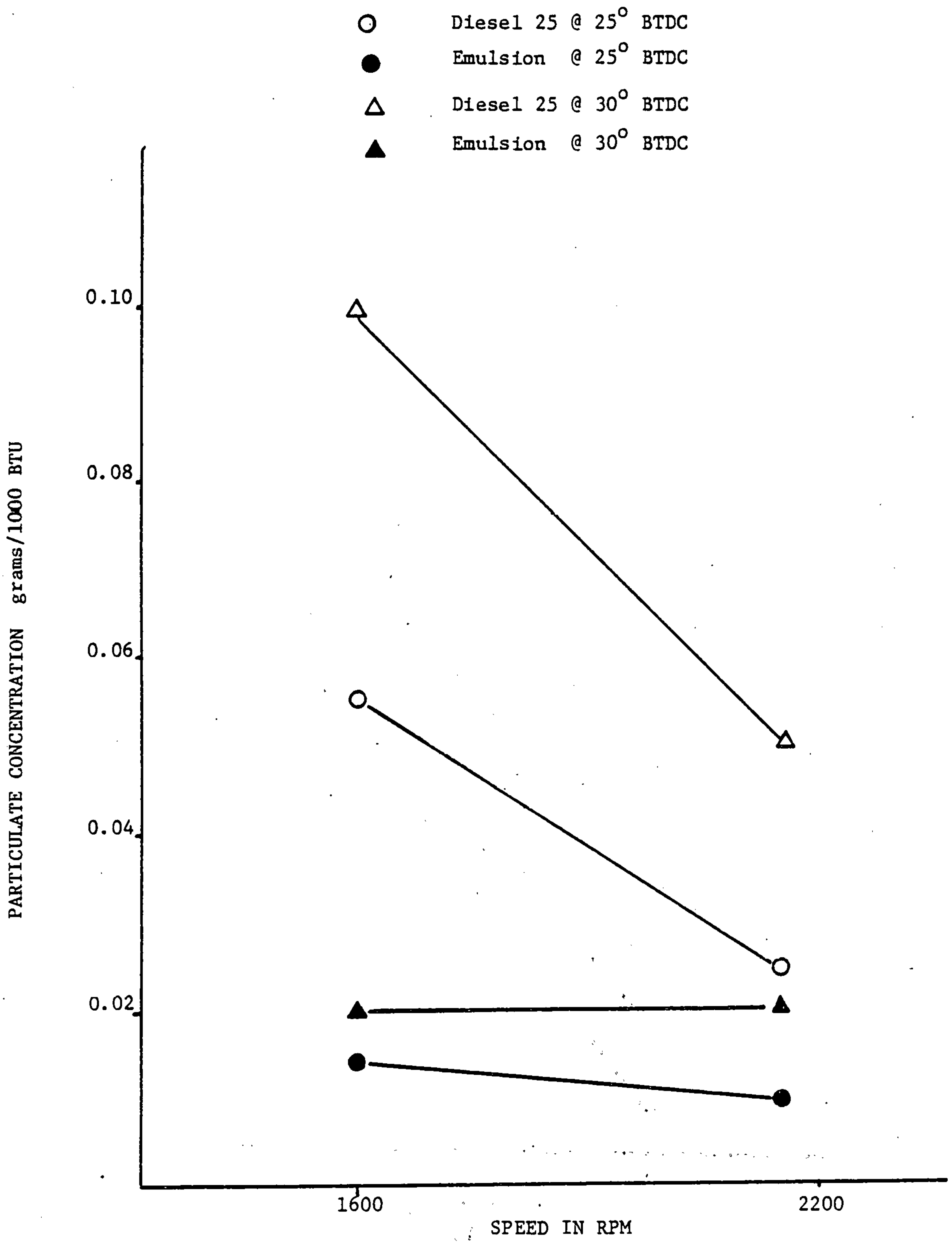


FIGURE 4

PARTICULATE EMISSION RATE AT FULL LOAD



Dup

EVALUATION OF METHANOL FOR REDUCED EXHAUST EMISSIONS IN A SINGLE-CYLINDER RESEARCH ENGINE

BY

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INTRODUCTION

Many studies have been made to evaluate the potential of alcohol fuels for internal combustion engines. Of these studies, single-cylinder engine investigations [1,2,3,4]* contributed significantly in characterizing combustion characteristics and emission data with methanol and ethanol. These engines permit flexibility for independently controlling the operating parameters and instrumentation. Some of the earlier investigations cited here were conducted on the older version of the Standard ASTM-CFR variable compression ratio engine of an "undersquare" (bore less than stroke) design with a flat combustion chamber and low speed with very little squish effect.

In a comparable study [5] Brinkman chose a late version of the CFR engine with removable dome head (RDH-CFR) which has a hemispherical combustion chamber and a domed piston. This engine is of "oversquare" design which permits a higher range of compression ratios and speed. Brinkman's study is significant as it generated evidence which explains some of the conflicting results of various workers, particularly those of Bernhardt et. al. [6] with respect to compression ratio effects on NO_x emissions. The results also agreed with the computer predictions of Browning and Pefley [7]. The work of Brinkman stimulated the authors to do further work using an RHD-CFR engine to bridge some gaps remaining from earlier work.

The present investigation examines the influence of different operating parameters on the formation of oxides of nitrogen (NO_x), carbon monoxide(CO), unburned fuel (UBF) and the aldehydes when fueled by methanol and methanol-water mixtures. Also, the effect of adding small quantities of aniline on the burning rate and aldehydes exhaust have been explored.

EXPERIMENTAL

Neat methanol, methanol and 10 percent water mixture, and methanol with a small percent of aniline were used in a single cylinder RHD-CFR. Two sets of experiments were conducted, one without mixture preheat and the other with mixture preheat. Table 1 gives the engine data and operating conditions.

For non-preheated operation,carburetion was by a Carter single throat updraft carburetor with the fuel supplied at a pressure of 3.5 to 4.0 psi by use of a nitrogen blanket. The mixture screw was used to adjust the air-fuel ratio.

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*Numbers in brackets designate references at end of paper.

Fuel flow was timed with a stopwatch as the alcohol was drawn out of a glass burette connected in parallel with the fuel tank. Air flow was determined by the use of a Meriam laminar flow element in conjunction with the 1" oil filled inclined manometer. Thermocouples sensed temperatures of the intake manifold, fuel, oil,water and exhaust.

The arrangement for preheating the mixture consisted of variable bank of electric resistance heaters totaling 5800 watts which controlled the mixture temperature to ±2°F. A fuel atomizer was used in place of a carburetor for mixture preparation. A sight glass in the intake system just outside the engine allowed monitoring of the degree of vaporization. Droplets on the wall were just noticeable when running under the richest condition selected. (During the other modes, vaporization was virtually 100% complete).

The emission sampling system consisted of three stainless steel sample lines in parallel drawing gases from the exhaust. Two lines were after the muffler and approximately 6 feet downstream of the engine. One was heated and exhausted to a Beckman 402 flame ionization detector (FID) for unburned fuel detection. The response factor of this FID to methanol has been determined to be 0.73 of the response due to propane. The second was routed through a water trap where it was cooled to remove water vapor through a filter to protect the instruments from particulates and to a diaphragm pump. From there it was manifolded to the NO_x, CO, CO_2, and oxygen (O_2) detectors. The NO_x detector was a chemiluminescence type, built at the U.S. Department of Energy's Bartlesville (Okla.) Energy Technology Center. Carbon monoxide and CO_2 detection was by Beckman nondispersive (NDIR) instruments.

The third sample line consisted of a heated stainless steel line drawing gases through a probe inserted into the center of the exhaust pipe approximately 7" downstream of the exhaust valve. This line led to an impinger where exhaust gas was bubbled through 25 ml of a 3-methyl-2 benzothioazalone hydrazone (MBTH) solution. The exhaust gas was drawn through the impinger by a diaphragm pump. Flow rate was controlled by a needle valve and monitored with a rotometer. Sampling was for 1 minute at 130 cc per minute.

The engine was run at least an hour prior to the taking of the data. The instruments were calibrated at least once a day. Each exhaust line filter was changed daily.

For each of the fuel combinations shown in Table 1, the following tests were run without mixture preheat.

(a) At a fixed compression ratio (CR), equivalence ratio* was varied from rich to lean (0.7-1.2) while emissions and performance data were taken at set intervals. The compression ratio was then varied and tests were repeated. The compression ratios covered a range of 7 to 11:1.

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*Equivalence ratio (Φ) is defined as stoichiometric air-fuel ratio/actual air-fuel ratio.

(b) At stoichiometric air-fuel ratio, compression ratio was changed in steps from 7 to 11. At a specific compression ratio, a traverse was made from lean to rich equivalence ratio. Thus, this set proved to be a cross-check on the tests in the first set.

The test conditions explored with intake mixture preheat included an equivalence ratio traverse at 10:1 CR and a compression ratio traverse at stoichiometric equivalence ratio. The fuels used were neat methanol and 99% methanol plus 1% aniline blend.

Computer printouts of the raw and calculated data were obtained for each set of tests. At selected test points, cylinder pressure-time traces were generated and stored on magnetic discs. These signals were subsequently recalled and processed to give digital printouts of pressure-time history with time intervals of 10^{-4} seconds between each pressure reading. These data were used to compute average flame speed and other performance characteristics.

After the completion of firing tests, the engine was motored keeping the oil temperature at the operating level and motoring torque was measured for each of the compression ratios.

MIXTURE BURNING RATE FROM THERMODYNAMIC ANALYSIS

A thermodynamic analysis of the measured cylinder pressure trace was carried out through a computer program described in references [8] and [9] and run on IBM System 370/155. This program takes into consideration the effects of intake air humidity, residual gas dilution, heat transfer from the cylinder walls, in addition to the usual engine operating variables such as intake and exhaust conditions, speed, compression ratio, ignition timing, mixture characteristics, and engine geometry. Instantaneous heat loss from the cylinder gases is determined from Eichelberg's equation [10]. Precombustion energy release is estimated from the equation proposed by Johnson et. al[11]. The values of the cylinder pressure data at different small intervals (generated in the computer printouts referred to previously) are used as input. The intake process is analyzed stepwise assuming the intake mixture to behave as an ideal gas. The compression process is analyzed stepwise till the point of ignition, taking into consideration the precombustion energy in the mixture, if any. The calculations pertaining to the combustion phase commence at the point of ignition and the burned products are assumed to be in chemical equilibrium in a system of twelve components comprising CO_2, H_2, O_2, N_2, H, O, N, H_2O, NO, OH, CO, and CH_4. An interactive technique is used to arrive at the final flame volume at the end of each interval which will be compatible with the measured pressure and at the same time satisfy the energy balance for the burned and unburned volumes. The above procedure was carried out in steps from interval to interval and the progressive flame growth and flame velocity were determined. The computation of the combustion process ends when the burned volume approaces the total chamber volume. The expansion and exhaust processes were then analyzed at the end of the cycle and the indicated output and efficiency were calculated.

The computed burning rate from some selected pressure-time data appear in Table 2. Note that the calculated flame speed and indicated thermal efficiency with the addition of 1% by volume of aniline were found to be the highest of all the values shown in Table 2.

Figure 1 shows the variation of cylinder gas pressure and burned gas temperature as functions of crank angle as the flame progresses for neat methanol, methanol and 1% aniline, and methanol with 10% water at a CR = 11 and $\Phi = 1$.

The work of Harrington and Pilot of Ford Motor Co. [12] appears to be the only source which provides comparable combustion characteristics information of methanol in a single cylinder engine. Combustion analysis was made using instrumentation developed by Harrington. For 100% methanol fuel, from Ref. [12] it was reported 56° crank angle, by measurement, was required to combust 95% of the mass in the cylinder. Computer calculation in our study showed this to require 55.5° of crank angle. Although the engine speeds and equivalence ratios were the same, the compression ratios were 8 to 1 and 11 to 1 and the combustion chamber shapes were flat and hemispherical for the respective tests by Harrington and ourselves.

With 10% water, the burning interval is increased from 55.5° CA to 63° CA while with aniline the interval is 45° CA. This fast burning rate may be one--but not necessarily the only--cause of the reduced aldehydes when aniline is added. This will be discussed in the following section.

EMISSIONS--RESULTS AND DISCUSSION

Emissions of unburned fuel (UBF), oxides of nitrogen (NO_x) and CO at various equivalence ratios without mixture preheat appear in Figure 2 for neat methanol at a 10:1 CR. The emissions measurements are reported as ppm for UBF, NO_x and volume percentage for CO. Figure 3 portrays the emissions data from the compression ratio traverse at stoichiometric ratio ($\Phi = 1$) using neat methanol without preheat. Data shown in Figure 4 refer to the preheated mixture exhaust emissions at 10:1 using neat methanol.

In order to compare this evidence with other work the emissions data of UBF and NO_x were recalculated on a microgram per Joule basis (μg/J) and grams per indicated horsepower hour basis (gm/IHP hr). Table 3 typifies one set of calculations.

UNBURNED FUEL

At 10:1 CR, 1500 rpm, MBT spark timing and a mixture temperature of about 2°C (Fig. 2) the UBF shows the characteristic U-shaped curve reaching a minimum at approximately $\Phi = 0.83$. This minimum closely agrees with the findings of Pefley, et al. [2] and Hilden, et al. [4]. It is not possible to make exact comparisons of the minimum values of HC as the compression ratios, engine geometries, speeds and mixture temperatures in the investigations were different. However, approximate comparisons on a unit energy base have some usefulness. A value of 4.2 μg/J observed by Hilden at a CR of 8 and a mixture temperature of 9 ± 5°C. However, these values are very much higher than the 0.15 μg/J from Ref. 2 where higher, 21°C, mixture temperature and lower engine speed were used.

Figure 4, in comparison with Figure 2, characteristically shows the strong effect of increasing mixture temperature on reducing UBF. A mixture temperature of 77°C lowered the UBF minimum value by fivefold. However, this value (0.84 μg/J) is still somewhat higher than Ref. 2. Further study of test differences by the authors is necessary to reconcile this difference.

The UBF variation with CR shown in Fig. 3 is in good agreement with Brinkman's work. He conducted the investigation on an engine with the same geometry at MBT timing. It should be kept in mind that only trends can be compared as the speed and mixture preheat are different in both cases. However, some generalities in relative values are striking. For instance, the relative increase of UBF as CR is raised from 8 to 11 is about 20% in our case. Interpolating from Brinkman's curves for $\Phi = 1$, the increase is found to be about 30%.

NO_X EMISSIONS

The profile of NO_X emissions obtained in our work (Figs. 2 and 3) is in keeping with well established trends. At a CR of 11, the NO_X peak occurs at $\Phi = 0.9$ with a value of 5.5 μg/J. This is in reasonable agreement with the 5.2 μg/J of Ref. 2 considering the differences in engine geometries, and operating variables.

The increase of 67% in NO_X emissions due to intake mixture preheating (Fig. 4) can be explained by an increase in peak flame temperature and is reflected in an increase in exhaust temperature of 100°F at the condition of maximum NO_X concentration. The ppm increase at the maximum values per degree of mixture temperature increase is about 9 ppm/°F and again is found to agree well with Ref. 2. The effect of adding water was found to lower the combustion temperatures and, hence, reduce NO_X exhaust emissions, which is in agreement with others.

CARBON MONOXIDE EMISSION

These trends are similar to established patterns and do not call for detailed discussion.

ALDEHYDE EMISSIONS

Aldehyde concentration for neat methanol fuel without preheat increases with an increase in compression ratio (Fig. 5). This can be explained in the light of quench zone phenomena which caused increases in UBF with CR. However, the more significant observation is the substantial reduction of aldehydes with the addition of 1% by volume of aniline (see also Table 4a). Aldehyde concentration was reduced from 757 ppm to 345 ppm at the compression ratio of 11. With neat methanol, aldehyde concentration increased from 393 to 757 ppm with the increase of CR from 7 to 11 but there was no significant increase of aldehyde concentration with CR when aniline was added.

No significant change in aldehyde concentration relative to neat methanol was observed with variation of equivalence ratio while holding the CR onstant at 10:1,(Table 4b). Similar effects were observed when 0.75% aniline was added instead of 1% (Table 4C).

Aniline belongs to a class of additives which reduce ignition delay at small concentrations and increase the ignition delay at large concentrations [14]. It has been reported by authors of Ref. 14 that the critical concentration is about 0.8% by volume from engine tests. Hence it was decided to use only 0.75 and 1% of this additive.

Aldehyde concentrations decreased markedly with preheating (Fig. 6) for the same reasons as for UBF if it is assumed that aldehydes are produced by "cool flame" reactions in the quench layer [11].

From Figs. 5 and 6 and Tables 4a, b, c, it can be observed that the effect of the addition of aniline on reducing aldehyde production seems significant under all conditions including mixture preheat.

However, it is important to note that the effect of preheating caused a much greater reduction in aldehyde emissions than the addition aniline did. This was true at all compression ratios.

It was found that aniline addition had virtually no effect on NO_x, UBF, or CO emissions. Unregulated emissions have not as yet been explored.

CONCLUSIONS

- There is good agreement of our results with recent contemporary work on single cylinder engines fueled with methanol.
- The addition of aniline to methanol causes an increase in flame speed and a reduction in aldehyde emissions.
- Water addition to methanol causes reduced flame speed, lower peak flame temperature, and as a consequence, lower NO_x emissions.
- Intake mixture preheating causes significant reduction in UBF and aldehyde emissions and an increase in NO_x emissions at MBT timing which was retarded when compared to operation without preheat.

FURTHER INVESTIGATIONS

Further research is needed relative to unregulated emissions consequences from the addition of aniline.

Time resolved sampling of wall quenched exhaust gas or hot motored techniques and analysis of the early products of oxidation seem to offer deeper insights into the cause of aldehyde formation and its control with suitable additives and needs to be pursued.

ACKNOWLEDGEMENTS

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TABLE 4a

EFFECTS OF ANILINE ON ALDEHYDES AT VARIABLE CR AND STOICHIOMETRIC EQUIVALENCE RATIO

(Without Preheat)

Compression Ratio	7	8	9	10	11
Aldehydes PPM With Neat Methanol	393	589	729	723	757
Aldehydes PPM With 99% Methanol plus 1% Aniline (by Vol.)	353	308	378	336	345

TABLE 4b

EFFECT OF ANILINE ON ALDEHYDES AT CONSTANT CR AND VARIABLE Φ

(Without Preheat)

Equivalence Ratio	0.80	0.93	1.01	1.12	1.17	0.83	1.02	1.16
Aldehydes PPM with 99% Methanol plus 1% Aniline (vol.)	362	320	311	257	210	336	336	261

TABLE 4c

EFFECT OF .75% ANILINE ON ALDEHYDE EMISSIONS @ 10:1 CR

(Without Preheat)

Equivalence Ratio	0.81	0.98	1.12	1.13
Aldehydes PPM	353	261	294	244

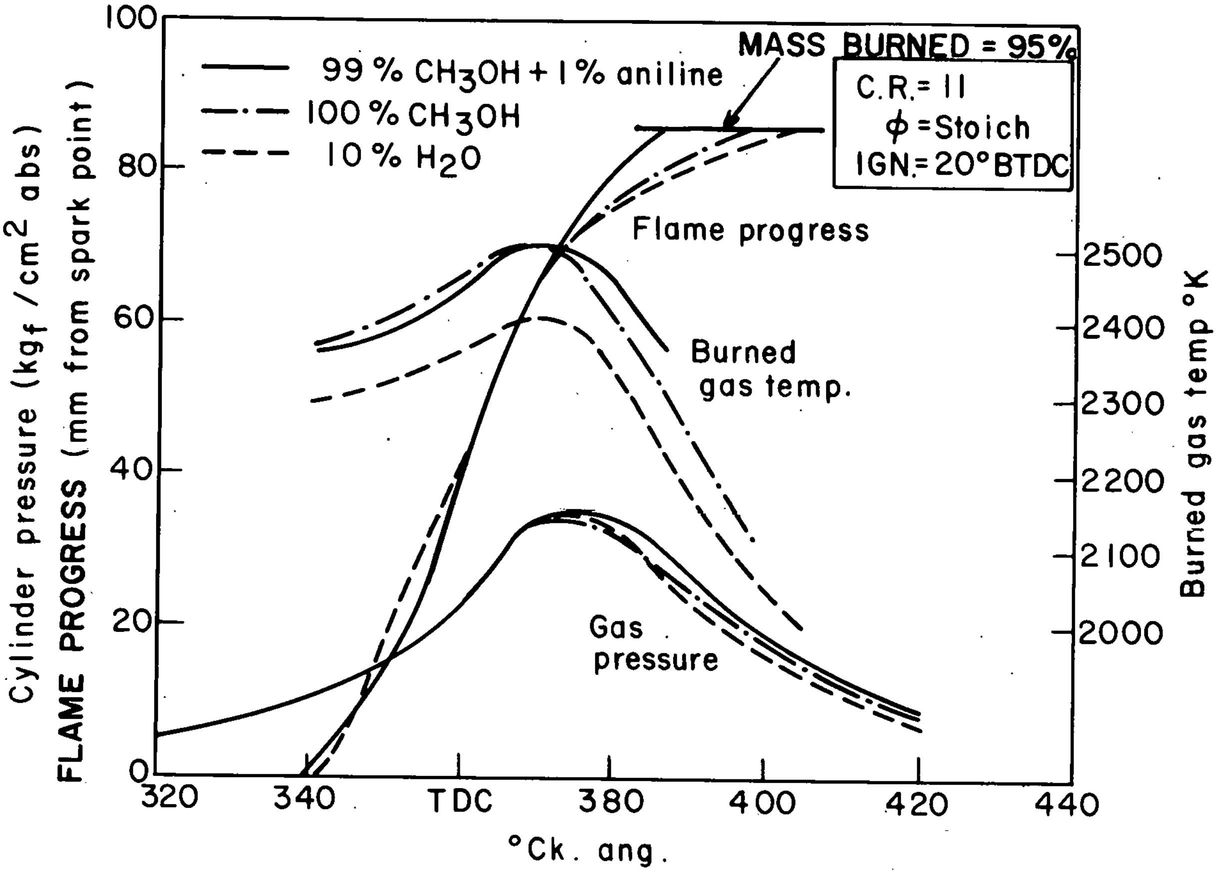

FIG: I - HISTORY OF FLAME PROGRESS

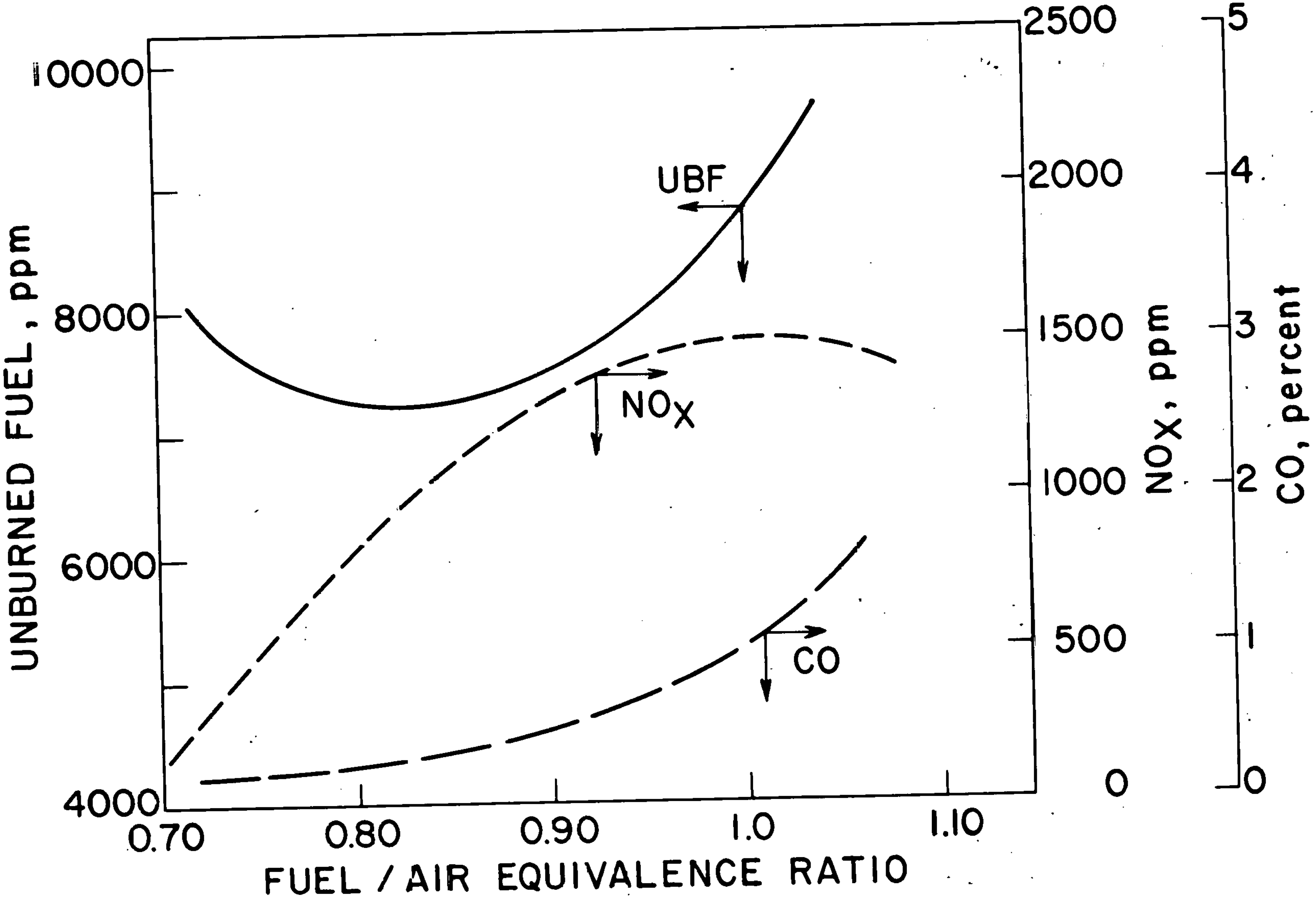

FIGURE : 2 - EXHAUST EMISSIONS FROM THE EQUIVALENCE RATIO TRAVERSE AT 10:1 CR USING NEAT METHANOL WITHOUT MIXTURE PREHEAT.

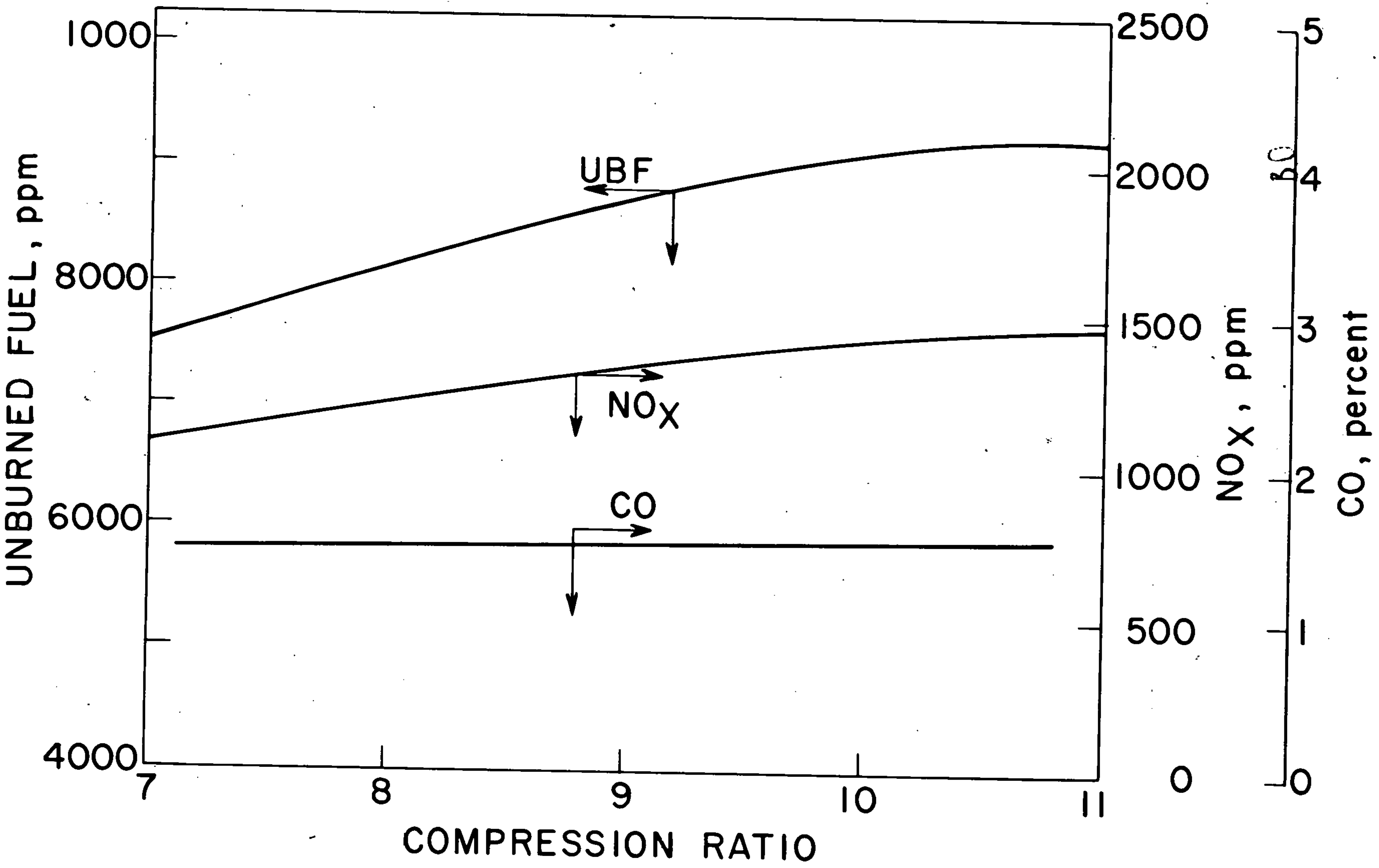

FIGURE: 3-EXHAUST EMISSIONS FROM THE COMPRESSION RATIO TRAVERSE AT STOICHIOMETRIC USING NEAT METHANOL WITHOUT MIXTURE PREHEAT.

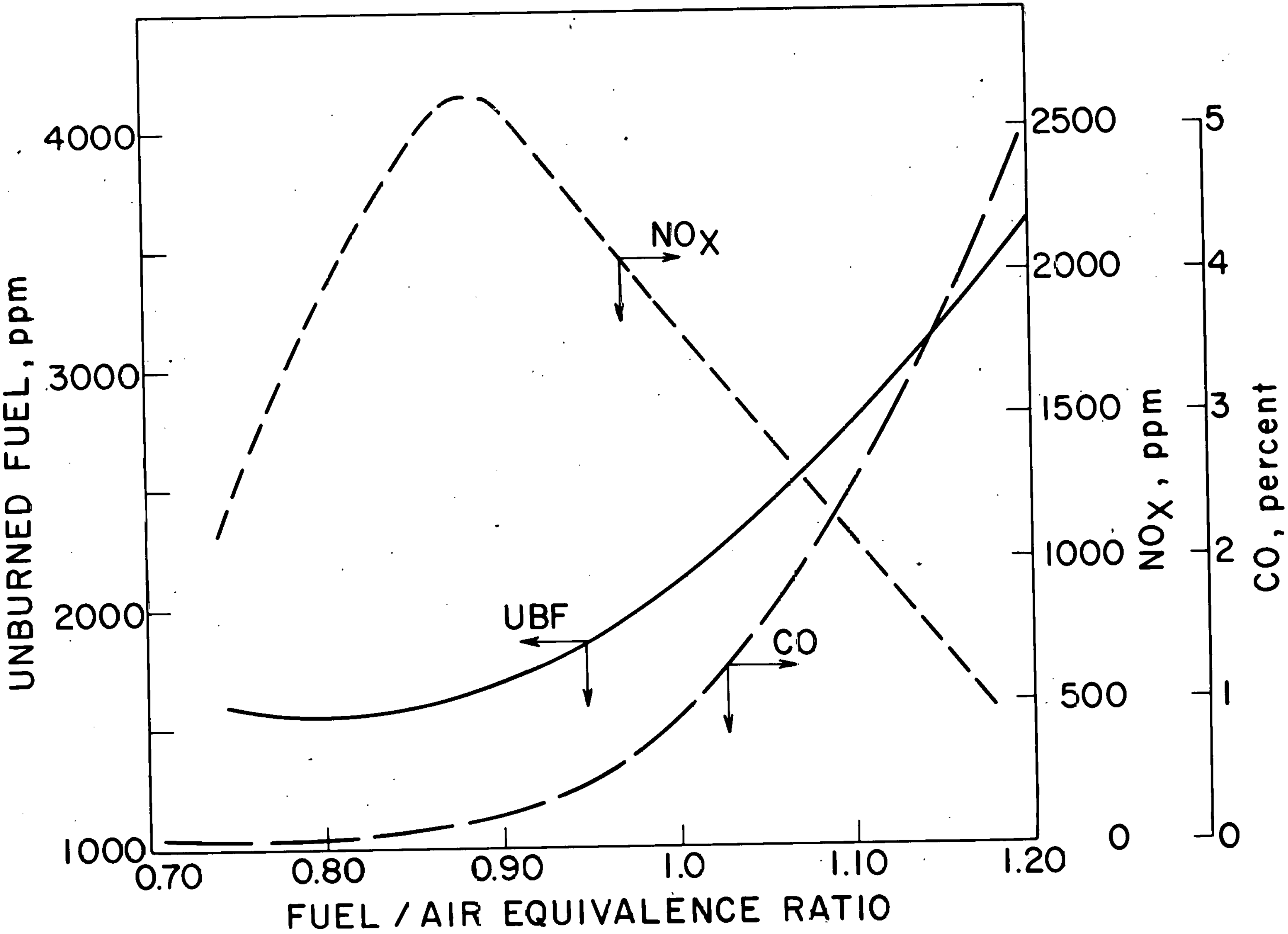

FIGURE: 4 - PREHEATED EXHAUST EMISSIONS AT 10:1 CR USING NEAT METHANOL.

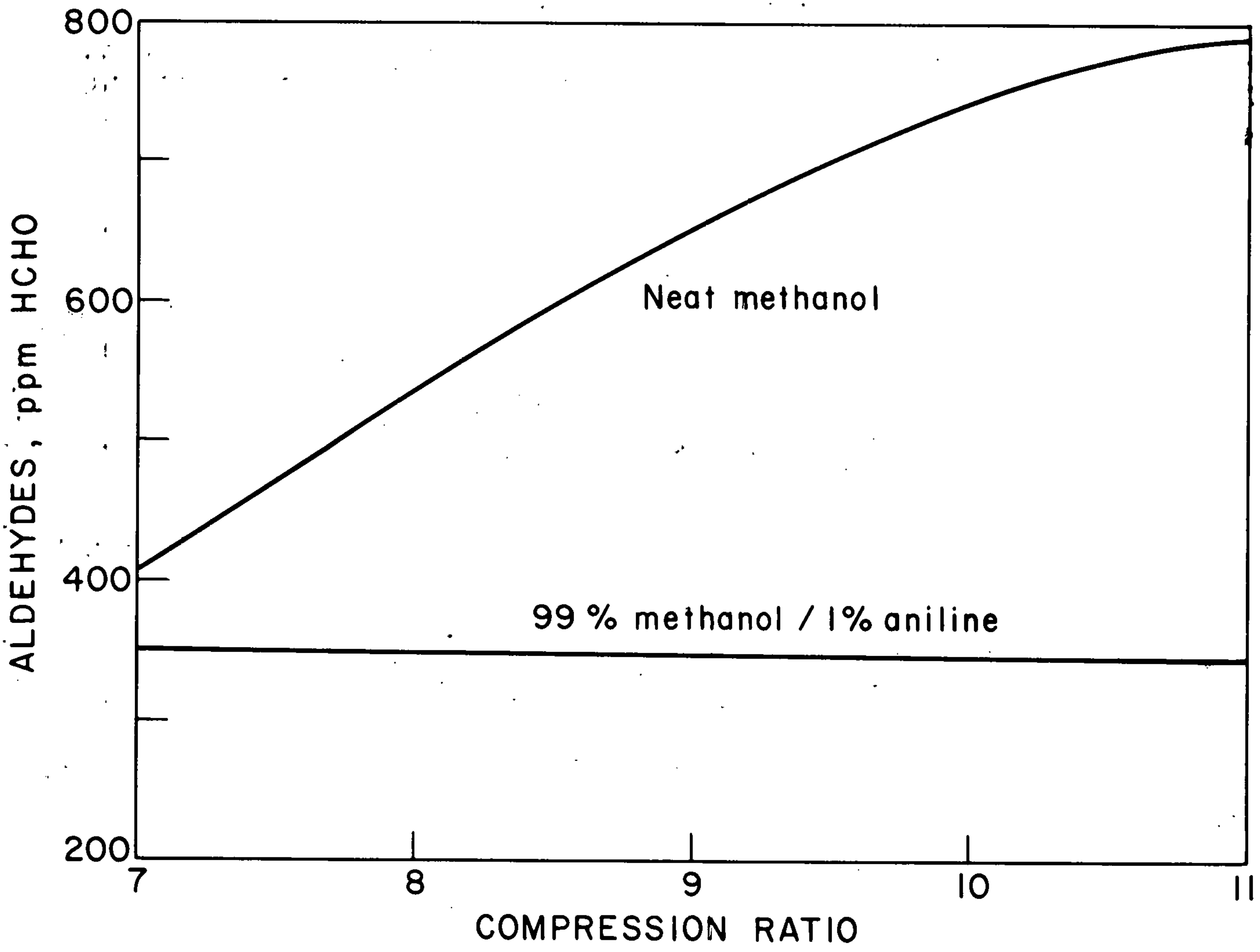

FIGURE 5 - EFFECT OF ANILINE ADDITION AT VARIOUS COMPRESSION RATIOS AT STOICHIOMETRIC WITHOUT PREHEAT.

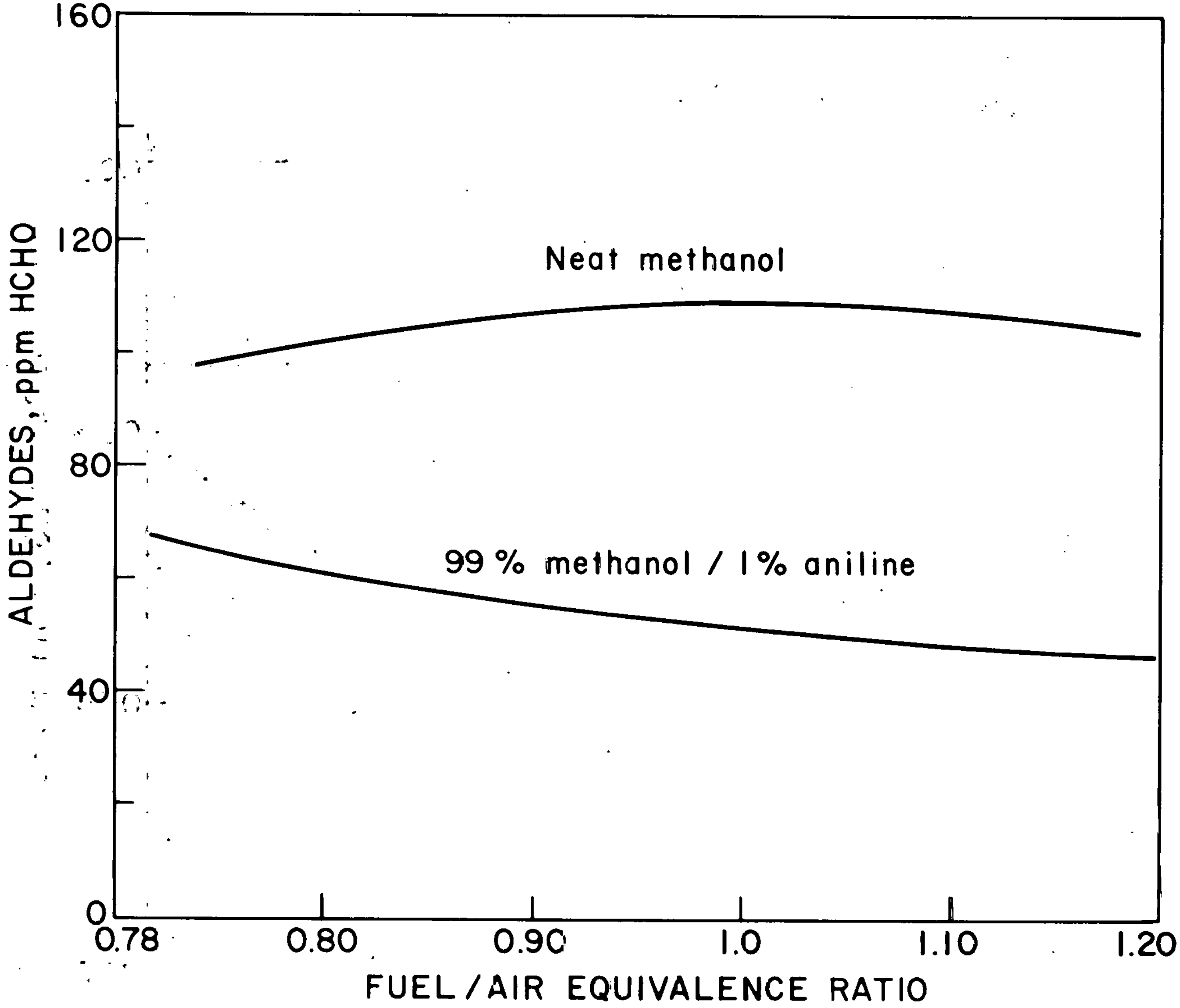

FIGURE: 6 - EFFECT OF ANILINE ADDITION AT VARIOUS EQUIVALENCE RATIOS WITH PREHEATED MIXTURE AT 10:1 CR.

TABLE 1
TEST ENGINE SPECIFICATIONS AND OPERATING CONDITIONS

Engine Data
Bore = 96.8 mm, Stroke = 92.1 mm, Displacement = 680 cc
Hemispherical Head (RHD-CFR)

Operating Conditions

Speed 1500 rpm	Oil Temperature 178°F	
Manifold Vacuum 2.2"Hg.	Water temperature 215°F	
Spark Timing MBT		
Mixture Temperature	Without preheat	With preheat
100% Methanol	36°F	170°F
90% Methanol + 10% water (vol)	41°F	"
99% Methanol + 1% aniline (vol)	36°F	"

TABLE 2
COMPUTER PREDICTION OF FLAME SPEED

No.	Fuel	CR	Φ	MBT Spark Advance °BTDC	Average Flame Speed m/sec	Peak Combustion Temp °k	Indicated Thermal Efficiency %
1.	99% CH_3OH 1.0% Aniline	11	1.02	20	19.8	2509	30.15
2.	CH_3OH (90%) H_2O (10%)	9	1.02	25	15.8	2359	22.88
3.	CH_3OH (90%) H_2O (10%)	11	1.01	20	14.8	2445	25.00
4.	CH_3OH	10	1.15	25	16.2	2458	19.95
5.	CH_3OH	9	0.98	25	18.5	2523	24.17
6.	CH_3OH	11	0.98	20	16.8	2504	28.56

TABLE 3 - EQUIVALENCE RATIO TRAVERSE @ 10:1 CR USING NEAT METHANOL

Fuel/Air Eq. Ratio ϕ	IHP	ISFC	MBT Spark Timing °BTDC	UBF				NO_x				CO %	Aldehydes PPM HCHO
				PPM	gm/hr	gm/IHP.HR	μg/J	PPM	gm/HR	gm/IHP.HR	μg/J		
0.72	5.06	.77	35	8080	137.0	27.07	10.08	297	2.9	0.57	0.213	0.29	437
0.80	5.56	.75	35	7160	111.9	20.12	7.49	790	7.7	1.38	0.516	0.36	303
0.95	6.16	.81	25	8560	129.0	20.95	7.79	1375	11.6	1.88	0.701	0.79	398
1.04	6.56	.82	25	9450	161.9	24.70	9.19	1520	14.1	2.15	0.800	1.44	723

THE INFLUENCE OF ENGINE PARAMETERS ON THE ALDEHYDE EMISSIONS OF A METHANOL OPERATED FOUR-STROKE OTTO CYCLE ENGINE

by

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Abstract

The influence of air-fuel ratio, ignition timing, compression ratio and configuration of the combustion chamber on the aldehyde emissions were investigated on a single-cylinder spark ignition engine. The investigations were conducted in gasoline and methanol operation. Also the effect of water content in methanol was ascertained. The results show higher aldehyde emission with methanol than with gasoline over the entire relative air-fuel ratio range. In the case of methanol with 5 % and 10 % water content the aldehyde emissions lie higher than with straight methanol. Furthermore the influence of a platinum-rhodium catalyst on the aldehyde emissions was determined at various speeds and loads on a four-cylinder four-stroke otto cycle engine. With that catalyst the aldehyde emissions in methanol operation could be reduced, without supply of secondary air by about 50 % in the fuel-rich range and up to about 90 % in the lean range.

Introduction

Investigations conducted in recent years on methanol operated four-stroke otto cycle engines have revealed a number of advantages over gasoline engines (Table 1) [1, 2, 3].+)

	Methanol over Gasoline	%
Output	increase	9
Efficiency	increase	13
CO	decrease	10...25
NO_x	decrease	40...65
HC	decrease	30...40
Aromatic Compounds	decrease	-
Aldehydes	increase	70

Table 1: Four-stroke otto cycle engine: Comparison of methanol with gasoline

There is a strong potential for lower exhaust emissions, especially regarding NO_x and HC, as well as aromatic and sulfur compounds. This advantage is conflicting with a higher aldehyde content in the exhaust.

+) Numbers in brackets [1] designate References at end of paper

Analyses of the aldehyde emissions of methanol fueled engines have shown that these are predominantly low-molecular aliphatic aldehydes, with formaldehyde accounting for about 60 - 70 %, the rest comprising about 7 % acetaldehyde and about 9.5 % acrolein [4, 5, 6]. These compounds can irritate the mucous membranes of the eyes and respiratory system and contribute to the formation of photochemical smog. The introduction of a methanol technology therefore requires a careful investigation of the aldehyde emissions and possibilities for their reduction. Solutions can be developed only if comprehensive knowledge on the influences of engine and non-engine parameters is available. This paper reports on investigations intended to contribute to this knowledge.

Test Conditions and Description

For the determination of aldehyde emissions as a function of engine parameters such as ignition timing, relative air-fuel ratio, compression ratio and configuration of the combustion chamber, a single-cylinder spark ignition engine of 80 mm stroke, 80 mm bore (swept volume $V_H = 403 \cdot cm^3$) and a rated speed of 5000 rpm was used. Two different combustion chamber configurations have been investigated as shown in Fig. 1 for piston top-dead-centre position: A disc shaped chamber with a flat piston crown (1 b) and one with a piston bowl of 60 mm diameter (1 a). The compression ratio was changed by varying the depth of the piston bowl or, for the disc shaped combustion chamber, by varying the distance between the piston top and the cylinder head. The fuel was injected intermittently into the inlet pipe about 18 cm before the closed inlet valve. All examinations with the single-cylinder engine were made at fully opened throttle (full load) and at a speed of n = 2500 rpm.

The investigations with regard to the load and speed influence were conducted on a four-cylinder four-stroke otto cycle engine having a stroke-bore ratio of 79.5/80 mm, a combustion chamber with a piston bowl and a compression ratio of 9.4. Fuel was injected continuously into the inlet pipes near the inlet valves with a Bosch K-Jetronic system. This engine was also used to investigate the influence of catalytic oxidation on the aldehyde emissions. To this end a catalyst was positioned in the exhaust system 130 cm after the cylinder head. The reactor volume was 1200 cm^3 and the active layer consisted of platinum and rhodium. The oil and water temperatures in these examinations on the single-cylinder and multi-cylinder engines were kept at about 88° and 80°C, respectively.

To measure the total aldehyde emissions, the 3-methyl 2-benzothiazolone hydrazone (MBTH) method was used as it is described in the pertinent literature [7]. Sampling was carried out according to [8, 9]. A flask having a volume of 391 ml is filled with 50 ml of a 0.05 % MBTH solution which is evacuated to a partial vacuum of about 100 mmHg (absolute), with the flask ambient temperature being measured. By opening the flask cock, exhaust gas is sucked through a very short bleeding probe into the flask. Of this sample, which is allowed to stand for about one hour, 10 ml is mixed with 1 ml of an 1.6 % aminosulfonic acid and with 1 ml of a 1 % solution of ferric chloride and replenished to 50 ml with distilled water. After about 20 minutes, the sample extinction is measured with a spectrophotometer of the Perkin Elmer Company at a wavelength of 628 nm. The aldehyde concentration is determined by means of a calibration curve prepared for formaldehyde.

In applying such measuring methods, knowledge as to reproducibility of measurements and the cross sensitivity to disturbing substances is of vital importance. In [9, 10] it is reported on the reproducibility of test values in connection with different sampling methods, and in [5, 9] also on the cross sensitivity of the MBTH method with regard to nitrogen oxides. The reproducibility of the measuring method was also ascertained by us in a series of tests. To this end, ten samples per operating point were taken successively with four minutes intervall with the engine running on gasoline, methanol, or on a mixture of 90 weight percent methanol and 10 weight percent water. These examinations were conducted on the single cylinder as well as on the multi-cylinder engine. It was found that the relative standard deviation for the single-cylinder engine averages about 5 % to 8 %, and for the multi-cylinder engine 4 % which means reasonable good reproducibility. This is in accordance with the findings of other researchers. The lower relative standard deviation with the 4-cylinder engine may be due to the greater number of combustion cycles which during the brief period of suction into the flask furnish a more averaged composition of the exhaust gas.

The cross sensitivity of the measured aldehyde concentrations to nitrogen oxide (NO) was determined by two mixtures with nitrogen each containing the same fraction of acetaldehyde (68 ppm) and two different nitrogen oxide levels (4600 ppm and 7500 ppm). With 4600 ppm/7500 ppm NO an about 10 %/16 % lower aldehyde concentration was measured, compared with the aldehyde concentration measured without presence of NO.This means for gasoline with about 4600 ppm NO within the relative air-fuel ratio (λ) range around 1.1 a too low measurement of aldehyde emissions of about 10 %. For methanol corresponding to the lower NO concentration of about 2800 within this range the measured aldehyd concentration is only 6 % too low.

Influence of Ignition Timing and Relative Air-Fuel Ratio on Aldehyde Emissions

It will be remembered that in the conventional spark ignition engine the combustion process and thus output, fuel consumption and exhaust emissions are largely determined by the ignition timing. Fig. 2 shows the influence of spark setting on the aldehyde emissions. Here the aldehyde emission is plotted versus ignition timing for different relative air-fuel ratios λ under gasoline and methanol conditions at a compression ratio of 8.1 with the disc shaped combustion chamber. It can be seen that with gasoline operation both in the fuel-rich (λ = 0.82 and 0,95) and n the lean range (λ = 1.1 and 1.22) the aldehyde emissions as a unction of ignition timing take a rather flat course. Futhermore, it becomes evident that the aldehydes tend to increase as the relative air-fuel ratio rises.

The lower portion of the illustration shows the influence of the ignition timing under methanol conditions. The aldehyde emissions are much higher than in the case of gasoline. For a lean mixture, the maximum aldehyde emissions occur at about the maximum brake torque (MBT) spark. Under fuel-rich conditions (λ = 0,85 and 0,93) the aldehyde emissions rise steeply as the spark advance decreases.

Fig. 3 shows the influence of the relative air-fuel ratio on aldehyde emission for the piston bowl combustion chamber. The fuels examined were gasoline, methanol and a mixture of 90 % methanol and 10 % water. As became evident also in Fig. 2, the aldehyde emissions with gasoline increase steadily from the rich to the lean range, i.e. from about 20 ppm to roughly 70 ppm. As compared with gasoline, the aldehyde emissions with methanol in the lean range are higher by approximately factor three. At λ = 0.9 they reach a minimum of about 120 ppm. Toward the rich and lean range the aldehydes rise to about 200 ppm. If 10 percent-in-weight water is added to methanol, the aldehyde emissions are markedly increased. From a pronounced maximum at about λ = 1, the aldehydes diminish toward the lean and rich ranges, although they continue to be much higher than in the case of straight methanol.

It should be mentioned here that the aldehyde emissions may be higher than the total hydrocarbons measured with a FID. This applies especially for a range of λ = 1 to 1.2. Our investigations have shown that the aldehyde emissions are measured too low with a FID. For instance propion- and acetaldehyde concentrations of 200 ppm are indicated with only 10 to 20 percent of this value.

The strong influence of water in methanol on the aldehyde emissions is shown also in Fig. 4. Here, using the disc shaped combustion chamber for methanol, the aldehyde emissions are plotted against the relative air-fuel ratio for 5 % and 10 % water content and straight methanol. In contrast to Fig. 3, the point of ignition was now kept constant at 40^{o} before top dead centre. With 10 % water (90 : 10), the maximum of aldehyde emissions in the rich range is highest and comes close to λ = 1. With 5 % water parts (95 : 5), it drops to about half the value, shifting toward the lean mixture. For straight methanol, the values again are considerably below those of 5 % water content.

The influence of increased speed on aldehyde emissions was examined for the relative air-fuel ratios λ = 0,95 and 1.1 with gasoline and methanol operation. It was found that at a speed of n = 4000 rpm and a MBT spark the aldehyde concentrations are approximately equal to that at 2500 rpm. The increase of aldehyde concentrations with retarded ignition is higher at 4000 rpm than at 2500 rpm. Investigations of the influence of load have shown that the aldehyde emissions increase with decreasing load, MBT-spark and constant air-fuel ratio provided.

Influence of the Compression Ratio and the Combustion Chamber Configuration on Aldehyde Emissions

An outstanding advantage of methanol is its high knock resistance, which makes it possible to increase the compression ratio beyond that of present-days gasoline engines. This has a particularly favourable effect on the engine efficiency.

The influence of different compression ratios (CR) on aldehyde emissions with the piston bowl combustion chamber and maximum brake torque spark is shown in Fig. 5 as a function of the relative air-fuel ratio. The results show that both with gasoline and with methanol the aldehyde emissions rise over the entire range of air-fuel ratios if the compression ratio is increased from 8.1 to 9.3. An increase of the compression ratio under methanol conditions to 12.8 results in a reduction of aldehydes in the rich range as against CR = 9.3. In the lean range of $\lambda = 1.1$ to 1.3 and with a compression ratio of 12.8 the aldehyde emissions are higher by about 45 ppm compared with CR = 9.3.

With a methanol-water mixture (90 :10), the influence of compression ratio was examined again for the same operating and engine conditions. The results are shown in Fig. 6. It is apparent that an increase of the compression ratio from 8.1 to 12.8 will produce lower aldehyde emissions over the entire range of air fuel ratios.

The configuration of the combustion chamber is also an important design parameter. The disc-shaped type and the piston bowl type have been compared at a compression ratio of 8.1. Fuel consumption and output for both types of combustion chamber are at about the same level. The NO and hydrocarbon emissions are a little higher under lean conditions with the piston bowl combustion chamber. The influence of the combustion chamber on aldehyde emissions is illustrated in Figs. 7 and 8. The piston bowl combustion chamber proves to be more favourable at a compression of 8.1 both for gasoline and methanol (Fig. 7). With a compression ratio of 12.8 and for methanol conditions, however, the disc shaped combustion chamber produces lower aldehyde emissions in the lean range as is shown by Fig. 8.

Reflection on the Formation Process of Aldehydes

The results described above reveal a considerable influence of various engine parameters and fuels (gasoline, methanol, methanol and water) on aldehyde emissions. An explanation of these influences would require some knowledge on the formation and decomposition mechanisms of aldehydes during the combustion and exhaust process.

To obtain more background on the formation of aldehydes, two important basic facts were investigated mathematically.

1. The occurence of formaldehyde concentration in chemical equilibrium of burned methanol-air mixtures.

2. The kinetic decomposition process of formaldehyde in the burned mixture.

For the calculations all components or reactions which are contained in the mechanism proposed by Bowman /11/ were considered.

The calculations of the formaldehyd concentration at chemical equilibrium were conducted with various relative air-fuel ratios (λ= 0 to λ= 1) at pressures of 50 bar and 1 bar and various temperatures in the range from 400 K to 2000 K. The calcuation show that the formaldehyde concentration decreases with decreasing temperatures for all relative air-fuel ratios investigated. Within the temperature range of 1200 K up to 2000 K at 50 bar and for practical air-fuel ratios the equilibrial concentrations of formaldehyde are well below 0.1 ppm. For a temperature of about 700 K the CH_2O concentrations are even lower by factors of ten. At all temperatures the formaldehyde concentrations lies even lower at a pressure of 1 bar than at 50 bar. By increasing the air-fuel ratio the CH_2O concentration decreases. At the same conditions but with ten percent water in methanol the formaldehyde concentrations are slightly higher than with straigt methanol. All these calculations show that formaldehyde concentrations are infinitely small in the possible states of equilibrium of the burned gas during the process of a methanol fueled engine. The measured high aldehyde emissions cannot be explained therefore by any equilibrial concentration during the process.

It is stated by several researchers, that methanol combustion proceeds via steps which comprise the formation and decomposition of formaldehyde (CH_2O). Therefore, aldehydes formed in the reaction zone of the flame could survive in spite of adverse equilibrium conditions, if the decomposition process is sufficiently slow.

For investigating this possibility a reaction kinetic assessment was carried out. Proceeding from the chemical state of equilibrium of burnt gases of a methanol-air mixture (λ = 1) the half-life period for formaldehyde with concentrations above equilibrium value was calculated. This assessment was made for two different combustion chamber conditions (T = 3000 K, p = 50 bar and T = 1500 K, p = 1 bar) and a formaldehyde concentration of 200 ppm (in the order of the aldehyde concentrations measured in exhaust gas). Under these conditions the half-life periods are approximately 10^{-7} sec (T = 1500 K, p = 1 bar) and 10^{-12} sec (T = 3000 K, p = 50 bar). These times correspond at an engine-speed of 2500 rpm to approximately 10^{-3} and 10^{-8} degrees crank angle respectively. In view of these short half-life periods, it may be assumed that the aldehyde concentrations measured in the exhaust gas do not originate from the bulk gas in the combustion chamber. It can be concluded that the aldehyde emissions result from wall quenching. Also secondary reactions of the quenching zone contents during the exhaust process could contribute.

Unfortunately there is still a lack of knowledge on the mechanism of wall quenching. It therefore seems impossible up to now to safely explain the engine results of this investigation on a theoretical base.

Effect of an Exhaust Catalyst on Aldehyde Emissions

The results presented above do not reveal powerfull possibilities to reduce aldehyde emissions in methanol operation. For this reason, the influence of an exhaust catalyst upon the emission of aldehydes was examined with the multi-cylinder engine.

Fig. 9 shows the aldehyde concentrations before and after the catalyst for three speeds as a function of load. These investigations were conducted with methanol using the ignition timing required for petrol conditions and a constant relative air-fuel ratio of 1.05. These conditions produce a marked decrease of the aldehydes as the speed increases. It can be seen that at all speeds examined and over the entire load range the aldehyde emissions are diminished by the catalyst to about 20 ppm.

Also the effect of the catalyst as a function of the relative air-fuel ratio was examined. The investigations were conducted for two loads corresponding to 2.45 bar and 7.38 bar and a speed of n = 3000 rpm. Here also the spark timing was set for gasoline operation. The exhaust gas temperatures at part load with a relative air-fuel ratio of approximately 1 in front of and behind the catalyst are 400° and 406°C. With the same air-fuel ratio the exhaust gas temperatures at 7.38 bar BMEP in front of and behind the catalyst are 540°C and 545°C. Fig. 10 shows that for both loads the aldehyde emissions decrease with increasing air-fuel ratio in the fuel-rich range and increase again for leaner mixtures. The aldehydes measured after the catalyst have the same tendency on a lower level in the rich range up to about $\lambda = 1.05$. For lean operation the low levels after catalyst remain nearly constant. The conversion rate as a function of the relative air-fuel ratio is shown in Fig. 10 below. Accordingly, the aldehydes are converted already at a relative air-fuel ratio of $\lambda = 0.8$ by about 50 % at both BMEP-levels. The conversion rate increases to about 90 % at a relative air-fuel ratio of $\lambda = 1.1$. Thus the exhaust catalyst proves to be a valuable device for lowering the aldehyde emission levels effectivly.

Summary

(1) With methanol the aldehyde emissions at a comparable operating point are higher by a factor of two to three than with gasoline.

(2) As opposed to gasoline, with methanol an advanced ignition within the rich range can result in a significantly lower aldehyde emission.

(3) At a maximum brake torque spark and a compression ratio of 8.1, straigt methanol shows no marked influence of the air-fuel ratio on aldehyde emissions. With gasoline, the aldehydes increase at MBT spark as the air-fuel ratio rises.

(4) Increasing water content in methanol produces increasing aldehyde emissions especially near the stoichiometric air-fuel ratio. With a compression ratio of 8.1 and stoichiometric mxiture the aldehyde emissions may be higher by factor of four with 10 % water content compared to straight methanol.

(5) The influence of the compression ratio on the aldehyde emission is not uniform. In the lean range, aldehydes always increase as the compression ratio rises. With 10 % water content the influence of the compression ratio may be reversed.

(6) The configuration of the combustion chamber has an influence on aldehyde emission. With a lower compression ratio of 8.1 the piston bowl type and at higher compression ratios the disc-shaped type proved to be more favourable.

(7) According to results of equilibrium calculations and kinetic studies the measured aldehyde emissions cannot be explained by processes in the bulk gas within the combustion chamber. The probable source is wall quenching.

(8) With an oxidizing platinum-rhodium exhaust catalyst, the aldehyde emissions in methanol operation can be reduced, without supply of secondary air, by about 50 % in the fuel rich range and by about 90 % in the lean range.

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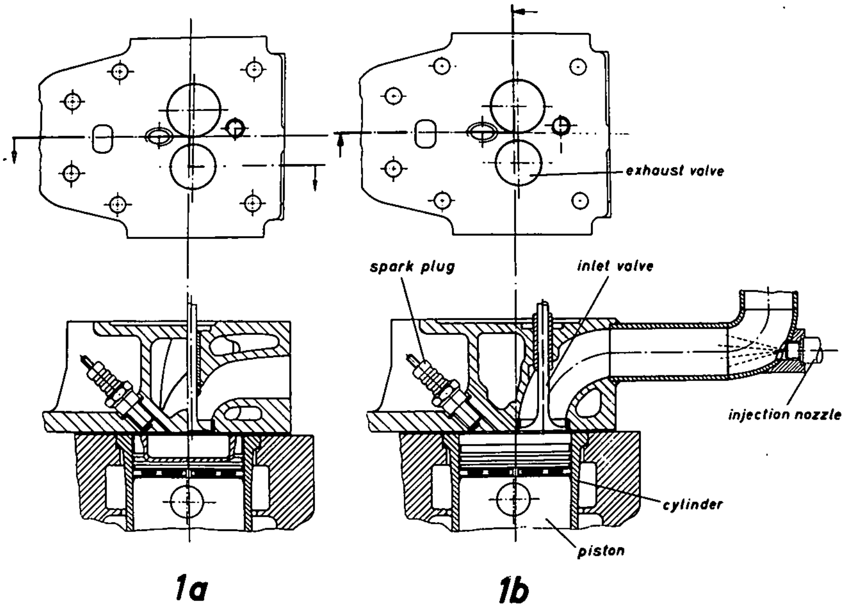

Fig. 1: Combustion chamber configuration

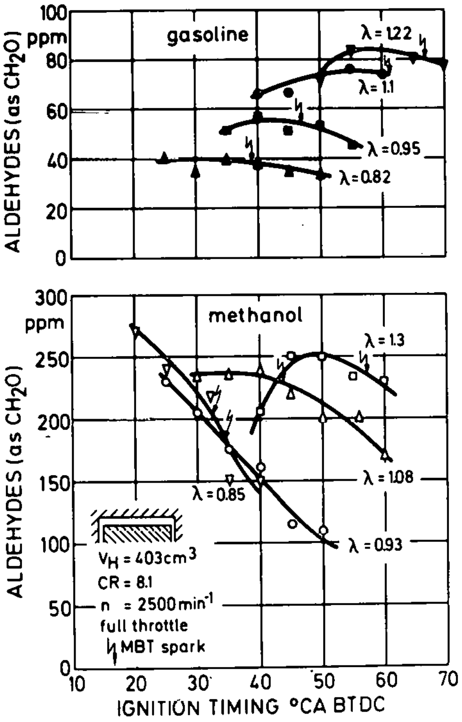

Fig. 2: Aldehyde emissions versus ignition timing for gasoline and methanol. Disc shaped combustion chamber

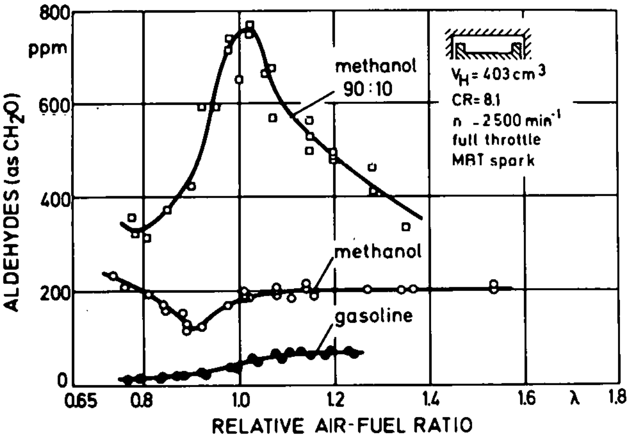

Fig. 3: Aldehyde emissions versus relative air-fuel ratio for gasoline, straight methanol and methanol (90 : 10). Piston bowl combustion chamber

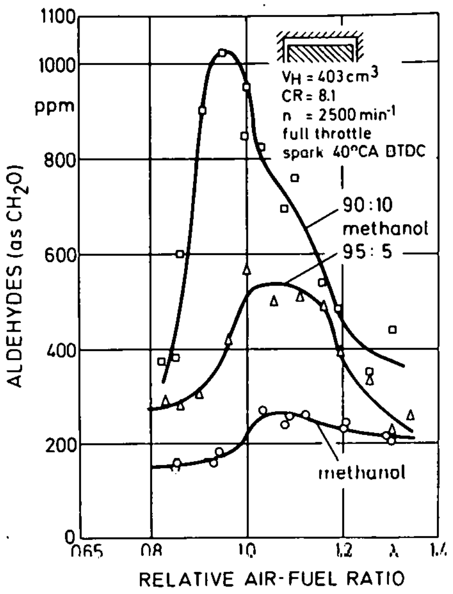

Fig. 4: Aldehyde emissions versus relative air-fuel ratio for straight methanol, methanol (90 : 5) and 90 : 10). Disc shaped combustion chamber

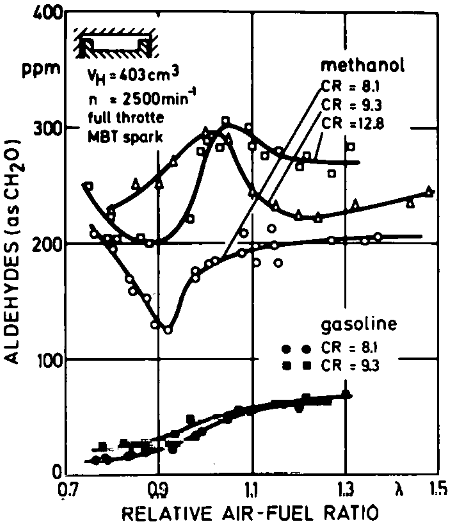

Fig. 5: Aldehyde emissions versus relative air-fuel ratio for gasoline and methanol for various compression ratios (CR). Piston bowl combustion chamber

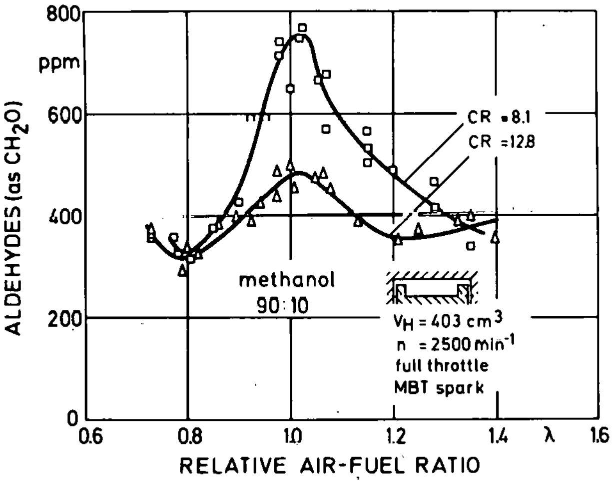

Fig. 6: Aldehyde emissions for methanol (90 : 10) versus relative air-fuel ratio for compression ratios CR = 8.1 and CR = 12.8. Piston bowl combustion chamber

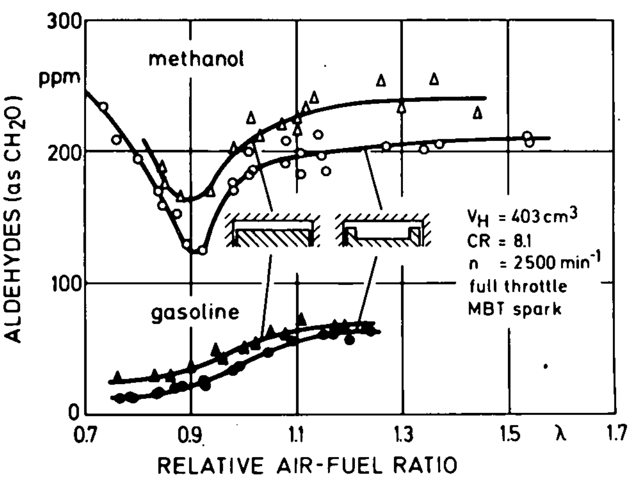

Fig. 7: Aldehyde emissions for gasoline and methanol versus relative air-fuel ratio for disc shaped combustion chamber and piston bowl combustion chamber

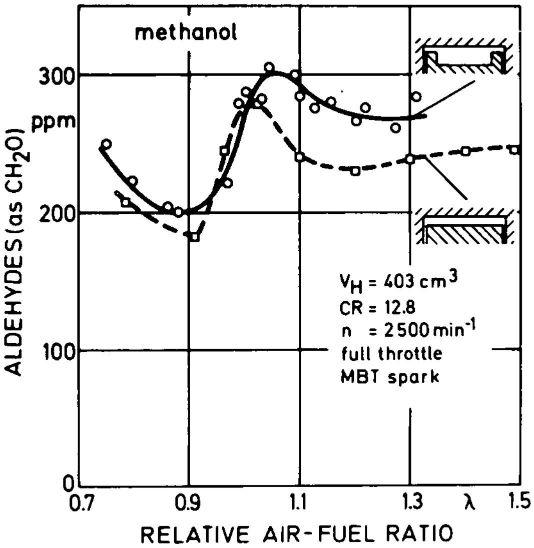

Fig. 8: Aldehyde emissions for methanol versus relative air-fuel ratio for disc shaped combustion chamber and piston bowl combustion chamber

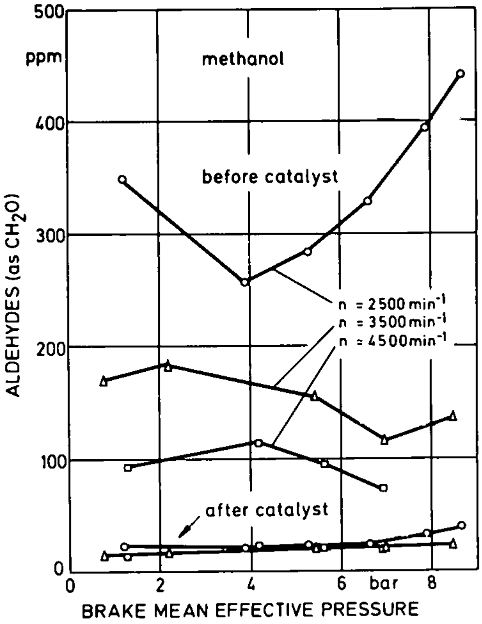

Fig. 9: Aldehyde emissions (before and after catalyst) for methanol versus BMEP for various speeds. Four-stroke otto cycle engine, swept volume $V_H = 1588\ cm^3$

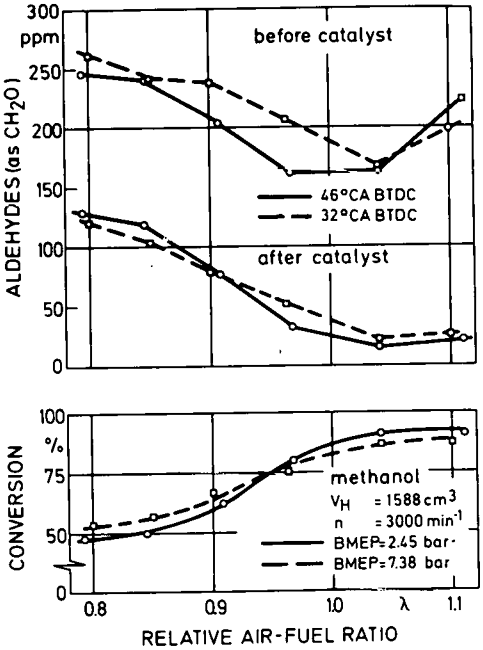

Fig. 10: Aldehyde emissions (before and after catalyst) for methanol versus relative air-fuel ratio. Conversion for aldehydes versus relative air-fuel ratio

A MOTOR VEHICLE POWERPLANT FOR ETHANOL AND METHANOL OPERATION

by

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THE CHARACTERISTIC PROPERTIES OF ALCOHOL FUELS

In the selection of possible substitutes for present motor vehicle fuels preference should be given to those alternatives that would require a minimum of engineering modifications to present-day powerplants. This then would keep the necessary investments low while it would at the same time minimize any risks that might be posed by new engineering concepts. Alcohols as alternatives to gasoline offer the following advantages:

- Alcohols are liquid-state fuels and fit into the present infrastructure of the distribution and sales network. In addition to that there is available a proven technology for the adaptation of liquid-state fuels to the engine requirements.

- Viscosity and density of alcohol fuels are similar to those of gasoline and permit the use of present carburetor and injection systems.

- The almost identical calorific value of mixtures of gasoline and alcohol with air permits the use of the present-day engine/vehicle concepts because the same engine size can be used in a given vehicle concept.

Methanol and ethanol are the two most simple alcohols that are especially well suited for automotive engine operation. Their production consumes the least energy,and they offer some other advantages over other alcohols in automotive applications, such as a comparatively low boiling point.

A comparison of the most significant characteristics of gasoline, ethanol, and methanol for automotive application shows the following essential differences [1]*(Fig. 1):

- Alcohols have a lower calorific value than gasoline because they contain substantial chemically combined oxygen quantities.

- The difference in the required amount of air is determined by the oxygen content of the fuel.

- The higher octane numbers of alcohol permits engines with higher thermal efficiency.

- Compared with gasoline, alcohols have a markedly higher vaporization heat. This requires a more intense heat introduction for mixture preparation and may lead to higher efficiency in the thermodynamic process.

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*Numbers in brackets designate References at end of paper.

- The low vapor pressure and the lack of low boiling-point components poses problems for the mixture formation system.

- The lower volatility together with the high vaporization heat poses cold-start problems.

Fig. 2 shows the vapor pressure data of ethanol, methanol, and gasoline as a function of temperature [2]. Winter gasoline has the same vapor pressure at the usual cold-start-temperature limit of roughly -20°C for production vehicles as has methanol at +10°C or ethanol at +22°C. This roughly corresponds to the engine cold-start limits for these fuels.

THE USE OF ALCOHOL FUELS IN AUTOMOBILE ENGINES

Compression Ratio

The design of engines for ethanol and methanol operation, on the basis of present-day production gasoline engines, requires first an adaptation of the compression ratio to the octane number of the alcohol fuels [3,4]. When the compression ratio of a production engine for unleaded fuel operation is 8.2, alcohol fuel operation permits an increase of the compression ratio to between 12.5 and 13. This increases the economy of operation as shown in Fig. 3 where economy rises by approximately 6.5% at low partial load operation (60 km/h or 37 mph). A rise in economy by 11.5% is possible at higher velocities (100 km/h or 62 mph). This gain in economy results from the higher compression ratio. In addition, an alcohol fuel increases economy by roughly 3 or 5% (methanol) even if the engine has the same compression ratio as the gasoline engine. This is the result of the improved thermodynamic efficiency when some of the high vaporization heat of the alcohol is used for the internal cooling during compression stroke.

Mixture Formation

The adjustment of the air/fuel ratio shows that combustion can occur at a much leaner mixture than in the case of gasoline [3,5]. Maximum economy at partial load, however, is similar to that of a gasoline engine, i.e. 10 to 20% leaner than the stoichiometric mixture (Fig. 4).

The low volatility and vapor pressure of alcohols reduce fuel vaporization in the intake manifold. This leads to non-uniform mixture distribution to the individual cylinders, especially in carburetor engines. The fuel/air mixture, therefore, requires stronger heat-up so that the initial uniform distribution can be reached again. Experience has shown that a heating system which suffices for methanol operation is not adequate for ethanol operation. It must be concluded that fuel vaporization in the intake manifold is determined less by the vaporization heat of the fuel than by its volatility.

Practical applications have shown that the alcohol engine is more economic than the conventional gasoline engine. Fig. 5 shows the different fuel consumption data for partial-load operation.

Economy may be further increased with the aid of a more sophisticated mixture formation system. An injection system, for instance, may lower the energy demand during partial-load road operation by an average of 5%.

The causes are the more precise distribution of the mixture to the individual cylinders and the improved thermodynamic efficiency provided by a lower mixture temperature and the ensuing lower compression work.

Ignition

Partial-load operation shows that alcohol-operated engines require less ignition advance than gasoline engines. The reasons are the higher rate of flame propagation of alcohol fuels and the higher compression ratio.

A high-energy ignition system was found to be useful for improved driveability, especially in the case of cold engines. There are, however, marked differences from the gasoline engine during full-load operation. Alcohol-powered engines with the highest possible compression ratio for optimized partial-load efficiency show that the maximum possible mean effective pressure cannot be utilized during full-load operation without getting into the knock range. This high speed knocking is attributed to the comparatively lowmotor octane number of alcohol fuels. Fig. 6 shows the necessary ignition timing required for the maximum mean effective pressure without knocking.

It is obvious that the maximum possible output cannot be fully reached. The knock limit is distinctly a function of the temperature. Fig. 7 shows the reduction of the knock limit during full-load operation as a function of the increase in mixture temperature. A rise in coolant temperature has the same effect as an increase in ambient temperature. An increase in the mixture temperature by 5°C shifts the knock limit curve by almost 5° crank angle. This means that the mixture temperature at full load should be as low as possible in order to ensure good mixture distribution. The subject engine should be equipped with a knock sensor in order to ensure proper input of ambient temperature data. The sensor would then initiate the required ignition adjustment. Fig. 7 also shows that ethanol mixture temperatures are higher than methanol temperatures. The reason is the difference between the vaporization heat.

Pre-ignition

The use of pure methanol fuels tends to pose combustion problems in the high output range. Engine operation above the load limit is likely to result in rough running, loud noise and fast component temperature rises until component failure. The sequence of events takes place in such a short period of time that in most cases the engine cannot be shut off early enough. Studies of the combustion process have shown that the essential cause is pre-ignition of the mixture. This especially applies to methanol because of its strong tendency to catalytic decomposition. The strong inclination of methanol to pre-ignition was confirmed by the results of ignition system investigations of high-compression alcohol-fuel-powered engines. The first trigger element of the undesirable pre-ignition was found to be the spark plug. This effect was eliminated by the selection of a plug design with a high heat range. Fig. 8 shows the required heat ranges for spark plugs in various design concepts of high-compression alcohol-fueled engines, together with the spark plug temperatures. It is obvious that the 65 kW carburetor engine needs a heat range of 240 in order to ensure safe operation without pre-ignition. A higher heat range of 260 is required despite the lower spark plug temperature if the output of the same engine concept is reduced to roughly 56 kW by leaner operation. A higher output version of the same engine with wider intake cross section requires spark plug heat ranges between 370 and 400. This establishes a limit range for the practical use of a concept like that. Fig. 8 further indicates that the same engine on ethanol operation requires a heat range that is close to that of the production engine. The spark plug temperature, too, is markedly lower than that of the methanol-powered engine [6].

It may be concluded from these results that the combustion chamber temperature must be kept at a level that ensures the prevention of pre-ignition.

SELECTION OF THE ENGINE CONCEPT

The weighting of the available selection criteria leads to the definition of priorities and thus to the determination of the engine concept. In this case, major significance was attributed to favorable energy consumption during partial-load operation, good driveability and emission behavior, and simple engineering. Therefore, the full-load behavior was subordinated to those requirements. This means that the compression ratio of the engine was to be as high as possible in order to permit favorable partial-load fuel consumption. Fig. 3 shows that an increase of the compression ratio in the partial-load range to values between 12.5 and 13 resulted in a marked improvement in efficiency. Fig. 9 shows that the efficiency in partial-load operation clearly is a function of ignition timing. The objective set for the concept design was to prevent a more than 3% excess minimum fuel consumption in partial-load road operation by proper selection of air/fuel mixture ratio and ignition timing.

This concept definition together with the effects of the parameters outlined above leads to limitations in the full-load range where pre-ignition and knocking must be avoided. Therefore, the maximum output must be limited so that excess combustion chamber temperatures are avoided. This may be accomplished by the following approaches:

(1) Throttling
(2) Ignition retard
(3) Mixture enrichment.

Throttling appears to be the most economical approach, while ignition retard should be used only if necessary in order to avoid effects on partial-load behavior. Fig. 10 shows, in addition to the effects of pre-ignition on partial-load consumption, the dependency of the maximum mean effective pressure during full-load operation. Too much mixture enrichment should not be employed because of the resulting effects on economy. Furthermore, the mixture temperature at full-load operation should be as low as is justifiable in view of the mixture quality. These considerations resulted in the present concept definition of a high-compression-throttled engine.

Investigations were performed on a number of possible ways to improve cold-start and driving behavior of alcohol-powered engines. The most useful and economical method was found to be the addition of low-boiling components to the fuel. The following results are achieved without any additional processes if the vapor pressure of the alcohol fuel is brought to the presently common values of summer and winter gasolines:

- Cold start-up even at low temperature
- Good driving behavior at cold engine temperatures with only moderate mixture enrichment
- Reduction of the higher cost for mixture heating of carburetor engines for alcohol fuel operation.

The required increase of vapor pressure may be accomplished by the use of some known low-boiling-point hydrocarbons and also by alcohol derivatives such as dimethyl ether. Fig. 11 illustrates these effects and shows the values produced by isopentane with ethanol and methanol as an example.

COMPARISON BETWEEN ETHANOL AND METHANOL OPERATION

Their almost identical knock characteristics permit the use of ethanol and methanol in the same engine concept, i.e. at high compression ratios in the range of 12.5 to 13. The only requirement is the adjustment of the carburetor calibration to the difference in air intake. Both fuels can use the same ignition control. After proper tuning, both fuels yielded the same fuel economy in the partial-load range and the same full-load data. Fig. 12 shows the mean effective pressure at full load as an example.

While stationary tests on the engine dynamometer produce virtually the same results for both fuels, pure-ethanol-powered vehicles show a markedly worse start-up and driving behavior. This applies especially at low ambient temperatures.

The higher boiling point temperature and the even lower vapor pressure of ethanol detrimentally affects start-up and driving behavior especially in carburetor operation and requires the addition of a higher portion of more volatile fuel components in order to achieve the same effects as methanol. The increase in fuel vapor pressure of course improves driveability and cold-start behavior. It was found that alcohol fuels with a vapor pressure of roughly 0.6 bar produce acceptable start-up behavior and driveability in summer operation. In order to achieve this result, ethanol requires more low-boiling additives than methanol.

ROAD TESTING

Daily routine and special tests in extreme climatic conditions (in winter in the north of Sweden and in summer in the south of Spain) were performed on alcohol-powered vehicles. No significant problems were encountered. Despite the high vapor pressures of the blends of alcohols and low-boiling additives, no problems were posed by the fuel system. It is obvious that the high evaporation temperature causes additional drops in temperature. The carburetor and fuel pump temperatures under extreme summer conditions were by 15 to 20°C lower than the corresponding temperatures in production gasoline-engine vehicles.

EMISSIONS

Stationary Operation

The basic emission behavior of alcohol-powered engines is observed during stationary engine operation. This was reported repeatedly in the literature [3,5]:

- CO emissions versus air/fuel ratio are similar to those from gasoline-powered engines.
- HC emissions are lower than those from gasoline engines. It should be borne in mind, though, that there are differences in the analytical assessment which are caused by the different HC spectrum.
- NOx emissions are lower than those from comparable gasoline engines if the air/fuel ratio and ignition timing are set properly.
- Markedly higher aldehyde emissions are found than from gasoline engines; formaldehyde from methanol and acetaldehyde from ethanol.

Significant reductions of the high aldehyde emissions cannot be achieved by modifications of the engine parameters or fuel blend composition. Changes to the air/fuel ratio, ignition timing, mixture temperature, and fuel water content, without any losses in economy (i.e. increase in fuel consumption) produced minor effects only. Aldehyde emissions were lowered by roughly 30% by the use of a sophisticated mixture formation system. The magnitude of aldehyde emissions from gasoline engines was not reached, though.

Non-Stationary Operation

Dynamometer measurements essentially confirmed the results from the engine bench tests. The European ECE Test Cycle produced the following emission data from alcohol-powered vehicles:

CO: 60% of the emissions from a production gasoline engine
HC: 78% of the emissions from a production gasoline engine
NOx: 55% of the emissions from a production gasoline engine

The aldehyde emissions were markedly higher than those from gasoline engines and showed the following characteristics:

- Minor differences between cold- and warm-engine operation.
- No distinct or satisfactory improvements are produced by engine modifications, injection systems, secondary air systems and thermal reactor.
- The installation of catalysts without additional secondary air systems leads to a marked reduction of aldehyde emissions to approximately the levels of the gasoline engine.

These promising efforts toward the lowering of the aldehyde emissions have not been concluded at this time. Later reports will deal with this subject further.

SUMMARY

A number of chemical and physical characteristics advocate the use of alcohols as alternatives to the present gasoline fuels. A special alcohol-powered engine was developed and showed the particular characteristics of methanol and ethanol. This especially applies to the inclination of methanol to pre-ignition and the necessity of more sophisticated mixture formation.

The energy consumption of the alcohol-powered engine is markedly lower than that of the production gasoline engine.

Vehicles with alcohol-powered engines produce markedly lower exhaust gas emissions of HC, CO, and NOx than comparable gasoline-powered vehicles. Catalysts may reduce the markedly higher aldehyde emission levels to those of gasoline engines.

ACKNOWLEDGEMENTS

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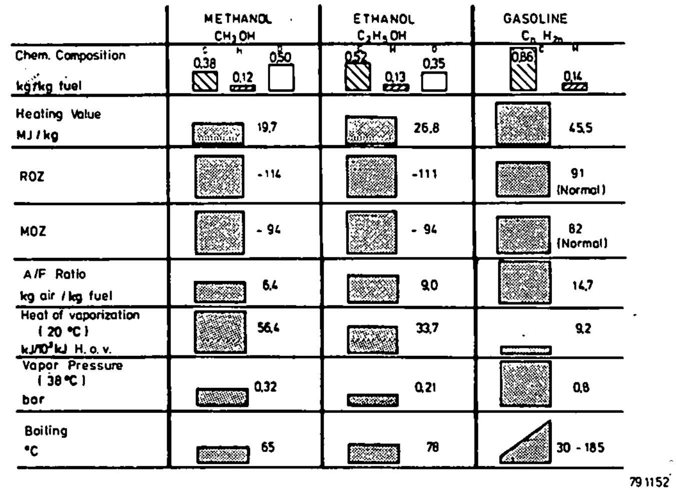
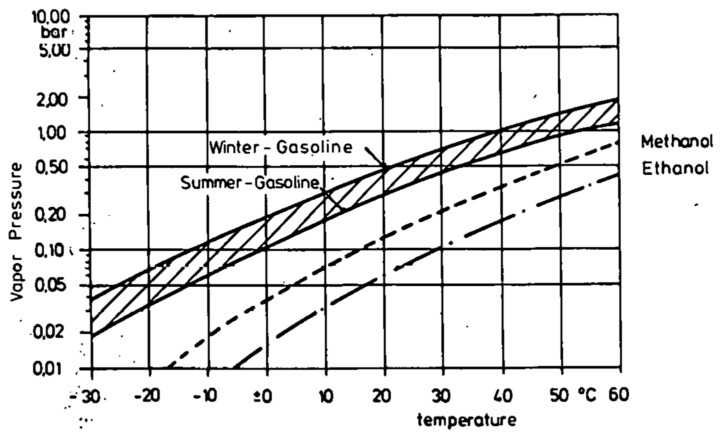


	METHANOL CH_3OH	ETHANOL C_2H_5OH	GASOLINE C_nH_{2n}
Chem. Composition kg/kg fuel	C 0,38 H 0,12 O 0,50	C 0,52 H 0,13 O 0,35	C 0,86 H 0,14
Heating Value MJ/kg	19,7	26,8	45,5
ROZ	-114	-111	91 (Normal)
MOZ	- 94	- 94	82 (Normal)
A/F Ratio kg air / kg fuel	6,4	9,0	14,7
Heat of vaporization (20 °C) kJ/10³kJ H. o. v.	56,4	33,7	9,2
Vapor Pressure (38 °C) bar	0,32	0,21	0,8
Boiling °C	65	78	30 - 185

Important properties of alcohols and gasoline for energy utilisation

79 11 52

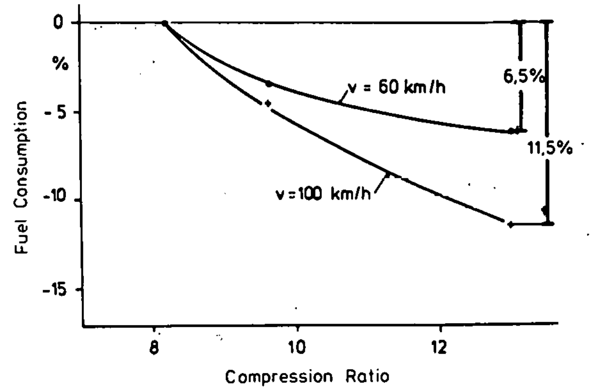
Fig. 1



Vapor pressure of ethanol, methanol and gasoline depending on temperature

79 11 53

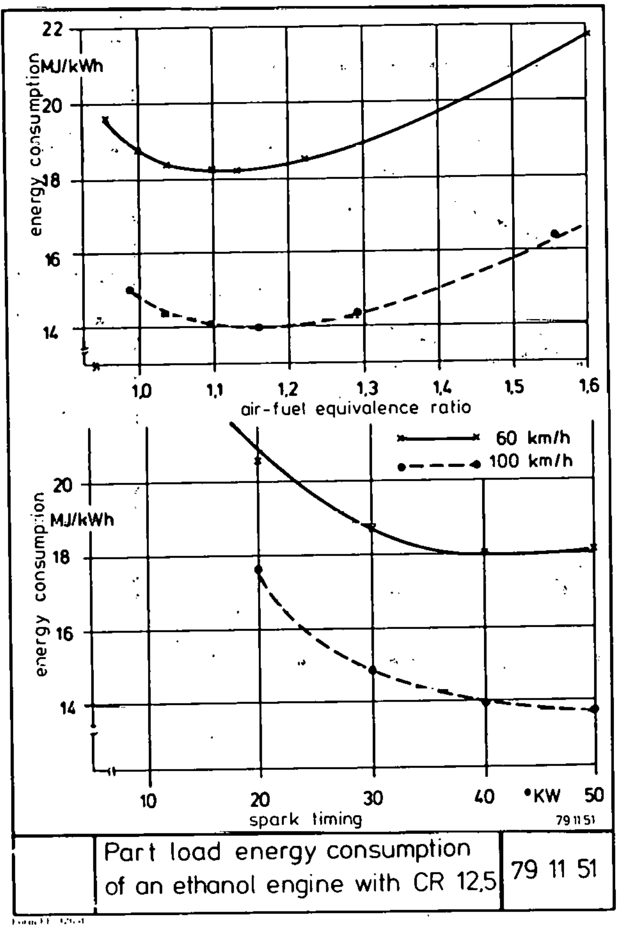
Fig. 2



Decrease of fuel consumption of an alcohol engine by increasing compression ratio

79 11 54

Fig. 3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MJ/kWh
20
18
16
14
energy consumption
1,0
1,1
1,2
1,3
1,4
1,5
1,6
air-fuel equivalence ratio
60 km/h
100 km/h
20
MJ/kWh
18
16
14
energy consumption
10
20
30
40
°KW
50
spark timing
79 11 51
Part load energy consumption of an ethanol engine with CR 12,5
79 11 51

Fig. 4

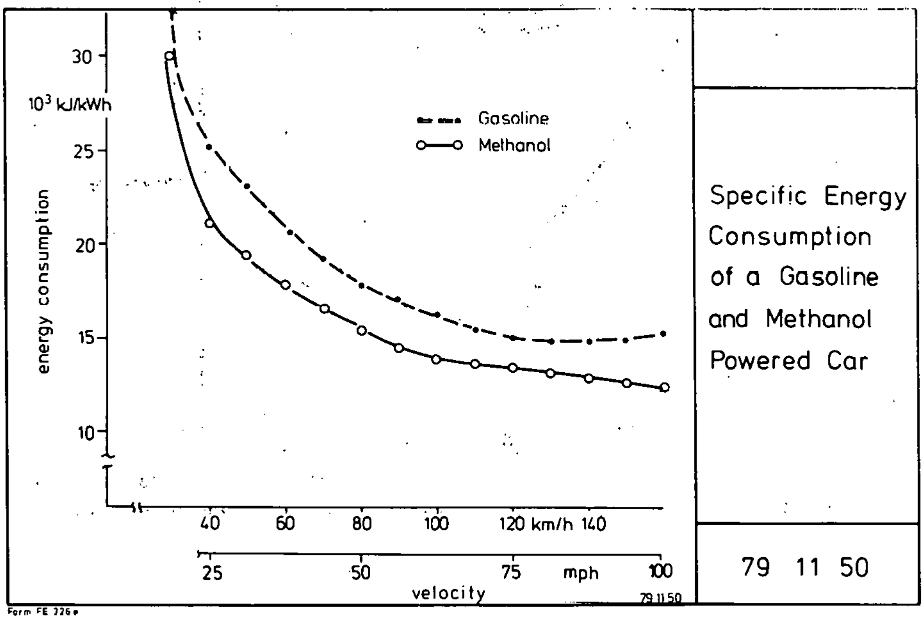
30
10³ kJ/kWh
25
20
15
10
energy consumption
Gasoline
Methanol
40
60
80
100
120 km/h 140
25
50
75
mph
100
velocity
79 11 50
Specific Energy Consumption of a Gasoline and Methanol Powered Car
79 11 50
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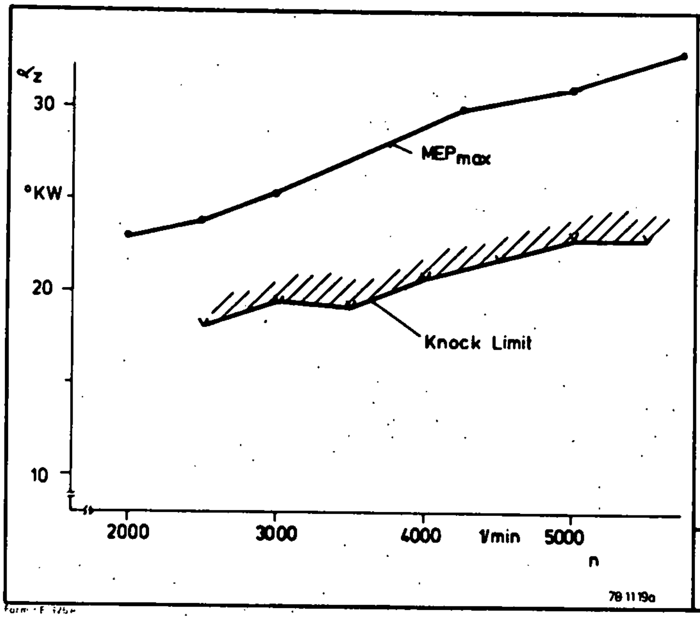
Fig. 5



Spark timing for max MEP and Knock Limit

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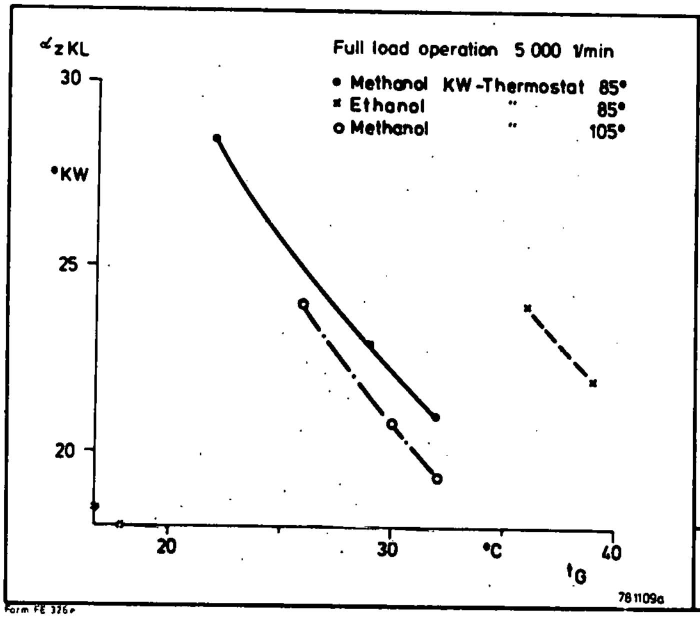
Fig. 6



Knock Limit α_{zKL} versus mixture temperature t_G

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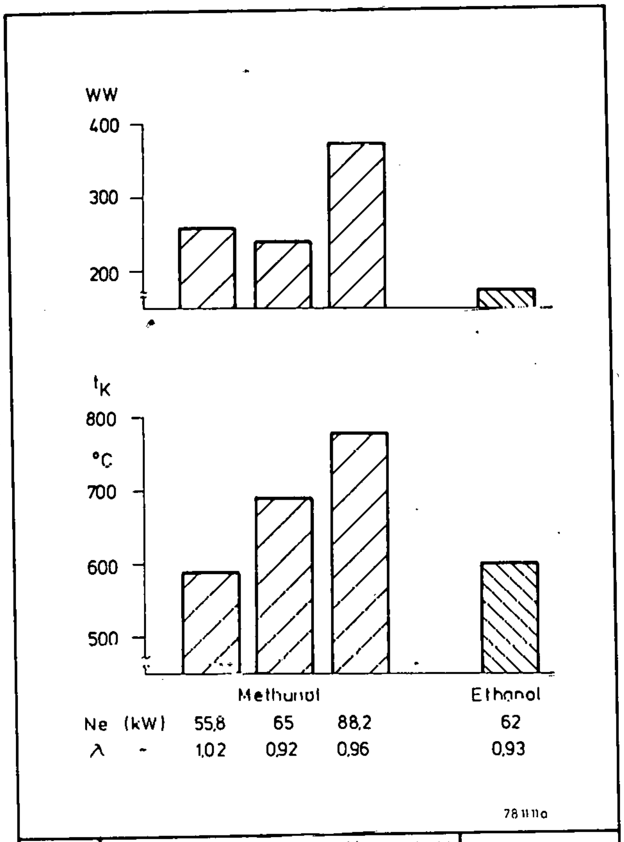
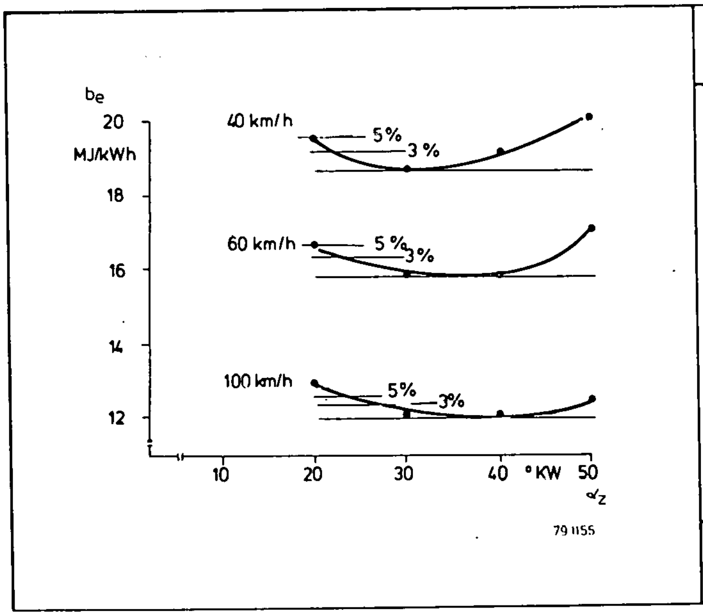
Fig. 7



Spark plug heat rating WW and -temperature t_K for different alcohol engines

78 11 11a

Fig. 8



Part load energy consumption be versus spark timing α_z

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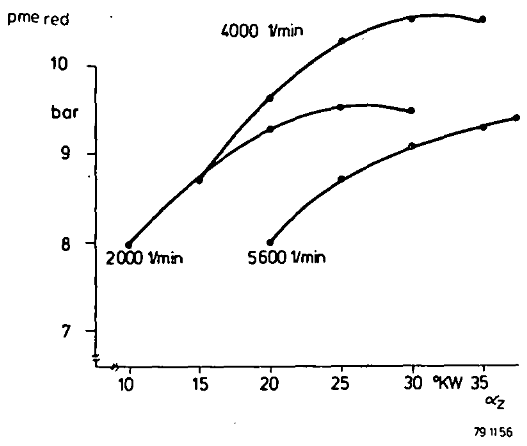
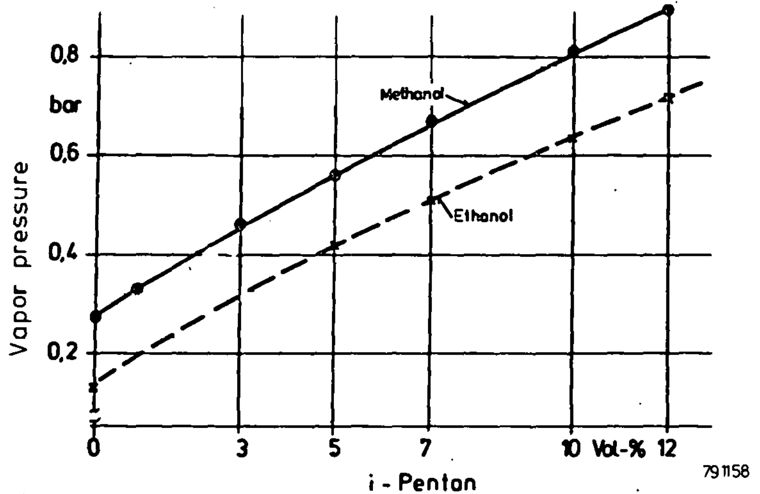
Fig. 9



Mean effective pressure pme_{red} of full throttle versus spark timing α_z

79 11 56

Fig. 10



Vapor pressure of Ethanol and Methanol mixtures with i - Pentan

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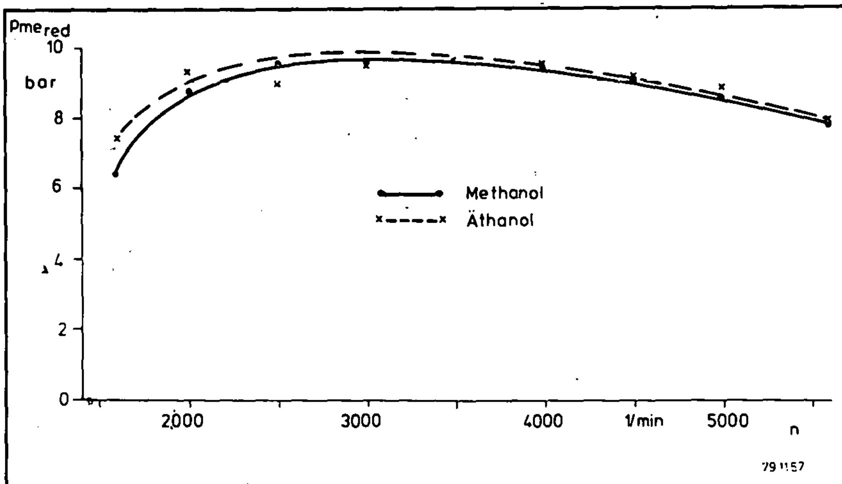
Fig. 11



Mean effective pressure pme_{red} of full load for different alcohol fuels in the same engine

79 11 57

Fig. 12

DUAL-FUELING A DIESEL ENGINE WITH CARBURETED ALCOHOL

by

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ABSTRACT

Alcohol as a motor fuel has been the subject of research over the past few years. The use of this fuel for trucks, as well as for agricultural and industrial equipment having diesel engines, is under consideration in this paper. This investigation was aimed at determining whether the low cost procedure of adding a carburetor to the combustion air intake system of a diesel engine was a feasible method of accomplishing at least partial substitution of alcohol for diesel fuel.

It was found, for a duty cycle common to a farm tractor, that approximately 56 percent of the energy for a diesel-engined unit could be supplied by carbureted ethanol or 47 percent by carbureted methanol.

Knock, associated with the use of all but the leaner air/alcohol mixtures, limited the extent of substitution of alcohol for diesel fuel to these intermediate levels.

INTRODUCTION

As the world petroleum supply is being expended at an increasing rate, man has begun to develop workable petroleum substitutes. Alcohol has been a strong candidate since it can be made from renewable resources and, thus, would be a net addition to the energy supply without over-drawing fossil fuel reserves.

The interest in alcohol as a fuel for internal combustion engines arose in the U.S. as a possible way to reduce automobile exhaust pollutants. Methanol is most promising in the U.S. since it can be derived from coal reserves and forests. However, in countries where coal is scarce, ethanol appears to be a feasible motor fuel for automobiles due to the possibility of utilizing agricultural surpluses and residues as raw material in the ethanol production process. Emphasis on ethanol use has increased in Brazil because of the vast land area (8,500,000 km^2) and favorable latitudes are excellent for producing food and, subsequently, fuel from sugar cane, cassava, and other renewable raw materials.

REVIEW OF LITERATURE

Several different methods of dual-fueling diesel engines with alcohol have been investigated by various researchers. Among the methods reported by Holmér [1]* were:

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*Numbers in brackets [1] designate References at end of paper.

a) the mixing of alcohol and diesel fuel within the intake gallery of the injection pump,

b) using two injection pumps (one for alcohol and one for diesel fuel) to supply fuel to a single injector and,

c) the use of two injectors in each cylinder along with the separate fuel system for each.

With the later system as much as 82 percent of the fuel energy could be supplied from methanol.

Both Barnes et al. [2] and Pefley [3] injected alcohol into the intake air between the turbocharger and the intake manifold of a turbocharged diesel engine. The former obtained as much as 54, 41 and 39 percent of the fuel energy from methanol, isopropanol and ethanol respectively, while the latter found the maximum proportion of energy obtainable from methanol to be 37 and 33 percent at part load and overload respectively, as limited by misfiring and knocking.

Panchapakesan et al. [4] carbureted ethanol into the air intake of a diesel engine. With diesel fuel injection beginning at 27 degrees BTDC alcohol use was severely limited by misfiring at low levels of diesel fuel injection. However, by advancing injection to 33 degrees BTDC ethanol could be used to supply as much as 80 percent of the fuel energy at maximum load levels.

Generally, it was found that the extent to which alcohol could be substituted for diesel fuel was limited by ignition delays and related misfiring and knocking caused both by the chemical characteristics of the alcohol as well as by the cooling effects that alcohol evaporation had on the intake charge. Also, it was generally found that the use of alcohol in the inducted air stream increased the maximum torque capabilities of the engine both by making more complete use of the oxygen in the cylinder, and by cooling the induced charge so that a larger maximum mass of oxygen could be taken into each cylinder on the intake stroke.

The above authors also found that the use of alcohol did not increase, and usually caused a decrease in the proportion of nitrogen oxides in the exhaust. The use of alcohol generally caused increases in the proportions of carbon monoxide and unburned hydrocarbons in the exhaust. Holmér [1], however, hound that the proportion of unburned hydrocarbons could be reduced by throttling the exhaust.

Thermal efficiencies tended to be slightly higher at full load conditions and slightly lower at low load conditions when alcohol was used in a dual-fueling mode as opposed to when injected diesel fuel was used alone.

EQUIPMENT AND PROCEDURE

The engine used was a Hallett, model AC-1, single cylinder, air cooled, naturally aspirated, direct injection, diesel engine with 3.50-inch bore, 3.62-inch stroke and a 20:1 compression ratio. Fuel injection was timed to start at 16 degrees before top dead center. Injection ended at 3 degrees after TDC at idle and 25 degrees after TDC at 80 percent of maximum torque.

At 1200 rpm, maximum brake torque was 27.2 Newton-meters and friction torque was 7.67 Newton-meters.

The intake of the engine was fitted with an updraft carburetor with an adjustable main jet. Wide-open throttle was used at all times. The carburetor, in some cases, was preceeded by a counter-current heat exchanger to transfer heat from the exhaust gas to the intake air.

The dynamometer consisted of a cradled, three-phase, 7 1/2 horsepower induction motor with a synchronous speed of 1200 rpm. This direct-connected unit also served as a starter and permitted engine operation at air/diesel-fuel ratios so high that indicated torque was less than friction torque, thus requiring supplemental power input to the engine from the electric motor/dynamometer.

Air flow was measured by an orifice meter attached to a double surge tank. Fuel flows were measured by timing the output from pipettes of calibrated volume.

Thermocouples were used to measure exhaust temperature as well as temperatures of the intake air, upstream and downstream from the carburetor.

A Sun, infra-red, Exhaust Performance Analyzer model EPA-75 was used to determine the proportions of carbon monoxide and unburned hydrocarbons in the exhaust gas.

The fuels used conisted of:

a) number 2 diesel fuel with a cetane number of 50.7 and an API gravity of 36,

b) ethanol having a water content of 6.3 percent by volume*, and

c) methanol with a negligible water content.

All tests were run at 1200 ± 30 rpm. The procedure used was to fix the air/diesel-fuel ratio and to take system performance data at progressively richer levels of air/alcohol ratio as the carburetor jet was opened. Testing at any given air/diesel-fuel ratio was terminated when an air/alcohol ratio was reached which caused incipient knock.

Two series of tests were conducted. The primary series consisted of tests at all feasible combinations of:

a) varying air/diesel-fuel ratios (6 or 7 levels),

b) varying air/alcohol ratios (5 or 6 levels),

c) two alcohol types -- ethanol and methanol, and

d) two intake air temperature regimes -- ambient and preheated.

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*For tests with fuels having various water contents, anhydrous ethanol was used, alone, and in varying mixtures with water.

Air preheater use was included as a test variable in order to determine the effect of this practice, which might be required with multi-cylinder engines to achieve the full evaporation necessary for uniform manifold distribution of the alcohol.

The second series of tests was done using both ethanol-water mixtures and methanol-water mixtures for carburetion. The one air/diesel-fuel ratio used was that required for idling. Air/alcohol ratios tested were only those at incipient knock. Ratios of water/(alcohol plus water) used were 0, 5, 10, 15, 20, 30, 40 and 50 percent by volume.

EXPERIMENTAL RESULTS

Performance

System output performance in the primary series of tests is illustrated in Figures 1 and 2. The curves in these and all other figures are fitted to the data using a least-squares format of the type $y = a + bx + cx^2$. Data presented in these two figures illustrate that:

a) air/diesel-fuel ratios leaner than those required to idle the engine were satisfactory to cause ignition of the carbureted alcohol charge even at the richest air/alcohol ratios used.

b) the richest air/alcohol ratios that could be used without serious knock, in combination with minimum diesel fuel injection, were not able to produce more than about 50 percent of maximum engine torque. Increasing diesel fuel injection did not increase the richness of air/alcohol ratios that could be tolerated without knock, but did result in increases of engine torque up to full load values.

c) maximum torque values obtained with alcohols carbureted into ambient temperature air were higher than the 27.2 Newton-meters maximum torque obtained with diesel fuel alone.

Maximum Performance Conditions

	Air Temperature					
	Ambient			Preheated		
Carbureted Fuel	Max. torque*	Air/ alcohol**	Air/ diesel fuel	Max. torque*	Air/ alcohol**	Air/ diesel fuel
Ethanol	120	41.5	27.5	92	46.8	30.3
Methanol	105	39.2	26.0	90	63.9	22.5

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*Percent of maximum torque with diesel fuel alone
**Incipient knock conditions prevailing.

d) use of the exhaust-intake heat exchanger for preheating intake air had little effect at low torque values, but at high torque values it caused suppression of maximum torque values due to air density reductions which accompanied air temperature increases.

e) the rate of torque increase with increases in alcohol/air ratio was greater for ethanol than for methanol due to the greater heating value of the former fuel (12,780 vs. 9770 Btu per lb, HHV [5]).

f) when oxygen in the cylinder was the factor limiting output torque, over-fueling with alcohol had only a minor effect in increasing torque.

Efficiency

Data presented in Figure 3, however, indicate that at torques approaching those at which oxygen in the cylinder limited further torque increase, that over-fueling with alcohol produced higher brake thermal efficiencies than did over-fueling with diesel fuel. In these tests, this characteristic was more noticable with ethanol use than with the use of methanol.

At low torque levels brake thermal efficiencies appeared higher with diesel fuel alone than with alcohol dual-fueling. This reversal of relative efficiency characteristics between high-torque and low-torque conditions was also noticed by Barnes et al. [2] and Panchapakesan et al. [4].

The use of the air preheater reduced the mass of oxygen that could be inducted into the cylinder on each intake stroke -- particularly at high torques when air temperatures were increased most. At these higher torques greater over-fueling was required with preheated air than with ambient air temperatures to obtain a given torque level, causing brake thermal efficiencies to be lower with preheated air.

Effect of the Air Preheater

Performance characteristics of the exhaust-intake heat exchanger relative to the heat requirements for alcohol evaporation are presented in Figure 4. These indicate that even when no alcohol was used (diesel fuel only curve) that there was a cooling of the air as it passed through the carburetor portion of the intake system, which was not insulated. At low inlet temperatures to the carburetor, there was insufficient heat in the air to evaporate all the alcohol. As carburetor inlet temperatures increased the proportion of unevaporated alcohol decreased until engine inlet temperatures were approximately those of the ambient air. For carburetor inlet temperatures above this level, engine inlet temperature drops increased parallel to those for the case of diesel fuel only, indicating no further cooling effects of alcohol evaporation. The curves in Figure 4 indicate that full alcohol evaporation was to be obtained with carburetor inlet temperatures of approximately 67°C, 88°C and 133°C for ethanol at air/alcohol ratios of 73 and 40 and methanol at an air/alcohol ratio of 34 respectively. Methanol has a higher latent heat of vaporization than ethanol (481 Btu per lb vs. 369 Btu per lb).

Exhaust Temperatures

The reason that low carburetor inlet temperatures and resulting incomplete alcohol evaporation occurred even with the use of the heat exchanger, was due to the typically low exhaust temperatures at low torques (Figure 5). Conversely, high exhaust temperatures at high torque caused overheating of the intake air, beyond that required for alcohol evaporation in all but the most extreme cases. This latter phenomenon gave rise to exhaust temperatures, which at high torque levels, while using the heat exchanger, were higher than those obtained with diesel fuel alone, despite the fact that alcohol was being used. On the other hand, when the heat exchanger was not used to preheat intake air, exhaust temperatures were generally lower (by approximately 50°C) when carbureted alcohol was used than were those obtained with diesel fuel alone.

Pollutants in the Exhaust

System responses in terms of the proportions of both carbon monoxide and unburned hydrocarbons in the exhaust gas are illustrated in Figures 6 and 7. In both cases these pollutant proportions were generally greater when alcohol was used than when diesel-fuel alone was used. This difference was minimum at high torque levels, but increased noticably as torque decreased. Reduction in the richness of the air/alcohol ratio reduced the concentration of both pollutants. Methanol appeared to cause slightly lower concentrations of the pollutants than did ethanol. The use of the air preheater was responsible for a noticable reduction in pollutant concentrations. The phenomenon of increased concentrations of carbon monoxide and unburned hydrocarbons in the exhaust gas upon dual-fueling of alcohol (as compared to those with operation on diesel fuel alone) was also reported by Holmér [1], Barnes et al. [2], Pefley [3] and Panchapakesan [4]. However, all but the first of these reports of research indicate that alcohol use was associated with reductions in the concentration of oxides of nitrogen in the exhaust gas.

Effects of Water Concentration in the Carbureted Fuel

Ethanol production from biological materials can be less energy intensive if certain levels of water can be tolerated in the final product. The results from tests with various alcohol-water mixtures are illustrated in Figure 8 and 9. Generally, alcohol/air ratios* which could be tolerated without undue knock needed to be more lean as the proportion of water in the carbureted mixture increased. Since diesel fuel injection was fixed at the level required for idling the engine with no carbureted fuel, the brake torque available without undue knock, also decreased as the water proportion increased. In both these respects, methanol mixtures appeared more likely to knock than ethanol mixtures, thus at any given water proportion, torque and alcohol/air ratios were lower for methanol than for ethanol.

Reduced torque values caused lower levels of brake thermal efficiency as water content of the fuel increased. Exhaust temperatures also tended to

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*In Figure 8 as well as in all other figures where either air/alcohol or alcohol/air ratios are given, the value used refers to the ratio of air mass and the mass of pure alcohol, exclusive of all water.

decrease as water content of the fuel increased. At the low torques and temperatures associated with these tests, it appeared that the effects of the higher latent heat of vaporization of methanol (as opposed to that for ethanol) were responsible for the accentuated tendency for knock with methanol and the necessity to restrict its use to more lean mixtures than was the case for ethanol.

DISCUSSION OF RESULTS

All the results from these tests tend to point to the ignition delay characteristics of the alcohol fuel as the factor responsible for the onset of the knocking phenomenon which governs diesel engine performance with carbureted alcohol. Certain factors commonly associated with reduced cylinder temperatures, such as the higher latent heat of vaporization of methanol and the induction of water into the cylinder, tended to be associated with an increased tendency for knock. However, other such factors like preheating intake air and higher cylinder temperatures associated with high engine torque did not, in these tests, allow the use of richer air/alcohol mixtures prior to the onset of knock. Holmér [1] and Panchapakesan et al. [4] reported the use of chemical additives to the alcohol to reduce ignition delay. Panchapakesan et al. [4] had considerable success in minimizing ignition delay problems by advancing the timing of diesel fuel injection -- a procedure that could not be conveniently accomplished with the engine used in this investigation.

The limitations imposed (by ignition delay and associated knock) on the extent of alcohol use in engines such as the one used here, tend to restrict the degree of substitution for petroleum fuel that might be accomplished by fitting an alcohol carburetor to a diesel engine. In order to examine what degree of fuel substitution might be achieved within the engine performance restrictions determined in these tests, Figure 10 was prepared to show the maximum proportion of fuel energy that could be provided by alcohol. Peak values of from 60 to 70 percent appear at about 50 percent of maximum engine torque. As torques decrease from this point the percentage drops as the diesel fuel used for pilot injection becomes a larger part of the total fuel use. As torques increase from the 50 percent of maximum point, added fuel energy must come from diesel fuel since any additional alcohol use would cause knock.

Practical implementation of the characteristics described in Figure 10 might be done by using a valve which would vary the proportion of inlet air drawn through a fixed-jet carburetor. Some coordinating linkage would be required between the valve and the diesel injection pump so that:

a) a minimum diesel injection level just sufficient for pilot ignition would be maintained at all times.

b) carbureted alcohol would be used for idling, and in varying amounts to meet all torque levels up to that achieved by the minimum pilot diesel injection in conjunction with an air/alcohol ratio just short of that which would produce knock.

c) torque levels beyond that described in (b) above, would be met by injecting increased amounts of diesel fuel beyond that required for pilot ignition.

The degree of substitution of alcohol for petroleum fuel using an engine with a control system as described above could be determined once the characteristics of the engine duty cycle were known. Ricketts and Weber [6] made field measurements with a farm tractor and found the following:

Subrange of Engine Torque (percent of maximum)	0-20	20-40	40-60	60-80	80-100
Percentage of total annual fuel consumption	10.8	11.6	18.4	32.3	26.9

Application of these values to the proportions given in Figure 10 provide a basis for estimating that 56 percent of the fuel energy requirements for a diesel engine with such a duty cycle could be met by carbureted ethanol, or alternately, 47 percent could be met by carbureted methanol.

CONCLUSIONS

It is concluded from the test data obtained that approximately 50 percent of the fuel energy for a diesel engine with a common duty cycle could be met with carbureted alcohol.

The main reason that it is difficult to achieve a higher degree of alcohol substitution by carburetion is because this technique is limited to comparatively lean air/alcohol mixtures, since richer mixtures cause objectionable knocking in the engine.

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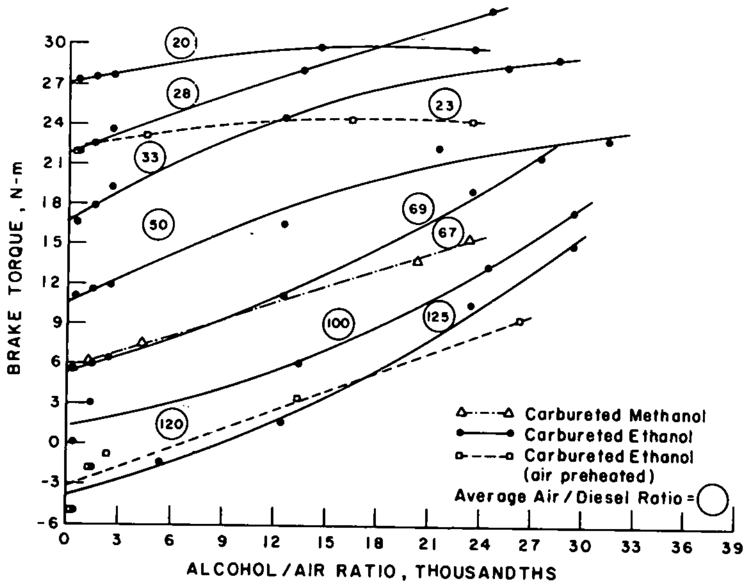
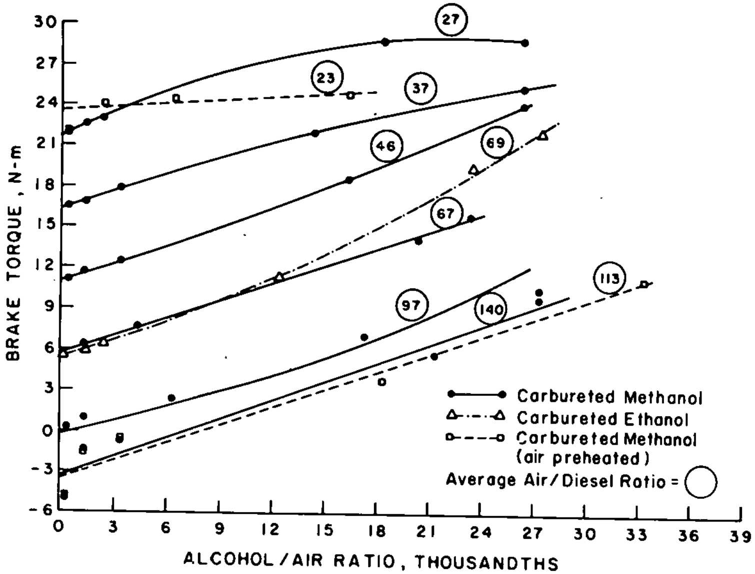




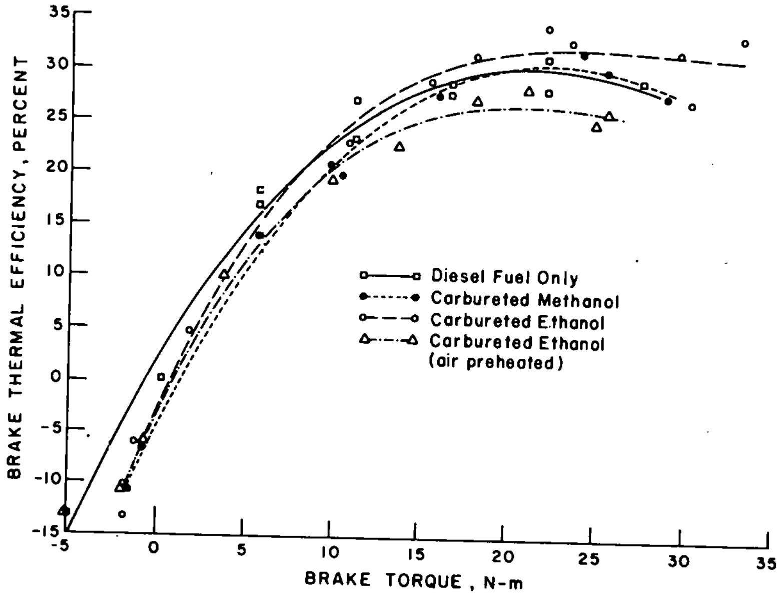
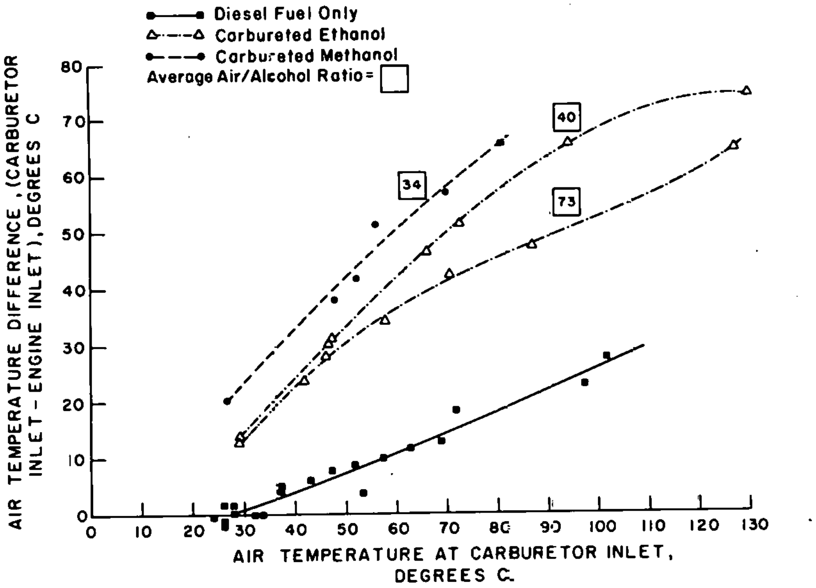
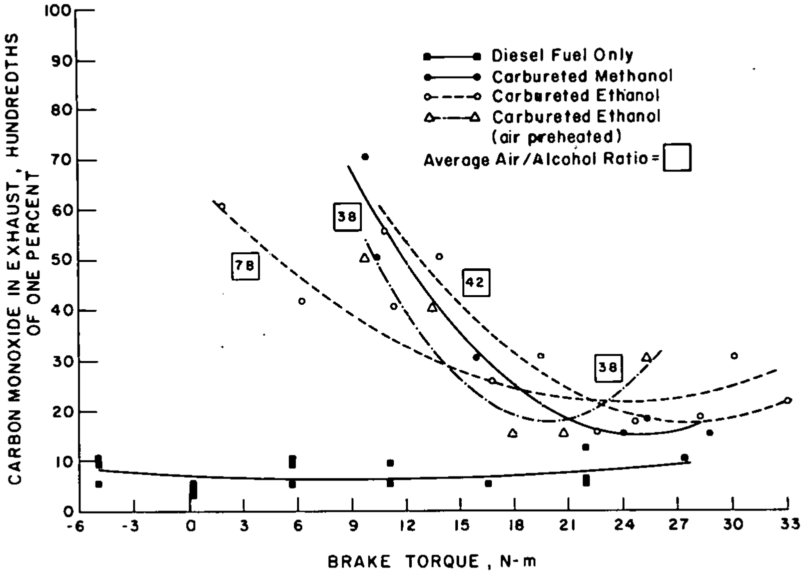


Fig. 1 (upper left) Engine performance with carbureted ethanol.

Fig. 2 (lower left) Engine performance with carbureted methanol.

Fig. 3 (above) Effects of carbureted alcohol on brake thermal efficiency at various torque levels. Points plotted for alcohol curves are those having alcohol/air ratios greater than 0.012.





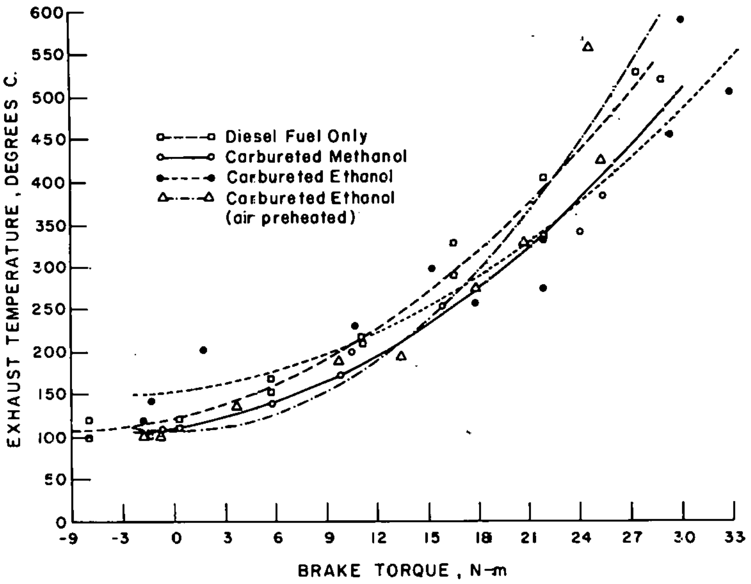


Fig. 4 (upper left) Combined effects of the exhaust-intake heat exchanger for preheating intake air, and the cooling characteristics of alcohol evaporation. Points at 27°C (ambient air temperature) were obtained with the preheater disconnected.

Fig. 5 (lower left) Exhaust temperatures at various levels of engine torque.

Fig. 6 (above) Effects of carbureted alcohol on carbon monoxide emissions at various torque levels.

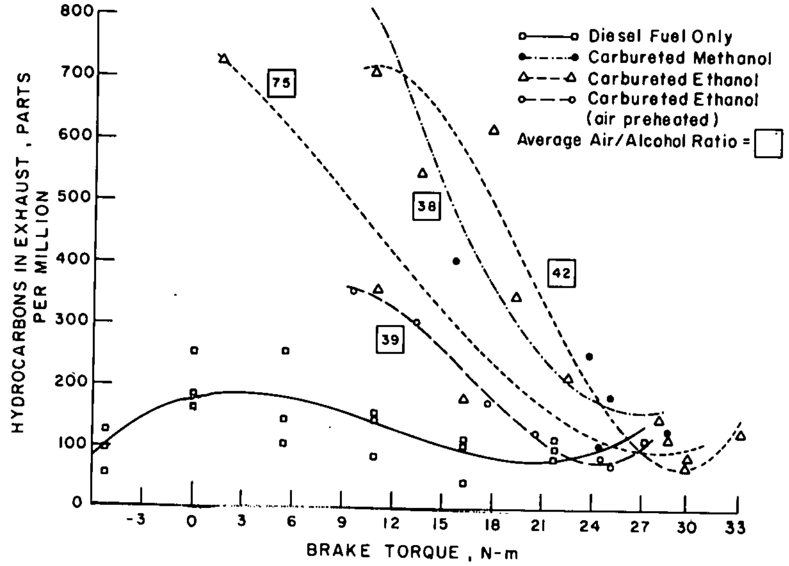


Fig. 7. Effects of carbureted alcohol on unburned hydrocarbon emissions at various torque levels.

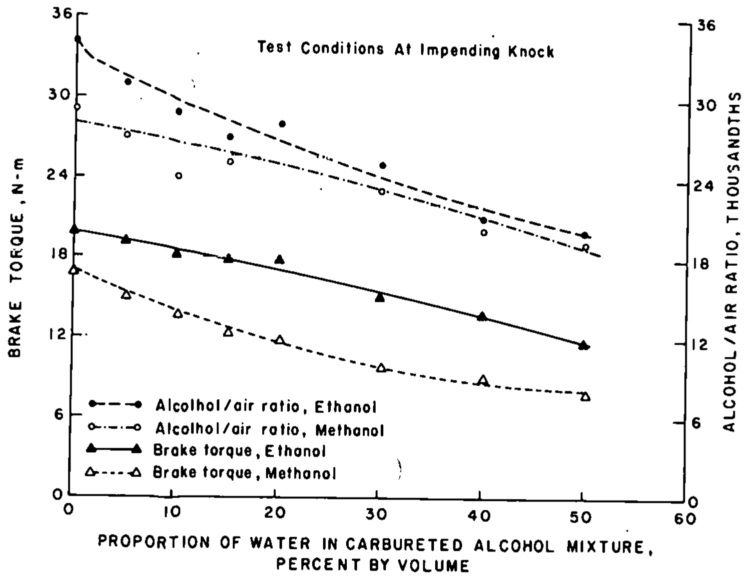


Fig. 8. Effects of various proportions of water in the carbureted alcohol on engine torque and alcohol/air ratios at incipient knock. The air/diesel-fuel ratio used was that required to idle the engine (approx. 85:1). Air temperatures at the carburetor inlet were those of the ambient air.

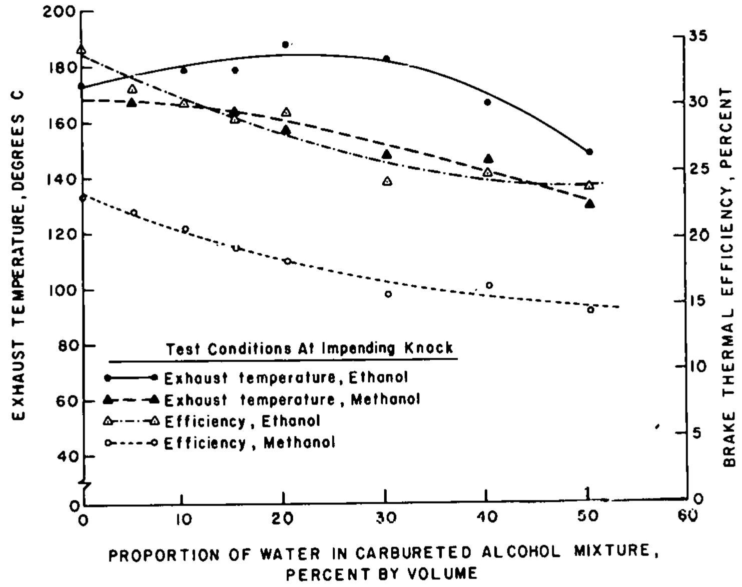


Fig. 9. Effects of various proportions of water in the carbureted alcohol-water mixture, on exhaust temperature and brake thermal efficiency. All points were at incipient knock and with the air/diesel-fuel ratio required for idling (approx. 85:1). Air temperatures at the carburetor inlet were those of the ambient air.

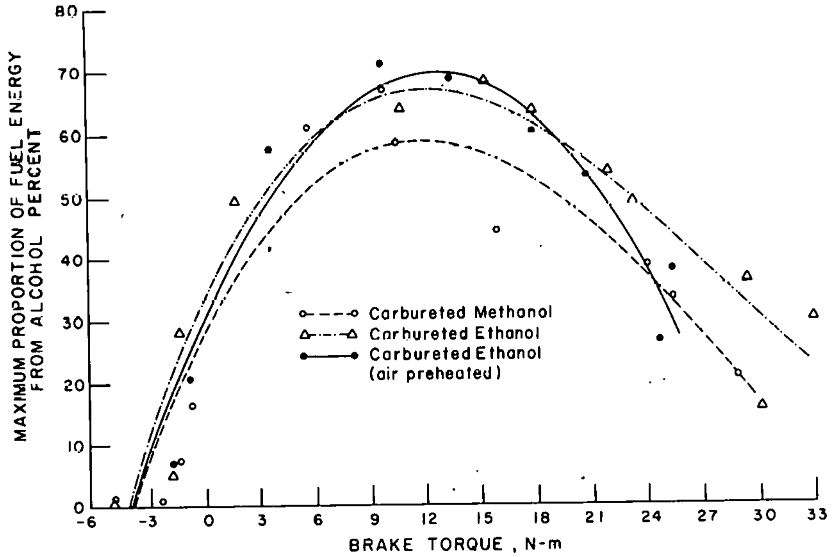


Fig. 10. Maximum possible proportions of fuel energy, at various torque levels, that could be supplied by carbureted alcohol.

A NEW WAY OF DIRECT INJECTION OF METHANOL IN A DIESEL ENGINE

by

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Abstract

An ignition spray conception for dual-fuelling a diesel engine with methanol has been developed. In order to optimize this combustion system, important engine parameters such as the amount of gasoil pilot fuel, injection timing and injection rate of gasoil and methanol and the influence of compression ratio were investigated. Over the whole operating range, a good efficiency and low combustion noise are achieved with this new design. Compared with conventional diesel engines there is no visible smoke and the emission of gaseous pollutants is also lower.

Introduction

In the past repeated attempts have been made to use alcohols as a fuel in diesel engines [1 - 3]+). Alcohols feature smokefree combustion, but have poor self-ignition characteristics. For the latter reason, alcohol cannot simply replace gasoil in the conventional diesel engine. Measures for securing ignition must be taken as for instance dual-fuelling.

In the framework of a research program comissioned by the German Federal Ministry for Research and Technology, the research department of the Klöckner-Humboldt-Deutz AG at Cologne (KHD) and the Institute of Applied Thermodynamics at Aachen (LAT) are jointly investigating and developing gasoil-alcohol dual-fuelling systems for diesel-powered vehicles [4 - 7]. The program is aimed at replacing a major portion of gasoil with methanol, maintaining a high efficiency, and reducing both the particulate emissions and the gaseous pollutants as far as possible.

In this research work different methods for dual-fuelling have been investigated. Such methods are the injection of methanol into the intake manifold, the formation of a gasoil-methanol emulsion and the direct injection of methanol into the combustion chamber. With the manifold injection method, methanol is mixed with the manifold air flow, the ignition being induced by the conventionally injected gasoil. With the gasoil-methanol emulsion method, the diesel fuel is replaced by a mixture of gasoil and methanol. The production of a stabilized diesel-methanol mixture having so far been unsuccessful, an emulsion must be produced in the fuel injection system by a continuous intensive mechanical mixing process.

+) Numbers in brackets [1] designate References at the end of paper.

Both methods tend to a knocking combustion within the full load range when using a high proportion of methanol. Moreover, owing to excessive ignition lag, misfiring can occur at part load. In view of these problems, the present state of development allows for a replacement of diesel fuel by methanol only to a limited extent.

No such limitations become apparent with direct injection of methanol in combination with a separated gasoil ignition spray. This method was found to be the most promising one for obtaining a high methanol proportion in the diesel engine.

The investigations were carried out on two direct injection diesel engines featuring different combustion chamber configurations. In one of these engines types, the fuel is injected through a centrally located multihole nozzle into an open mexican hat type combustion chamber in the piston crown. For the other combustion process, the fuel is injected nearly parallel and in close proximity to the wall of an inclined cylindrical piston cavity. This process is known as the D-Process of the KHD Company [8] . This paper covers investigations of the latter process, i.e. of direct injection of methanol into the D-Process combustion chamber.

Test Engine and Combustion Systems

The investigations were conducted on an air-cooled single-cylinder test engine of 130 mm stroke and 125 mm bore.

According to the dual-fuelling method, methanol and gasoil are both injected directly into the combustion chamber. For this process, two separate fuel-injection systems are needed. Methanol is injected through a two-hole nozzle close to the wall of the combustion chamber (Fig. 1). Aided by an air swirl, a considerable stratification of charge is achieved by the formation of a methanol-air mixture ringe close to the combustion chamber wall. To initiate the combustion of methanol, a gasoil ignition spray is injected through a one-hole nozzle.

Contrary to most other open-chamber combustion system, the mixture stratification provided by the D-Process together with the injection geometry, allows initial separation of the gasoil-ignition spray and the methanol air mixture. Safe ignition of the ignition spray is thus ensured, avoiding an unfavourable interaction of the two different fuel sprays. Investigations proved that there is no undue ignition delay of the ignition fuel which could be caused by the cooling effect of evaporating methanol.

Fig. 2 shows a characteristic cylinder pressure curve at full load. Near the end of compression the injection of a small amount of gasoil starts. Shortly after the gasoil spray the methanol injection begins. Ignition occurs after the beginning of the methanol injection. The relatively smooth cylinder pressure, compared with standard diesel engines, characterizes the soft combustion in gasoil-methanol operation.

In order to optimize this combustion system, important engine parameters such as the amount of gasoil for the ignition spray, injection timing and injection rate of gasoil and methanol and the influence of the compression ratio have been investigated. These parameters influence exhaust gas emissions, efficiency, engine performance and driveability. These influences are shown in the following survey.

Influence of Injection Timing

The examination of the influence of methanol and gasoil injection timing was carried out for a gasoil injection quantity of 20 mm^3/cycle. This amount of gasoil is roughly equivalent to the fuel consumption of the idling single cylinder diesel engine. In Fig. 3, the brake specific fuel consumption in terms of energy (BSEC), the HC emissions and the maximum rate of pressure rise are plotted versus the dynamic methanol injection timing. The start of gasoil injection was kept constant for the different engine speeds. According to Fig. 3, fuel consumption and hydrocarbon emissions are nearly independent of the methanol injection timing within a wide range of crank angle degrees. To ensure a low combustion noise, the methanol injection should start as late as possible.

Figure 4 illustrates the influence of the gasoil injection timing on fuel consumption, HC emissions and maximum rate of pressure rise. The figure also indicates the optimized injection timings for methanol at the different engine speeds. It becomes evident that the fuel consumption is optimal whenever the gasoil and methanol injection timing is nearly simultaneous. The influence of gasoil injection timing on hydrocarbon emissions and maximum pressure rise is not very significant provided the gasoil injection starts earlier than or simultaneous with the start of methanol injection.

The influence of the injection timings shown for a brake mean effective pressure of 5 bar is typical for the entire speed and load range of the engine.

Influence of Gasoil Injection Quantity

Investigations have shown that the gasoil ignition spray is necessary not only to ignite the methanol, but also to control the further combustion process. For this reason, both the timing and the duration of gasoil injection are of similar importance. This requires an optimization of the quantity and injection rate of the ignition fuel.

Figure 5 shows the influence of the gasoil injection quantity on efficiency, HC and CO emissions at an engine speed of 1600 rpm for various brake mean effective pressures. It is only at full load that an appreciable influence of the gasoil injection quantity on the efficiency is registered. Irrespective of the mean effective pressure, the HC emissions are lowest with injection quantities between 10 and 20 mm^3/cycle. Although the ignition reliability of the engine is still fully ensured with ignition spray quantities below 10 mm^3/cycle, the CO emissions increase markedly at both very low and very high loads. The influence of ignition spray quantity on the NO_x emissions, peak pressure and the combustion noise (not shown here) is insignificant. Smoke is negligible if an injection quantity of 30 mm^3/cycle is not exceeded.

Taking into account the entire operating range, a constant gasoil ignition spray quantity of about 15 mm^3/cycle is regarded to be the optimal value in view of a high methanol proportion on the one side, and of maintaining a good efficiency and low amount of gaseous pollutants on the other. If the gasoil proportion is to be reduced further, the ignition spray quantity could be diminished within the mean load range. It must be queried however, whether the technical expenditure thereby required is justified.

Influence of Injection Duration

Because of the lower calorific value of methanol compared with diesel fuel, it is necessary to inject about double the quantity of methanol. This requires a suitable adaption of the injection rate. In any case, the methanol injection has to be timed so as to end the burning process at about the same crank angle as with conventional diesel operation.

For an engine speed of 1600 rpm and a mean effective pressure of 7 bar, Fig. 6 represents the cylinder pressure curve and the burning rate as a function of the crank angle, both for standard diesel and for gasoil-methanol dual-fuel operation. In dual-fuel operation using the standard Bosch A-type pump (plunger diameter 9.5 mm), the maximum burning rate and the combustion end with methanol injection are reached about 7 degrees crank angle later than with the standard diesel process. At full load this becomes noticeable by a loss of efficiency and a rise of the CO emissions (compare Figs. 7 and 8). If a Bosch P-type pump, having a steeper cam form and a greater plunger diameter (11 mm), is used, the injection rate can be increased and about the same combustion duration as with the standard diesel operation can be achieved. In this context, an examination of the location of the ignition spray has shown that the spatially separation of methanol and gasoil sprays in the combustion chamber is of importance (Fig. 1). Without too much interaction with the methanol spray, the gasoil spray acts like an ignition torch and promotes the combustion of methanol.

Engine tests with different needle lift curves, schematically plotted in Fig. 6, also showed the relation between the injection duration of methanol and gasoil. Whenever, within the full-load range, the gasoil injection ends much earlier than the methanol injection, the CO emissions and to a minor extent the HC emissions increase. This can be seen in Fig. 8 by comparing the A-type pump and P-type pump results for loads higher than 6 bar BMEP. In this connection reference may be made also to the influence of the ignition spray quantity (Fig. 6). Cam shape and plunger size for the gasoil injection pump therefore result from the optimal ignition spray quantity and the duration of gasoil injection which in turn have to be fixed in relation to methanol injection duration.

Comparison with Standard Diesel Engine

Figure 7 illustrates the Bosch-smoke value, the efficiency and the the caloric proportion of methanol as a function of the mean effective pressure for an engine speed of 1600 rpm. The ignition spray quantity was kept constant at 20 mm^3/cycle, which results in the illustrated course of the caloric proportion of methanol. With a smoke value not exceeding 0.3 at full load, a soot-free operation may be spoken of. The efficiency is largely identical with that of pure diesel operation.

Figure 8 shows the behaviour of the gaseous pollutants. Over the entire load range, the NO_x emissions amount to less than one half of the values for pure diesel operation. The HC and CO emissions are the same as, or partly lower than, that of regular diesel operation. The reason for the improved CO and HC emissions at low load is that with dual-fuel operation, in contrast to pure diesel operation, the gasoil injection system is better tuned for small injection quantities.

Figure 9 shows that the peak pressures above a mean effective pressure of 4 bar are lower than with pure diesel operation. At full load the decrease is about 10 bar. As shown in the lower curves, the maximum rate of pressure rise is on the average 1 bar/°CA below the already low pressure gradient of the conventional D-process. This behaviour has a favourable effect on the mechanical engine stress.

Figure 10 shows the specific fuel consumption, the smoke value and the maximum rate of pressure rise versus load for a speed of 2400 rpm. The improved fuel consumption at full load with direct methanol injection as compared to pure diesel operation was found also by Holmér for a different combustion system [9]. In his investigations, however, the peak pressure was higher for dual fuelling whereas in the D-Process both the peak pressure and the maximum pressure rise remain below the values of pure diesel operation.

The fuel consumption and emission behavoiur shown here for the engine speeds of 1600 and 2400 rpm was confirmed also at other engine speeds. In dual fuelling mode the direct injection of methanol thus permits the gasoil to be largely replaced by methanol. It should be emphasized that while the same good efficiency as with a conventional diesel is maintained, there is practically soot-free operation and the NO_x emissions are less than half for the entire operating range.

Influence of Compression Ratio

The variation of the compression ratio was achieved by a geometrically similar enlargement or reduction of the piston combustion chamber. In this investigation the P-type pump with a plunger diameter of 12 mm was used for the injection of methanol.

Figure 11 shows the influence of the compression ratio upon efficiency, rate of pressure rise and CO emissions. Both an increase of the standard compression ratio $\varepsilon = 18.2 : 1$ to $19.3 : 1$ and a reduction to $16.4 : 1$ and $14.5 : 1$ result in an improved efficiency at full load. In assessing this behaviour, it should be taken into account that direct influences of the compression ratio can be affected by secondary influences due to a more or less optimization of other parameters. At part load, an influence of the compression ratio can hardly be registered. At full load, the maximum rate of pressure rise is lowest at $\varepsilon = 16.4 : 1$, while $\varepsilon = 14.5 : 1$ shows the highest values. Below a mean effective pressure of 5 bar, the highest pressure rise values are obtained with $\varepsilon = 19.3$.

As there is no soot limit in dual-fuel operation, the marked increase of the CO emission may be used to define the maximum load. The relatively strong increase of CO emissions at $\varepsilon = 14.5 : 1$ within the part and low load range suggests that a reduction of the compression ratio down to this value is unreasonable.

The results of investigations at different speeds also suggest that a reduction of the compression ratio to $\varepsilon = 16.4$ may be quite reasonable with regard to mechanical stress, combustion noise and achievable maximum load. In terms of fuel economy and minimum exhaust gas emissions, an increase of the compression ratio may be also of interest. The ultimate selection of the compression ratio will eventually be determined by the cold start and warming-up behaviour of the dual-fuel engine. Investigations in this direction as well as an optimization of the air swirl for the various compression ratios are being conducted.

Aldehyde Emissions

Conventional spark ignition engines run on pure methanol have become known to have an increased aldehyde emission. Therefore the aliphatic aldehydes in the exhaust were measured by means of the "MBTH funnel" method [10]. The investigations made by this method produced a good repeatability of the test results.

Figure 12 illustrates the aldehyde emissions, the HC emissions, and the caloric methanol proportion as a function of the mean effective pressure both for dual-fuelling mode and for pure gasoil conditions. In the dual-fuel mode, the aldehyde emissions for all three compression ratios examined are lower than under conventional diesel conditions ($\varepsilon = 18.2$) both at part load and at full load. At idle the previously mentioned better adaption of the gasoil injection system to smaller injection quantities in dual-fuelling mode is likely to account for this result. It should be mentioned that the behaviour of HC and aldehyde emissions with different compression ratios is not always corresponding. In view of the high caloric proportion of methanol at higher loads and in comparison with the standard diesel engine, the aldehyde emission values registered in methanol dual-fuelling mode may be regarded as very low. It should be stressed, that the aldehyde emissions never exeed those of the standard diesel.

Conclusions

The investigations with the described direct injection dual-fuelling concept using the D-Process combustion chamber showed the following benefits:

- A large portion of gasoil can be substituted by methanol, while maintaining a reliable ignition and knock-free combustion.
- Efficiency is equal to, or better than the efficiency of the standard diesel engine.
- Lower peak pressures and maximum rates of pressure rise are achieved.
- Very low smoke values (no visible smoke) are attained and a soot-limit is non-existent.
- Due to the absence of a soot-limit an increase in performance is possible.
- The NO_x emissions are reduced by more than half in comparison to standard diesel operation.
- The HC and CO emissions are equal to, or lower than the corresponding emissions of the standard diesel operation.
- The aldehyde emissions are lower than those of the standard diesel operation.
- The thermal and mechanical stress of the engine are reduced.
- The compression ratio can be varied over a wide range (ε = 14.5 : 1 - 19.3 : 1) without negatively affecting the normal operating behaviour.

This dual-fuel engine will be further investigated and developed. If methanol can be produced at a reasonably low price, this engine could be a good choice, particularly for public transport vehicles for instance buses.

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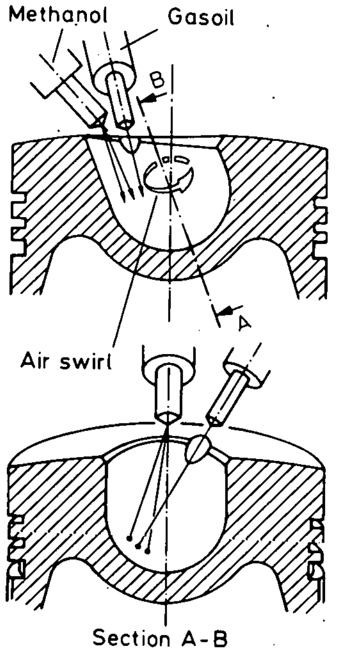

Fig. 1 Combustion chamber (D-process), position of injection nozzles and direction of injection sprays

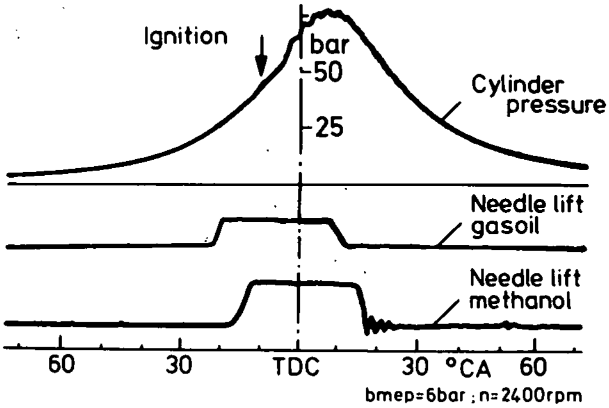

Fig. 2 Cylinder pressure and needle lift diagrams of the dual fuel engine

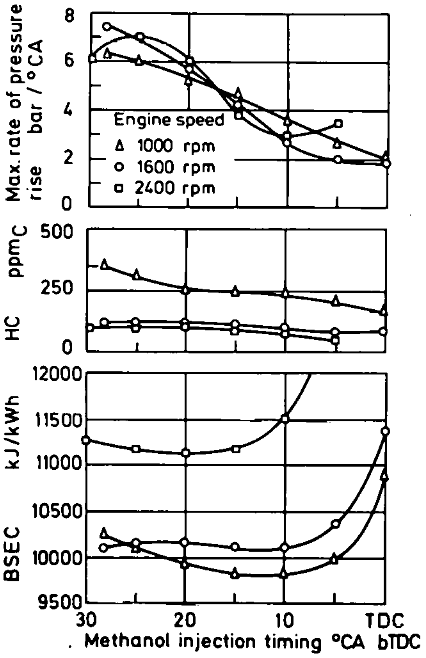

Fig. 3 Energy consumption, HC emissions and pressure rise versus dynamic methanol injection timing (bmep = 5 bar)

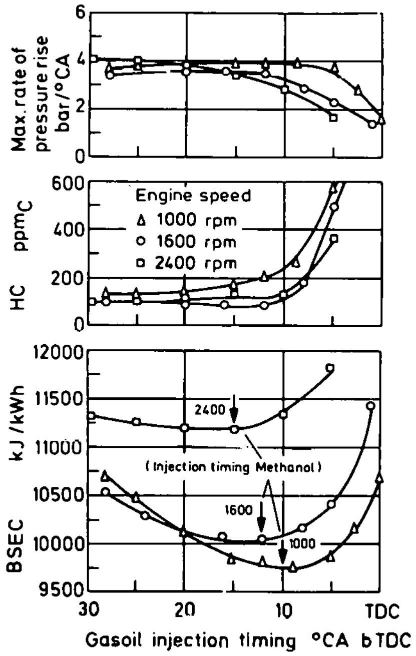

Fig. 4 Energy consumption, HC emissions and pressure rise versus dynamic gasoil injection timing (bmep = 5 bar)

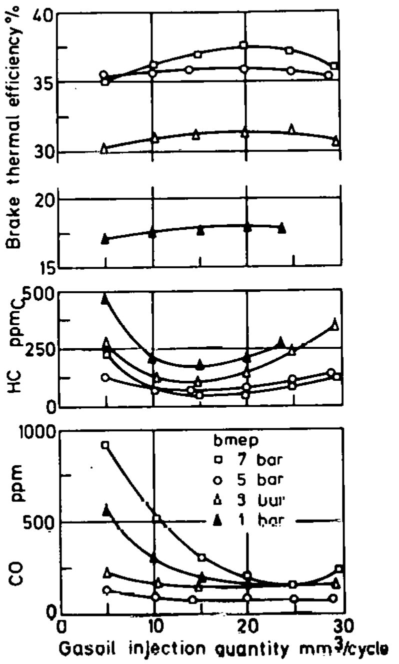

Fig. 5 Influence of gasoil injection quantity on efficiency and exhaust emissions (n = 1600 rpm)

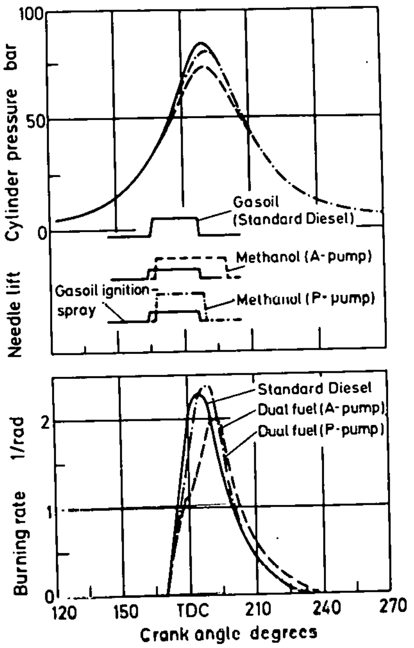

Fig. 6 Influence of injection duration on cylinder pressure and burning rate (bmep = 7 bar, n = 1600 rpm)

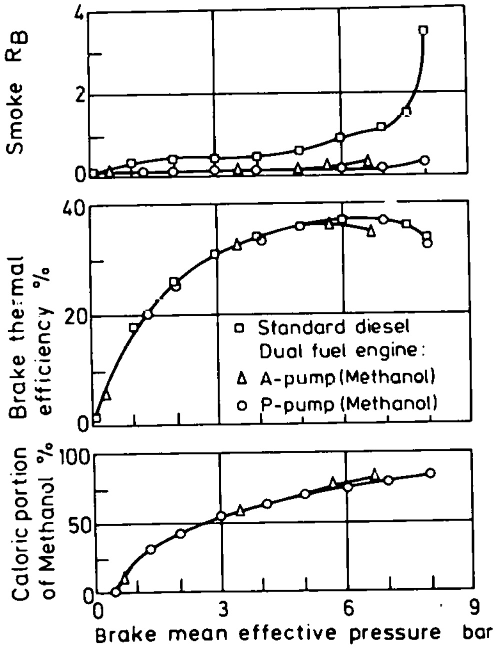

Fig. 7 Efficiency and smoke of standard diesel and dual fuel engine (n = 1600 rpm)

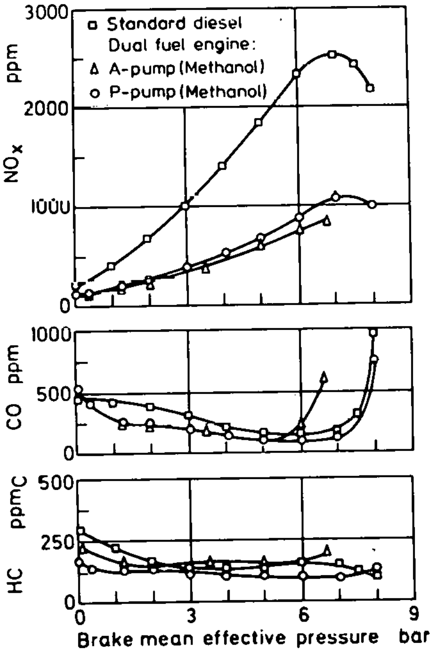

Fig. 8 Exhaust emissions of standard diesel and dual fuel engine (n = 1600 rpm)

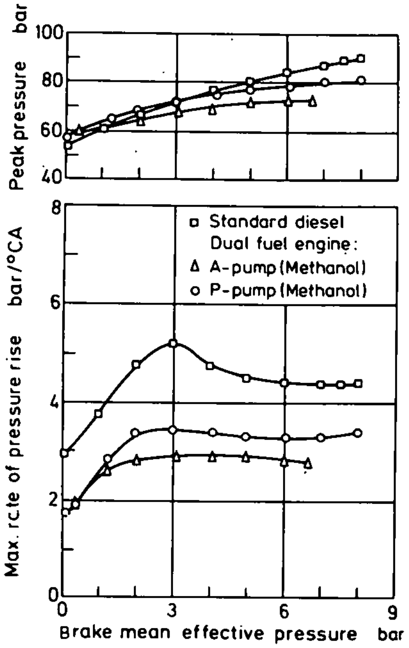

Fig. 9 Peak pressure and pressure rise of standard diesel and dual fuel engine (n = 1600 rpm)

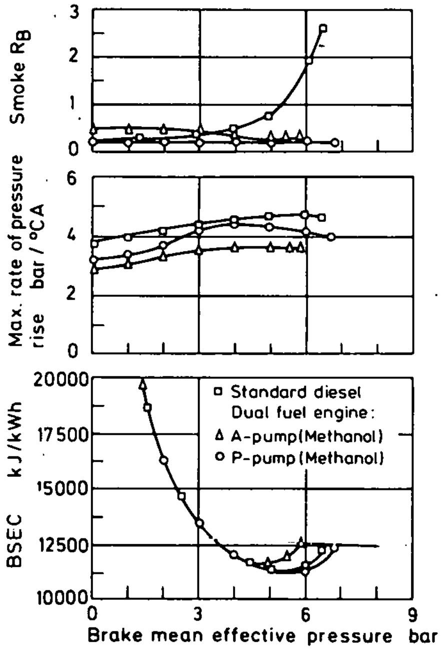

Fig. 10 Energy consumption, pressure rise and smoke of standard diesel and dual fuel engine (n = 2400 rpm)

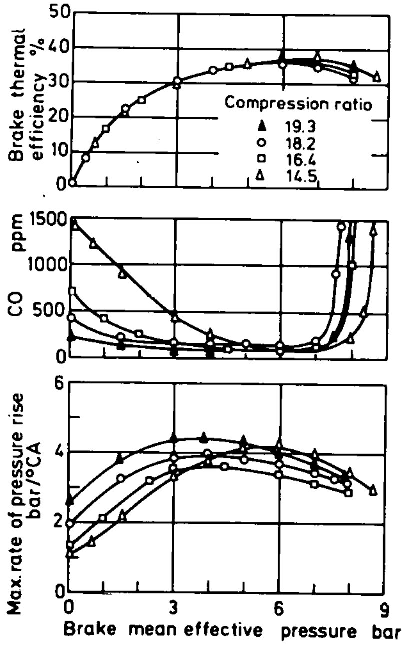

Fig. 11 Influence of compression ratio on efficiency, CO emissions and pressure rise (n = 1600 rpm)

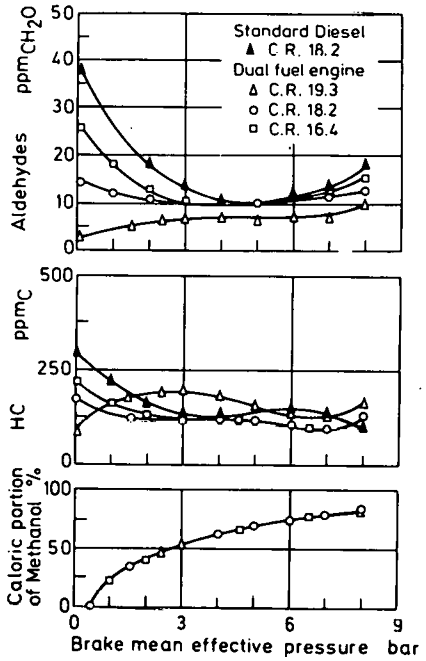

Fig. 12 Aldehyde emissions of standard diesel and dual fuel engine (n = 1600 rpm)

THE UTILIZATION OF DIFFERENT FUELS IN A DIESEL ENGINE WITH TWO SEPARATE INJECTION SYSTEMS

by

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Development work has been carried out on a turbo charged direct injection diesel engine with two separate injection systems to investigate the possibility of using methanol and ethanol. In order to investigate the possibility of maximizing the total energy balance, including the production of the fuel, testing has been done with different concentrations of ethanol in water and with crude gasoline.

INTRODUCTION

The Volvo Truck Corporation has, on behalf of Swedish Methanol Development AB, investigated the possibility of using methanol as a fuel in diesel engines [1]*. The most promising concept was the dual fuel engine with two separate injection systems.

INVESTIGATION FIELD

Endurance testing has been done in a test cell and using a truck with methanol. Since the system worked very well with methanol, the development work has continued with ethanol.

Ethanol is made by the fermentation of organic material. This process can so far not give a higher concentration than 20 % ethanol. An energy-consuming distillation has to be carried out to make a useable fuel. To investigate the possiblity of maximizing the total energy balance, including the production of the fuel, testing has been done with different concentrations of ethanol in water to establish the minimum need for acceptable combustion.

Otto engines need gasoline with a high octane number. In order to investigate if low octane gasoline can be used, which provides the twofold benefit of saving energy in the production of the fuel and higher thermal engine efficiency, testing has been done with crude gasoline.

ENGINE

Design

The testing has been carried out on a Volvo TD100A, a six cylinder inline turbocharged direct injection diesel engine with a displacement of 10 litres and a compression ratio of 15:1. The standard engine has been fitted with a distributor type injection pump (fig. 1), and a single hole injector in each cylinder head oriented at the other limit of the combustion chamber in the piston crown (fig. 2). The igniting fuel (diesel) is injected through this system while the main fuel is injected through the original system which has an inline injection pump and centrally located four-hole injectors.

*) Numbers in brackets[1] designate References at end of paper

Plunger, pipe and injector hole diameters have been adjusted to have the capacity to inject fuel with low energy per volume and still maintain full engine power. The fuel rate is controlled by an aneroid sensing in the inlet manifold pressure to avoid overfuelling at low engine speed.

Optimizing the injection of the igniting fuel

Diesel fuel with a cetane number of 52 has been used as igniting fuel. Direction, quantity and timing has to be optimized to provide safe ignition under all conditions with the lowest possible emission of hydrocarbon (HC) and smoke.

The diesel fuel is injected against the air swirl. Thus the fuel droplets are picked up and carried around the center of the cylinder by the air forming a rich air/fuel zone and preventing the fuel from hitting the wall of the combustion chamber in the piston (fig. 3). The optimum direction is when the center of the spray is a tangent of a circle concentric to the combustion chamber and with a radius 0.35-0.45 of the radius of the chamber. If the fuel is injected closer to the center, emission of HC will be less but the amount of fuel which can be injected until smoke appears will also be less. The minimum emission of HC has been 50 ppmC while, when fuel is injected in the same direction as the swirl, 700 ppmC has been obtained.

At low load only diesel fuel is injected. A critical point is when the second fuel (methanol, ethanol, gasoline etc) is also injected through the central injector when the load increased. If the quantity of diesel fuel injected is too low, the emission of HC will be high (fig. 4). On the other hand smoke will appear with too high a quantity.

It is essential that the igniting fuel is injected and ignited prior to the injection of the second fuel to minimize emission of HC (fig. 5).

PERFORMANCE TEST

The fuels listed in the table below have been tested

	Castor oil % volume of fuel	Water %weight added	Lower Heating Value		Density kg/m^3	Energy loss due to water. % of pure fuel energy	Cetane number
			MJ/kg	MJ/dm^3			
Methanol	1	-	19.88	15.84	797	0	3
Methanol	1	15	16.51	13.64	827	2.3	2
Ethanol	1	-	27.01	21.39	792	0	8
Ethanol	1	10	24.05	19.55	813	1.1	
Ethanol	1	30	18.13	15.48	854	4.1	
Ethanol	1	50	12.22	10.95	896	9.5	
Ethanol	1	80	3.34	3.20	958	38.2	
Crude gasoline		-	44.0	32.4	736		40
Diesel		-	42.9	35.6	830		52

Methanol

The main development has been done with methanol [1]. Compared to a standard diesel engine, methanol gives less smoke and exhaust temperature before the turbine (fig. 6). The higher rate of combustion gives a higher peak pressure and higher thermal efficiency (mechanical energy at the flywheel compared to the low heat energy of the fuel). The torque at low engine speeds is not limited by smoke and could be increased until emission of CO set a limit (not done in this test).

HC is less than or equal to the diesel engine over the load range (fig. 7). With retarded injection, 5 g/hph emission of HC + NO_x is met in a 13-mode U.S. Federal cycle with only a small reduction of efficiency at high speed compared to the standard diesel engine.

Methanol produced on a large scale will contain some water. 15 % water will not influence the performance (fig. 6 and 7). To obtain full power the fuel delivery has to be higher.

Ethanol

The engine development for methanol has been tested with ethanol without any alteration. Water up to 80% has been added. The performance is mainly the same (fig. 8 and 9) with up to 50% added water. Exhaust temperature fall with the quantity of added water due to cooling by water evaporation. Smoke has been measured with 50% water but it may be condensed water vapor in the opaciometer.

It was not possible to obtain any ignition of ethanol with 80% water. With increased injection of ethanol and water, the combustion of the diesel fuel was influenced. The power decreased and HC increased (fig. 10).

Crude gasoline

The greatest saving of energy seems to be in the production. Therefore testing has been done with crude gasoline which has an octane number of 52 and a cetane number of about 40.

The performance is the same as with diesel when no preinjection is used (fig. 11). With preinjection of diesel the efficiency decreases and smoke increases at high BMEP (fig. 12). On the other hand HC emission is lower at low BMEP and the ignition is reliable down a lower ambient temperature. Hence a crude gasoline engine shall have preinjection only at low load. The preinjected fuel could also be crude gasoline while the preinjected fuel is kept in a fuel rich zone for a longer time which widens the possibility of ignition.

ENDURANCE TEST

Bench test

Two 1000 hour cycle tests have been carried out with methanol. The cycle time is one hour with seven full load steps at different speeds, one high idling speed step and one low idling, during which cold water is forced through the engine.

In the first test the only fault was wear between the injector needle and the spring washer causing the opening pressure to fall from 14.7 MPa to between 4.1 and 11.8 MPa. This was recognized after the test which indicates how insensitive the combustion is according to the injection of methanol as no loss in power and no heavy smoke was recognized. The wear was as in a standard engine except the liners which had a lower rate of wear.

The second test has been carried out with no castor oil in the methanol but with pressure lubricated injection pump plungers. To solve the wear problem in the injector, the back pressure in the fuel leakage pipe was kept high to have the methanol in liquid state at the temperature which exists in the injector. This was no solution so this wear problem still remains. Several plunger liners cracked, which so far is not understood as the pressures are within safe limits.

During both tests no sign of methanol in the lubricant has been detected.

During the first test the drive belt of the diesel pump failed. The second test was carried out with a gear drive without any problems.

Road test

30000 km has been run by a vehicle in construction work by a trucker in Gothenburg. The injection pump for methanol was a standard one, uprated to give maximum possible fuel, giving a rated power of 150 kW which is 80 % of standard power. The truck with trailer has a gross weight of 42 tons. Hence the engine has low power most of the time the truck was run without trailer which reduces the gross weight to 22 tons. In spite of the low load factor the methanol represents 70 % of the fuel energy used. On the average the fuel consumption was 13 dm^3/100 km diesel and 65 dm^3/100 km methanol.

During cold starting and the first part of running warm, only diesel fuel is injected [1]. When methanol is injected too early, misfiring can occur. An electric preheater will save time and was installed during the winter.

The engine wear was normal. No excess wear and no abnormal fall of opening pressure was found in the methanol injectors in the truck test.

SUMMARY

A diesel engine with two separate injection systems broadens the possible use of the engine.

Two separate fuels can be used when a small fraction of one fuel with a high cetane number is injected and ignited prior to the main fuel. A broad range of light liquidized fuel can be used with the same efficiency as the diesel. There is no demand for octane number or cetane number.

The method described of injecting the igniting fuel against the air swirl gives a very low emission of hydrocarbon and improves ignition which lowers the need for cetane number or makes the use of a lower compression ratio possible in high output diesel engines.

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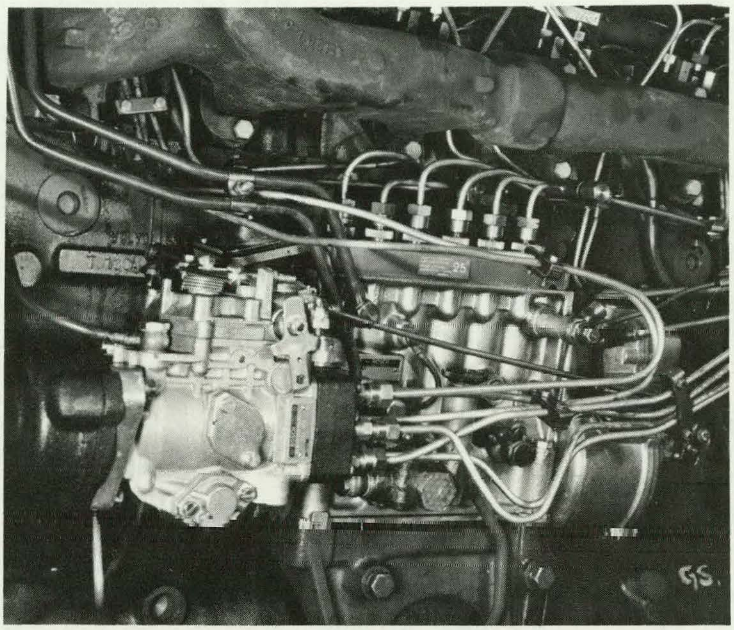

Fig 1. Arrangement of the injection pumps.

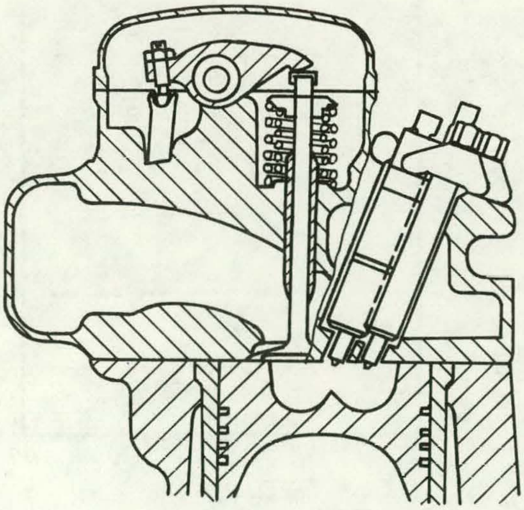

Fig 2. The cylinder head with two injectors.

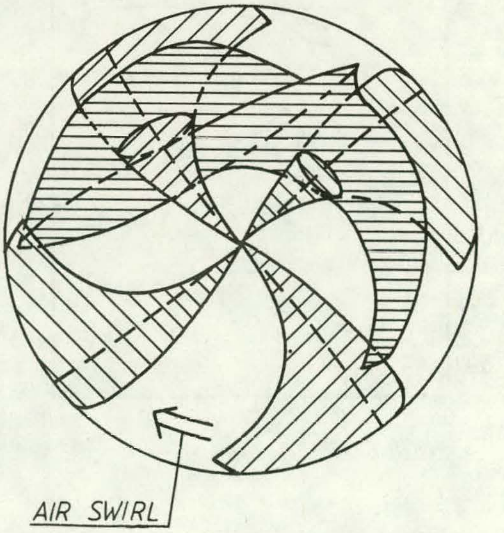

Fig 3. The fuel jets in the combustion chamber.

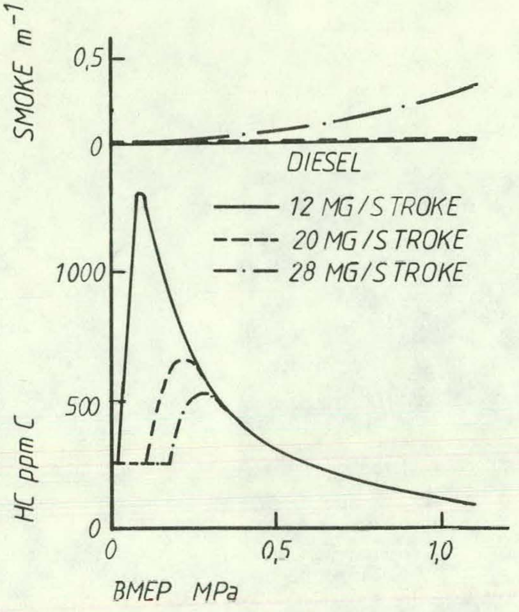

Fig 4. Influence of disel injection amount on smoke and HC emission. Part load at engine speed 15 rps.

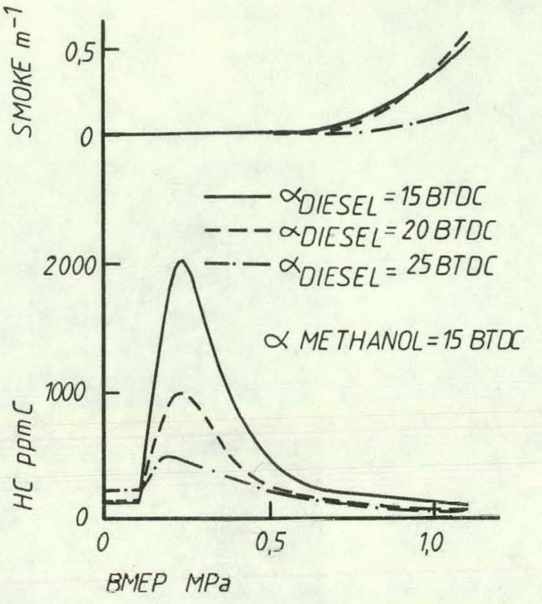

Fig 5. Influence of diesel dynamic injection timing on smoke and HC-emission. Part load at engine speed 15 rps.

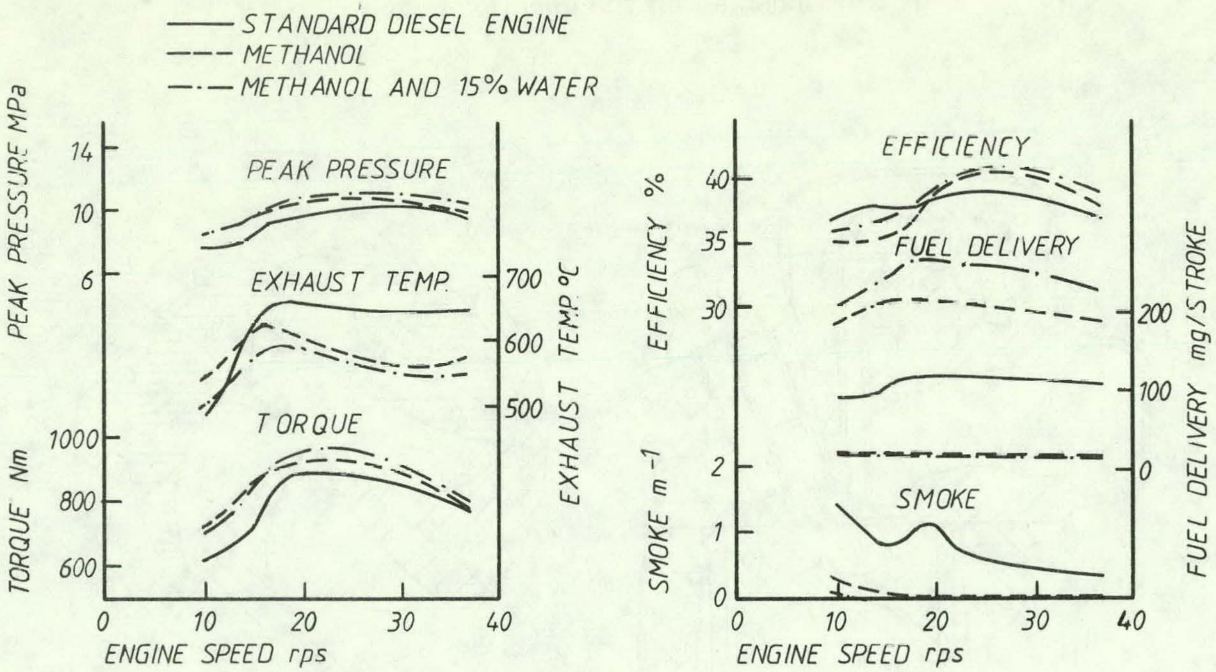

Fig 6. Comparison of full load performance of standard diesel engine and dual fuel engine with methanol and with methanol and 15% water.

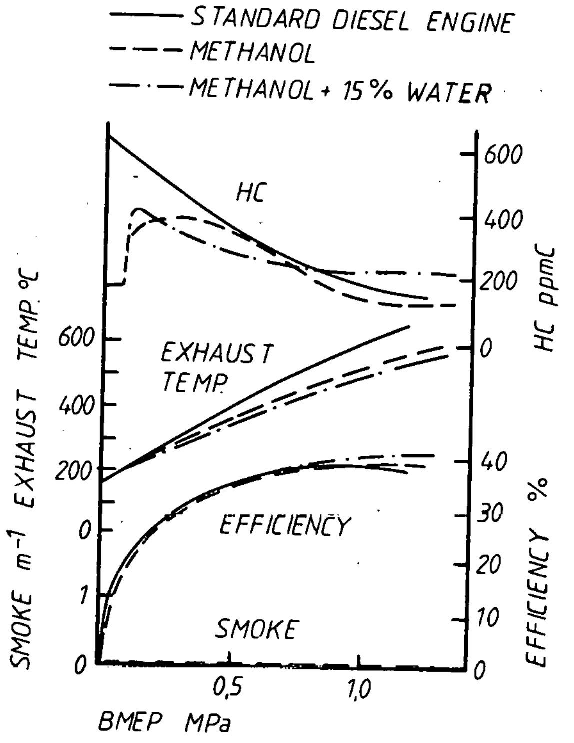

Fig 7. Part load performance at engine speed 25 rps.

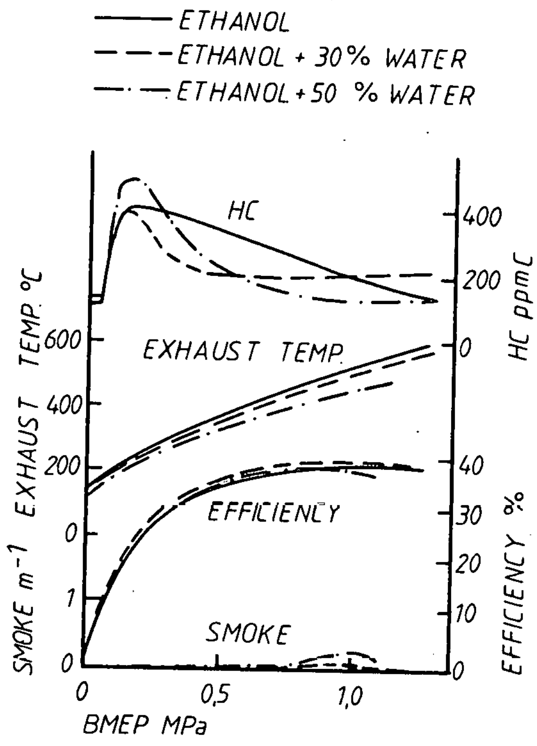

Fig 9. Part load performance at engine speed 25 rps.

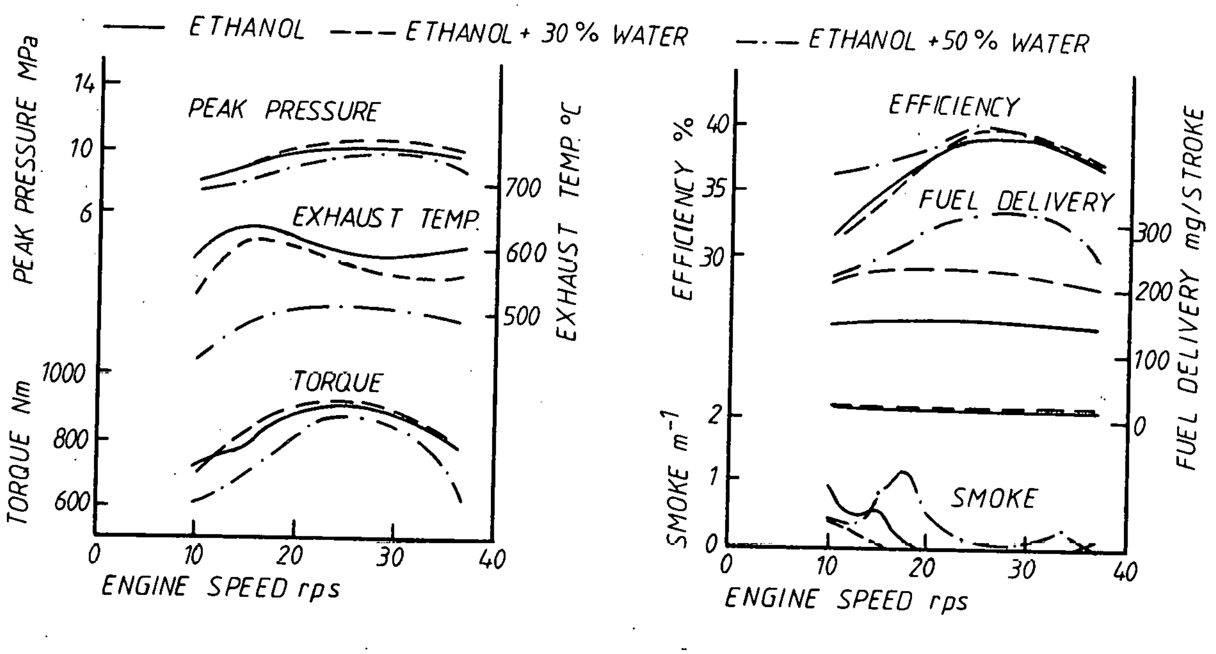

Fig 8. Comparison of full load performance of dual fuel engine with different concentration of ethanol in water.

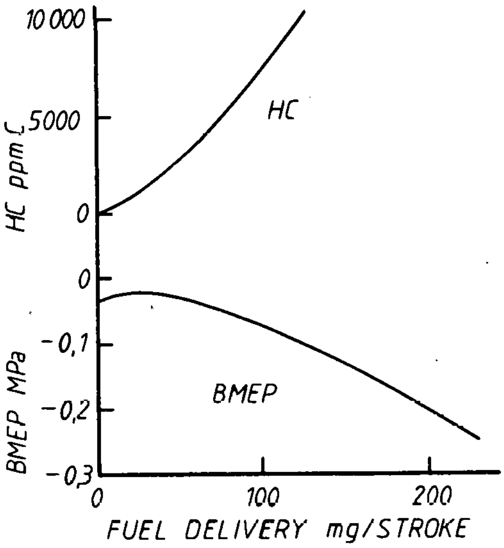

Fig. 10 Influence of fuel delivery, 20% ethanol and 80% water on BMEP and HC emission. Part load at engine speed 37 rps.

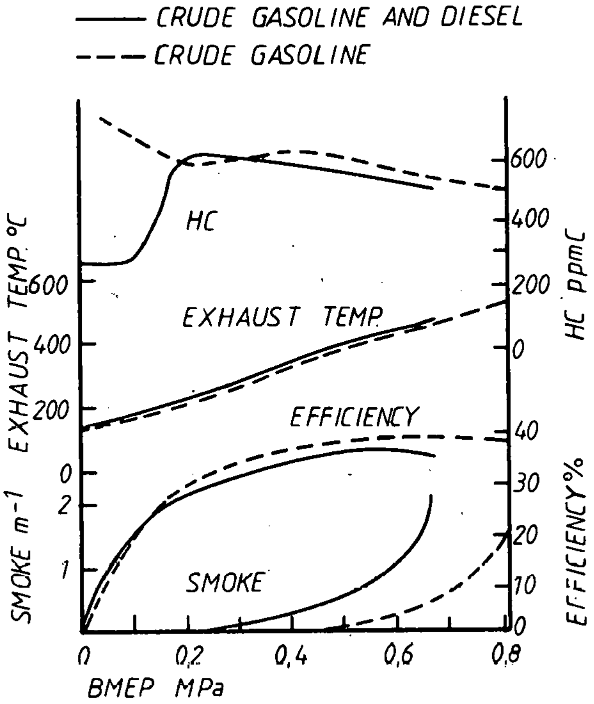

Fig 12. Part load performance at engine speed 15 rps.

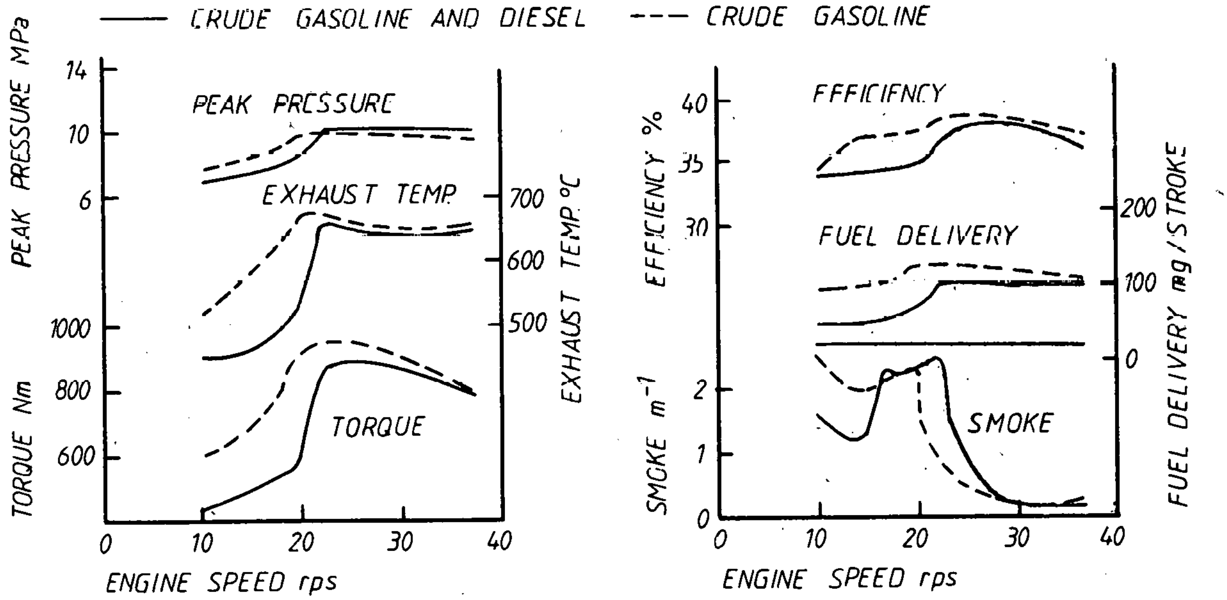

Fig 11. Comparison of full load performance of dual fuel engine with crude gasoline and diesel and with only crude gasoline.

ECONOMICS OF METHANOL IN MOTOR FUEL - VALUE AND COST OF PRODUCTION

by

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1 INTRODUCTION

Within the next few years important decisions have to be taken about the future quality and supply of motor fuels. Sweden´s situation in this respect is dealt with in the paper by Dr. L A Bern. It gives the background to this paper.

All changes concerning motor fuels will influence the operation of the refineries and their future development. This paper will discuss a number of cases, which have been studied, partly by computor simulations, and will try to value methanol as a gasoline component and compare this value to production costs.

2 TECHNICAL FACTORS

Technical questions about low/zero lead and methanol containing fuels were treated in several papers (1) (2) (3) at the previous alcohol symposium at Wolfsburg, Germany in November 1977. In our study one set of calculations has a hydroskimming refinery as a base and another has the combined Swedish refining industry as base. The base cases have been altered by buying in gasoline components or adding conversion units. Treating all the Swedish refineries as a unit is, of course, an oversimplification, tending to give too favourable results, as it presumes free movements of intermediates, which do not occur in reality.

The configuration of all refineries together is given in Table 1. Reforming and desulfurization capacities are above average European level.

The market for finished products is given in Table 2. The range of gasoline specifications and other product specifications used is shown in Table 3.

The gasoline specifications have been maintained at about the same level as present also at reduced or zero lead levels in order to make use of the fuels in the existing European engine population possible

The sulfur content of most of the fuel oils has been lowered as decided for Sweden in the mid 80´s. The availability of light, low-sulfur crudes has been limited to 30% of the total, as a country importing all its oil needs hardly can obtain a higher share (60% would be required for Sweden) in a competitive situation. This means that indirect desulfurization will not be sufficient in the future but direct desulfurization of residual oil (ARDS) has to be applied too. Such methods are today only practised in Japan and California. The long range outlook for the crude slate is a shift towards heavier, high-sulfur crudes, corresponding to the composition of the total reserves.

3 ECONOMICAL FACTORS

When trying to put a value on methanol as a gasoline component or motor fuel, prices of conventional gasoline and other refinery products have to be used. Market spot prices are too volatile to be used and "equilibrium" prices have therefore been calculated. The level of these prices depends on crude costs and the refinery situation. They have been calculated for present Western Europe overcapacity condition (~65% utilization of hydroskimming capacity) and for future, hopefully, normal conditions with 90% utilization and 20-25% ROI on all refinery units. The prices obtained are given below.

	Overcapacity conditions	Normal ROI	
Crude,Arabian Light	100	100	$/tonne landed
LPG	140	141	" "
Premium gasoline	157	182	" "
Regular "	153	177	" "
Naphta	140	141	" "
Middle distillates	130	132	" "
HSFO	72	87	" "

Market factors will, of course, ultimately set prices. At a lasting surplus of heavy, high sulfur fuel oils (HSFO) even its equilibrium price may be difficult to recover. A slight upward adjustment of the prices of the lighter products has to be made to maintain profitability.

In many of the cases studied only comparisons between routes are made and prices then influence the conclusions only slightly.

The sulfur premium, i e the difference LSFO-HSFO, is low in Europe, ~10 $/tonne, due to good availability of low-S crudes and only mild restrictions on the sulfur contents and there are no signs of changes in these respects up to the mid 80´s. The difference is too low to justify desulfurization, indirect or direct. The latter is estimated to cost 35 à 40 $/t HFO of Arabian Light for 1% S in the HFO.

4 CASES STUDIED

In all cases the aim has been to maximize gasoline (motor fuel) production. The existing Swedish refinery industry can only meet the market demands anticipated for a few minor products (LPG, Kerosine, lubricants, asphalt, bunkers). Imports of finished products are required to meet the demands. The share of imports should be least for gasoline.

4.1 No methanol. Reduced or zero lead content (Table 4)

Lowering the lead level to 0,15 g/lit has as consequence that the refineries show a production deficit of more than half the premium demand (case 1) although octane requirements had been relaxed to RON97 and 92 for premium and regular respectively. More premium and less regular could have been made at the expense of the total volume but is not chosen by the computor even at a 20 $/tonne difference. All light naphta cannot be used in the gasoline. Limiting factor is the catalytic reforming capacity.

Introduction of catalytic cracking (case 17) in the industry with a capacity of nearly 2 Mt/yr (about 10% of crude capacity) would allow production of 82% of the premium (at the relaxed octane level) and full amount of petrochemical naphta would be freed. Cracking of the large amount of vacuum gas oil leads, however, to shortfall of LFO as part of the gas oil must be used to dilute HFO to meet specifications.

Without lead no premium at all could be produced (case 9) in the base case. Introduction of isomerization and isopentane recovery units (case 12) would help a little if RON is relaxed to 98 and reforming capacity is expanded.

Imports of high severety cracker gasoline in large amounts, 1,4 mt/yr, and expanding the reforming to 100 RON severety at capacity (case 13) would allow production of 85% of the premium and 100% if RON was again relaxed to 98.

In conclusion lead free gasoline would be impossible to produce at specifications required for existing European cars. Optimal refinery operation and engine performance would require lower octane demands and low compression motors (4) and this development we now witnes in the USA.

4.2 With methanol. Reduced or zero lead content (Table 5)

In the 0,15 g Pb/lit cases the introduction of alcohols (methanol) as blends with 20%v alcohols makes production of the total amounts of gasoline possible (case 2). The blend volume was set 7%v higher than for conventional gasoline to compensate for the lower energy content but this means that about 3% less energy is produced. Such a gain is expected for methanol blends for the same distance driven in comparison with conventional gasoline.

The gasoline demand could have been met also when the blend volume was set 10%v higher (no energy gain at use) or when premium/regular ratio was increased from 1/1 to 1,5/1 or when the RON/MON requirement was raised to 99/87 for premium and 93/83 for regular from the somewhat relaxed values used in the base cases.

Introduction of methanol in a refinery with catalytic cracker (case 18) would allow full production of premium at somewhat lower and heavier crude input. The cracker would, however, be utilized only to 70% of capacity and the reformer to much less than 50%.

In all the methanol cases the reformer capacity is not fully used and the severety could be lowered to around RON 90. If only 10%v methanol was blended in the premium demand could not be fully met (13% missing).

Octane numbers obtained are controlled by RON on the relaxed level but will be controlled also by MON on the higher level.

In the zero lead cases the introduction of 20%v methanol (case 10) increases the premium production from zero to 2/3 of the demand. Limiting factors are reformer capacity and lack of reformer feed. In this case MON is controlling and there is a give away of about 2,5 RON units.

4.3 Economic valuation

A first estimate of the value of methanol as a gasoline component might be done by comparing cases with and without methanol under the presumption that the refiner will have the same revenue of the product slates minus feedstocks in compared cases and that the gasoline customer pays the same for driving a certain distance irrespective of different motor fuels. Operating costs are considered equal except for refinery fuels. Using the equilibrium prices in section 3 a comparison between cases 2 and 1 (0,15 g Pb/lit-level) gives breakeven values of methanol in the range 135-150 $/tonne, which would be the prices the refinery could afford to pay for methanol.

In the conversion refinery the introduction of methanol, cases 18 and 17, resulted in lower breakeven value, 105-110 $/tonne, mainly due to the fact that market constraints for gasoline do not allow full utilization of capacities. Gasolines with higher octanes could have been made.

The same comparison on zero lead level, cases 10 and 9, yielded methanol breakeven values of 120-140 $/tonne.

A case with only 10%v methanol blended in (not shown here) resulted in somewhat higher breakeven value than at 20%v. Another case producing a higher ratio of premium over regular (not shown here) also resulted in higher breakeven values.

The values above should be treated with caution and only be taken as indications for more detailed investigations.

In a parallel study of a hydroskimming refinery operating with 7 Mt/yr Arabian Light crude input the possibilities were studied to produce gasolines (prem/reg ratio 1,5) with and without methanol on 0,15 g Pb/lit level. The results given below again show that all naphta cannot be incorporated in the gasoline pool but methanol will allow this and also lower the demands on the reformer.

Methanol used, Mt/yr	-	0,38
Gasolines,Mt/yr	1,25	1,82
Surplus naphta,Mt/yr	0,14	-
Composition %v		
Butanes	10	6
Light naphta	11	16
Reformate (RON clear)	79(96,5)	58(91,3)
Methanol	-	20

Considering changes in operating requirements and costs and using the equilibrium prices for gasoline and naphta from section 3 the breakeven value of methanol was calculated as function of the energy gain at the end use.

Reduction of energy consumed,%		0	1	2	3	5
Breakeven value of methanol	Overcapacity conditions,$/t	94	101	109	117	131
	Value as % of premium	60	64	69	75	84
	Normal conditions,$/t	119	128	136	145	162
	Value as % of premium	65	70	75	80	89

The values are about the same range as obtained in the comparison above. A price of the methanol bought in of about 75% of the price of premium gasoline therefore seems reasonable. Incidently this corresponds to the ratio that has prevailed on the market during the last years.

In the next phase of the studies methanol was produced within the refinery from vacuum residues by gasification with oxygen and synthesis (case 5). The sulfur removal is taken care of at the synthesis gas purification. Consumption of residues corresponding to production of methanol for 20% blending needs is not sufficient to meet the max 1% S requirement for the fuel oils even if all vacuum gas oil is deep desulfurized. ARDS would be required as complement. In the study the methanol production was therefore raised to consume all residues which could not be used for back-blending into desulfurized vacuum gas oils. In this case a much heavier crude slate seems advantageous, which is an interesting feature. The above mentioned 7 Mt/yr refinery expanded with vacuum distillation, VGO-desulfurization and a methanol plant (all are existing technologies) would produce close to 1 Mt/yr methanol and low sulfur, low metal fuel oils.

The cost of production mainly depends on two factors, new capital costs and the sulfur premium. Assuming a 10% integration advantage, when methanol is produced within the refinery, compared to a grass roots plant the following figures were obtained for methanol cost per tonne when the price of high-sulfur fuel oil was set to 91 $/tonne.

ROI+depreciation as % of investment		15	20	25	30
Sulfur premium $/tonne	10	166	183	200	217
	20	142	159	175	192
	30	117	134	151	168
	40	93	109	126	143

At today´s sulfur premiums, ∼10 $/tonne, the methanol cost would not come near the breakeven values calculated above. To do this premiums of the magnetude to justify direct desulfurization (hydrocracking), ∼35 $/tonne, or low demands on ROI (=subsidies) would be required.

In a further development of the study the "methanol refinery" above is compared to a conventional refinery expanded to meet the same demands of transport work and sulfur levels through units for catalytic cracking, alkylation and direct desulfurization (ARDS). This route would be based on existing advanced refinery technology and has been widely accomplished in the US (except for ARDS) and is in progress in Europe.

The surplus of methanol from the methanol refinery over blending needs (with 3% energy gain) is assumed for use half in straight methanol engines (consuming 80% of the gasoline energy) and half in diesel engines (no energy gain). For comparison of the two refinery types the following outputs of the main streams would be required when starting from 7 Mt/yr Arabian Light crude.

	Methanol refinery	FCC/ARDS/Alky refinery	
Gasoline pool, total	2086 1)	1834	kt/yr
Hydrocarbon basestock	1405		"
MeOH for blends	368		"
MeOH for straight use	313		"
Middle distillate pool, total	2403 2)	2249	"
Hydrocarbons	2090		"
MeOH in diesels	313		"
Heavy fuel oil, 1% S	2444	2482	"
Gasoline composition			
Butanes	6	8	
Light naphta	16	10	
Reformate (RON clear)	58(91,3)	55(98)	
FCC-gasoline(RON clear)	-	19(94)	
Alkylate	-	8	
Methanol	20	-	
RON/MON averge pool 3)	97,8/86	96/87,6	

1) Equivalent pure gasoline 1774
2) Equivalent hydrocarbons 2249
3) RON/MON pool average 96/86 min(prem 98/88, reg 93/83) at Pb 0,15 g/lit. Prem/reg-ratio 1,5

As the FCC-gasoline, even as leaded, has lower octane numbers than the pool average, production of alkylates proved necessary to avoid expelling of light naphta or wasteful reformer operation at severeties above 100.

Calculating new investments and operating costs(over atmospheric distillation, reforming and middle distillate desulfurization) gives the following changes of the cash flows.

	Methanol refinery	FCC/ARDS/Alky refinery	
New investments	334	240	M$
Increased income	-	14,3	M$/yr
" operating costs	61,4	51,0	"
Decreased cash flow	-61,4	-36,7	"
Incremental investment	0^x	-94	M$
" cash flow	0^x	+24,7	M$/yr

^{x}base case

The decreased cash flows indicate that the sulfur premium is too low to justify ARDS or residue gasification.

The FCC/ARDS route obviously is the most attractive one and a refiner, who is asked to produce methanol from his vacuum residues, has to demand subsidies to obtain an acceptable return also on the incremental investment. This result is independent of present or future price levels of gasoline and middle distillates, as the outputs are equal.

The subsidy is calculated below with the presumption that the customer pays the same for driving a certain distance. The size of the subsidy will depend on the demand on the return, the fuel oil price level and the sulfur premium. The figures below are calculated for HSFO at 91 $/tonne and a sulfur premium of 10 $/tonne.

ROI+depreciation,% of investment	15	20	25	30
Production cost of methanol,$/t	166	183	200	217
Subsidy,$/t	39	44	48	53
value of methanol in motor fuel pools	127	139	152	164

The subsidy required will be a little higher for higher fuel oil prices and sulfur premiums depending on the higher energy yields at ARDS compared to residue gasification. As long as ARDS can be used the FCC/ARDS route always has an advantage in strict economic terms over the methanol refinery.

ARDS is limited to low and medium metal residual oils, whereas residue gasification can also be accomplished with very high metal residues. If the conventional refinery had to go to desulfurization methods such as Flexicoking or similar the two routes would probably have been more equally competitive as the energy yield figures are more similar.

The methanol refinery would probably prefer a heavier crude slate than a conventional refinery.

5 COSTS OF EXTERNALLY PRODUCED METHANOL

Production costs for methanol will depend on many factors such as type and price of feedstocks, plant size and localization.

The influence of size for single train plants on production costs is illustrated in Figure 1. It also shows the relative feedstock costs and supplementary energy needs for plant and transport for such geographically spread feedstocks as forestry wase or peat.

Figure 1

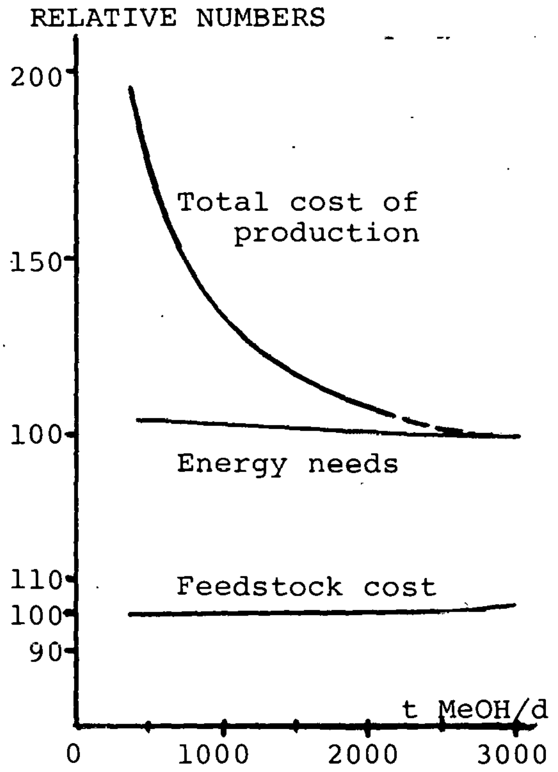

Figure 2

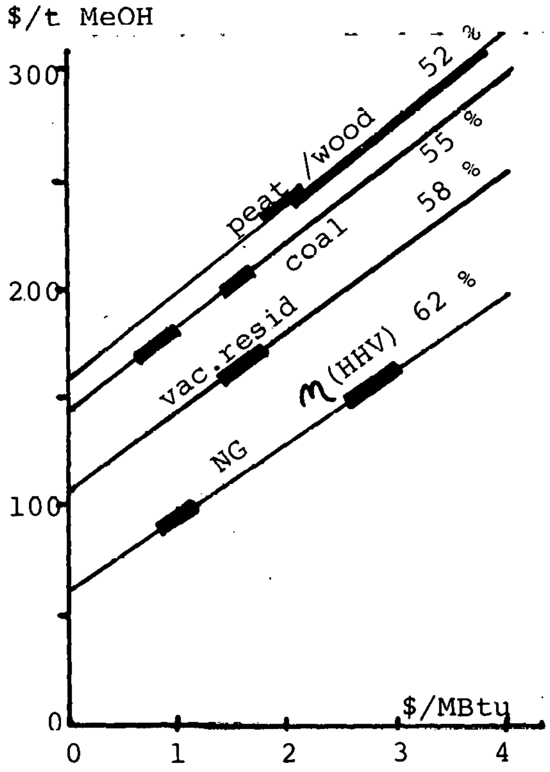

Figure 2 shows calculated methanol costs as function of feedstock costs for a 2000 t/d plant based on natural gas, vacuum residues, hard coals and wood/peat. Investment costs of 128, 212, 285 and 310 M$ (mid 1978 NW Europe) resp; 20% ROI+depreciation; yield figures anticipated for future plants. The thick parts of the curves indicate feedstock costs of interest. For cheap natural gas (~ 1$/MBtu) in remote surplus areas and prices for the North Sea area are indicated. For resids a price for fairly high sulfur premium is indicated and for coals minemouth prices and import prices to NW Europe are indicated.

Price for milled peat in Sweden is indicated. For wood there is still uncertainty over recovery costs for forestry waste and future short rotation forestry material.

For very large coal-based plants lower methanol costs have been presented in the paper of Boik (5) and in the study for DOE by Badger Plants, Inc. (6).

Note

The prefix M and k resp is used for Mega (=million) and kilo (=thousand).

Acknowledgements

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Table 1 REFINERY CAPACITIES

Units	kt/yr
Crude dist.(Arabian Light)	22.000
Vacuum distillation	5.500
Naphta,kero hydrotreating	4.500
Gas oil desulfurization	4.500
Catalytic reforming(95RON)	3.500
Visbreaking	2.060
Sulfur recovery	63
LPG recovery	570
C_5splitting	150

Table 2 PRODUCT TONNAGES

Product	kt/yr
LPG	180
Naphta	1.200
Premium gasoline	2.000
Regular gasoline	2.000
ATK	500
Diesel oil	2.600
Light fuel oil	6.400
Heavy fuel oil No4	7.000
Heavy fuel oil No5	7.000
Heavy fuel oil 2,5%S	400
Int.bunkers	1.100
Lubricants	200

Table 3 PRODUCT QUALITY SPECIFICATIONS

Motor Gasoline Quality		Premium		Regular			
Lead	g Pb/l max	Nil	0.15	Nil	0.15		
RON	min	98-99	97-99	93	92-93		
MON	min	87	85-88	82-83	81-83		
Distillation	50% °C max	110					
	90%	180					
	FBP	205					
RVP kp/cm^2 max	with alcohol	0.9-1.0					
	without alcohol	0.8-0.9					
$D_{100^{\circ}C}$	%vol	45-62					
Benzene	%vol max	5					
Aromatics	" min	25					
Olefins	" max	10					
Gas Oil and Fuel Oil Quality		Diesel	LFO	HFO4	HFO5	HFO	Bunkers
Sulphur %wt		0.2	0.3	1.0	1.0	2.5	3.5
Viscosity-cSt 20 °C		2-6	2-6	-	-	-	-
	Red 1 100 °F max	-	-	650	1500	3500	3500
Pour point °F max		-15	- 5	70	90	-	-
Cloud point °F max		0	4	-	-	-	-
Flash point °F min		140	140	150	150	150	150
Cetane Number		45	-	-	-	-	-
		Refinery fuel max 1%S					

Table 4

Case	1 Base-0,15		17 Cat cracker	9 Base-0	12 Isopentane	13 Import cracked
MeOH/iBuOH,%v	-		-	-	-	-
Gasoline req'd over base,%v	-		1	-	-	-
Prem/reg-ratio	1/1		1/1	1/1	1/1	1/1
Lead level,gPb/l	0,15		0,15	zero	zero	zero
PRODUCTS,kt/yr	Req'd	Made	Made	Made	Made	Made
Premium gasoline	2000	880	1641	-	740	1700
Regular "	2000	2000	2000	2000	2000	2000
LPG	180	180	180	180	180	180
Naphta	1200	372	1200	1200	460	840
Diesel/LFO	9000	3437	2600	3511	3470	3488
HFO No5	7000	2312	2120	2865	2838	2807
Bunkers	1100	1100	556	587	588	587
Refinery fuels	-	1025	1105	991	1082	1071
PROCESSING,kt/yr	Avail.	Used	Used	Used	Used	Used
Cat.reforming	3500	3500	3012	2705	3500	3500
Ref severety RON	95	96	95	93	97.5	100
Cat cracking	-	-	1948 2)	-	-	1380 3)
Isomer/i-pentane	-	-	-	-	697	-
GASOLINE OCTANES	Req'd	Prod.	Prod.	Prod.	Prod.	Prod.
RON prem/reg 1)	97/92	97/92	97/92	-/93	98/93	99/93
MON " " 1)	85/81	$88\frac{1}{2}/86$	$87\frac{1}{2}/84\frac{1}{2}$	-/84	$88\frac{1}{2}/85$	$88/83\frac{1}{2}$
CRUDE-USE,kt/yr						
North Sea	-	6200	6033	6200	6200	6200
Iranian Light	-	5975	6759	5420	5491	5502
Kuwait	-	7511	7111	8123	8076	7997

1) 0.3 margin not shown
2) Thruput
3) Import from high severety operation

Table 5

Case	2 Base-MeOH-0.15		7 MeOH, hi-ON	18 FCC+ MeOH	5 Resid-MeOH	10 MeOH-O
MeOH/i-BuOH,%v	18/2		18/2	18/2	18/2	18/2
Gasoline req`d over base,%v	7		7	7	7	7
Prem/reg-ratio	1/1		1/1	1/1	1/1	1/1
Lead level,gPb/l	0,15		0,15	0,15	0,15	zero
PRODUCTS,kt/yr	Req`d	Made	Made	Made	Made	Made
Premium gasoline	2120	2120	2120	2120	2120	1401
Regular "	2120	2160	2160	2160	2160	2100
LPG	180	85	152	180	180	180
Naphta	1200	231	233	1200	145	627
Diesel/LFO	9000	3225	3102	2600	3589	3287
HFO No5	7000	2347	2316	1697	2715	2300
Bunkers	1100	1100	1100	1100	699	1100
Refinery fuels	-	939	996	923	1160	1018
PROCESSING,kt/yr	Avail.	Used	Used	Used	Used	Used
Cat.reforming	3500	2644	3209	1611	2832	3500
Ref.severety,RON	95	≤ 90	93,3	90	90,6	94,6
Cat.cracking	-	-	-	1397[2]	-	-
MeOH production	-	918[3]	896[3]	919[3]	912	737[3]
GASOLINE OCTANES	Req`d	Prod.	Prod.	Prod.	Prod.	Prod.
RON,prem/reg[1]	97/92	97/92	99/93	97/92	97/92	$101\frac{1}{2}/95\frac{1}{2}$
MON,prem/reg[1]	85/81	86/83	87/83	85/82	86/83	87/82
CRUDE-USE,kt/yr						
North Sea	6200	6200	6200	6200	6200	6200
Iranian Light	5876	5876	5941	5815	4522	5975
Kuwait	7594	7594	7521	7488	10368	7479

1) 0.3 margin not shown
2) Thruput
3) Import

THE ENERGETICS OF ALTERNATIVE BIOMASS SOURCES FOR ETHANOL PRODUCTION IN BRAZIL

by

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INTRODUCTION

The need for renewable energy sources lead Brazil to establish the National Alcohol Program (PNA) in 1975. This program sought to increase ethanol production though appropriate economic policy actions involving the traditional technology already in widespread use in the country. First priority was clearly given to quick response and immediate application instead of technological improvements on existing techniques or alternate fuels.

Ethanol production in Brazil has in fact expanded rapidly in the last few years in response to the government policy of economic incentive. About 80-90% of the total funds invested in industrial alcohol plants was borrowed from the Bank of Brazil at interest rates lower than inflation rates.

Ethanol[1] and gasoline[2] production

year	ethanol 10^3 m^3		gasoline 10^3 m^3	ethanol-gasoline mixture (%)
	total	fuel		
72	681	389	12004	3.24
73	666	306	13929	2.20
74	625	217	14322	1.52
75	556	233	14619	1.59
76	664	300	14724	2.04
77		1177	14103	8.35
78[3]		1589	14448	11.00
80[3]		2465	14501	17.00
84[3]		3184	15922	20.00

1-Source:Instituto do Açucar e do Alcool. Ministerio da Industria e do Comercio. Brasilia.
2-Balanço Energetico Nacional.Ministerio das Minas e Energia. 1978
3-Estimative.

Considering the high artificial price of gasoline for the consumer in Brazil (US$0.42/liter) the increase in ethanol production occurred without technological developments to improve efficiencies and lower production costs.

Within the contraints of the relatively small flexibility of PETROBRAS refineries in varying the relative production amount of petroleum derivative, it is only justifiable to

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hird International Symposium of Alcohol Fuels Technology.
alifornia, U.S.A. 1979.

increase substantially ethanol production for gasoline substitution if there is simultaneous reduction or substitution of the demand of others petroleum products.

In the particular case of Diesel oil, the substitution by ethanol presents some technical and economic difficulties, but it is expected to find some possible technical solution in the future.

Liquid fuels prices[1] per liter, in Brazil

fuels	production final price	consumer price
ethanol	0.29	0.42
gasoline	0.19	0.42
diesel oil	0.11	0.22
fuel oil	0.045	0.065

1-Conversion rate: Cr$22.00/dollar

These considerations and data on the economical aspects of the problem, show the need of a high production of petroleum substitutives. To reach a large ethanol production it is important to analyse the physical constraints imposed by the amount of available land and the particular conditions of soil quality and climate for raw material cultivation. Sugar cane is practically the only raw material exploited on a commercial basis for ethanol production and requires soils of good fertility and special climate conditions; these conditions are already a limiting factor for sugar cane expansion, since its cultivation competes already with other food crops in the utilization of good quality soils. So, it is more and more necessary to search other raw materials and fuels that could become part of a brazilian solution to its energy needs.

The objective of this paper is to present an energy comparison of different raw material- sugar cane, sweet sorghum, cassava, eucalyptus and pinus -, and to provide subsidies for the research and selection of crops for ethanol production.

AGRICULTURE AND ENERGY

Composition and Yield of Raw Materials

The composition and yield of sugar cane, sweet sorghum, cassava, eucalyptus and pinus, are presented in tables 1a, 1b and 2.

Table 1a- Composition % {1, 2, 3, 4, 5, 6}*

	sugar cane	sweet sorghum		cassava	
	stems	stems	grains	roots	"ramas"
moisture	72-76	68-72	11-15	68	76
fiber	9-13	14-17	2-3	1.4	23
sucrose	12-16	9-12	1-2	2.0	
glucose	0.2-1.5	1.0-4.0		1.2	
starch			55-65	25-35	
total sugar[1]	13.0-17.0	12.0-16.5	1.0-2.0		

1) fermentable sugars (glucose %):sucrose x 1.05 plus glucose

---

* { }- references

Table 1b- Composition % {3, 7, 8, 9, 10}

	eucalyptus	pinus	sugar cane fiber	sweet sorghum fiber
cellulose (alfa)	50.0	50.0	40.0	35.0
hemicellulose	20.0	15.0	27.0	27.0
hexosans	2.5	9.6	1.0	
manans	1.3	7.0		
galactans	1.2	2.6		
pentosans	17.5	5.4	26.0	
xylans	16.8	3.9	25.0	
arabans	0.7	1.5	1.0	
lignine	25.0	30.0	22.0	20.0

Table 2- Yields and dry matter production (t/ha) { 5, 11, 12, 13, 22, 23}

crops[1]	yield /year	yield /month	dry matter /year	dry matter /month
sugar cane	45-60	3.8-5.0	12.6-16.8	1.1-1.4
	52[3]	4.3	14.6	1.2
sweet sorghum				
stems	30-40	6.7-8.9	9.6-12.8	2.1-2.9
	35	7.8	11.2	2.5
grains	2-4	0.4-0.9	1.7-3.5	0.3-0.8
	3	0.7	2.6	0.6
cassava				
roots	10-15	1.1-1.7	3.2-4.8	0.3-0.5
	12.5	1.3	4.0	0.4
"ramas"[2]	7.5-10.0	0.7-1.1	1.8-2.4	0.1-0.3
	8.8	0.8	2.1	0.2
eucalyptus			11.8	1.0
pinus			14.6	1.2

1)plant cane has a 18 month cycle (land is required for 2 years) and 3-4 ratoons of 12 months; sweet sorghum: 4.5 months; cassava: 15-22 months (land is required for 2 years) eucalyptus: 7 years (2 ratoons of 7 years); pinus: 25 years (7 partial harvests in this period); 2)"ramas":aerial part of cassava plant; 3)average.

Except for sweet sorghum wich is not cultivated on commercial basis, these data are representative of plantations in the State of Sao Paulo.

Yields of Glucose and Ethanol

Table 3 and 4 shows the yields of glucose, residues and ethanol. In order to make possible a better comparison between raw materials we considered 2 systems, according to the cellulose utilization for ethanol production or not. System I is related to the processing of fermentable sugars and starch. System II involves also processing of cellulose.

Table 3- Yields (t/ha) of glucose[1] and residues (dry basis)*

	system I				system II			
	glucose		fiber		glucose		lignine	
	/year	/month	/year	/month	/year	/month	/year	/month
sugar cane	7.8	0.65	5.7	0.48	9.5	0.79	1.3	0.1
sweet sorghum	6.7	1.45	5.4	1.20	8.3	1.85	1.1	0.1
stems	5.0	1.11	5.4	1.20	6.6	1.47	1.1	0.1
grains	1.7	0.38	-	-	1.7	0.38	-	-
cassava	4.0	0.17	1.8	0.08	4.6	0.38	0.4	0.03
roots	4.0	0.17	-	-	4.0	0.33	-	-
"ramas"	-	-	1.8	0.08	0.6	0.05	0.4	0.03
eucalyptus	-	-	-	-	4.3	0.36	3.0	0.25
pinus	-	-	-	-	6.1	0.51	4.4	0.37

1)glucose conversion factors:sucrose x 1.05;starch x 0.95;cellulose x 0.70
* {5, 6, 7, 8, 9, 14, 15 }

Table 4- Yields (liters/ha) of ethanol[1] {6, 8, 14, 15}

	system I		system II	
	/year	/month	/year	/month
sugar cane	4541	378	5530	461
sweet sorghum	3900	867	4832	1074
stems	2911	647	3843	854
grains	989	220	989	220
cassava	2329	194	2678	223
roots	2329	194	2329	194
"ramas"	-	-	349	29
eucalyptus	-	-	2503	209
pinus	-	-	3551	296

1)ethanol conversion factor: 58.22 liters/100kg glucose (20ºC)

Agricultural Energy

In table 5 is listed, in a resumed form, the energy expended in the agricultural phase of the alcohol production. These figures were obtained according to a recent study carried in the State of Sao Paulo and the utilization of input-output brazilian matrix {17}; it represents a more realistic evaluation than previous studies {19}.

Table 5- Energy (Mcal/ha/year) expended in agricultural production

	sugar cane	%	s. sorghum[1]	%	cassava	%	eucalyptus	%	pinus	%
fuel	2475	61.3	987	53.2	561	55.2	381	71.6	316	74.1
fertilizer	997	24.7	1122	40.1	448	29.4	36	6.8	1	0.2
defensive	332	8.2	69	2.5	53	3.5	60	11.3	86	20.3
machinery	119	2.9	65	3.0	39	2.6	21	4.0	17	4.0
labor	116	2.9	12	0.4	73	4.8	34	6.4	-	-
other	-	-	23	0.8	51	3.3	-	-	6	1.4
total	4039		2798		1525		532		426	

Source: Internal Report, Instituto de Fisica, Sao Paulo

1) estimative

INDUSTRIAL ENERGY

The industrial energy considered was: a) the energy invested in the capital good,-expresses energy embodied in the equipment; b) operational energy-expresses energy of chemical products and other materials consumed in the processing of the final good; c) maintenance; d) combustible - expresses the energy for industrial processing of raw material.

Industrial energy figures for ethanol production from fermentable sugars are shown in table 7. They were calculated based on reference {21}, wich presents details for that evaluation. For ethanol production from cellulose, it was first evaluated the energy consumption based on reference {16}. Ethanol production from starch is estimated based on ethanol from cellulose. Table 6 presents the results of the calculations.

Industrial processing energy (combustible) is the major component, representing 90% of the total energy of industrialization This fact shows that from an energy point of view a program for utilization of fuels produced from biomass will only be successful if the combustible used for industrial processing is also from a renewable source.

Another aspect concerns the importance of energy conservation measures. In Brasil this is particularly important in sugar cane distilleries if one considers that: a) present energy spent on industrial processing is the same as 30 years ago, and b) bagasse drying is not used. The surplus energy from bagasse could be used in electric power generation {24}.

Table 6- Industrial energy of ethanol production (Kcal/liter)

	fermentable sugars[1]	cellulose[2]
capital goods (20 years lifetime)	168.9	91.6
operation	131.1	452.6
maintenance	168.9	91.6
processing (combustible)	4932.8	6000.0

1) Source: reference 21; sugar cane and sweet sorghum stalks

2) Wood

Table 7 - Industrial energy (Mcal/ha/year)

	cap. goods		operation		maintenance		sub total		combustible		total	
	I	II	I	II	I	II	I	II	I	II	I	II[1]
sugar cane	767	858	595	1043	767	858	2129	2759	19252	25351	21381	28110
sugars	767	767	595	595	767	767	2129	2129	19252	19252	21381	21381
cellulose	-	91	-	448	-	91	-	630	-	6099	-	6729
sweet sorghum	583	668	830	1252	583	668	1996	2588	17297	23044	19293	25632
sugars	492	492	382	382	492	492	1366	1366	12342	12342	13708	13708
starch	91	91	448	448	91	91	630	630	4955	4955	5585	5585
cellulose	-	85	-	422	-	85	-	592	-	5747	-	6339
cassava	213	245	1054	1212	213	245	1480	1702	11669	13821	13149	15523
starch	213	213	1054	1054	213	213	1480	1480	11669	11669	13149	13149
cellulose	-	32	-	158	-	32	-	222	-	2152	-	2374
eucalyptus	-	229	-	1133	-	229	-	1591	-	15435	-	17026
pinus	-	325	-	1607	-	325	-	2257	-	21898	-	24155

1) system I and II

ENERGY BALANCE

Considering the results shown in table 7 and other available information {19,21}, a concept of a "self sufficient hectare" was used: it consists of the partial utilization of 1 ha by an eucalyptus plantation (or any other wood) occupying an area just in order to provide the sufficient industrial processing energy required by the crop cultivated on the rest of the hectare. For example, for cassava industrialization (system I), taking as a basis 1 ha as modulus, 0.91 ha of this crop would be cultivated, leaving 0.09 ha to be used for eucalyptus plantation; this wood supply the necessary energy for the industrialization of cassava.

Based on figures of tables 8 and 9, it is possible to distinguish some important aspects:

a) All raw materials have a low overall efficiency (Et/A+I) and there is a wide difference between them (0.63-0.90) at the present state of the technique. When combustible energy for industrial processing is not taken into account - Et/A+I-Ip - (it is considered part of the system), the efficiencies are higher but still keeping a wide difference (3.41-5.96)

b) The efficiency of agricultural energy - Et/A - presents the widest variation (5.7-36.8). Considering the efficiency for agricultural combustible energy - Et/Ac - , the general trends are similar (9.2-49.8)

Wood is 2 to 7 times more efficient than other raw material in relation to agricultural energy; the other raw material have, in a general sense, similar efficiencies.

c) The efficiency of industrial energy (Et/I), differing from agricultural energy, shows much lower values for wood and other cellulosic material.Considering the efficiency rate,it is remarkable that the industrial energy, and not agricultural energy, is responsible for lower efficiencies.

Observing other industrial energetic efficiencies Et/Ip and Et/I-Ip) it is seen that industrial processing energy has a dramatic effect upon the energy balance.

In distillation process it is well accepted that it is possible to reach better energetic efficiencies. But concerning sugar cane the necessity of high pressure steam to drive the mills is a limiting factor over low pressure steam economy.

Also, those efficiencies always shows lower values for cellulose industrialization.This fact suggests the need to achiev better efficiencies for cellulose hydrolisis which is considered very low {25}; research is being done showing the possibility to obtain efficiencies 100% higher {25}.

The Et/I-Ip coefficient is based on the use of renewable for industrial processing, furnished by an eucalyptus plantation, which allows the achievement of higher efficiencies (6.4-10.8).

Analyzing Et/I-Ip coefficient,the industrial operation energy and the ethanol yield, it is observed that cellulose problem is more related, once again, with acid hydrolisis efficiency; the industrial operation energy plays a less important role, once it is much lower.

Table 8- Energy balance (Mcal/ha/year) for a "self sufficient hectare"[1]

	area[1]	ethanol	agriculture[2]			industry[3]		residues[4]		balance
	%		a	b	total	c	d	e	f	
sugar cane										
system I	100.0	22878	4039	-	4039	2129	19252	21090	+ 1838	18548
system II	70.7	19690	2854	156	3010	1951	17915	3400	-14515	14729
sweet sorghum										
system I	100.0	19648	2798	-	2798	1996	17295	19980	+ 2684	17538
system II	72.3	17603	2023	147	2170	1871	16667	2943	-13724	13562
stems										
system I	100.0	14666	2798	-	2798	1366	12341	19980	+ 7639	18141
system II	78.0	15092	2181	117	2298	1527	14100	3173	-10927	11267
cassava										
system I	90.8	10657	1385	49	1434	1480	10598	6049	- 4549	7743
system II	80.1	10802	1221	106	1327	1702	11065	1185	- 9880	7773
eucalyptus	91.2	11596	489	43	532	1591	14194	10208	- 3986	9473
pinus	89.8	16069	383	54	437	2257	19659	14623	- 5046	13375

1) see text; area % occupied by the crop (the other part is occupied by an eucalyptus plantation to provide energy); 2) agricultural energy: a) energy expended by the crop; b) energy expended by the eucalyptus plantation; 3) industrial energy: c) energy expended with capital goods, operation and maintenance; d) energy expended with combustible for industrial processing; 4) residues (fiber and lignine): e) energy produced by residues; f) energy balance of residues energy and energy necessary for industrial processing.

Table 9- Energy efficiency coefficients

	$\frac{Et}{A}$	$\frac{Et}{Ac}$	$\frac{Et}{I}$	$\frac{Et}{I-Ip}$	$\frac{Et}{Ip}$	$\frac{Et}{A+I-Ip}$	$\frac{Et}{A+I}$
sugar cane							
system I	5.66	9.24	1.07	10.75	1.19	3.71	0.90
system II	6.54	10.57	0.70	7.14	1.10	3.41	0.63
sweet sorghum							
system I	7.02	13.21	1.02	9.84	1.14	4.10	0.89
system II	8.11	16.28	0.69	6.80	1.06	3.70	0.63
stems							
system I	5.24	9.86	1.07	10.74	1.19	3.52	0.89
system II	6.57	12.13	0.75	7.71	1.07	3.55	0.68
cassava							
system I	7.43	13.34	0.81	7.20	1.01	3.66	0.73
system II	8.14	14.40	0.70	6.35	0.98	3.57	0.64
eucaliptus	21.80	30.44	0.68	7.29	0.82	5.46	0.66
pinus	36.77	49.75	0.67	7.12	0.82	5.96	0.65

Et - Ethanol energy; A - Agricultural energy; Ac - Agricultural combustible energy; I - Industrial energy; Ip - Industrial processing (combustible) energy

CONCLUSIONS

The agricultural energy balance shows clearly the high energetic efficiency of forest crops. The tropical conifer forest has showed better results than eucalyptus, due not only to higher crop yields but also to its composition.

This favorable aspect of forest crops associated to the existence of a successful 12-year program of reforestation in Brazil, would allow a rapid response to higher biomass needs at low costs, also allowing any farmer (even with low purchasing power) to participate in the energy production program.

The energy balance analysis is not conclusive. It is necessary to consider particular aspects of the country and its different regions, such as technological development, social aspects, climate and land availability and quality. In spite of the good results shown by the sugar cane energy balance, the expansion of this crop is limited by two factors: a) availability of high fertility soils and an adequate topography for mechanization and, b) high investments for cultivation (energy intensive crop), which are only possible for a more limited part of rural properties.

In particular for cellulosic material, the high energetic gain in the agricultural stage becomes seriously absorbed by the industrial efficiency due to: a) low acid hydrolysis efficiency with a consequentely low ethanol yield, and b) high energy consumption for industrial processing, requiring 6170 kcal/liter which is superior to the calorific value of ethanol (5038 kcal/liter), and leading to energetic deficit.

Besides the wood crop agricultural energetic aspect which recomends it for the biomass production program, other factors, peculiar to Brazil, must be added to the previous one making it acceptable when a national energetic program is aimed; they are: a) wood crops adjustment to utilization of large areas having low soil fertility, low water availability and low populational density; b) adoption, by brazilian government, of policies to concentrate efforts on ethanol production; c) necessity to produce liquid combustible in large scale and using national technology.

In so considering, it is suggested the intensification of research on cellulose hydrolisis, specially on enzimatic hydrolitic process development, for being the latter much more efficient than the acid process which probabily will make cellulose industrialization more efficient.

Energy conservation is showed as another important technological improvement to be reviewed specially regarding to distillation process and combustible residues (bagasse, e. g.) drying.

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GASOLINE/METHANOL FUEL DISTRIBUTION AND HANDLING TRIAL

by

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ABSTRACT

It seems very likely that petroleum will not continue to be the main source of transportation fuel indefinitely. Since the energy disruption of 1973/74 and the escalating crude oil prices that have followed, several governments for political, strategic and economic reasons have decided to explore alternative forms of energy for the transport sector. The questions at present are the selection of an alternative fuel and its rate of introduction. Alcohols such as methanol and ethanol, produced from indigenous raw materials such as coal, natural gas, crops etc. are seen by many countries as attractive fuel extenders and in some cases as complete gasoline substitutes.

Basic work carried out so far has confirmed the feasibility of using fuels containing alcohols as fuel components in vehicles. However, apart from the vehicle, consideration to other possible limiting factors, e.g. fuel stability, toxicity, increased aldehyde emissions, must be given before final selection of an alternative fuel is made. This present paper will discuss the implications that methanol, as a fuel component, is likely to have on the distribution network.

In order to assess the extent of the problem in the distribution network, under realistic conditions, a small (1200 m^3) distribution/handling trial has been carried out in West Germany.

There are three possible ways to blend and distribute gasoline/methanol blends:

- in-line blending of methanol with gasoline at the refinery.
- distributing methanol and gasoline separately to bulk storage terminals for blending.
- distributing methanol and gasoline separately to service stations with blends being prepared through suitable mixer pumps just prior to vehicle fuel tank.

Each of these techniques has advantages and disadvantages. However, for reasons explained in the paper, blending at the refinery was selected and transportation to the storage terminal carried out using one of the overland transportation systems, i.e., by rail, pipeline, or road tanker.

The basic outline of the trial selected was:

- fuel containing 15 % by volume methanol (without solubilizers) blended by conventional in-line blending techniques into a floating roof blending/storage tank.
- transportation by railcar of the fuel to a storage terminal.
- over a six month period portions of the fuel transported by road tanker to a service station underground tank.
- automatically pumped by a conventional service station pump at a specified rate into a second underground tank. Underground tanks differ in their preparation of their inner walls.

The fuel was not used in any vehicle application, it was returned to the refinery to be reprocessed.

During the test programme the fuel qualities, phase separation and facilities operations were continuously monitored. Corrosion and changes in the properties of elastomers, used throughout the distribution network, were examined at the end of the programme.

In general the ingress of water occurs in varying amounts in todays gasoline distribution system, but little quantitative data has been published on the subject. The major portion of the paper gives and discusses quantitative data on the extent of water ingress, and by which means it occurs, ge.g. rainwater entering through the seals of floating roof tanks, diurnal breathing of storage/underground service station tanks, or entry of water into underground service station tanks if seals are improperly fitted following receipt of product. The extent of water ingress and the effect of low ambient temperatures have on blended fuel in these relatively large blending/storage tanks as opposed to experiments carried out in laboratories are further discussed.

Precautions necessary to prevent water ingress into the prepared blends are outlined. For example more suitable sealings for floating roof tanks, or wider use of floating/fixed roof combination tanks. Also the use of desiccant breathers, and conversion of the product take-off lines so that they can be operated on top of the product. An attempt is made to highlight the major modifications/new facilities required.

Other potential problems arising from corrosion and elastomer incompatability either in the blend or in possible rich aqueous-methanol phases will be indicated. Further thoughts have to be given to new problems arising out of the trial. For example, potential environmental hazards that could result if no change is made to current refinery procedure. At present „water bottoms" are discarded, periodically, in an environmental acceptable manner. However, with fuels containing methanol it will be necessary to subject „bottoms", which could be rich in methanol, to further treatment, not only from an environmental point of view but also because the „bottoms" contain a valuable energy/fuel component.

The results of the trial will be used to form a platform for a proposed large distribution/vehicle fleet trial in the very near future.

GASOLINE/METHANOL FUEL DISTRIBUTION AND HANDLING TRIAL

by

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1. INTRODUCTION

Although road vehicles worldwide are using only about 15 % of the total energy or roughly 30 % of the crude oil produced, it seems very likely that petroleum products will not continue to be the main source of transportation fuel for road vehicles indefinitely(1)*. If we continue to burn oil at the present rate, future supplies of gasoline will have to be obtained from alternative sources other than normal crude oil Figure 1 shows(2) how the time scale for oil is affected by different rates of growth in energy demand. The current rate is between 3 and 3.5 %. However, whatever the rate, demand will eventually exceed supply. It is anticipated that alternative sources of energy, such as coal and nuclear power, will be used more extensively, particularly in Europe, for base power generation replacing the heavy fuel oil which can be converted into lighter materials, such as motor gasoline, albeit at the expense of energy required in the refinery to carry out the conversion. To help stretch out the available supplies, greater use could be made of the petroleum components at either end of the gasoline boiling range, e.g., LPG (Liquid Petroleum Gases), or heavier fractions from the other end, e.g., increasing the distillation end points of gasoline and diesel fuels.

Other factors though, such as the energy disruption in 1973/74, the Iranian supply problem in 1979, and the escalating crude oil prices that have followed, have promoted several governments for political, strategic, and economic reasons, or combinations of these, to explore alternative forms of energy for the automotive sector.

Special requirements of automotive fuels place added constraints on any solution. For example, high energy density with respect to both mass and volume is a particularly important factor for an automotive fuel, as the fuel must be carried around by the vehicle. Automotive fuels must also be safe to use and handle. They must be convenient to transport, store, transfer from storage facility to vehicle and deliver via the vehicle's fuel system. Last, but not least, they must be environmentally acceptable. It is accepted that on the question of alternative fuels that the transition from petroleum-based fuels would be greatly simplified from the standpoint of distribution and marketing, as well as vehicle design, if synthetic gasoline and diesel fuel (e.g., derived from coal) could be produced in sufficient volume at reasonable cost. Such production processes do exist, e.g., Fischer-Tropsch process, which is being used in South Africa today, but has only an efficiency of 45 %. Until the time comes when the technology is available to improve the cost effectiveness of such processes, the production and utilization of alcohols from renewable sources are seen by many countries as attractive fuel extenders in the short term and in some cases even as complete gasoline substitutes. Figure 2 indicates countries with interest in alcohol fuels around the world, mainly areas where only basic research work is being carried out, but others where blends of ethanol in gasoline are already in commercial use, e.g., Brazil, South Africa, and Cuba.

Alcohols, mainly methanol and ethanol, can be produced from a wide variety of indigenous raw materials, such as coal, natural gas, and biomass. Extensive Research and Development programmes, carried out so far, have concentrated mainly on the practicalities and possibilities of using alcohols as fuels and fuel components in vehicles. As a result, many investigators (3), including ourselves (4),

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*Numbers in brackets (I) designate References at end of paper.

have shown that it is feasible to use alcohols as automotive fuel components. However, apart from the application in the vehicle, other possible limiting factors, e.g., fuel stability in distribution systems, toxicity, increased aldehyde emissions, which have been less investigated, must be considered before final selection of an alternative fuel is made. This present paper discusses some of the implications that methanol, as a fuel component, is likely to have on a distribution network.

2. THE DISTRIBUTION OF GASOLINE/METHANOL FUELS

The use of methanol as a gasoline blending component is only commercially acceptable if the gasoline/methanol blend remains homogenous until the fuel is pumped into the engine. Methanol, because of its inherent polar nature, is infinitely soluble in water and has only limited solubility in hydrocarbons. The latter is affected by the chemical composition of the fuel (paraffins, olefins and aromatics), with a high aromatic content gasoline (preferably aromatics of low molecular weight) providing the best solubility(4). Small amounts of water and/or low temperature will cause phase separation.

For the distribution of gasoline/methanol blends there are three systems which should be considered. Figure 3 illustrates the required number of blending points for each system in the area of one refinery:

1. in-line blending of methanol with gasoline at the refinery.
2. distributing methanol and gasoline separately to bulk storage terminals for blending and onward distribution as gasoline/methanol fuel
3. distributing methanol and gasoline separately to service stations for blending in a suitable blender pump just prior to the vehicle fuel tank

Each of these systems has of course certain advantages and disadvantages depending on many circumstances. For each of the systems one can foresee the following associated advantages/disadvantages:

1. Refinery Blending

ADVANTAGES:

- the fuel meets specifications before leaving the refinery
- the blending is carried out by skilled operators under optimum conditions
- only a few supply points are required for the methanol component

DISADVANTAGES:

- the potential risk of ingress of water (and subsequent phase separation) is high because it is the furthest point from the vehicle fuel tank. This is particularly true when blending tanks, which normally have only floating roofs, are used as storage tanks for short periods, or if marine transportation is employed in the distribution network
- potential increase in corrosion within distribution network due to ingress of water.

2. Storage Depot Blending

ADVANTAGES:

- reduced risk of phase separation compared with refinery blending, as the storage depo closer to the service station. This would be the case if marine transportation is used between the refinery and storage depot. The risk of water ingress into storage depot tanks, which are normally fixed roof tanks should be lower than with the floating roof blending tanks.

- regional distribution of gasoline/methanol blends permitted, escpecially in countries with few refineries, but with large climate variations in any one season due to large land mass.

DISADVANTAGES:

- higher distribution costs compared with refinery blending
- poor blending control with existing facilities
- training of depot operators in blending techniques necessary
- increase quality control checks
- numerous supply points for methanol involved
- increased risks of pure methanol spills, and operator exposure to methanol vapours

3. Service Station Blending

ADVANTAGES:

- minimal risk of phase separation as time for water ingress is short compared with previous two systems
- greater flexibility when future car generations are introduced that will permit the usage of higher alcohol contents, i.e., cars with multifuel capability that would be valuable in the initial stages of setting up a methanol distribution system.

DISADVANTAGES:

- extremely high distribution costs
- high capital investment required, e.g., more tankage at service station required and complete change to blender pumps
- good blending control, but no quality check on finished blend
- high risk of methanol spills, and customer exposure to methanol vapours

It can be seen from the above that blending the methanol into the gasoline as close to the refinery as possible ensures that the fuel is distributed in the most economic way. However, because of potential fuel instability, and hence quality problems, in the currently available distribution network, it is desirable to blend the methanol intothengasoline as close to the end use as is practical, i.e., system 3. Blending at the service station would also be attractive if it would be possible to use the currently manufactured and distributed gasoline as the hydrocarbon base for the finished methanol containing fuel. Test work carried out so far, however, indicates that this is not possible because the resulting performance aspects are uncontrolled and problems with vapour lock and cold starting could occur. This requires tailoring the hydrocarbon base for the methanol blend which is best carried out at the refinery.

Climate and complexity of distribution systems vary from country to country, e.g., use of marine or overland transport, pipeline, and the extent of use of intermediate storage. Each country will have to be evaluated on an individual basis. For example, West Germany has a mid-European climate, and as shown in Figure 4 for a major oil company with four refineries supplying service stations over e whole of West Germany, a large percentage (40 %) is delivered directly to the service stations. The other 60 % is transported to intermediate storage by means of rail truck (25 %), pipeline (20 %)

and marine (15 %). A small percentage (5 %) of the rail truck transportation goes into a second storage depot before being finally distributed to service stations. From the practical aspects there is, in West Germany, a case to evaluate system 1, i.e., blending in the refinery.

3. OBJECTIVES AND TARGETS

This paper describes a small distribution trial, where an attempt has been made to highlight problems that may occur when a fuel containing methanol is blended in a refinery, and subsequently distributed via an intermediate storage depot, and finally to a service station.

A typical distribution network was indicated in the previous section. Blending tanks with floating roofs and with capacities ranging from 2000 m^3 to 15000 m^3 are common. In-line blending procedures are used, and it is not uncommon for 1 to 2 m^3 of water bottoms, normally not removed by draining procedures, to be present in the tank prior to blending. Fuel can remain in the blending tanks for up to three or four weeks before being transported by rail truck, pipeline, or marine to intermediate storage, or directly to service station outlets.

Storage depot tanks vary in size depending on the area which they supply. In Europe it is general that fixed roof storage tanks are used, and the fuel can remain up to two months in the tank. Transportation from the storage depot to the service stations is by road tanker, or if secondary storage is required, by rail truck.

Underground tanks at service stations also vary in size, but 10 m^3 are very common. Tank construction can either be of double-walled steel or a single wall that has an inner protective coating. Fuel deliveries to the underground tanks can be as short as every 2 days up to 10 days or longer. Forecourt dispensing pumps are in general very similar, each pump designed to supply a single quality of fuel. There are exceptions in that some companies make use of blending (or mixing) pumps which enables the customer to choose 2 or 3 qualities between two extreme qualities, e.g., in Germany between Normal and Super gasolines. Whatever the pump used, each vehicle on average takes on 35 litres each visit to the service station. The average throughput of a single service station pump is 350 m^3 per year.

For the trial it was only possible to follow one particular distribution route and for practical purposes, only a small blend of 1200 m^3 was produced. The chosen route used an overland distribution system, and, although tailored down, consisted of blending the fuel in the refinery, transfer to intermediate storage by means of rail truck, transfer from storage to a service station by road tanker and finally dispensing of the fuel by conventional service station pump. The schematic flow diagram of the trial is shown in Figure 5. Realistic conditions, as described above, were adhered to as close as possible. In more detail the trial proceeded as follows:

- Approximately 1200 m^3 fuel containing 15 % of methanol (without the use of solubilizes) was blended by conventional refinery in-line blending techniques into a floating roof tank. The tank contained 1 – 2 m^3 of water bottoms.
- After three weeks in the blending tank the fuel was transported by rail truck to a storage depot where the fuel was stored in a fixed roof tank for five months.
- During the five month storage period, approximately 15 m^3/week of fuel was transported by road tanker to a service station and delivered into an underground tank.
- In the service station the fuel was pumped, automatically in a discontinual way, by a conventional forecourt pump at a rate of 40 litres/min. The pump dispensed approximately 40 litre every 10 minutes into a second underground tank. The underground tanks differed in that on was a double-walled steel tank, and the other a steel tank coated with graphite filled expoxy

resin.

- The fuel from the second underground tank was returned to the refinery to recover the hydrocarbon components for further use in mogas production.

The aims of the trial were to highlight and quantify the areas of water ingress, monitor any changes that occur both in the fuel quality and in contacted materials as it proceeds through the distribution network. Investigations of both the rail truck or the road tanker were not included in this trial, as the rail truck was required only once. and it was not practical to use a dedicated road tanker for six months. The compatibility of materials, used in the construction of tanks, and the materials used in meters, pumps, and valves, e.g., seals and gaskets, were investigated, however, the obtained information is limited due to the short trial period (six months). Many of these were inspected and photographed both before and after test phases, and in some instances during a test phase.

The findings from this trial, nevertheless, give an excellent basis for a larger distribution/handling trial involving approximately 1,500 vehicles to be carried out over the next three or four years. The details of this larger trial, which we will participate in, will be outlined in another paper at this Symposium (5). It is part of the West German Government's Research Programme on „Alternative Energies for Road Vehicles".

4. GASOLINE/METHANOL DISTRIBUTION TRIAL

4.1 Blending in the Refinery

The components (reformate, cat. cracked, and butane) used for blending the fuel were selected from a conversion type refinery(4) as this type will increase in Europe and might even dominate in countries such as West Germany. The methanol component was of Chemical Grade and contained less than 0.05 %v water on delivery to the refinery. The methanol was stored in the refinery in a fixed roof tank for a period of six weeks (normal stock cover is 50 to 60 days). Over this period of time, the water content of the methanol which occupied half the volume of the tank capacity, increased by only 0.01 %v.

The target properties of the blend were such that they did not necessarily fulfil current specifications for conventional automotive fuel, but that the blend was broadly suitable for use in gasoline engines. The composition of the blend was optimised from both a production and cost point of view as described in a previous paper(4). Due to certain practical reasons no lead could be added to the blend with the result that the Research Octane Number (RON) was 100 and the Motor Octane Number (MON) 85.5. However, the addition of 0.15 g lead/litre to the blend would ensure that both minimum RON (98) and minimum (88), as required by present German specification for Super fuel, would be achieved. The omission of lead from the blend in no way affected the results obtained from the trial.

4.1.1 Results and Discussion on Blending Phase of Trial

Normal refinery in-line blending techniques were used to blend a Premium grade fuel containing 15 %v methanol. Shortly after completion of blending (30 min), and at regular intervals over three weeks, samples of the 1200 m^3 blend were taken from the tank and analysed. A sampling procedure was used which allows samples to be taken at various heights (every cm) from the bottom of the tank.

From the analytical results the following were deduced:

- Shortly after blending a „bottom phase" of 1.35 %v (15.5 m^3) was recorded which had the composition as shown in Figure 6(a). From this Figure, a plot of amount of bottom phase against water, methanol and hydrocarbon compositions, it can be seen that the methanol-rich „bottom phase" consists of several phases. The lower phases consist mainly of methanol and water and the upper phases mainly of hydrocarbon and methanol.
- After three weeks in the blending tank, the „bottom phase" had increased to 2.9 %v (33 m^3), and had the composition as shown in Figure 6 (b). Again the composition of the methanol-rich „bottom phase" consists of several phases similar to those described above for Figure 6 (a). Changes in the upper fuel phase properties over the three weeks are given in Table 1 . They show a decrease in methanol content from 12.8 %v to 11.7 %v, and an increase in water content from 0.14 %w up to 0.20 %w. The result of these two changes was an increase in phase separation temperature from 0°C to 11°C. Both Reid Vapour Pressure (RVP) and percentage of fuel evaporated at 70° C (E 70) decreased slightly. Octane quality remained approximately constant.

TABLE 1 : INSPECTION PROPERTIES OF FUEL PHASE IN BLENDING TANK

PROPERTY \ TIME AFTER BLENDING		30 MIN.	2 DAYS	4 DAYS	7 DAYS	10 DAYS	14 DAYS	17 DAYS	21 DAYS
Methanol Content	%v	12.8	-	-	12.3	-	12.0	-	11.7
Water Content	%v (%w)	0.11 (0.14)	0.11 (0.14)	0.12 (0.15)	0.12 (0.15)	0.13 (0.17)	0.13 (0.17)	0.15 (0.19)	0.16 (0.20)
Phase Separation Temperature	°C	0	0	+1	+2.5	+6	+7	+10	+11
Density at 15°C	g/ml	-	0.775	-	-	0.775	-	0.775	0.775
RON		-	99.9	-	99.7	-	-	99.6	99.6
MON		-	85.6	-	85.3	-	-	85.4	85.2
RVP	mbar	-	880	-	-	840	-	840	850
E 70	%v	-	40	-	-	39	-	39	39

The increase in bottom phase (17.5 m^3) was due to the large amounts of water (4m^3) collected in the tank mainly from heavy rainfall (85 mm), together with high relative humidity recorded during the test period. The rate of increase of the „bottom phase" plotted against test period time is shown in Figure 7, together with the cumulative rainfall over the same period of time. It shows the proportional increase of „bottom phase" with increase in cumulative rainfall.

Some preliminary conclusions may be drawn from this part of the trial. It seems desirable that floating roof tanks should be avoided for blending/storing of fuels containing methanol. An improvement to the potential problem of phase separation would be the installation of secondary seals on the existing floating roof tanks. Such concepts are used in some areas for better control of vapour emissions. These secondary seals are reported (6) to substantially eliminate rainwater ingress. Another safer solution could be to retrofit existing floating roof tanks with light aluminium fixed roofs, and build all new tanks with floating roof combined with an additional fixed roof. The drying of tanks prior to blending (i.e., more intensive refinery housekeeping) would also be a requirement to ensure fuel stability.

While it may be necessary to use water solubilizing agents, such as isobutanol or tertiary butanol (most cost effective additives), especially at low ambient temperatures, e.g., in the winter seasons for reasons given later, they alone would not solve the problem of phase separation with floating roof tanks (unless used in impractical amounts), and may in fact compound the problem. The reasoning behind this latter comment is that in our investigation we found at the end of the three week test period, there was 7.5 m^3 (or 0.65 %v of tanks contents) water in the tank. This is a water content far in excess (0.4 %v) which theoretically could cause the separation from the bulk fuel over 200 m^3 of methanol-rich phase in the tank. The most probable reasons why complete separation does not take place are due in part to the relative stillness within the tank and hence slow reaction at the interface of the two phases, and the fact that rainwater enters the tank only at an area close to the wall. While some of the water is absorbed into the fuel, most drops („rains") through the fuel together with some methanol to the bottom of the tank. The inclusion of a solubilizing agent in practical amounts (1 %v to 4 %v) would give better stability, but at the same time would allow more water to be absorbed in the fuel compared with using methanol alone. This would result both in phase separation (albeit reduced) and a fuel saturated with water, allowing little flexibility with respect to controlling water ingress in the remaining distribution network.

4.2 Intermediate Storage

Before proceeding with the intermediate storage stage of the trial, the aqueous-methanol-rich phase was carefully removed from the bottom of the blending tank. This was to avoid further phase separation taking place which might have resulted from the mixing of both the upper and bottom phases when the blending tank was emptied and storage tank subsequently filled. Prior to being transported by rail truck to the storage depot, fresh methanol was blended into the fuel to replace that lost due to phase separation in the blending stage. This increased the methanol content from 11.7 %v to 14.6 %v.

4.2.1 Results and Discussion on Intermediate Storage Phase of Trial

The tank used for storage was a 1200 m^3 fixed roof tank. From the storage tank, 15 m^3 of fuel was loaded weekly, and transported by road tanker to the service station.

After one month of storage, the fuel began to separate into two phases due to a decrease in ambient temperature. The incidence of phase separation, together with the recorded tank temperatures during the 20 week period, are shown in Figure 8, which can be described in three separate stages. Initially no phase separation occurs until the tank temperature falls to about 8°C, this is followed by a steep decrease down to –8°C in tank temperature with a corresponding steep increase in amount of separated bottom phase. Finally, as the tank temperature rises and stabilizes between –5°C and 0°C, the calclulated amount of bottom phase also stabilizes around 11 %v.

Property changes compared with storage time in the upper fuel phase show (Table 2) both a decrease in methanol content, 14.6 %v to 9.9 %v, and in water content, 0.17 %v to 0.10 %v. The decrease in methanol content results in decreases both in percent of fuel evaporated at 70° C (E 70) and in RON. Within experimental error both Reid Vapour PRessure (RVP) and MON are uneffected, but there is a small decrease in the aromatic:non-aromatic ratio of the hydrocarbon component in the upper fuel phase.

The phase separation was mainly temperature induced and, as described above, occured at approximately 8°C at a water content in the fuel of 0.20 %v (0.26 %w). The increase in water content in the storage tank over the 20 week storage period was less than 0.02 %v. The reasons for the low water ingress being due mainly to the use of a fixed roof tank, and a combination of the relatively dry air during the second half of the test period when temperatures were sub zero and the fact that the water vapour entering the tank due to diurnal breathing is partially prevented by the presence of the vapour of the fuel from contacting the liquid surface. It might be possible to reduce the latter if use is made of desiccant breathers as practised in the storage of hygroscopic liquid chemicals and fuels which are susceptible to water contamination.

Unlike the composition of the „bottom phase" in the blending tank which consisted of several ıases, the bottom phase in the storage tank was in the main only one uniform phase due to the lower water concentration. Figure 9 compares the compositions of the fuel at the start of storage, and of the upper and bottom phases after 8 and 20 weeks in the storage tank.

TABLE 2 : INSPECTION PROPERTIES OF FUEL PHASE IN STORAGE TANK

STORAGE PERIOD PROPERTY		START	4 WEEKS	5 WEEKS	8 WEEKS	10 WEEKS	13 WEEKS	15 WEEKS	17 WEEKS	20 WEEKS
Density at 15°C	g/ml	0.775	0.775	0.775	0.776	0.776	0.776	0.775	0.775	0.774
RVP	mbar	860	880	880	860	840	850	830	840	840
E 70	%v	44	44	42.5	41	40	39	38	38	38
RON		100.0	99.6	99.6	99.5	99.0	98.6	98.9	98.6	98.6
MON		85.6	85.4	85.3	85.5	85.5	85.5	85.3	85.3	85.1
Methanol Content	%v	14.6	14.6	13.5	12.9	11.9	10.5	9.8	9.8	9.9
Water Content	%v (%w)	0.17 (0.22)	0.19 (0.25)	0.17 (0.22)	0.16 (0.20)	0.13 (0.17)	0.12 (0.15)	0.09 (0.12)	0.09 (0.12)	0.10 (0.13)
Non-Aromatic Content	%v	48.0	48.0	48.5	49.0	50.0	51.0	52.0	51.5	52.5
Aromatic Content	%v	37.0	37.0	37.5	37.5	38.0	38.5	38.0	39.0	37.5

The bottom phase had a RON of over 107 and a MON of 88. This was due mainly to the large amount of methanol in the phase (50–53 %v), and in part to an increase in the aromatic:non-aromatic ratio (0.94) of the hydrocarbon component compared with the originally blended fuel (0.77). Analysis showed also that there is an increase in the ratio of low molecular weight aromatic (most polar) content to high molecular weight aromatic contents in the bottom phase.

Laboratory tests have shown that partial substitution of methanol by isobutanol would have prevented phase separation in the storage tank. Figure 10 indicates the increased stability achieved with the fuel used in the trial, by the use of incremental amounts of isobutanol for varying temperatures and water contents. It can be seen that with a water content of 0.25 %w, 1 %v and 3 %v of isobutanol are required for ambients of –5°C (summer) and –25°C (winter) respectively, which can be regarded as those required for mid-European type climate.

4.3 Service Station

4.3.1 Underground Tanks

Three types of underground tanks are commonly used to store conventional gasoline prior to its dispension into vehicle. In this present trial two types were investigated; a double-walled steel tank, and a steel tank which had an inner lining of graphite filled epoxy resin for protection against corrosion. Both had a capacity of 15 m^3. Future tanks will be of the double-walled design.

A third type, used very infrequently in West Germany, is that of fibre-glass laminate. It was not investigated in this present study, but has been found(7) to be affected by fuels containing methanol. According to the manufacturers of the tank, however, the changes that occurred to the laminate were probably not beyond acceptable limits for underground tanks. A potentially serious problem indicated was that of a trend towards increased gum content in the fuels containing methanol and if wider use is to be made of this type of tank, then further investigation is required.

4.3.2 Results and Discussion on Service Station Underground Tanks

Approximately 250 m^3, in weekly 15 m^3 charges, were delivered to the dry steel underground tank in the service station. Due to the occurrence of phase separation in the storage tank, the prope of the delivered fuel varied widely, and as shown in Figure 11, these can be described in three distinct stages.

Initially, the quality of the fuel delivered (first 100 m^3) was similar to that produced in the blending tank prior to storage. The methanol content decreased from 14.6 %v to 12.9 %v due to phase separation in the storage tank, as described above. However, as the product take-off point (50 cm from tank bottom) in the storage tank was above the interface of the upper fuel and bottom phases, only the upper phase was delivered. As a result of the methanol content decrease, slight decreases in the percentage of fuel evaporated at 70°C (E 70) and 100° C (E 100) and octane quality (RON and MON) were observed (Figure 11 (b) and (c)).

As the amount of bottom phase in the storage tank increased above the product take-off point, a second stage resulted. At first inhomogeneous mixtures of the bottom and upper phase, followed by the bottom phase alone were delivered as indicated by the steep increase in methanol content, up to 52 %v, in Figure 11 (a). Due to the increase in methanol content, large increases resulted in the E 70, E 100, and RON values, and a small increase in the MON value (Figure 11 (b) and (c)).

Finally, as no further phase separation took place in the storage tank, and because the bottom phase was being gradually removed, a decrease in methanol content, down to 13.5 %v, occurred (Figure 11 (a)) as inhomogeneous mixtures of the upper and bottom phases were delivered. The decrease in methanol contents gave corresponding decreases in E 70, E 100, RON and MON (Figure 11 (b) and (c)).

The fuels containing high methanol contents with corresponding increases in air-fuel equivalence ratios (shown in Figure 11 (a) and set for $\lambda = 1$ for fuel containing 15 %v methanol), E 70, and E 100 values would probably lead to misfire, loss of power and driveability problems if used in vehicles.

To ensure that delivery of inhomogeneous mixtures of fuel, resulting from phase separation, does not take place, possible use could be made of floating product take-off lines. These take-off lines, already in use for some refinery products, only take product from the surface of the fuel.

The ingress of water, measured for each charge between the initial delivery in the first underground tank and that dispensed into the second unterground tank, was at the maximum 0.02 %v and in most cases below 0.01 %v.

4.3.3 Dispensing Pump

A currently manufactured gasoline pump was used to dispense 250 m^3 of fuel into a second underground tank. The methanol and water contents of the fuel dispensed ranged from 13 %v to 52 %v, and 0.20 % to 1.3 %v respectively. The following observations were made concerning the pump:

- At times when the pump was not dispensing, the fuel in the sight-glass became inhomogeneous due to phase separation, when ambient temperatures were below temperatures in the underground tank. The inhomogenity cleared immediately when fuel was dispensed.
- At the end of the trial the average errors between the indicated amount on the pump, and that accurately measured, were –0.40 % at a flow rate of 40 l/min., and –0.35 % at a flow rate of 5 l/min. These errors are within the manufacturers' tolerance levels for the pump.

Basically, the pump is suitable for dispensing fuels containing methanol. However, certain modifications to some construction materials will have to be made in order that they are compatible discussed below) with fuels containing methanol.

4.4 Compatibility of Construction Materials Used in Distribution Network

The solvent properties of conventional gasoline and methanol differ due to the latter being polar and being able to solubilize large quantities of water. It is important, therefore, when one is considering fuels containing methanol to investigate the compatibility with construction materials and equipment used in distribution networks that are designed for conventional gasolines.

4.4.1 Tanks

The blending tank, storage tank and one underground tank were of steel construction, and although cleaned prior to the trial, were all covered with a layer of rust. At the end of the trial period, the tanks appeared cleaner in the respect of less rust. This was particularly true for the floors and lower parts of the walls in both the blending and storage tank and for the wall in the underground tank. It is known (8) that water containing methanol readily dissolves rust films thus exposing the blank metal. Entry of air into the system then would accelerate the corrosion processes and decrease the life of the tanks. The use of corrosion inhibitors in the fuel wold minimize corrosion. However, at present little is known about effective inhibitors in hydrocarbon/methanol/water systems and if negative side effects in engine combustion systems would occur.

To protect these tanks it may be necessary to use protective paints, e.g., cement paints or stoving lacquers, or protective linings. One protective coating investigated was a graphite filled epoxy resin lining on an underground tank. This is already in use with conventional gasolines. For the six month duration of the trial, no adverse effects were found with this protective lining with fuels containing up to 52 % methanol. While the components for protective coatings are all very similar, the effeciency depends very much on the application of the coating on the tank wall.

4.4.2 Dispensing Pump

At the end of the trial, the dispensing pump was dismantled and on inspection showed the following:

- the fuel filter was starting to fall apart due to the adhesive, used in its construction, having disintegrated (Figure 12)
- at least eleven seals or sealing rings made of „Viton" A had swollen
- a corner return valve, also made out of „Viton" A, which is under mechanical stress had also swollen, but was not destroyed as in a previous investigation(9)
- two plastic components had lost their original shape

Other materials to replace the above components have to be found to make the pump compatible with fuels containing methanol.

4.5 Environmental Aspects

Environmental concerns over the use of methanol as an automotive fuel lie basically in three areas; spills and chronic leakages, evaporative emissions, and vehicle emissions. Discussion on vehicle emissions are outside the scope of this paper, however, as mentioned above the emission of oxygenated compounds must be fully investigated before final selection of an alternative fuel is made. Evaporative emissions occurring during the storage and distribution of methanol are reported (10) to be relatively low when used as a solvent or chemical. Methanol evaporative emissions would, however, increase when blended with volatile hydrocarbons due to the positive deviation from Raoult's Law resulting in a much higher vapour pressure compared with the individual vapour pressures of the hydrocarbon components and the methanol[4]. Investigations are required in this area which may result in the wider use of current control techniques used for hydrocarbon emissions, such as storage tanks with internal floating roofs, and the increased use of pipeline transfers. Correct operation of existing equipment must also be adhered to, particularly in respect of the elimination of splash loading of transport compartments, the maintenance of pressure settings on fixed roof tanks, and the avoidance of spillage and leakage.

Accidental spillage and chronic leakage of both methanol component and fuels containing methanol will occur, necessitating the assessment of current technology of cleansing mechanisms, and the development of techniques for the reclamation of contaminated areas. However, the potential threat to terrestrial and aquatic systems will be alleviated by the infinite solubility of mehtanol in water, its high rate of diffusion, and inherent biogradability.

Further thoughts have to be given to new problems arising out of the trial. For example, potential environmental hazards that could result if no change is made to current refinery procedure. At present ,,water bottoms" are discarded, periodically, in an environmental acceptable manner. However, with fuels containing methanol it will be necessary to subject the methanol-rich ,,bottoms" to further treatment, not only from an environmental point of view but also because the ,,bottoms" contain valuable energy/fuel components.

5. SUMMARY

(a) If we continue to burn oil at the present rate, future supplies of gasoline will have to be obtained from alternative sources other than crude oil. Synthetic hydrocarbons would appear to be the most acceptable from the standpoints of distributing, marketing, and vehicle design. However, in the short-term, economic technology for their production will not be available. During this time the production and utilization of alcohols from renewable sources as fuel components are considered to be rather attractive alternatives.

(b) Previous work has concentrated mainly on engine application, whereas detailed investigations concerning the infra-structure of distribution systems have not been carried out. Before final decisions on alternatives are made, it is necessary to fully understand possible limiting factors, such as the instability of fuels containing methanol in the presence of small amounts of water and/or low temperatures, and the resulting effect they will have on distribution network systems.

(c) There are three possible distributing systems for gasoline/methanol blends; blending of methanol with gasoline at the refinery, at the intermediate storage depot, or at the service stations. From both the economics and product quality guarantee it is best to blend the finished fuel in the refinery.

(d) An attempt has been made to highlight problem areas and suggest possible solutions when fuels containing methanol are distributed via the current distribution network, i.e., blending in the refinery, through intermediate storage, and finally to service station.

(e) From the trial it is generally concluded that current distribution systems would be unsuitable for fuels containing methanol. Some of the problems encountered and suggestions for possible solutions are as follows:

- with the floating roof blending tank water ingress at the rate of over 0.1 %v H_2O/week, mainly from rainwater, was recorded. This together with ,,water bottoms", present in the tank prior to blending, caused phase separation. An improvement to the potential problem of phase separation on existing tanks would be the installation of secondary seals. A safer solution would be the retrofitting of tanks with light aluminium fixed roofs. All new tanks could be built with combinations of floating and fixed roofs. More intensive refinery housekeeping would eliminate „water bottoms".

- with the fixed roof storage tank, phase separation occurred due to low ambient temperatures with fuels containing 0.2 %v water. The water ingress in the storage tank was only 0.02 %v over a 20 week storage period. It might be possible to reduce the latter by making use of desiccant breathers. Phase separation due to low ambient temperatures in fuels containing less than 0.2 %v water can be eliminated by the addition, up to 3 %v, of higher molecular weight alcohols, e.g., isobutanol, to the fuel.
- with the present configuration of the loading system from storage tanks to road tankers there might be a high risk of inhomogeneous fuel being delivered to service stations if phase separation has occurred in the storage tank. An inhomogenity gives rise to uncontrolled fuel quality which probably would result in driveability problems in vehicles. To ensure that delivery of inhomogeneous mixtures of fuel does not take place, possible use could be made of floating product take-off lines.
- water ingress in the service station underground tank was, in most cases, below 0.01 %v H_2O for each charge delivered and in cases in which a homogeneous fuel was delivered no phase separation took place.
- no adverse compatibility effects were found with an underground tank having a protective lining (graphite filled epoxy resin) with fuels containing up to 52 %v methanol.
- basically the forecourt pump used in the trial is suitable for dispensing fuels containing methanol. However, certain modifications/replacements to some materials, e.g., filter, „Viton" A seals and sealing rings, and some plastics, will have to be carried out in order that they are compatible.

(f) The findings from this trial give an excellent basis for a larger distribution/handling trial involving 1500 vehicles to be sponsored by the West German Government over the next four years, as part of their programme on „Alternative Energies for Road Vehicles". Investigations have to be aimed to eliminate phase separation by incorporating some of the above suggestions, and to quantify, in more detail, the implication of fuels containing methanol on the transport systems, i.e., marine, rail, and road.

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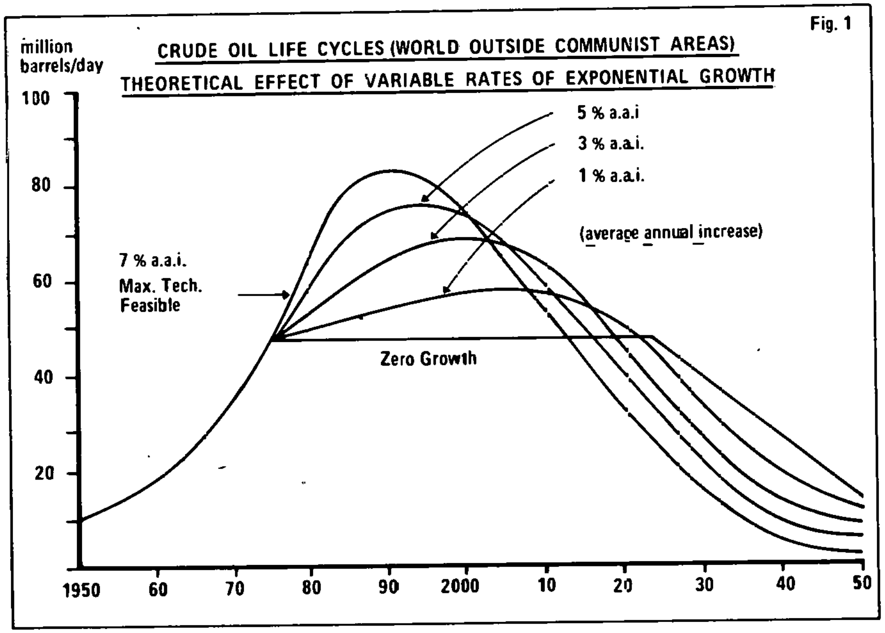


Fig. 1

CRUDE OIL LIFE CYCLES (WORLD OUTSIDE COMMUNIST AREAS)
THEORETICAL EFFECT OF VARIABLE RATES OF EXPONENTIAL GROWTH

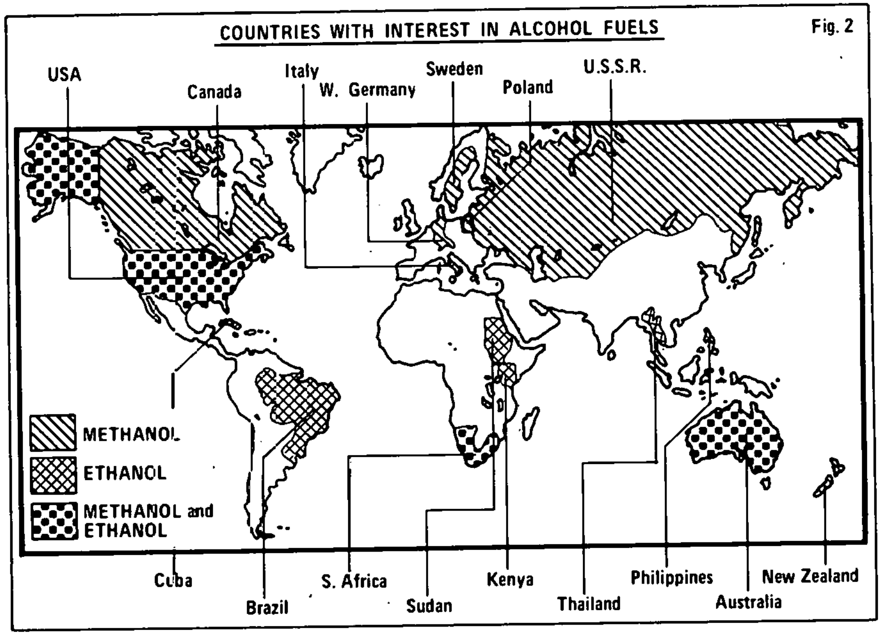


Fig. 2

COUNTRIES WITH INTEREST IN ALCOHOL FUELS

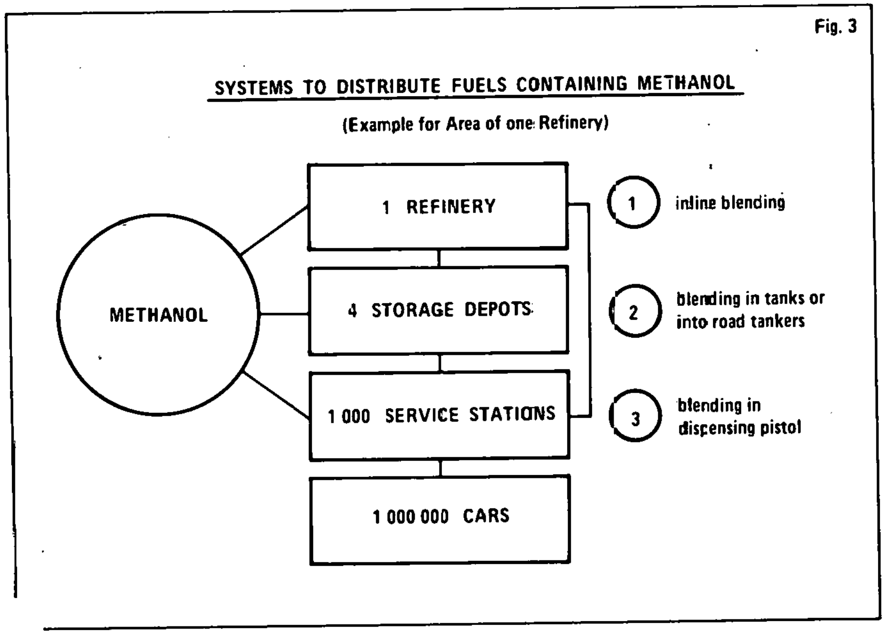


Fig. 3

SYSTEMS TO DISTRIBUTE FUELS CONTAINING METHANOL

(Example for Area of one Refinery)

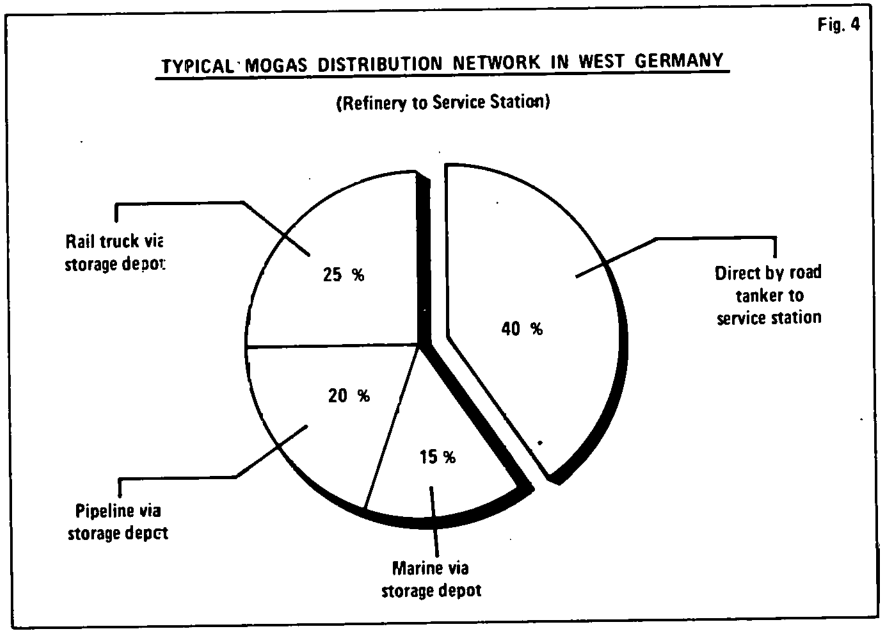


Fig. 4

TYPICAL MOGAS DISTRIBUTION NETWORK IN WEST GERMANY

(Refinery to Service Station)

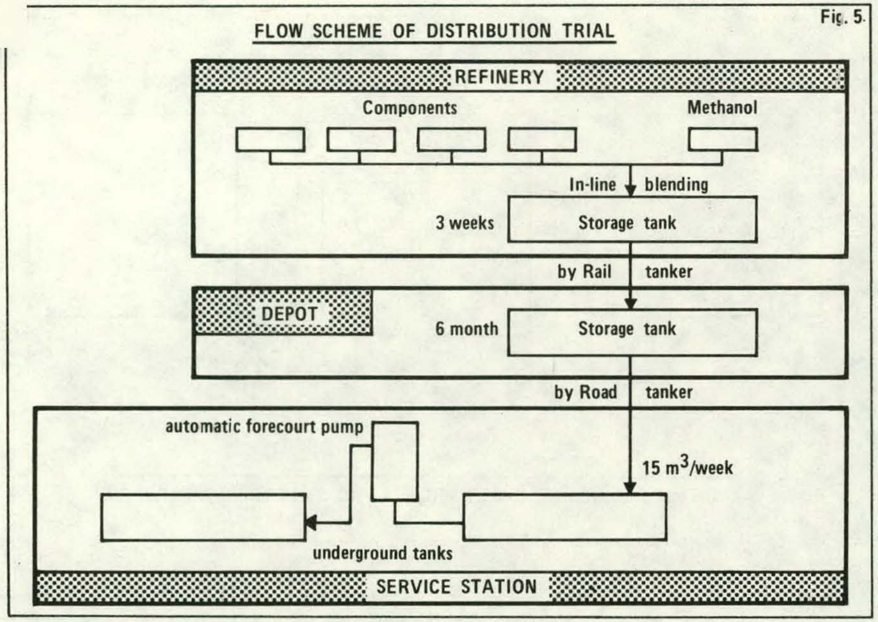


Fig. 5

FLOW SCHEME OF DISTRIBUTION TRIAL

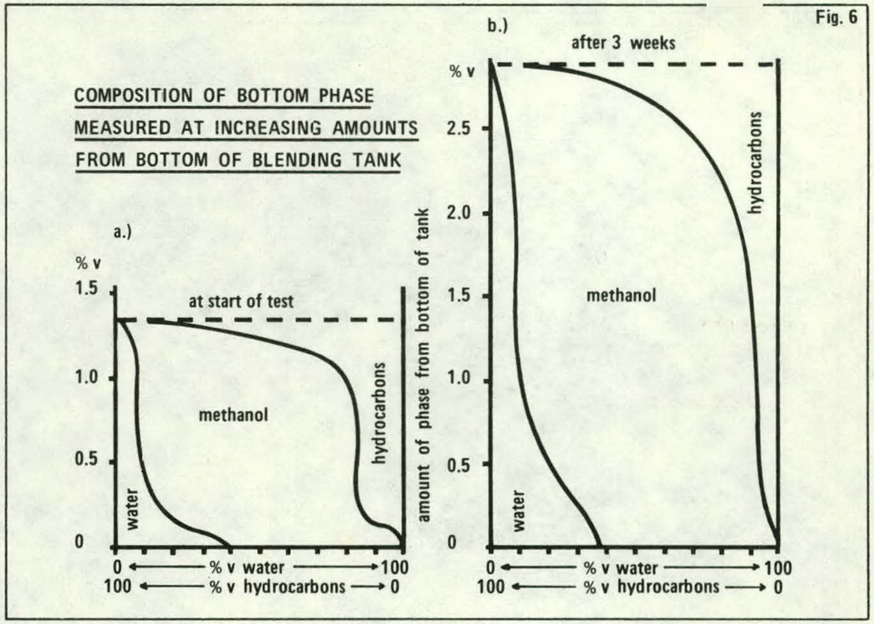


Fig. 6

COMPOSITION OF BOTTOM PHASE MEASURED AT INCREASING AMOUNTS FROM BOTTOM OF BLENDING TANK

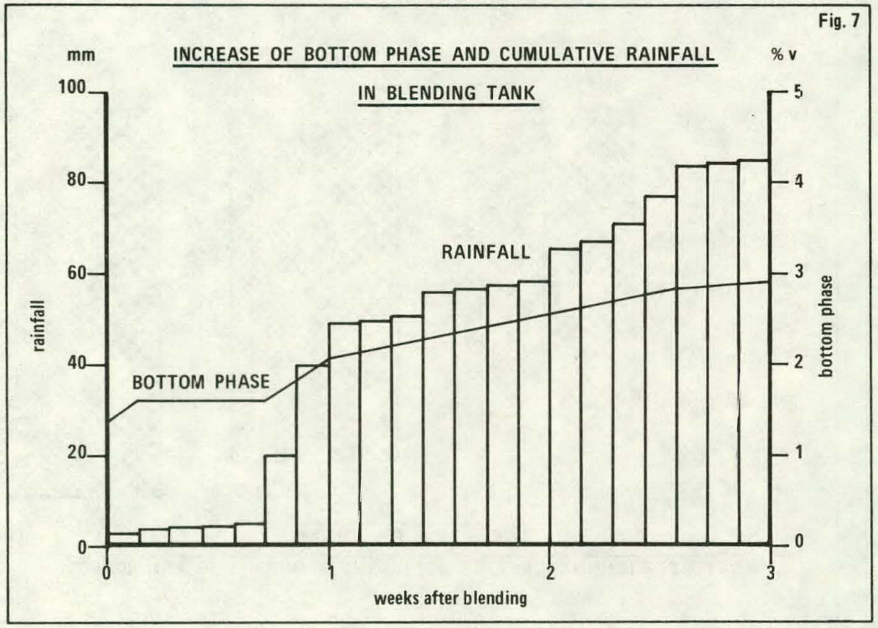


Fig. 7

INCREASE OF BOTTOM PHASE AND CUMULATIVE RAINFALL IN BLENDING TANK

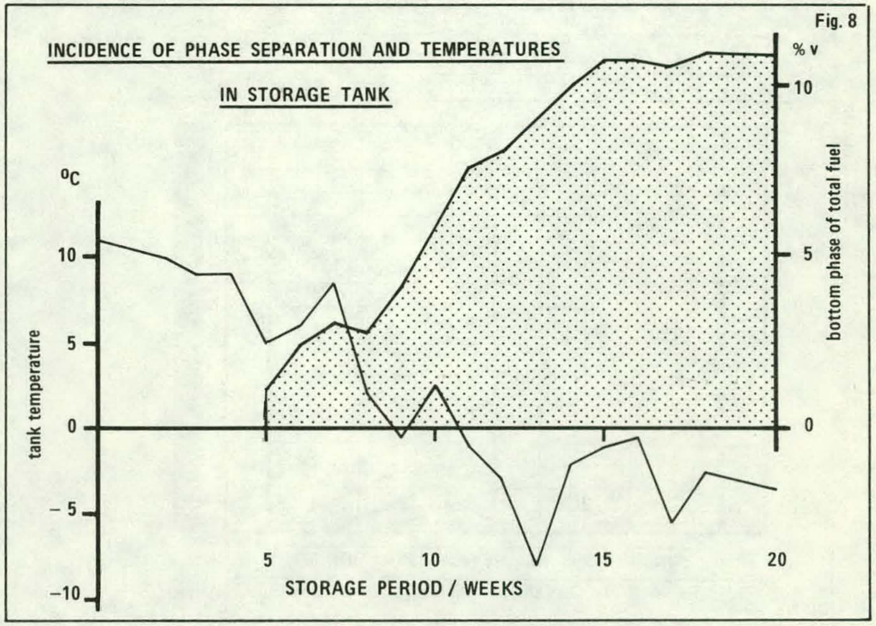


Fig. 8

INCIDENCE OF PHASE SEPARATION AND TEMPERATURES IN STORAGE TANK

Fig. 9

COMPOSITION OF FUEL AT START, AFTER 8 WEEKS, AND AFTER 20 WEEKS IN STORAGE TANK (% V)

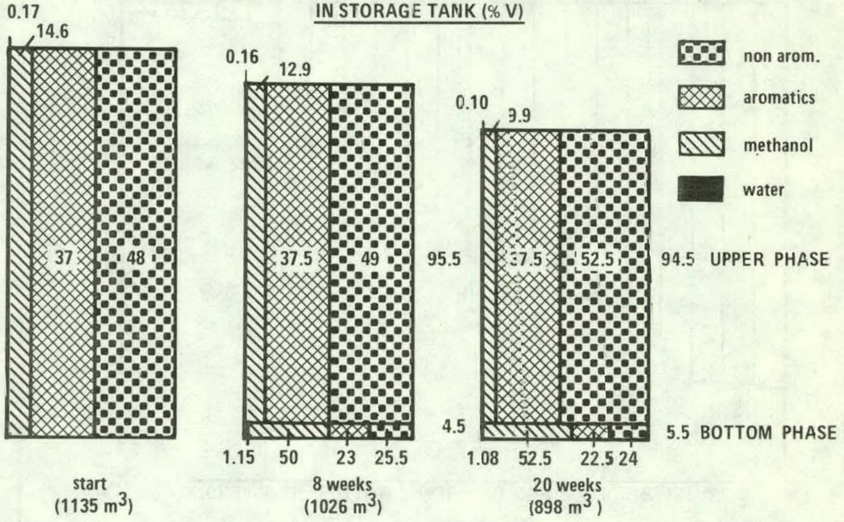


Fig. 10

EFFECT OF SUBSTITUTING ISOBUTÀNOL FOR METHANOL ON THE PHASE SEPARATION TEMPERATURE

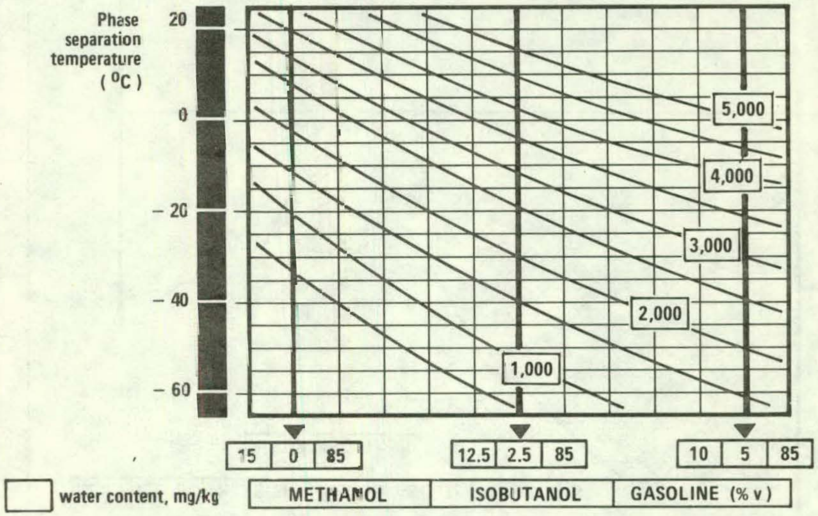


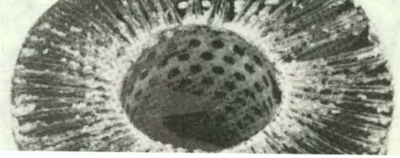
Fig. 11

INSPECTION PROPERTIES OF FUEL DELIVERED TO SERVICE STATION

Fig. 12

DISPENSING PUMP FILTER

(Methanol fuel attack on adhesive material)



ETHANOL FROM MUNICIPAL CELLULOSIC WASTES

by

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INTRODUCTION AND BACKGROUND

This paper addresses the use of municipal cellulosic wastes as a feedstock for producing ethanol fuels, and describes the application of enzymatic hydrolysis technology for their production. The concept incorporates recent process technology developments within the framework of an existing industry familiar with large-scale ethanol fermentation (the brewing industry). Preliminary indications are that the cost of producing ethanol via enzymatic hydrolysis in an existing plant with minimal facility modifications (low capital investment) can be significantly less than that of ethanol from grain fermentation.

Ethanol is an alcohol fuel that is among the non-petroleum fuel options which can be derived from renewable resources. Several studies have examined the role of alcohol fuels as replacements for or extenders of today's petroleum liquids, the status of alcohol production and utilization technologies, and the status of existing and planned activities by both Government and industry. The Consensus of these study efforts is that alcohols are a viable near-term liquid fuel alternative, particularly as automotive fuels. Furthermore, the combination of renewable (biomass and wastes) and more abundant resource materials (such as coal) can provide the base to supply all the projected U. S. liquid fuels needs for the year 2000 and probably for some time beyond. (1)** Alcohol fuels from biomass and municipal solid wastes can satisfy nearly 40% of the U. S. liquid fuels energy demand projected for the year 2000. (1)

The technology of producing ethanol via fermentation is well known and widely practiced. In addition, over the last several years, significant gains have been made in the state of the art of alcohol use in spark ignition engines. (2) Beginning in Fiscal Year 1979, the U.S. Department of Energy will initiate vehicle fleet testing of alcohol/gasoline blends and will later expand this project to include fleet tests of neat alcohol fuels. (3) It is envisioned that, by 1985, the majority of technical work (relative to automotive use) will be sufficiently completed for industry to initiate commercialization. A mixture of 90% unleaded gasoline and 10% ethyl alcohol is being marketed in several midwestern states (including Nebraska, Illinois and Iowa). State and Federal tax credits have permitted ethanol/gasoline blends to be cost-competitive with some of today's unleaded gasolines. All of the above indicate a growing National interest, both technically and at the "grass roots" level, in the use of ethanol as a viable liquid fuel.

In recent times, the chief deterrents to the widespread use of ethanol as a fuel have been economics and the availability of significant alcohol fuel quantities. Costs are principally affected by the price of resource materials, plant facilities, and transportation of feedstocks. Alcohol availability is a function of production plant capacity, which is presently sufficient to satisfy beverage and industrial use demands (over 80% of industrial ethanol is derived from petroleum products through ethylene hydration). Therefore, even if ethanol's economics were competitive, plant capacity (to produce ethanol from renewable

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--Numbers in parentheses designate references at the end of the paper.

resources) would have to be significantly expanded to satisfy even 1% of the Nation's current automotive fuel demand. (4)

Cellulose is one of the world's most abundant organic materials which can be used as a source of food, fuel and chemicals. The net worldwide production of cellulose is estimated at over one hundred billion tons per year. (5) From one ton of waste paper, about one-half ton of glucose can be produced and subsequently fermented to 78 gallons of ethanol. Conversion of cellulose to glucose can be accomplished by either acid hydrolysis or by enzymatic hydrolysis. Among the advantages of enzymatic hydrolysis is that the process takes place at moderate conditions so that the glucose yield is high and directly related to the weight of the cellulose used. Glucose syrups produced enzymatically are fairly pure and constant in composition.

The concept discussed in the remainder of this paper describes a means for:

1. Producing competitively priced ethanol from urban refuse,
2. Placing a laboratory-level-proven ethanol production technology into commercial practice within the brewing industry, an industry that is already familiar with the technology of enzyme and large-volume ethanol production,
3. Helping to solve a national problem of urban waste disposal,
4. Incorporating an in-place, nationally-dispersed network of plant facilities for ethanol production, and
5. Taking advantage of the consolidation of brewing industry firms and production facilities which has led to an increase in idle, large-scale fermentation plants.

While a detailed engineering assessment has not been completed to date, preliminary findings and analyses (presented herein) indicate that the overall concept is feasible and warrants further study. As of this writing, the idle brewery alluded to in this paper has not undergone any modification or renovation to produce ethanol per the proposed concept.

APPLICATIONS FOR THE ETHANOL PRODUCT

Two principal market applications have been considered for the ethanol product: the industrial sector and the fuels market (as a blending agent for automotive gasoline).

Industrial Applications

About 80% of the industrial ethanol is derived synthetically from petroleum via ethylene hydration. Production of synthetic ethanol in 1978 was about 1.5 billion lbs. (227 million gallons), yet the industry capacity is about 2.07 billion lbs. (307 million gallons). Over the last ten years, overall ethanol production has decreased by 38%, but the trend is starting to reverse. Producers project ethanol production to advance at about 1% to 3% per year in the next five years. Generally, ethanol is divided into two basic products: 190° proof (95%) ethanol and 200° proof, or anhydrous ethanol. The anhydrous variety amounts to about 40% of synthetic ethanol production and is used for aerosols and in some chemical intermediate products in which the presence of water would be detrimental. Because of its purer nature, 200° proof ethanol commands a price of about 10 cents per gallon more than 190° proof ethanol (currently selling at about $1.20 per gallon) which is used in solvents, inks, flavors, fragrances and other industrial applications. (6)

Entry into the industrial market would be a function of the cost competitiveness of the ethanol-from-cellulosic-waste concept; thus market price/demand relationships would need to be closely monitored on an ongoing basis.

Automotive Fuel Applications

Fuels based on alcohols, neat or as blends with gasoline, have been identified as being among the likeliest candidates for the replacement of petroleum-based automotive fuels. Because of their potential utility in transitional and even emergency alternative fuel applications, alcohol fuels may be called upon to power a substantial number of vehicles configured to reflect today's internal combustion engine technology and the evolutionary developments which follow. In the context of such applications, the requirement is first for an acceptable fuel, and secondarily for a better fuel than current transportation liquids. Regulatory standards for environmental acceptability and energy conservation must be satisfied and so must current commercial and public standards of highway vehicle utility, economy and performance. With respect to these latter requirements, the particular problems characterizing the use of alcohols in current engines arise from the markedly different physical and chemical properties of the alcohols, relative to gasoline.

A recent alcohol fuels assessment determined that for alcohol blends (with gasoline) of up to about 10% there were no significant advantages or disadvantages in fuel economy or exhaust emissions, however, numerous researchers have proven the octane benefit provided by the addition of alcohol to gasoline. (2) A 10% (volume) blend of ethanol in unleaded regular gasoline is being offered by a number of midwestern (Nebraska, Illinois, Iowa and others) fuel service outlets, and demand for the blend appears to be strong. With rising gasoline prices and alcohol blend fuel tax credits offered at both the Federal (4 cents per gallon) and state levels, the price gap between gasoline and current ethanol/gasoline blends appears to be closing.

The Federally mandated phasedown of lead alkyl octane improvers and ban on the use of methylcyclopentadienyl manganese tricarbonyl (MMT) as an additive have put pressure on petroleum refiners to increase the use of aromatics in gasoline. These supply pressures will continue unless the U.S. economy slows so much that sales of gasoline are affected. Increasingly, refiners are turning to the use of benzene-containing catalytic reformate as the major source of high-octane material for gasoline. The market for such blending agents is huge since about 35% of all motor gasoline sold in the U.S. is unleaded and this percentage is increasing rapidly because newer automobiles use unleaded gasoline. The octane value of benzene is about the same as that of ethanol (106 Research Octane Number); the current price of benzene is about 85 cents per gallon and is expected to rise with increased demand. (7, 8) Thus as the price of benzene approaches that of ethanol, the economics of ethanol/gasoline blends become more favorable.

In FY 1979, the U.S. Department of Energy intends to initiate fleet testing of alcohol/gasoline blends in order to prove the practicability and reliability of blends as a transition strategy to alcohol fuels or as a progenitor of alcohol/synfuel blends. (3) This test project is expected to be followed subsequently by similar fleet tests of neat alcohols. Firm details (relative to fleet size, selection and location) are still in the planning stage, but it is anticipated that to the extent possible, alcohols (including ethanol) from non-petroleum-based resources will be sought. The fleet test project is planned to span five years and be conducted in a manner that represents the range of typical U.S. climate/terrain. Even though fleet size and selection have not been initiated as yet, by the time the project is completed, several hundred thousand gallons of ethanol (for blends) could be consumed.

CHARACTERISTICS OF THE BREWING INDUSTRY

The uniqueness of the concept described by this paper stems from:

1. More broadly, the opportunity to utilize excess capacity in nationally-distributed brewing facilities for the production of ethyl alcohol, and
2. More specifically, the coupling of a readily available waste cellulosic feedstock (obtained as a product from a municipal waste resource reclamation facility) with minimal modifications to an idle brewery for ethanol production.

Pertinent characteristics of the brewing industry (item 1, above) will be discussed in this section while more explicit details on item 2 are presented elsewhere in this paper.

In 1978, the brewing industry sold 162.4 million barrels of beer and had a nameplate capacity of about 200 million barrels thus, about 37.6 million barrels of capacity were not utilized.(9) Additionally, beer brewing is a seasonal industry with peak months of about 10% of capacity. About 40 million barrels additional could be made available from off-peak production capacity for a total additional capacity of 77.6 million barrels (for the year 1978).

With a conversion factor of between 5 and 15 gallons of ethanol per barrel of beer, the total ethanol potential that could be supplied by the brewing industry, without impacting current beer production, is between 388 million and 1.16 billion gallons. This is 26% to 280% more than the entire capacity of the synthetic ethanol industry and equal to about 0.4% to 1.2% of current annual U.S. gasoline consumption (about 100 billion gallons per year). Viewed in another way, ethanol produced from excess brewing industry capacity could satisfy 4% to 12% of a national market for a 10% ethanol/gasoline blend.

The brewing industry is widespread and well distributed throughout the United States with operating breweries in 32 of the 50 states. Table 1 is a listing of all U.S. breweries that are authorized to operate by the U.S. Treasury Department (Bureau of Alcohol, Tobacco and Firearms) as of June, 1978. (10) This list does not include a relatively small number of breweries operated for experimental, research or training purposes. Note that there are 11 breweries which have become idled (thus exemplifying the current excess-capacity situation), mostly for reasons of economy. This is the result of an industry trend toward consolidation.

ETHANOL FROM THE ENZYMATIC HYDROLYSIS OF CELLULOSIC WASTES

Perhaps the simplest way to describe the enzymatic hydrolysis process is to visualize a starch molecule as a long string of connected sugar molecules and the enzyme as a scissors that, starting from one end of the string, successively cuts off one sugar molecule at a time until the string is gone. Similarly, but in a more complex fashion and with different sugars, cellulose is a long-chain polysaccharide that can be enzymatically reduced to mostly glucose sugar via cellulase (cellulase is the enzyme which converts cellulose to sugars). Once the simple sugars are produced, they can be fermented (by yeasts) in much the same way that grains and fruits are fermented to produce alcoholic beverages. A distillation column is then used to separate high-purity ethanol from the fermentation liquid.

Over the last several years, significant technological advancements have been made in the enzymatic hydrolysis process. In particular, the U.S. Department of Energy's Fuels From Biomass Program and the National Science Foundation sponsor major projects in enzymatic process technology improvements. Notable accomplishments have resulted from work conducted by the U.S. Army Natick R&D Center. Specifically, scientists at the Natick Laboratory have developed an enzymatic process which is based on the use of cellulase derived from mutant strains of the fungus *Trichoderma viride*. A pre-pilot plant unit with a capacity of approximately 125 lbs. per day is in operation. Recent advances in enzyme production, saccharification (conversion to sugars) and materials pretreatment have brought this particular process nearly to the stage of commercial application. More recently, the Laboratory is developing a process for production of large amounts of a cellulase enzyme from the fungus *Trichoderma reesei*.

Application To An Existing Brewery

In August, 1978, for reasons of economy, the Highlandtown (Baltimore City, Maryland) Plant of Carling National Breweries was consolidated into Carling National's Beltway Plant in Baltimore County. The Highlandtown Plant still contains fermentation, packaging and warehousing facilities which have remained essentially undisturbed. With modifications that would require basically the installation of enzyme production and ethanol distillation apparatus, the plant could be converted to ethanol production at a fraction of the expense required for a completely new plant. The remainder of this paper presents a preliminary evaluation of a concept which incorporates the use of enzymatic hydrolysis (on a cellulosic feedstock produced from municipal wastes generated in the metropolitan Baltimore area) in the idle Carling National plant to produce a fermentable product which can be distilled to anhydrous ethanol. The enzymatic process envisioned is based on the relatively new cellulase-producing fungus *Trichoderma reesei* developed by the U.S. Army Natick Laboratory.

Source and Characteristics of Cellulosic Feedstock

Feedstock for the envisioned concept would consist of the cellulosic fraction from municipal solid wastes. Currently, about 4,200 tons of refuse is generated daily in the metropolitan Baltimore area. This amount is nearly ten times that needed to supply a converted brewery producing five million gallons per year of anhydrous ethyl alcohol.

A resource reclamation facility currently operating in suburban Baltimore County (near Texas, Maryland) has the capability of processing about 1,500 tons of refuse per day to about 1,125 tons of highly cellulosic material per day. At this facility, the incoming raw waste is shredded and mechanically separated into various fractions--ferrous metals, other metals, residue, and a highly cellulosic material commonly referred to as RDF (refuse derived fuel). It is the cellulosic material or RDF that would serve as the ethanol feedstock for the proposed plant conversion concept. Characteristics of the RDF product are as follows: (11,12)

Method of Production: Mechanically separated, air classified and trommeled
Fraction of RDF to Waste Input: 70% to 75% (by weight)
Moisture Content: 10% to 30% (by weight)
Sulfur Content: ~0.2% (by weight)

Plastic and Other Inert Materials: 3.4% or less (by weight)
Ash Content: 6% to 12% (by weight)
Heating Value (wet): 6,500 Btu per lb.
Heating Value (dry): 8,000 Btu per lb. (calculated)

RDF could be supplied in the form of "fluff" (loose, unpressed material) or as pellets about one-inch diameter by two-to-three inches long. The fluff form is more amenable to hydrolysis. For several reasons, RDF from the Baltimore County facility appears to be a logical choice of feedstock:

1. Transportation distance is minimal (about 10-12 miles) between the Baltimore County facility and the idle brewery in Baltimore City.
2. The resource reclamation facility has the capability of supplying all the feedstock requirements for a 5 million gallon per year ethanol plant.
3. The RDF output is a very suitable material for the envisioned process.

In addition to the above, it is contemplated that, in the near future, at least one additional resource reclamation facility may be built in the Baltimore metro area, thus providing an additional source of feedstock supply (if needed).

PLANT CONVERSION REQUIREMENTS AND PROCESS DESCRIPTION

As mentioned previously, minimal modifications are required to convert an existing brewery to the production of ethanol from municipal cellulosic wastes. These modifications include the addition of enzyme production, cellulose pretreatment, hydrolysis processing, ethanol distillation and certain waste recovery equipment. Fermentation, materials handling, and storage equipment are essentially in place, as are portions of waste recovery equipment, all utility supplies (steam, electricity, water) and the physical housing structure. Labor is available and training requirements are minimal since brewing personnel are familiar with large-scale ethanol fermentation.

Figure 1 illustrates the envisioned process by which ethanol can be produced from muncipal cellulosic wastes. Conversion of ethanol from cellulose begins with the production of the enzyme. This is accomplished by obtaining a very small amount of the Trichoderma fungus and growing it in a culture medium containing shredded cellulose (most probably from the same source of cellulosic material that will be hydrolyzed) and various nutrients.

As the fungus grows, it secretes cellulase enzyme into the medium. Following its growth, the culture is filtered to remove the filament-like fungus (mycelium). The filtrate, or broth, contains the enyzme that is used in the saccharification (hydrolysis) reactor. After adjusting the acidity of the enzyme broth to the correct pH, pretreated cellulosic material is introduced into the enzyme solution and allowed to react with the cellulase to produce glucose. Saccharification takes place at atmospheric pressure and at a temperature of about 50°C.

The rate and extent of hydrolysis will depend on the particular composition of the cellulosic material and the type of pretreatment employed. For the cellulosic material (RDF) envisioned, pretreatment will entail removal of non-cellulosic "contaminants" (plastics, ash, etc.) to the extent that it is practical, followed by the addition of water to form a mash.

A glucose syrup of about 10% concentration is the desired product of the hydrolysis process. In addition, byproducts containing unreacted cellulose and enzyme are produced (sludge). These byproducts could be recycled back to the reaction vessel to the extent possible, or could be used directly as fuel for process steam generation, but their fuel values will have to be established because they contain a large quantity of water. Since the idle Carling brewery contains excess fermentation capacity (beyond that which is needed to produce 5 million gallons of ethanol per year), it is also possible to utilize this excess capacity for digesting the byproduct sludge (via anaerobic methanogenic bacteria) to produce a medium Btu gas which in turn can be used for generating process steam.

After the crude glucose syrup (from the hydrolysis process) is filtered, yeast is added so that fermentation can take place. This part of the process yields carbon dioxide, spent yeast, and a fermented liquid (called beer) which contains about 4% (by volume) ethyl alcohol. Carbon dioxide can be removed, compressed and sold as a byproduct through existing market channels. A portion of the spent yeast product can be recovered and recycled. The non-recoverable portion contains protein which is valuable as an animal feed ingredient.

The 4% alcohol product is fed to a beer still for the first distillation step in the concentration of the alcohol. The overhead, containing about 50% to 60% ethanol in water with other volatiles is condensed while the bottom residue, known as stillage or slops, can be utilized as livestock feed as it contains proteins, residual sugars and vitamins. In the Baltimore area, a market exists for the wet stillage product, thereby eliminating the costly and energy-consuming process of stillage drying. It should be noted, however, that in the case of sugar solutions produced via enzymatic hydrolysis, there may be some constituents that make this stillage product unacceptable for feed, therefore, no facilities for the production of distiller's feed from the stillage have been included in the concept design.

The dilute alcohol solution passes to another distillation column, termed an aldehyde or purifying column, where aldehydes and other low-boiling inpurities are removed as overhead products. The column bottoms are primarily fusel oil (mainly amyl alcohols). The aldehydes and fusel oil may be purified and sold for industrial use but it may be more economical to burn them in the plant boilers.

The effluent from the middle of the aldehyde column is sent to a rectifying column where the alcohol solution is concentrated to about 95% (volume) ethanol. The low-boiling overheads contain some residual aldehydes in alcohol and are returned to the aldehyde column. Some fusel oil is removed further down the column and combined with the fusel oil from the aldehyde column. Water is discharged from the bottom.

The usual method for producing anhydrous ethanol from a 95% (volume) solution is to add a third component which forms an azeotrope with one or both of the original constituents. Benzene has generally been used for dehydrating ethanol in this manner but other compounds (e.g., ethers, hexane) can be used as well. Although only one additional distillation column is needed to obtain the dehydrated ethanol product, two or more columns plus auxiliary equipment are required to recycle and recover the benzene and aqueous alcohol. (13)

Since the anhydrous ethanol product will not be used for beverage purposes, it must be denatured in accordance with procedures/formulas acceptable to the U.S. Treasury Department's Bureau of Alcohol, Tobacco and Firearms. While the BATF currently authorizes six formulas which may be used for ethanol fuel purposes (14), it is important to note that the selection of denaturants must properly consider the effect of the denaturant on fuel properties and combustion products. The DOE's Alternative Fuels Utilization Program is currently sponsoring research that will investigate the most appropriate denaturants for fuel-grade ethanol. (15) Accordingly, results of this work would serve as the basis for selecting denaturants to be used in a fuel-grade ethanol product.

Material Flows, Energy Use and Economics

Figure 1 also presents the approximate input/output material flows required to produce five million gallons per year of anhydrous ethanol in a batch-type process operating at about 7,920 hours per year. The input feedstock requirement is 262 million lbs. of RDF per year, of which 6.6% is needed for enzyme production. Enzyme production is estimated to occur at a rate of 100 IU (International Units) per liter per hour. Hydrolysis conversion efficiency is taken as 45% (i.e., 45% of the cellulose is converted to fermentable sugars). Fermentation of sugars to ethanol is assumed to occur at an efficiency of 40%. All yearly flow values noted on Figure 1 are approximate and those for the enzyme production and hydrolysis steps were developed from several sources, principally, references 16, 17, and 18.

At this point, it is worthwhile to mention several comments about process design characteristics. For example, the hydrolysis step is based on an input cellulose/water slurry containing 30% cellulose solids. This, combined with the noted cellulase enzyme input is expected to permit cellulose hydrolysis in a cycle period of 24 hours. The energy requirements for pumping a 30% solids slurry are a function of several factors including solids concentration and pumping distance. While pumping/transfer equipment exists for this kind of high-solid content material (e.g., wood pulp and coal slurry applications), a detailed engineering analysis of equipment sizing, energy use and layout is required.

Several studies have examined the potential for utilizing the hydrolysis sludge effluent directly as a fuel for process heat. Process research to date has shown that this effluent contains a minimum of 50% water, thus its energy value (for direct combustion) is probably on the order of 5,000 Btu per lb. at best. Separation of the water from the sludge would be needed prior to any use as a fuel. Note that the process described in Figure 1 illustrates the application of anaerobic digestion (of the hydrolysis sludge effluent) and subsequent generation of medium Btu gas. This gas could supply about 30% of the fuel needed for process steam. It should be noted, however, that residence times for digestion are on the order of 6 to 10 days (as opposed to a 24-hour hydrolysis cycle), thus materials flow considerations and any need for sludge "storage" may outweigh the advantages of this concept. More detailed engineering analysis is required.

Although several studies have identified the potential cost-saving opportunities offered by incorporating recycle of process materials (enzyme, process water, etc.), no recycle steps have been shown on the process flow chart. The reason for this is because the trade-off between the reduction in materials cost and the increase in process complexity and equipment costs has not been fully assessed. Analysis of recycle systems is an area in need of hardware-oriented R&D.

Estimated process utility requirements are summarized below:

Steam - 76,000 lb. per hour
Cooling Water - 3,411 gal. per minute
Refrigeration - 620 tons
Process Water - 741 gal. per minute
Electricity - 4,982 kW

From the above, the net process thermal efficiency is estimated to be:

$$\frac{5 \text{ X } 10^6 \text{ gal/yr X } 84{,}200 \text{ Btu/gal}}{262 \text{ X } 10^6 \text{ lb/yr X } 6{,}500 \text{ Btu/lb.} + 600 \text{ X } 10^9 \text{ Btu/yr} + 135 \text{ X } 10^9 \text{ Btu/yr}} = 17\%$$

Gross (output ethanol to input RDF only) process thermal efficiency is estimated to be about 25%. Including the generation of medium Btu gas increases the net process efficiency to about 19%.

Estimated capital, operating and ethanol production costs are summarized below. Profit is not included.

Fixed Costs		
Capital Investment (Equipment)	$7,000,000	
Working Capital	500,000	
TOTAL CAPITAL	$7,500,000	
Annual Costs		
RDF Feedstock ($15/ton, delivered)	$1,965,000	(39¢/gal.)
*Plant Operating Expenses and Other Materials Costs	$3,200,000	(64¢/gal.)
Sales, General & Administrative	300,000	(6¢/gal.)
TOTAL ANNUAL COST	$5,465,000	($1.09/gal)

*Includes all utility, maintenance, labor, materials (other than feedstock), and equipment amortization/depreciation costs.

From Carling National's experience, it has been found that the cost of producing salable byproducts (CO_2, distillers feed, etc.) is equal to or less than the income generated by their sale. Thus, the above cost estimate has conservatively estimated byproduct production costs to equal sales revenues.

SUMMARY AND CONCLUSIONS

This paper has presented a preliminary analysis of the use of municipal cellulosic wastes in conjunction with the application of enzymatic hydrolysis technology for the production of ethanol. The envisioned concept appears feasible, but more thorough engineering analysis is required before firm process details can be established. The cost of producing ethanol in a converted idle brewery was shown to be competitive with synthetically-derived ethanol from petroleum. The per-gallon-of-ethanol feedstock cost of 39¢ is significantly less than that of corn (about 90¢ per gallon) as used in several fermentation ethanol plants. The close promixity of cellulosic feedstock supply to the idle Carling brewery offers a significant cost advantage, as does the availability of the plant and associated fermentation equipment. The nationally dispersed system of breweries (and its excess capacity) and its distribution in urban/surburban waste generating areas may offer a means of developing a nationwide ethanol fuel supply. The complexity or practicality of utilizing this excess beer-producing capacity have not been addressed.

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LOCATION	COMPANY	BREWERY OPERATING	 IDLE	CAPACITY TO CLOSEST MILLION BBL/YEAR
AK: Anchorage	Prinz Brau	✓		*
AZ: Phoenix	Carling National	✓		*
CA: San Francisco	Anchor	✓		*
Los Angeles	Anheuser-Busch	✓		4
Fairfield	Anheuser-Busch	✓		3
San Francisco	General		✓	1
Azusa	Miller	✓		2
Sonoma	New Albion	✓		*
Los Angeles	Pabst	✓		1
Los Angeles	Schlitz	✓		3
CO: Golden	Coors	✓		1.5
CT: New Haven	Hull	✓		*
FL: Jacksonville	Anheuser-Busch	✓		5
Tampa	Anheuser-Busch	✓		2
Auburndale	Duncan	✓		*
Tampa	Schlitz	✓		1
GA: Pabst	Pabst	✓		5
HI: Aiea	Schlitz	✓		*
Honolulu	Honolulu	✓		*
IL: Belleville	Carling National	✓		1
Chicago	Peter Hand		✓	1
Peoria	Pabst	✓		3
IN: Fort Wayne	Falstaff	✓		1
Evansville	Heileman	✓		2
IA: Dubuque	Pickett	✓		*
KY: Louisville	Falls City		✓	*
Newport	Heileman	✓		1
LA: New Orleans	Dixie	✓		*
New Orleans	Falstaff	✓		1
MD: Baltimore	Carling National	✓		1
Baltimore	Carling National		✓	2
Baltimore	Schaefer		✓	1
MI: Frankenmuth	Carling National	✓		1
Frankenmuth	Geyer	✓		*
Detroit	Stroh	✓		6
MN: St. Paul	Heileman	✓		1
Cold Spring	Cold Spring	✓		*
St. Paul	Olympia	✓		3
New Ulm	Schell	✓		*
MO: St. Louis	Anheuser-Busch	✓		11
St. Louis	Falstaff		✓	1
NB: Omaha	Falstaff	✓		1
NH: Merrimack	Anheuser-Busch	✓		2
NJ: Newark	Anheuser-Busch	✓		5
Trenton	Champale	✓		*
Hammondton	Eastern	✓		1
Newark	Pabst	✓		3
Orange	Rheingold		✓	3
NY: Rochester	Genessee	✓		3
Dunkirk	Koch	✓		1
South Volney	Miller	✓		6
Baldwinsville	Schlitz	✓		2
Utica	West End	✓		1
NC: Winston Salem	Schlitz	✓		6
ND: Fargo	ND State	✓		*
OH: Columbia	Anheuser-Busch	✓		6
Cincinnati	Hudepohl	✓		1
Cleveland	Schmidt	✓		1
Cincinnati	Schoenling	✓		1
OR: Portland	Blitz	✓		1
PA: Erie	Erie		✓	*
Shamokin	Fuhrman & Schmidt		✓	*
Allentown	Horlacher		✓	*
Allentown	Schaefer	✓		4
Smithton	Jones'	✓		*
Latrobe	Latrobe	✓		*
Reading	Reading		✓	*
Wilkes Barre	Lion	✓		*
Philadelphia	Ortlieb	✓		*
Pittsburgh	Pittsburgh	✓		1
Philadelphia	Schmidt	✓		3
St. Marys	Straub	✓		*
Pottsville	Yuengling	✓		*
RI: Cranston	Falstaff	✓		2
TN: Memphis	Schlitz	✓		6
TX: Houston	Anheuser-Busch	✓		2
Galveston	Falstaff	✓		1
San Antonio	Olympia	✓		1
Ft. Worth	Miller	✓		7
Longview	Schlitz	✓		4
San Antonio	Pearl	✓		1
Shiner	Spoetzl	✓		*
VA: Norfolk	Champale	✓		*
Williamsburg	Anheuser-Busch	✓		3
WA: Tacoma	Carling National	✓		1
Vancouver	General	✓		1
Olympia	Olympia	✓		5
Seattle	Heileman	✓		1
WI: La Crosse	Heileman	✓		3
Monroe	Huber	✓		*
Chippewa Falls	Leinenkugel	✓		*
Milwaukee	Miller	✓		10
Milwaukee	Pabst	✓		6
Milwaukee	Schlitz	✓		7
Stevens Point	Stevens Point	✓		*
Eau Claire	Walter	✓		*

*, Less than one million BBL capacity

TABLE 1, BREWERIES AUTHORIZED TO OPERATE IN THE U.S.

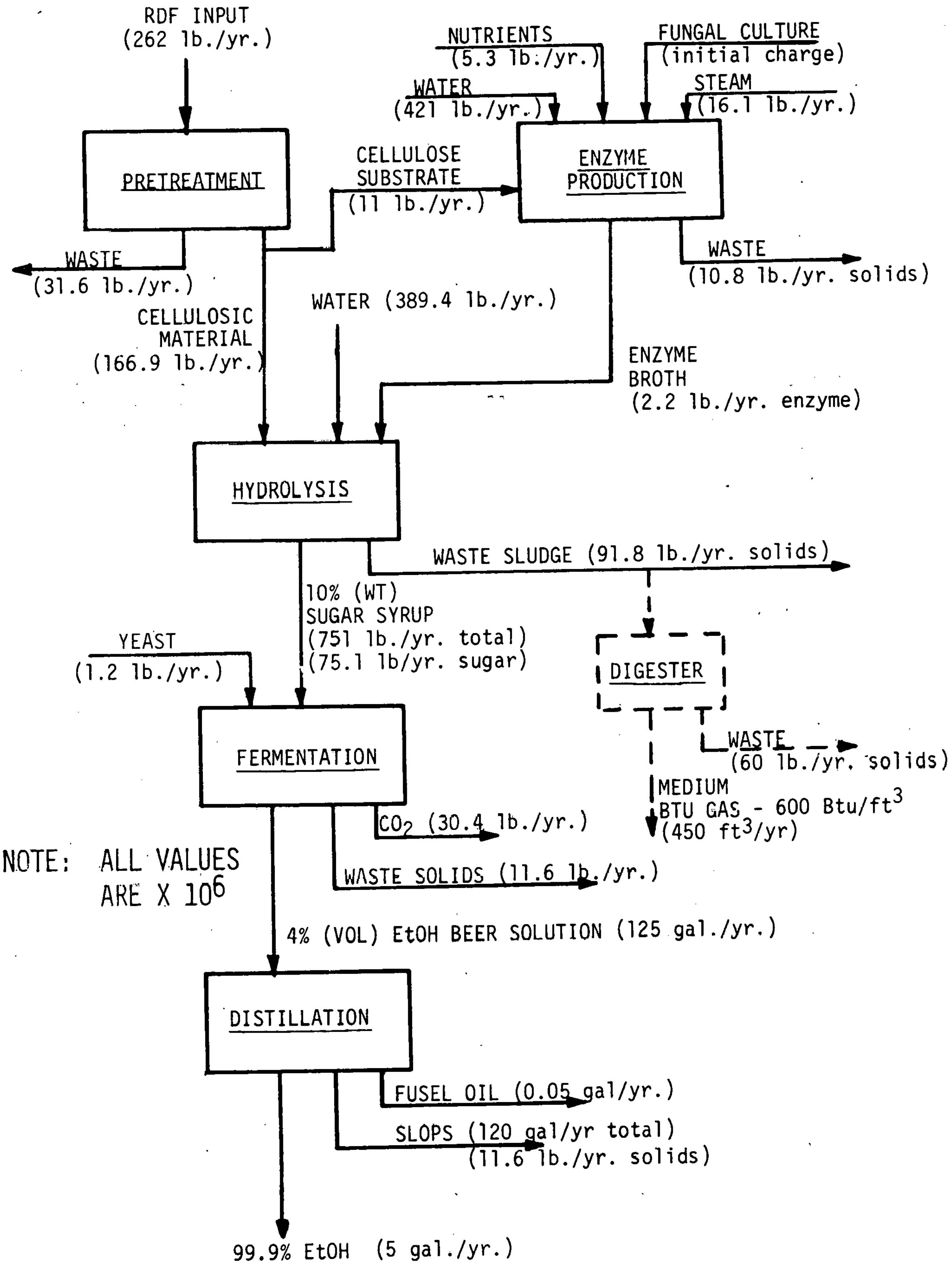

FIGURE 1, SIMPLIFIED PROCESS FLOW

ENGINEERING OF A FUEL SCALE METHANOL PLANT

by

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SYNOPSIS

The world's two largest methanol plants, each having a design capacity of 2750 tons/day, are being engineered by Davy International Limited of London, England, for construction in the USSR. The detailed engineering has highlighted the technical problems associated with the design, engineering and procurement of the equipment and bulk commodities associated with the sheer scale of plants of this size. These problems are described.

The economics of fuel methanol production have often been assessed utilising a plant size of 5000 tons/day. The realities associated with the engineering of methanol plants of this even larger scale are investigated and conclusions drawn.

INTRODUCTION

The contract, which Davy signed in May 1977 with the USSR importing organisation Techmashimport, is the largest single order ever placed by the USSR with a UK contractor. The order is valued at US$ 275 x 10^6 and is for the world's two largest methanol plants, each with a daily capacity of 2750 tons. When taking into account the facilities and services provided by the client, the total value of each plant works out at around US$ 225 x 10^6 or US$ 450 x 10^6 total.

The process design of the plant is based on the ICI Low Pressure Methanol Process (1)*, and incorporates the Davy "Low Carbon Concept" (2) and the "Reduced Energy Concept" (3). The principal features of the latter concept are the gas heated reboilers in the distillation area and the preheating of high pressure boiler feedwater in the methanol synthesis loop.

Because of the size of the plant it was necessary to have certain sections of the process route arranged in two streams. Limitations in size were imposed by the transport of equipment to site even though special procedures and equipment were incorporated in the contract to take care of some of the very large items. In addition, Techmashimport stipulated that all equipment should be within present day experience. Accordingly, the plant has single stream feedstock pretreatment, double stream reforming, single stream synthesis gas compression, double stream methanol synthesis, single stream methanol condensation and recovery, single stream topping column and double stream refining column.

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*Numbers in brackets (1) designate References at end of paper

A significant feature reflected in the layout and the detailed design is the extreme conditions of ambient temperature experienced by the two sites. Of the two sites, Tomsk is marginally more extreme with absolute maximum and minimum temperatures of +97°F and -67°F respectively. For over 5 months of the year the ambient temperature rarely rises above freezing and there are extended periods when the temperature lies between -5°F and -30°F. Gubaha is warmer by about 15°F in winter and cooler by about 7°F in summer. However, on both sites there is need to take the low ambient conditions into account and extensive winterisation has been applied to the design

PROCESS DESCRIPTION

Natural Gas Compression and Pretreatment

Natural gas is received from the client at about 85 psig and normally 60°F. Theoretically the gas is free of liquid water and liquid hydrocarbons. However, it may be delivered at low temperature, -67°F in the extreme case. Accordingly, the gas is preheated to about 60-70°F. Low pressure steam is used to preheat the natural gas through the medium of a methanol bath to ensure that the steam condensate does not become frozen by the low temperature natural gas.

After passing through a separator to remove any liquids and solids, the gas splits into a feedstock stream and several fuel streams. The separator, as is the case for many of the other separators in this plant, takes the form of a nest of cyclones. This type of separator has been selected for its excellent efficiency and turndown flexibility and it also demonstrates an increased resistance to blocking by solids. Additionally, the multi-cyclone bank can be contained in a shell of relatively small diameter and consequently gives shipping and cost advantages. The fuel streams feed the burners in the reformers, the auxiliary boiler, feedstock preheater and pilots for the flare.

The feedstock natural gas passes to the natural gas compressor where it is compressed in two barrels in series to 425 psig, at the outlet from the second barrel. The natural gas compressor is a centrifugal machine, normally operating at about 8000 rpm. The compressor absorbs about 11,000 HP which is supplied by a directly coupled condensing steam turbine taking medium pressure superheated steam as feed.

Any natural gas liquids from the separators are vapourised for use as fuel. Since there is the possibility of the natural gas liquids being at temperatures below 32°F, the vapouriser is of a special design. The steam condensate is kept warm by the incoming steam by making use of a bayonet tube type of construction rather than the conventional U tube.

The compressed gas and recycle gas mixture is heated to 750°F in a vertical up-shot gas fired heater with six passes on the feedstock side for both the radiant and convective sections before being passed through a bed of cobalt molybdate catalyst and then through the two Zinc Oxide beds in parallel, where the sulphur content of the feedstock is reduced to less than 0.5 ppm. After the desulphurisation section, the feedstock is split into two streams for reforming.

Reforming and Heat Recovery

The flow of feedstock to each reformer mixes with a controlled flow of medium pressure steam and the mixed steam and feedstock are further preheated in the fuel gas duct of the reformer prior to being distributed through the manifolds and inlet pigtails to the catalyst filled reforming tubes. Each reforming furnace contains 496 x 4" tubes approximately 40 ft. long arranged in 16 rows of 31 tubes each. Reformed gas is collected through the outlet pigtails into incoloy sub manifolds which in turn feed refractory lined mains. Two such mains from each furnace feed the two reformed gas boilers where heat recovery from reformed gas starts. The reformed gas leaves the reforming furnace at approximately 270 psig and 1580°F.

In the reforming furnace box 153 burners arranged in 17 rows fire downwards to provide the necessary heat of reaction for reforming. The burners normally use a mixture of purge gas and natural gas as fuel with natural gas alone for start up. All the purge gas discharged from the synthesis loop is used either in the reforming furnace as fuel or as recycle gas for desulphurisation.

All burners in the reformer receive preheated combustion air supplied from a steam turbine driven combustion air fan. The flue gases are extracted by a steam turbine driven induced draught fan and are discharged to the stack. The furnace itself operates under very slight negative pressure thus ensuring a cool casing and operator protection from the hot flue gases.

Heat recovery from the flue gases consists of a radiant shield boiler, two stages of high pressure steam superheater, steam plus feedstock preheating, a flue gas boiler and combustion air preheating. All the items except the combustion air preheaters are located in a refractory lined steel duct which is fed by flue gases from the reforming furnace.

Two combustion air preheaters operate in parallel. Each is a rotary device where a rotating "heat sink" is sequentially passed through the hot flue gases where it is warmed up and the cold combustion air where it is cooled, thus transferring the heat from the flue gases to the combustion air. Two combustion preheaters are used in parallel due to transportation difficulties of a single unit.

Heat from the reformed gas is recovered in the two reformed gas boilers operating in parallel. After this the reformed gas streams from the two halves of the furnace are combined to pass through H.P. boiler feed heating, refining column reboiler, topping column reboiler, deaerator feed water heater, air cooling and water cooling to reduce the gas temperature to 104°F. During the course of this cooling, condensation of steam takes place from the refining column reboiler onwards. This condensate is removed in the separators and passed to the condensate stripper where CO_2 and other dissolved gases are extracted before the condensate is cooled and returned to the water treatment plant.

Each reformer has an independent high pressure steam raising facility operating at approximately 1650 psig. For each reformer, 190 tons per hour of steam leaves the superheater at approximately 1520 psig and 915°F for use in the turbines driving the circulator and the synthesis gas make-up compressor.

Compression and Methanol Synthesis

Synthesis gas from the two reformed gas heat recovery streams is compressed from about 200 psig to about 1150 psig in a two barrel centrifugal compressor driven by a steam turbine. The steam turbine is located between the two sections of compressor and drives them directly at about 7500 rpm at normal operating conditions. The compressor absorbs 41600 HP, which is near the limit of power which can be supplied by a single turbine operating in this range of speed and steam conditions.

The synthesis gas from the compressor is cooled and the condensed water removed before the gas is passed to the suction side of the circulator in the synthesis loop.

The circulator takes suction at about 1150 psig and delivers the loop circulating gas at 1240 psig. It operates at about 6000 rpm and absorbs 18000 HP.

From the circulator, the gas flow splits into two identical streams each consisting of a synthesis reactor and associated heat exchangers. Double streaming is necessary owing to the size of the equipment involved. In each stream the gas splits into two parts, the quenches which go directly to the three inter stage distributors within the reactor, and the reactor feed which goes through heat exchange to the reactor inlet. The feed gas passes through two interchanges where it is heated by effluent gas from the reactor.

The synthesis reactor operates between 460°F and 520°F at 1150 psig under normal conditions. Since the synthesis reaction is exothermic, the temperature rises as the reaction proceeds. It is therefore necessary to inject cold 'quench' gas at three levels in the reactor in order to moderate the temperature rise.

The performance and reliability of the ICI process largely results from synthesis catalyst performance and the mechanical design of the reactor vessel. The quench reactor is a hot-wall vessel requiring no internal catalyst support basket. The catalyst is contained in a single bed supported by an inert material. The reactor is controlled and quenched by the introduction of cold gas through spargers spaced at appropriate levels in the catalyst bed. Each horizontal layer of spargers that run across the converter from side to side has an outer surface covered with wire mesh and a central pipe to distribute cold gas along its entire length.

The quench gas discharges at a large number of points in the space contained by the wire mesh, where it mixes and cools the hot reaction gas entering through the mesh. This arrangement, with free space for catalyst passage between spargers, allows very rapid catalyst loading and unloading.

From the last bed the gas mixture leaves the reactor and is split into two streams, one passing to boiler feedwater heating, the other to the second stage of heating the reactor feed gas. The two streams are recombined to pass through the first stage of heating the reactor feed gas before being cooled to 110°F.

The gas-liquid mixture from the condenser passes to the crude methanol separator from which the gas portion passes to the circulator suction. The liquid, principally an 80:20 mixture of methanol and water, passes to two stages of pressure let down before being transferred to storage.

Methanol Purification

Purification takes place in two stages of distillation; topping to remove the permanent gases and light ends followed by refining to remove the water and heavier organic materials. A single topping column is used to process the total methanol production but two columns operating in parallel are required for the refining stage. Both columns operate at less than 15 psig normally.

The topping column is reboiled by two gas heated reboilers, one in each reformed gas stream. Topped methanol is pumped from the base of the topping column and is fed directly to the refining columns.

In the refining column water is concentrated at the base and the methanol at the top. Each column is reboiled using a gas heated reboiler which provides about two-thirds of the required heat. A steam heated reboiler using L.P. steam provides the balance of the heat. The water from the base of the refining columns is held in an underground sump whilst the concentration of organics is checked, before being passed to biological treatment.

The product is drawn off from a tray about 3 from the top to ensure that it is free of light ends and is cooled before being passed to one of the test tanks in the storage area.

Methanol Storage and Loading

The storage area contains a crude methanol tank, a fuel oil tank, two test tanks of 2500 m^3 capacity and two refined methanol storage tanks of 20,000 m^3 capacity. While methanol from the production plant is flowing to one of the test tanks, the methanol in the other tank is being tested and then transferred, if satisfactory, to the main storage tank.

From the storage tanks methanol is loaded to rail tank cars in trains of up to 11 cars each. Two such trains can be loaded simultaneously. The loading sequence is carried out totally automatically after the loading arms have been positioned in the tank cars and the various safety circuits have been completed. On completion of loading the train may not be given the clear signal to depart until all the loading arms have been stowed and the necessary auxiliary actions completed.

The storage and loading area is provided with a foam generating system which can pump alcohol resistant foam into any of the storage tanks, into the loading area by overhead sprays or feed strategically located monitors which can be used to fight local fires inside the concrete bund area in which the storage tanks are located. An unusual feature of the storage system is the tank vent purification system. It is a USSR requirement that toxic and hazardous effluents are not discharged directly to the atmosphere. Hence, the gases discharged from the rail tank cars during loading, together with the gases breathing from the storage tanks are collected together, mixed with an excess of preheated air and passed over a platinum based catalyst. The vent gases are principally nitrogen from the storage tank blanketting and air from the tank car loading but there are also quantities of methanol vapour and some erstwhile dissolved gases, principally CO, CO_2 and H_2. The methanol and other combustible gases are converted over the platinum to CO_2 and waterand discharged to the atmosphere from a relatively low stack.

Steam and Boiler Feedwater Systems

High pressure superheated steam is raised in the two reforming steam systems as previously described and is augmented by steam from an auxiliary boiler which uses natural gas as fuel. The auxiliary boiler has the characteristic of fast response to changing load on the steam system to cater for the situation where steam production may be greatly reduced due to one reformer tripping out of service while the steam demand remains high. The boiler has a conventional water walled combustion chamber where the steam is raised followed by a two stage superheater, economiser and combustion air heater heated by the flue gases from the combustion chamber.

Steam from the three boilers is fed to the turbines driving the circulator and the synthesis gas make-up compressor. The medium pressure steam is used in the reforming furnaces and to drive turbines for the natural gas compressor, the boiler feedwater pump, the induced draft and combustion air fans on each reformer, one of the cooling water pumps and a number of service pumps such as lubrication pumps for the turbines and compressors. With the exception of the natural gas compressor turbine which is a condensing machine, these turbines all pass out steam to the low pressure system. This supplies steam to the steam heated reboilers and to the tracing system and other winterisation users

The water treatment plant receives raw water from the client and treats this by clarification and filtration. The filtered water is then treated in a conventional de-ionising unit of cation bed, degasser, anion bed and mixed bed.

The high pressure boiler feedwater pumps are in two stages, a booster pump taking suction from the deaerator and a high pressure stage delivering water at about 1900 psig. For improved security there are three full size pumps in parallel, two turbine driven and one driven by a 4000 HP electric motor. The latter is used at start up and otherwise is on permanent standby duty being automatically started on failure of the running pump.

TRANSPORTATION

Mention has already been made of the large size of certain of the items of equipment. Equipment delivery is further complicated by the route the equipment has to follow to reach the two sites and the natural hazards of these routes. For equipment able to be carried by the railway system the route is fairly simple: ship to Leningrad then by railway direct to site. The only problem concerns items which deteriorate if subject to very cold temperatures. Thus the resins for the deionising units and refractories for the furnaces must be transported during the summer and must arrive after the heated construction storage buildings have been completed.

For items unable to fit on the railway gauge, the route to Gubaha is simpler than that to Tomsk. Such items are transferred from ship to large canal barge at Leningrad and progress through the canal system to a point some 75 miles from the site. The journey so far must take place during the summer when the canals are ice free. However the next stage is across a marshy tract of land only passable during the winter when the marsh freezes and a rough roadway can be cut. Hence the oversize equipment must wait until it can be ferried a piece at a time over the frozen marsh on a low loader. This low loader is part of Davy's supply and is sent in parts to be assembled prior to use. It has a capacity of 550 tons. Even this route has its size limitations and the refining columns must be transported in two pieces and welded up on site prior to erection.

For oversize equipment going to Tomsk, the route requires the use of a sea going barge which is loaded up with particular oversize items at UK ports. Then, under the supervision of a Russian tug master, it is towed around the north of Norway and the USSR to the estuary of the Ob River, up the Ob to its tributary the Tom and so to a landing point 12 miles from the plant site. As for Gubaha, the route is subject to a weather window through which the oversize consignment must pass as the Arctic Ocean is only passable for a limited season and the river Ob is frozen for about 6 months of the year. To miss the weather window in this case means a delay of almost a year. The sea going barge is part of Davy's supply and is worth about US\$ 2 x 10^6. Its cargo is worth almost US\$ 3 x 10^6. A modest benefit of this method is that the refining columns can be transported in one piece.

EQUIPMENT ENGINEERING

Vessels

Each synthesis reactor, 14'-6" diameter, 30'-6" tan to tan with hemispherical ends, weighs 185 tons without internals, catalyst or platforms. Wall thickness is about $4\frac{1}{2}$" and the material is a low alloy steel with Cr, Ni, Mn, Mo and V additions which gives good strength at operating temperatures under the hydrogen embrittlement conditions as well as good impact strength at low ambient temperature. Because of the potential for cracking within the welds of such thick material, the design of the vessel is arranged to minimise areas of high stress concentration. The relatively recently developed technique of fracture mechanics (in accordance with ASME III AppG) has been used to analyse the acceptable manufacturing defect sizes, location and frequency of cracks in welds together with rigorous inspection on completion the welding, as cracks during manufacture are unavoidable.

The refining column 200 ft.high and 16'-6" diameter has a different design requirement. This is a relatively thin walled vessel with thickness around ¾"weighing 260 tons without internals or platforming. Trayed and platformed prior to erection, it has an all up weight of 405 tons. With this item, the maintenance of circularity is a potential problem, particularly during transportation and erection. Special transport "spiders" are placed at intervals inside the column to overcome this deformation problem.

Each Zinc Oxide vessel 13 ft. diameter and 40 ft. tan to tan weighs 90 tons and is made from plate approximately 2" thick. Operating at 750°F this vessel is designed within the creep range of the material of construction. Because of the relaxation of stresses under operating conditions there is the reversal of stresses at shut down which may impose greater loads on nozzles, for example, than during operation. Accordingly, there has been a very conservative choice of stress values used in the design to ensure that at all times the stresses are within acceptable limits. Fracture mechanics assessment is employed to ensure that reversal stresses during shutdown are not damaging to these items.

All of these vessels and others similarly designed have to travel on the sea going barge. The transportation saddles for all these have therefore been designed to accommodate a loading of 2g so that even if the barge overturns, the vessels will not break free but will merely be able to continue on their way upsidedown! Similar considerations have been incorporated into the design of the attaching devices required when the items are being transported overland by the low loader.

Shell and Tube Exchangers

The exchangers in the synthesis loop provide some interesting design features similar to the design of the synthesis reactor in several aspects. As for the reactor, problems include high and low level temperature suitability of materials, very thick shell plates, design incorporating fracture mechanics and the need for very high quality low alloy steel. This steel is prepared by electric arc processes and is vacuum degassed. The nozzles, like those of the reactors are fabricated from forgings, some of which are very large and thick - upto 36" NB and 5" thick. To get some idea of the size of the equipment, the nine loop exchangers have a heat transfer area totalling about 100,000 Ft^2.

In addition there is the problem of welding dissimilar materials - such as low alloy and stainless steel - and choosing preheating and stress relieving temperatures which are appropriate to both materials involved. Also where different materials are used for the shell and tubes, eg. low alloy shell and stainless steel tubes, it is necessary to choose a special stainless steel with a thermal expansion coefficient close to that of the low alloy steel and it is obviously not practical to consider expansion bellows in a shell 2" thick and designed for 1300 psig.

Machinery

The criteria for machinery selection has been to ensure that all machines are within tried and proven limits of experience. This applies equally to the pumps, compressors, fans and turbines. The sealing and lubrication arrangements are normal for this type of application and the only slightly unusual feature has been the need to ensure that pump materials are suitable for dealing with very cold liquids (eg methanol from storage) even though the pumps themselves may be in heated buildings.

In the case of the synthesis gas compressor turbine driver, a special design audit was carried out in conjunction with the manufacturer to ensure that all aspects of the design were rated conservatively, bearing in mind the complex nature of a variable speed turbine of this size.

Air Cooled Exchangers

The air cooled exchangers occupy nearly 5% of the plot area of the two terraces on which the process plant is located and thus are a major feature of the layout. There are 14 different duties performed by the air coolers and a total of 16 different items of equipment. The sizes range from a single bay, 2 bank, 2 fan item for the natural gas compressor intercooler with a finned area of around 75,000 ft^2 and a process material of carbon steel to a 9 bay, 18 bank, 27 fan item for the crude methanol condenser with a finned area of about 650,000 ft^2 and a process material of stainless steel. In total per site there is a finned area in all the exchangers of over 4 million square feet, of which half the process material is stainless steel. There are 138 fans per site, varying in size between 10 ft and 16 ft diameter and absorbing between 15 and 100 HP each.

Reforming Furnaces and Waste Heat Recovery

Although the reforming furnaces are individually not the largest of their type ever built, as a group of two they have more tubes (992) than the largest single furnace (600 tubes). As the furnaces are constructed on site, transport of the pieces does not cause a major problem.

For the waste heat recovery, the rail gauge limits the size of the equipment to be located in the flue gas duct. Maximum prefabrication within this limit means that, for example, headers only are to be welded onto superheater and other coil exchangers. Winterisation considerations include housing the steam drum within a shelter to avoid the worst effects of thermal gradients in the shell material.

Piping

The unusual features which have had most impact on piping are the imposition of the USSR standards, the extreme winter climate and the large quantity of large size pipework.

The large size of the piepwork has considerable effect on pipe stressing as the large diameter pipes have to have thicker walls and are therefore less flexible. A case in point is the high pressure superheated steam line. This has a diameter of up to 20" and a wall thickness of almost 2". The pipe has to accommodate a change in temperature from -67°F up to 950°F. The cost of this single pipe system connecting the superheaters to the turbines is around US$ 0.5 x 10^6. The sheer size of some of the large valves means that considerable support structures are required just to hold up the valve when these are not located on the ground. Since relief valves are available in standard sizes only, it is necessary to install multiple relief valve assemblies to deal with the large capacities required. This leads to further support and stressing problems.

In each plant there is some 330,000 ft of piping weighing around 4500 tons and ranging in size from ½" to 36" nominal bore. The size of the model (scale 33⅓ : 1) which is being used as a design tool is 16 ft x 40 ft for the two production terraces only and it has required up to 40 model makers working on it at one time. These models are the largest ever produced by Davy.

Instrumentation

Apart from the cold winter temperatures and size of pipework into which control valves and flow elements have to be installed, the problems of instrument engineering have been the usual ones of fitting in a sophisticated, often intrinsically safe, electronic system into a plant containing a substantial network of power cables without compromising the integrity of the milliamp signals by interference from the power system.

The size of certain control valves has made their selection difficult as noise and the forces associated with shut off pressure are problems which have to be taken into account. In some cases the type of valve has had to be changed from the conventional choice, in others silencers or accoustic lagging have been incorporated.

PROJECTED PLANT CAPACITIES

If methanol is to be used as fuel then it is relevant, from an economic point of view, to consider what the maximum stream size might be.

From the point of view of world-wide capability and past experience of fabrication of equipment associated with large scale methanol plants, there are two areas of the plants that need close examination. The first being the reforming furnace and its associated flue gas heat recovery equipment and the second the synthesis gas compressor and its steam turbine driver.

Before examining these in detail, it should be noted that heat exchangers, piping, valves and control valves are not referred to in the following discussion as it is a common and acceptable practice to have multiples of these units when size limitations are reached (eg multiple shell heat exchangers in parallel and series and parallel 50% size control valves).

The largest reforming furnace known to be operating in the world has 600 reforming tubes and is of Davy modular design, each two rows of tubes representing a module. This furnace is thus a ten-module reformer. The principle of modular constructions is important in considering furnaces greater than this in size and will be discussed below.

If a 600 tube reformer is considered to be the limit of world experience, a methanol plant using this reformer could produce between 1500 and 2000 tons per day, depending on the feedstock composition.

However, as mentioned above, the Davy furnace is a modular one, and we are confident that much larger reformers can be built by adding modules like building blocks to the basic 600 tube reformer design. The operating conditions would be the same for each of the added modules, which are the important parameters.

A factor which could influence scale up, which was observed on the 600 tube reformer, is the potential for maldistribution (of feedstock, fuel, air and flue gas). There was evidence of some maldistribution, principally of flue gas in the large 600 tube reformer radiant section, which, although small, prompted Davy to examine this phenomenon in detail. The results of the examination have modelled very closely distribution patterns in the radiant box as well as the flue gas collection system at the hearth of the furnace. Minor changes have been made to the Davy design which we believe have further improved the distribution giving Davy the confidence to offer furnace designs containing up to 1200 tubes and thus giving the potential to produce in excess of 3000 tons per day from a single stream.

A comparison of the essential features of a 2750 ton/day case reformer with the 600 tube reformer is as follows:-

	2750 t/d reformer	600 tube reformer
No of reformer tubes	1008	600
Tube rows	24	20
Tubes/row	46	30
Radiant box length	164 ft	116 ft
height	40 ft	40 ft
width	41 ft	25 ft

* The apparent disproportionate increase in furnace length is due to increased tube row spacing from 5'6" to 6'6".

Most of the heat recovery items in the flue gas duct are associated with steam raising and superheating. Much larger, similar, equipment is designed and fabricated in power station applications and thus does not post new boundaries for this technology.

The second area where limits of experience are approached is in large compressor and turbing technology. Investigations have shown that synthesis gas centrifugal compressors can be bought to operate at suitable speeds and the necessary compression ratios and volumetric flows from vendors such as Nuovo Pignone (Italy) and Dresser Clarke (USA and Japan). The experience in ching steam turbine drivers is limited to an approximate power output of 00 HP for European supply (eg Siemens of W Germany) and about 39000 HP from US suppliers (eg General Electric).

Depending on the natural gas composition, and assuming a methanol synthesis pressure of approximately 1450 psig, between 2300 and 3000 tons per day could be produced utilising a 43000 HP synthesis gas compressor and turbine set. In comparison, the output from the two methanol plants Davy are engineering for Russian erection is limited to 2750 tons/day at a synthesis pressure of 1150 psig due to the very light (greater than 95% methane) natural gas feedstock.

In other areas of the methanol plant, questions can be asked about the maximum sizes of the reactor (the Methanol Converter) and perhaps distillation columns. At the 2750 tons per day plant size, the reactor diameter would be approximately 18 ft, a marginal increase on an operating reactor of 17 ft diameter. The distillation column diameter would be 23 ft, which is much smaller than distillation columns operating in other duties (30 ft plus).

In summary, the reforming furnace is acknowledged as being a physical increase in size over existing reformers for a 2750 tons per day methanol plant, but due to modular construction principles and controlled operating parameters Davy consider the extension from 600 tubes to approximately 1000 tubes is acceptable.

Synthesis gas compression sets are available of sufficient power to produce methanol at or greater than a rate of 2000 tons per day.

For the 2750 tons per day plant reactor and column dimensions are at or within the limit of proven operating experience. However, transportation weight restrictions may possibly cause double streaming, especially of the reactor.

Of the remaining equipment in the plant, heat exchangers, piping valves and control valves would be installed as multiple units where necessary.

It seems reasonable to predict, therefore, that the next generation of large methanol plants will have single streams capable of producing between 2000 and 3000 tons per day of refined product.

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THE PRODUCTION OF GRAIN ALCOHOL AND ELECTRIC POWER WITH COGENERATION OF STEAM

by

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INTRODUCTION

The production of anhydrous ethanol by the fermentation of grain requires steam for cooking the grain mash, operation of the distillation columns, and drying of the stillage to produce cattle feed. All of these heating operations make use of the latent heat of condensation of saturated steam. On the other hand, electric power is generated by expanding high pressure, super heated steam through turbines to drive electric generators. The exhaust steam from the turbines is at or near saturation conditions and is condensed with cooling water. The condensate is recycled to the boiler. The latent heat of condensation in this case is lost. By combining electric power generation with grain alcohol production it is possible to increase the thermal efficiency of the combined operations above that of the average for the individual processes. The combined operation also requires a lower capital investment and has a lower operating cost than the independent operations.

In 1977 the Nebraska Grain Alcohol and Chemical Company of Lincoln, Nebraska, and the Hastings (Nebraska) Utilities Board explored the possibility of a joint venture for the construction of a 70 megawatt steam power plant and a 20 million gallon per year anhydrous grain alcohol plant. In Nebraska all power producing facilities are publicly owned. As a result of legal questions and potential problems which arose regarding a joint venture between a private company producing alcohol and a public power system, only the 70 megawatt public power plant was constructed. However, the results of the studies on cogeneration are still valid and are presented here.

ELECTRICAL GENERATING FACILITY

The steam driven electric power generating facility proposed for construction by the Hastings Utilities Board was designed to produce 70 megawatts of power at rated capacity and 83 megawatts of power at maximum capacity. The maximum steam pressure is 1450 psig at a temperature of 1000°F (407° of super heat). The turbine system includes intermediate reheat to 1000°F at an interstage pressure of 385 psia when operating at rated load and 77 psia when operating at minimum load. For purposes of these studies a generator efficiency of 95%, a turbine efficiency of 90%, and a furnace efficiency of 88% have been assumed. The steam rate to the turbines for power generation (excluding auxiliary steam in the plant) is 358,500 pounds per hour at the rated capacity of 70 megawatts. The exhaust steam condenser duty is 373.1 million Btu's per hour. Figure 1 is a simplified flow diagram for this power generating system.

ALCOHOL PRODUCTION FACILITY

The base case alcohol plant has a capacity for producing 20 million gallons per year of anhydrous ethanol from corn. Figure 2 is a block-flow diagram for such a plant. Details of the process for converting corn to grain alcohol and the detailed energy requirements are discussed elsewhere (1,2,3). The exact steam requirements for the production of grain alcohol will depend on the amount of heat recovery that is incorporated in the grain alcohol plant. For purposes of this study we have used a steam requirement of 187,000 lbs per hour of saturated steam at a pressure of 85 psig. In this case the boiler plant efficiency for the alcohol plant was assumed to be 82% which is consistent with the package type boilers which would be installed in a grain alcohol plant of this capacity.

COGENERATION CASE

Figure 3 is block-flow diagram for the case in which both 70 megawatts of electric power and 20 million gallons per year of ethanol are produced using cogeneration. A larger amount of steam (472,600 lbs per hour) is generated in this case than in the base case for power generation (358,500 lbs per hour). In both cases the steam is generated at 1450 psig and 1,000°F. After passing through the first stage turbine 187,000 lbs per hour of steam are withdrawn at 85 psig for use in the alcohol plant and the remaining 285,600 pounds per hour of steam is returned to the boiler for reheating to 1,000°F. This steam goes through the second stage turbine generating the balance of the electric power. The condenser duty for the plant after the second stage generation is 297.2 million Btu's in the cogeneration case as opposed to 373.1 million Btu's in the base power generation case (see Figure 1).

Table I summarizes the conditions for the base case of generating 70 megawatts of electrical power with the cogeneration case in which 20 million gallons per year of anhydrous ethanol are produced in conjuction with the power generation. In this table all benefits from cogeneration are applied to the power generation which shows an increase in efficiency from a base case value of 33.7% to a value of 38.3%. Table II is a similar comparison in which all benefits of cogeneration are applied to the grain alcohol plant. To express the efficiency of operation in this table we have used the ratio of the energy content of the ethanol produced divided by the energy consumed. In the base case for alcohol production along this ratio is 0.816 however, in the cogeneration case the ratio of energy produced to energy consumed is 1.276.

In Table III an overall comparison of energy produced in the form of electric power and ethanol is compared to the total energy consumed in the production of both products. In the base case i.e., separate plants for the production of each the energy ratio is 0.465 while in the cogeneration case this ratio is 0.514 again showing an improved efficiency with cogeneration.

Finally Table IV summarizes the effect of alcohol production capacity on the steam production, fuel consumption, power generation efficiency and energy ratios. The ratio of total energy produced to total energy consumed increases by 88.4% as the anhydrous ethanol production is increased from zero to 40 million gallons per year. The power generation efficiency as discussed in conjuction with Table I is increased by 32%. On the other hand, the ethanol energy ratio is constant in the cogeneration cases because the steam requirement per gallon of ethanol produced is constant. The value of the ethanol energy ratio however, would be a different constant value for difference levels of power generation.

It is especially interesting to note that with a separate power plant and alcohol plant a greater total steam generating capacity (in two separate boilers) is required than in the cogeneration case. This saving in steam generation, of course, is the result of generating the steam at high temperature and pressure and extracting electric power from it before using a portion in the alcohol plant. The reduced steam demand results in a capital investment saving of about $4 million compared to the cost of the steam generating facilities in the cogeneration case with the production of 20 million gallons per year of anhydrous ethanol.

CONCLUSIONS

The production of electric power and grain alcohol using a common steam generating facility with electrical energy being generated from the high pressure steam before a portion is diverted for use in processing in the alcohol plant has both economic and energy advantages. In the case studied for the production of 70 megawatts of electric power and 20 million gallons per year of anhydrous grain alcohol the steam cogeneration was reduced from 545,500 lbs per hour in separate facilities for power and alcohol production to 472,600 lbs per hour in a cogeneration plant. This represents a reduction of 13.4% in steam demand. At a production rate of 10 million gallons per year of ethanol this reduction is 8% and at 40 million gallons per year it is 19.9%. The energy produced as electrical power and grain alcohol per unit of energy consumed in firing the steam boilers and providing electricity for operation of the alcohol plant is also higher in the cogeneration case than with separate plants. It appears that cogeneration of electricity and grain alcohol is attractive from both the economic and energy standpoints.

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TABLE I

COMPARISON OF POWER GENERATION WITH AND WITHOUT COGENERATION OF GRAIN ALCOHOL

	Base Case	Cogeneration Case
1. Electric Power, Megawatts	70	70
2. Anhydrous Ethanol, 10^6 Gal/Yr	0	20
3. Maximum Steam Pressure/Temp.	1450 psig/1000°F	1450 psig/1000°F
4. Steam Reheat Temperature	1000°F	1000°F
5. Steam For Ethanol Plant, Pressure/Temp	--	85 psig/326°F
6. Power Plant Condenser Duty, 10^6 Btu/Hr	373.1	297.2
7. Turbine & Generator Losses, 10^6 Btu/Hr	12.5	12.5
8. Boiler Plant Efficiency	88%	88%
9. Power Generation Efficiency	33.7%	38.3%

TABLE II

COMPARISON OF GRAIN ALCOHOL PRODUCTION WITH AND WITHOUT COGENERATION OF POWER

	Base Case	Cogeneration Case
1. Anhydrous Ethanol, 10^6 Gal/Yr	20	20
2. Electrical Power, Megawatts	0	70
3. Absorbed Heat For Steam Gen., 10^6 Btu/Hr	207.1	140.2
4. Boiler Plant Efficiency	82%	88%
5. Electricity Used	6.0	6.0
6. Energy Content of Ethanol, 10^6 Btu/Hr	211.0	211.0
7. Ethanol Energy/Energy Consumed	0.816	1.276

TABLE III

COGENERATION OF GRAIN ALCOHOL AND ELECTRIC POWER OVERALL EFFICIENCY

		Base Case (Separate Plants)	Cogeneration Case
1.	Electric Power, Megawatts	70	70
2.	Anhydrous Ethanol, 10^6 Gal/Yr	20	20
3.	Electric Power, 10^6 Btu/Hr	239.1	239.1
4.	Ethanol Energy Content, 10^6 Btu/Hr	211.0	211.0
5.	Fuel Consumption, 10^6 Btu/Hr	968.5	875.2
6.	Energy Produced/Energy Consumed	0.465	0.514

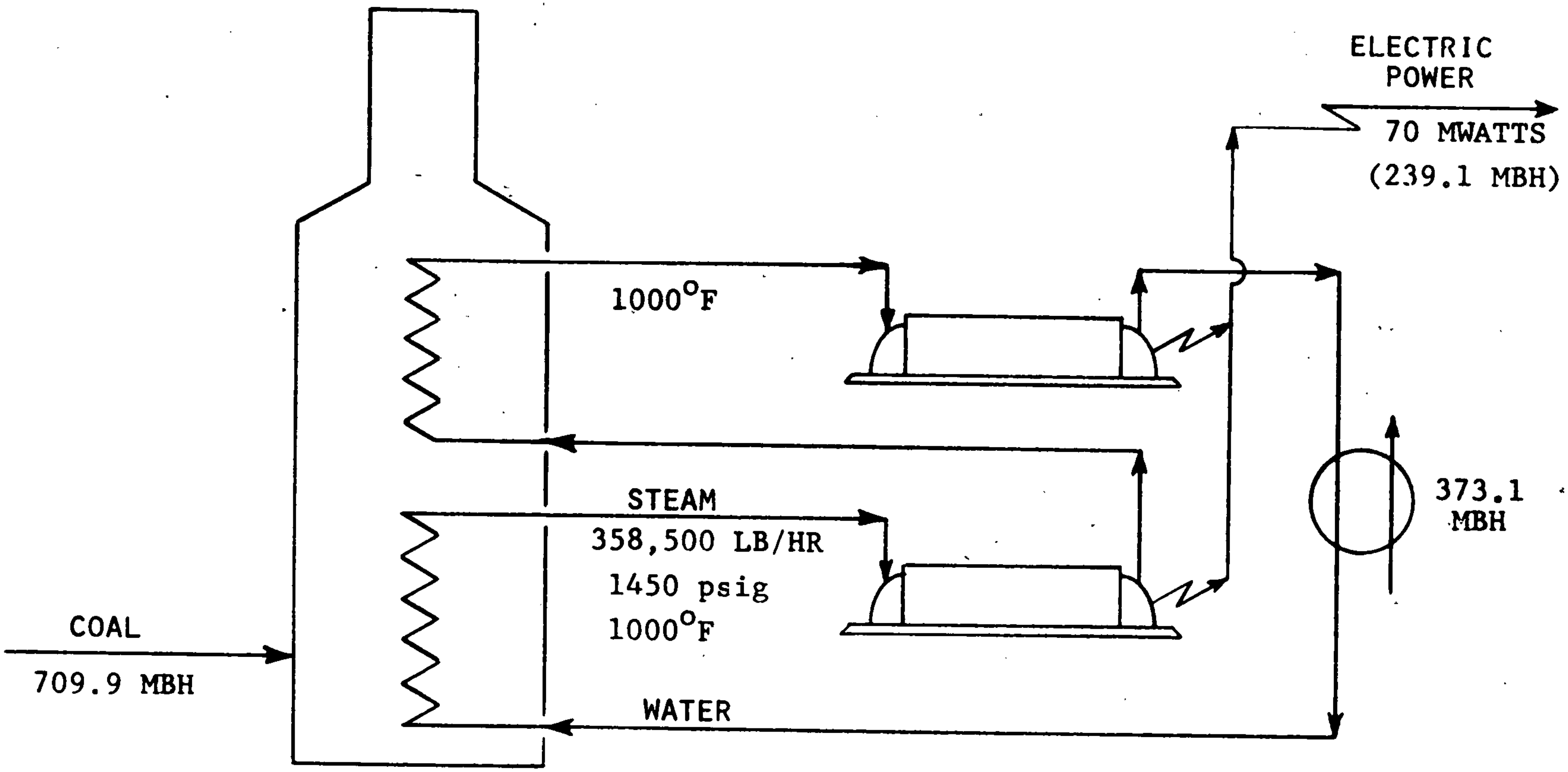
TABLE IV

COMPARISON OF ENERGY EFFICIENCIES FOR COGENERATION OF GRAIN ALCOHOL AND ELECTRIC POWER

		ETHANOL PRODUCTION 10^6 GAL/YR			
		0	10	20	40
1.	Electric Power, Megawatts	70	70	70	70
2.	Electric Power, 10^6 Btu/Hr	239.1	239.1	239.1	239.1
3.	Total Steam Production, 10^3 Lb/Hr	358.5	415.6	472.6	586.6
4.	Condenser Duty, 10^6 Btu/Hr	373.1	335.2	297.2	221.2
5.	Ethanol Energy content 10^6 But/Hr	0	105.5	211.0	422.0
6.	Fuel Consumption, 10^6 Btu/Hr	709.9	792.7	875.2	1040.4
7.	Power Generation Efficiency (Table I)	33.7%	35.8%	38.3%	44.5%
8.	Ethanol Energy Ratio (Table II)	--	1.276	1.276	1.276
9.	Total Energy Ratio (Table III)	.337	.435	.514	.635

FIGURE 1

BASE CASE POWER PLANT



MBH = MILLION BTU/HR

FIGURE 2

BLOCK FLOW DIAGRAM
FERMENTATION ETHANOL PLANT

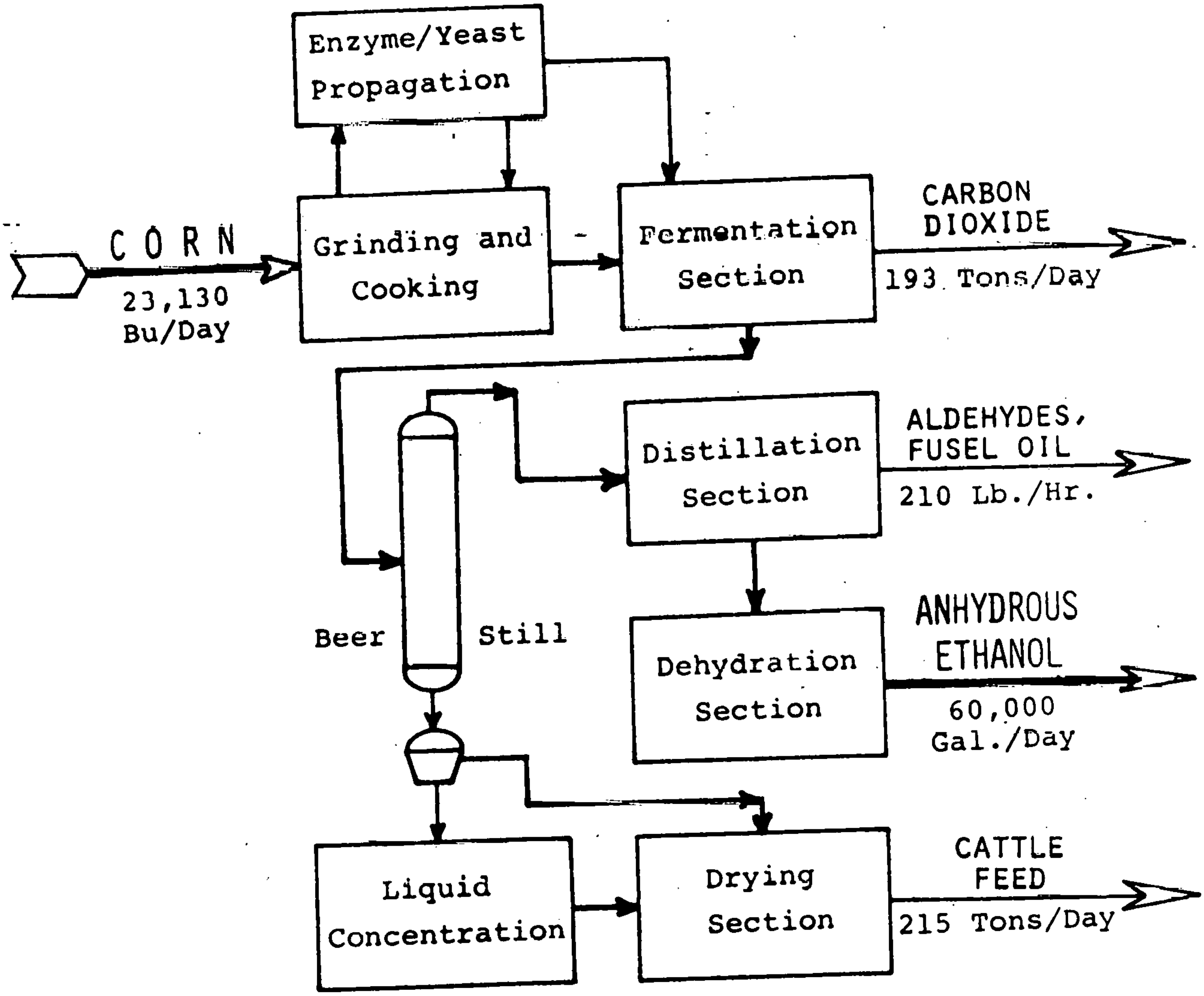
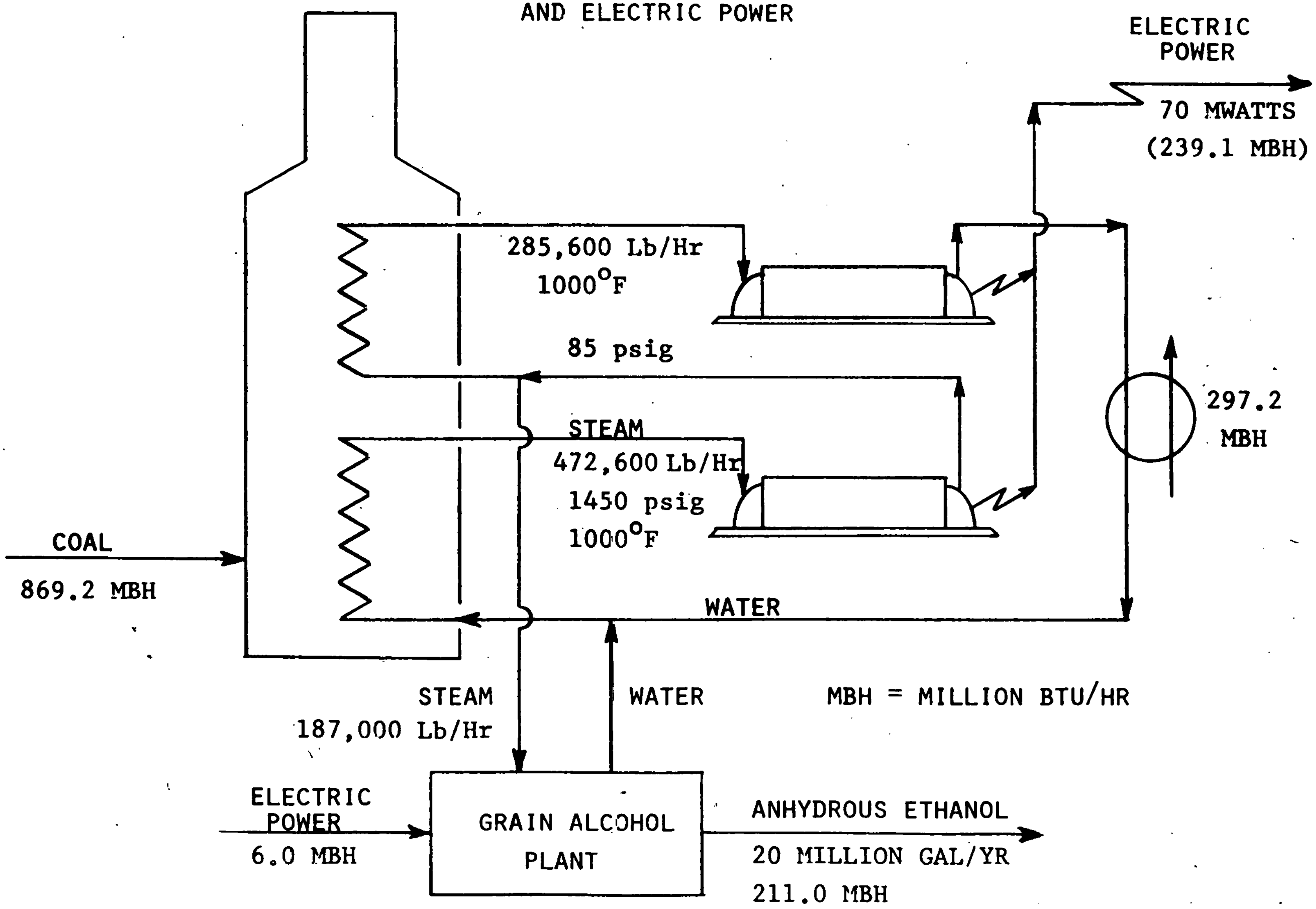


FIGURE 3

COGENERATION OF ETHANOL AND ELECTRIC POWER



PRODUCTION OF ETHANOL FROM LIGNOCELLULOSE - CURRENT STATUS

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ABSTRACT

Recent interest in producing ethanol from renewable resources has focused on the use of lignocellulose as a possible feedstock. Ethanol production could become a compatible addition to integrated forest products operations. This paper outlines the status of the various process steps available for liberating fermentable sugars from the lignocellulose, for fermenting the sugars to alcohol and for recovering alcohol and by-products. Process and laboratory studies associated with these steps are discussed. Finally, this paper outlines some of the developmental activities which will lead towards commercialization.

INTRODUCTION

Production of motor fuel quality ethanol is of increasing interest as a means of reducing United States' dependence on foreign oil. Lignocellulose is being seriously considered as a feedstock candidate. Many alternative processes which have been investigated in various laboratories will provide a foundation for future development and commercialization.

Ethanol production is particularly suited to complement existing forest product operations by utilizing lower valued or by-product materials (e.g., sulfite waste liquor). In addition, specific silvicultural development could be integrated into existing cultivation to assure feedstock requirements.

Today's production of ethanol via fermentation involves conversion of sugars and starches. Starch is hydrolyzed to liberate sugars, the sugars fermented to ethanol and the ethanol recovered and dehydrated. Similarly, the cellulosic fraction and the C_6 hemicellulose constituents of lignocellulose can also be hydrolyzed to yield fermentable sugars for conversion to ethanol (see Figure 1). However, since these fermentable sugars only constitute a fraction of the lignocellulose feedstock, effective separation and use of the unconverted materials is necessary.

Ethanol is produced via fermentation in an aqueous broth. The concentration of ethanol thus produced is generally low, ranging from 2 to 12 percent. Therefore, considerable energy is needed to recover the product if the ethanol is to be used in an anhydrous form. This has been one of the major limitations of the fermentation route to ethanol production.

The production of ethanol from cellulose is not new. [illegible]act, much of the related R&D work was carried out in the 40's and 50's. Commercial facilities in the U.S. and abroad have used cellulosic sugars for ethanol production. Because of the dwindling supply of fossil feedstocks, recent interests are focused on integrated processes which may consume all fractions of lignocellulose. The following describes the current developmental status of the various process steps involved for possible future commercialization.

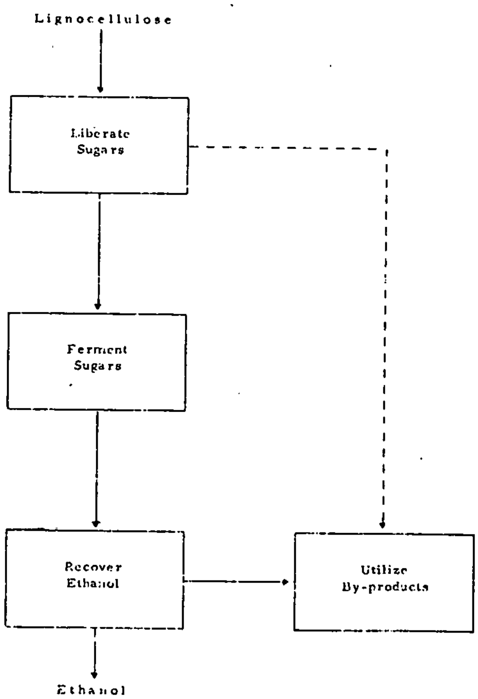

Figure 1

LIBERATION OF FERMENTABLE SUGARS

Successful commercialization of lignocellulose-to-ethanol requires the development of effective ways of liberating fermentable sugars from cellulosic biomass. Of the various approaches to liberation of sugars, the three most important process categories are, weak-acid, strong-acid, and enzymatic hydrolysis.

Weak Acid Hydrolysis

Weak acid hydrolysis leaching processes have used approximately 0.5% H_2SO_4 to liberate glucose from a packed bed of ground wood. Operating at relatively low temperatures of 150 to 190° C, the Madison-Scholler process[1] as practiced today in the Soviet Union yields about 50 percent of theoretical sugars as a 4 percent glucose solution along with a significant degradation of glucose to undesirable by-products. The low concentration glucose is fermented to 2 percent ethanol thus requiring an energy intensive ethanol distillation procedure. The corrosion problems inherent in a typical weak-acid hydrolysis at less than 200° C have not been significant.

Researchers have gone beyond the dilute sulfuric acid used commercially by German, American, and Russian facilities.[2] Exposure of biomass to weak acid at higher temperatures for shorter times results in higher glucose yields and reduced glucose degradation to by-products. In addition, production of higher concentration sugar hydrolysates is desirable to minimize fermentation and product recovery costs. Temperatures have been raised to 500° C and residence times reduced from hours to seconds. Weak-acid processes are now experimenting with CO_2, carbonic acid, maleic acid, and gaseous nitric acid, reportedly minimizing corrosion problems at higher temperatures.[3] Weak acid hydrolysis processes are currently being studied by several investigators attempting process improvements by improving equipment design. Recent developments include hydrolysis of high-concentration slurry fed through a continuous extruder and hydrolysis of wood chips fed directly through a novel steam pulping/acid hydrolysis device.

Equipment which can provide high temperatures and short time exposure of the biomass such as modified explosive defibration equipment could potentially increase glucose yield to approximately 70 percent of theoretical at about a 20 percent post hydrolysis glucose concentration. Such developmental processing alternatives are expected to significantly improve process economics and energy efficiency.

When high temperature and short contact time hydrolysis is performed in the presence of hemicellulose sugars, toxic materials (e.g., furfural) which inhibit the ethanol fermentation are produced. This toxicity problem can be successfully minimized either by addition of catalyst prior to hydrolysis and/or by flashing or steam stripping after hydrolysis.

Strong Acid Hydrolysis

Strong acid hydrolysis processes, originally developed primarily to produce crystalline glucose at >90% yield, are of increasing interest today because of recent advances in corrosion resistant materials of construction. Strong acid typically refers to processes using approximately 35 to 42% HCl or 70 to 80% H_2SO_4 to hydrolyze cellulose at very low temperatures (e.g., 20 to 45° C).

Strong acid processes also differ significantly in the methods of recovering strong-acid and sugars from the acid/sugar hydrolysate.[4] For example HCl is recovered from the Udic Rheinau hydrolysates in evaporators whereas HCl is recovered in the Nagouchi-Chisso flash saccharification process in a flash drier. The Hokkaido process, on the other hand, uses electrodialysis membranes to retain glucose while allowing the H_2SO_4 to pass through. The Hokkaido process has been demonstrated in a 100 ton/day facility. It has also been suggested that certain chemicals may suppress the solubility of glucose in the presence of H_2SO_4. The glucose thus precipitated can be removed along with the lignin and undigested cellulose by filtration from the acid. Each of the acid recovery processes investigated to date involves an energy intensive evaporation/reconcentration step.

Post hydrolysis glucose concentrations of up to 20 percent are possible. High glucose yield minimize feedstock costs, and high post-hydrolysis sugar concentration reduces downstream evaporation and ethanol recovery (distillation) costs. Prehydrolysis hemicellulose removal facilitates the attack of strong acid on the remaining cellulose. Along with the strong-acid hydrolysis processes, a variety of hemicellulose removal (prehydrolysis) processes have been developed. Hemicellulose sugars have been removed by weak-acid leaching, strong-acid leaching, and by steam with direct in-situ furfural production. In general, prehydrolysis hemicellulose removal leaves the lignincellulose matrix intact for easy recovery by filtration.

Enzymatic Hydrolysis

Enzymatic hydrolysis of cellulose has recently been the subject of considerable interest in the United States and abroad. However, commercialization of this approach has been held back thus far by such factors as pretreatment requirements, cost of enzymes, low volumetric production rates, and contamination hazards associated with low osmotic pressures, relatively low temperatures, and near neutral pH.

Effective pretreatment of lignocellulose prior to enzyme attack is particularly important in approaching high glucose yields by increasing cellulose availability. The pretreatment processes include mechanical, semi-chemical and chemical pulping operations. In general, chemical pulping operations will produce cellulose fibers relatively free of hemicellulose and lignin whereas mechanical and most semi-chemical pulping operations will not. In these latter operations the hemicellulose, lignin and cellulose remain in suspension. The availability of cellulose fiber to enzymatic attack varies with the degree of disruption of the lignin shields surrounding the cellulose fiber.

In general, chemical pulping processes are relativ- expensive requiring energy intensive recovery of pulping agents. It is necessary to select pulping processes that fit well into the overall processing scheme, in order to maximize energy recovery in commercial operations. The use of ethanol as a pulping agent has been considered.

The use of ethanol meshes well with enzymatic hydrolysis and fermentation. Pulping agent reconcentration could be accomplished in the beer still, and pulping agent lost with the cellulose would pass through the fermenter and would also be recovered in the beer still with minimal toxic inhibition of the fermentation. This type of pretreatment would provide high grade cellulose product to the hydrolysis, simultaneously producing separate lignin and hemicellulose concentrates as by-products.

Lignin and hemicellulose components of pulping processes do not necessarily adversely affect ethanol fermentation. Therefore, lignin and hemicellulose can be separated from the main product stream either prior to the hydrolysis step or after fermentation, in the beer still bottoms product.

Extensive studies of mechanical degradation of lignocellulose[5], such as by ball milling, have also indicated improvements in enzymatic hydrolysability. However, these pretreatment processes tend to be energy intensive.

Developmental activities are being carried out whereby the fermentation and enzyme hydrolysis steps are combined into one single operation.[6] As glucose is liberated from cellulose by enzymes, yeasts present in the solution convert the glucose quickly to ethanol. Since a high concentration of glucose retards (inhibits) both enzyme and yeast activity, combining hydrolysis and fermentation increases enzymatic rates, thus reducing total required vessel volume.

The combined enzyme hydrolysis-fermentation approach has also been constrained by a necessary compromise in operating temperatures. The temperature, which may be optimal for micro-organisms to convert glucose to ethanol, is likely to be suboptimal for enzyme hydrolysis. With current technology very large vessels are required to provide adequate residence time.

Enzyme cost in general has been high. However, the production costs have recently been significantly reduced by genetic improvements and further such improvements are deemed possible. Inexpensive enzymes would permit increased enzyme dosages. Higher enzyme dosage will increase glucose yields and concentrations, thus reducing downstream capital and operating costs.

A variety of micro-organisms produce cellulases with differing properties. QM 9414 mutant of *Trichoderma viride* has received the most genetic development because its range of cellulase enzymes is particularly well balanced. Optimum hydrolysis temperatures are on the order of 50° C. Alternative organisms such as *Schizophylum commune* are also reportedly the subject of genetic studies, because, in addition to having a range of cellulases, they reportedly produce ligninases, and have an optimum cellulose hydrolysis temperature of less than 40° C.

In addition to these aerobic organisms, a number of anaerobic cellulase producers are being studied. In particular, organisms which both hydrolyze glucose and produce ethanol are of increasing interest. Although an enzymatic hydrolysis plant built today would probably be designed based on *T. viride* enzymes, the same plant would probably be capable of changing to alternative enzymes from other organisms should future genetic studies prove successful.

FERMENTATION

Numerous fermentation schemes, utilizing *Saccharomyces cerevessie* (a yeast) will ferment hexose (e.g., glucose, mannose) sugars with approximately the same yields of ethanol, although schemes that retain and reuse cell mass reportedly increase yields marginally as compared to batch fermentation. The technical challenge involves selecting fermentation schemes on the basis of compatibility with pretreatment processes and cost effective operation of the overall processing scheme. Current operations are mostly carried out in batch fermenters.

Batch fermentation assures minimum contamination hazards and simplest operation, but has large fermentation volume and labor requirements.

Semi-continuous and continuous cell (yeast) recycle operations, equipped with appropriate cell wash steps, are relatively high rate, cost effective schemes provided the fermentation feed from pretreatment is low in nondegradable suspended solids. Applied to hydrolysate (sugar) fermentation, semi-continuous cell recycle operations reduce fermenter batch times to as low as 6-12 hours compared to approximately 48 hours for typical conventional batch fermentations. Faster rates result in smaller fermenters and lower capital costs.

Continuous cascade of open vats is currently applied to ethanol production from sulfite waste liquor, thus approaching plug flow digestion of hexoses. The mixed tank residence time and utilization of sugars are improved. It is less sensitive to slugging and process upsets than continuous fermentation with a single fermenter.

Packed columns, settling tower fermenters, and vacuum fermenters, like cell recycle fermentations, maximize the active yeast cell mass population in the fermenters, thus increasing fermenter productivity rates. Vacuum fermentation also maximizes productivity by removing the ethanol as it is formed.

High cell mass operations are adversely affected by high concentrations of inert suspended solids. In addition, vacuum fermentation is also affected by dissolved solids, thus requiring a relatively pure hexose or "cellulose" feed stream. Even with a "pure" feed stream, vacuum fermenters, as proposed by several researchers will have to be evaluated on the basis of large-scale operability, capital costs, and operating costs.

Low cost of open vat fermenters have proved satisfactory for both molasses and wood sugar commercial fermentations and are currently used commercially for a number of such processes. Generally, about three percent of the ethanol product is estimated lost with the CO_2 leaving open vats. Covered vats may prove ideal for a larger scale process. For newer fermentation schemes such as combined hydrolysis and fermentation, versatile high technology vessels (i.e., aerated, agitated) will be required to facilitate onsite production of Trichoderma viride, Schizophylum commune or alternate cellulase enzyme producing organisms. Fermentation of hemicellulose sugars to fuels and chemicals utilizing C_5 and C_6 sugars simultaneously will also require more advanced vessel designs since precise dissolved oxygen and oxygen transfer are often needed for the multi-organism fermentation.

PRODUCT RECOVERY

Ethanol produced in the fermenter at 2 to 12% concentration can be readily distilled from the fermentation beer to a 50 to 80% overhead product. Steam requirement for the beer still is a strong function of initial beer concentration. Further concentration to the 95% ethanol azeotrope is energy intensive. Production of absolute alcohol (100% ethanol) is usually accomplished by processing the beer still overhead product in a pair of azeotropic distillation columns. The azeotropic distillation involves azeotroping agent (e.g., benzene) trapped in the two column system with water exiting the base of the first column and ethanol exiting the base of the second. Since commercial azeotropic distillation schemes for producing absolute ethanol are all energy intensive, lower energy consuming schemes are being investigated.

Extractive distillation (50 to 80% ethanol) involving purifying the beer still overhead (50 to 80% ethanol) product by absorbing the ethanol in an extractive agent is being investigated as an alternative to azeotropic distillation. In this case, the relative volatility of water and ethanol are reversed, the water is forced overhead. The ethanol is separated from the extractive distillation agent in a second column, and the extractive agent is recycled. Alternatively, ethanol can be absorbed in gasoline (extractive agent), in which case a 10% ethanol solution is produced, and the second extractive agent regeneration column can be eliminated. This latter operation is particularly attractive, because it could potentially reduce the energy requirement of the separation, and because denaturing the product inline simplifies the government monitoring required for ethanol production.

Alternative operations such as liquid-liquid extraction of ethanol and recovery of ethanol with recently developed hydrophobic molecular sieves are also potentially of interest. These operations are still developmental with no known commercial applications to date.

BYPRODUCT UTILIZATION

Production of ethanol from lignocellulosic biomass will result in significant quantities of lignin and hemicellulose by-products. These by-products must be used to generate energy or be marketable in order to influence the total process economics in a favorable manner. A number of products can be produced from lignin. These include phenolic compound such as cresols, catechols, substituted phenols, and vanillin. With fast thermolysis, acetylene and ethylene can also be produced. The lignin market of today can easily be saturated by a major national cellulose conversion program. Therefore, the impact of producing chemicals from the conversion program must be assessed.

It is well known that hemicellulose sugar by-products could be used as animal feed, or converted to furfural and hydroxymethyl furfural or their derivatives. Furfural derivatives such as furfuryl alcohol, furan, tetrahydrofuran, maleic acid and anhydride, fumaric acid, and a score of other chemical derivatives could be reconsidered in view of an inexpensive furfural supply. Hydroxymethyl furfural (from C_6 hemicellulose) derivatives which include polyester, resin, nylon 6, nylon 66, and a variety of other materials may also become attractive as a result of rising petrochemical feedstock prices. Hemicellulose C_5 and C_6 carbon sugars can be used as fermentation substrates producing a variety of chemicals such as butanol, acetone, acetic acid, and methane. Hemicellulose C_6 sugars can be converted to ethanol as mentioned earlier. Hemicellulose C_5 sugars can be partially converted to ethanol by appropriate organisms. As with lignin, the production of chemicals from this by-product source needs extensive analysis.

SUMMARY

Considerable development activities remain with individual process steps to snythesize the most efficient overall process. Areas of particular interest include, --

- Sugar liberation
- Continuous fermentation
- Novel ethanol recovery techniques
- By-product utilization
- Overall energy efficiency

The major alternative ways of liberating sugars are all currently subject to further R&D efforts. The best alternative is not yet apparent. For example, the equipment to subject lignocellulose to weak acid at high temperature and short residence time needs further development. The use of solvent to suppress the solubility of glucose in order to recover the strong acid appears to be an intriguing concept which deserves further consideration. Development of enzymatic hydrolysis processes require the selection of most compatible pretreatment to maximize yield and minimize energy consumption. Genetic manipulation of microorganisms may further improve the efficiency of enzymatic hydrolysis.

Continuous fermentation and combined hydrolysis-fermentation are being studied to maximize productivity per unit fermenter volume, thus reducing fermentation costs. The combined enzyme hydrolysis-fermentation process appears to be promising. However, effective pretreatment is required to expose the cellulose fiber to enzymatic attack. New microorganisms need to be identified which can both prod the enzymes to degrade the lignocellulose and simultaneously ferment the sugar produced to ethanol. These steps must be compatible and synergistic.

Novel ethanol recovery/dehydration techniques require development and demonstration to improve process energy efficiency. Extractive distillation with gasoline, liquid-liquid extraction, and hydrophobic molecular sieves are examples of potentially energy efficient processes which require further study.

By-product utilization studies of particular interest include the conversion of lignin to chemicals and fuels, and the conversion of hemicellulose via furfural and hydroxymethyl furfural to chemicals. In addition, hemicellulose can be converted via fermentation to chemicals such as butanol and acetone, but genetic and process improvement are required to increase fermentation yields.

Overall process energy yields are of extreme importance in converting cellulose to ethanol fuel. Further efforts could significantly reduce the energy requirements for well designed commercial scale processes. In particular, energy requirements for liberation of sugars, ethanol recovery and by-product utilization must be carefully examined. Processes must be integrated to maximize overall energy cascade and recovery.

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A COMPARATIVE ECONOMIC ANALYSIS OF ALCOHOL FUELS PRODUCTION OPTIONS

by

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INTRODUCTION

Alcohol fuels are suitable for use in many applications where liquid fuels from petroleum are now used. During late 1977, the U.S. Department of Energy established an Alcohol Fuels Task Force to evaluate the potential of alcohol fuels. One of the major findings of the task force was that " ... the high cost of alcohol fuels relative to conventional sources of petroleum appears to be the major obstacle to widespread commercialization."[1]* After a report was issued by the Alcohol Fuels Task Force [2], the Department of Energy undertook an intensive review of alcohol fuels, with specific attention given to economic, technological, supply, and institutional barriers that prevent or deter commercialization.

Because of SRI International's extensive experience in the technical and economic evaluation of conversion processes for producing alcohol fuels, the Department of Energy selected SRI to prepare a comprehensive study of alcohol fuels production (technology and economics) to be used by the Department of Energy's Alcohol Fuels Policy Review.

The short-term study by SRI was completed in November of 1978 and a report was issued to the Department of Energy in the form of a working paper or discussion draft. [3] The report is not available as a final published project report but much of the report was based on SRI work completed or in progress at the time under contract EY-76-C-03-0015 PA-131 with the DOE Fuels from Biomass Branch. Final reports prepared under the Fuels from Biomass Branch project have subsequently been completed and are available through the United States National Technical Information Service [4,5,6].

The principal objective of the SRI study for the DOE Alcohol Policy Review was to prepare a comparative economic analysis of alternative alcohol fuel production technologies from a variety of feedstocks using a consistent set of design and economic bases. The technologies considered in the study ranged from commercially available processes to conceptual processes being developed in laboratory scale equipment. The feedstocks considered ranged from those now readily available, such as bituminous coal, lignite, municipal solid waste, and sugar cane, to those that are not now items of commercial trade, such as corn stover and wheat straw. The capacity of alcohol fuel production plants was specified based on consideration of feedstock availability and conversion plant economies of scale. The study illustrated the effect on alcohol fuel price of variations in conversion plant production capacity, feedstock cost, by-product credits, financing, and rate of return requirements.

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*Numbers in brackets [1] designate References at end of paper.

SELECTION OF CASES FOR ANALYSIS

The selection of feedstocks and of alcohol fuels production technologies was actually done concurrently because certain feedstocks may not be appropriate for all production processes. Table 1 summarizes the feedstocks and processes that were selected for the study. The seven different cases listed are those selected by DOE based on suggestions by SRI. The primary reasons for selection of the specific conversion processes are listed in the table.

It would have been desirable to consider an even wider variety of feedstocks in the study, such as several grades of coal (bituminous, subbituminous, lignite) a number of agricultural crops (grains--corn and wheat; sugar crops--sugar cane, sweet sorghum, and sugar beets), a number of agricultural residues (manures, wheat straw, rice straw, rice hulls, corn stover, soybean plant residues, fruit and vegetable processing plant residues), several types of forestry residues (logging residues, mill bark), and municipal wastes (solid waste or refuse, sewage sludge). Because of the short time frame for this study and the budgetary constraints, however, only those feedstocks that appear to be potentially available in large quantities and are relatively attractive (from a chemical composition standpoint) for alcohol fuels production by the processes selected were considered for analysis.

SELECTION OF FEEDSTOCK COST RANGES

Because feedstock costs will vary with demand requirements, it is necessary to roughly approximate the tonnages that may be required to establish base-case costs. If one assumes that the goal is to replace 10% of the current liquid transportation fuel* with alcohols (on an equivalent Btu basis), and that half will be ethanol from biomass and the other half methanol from coal, the annual feedstock requirements could be on the order of 90 million tons of coal and 300 million dry tons of biomass. Such an increase in coal demand is not likely to appreciably affect the future price for coal relative to other forecast changes in demand. The price for 300 million dry tons of biomass is difficult to estimate. The price will vary widely by type of crop or residue, the locale, and the quantity required at a specific site. Costs for specific feedstocks were estimated based on previous SRI studies and recommendations from the Alcohol Policy Review. The estimated feedstock costs are summarized in Table 2. Note that in the case of MSW, a tipping fee is charged and thus there is a payment made to the conversion plant operator for accepting the waste.

ETHANOL PRODUCTION CASES

The base-case ethanol plant capacity of 25 million gallons of ethanol per year (95 vol%) was selected on the basis of feedstock availability and plant economies of scale. The fermentable sugar solution that can be produced from hydrolysis of carbohydrates ($<$ 20 wt%) or from direct extraction or expression from sugar crops ($<$ 15 wt%) may be suitable for feeding directly to the fermentation operation (12-14 wt% desired). To ship this relatively dilute solution any distance would be prohibitively expensive, and further concentration of the solution would also be expensive. Therefore, the most economically attractive situation would appear to be to locate the C_6 (or C_{12}) sugar production facility adjacent to the fermentation facility. A plant with a capacity of 25 million gallons per year would require 500 tons per day of C_6 sugar equivalent.

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*This is not a goal established by the Department of Energy but was selected only as a basis for analysis in this study.

Table 1

SPECIFIC CASES TO BE EVALUATED FOR LARGE CAPACITY ALCOHOL FUELS PRODUCTION FACILITIES

Case	Alcohol Fuel Product	Approximate Quantity of Alcohol Product 10^9 Btu/d‡	Approximate Quantity of Alcohol Product Gal/d	Approximate Quantity of Alcohol Product 10^6 gal/yr	Feedstock Type	Feedstock Quantity (tons/d)	Status of Technology	Process Description	Reasons for Selection of Process Options
1	EtOH	6.1	76,000	25* (12.5 to 50)†	Fermentable Sugar (Unspecified source)	~ 500	Commercially available	Ethanol Production - Batch Fermentation	A typical, commercially proven process now widely used for fermentation ethanol production. Process design and cost data available at SRI.
							Commercially Available	Ethanol Recovery - Continuous Distillation	A typical, commercially proven process now widely used for ethanol recovery production. Process design and cost data available at SRI.
2	EtOH	6.1	76,000	25* (12.5 to 50)	Fermentable Sugar (unspecified source)	~ 500	Conceptual Design	Ethanol Production - Continuous Fermentation	A possible process option that may significantly reduce capital requirements and labor costs per unit of product output.
							Conceptual Design	Ethanol Recovery - Improved Separation Process	A possible process option that could improve the overall process energy balance
3a	EtOH	6.1	76,000	25* (12.5 to 50)†	Wheat straw	~ 3000	Research and development stage	Sugar Production - Enzymatic Hydrolysis to produce sugars from lignocellulosic materials	A class of advanced hydrolysis processes now being developed that appear to be technologically feasible:
3b	EtOH	6.1	76,000	25* (12.5 to 50)†	Corn stover	~ 1500	Research and development stage	Sugar Production - Purdue Hydrolysis Process to produce sugars from lignocellulosic materials	A specific acid hydrolysis process now being developed that could significantly increase the efficiency of hydrolysis.
4	MeOH	127.6	2,000,000	660* (330-990)†	Lignite	~19,000	Commercially available	Synthesis Gas Production - Koppers-Totzek Gasifier	Commercially proven for synthesis gas production. Produces relatively small amount of organic liquids. Can handle caking coals. Process design and cost data available at SRI.
							Commercially available	Methanol Synthesis - ICI Process	Most commonly used process for commercial plants built during last decade. Process design and cost data available at SRI.
5	MeOH	6.3	97,000	32* (21 to 64)†	Municipal Solid Waste	~ 1500 (as received)	Available for commercial use	Synthesis Gas Production - Union Carbide Purox Process	Union Carbide has operating experience in near commercial scale reactors for production of synthesis gas from MSW. Process design and cost data available at SRI
							Commercially Available	Methanol Synthesis - ICI Process	Same as for Case 4
6	MeOH	127.6	2,000,000	660* (330-990)†	Bituminous Coal	~ 8950	Advanced Development stage	Synthesis Gas Production - Texaco Partial Oxidation Process	Process has relatively high thermal efficiency and operates at desirable pressure (~ 1000 psi) for methanol production. Can handle caking coals. Process designed and cost data available at SRI.
							Development Stage	Methanol Synthesis - Chem Systems Process	Appears to be one of most promising new MeOH synthesis processes now under development. Process design and cost data available at SRI.
7	MeOH	11.1	172,000	57* (29 to 170)	Wood	~ 1000 (dry)	Development stage	Synthesis Gas Production - Pressurized Fluidized Bed Gasifier	Reactor is pressurized and has a high volumetric throughput rate. Process design and cost data available at SRI.
							"	Methanol Synthesis - Chem Systems Process	Same as for Case 6,

*Base case plant capacity.

†Range of plant capacities to be considered.

‡ Based on higher heating value.

Table 2

SUMMARY OF FEEDSTOCK COST ESTIMATES

Feedstock	Plant Location	Feedstock Cost (delivered to plant gate)			
		Base Case		Range	
		(\$/ton)*	(\$/10^6 Btu)	(\$/ton)	(\$/10^6 Btu)
Lignite	N. Dakota	\$ 7	\$0.50	\$ 5.5-9.0	\$0.39 to 0.64
Bituminous coal	Illinois	24.5	1.00	18.4-30.0	0.75 to 1.25
Wood and wood residues	Northwest/Southeast	19	1.00	10 to 30	0.53 to 1.58
Crop residues					
Corn stover	Ill/Ind/Iowa	25	1.67	15 to 35	1.0 to 2.3
Wheat straw	Kansas/Nebraska	25	1.67	15 to 35	1.0 to 2.3
Sugar crop (sugar cane)	Florida, Louisiana	65	4.3	50 to 65	3.3 to 4.3
Municipal solid waste	Large East Coast City	-12 (credit)	-1.33 (credit)	-6 to -18 (credit)	-0.7 to -2.0 (credit)

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*Dry tons except for coal.

For the analysis of ethanol production economics, the production of C_6 or C_{12} sugar was considered as one venture and the fermentation plant as a separate venture. Cost correlations of ethanol price as a function of the sugar cost to the fermentation plant operator and the sugar concentration were prepared for Cases 1 and 2. A conventional batch fermentation plant was considered in Case 1. A conceptual continuous fermentation plant with a somewhat improved ethanol distillation system was considered in Case 2. (See Reference [7] for details.)

The cost correlations developed in Cases 1 and 2 were used to estimate ethanol prices from a number of different C_6 or C_{12} sugar sources. The sugar prices estimated for DOE early in 1978 using a sugar cane feedstock and an aquatic biomass feedstock were used as input data for a portion of the study. To supply sugar from cane on the mainland of the United States would require concentration and storage of 50% of the sugar solution produced because the processing season is only 165 days per year at most. Therefore, a plant would have to produce close to 1000 tons of fermentable sugar (in solution) per day. Some plants in the United States approach this capacity and therefore it should be possible to supply a 25-million-gallon-per-year plant with cane sugar. Other sugar crops are also potential sugar sources. For example, supplying a 25-million-gallon ethanol plant with beet sugar should also be possible but would probably be more expensive. (Such a quantity of sugar from sweet sorghum is not now produced but SRI did consider the production of ethanol from a conversion plant processing both sugar cane and sweet sorghum in a later study [6].)

The production of C_6 sugars from aquatic biomass is highly speculative relative to the possibilities of C_6 sugar production from sugar crops. The details concerning the estimation of sugar price from this source are given in Reference [5].

A special ethanol production case considered in the study concerned the use of a food processing waste--cheese whey. The ethanol plant capacity in this case was small relative to the other cases previously described. The results of that analysis are described in the summary of findings section.

The use of agricultural residues was considered for C_6 sugar production in Cases 3a and 3b (see Table 1). A conceptual enzymatic hydrolysis process was considered in Case 3a and an acid hydrolysis process being developed at Purdue University was considered for Case 3b. (See References [5] and [6] for a detailed discussion of these technologies.) Wheat straw and corn stover were chosen the feedstocks because of the tonnage of these materials potentially available and their relatively high density in specific regions compared with other crop residues. SRI has estimated for the year 1975 that about 75% (or 94 million dry tons) of the approximately 122 million dry tons of high-moisture-content herbaceous agricultural residues were from corn production. For the same year, about 50% (or 117 million dry tons) of the low-moisture-content herbaceous agricultural residues were from wheat production. To supply the fermentable sugar requirements of a 25-million-gallon ethanol plant may require 1500 to 3000 dry tons per day of residue (specific amount depends on chemical composition of residue and the process conversion efficiency) or about 0.5 to 1.0 million dry tons per year.

To supply 2000 dry tons per day would probably require collection of residues from a crop production area in excess of 500,000 acres, which means collection from an area within a 15+ mile radius of the plant site. It is not certain that such a tonnage of material could actually be economically transported to the plant site. Therefore, for an ethanol plant supplied by agricultural residues, 25 million gallons per year may be the maximum plant capacity. Ethanol prices from corn stover and wheat straw were estimated using the cost correlations developed in Cases 1 and 2.

METHANOL PRODUCTION CASES

Methanol production from coal was considered in Cases 4 and 6. Currently most of the large methanol plants produce ≤ 2500 tons of methanol per day (≤ 750,000 gal/day) from steam reforming of natural gas. Proponents of methanol fuel plants are considering single-train process units with a capacity to produce between 750,000 to 1,500,000 gallons per day of methanol, with total plant capacities as high as 9 million gallons per day. The plant size specified for the bituminous coal-to-methanol case would have two process trains and a total output of 2 million gallons per day (660 million gallons per year). The coal feedstock requirement for the plant would be 8950 tons per day. Note that 8950 tons per day is approximately the same tonnage as is required to operate a 1000-MW coal-fired power plant (heat rate ~ 9500 Btu/kWh and a capacity factor of 0.75). Numerous large coal-fired power plants in many regions of the country burn far more coal than this. For example, the 1400-MW coal-fired plant operated by Pacific Power and Light Co. at Centralia, Washington, burns about 15,000 tons per day of coal. The large coal gasification plants (250 million scf CH_4/day) now being proposed would require on the order of 25,000 tons per day of coal to supply coal for gasification as well as plant utility requirements. Therefore, the plant being proposed for the base-case analysis as well as the range of plant capacities for cost sensitivity analysis appear to be reasonable in size from the standpoints of both process capacity and feedstock availability.

Production of methanol from municipal solid waste (MSW) was considered in the Case 5 analysis. Because of the logistics of collection and transportation of MSW, no resource recovery plants are currently being designed to process more than 3000 tons of as-received solid waste per day. The base-case plant size of 1500 tons per day will produce only about 5% of the quantity of methanol that will be produced by the base-case coal-to-methanol plants being considered in Cases 4 and 6. This MSW-to-methanol plant, however, will produce approximately the same amount of alcohol on a heat content basis as an ethanol plant with a capacity of 25 million gallons per year.

Methanol from wood was considered in the Case 7 analysis. The output of the base-case methanol plant will be almost twice that of the MSW-to-methanol plant. Approximately 1000 dry tons per day of wood or wood residues will be required to produce 172,000 gallons per day (57 million gal/yr) of methanol. Approximately 1000 dry tons per day of wood fuel will be required for the DOE-funded power production project planned for New England or the Burlington, Vermont, wood-fired power plant project. A plant capacity of 170 million gallons per year (requiring 3000 dry tons/day) was selected as the upper limit because of feedstock availability. Several pulp and paper mills in the United States currently receive more than 4000 dry tons per day of wood, but it is unlikely that any other sites could be found to duplicate such an operation. Most of the sites with substantial wood availability are already taken.

ECONOMIC ANALYSIS APPROACH

For each feedstock/conversion process/alcohol product option considered, a preliminary process design was completed in sufficient depth to allow a preliminary estimation of the investment cost, operating labor, utility, and feedstock requirements. Process flowsheets were prepared, mass flowrates were calculated, and overall plant mass balances were prepared. All the cost estimates were developed by using a consistent set of design and economic bases as summarized in the Appendix. An SRI-developed computer model was used to calculate revenue requirements for two types of ventures, the first being a typical industrial venture with 100% equity financing and a 15% discounted cash flow rate of return and the second being a highly leveraged (large debt financing) regulated utility type venture. (See Appendix for a description of the two types of ventures and a listing of the design and economic bases). All economic data are presented in first-quarter 1978 dollars.

SUMMARY OF FINDINGS

The estimated prices for ethanol and methanol are shown in Figure 1 for the feedstocks and conversion processes considered. Most of the estimated prices shown are those calculated for highly leveraged regulated ventures. Because one of the major proposed uses for alcohol fuels is as a supplement to or substitute for petroleum-derived transportation fuels, it is appropriate to present some reference prices for gasoline and chemical grade alcohols to provide perspective; these prices are shown in Table 3. Fuel-grade methanol and ethanol will not need to meet the high purity standards for methanol and ethanol products now marketed as chemical commodities. Therefore, prices would probably be somewhat lower. Also note that the prices listed in Table 3 are for nonregulated ventures and most of those in Figure 1 are for regulated ventures. Prices for alcohol fuels are presented on a dollar-per-million-Btu basis as well as on a dollar-per-gallon basis. It should be borne in mind that a gallon of ethanol has close to two-thirds the fuel value of gasoline and methanol has about one-half the fuel value.

Table 3

MARKET PRICES FOR GASOLINE AND ALCOHOLS

Item	Market Price (first-quarter 1978) $/Gal	 $/Million Btu
Gasoline	0.4	~ 3
Methanol	0.45-0.55*	7.0-8.6
Ethanol		
190-proof (95 vol%)	1.2†	14.9
199-200 proof	1.3†	16.2

*Plant gate, nonregulated financial venture basis.

†Delivered, no federal tax included; nonregulated financial venture basis.

The findings concerning alcohol fuel prices (based on first-quarter 1978 prices) are as follows:

Methanol Prices

- Coal feedstocks can be delivered in large quantities and at relatively low prices ($0.5 to $1.0/million Btu) to mine-located methanol fuel production plants. Hence, coal-to-methanol plants may be designed for larger capacities and can realize large economies of scale.
- Based on the results of this study, large coal-to-methanol plants (1 to 3 million gallons of methanol/day) using either existing or advanced technologies should be able to produce the lowest priced alcohol fuels--$5.0 to 7.0 per million Btu (or $0.32 to $0.45/gal)‡ from regulated ventures.
- Estimated methanol prices are much higher for a nonregulated venture relative to a regulated venture (because of the higher rate of capital recovery for the nonregulated case). For example, for the bituminous coal-to-methanol case, the methanol price would probably increase 45% or from about $4.8/million Btu ($0.32/gal) for the regulated venture to $6.9/million Btu ($0.44/gal) for the nonregulated venture.

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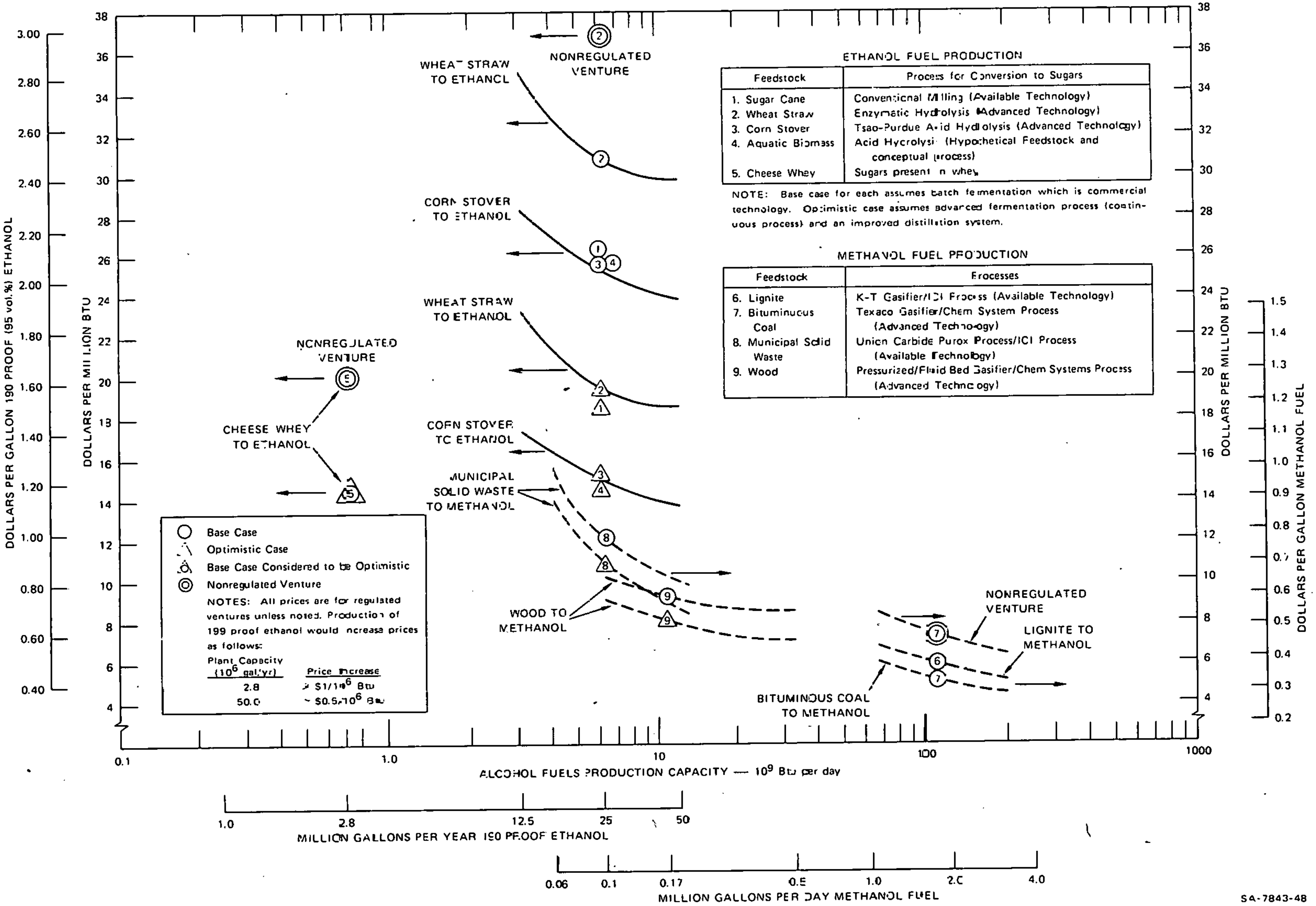
‡The lower cost applies to the plant of larger capacity; that is, the price of $0.32/gal applies to a 3-million-gallon-per-day plant.



ETHANOL FUEL PRODUCTION

Feedstock	Process for Conversion to Sugars
1. Sugar Cane	Conventional Milling (Available Technology)
2. Wheat Straw	Enzymatic Hydrolysis (Advanced Technology)
3. Corn Stover	Tsao-Purdue Acid Hydrolysis (Advanced Technology)
4. Aquatic Biomass	Acid Hydrolysis (Hypothetical Feedstock and conceptual process)
5. Cheese Whey	Sugars present in whey

NOTE: Base case for each assumes batch fermentation which is commercial technology. Optimistic case assumes advanced fermentation process (continuous process) and an improved distillation system.

METHANOL FUEL PRODUCTION

Feedstock	Processes
6. Lignite	K-T Gasifier/ICI Process (Available Technology)
7. Bituminous Coal	Texaco Gasifier/Chem System Process (Advanced Technology)
8. Municipal Solid Waste	Union Carbide Purox Process/ICI Process (Available Technology)
9. Wood	Pressurized/Fluid Bed Gasifier/Chem Systems Process (Advanced Technology)

○ Base Case

△ Optimistic Case

△ Base Case Considered to be Optimistic

◎ Nonregulated Venture

NOTES: All prices are for regulated ventures unless noted. Production of 199 proof ethanol would increase prices as follows:

Plant Capacity (10^6 gal/yr)	Price Increase
2.8	≈ \$1/10^6 Btu
50.0	~ \$0.5/10^6 Btu

FIGURE I SUMMARY OF ESTIMATED PRICES FOR ALCOHOL FUELS

- Using advanced technologies, large wood-to-methanol plants (100,000 to 500,000 gallons of methanol/day) are potentially the second cheapest source of alcohol fuels--\$8.5 to \$10 per million Btu (\$0.54 to \$0.64/gal) with a delivered wood cost equivalent to about \$1 per million Btu, and \$7 to \$9 per million Btu (\$0.45 to \$0.58/gal) with a delivered wood cost equivalent to about \$0.5 per million Btu (regulated ventures).
- Using available (although not commercially demonstrated) technology, municipal solid waste-to-methanol plants are potentially the third lowest price source of alcohol fuels of the options considered. The methanol price is strongly influenced by the fee paid to the conversion plant to accept the solid waste (tipping fee).* For tipping fees of \$12 to 18 per ton† and plant capacities to produce about 70,000 to 200,000 gallons of methanol per day, methanol prices would range from \$8-15 per million Btu (\$0.51 to 0.96/gal) for regulated ventures.

Ethanol Prices

- Estimated ethanol prices are also considerably higher for a large nonregulated venture as compared with a large regulated venture. The price will typically be about 20% higher for the nonregulated venture.
- Use of existing sugar crops (such as sugar cane, or sugar beets) as sources of sugar for fermentation to ethanol would probably allow production of 190-proof ethanol for a price of ≥ \$26 per million Btu (or ≥ \$2.1/gal) using existing technology. By assuming an optimistic feedstock cost and using advanced fermentation technology, the ethanol price might be reduced to ≥ \$18 per million Btu (or ≥ \$1.45/gal). The prices quoted above are for regulated ventures with a capacity to produce 25 million gallons per year (~ 76,000 gal/day) of 190-proof ethanol.‡
- Use of existing crop residues (such as wheat straw or corn stover) and advanced technologies to produce sugars and ferment the sugars to ethanol might result in ethanol prices (optimistic cases) ranging from \$14-24 per million Btu (or \$1.1 to 1.9/gal) for regulated ventures ranging in capacity from about 38,000 to 150,000 gallons of ethanol per day.

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*A tipping fee is equivalent to a negative feedstock cost.

†Tipping fees of \$12 to \$18 per ton are not likely except in very large metropolitan areas.

‡Using advanced sugar cane processing techniques, continuous fermentation, and two feedstocks (sugar cane and sweet sorghum), the ethanol prices from a regulated venture may be as low as \$1.20/gal [6].

- Some other potential sources of sugars for fermentation are aquatic biomass, wood, or sweet sorghum. Processing of these feedstocks might allow production of ethanol at prices ranging from $14 to 26 per million Btu (or $1.1 to $2.1/gal) for regulated ventures with a capacity to produce about 76,000 gallons of ethanol per day.
- Small capacity production operations may be able to produce ethanol at prices competitive with several other sources considered. Fermentation of cheese whey was the specific case analyzed in this study. For a regulated venture producing about 8,000 gallons ethanol per day, the ethanol price could be as low as $14-15 per million Btu (or $1.1-1.2/gal) if the whey is free at the dairy plant gate and if significant revenues are produced from sale of the fermented whey solids.
- To produce 199-proof fuel-grade ethanol from a 190-proof product would increase the price by $0.5 to 1.0 per million Btu (0.04 to $0.08/gal) depending on the plant capacity.

General Observation

- Both ethanol and methanol production operations are capital-intensive operations. Because methanol production operations have relatively high conversion efficiencies and generally lower feedstock costs (particularly for coal-based plants), they can produce alcohol at relatively low costs that tend to be dominated by fixed capital charges. On the other hand, ethanol production entails high feedstock costs and low conversion efficiencies, so that the feedstock cost is generally the major component of the total operating cost despite the high capital investment.

NOTICE

The estimated alcohol fuel prices presented in this paper may be revised by the Department of Energy due to changes in the bases for the financial analysis.

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Appendix

SUMMARY OF ECONOMIC ANALYSIS AND DESIGN BASES

Capital Investment Estimates (First-Quarter 1978 Dollars)

- All plant utilities except electric power generation are included in the plant facilities investment. Plant general service facilities are also included, such as office buildings, laboratory, maintenance and supply shops, plant roads, and sewers.

- Working capital includes 3 months of total labor expense, 2 months of other cash operating expenses, and 5 days of feedstock supply.
- Land costs are assumed to be $5000/acre.
- Organization and start-up costs are estimated as 5% of the plant facilities investment. Regulated utility start-up costs are capitalized, whereas nonregulated industry start-up costs are expensed.

Plant Operation

- After start-up is completed, the plant is assumed to operate at design capacity the equivalent of approximately 90% of the time unless specified otherwise. This level of operation is assumed in the first full year of operation and thereafter.
- Maintenance materials and supplies are estimated as 2% of the plant facilities investment.

- The following assumptions are used for conversion plant operating labor:

- Plant operating labor ($/hr)	8
- Plant supervision (% of plant operating labor)	15
- Maintenance labor (% of plant facilities investment)	2
- Administrative labor (% of operating, supervision, and maintenance labor)	20
- Payroll burden (% of all labor)	35

- Purchased utilities include electric power at 2.5¢/kWh and fresh water at $0.6/1000 gallons.
- Fixed costs such as local property taxes and insurance are estimated to be 2.5% of the plant facilities investment. General administrative and overhead expenses are assumed to be 2% of the plant facilities investment.

Financial Analysis

- Federal and state corporate taxes are assumed to total 52% applied to taxable income.
- No investment tax credit is considered.
- Depreciable investment includes:

  Regulated utility--plant facilities investment, interest during construction, paid-up royalties (if any), and start-up expenses

  Nonregulated private venture--plant facilities investment and paid-up royalties (if any).

- For the regulated utility case, the rate base in any year is the sum of the undepreciated plant investment, the cost of land, and the working capital. The return on rate base is a weighted average of the return on equity and the simple interest rate on debt as explained in References [4] and [5]. It is equivalent to a rate of return of $\sim$ 11%.
- For the nonregulated private venture case, a discounted cash flow (DCF) analysis is used with the DCF rate of return equal to 15%.
- The other important bases used for the financial analysis are summarized below:

	Regulated Utility Venture	Private Nonregulated Venture
Debt capital	65%	0
Equity capital	35%	100%
Debt capital interest rate	9%	--
Return on equity capital	15%	15%
Depreciation tax life	20 years	16 years
Depreciation method	Straight-line	Sum of years' digits
Interest rate during construction on debt capital	10%	--

THE PRODUCTION OF METHANOL FROM WOOD, PROCESSES, FORESTING AND ECONOMICS

by

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RENEWABLE SOURCES OF ENERGY

Over a few generations mankind has used and wasted energy accumulated by nature in millions of years and is still doing so. All of us are taking our share in this giant robbery of natures jewellery. Many people have reminded us of the mortality of civilisation on this globe. The human dream has been ever since we have realized this situation, to make proper use of solar energy, which at the same time is transmitted to our globe in abundance, but dissipated over its surface. Apparently the problem is collecting and accumulating this energy. According to these two basic requirements we can distinguish between systems for the utilization of solar energy, which merely collect this energy and those, which also permit its accumulation over a more or less extended period of time. Solar energy collectors have been designed to provide for instance electric power or heating energy for domestic use. These devices have good conversion efficiences, but are poor in accumulation. So the most effective heating can be provided at times when heat is not required in our houses; we should better run refrigeration on this basis. More advanced systems are those, the principles of which nature has donated to us and which allow accumulation of energy but have low conversion efficiency. Biomass produced by annual crops is perhaps the first of its kind and is already being used in the fermentation of alcohol for use as a vehicle fuel. The next of its kind, permitting energy accumulation over a slightly longer period than one year is hydroelectric power generation and here we should realize, that the driving force of this hydroelectric power cycle again is solar radiation. There are areas where hydroelectric power can be made available in the abundance. Hydrogen could be generated by electrolyses of water, but unfortunately this process is not suited for the production of methanol unless we provide a carbon donator from outside the system.

The third of the kind of energy accumulating and collecting systems is artificial foresting. Wood represents the accumulation of solar energy over a number of years. Artificial foresting requires systematic planting of those trees, which offer the best yields of roundwood. In turn these are the trees offering the best conversion efficiency of solar energy.

A macroscopic ecological equilibrium can be established by producing methanol from wood and using this methanol as a fuel in largely speaking the same area. This ecological equilibrium can be shown in the form of a material cycle presented in figure 1. It can be seen, that the atmosphere serves as a huge reservoir of all the components taking part in this cycle.

WOOD AS A RENEWABLE SOURCE OF ENERGY

So far wood has been shown as a prospective candidate to provide a collected and accumulated form of energy. Of course this does apply to certain areas but it does not apply to others and furthermore there are types of trees more or less suitable for our purpose. Obviously climatic conditions can make an area unsuitable for artificial foresting, but so can alternate applications like agricultural use as well and finally an area might be inaccessible for heavy machines needed in artificial foresting. To some extent this already narrows down our vision of a worldwide artificial foresting system to provide our vehicles fuel. The types of trees, their roundwood yields and their overall conversion efficiency of solar energy have been investigated in the state of Sao Paulo in Brazil. Some data are shown in table 1, which for reference purpose also shows respective figures from some other places.

Table 1

Typical Biomass Production Rates and solar energy conversion efficiencies (1), (2), (3), (4)

Crop	Area	Production Rate *) to/ha x a.	Solar Radiation kWh/a.	Conversion efficiency %
Maximum by hypothesis	US-average	224	1650	6,6
	US-southwest	263	1950	6,6
Achieved figures:				
Sugar Cane	Texas	112	1950	3,3
Algae	US	87		2,2
Eucalyptus	California	54	1950	1,4
Sudan grass		36		0,8
Sugar beet		33		0,8
Oak-pine forest	New York	13	1700	0,4
Corn	US-average	28./.44		0,7./.1,2
Eucalyptus	Sao Paulo 1968	14 **)	1900	
''	'' 1975	12,5		
''	'' 1980	31,5		

Note: *) Dry mass yields
**) Roundwood yields

ARTIFICIAL FORESTING

In terms of yield and wood density an eucalyptus species appears to be most prospective. The tree can be harvested every six to seven years, when roundwood material will be recovered of approx 20 to 25 cm diameter and 6 meters heigth. All branches and leafs will be left behind in the forest for future humus formation and the roots left in the soil will allow for a twice repeated growth of the tree. Going by the roundwood yields a cultivated area of approx. 2.000 square kilometers would allow to produce 1 million tonnes of methanol annually. In the ideal case, this area would be a circle of 25 kilometers radius around the processing plant and 1 million tonnes of methanol would replace approximately half a million tonnes of gasoline. For artificial foresting all of this area should be essentially free from major obstacles to the movement of heavy vehicles and cutting machines. Roads have to be provided for access to the various sections. Artificial foresting means, that the respective area has to be freed from its natural flora, precultivated trees have to be planted at even distances, their growth has to be controlled to some extent, and 6 or 7 years later the trees have to be cut, freed from branches and leafs in the forest and the recovered roundwood has to be carried to the processing plant. It can easily be foreseen, that the amount of human labour involved in such scheme is great, but it is very difficult to predict its amount with some accuracy. However there are similtarities to celluloses-producing plants and from here we have derived some information. Table 2 may give an approximate figure of expenses involved in recovering wood from artificial foresting activities. For ease of comparison we have converted local currency figures into dollars by the official exchange rate, but since in further developing our subject we may have to distinguish between domestic and foreign components of cost, we may call this a domestic dollar. The tabulation also shows the cost of transport for given distances and some traffic connections. As we can see from this listing, transport is the major component of the entire cost of wood at factory gate. Therefore logistic considerations shall be made later.

PROCESSES TO TRANSFORM WOOD TO METHANOL

If we look at the ultimate analysis of dry wood, we notice an atomic hydrogen to carbon ratio of 1,4 and an oxygene to carbon ratio of 0,7; these are approximate figures. Unfortunately any autothermal gasification does not produce the hydrogen to carbonoxide ratio of two, respectively does not correspond to the formula $(H_2 - CO_2) / (CO + CO_2) = 2$ which states the requirement of methanol synthesis.

Therefore we have two choices:
We either have to add hydrogen from a foreign source such as ıe water electrolysis, or we have to shift part of the

Table 2a

Offered Cost of eucalyptus round-wood at factory gate

Forest location		close to processing plant	remote area
		(in $/m3	roundwood)
Trading value of upright roundwood		3,55	1,75
Exploration cost		2,00	2,00
Road transport	50 km		2,85
	100 km	5,00	
Rail transport	200 km		5,25
		10,55	11,85

Table 2b

Estimated Cost of Eucalyptus roundwood at factory gate

Basis: 1 million m3/a roundwood supply from proprietary forests
in undeveloped areas, 70.000 ha land (at 500 $/ha).

Forest location	close to processing plant	remote area
	(in $/m3	roundwood)
Return on land property (6 % p.a.)	2,1	
Forest Cultivating and Recultivating		
Labor 1.000 men	8,0	
Equipment 35 % p.a. of investment	0,8	
Utilities	0,6	
Cutting and forest transport		
Labor 1.000 men	8,0	
Equipment 35 % p.a. of investment	0,3	
Utilities	0,6	
Subtotal	20,4	20,4
Truck transport 100 km		
Labor 500 men	4,0	
Equipment 35 % p.a. of investment	4,0	
Utilities	5,5	
Subtotal	13,5	
Alternatively:		
Truck transport 50 km		7,0
+Rail transport 200 km		8,0
Subtotal		15,0
Total	34,0	35,0

carbonmonoxide into hydrogen by means of the water gas shift reaction, thus forming an adequate amount of carbondioxide. This carbondioxide has to be removed from process gas and discarded to the atmosphere. Unfortunately even in the best considered case of gasification approximately 50 % of carbon contained in the wood entering the process has to be discarded to the atmosphere in the latter case. This also means, that 50 % of all the foresting and transport activities yield a carbondioxide stream, which is immediately returned to the atmosphere instead of being converted to methanol. So 50 % of all these efforts result in a short circuit just in order to overcome the inbalance of hydrogen to carbon ratio of raw material in comparison to the methanol product. Hydroelectric power is a renewable energy as well as we have seen before and therefore the highly energy intensive electrolysis of water might still be considered in cases, where hydroelectric power is in abundance, to balance the hydrogen requirements. For better illustration of this situation, we have amended the foregoing figure by hydroelectric power and water elctrolysis, see figure 1.

The basic two process block diagrams are shown in figures 2 and 3, which also give rough information on basic input data relative to one ton of methanol production. It can be seen, that the wood input is reduced to about half in case of the hybrid process, at the expense of drastically increased electric power input. In both cases there will be a boiler to provide steam requirements of the plant which are in excess of process waste heat, but this boiler is basically not designed to balance the mechanical power requirement of the plant. Compressors are mostly motor driven, since we count on cheap availability of electric power anyway. Of course the boiler will preferentially consume all combustible effluents from the plant like purge gas, tail gas and fusel oil.

The entire process sequences shown here are based on proven technology, although it was so far not combined this way. However the key to the whole process is a suitable and modern gasification technology. There is quite a tradition in gasifing wood to produce combustible gases, especially used as mobile generators on trucks and even on passenger vehicles. But producing combustible gas is a different technology than generating a synthesis gas which should be low in methane and should be available at elevated pressure in order to reduce compressor power requirements. Furthermore there is a large scale-up factor from those generators, for which experience is available, to the new generation, which in a reasonalbe mumber of parallel streams can handle almost 500 tons per hour of gasification feed. We have tried to evaluate the available technology in the light of large scale methanol process requirement and concluded, that a fluidized bed gasifier operated at highest possible temperature and at elevated pressure would best compromize with the requirements.

There are, of course, options to the selection of gasification process and consequently there are options to the process

Table 3

Main input data per ton of methanol from wood,
Investment estimate per annual ton of methanol

Process route Description	Dim	A 1	A 2	B	C	D
Wood (30 % moisture)	to	1,3	2,0	2,6	3,1	(4,9)
Charcoal (2 % moisture)	to	-	-	-	-	1,1
Electric Power	MWh	5,3	2,8	0,7	1,3	0,8
Demin. Water	m3	1,5	1	0,8	1,5	1,6
Cooling Water	m3	220	125	115	115	135
Investment (approx.)	$	580	500	400	450	500

A 1: 10 bar fluidized bed gasification, H2-balanced by water electrolysis.
A 2: 10 bar fluidized bed gasification, O2-balanced by water electrolysis.
B: 10 bar fluidized bed gasification, O2-balanced by air fractionation.
C: Atmospheric co-current gasification, O2-balanced by air fractionation.
D: As route C, but starting from charcoal.

sequence as well. We have figured the consumption data for some basically different gasification processes to illustrate the wide range of raw material input per ton of product, see figure 3. Apparently it is of importance to select advanced technology in gasification and in the entire process sequence. Since this not only keeps the cost of raw material low, but also and even more importantly raises the final product yield of a given area of land. Since there is no multiplication factor on available land, the raw material input data ultimately limit our possibilities to produce large quantities of methanol fuel.

With the aim to produce a synthesis gas suitable for methanol production from wood we can establish a number of requirements, to which the most suited gasification process will have to come closest. The most important requirements are:

a) highest product gas yield
b) lowest requirement of compression energy
c) best recovery of volatiles in terms of product yield
d) lowest methane residual
e) lowest wood crushing requirement

There is no process known to us, which meets all these requirements in the best way and therefore any selection will be a compromise.

INVESTMENT ESTIMATES

We have done investment estimates for these processes, firstly on a European basis,but then we have also considered the fraction of goods and services, which in accordance with our experience can be procured in South America, for instance Brazil. Since we are presently building the plant in this country which consists of comparable components in value, tonnage and technology, we feel confident about this type of cost differentiation. Table 4 shows a condensed form of those calculation results.

Table 4

Investment estimates of a ''Methanol from wood''-scheme
Capacity: 1 million to/a methanol from proprietary forests.

(Figures in million Ø)

Process route	A 1	A 2	B	C	D
Investment Estimate:					
of Process Units	150	200	290	320	
of Auxiliary Units	365	250	90	100	
of Off-Sites	65	50	20	30	
Subtotal Processing Plant:	580	500	400	450	500
of Transport Equipment (1)	15	25	30	35	55
of Foresting Equipment (2)	4	6	7	9	13
of Land Property (3)	40	60	80	95	150
approx. grand total	640	590	520	590	720
(incl. foreign currency)			(100)		

(1) assuming truck transport over 100 km distance
(2) for cutting and recultivation
(3) at roundwood yield of 19 m3/ha.a, cost of land 500 Ø/ha, 15 % void fraction

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Since the choice of the process-route not only affects the investment of the entire process plant itself, but also influences the investment for artificial foresting and transport of wood, we have taken these costs into account as well in above calculation by estimating the value of equipment involved and also estimating the value of forestable land required, for which we had some information.

OPERATING COST ESTIMATES

On the basis of calculated main consumptions and estimated investment figures we have tried to carry out production cost calculations. They can only be correct in so far as specific cost figures entered into these calculations prove correct.

Table 5

Production Cost Estimate
of a methanol plant based on wood gasification

Capacity: 1 mio tons/a methanol
Process route: 10 bar Fluidized bed gasification,
H2-balanced by water electrolysis. (A 1)
Investment: 580 mio $, foreign component: 25 %

Conversion Cost (excl. raw materials)

	Quantity	Unit	Unit cost $	$/to methanol	
				dom.	for.
a. Product-related cost					
Electric power	5,3	MWh	5 *	26,5	-
Demin. water	1,5	m3	0,5	0,75	-
Cooling water	220	m3	0,015	3,3	-
Catalysts & Chemicals	1	1	1,5		1,5
b. Labour (incl. overheads)	970	men	10.000 $/a	9,7	
c. Capital-related cost					
Depreciation	8	% p.a.		35	12
Avg. debt service	4	% p.a.		17	6
Maintenance materials	2,5	% p.a.		10	4,5
Insurance	2	% p.a.		12	
Subtotal Conversion Cost				114	24
Raw Material Cost					
a) given figures	1,3	to	12	16	
alt. b) own estimate	1,3	to	36	47	
Production Cost Total					
a)				130	+ 24
b)				161	+ 24

Note: * assumes availability of secondary energy.

Those calculations are shown in tables 5 and 6, which show those data we have selected. We may draw special attention to different assumptions we have made with respect to the cost of electric power. In those processes involving water electrolysis we have assumed that ''secondary energy'' will be available to run the plant. This secondary energy may be rated at 1/6 of the normal rate for industrial use of electric energy. The secondary energy is that part of the power generation capacity of the hydro-electric power station which can not be guaranteed under all circumstances of seasonal fluctuations. Hence this energy can be provided at a negotiated low price under the

Table 6

Production Cost Estimate of a methanol plant based on wood gasification

Capacity: 1 mio tons/a methanol
Process route: 10 bar Fluidized bed gasification, O2-balanced by air fractionation. (B)
Investment: 400 mio $, foreign component: 25 %

Conversion Cost (excl. raw materials)

	Quantity	Unit	Unit cost $	$/to methanol	
				dom.	for.
a. Product-related cost					
Electric power	0,7	MWh	30	21,0	-
Demin. water	0,8	m3	0,5	0,4	-
Cooling water	115	m3	0,015	1,7	-
Catalysts & Chemicals	1	1	1,5		1,5
b. Labor (incl. overheads)	1000	men	10.000 $/a	10,0	
c. Capital-related cost					
Depreciation	8	% p.a.		24,0	8,0
Avg. debt service	4	% p.a.		12,0	4,0
Maintenance materials	2,5	% p.a.		6,7	3,3
Insurance	2	% p.a.		8,0	
Subtotal Conversion Cost				84	17
Raw Material Cost					
a) given figures	2,6	to	12	31	
alt. b) own estimate	2,6	to	36	94	
Production Cost Total					
a)				115	+ 17
b)				178	+ 17

condition, that the consumer may be cut off supply during periods of water shortage. This may occur only once a year or even in the sequence of several years. During such a period, the methanol factory has to be stopped and therefore all capital related burdens as well as labour cost have to be carried by a shorter operation period than if the plant was supplied with guaranteed power, see figure 4.

In cases where no water electrolysis is involved, we have assumed that the plant will be provided with guaranteed electric power.

In the assessment of labour cost we have started from a staff-organization scheme going into the detail of individual assignments. Differences in the process routes basicially are due to the differences in yard services to handle the incoming quantities of wood.

Further there is a wide field of speculation with respect to depreciation and interest on loans. We have assumed a 12,5 years linear depreciation and an 8 % interest rate.

Finally we have used alternative figures on the cost of round wood in accordance with tables 2 a and 2 b. The figures used are 12 $ per ton and 36 $ per ton of round wood.

Under those assumptions plus some input data of minor importance we have arrived at production cost per ton of methanol as per table 7 for the various process routes. For the definition of process routes the legend of table 3 is referred.

LOGISTIC CONSIDERATIONS

The figures of table 2 indicate, that the cost of transporting the wood from forest to factory exceeds the value of wood itself. Another calculation on the fuel consumption for the transport of wood by heavy trucks has shown, that approximately 3 % of the methanol production is needed to carry the raw material over a distance of 100 km on solid roads.

Both these facts indicate the importance of economical transport. In terms of shortest raw material transport the methanol plant of 1 mio tons per year should ideally be located in the centre of a circle having 25 km radius, and there should be a system of solid roads in radial direction. However another constrain to logistic considerations is the requirement to provide cooling water to the plant which puts the factory at a river-bank. In the absence of a bridge this would already change the ideal location to the center of a semicircle of approx. 35 km radius. In both cases transport distances are not really large, but the whole transport has to be done on roads solely serving for this purpose. For practical purposes we cannot see the whole landscape subdivided in circles or even semicircles each being assigned to an individual methanol facility.

The methanol plant has 4 basic requirements, i.e. wood, water, electric power and traffic connection for the disposal of product. There is a place where all those can be made available most easily which is close to the dam of a hydro-electric power station. Here the round wood can be floated from any upstream place. It may be necessary to support the floats by divers and to manoeuvre them by tug-boats. We expect, that such scheme will reduce the cost of wood transport to somewath in the order of 25 % of those figures shown in table 2 b.

The recommended location of large methanol plants at the dams of hydro-electric power stations likewise eases the problem of product disposal, since in most cases there will already be a rail connection to carry structual material to the power station. Product output of the methanol facility will call for 3 trains of 25 cars each carring 40 tons of methanol daily.

THE GASOLINE SUBSTITUTING PRICE OF METHANOL

So far we have done calculations on the cost of methanol and we have also seen that in almost any case the cost of methanol produced from wood is above the world market level. But we have to ask for the economic implications, if we use this methanol to substitute a part of our petro-fuel to drive vehicles. Here we meet with at least two different aspects; one is of macro economic nature and assumes an open world market, but the other and generally the more important consideration is of national economic nature. May we attempt to answer to both questions.

Table 7

Gasoline substituting price (GSP) of methanol

Process route		A 1	A 1	B	B
Depreciation (DEPR)	years	12,5	12,5	12,5	12,5
Raw material (RM)	$/to	12	36	12	36
El. Power (EP)	S/MWh	5	5	30	30
		GSP in cts/l gasoline			
a) domestic part		29,2	34,0	22,5	27,4
b) foreign part		3,7	3,7	2,6	2,6
Total		32,9	37,7	25,1	30,0

Actual gasoline price ex refinery, without taxes: 20 cts/l (1978)

Sensitivity analyses

Relative change of:	RM	EP	INV	DEPR	INT	LAB
assumed:	1	1	1	1	1	1
Relative change of GSP:	0,11	0,13	0,44	0,20	0,10	0,06

In actual car operation one ton of methanol will replace approx. 650 litres of gasoline on the basis of net calorific values and combustion efficiencies. Table 7 shows the cost of that amount of methanol, which replaces one liter of gasoline, subdivided into a domestic and foreign components. These are costs at which methanol could be supplied to the refineries; they still do not cover taxes and distribution cost. For comparison the ex-refinery price of gasoline, again free from taxes and distribution costs, is indicated as well (on 1978 status). In the case of an open market we have to compare the total substitution price with gasoline cost. This shows, that the substitution price is upto twice as high as the actual price of gasoline. Although such comparison shows, that the methanol from wood scheme is not justifid under present days economic considerations, we can foresee a number of petro-price increases until such scheme comes to full operation, which will certainly narrow if not close the gap.

In reality the national economics even nowadays are strongly in favour of the scheme. This is indicated by comparison of the foreign component of the substituting price with the gasoline cost. The foreign currency component of substituting price is in the order of 15 % of gasoline cost. Resulting from this, the scheme creates considerable savings in foreign currency cash flow, since the gasoline cost almost in full represents foreign currency. In actual figures this means, that a 1 mio tons per year methanol plant will save the country foreign currency expentiture in the order of 100 mio $ annually, which is approximately the entire foreign component of investment.

SOCIAL ASPECTS

The realization of a scheme of large methanol plants on the basis of artificial foresting will offer permanent employment opportunities to approx. 7.500 people per plant unit and it will during the construction phase offer employment for another 20.000 to 30.000 people, if these plant units were built in sequence of about one per year.

CONCLUSIONS

Large methanol plants based on artificial foresting can even nowadays be economically justified, if the availability of foreign currency is restricted as it is the case in South American countries and they will be even more justified in the light of ever increasing petro-prices. An additional incentive is the generation of considerable employment to construct and operate those plant units.

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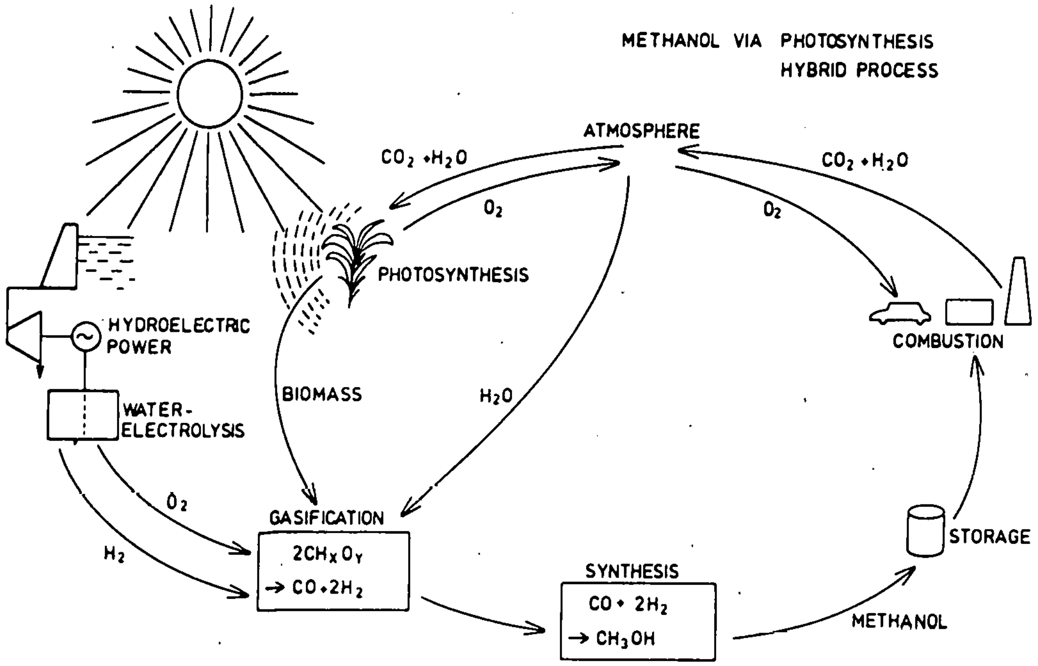
Figure 1



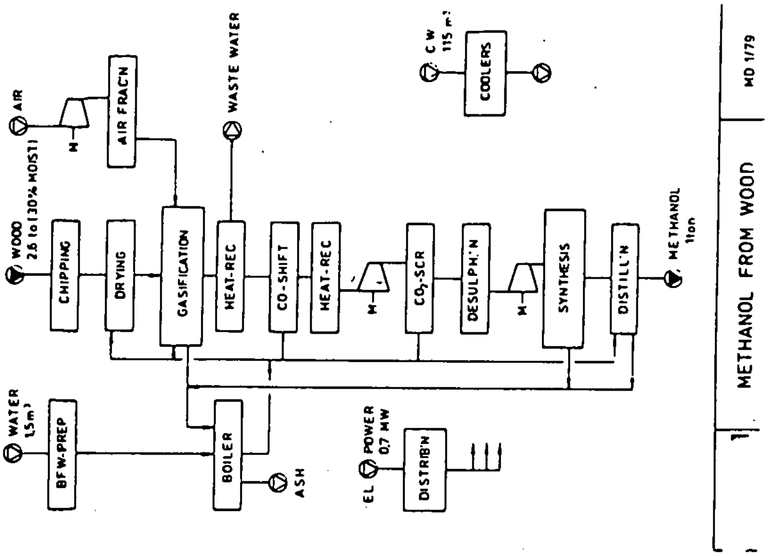


Figure 4

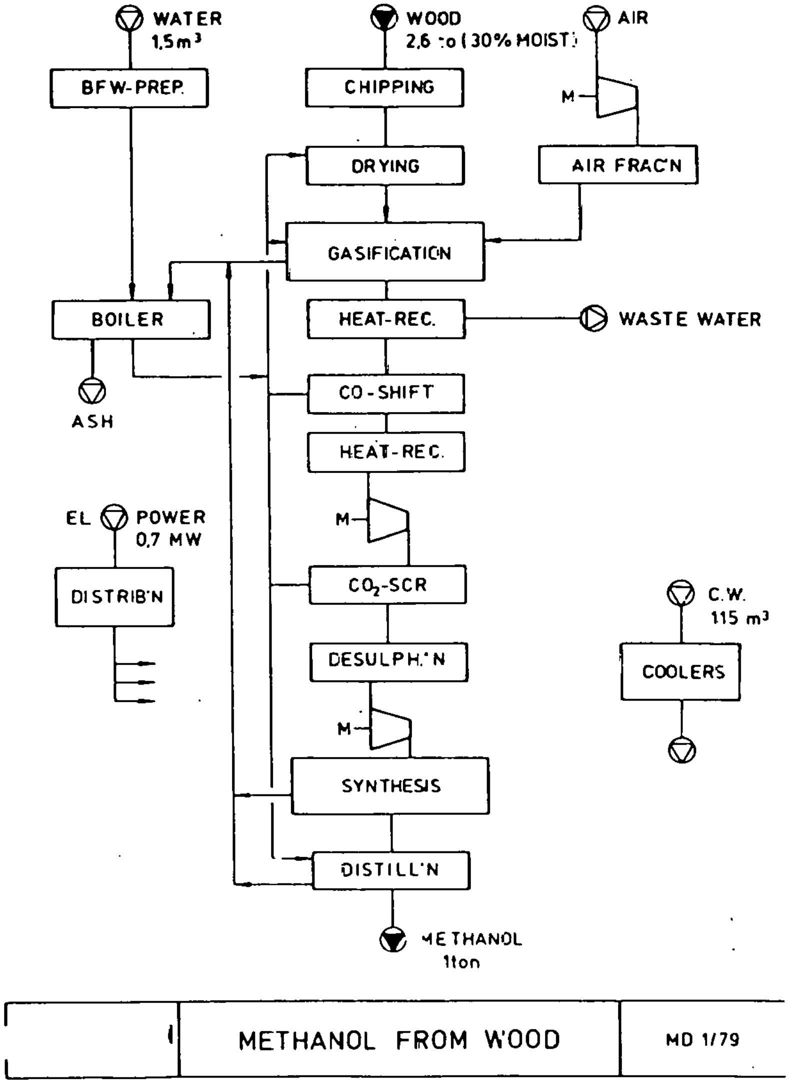


Figure 2

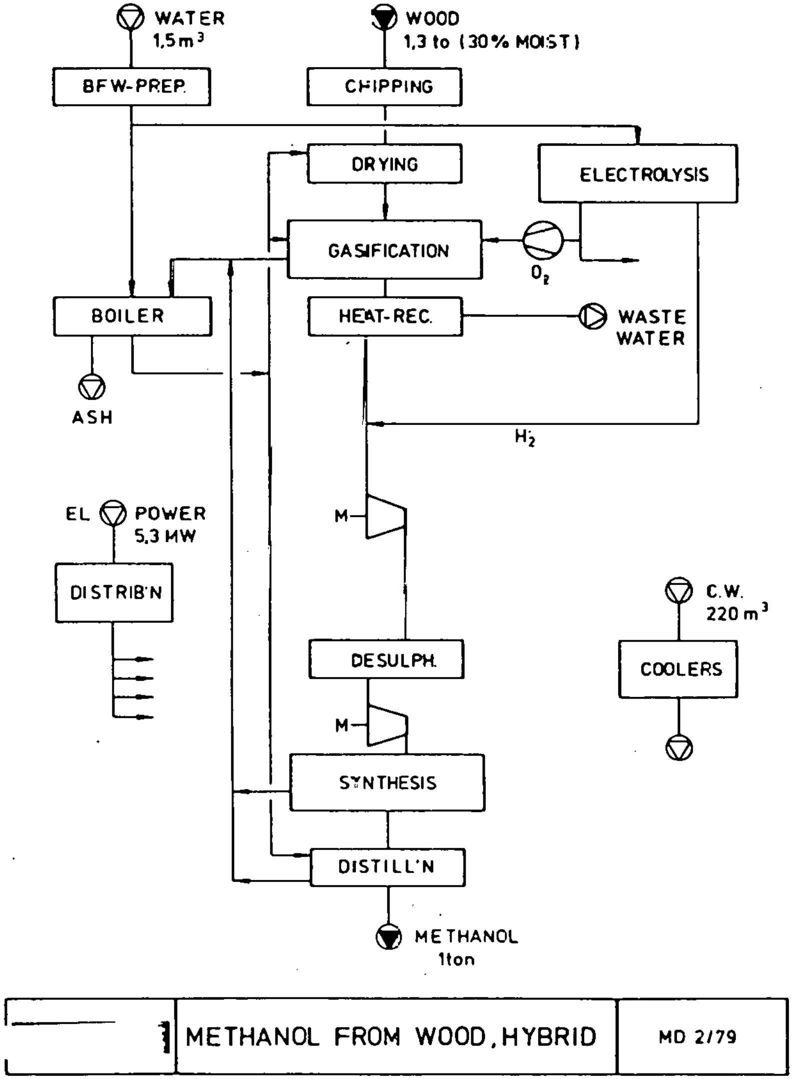


Figure 3

TECHNICAL AND ECONOMIC ASSESSMENT MOTOR FUEL ALCOHOL FROM GRAIN AND OTHER BIOMASS

by

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GENERAL

The primary objective of this study was to evaluate the technical and economical feasibility for production of grain motor fuel ethyl alcohol from a grass roots plant with a capacity of 50 million U. S. gal/yr. The base case evaluation includes a detailed process design using proven technology, a complete budget estimate of the plant investment including working capital, a detailed analysis of the annual operating cost using corn as the primary feedstock, and a complete financial analysis which establishes the alcohol selling price required to net to the investor a 15% discounted cash flow - interest rate of return.

In addition to the primary objective, other considerations discussed in the paper are: excursions on plant capacities, excursions on feedstock material, sensitivity analyses on financial parameters, and substitution of corn stover for coal as the primary fuel source.

The study shows that motor fuel alcohol must have a selling price of $1.05 to $1.13 per gallon (1978 dollars) to satisfy the requirements of the base case (the lower selling price reflects the economics of a 20 year plant life whereas the higher price reflects a 10 year plant life).

Variations in plant capacities cause the alcohol selling price to rise to $1.52 per gallon for a 10 million gallon per year plant; and drop to $0.98 per gallon for a 100 million gallon per year plant. Alternate feedstock materials cause the selling price to increase from $1.05/gallon (corn) to $1.40/gallon for sweet sorghum, and drop to a low of $1.02/gallon for milo (grain sorghum). Wheat requires an alcohol selling price of $1.31/gallon. Substitution of corn stover for coal as plant fuel causes a 4¢/gallon increase in the alcohol selling price. All of the above comparisons are based on a 20 year production life for the plant.

The base case alcohol plant has a total capital requirement of $63.6 MM in equivalent 1978 (year end) dollars. The fixed investment for the plant is $58.0 MM. The total production cost for e base case is $0.89/gallon of alcohol.

BASE CASE PRODUCTION OF ALCOHOL

The alcohol plant is sized to produce 50 MM gal/yr of motor fuel grade alcohol (199° proof) from corn. The alcohol product yield is 2.57 gallons per bushel of corn thereby requiring 19.46 MM bushels of corn per year. In addition to the primary alcohol product, the plant produces 177,111 T/yr of by-product Distiller's Dark Grains, and 10,428 T/yr of ammonium sulfate. The plant is assumed to be located in Central Illinois, close to a source of Illinois #6 coal which is to be used as fuel for the plant.

The alcohol plant, in general, uses existing process technology as currently employed in U. S. grain alcohol plants. The basic processing steps included in the plant are grain or biomass feed preparation, starch removal and saccharification, batch fermentation, alcohol distillation and purification, and by-product animal feed recovery. The plant operates as a continuous flow process, except for the fermentation and fungal amylase sections which are operated batchwise in order to allow for frequent sterilization of the equipment. The distillation system employs a two-pressure concept which significantly improves steam economy. This process concept, along with other heat economy measures, results in a total plant steam usage of 31.7 lbs/gallon of alcohol product. The distillation system uses 21.4 lbs/gallon of which 2.8 lbs/gallon is obtained as flash vapor from the mash cooking operation.

All utility requirements, with the exception of electricity, are produced within the boundaries of the plant. Water is obtained from a well field located close to the plant. The boiler burns relatively low cost, high sulfur coal (approximately $25/T compared to $40/T for low sulfur coal). Boiler flue gas is used to dry the stillage residue in producing the Distiller's Dark Grains by-product. Waste water is treated in a two-stage, activated sludge system. The sludge is dewatered and fed as supplemental fuel for the boiler. Cooling water is recycled from a two-cell cooling tower.

Approximately one-third of the plant power requirement is obtained from steam turbines. The coal fired boiler produces 600 psig/600°F steam which is used to drive turbines for the DDG evaporator re-compression system. The turbines exhaust steam at 150 psig which is suitable for satisfying all other process steam requirements. A breakdown of steam and power requirements for the base case plant is shown in Table 1.

GRAIN MOTOR FUEL ALCOHOL PLANT
BASE CASE - 50 MM GAL/YR

TABLE 1

PROCESS STEAM AND ELECTRICAL POWER BREAKDOWN

Section	Identification	Process Steam	Electrical
	Total Plant Requirement	200,000 pph	8,314 kw
100	Receiving, Storage, & Milling	0.0%	6.1%
200	Mash Cooking & Saccharification	30.5%	2.6%
300	Fungal Amylase Production	0.7%	20.4%
400	Fermentation	0.2%	4.0%
500	Distillation	58.5%	1.6%
600	DDG Recovery	6.4%	27.1%
700	Storage & Denaturing	0.0%	.7%
800	Utilities	2.7%	37.0%
900	Buildings	1.0%	0.5%
Total		100.0%	100.0%

Overall Material and Energy Flows

The major input raw materials are:

Item	Unit	Daily Quantity	1978 Unit Value
corn	bushels	58,955	$ 2.30/bu
coal	tons	296.7	24.50/ton
yeast	tons	1.2	0.40/lb
denaturant	gals	1,500	0.60/gal
ammonia	tons	9.2	120.00/ton

The plant products are:

Item	Unit	Daily Quantity	1978 Unit Value
grain motor fuel alcohol	gallons	151,515	\$1.05/gal
Distiller's Dark Grains	tons	536.7	110.00/ton
$(NH_4)_2SO_4$	tons	31.6	40.00/ton

The ammonium sulfate is a by-product of the flue gas desulfurization.

The three major energy input items are corn, coal, and electricity. The two primary energy containing items are alcohol and Distiller's Dark Grains.

The plant thermal efficiency can be calculated by several different methods. One method is to consider only the fossil fuel input items. This method gives an energy efficiency of 154.4% as shown below (values are Btu/hr):

$$\frac{535.0\ \text{MM (alcohol)}}{263.3\ \text{MM(coal)}+83.1\ \text{MM(electricity)*}} \times 100 = 154.4\%$$

Another method for determining the thermal efficiency is to consider the energy required to produce the corn crop, with credit given for the energy required to produce DDG (equivalent corn basis) as an additional energy input item. In Illinois, the average energy usage is 95,200 Btu/bu of corn (USDA, 1974 Data Base) which includes energy for field preparation, harvesting, fertilizer supplied, transportation, and other miscellaneous usages. This method results in an efficiency of 105.4% as shown below:

$$\frac{535.0\ \text{MM(alcohol)} + 76.0\ \text{MM(DDG)}}{263.3\ \text{MM(coal)}+83.1\ \text{MM(electricity)}+233.5\ \text{MM(corn)}} \times 100=105.4\%$$

A third method of calculating the thermal efficiency is to include the total thermal energy contained in the corn and dried grains. The method yields an overall plant efficiency of 61.8%

$$\frac{535.0\ \text{MM(alcohol)}+357.8\ \text{MM(dry grains)}}{263.3\ \text{MM(coal)}+83.1\ \text{MM(electricity)}+1099\ \text{MM(corn)}} \times 100=61.8\%$$

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* Based on 10,000 Btu/kwh

ECONOMICS FOR BASE CASE

Investment and Operating Cost

The investment required to build complete grass-roots facilities for a 50 MM gal/yr alcohol plant is $58.0 MM, last quarter 1978 cost basis. The investment includes all support facilities and fifty acres of land. Process steam is produced by a coal fired boiler. The boiler unit includes flue gas desulfurization equipment. The earliest start-up date, assuming a decision had been made to build the plant by January 1, 1979, is January 1983. Working capital is estimated at $7.9 MM for the first year of operation and is inflated at 7% per year for the life of the plant.

The annual operating cost is $44.51 MM or $0.89/gal of alcohol, last quater 1978 equivalent cost. This includes straight line depreciation over twenty years. The annual operating cost increases to $47.41 MM or $0.95/gal for a 10 year plant operating life. The operating cost is rather insensitive to plant investment since the capital investment items (fixed charges) are a small percentage of the total cost. The major operating cost item is the purchase price of corn.

Economic Analyses

The objective of the economic assessment is to establish a selling price for grain motor fuel alcohol which will cover the production cost and give a realistic return on company equity. The base case analysis uses a 15% Discounted Cash Flow - Interest Rate of Return (DCF-IROR). It is realized that a 15% DCF-IROR may not be large enough for a company to venture into production of grain motor fuel alcohol, consequently rates up to 20% DCF-IROR were also considered. (Since a cash flow analysis includes profits plus depreciation, a 15% DCF-IROR represents only about a 13% annual interest rate for a 20 year plant life).

The procedure used to establish the 1978 selling price includes the complicating effects of an inflationary economy.

Base Case Selling Price: 15% DCF-IROR

The base case selling price for grain motor fuel alcohol is $1.05/U. S. gallon based on a 20 year plant life and a 15% DCF-IROR. The selling price increases to $1.13/U.S. gallon when the plant is assumed to have an effective operating life of only 10 years. Many companies perform their venture analysis based on 10 years (although the plant has a life of 20 years) because the plant may become obsolete due to new technology. Figure 1 shows the actual selling prices over the life of the plant (7% inflationary economy).

EXCURSIONS ON PLANT CAPACITIES

In addition to the base case production rate of 50 MM gallons per year, capacities of 10 MM and 100 MM gallons per year were evaluated. The 1978 equivalent alcohol selling prices are $1.55 and $0.98 per gallon respectively for the 10 MM and 100 MM gallons per year plants. Table 2 summarizes the investment, operating expense, and alcohol selling price for three production capacities.

TABLE 2

SUMMARY OF INVESTMENT, OPERATING EXPENSE, AND ALCOHOL SELLING PRICE FOR 10, 50, AND 100 MM GAL/YR PLANT CAPACITIES
20 YEAR PLANT LIFE
($ MM, 1978 BASIS)

Plant Capacity	Investment		Operating Expense		15% DCF-IROR Alcohol Selling
MM Gal/Yr	Fixed	Working Cap.	Total	$/Gal	Price, $/Gal
10	25.2	2.7	12.2	1.24	1.55
50*	58.0	5.6	44.5	0.89	1.05*
100	100.0	10.9	83.6	0.84	0.98

EXCURSIONS ON FEEDSTOCK MATERIAL

In considering the production of motor fuel grade alcohol, the most logical primary feedstock choice is corn, because it is produced voluminously in major growing areas of the United States. Producers of industrial grade alcohol prefer corn because of its economic advantage.

Alternate feedstock materials considered in this work were wheat, milo (grain sorghum), and sweet sorghum.

In addition to alternate feedstock materials, an evaluation was made of the effect of substituting corn stover biomass for Illinois #6 coal for the fuel requirement of the plant.

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* Base Case

The results of these excursions are summarized in Table 3.

TABLE 3

GRAIN MOTOR FUEL ALCOHOL PLANT
SUMMARY OF EXCURSIONS ON FEEDSTOCK MATERIALS
20 YEAR OPERATING LIFE

Excursion	Feedstock Variable	Deprec. Period Years	Investment(1978) $ MM		
			Fixed	Working Capital	Total
Base Case	Corn	10	58.0	5.6	63.6
Wheat	Wheat	10	58.0	7.9	65.9
Milo	Milo	10	58.0	5.5	63.5
Sweet Sorghum	Sweet Sorghum	10	91.6	6.4	98.0
Corn Stover	Corn with Corn Stover Fuel	10	57.0	5.8	62.8

Excursion	Feedstock Variable	Operating Cost(1978)		1978 Alcohol Selling Pr.$/Gal		
		Total($MM)	$/Gal	10%DCF*	15%DCF*	20%DCF*
Base Case	Corn	44.5	0.89	0.97	1.05	1.16
Wheat	Wheat	57.1	1.14	1.23	1.31	1.44
Milo	Milo	42.6	0.85	0.94	1.02	1.13
Sweet Sorghum	Sweet Sorghum	58.8	1.18	1.28	1.40	1.59
Corn Stover	Corn with Corn Stover fuel	46.4	0.93	1.01	1.09	1.21

Wheat and milo can be processed in essentially the same equipment as the corn feed material. Sweet sorghum requires different front-end equipment, more steam generating capacity, and bagasse storage and handling facilities; consequently, the investment is considerably higher than for the base case (corn). The sweet sorghum excursion is designed for corn as the feed material during the dead season. It is assumed sweet sorghum can be harvested during only 165 days of the year. This becomes very expensive since a large portion of the plant equipment is idle during a large part of each year. In addition, sweet sorghum raw material is more expensive than corn; and the Distiller's Dark Grain by-product from sweet sorghum is less valuable than that from corn.

* DCF = Discounted Cash Flow - Interest Rate of Return

Another alternative would be to design the sweet sorghum plant to process double the sweet sorghum feed material during the active season, and concentrate approximately one-half the syrup for storage and use during the dead season. This alternative was not considered in detail because it became obvious that the investment would be higher than the combination corn/sorghum alternative due to the high cost of doubling the size of the front-end equipment, and energy use would increase.

The wheat excursion results in a relatively high alcohol selling price; whereas the milo excursion results in the lowest alcohol selling price. The wheat excursion is expensive for two reasons: 1) the raw material purchase price is high, $3.15/bu compared to corn at $2.30/bu, and 2) product conversion is less (2.5 gal/bu compared to corn at 2.6 gal/bu). The milo excursion results in the lowest selling price because the grain is less expensive than corn and product conversion is about the same. Milo production in this country is substantially less than corn. A major new market for milo could cause the milo market price to increase. This would reduce the advantage for production of alcohol from milo.

The corn stover (fuel) excursion results in a higher alcohol selling price because the corn stover fuel is approximately twice as expensive as Illinois #6 coal (on a net Btu basis). The selling price increases by 4¢/gallon of alcohol. The plant investment is about $1.0 MM less than the base case because flue gas desulfurization is not required and the increase in investment for the boiler and fuel handling equipment is less than the cost of the flue gas desulfurization system.

SENSITIVITY TO FINANCIAL PARAMETERS

The alcohol selling price sensitivity to a number of financial parameters was evaluated for the twofold purpose of establishing the cost benefits of governmentally supported incentives, and determining the effect of variables which may differ from the values chosen from the base case.

All of the sensitivity analyses are compared to the base case with a 20 year plant life ($1.05/gal alcohol selling price). The purchase price of corn is the only variable that impacts a substantial effect on the alcohol selling price. The non-budgetary governmentally supported incentives, such as loan guarantees, higher investment tax credit rates, and shorter depreciation schedules have only limited effect on reducing the base case selling price. The following general statements regarding the effects can be made.

Depreciation Schedule

Increasing the depreciation schedule (sum-of-years method) from 10 years to 20 years, increases the alcohol selling price by 2¢/gallon.

Reducing the depreciation schedule to 5 years does not reduce the selling price because the heavy losses which occur in the first five years of production are balanced by the investment tax credit.

Working Capital

Doubling the working capital from $5.6 MM to $11.2 MM causes a 3¢/gallon increase in the alcohol selling price.

Purchase Price of Corn

The purchase price of corn is the most significant variable. For every 10% increase in corn purchase price, the alcohol selling price increases by about 12¢/gallon assuming all other factors remain constant. As the purchase price of corn increases, the DDG by-product becomes more valuable; consequently, a 10% increase in the corn purchase price will increase the alcohol selling price by about 8¢/gallon.

DDG By-product

A 10% increase in the Distiller's Dark Grains by-product value effects a 4¢/gallon decrease in the alcohol selling price.

Leveraged Capital

The leveraged capital situation is influenced by the high taxes on corporate profits. The high taxes foster a high debt to equity ratio since the interest on debt money is tax deductible, but the dividends on profits are not. A practical limit is reached, however, where the interest paid during the early years of the project, and especially the years prior to full production, becomes such a burden that an increase in debt beyond a certain level is not beneficial. At the 15% DCF-IROR rate and a 10% interest rate for a 20 year project life, financing 80% of the plant investment and 100% of the working capital results in a 10¢/gallon decrease in the alcohol selling price (compared to 100% company equity).

The analyses herein are based on constant company equity throughout the life of the plant. Principal payments are subtracted from cash flow. This has the effect of minimizing company equity, minimizing total profits and increasing the risk of the venture. An alternative is to increase company equity by applying principal payments to equity, rather than subtracting the payments from cash flow. This should result in a higher alcohol selling price and reduce the risk of the venture. Highly leveraged capital situations affect investment tax credits which cannot be used during the 7 year time period allowed by the IRS; consequently, if the investment tax credit can be applied to other taxable profits, the leveraged capital situations would be marginally more favorable.

Investment Tax Credit

Increasing the investment tax credit rate from 10% to 50% reduces the alcohol selling price by 2¢/gallon. The investment tax credit rate could be marginally more significant if the company producing the alcohol has profits from other ventures against which the investment tax credit could be applied immediately. The analyses herein are based on a single venture company.

Acknowledgment

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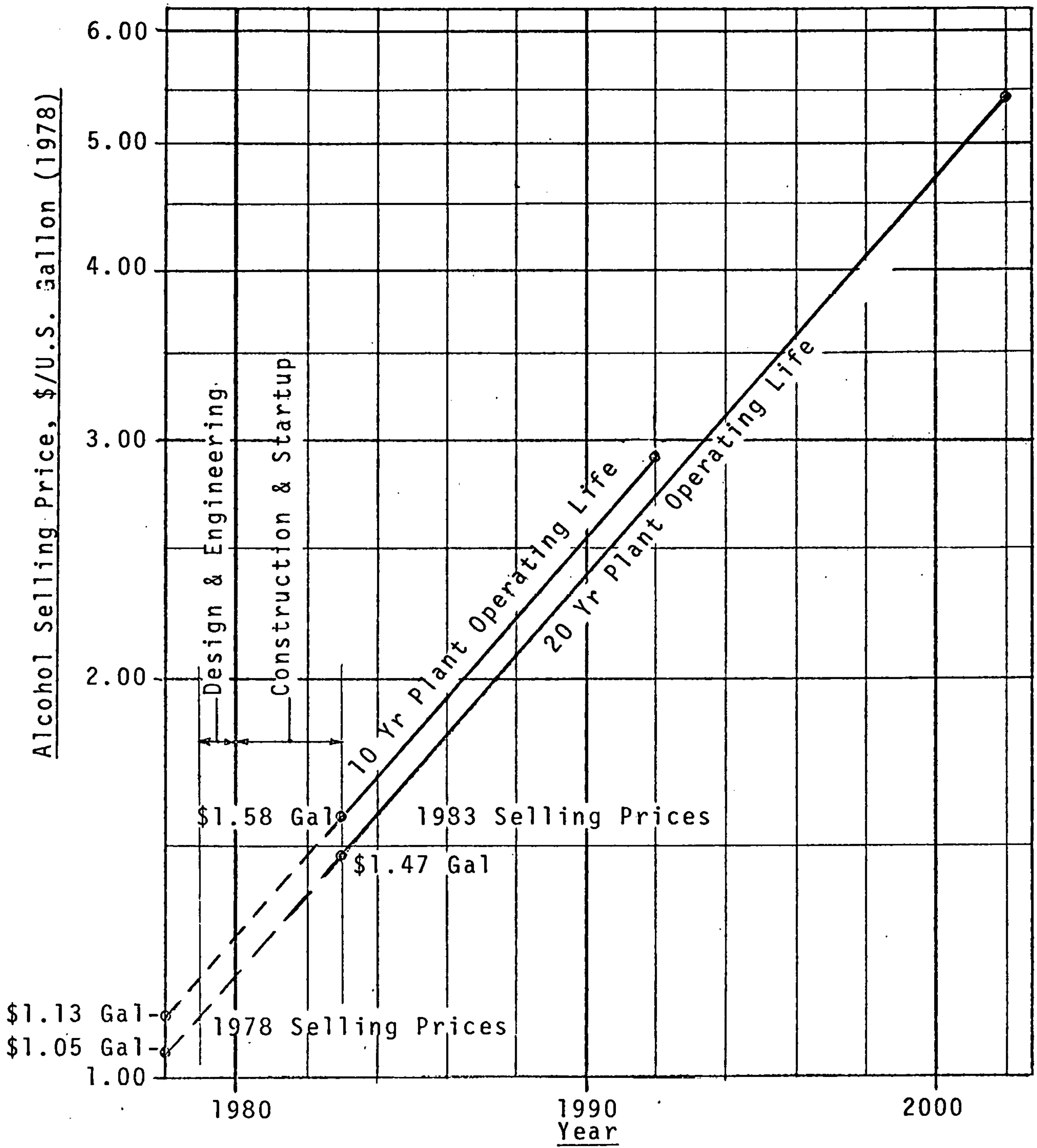
FIGURE 1
GRAIN MOTOR FUEL ALCOHOL STUDY
BASE CASE - 50 MM GAL/YEAR
100% COMPANY CAPITAL



1978 EQUIVALENT COST		ACTUAL 1981 INVESTMENT & 1st YEAR OPERATING W.C.	
Fixed Investment -	$58.0 MM	Fixed Investment -	$64.0 MM
Working Capital -	5.6 MM	Working Capital -	7.9 MM
Total Investment	$63.6 MM	Total	$71.9 MM

NOVEL CONTINUOUS FERMENTATION PROCESS FOR ETHYL ALCOHOL

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Introduction

The potentials of ethanol not only as a motor fuel but also as a bulk raw material for the chemical industry have been pointed out on many occasions in recent years (1). Technologies for large scale application in both directions are available (2). Technically it is mainly a question of new industrial plants and minor adjustments in the motor fuel distributory system to enable an ethanol-based petrochemistry if the ethanol were economically available in large amounts.

On the other hand renewable agricultural sources for ethanol production (i.e. carbohydrates) are present world wide in abundant amounts, as has been calculated by many authors (3).

It is only the technology of conversion of these raw materials into ethanol which has so far impeded large scale realization of the alcohol concept. Although practised since centuries in small plants mainly with the purpose of production of drinking alcohol (some 15 Million tons of ethanol are produced annually at present) (4) there is no technology available feasible for large scale ethyl alcohol fermentation, as was reported e.g. during the Int. Symp. of Alcohol Fuel Technology 1977 (5).

Conventional Technology

Existing processes are founded on drinking spirits and baker's yeast production, where the ethanol produced is looked upon as a highly valued beverage component and not as an organic chemical containing chemical energy. The fermentation reaction is a biological process yeast microorganisms acting as living biocatalysts to bring about the conversion of carbohydrates to ethanol. Only within the last two decades this process and its mechanisms have been scientifically understood by biochemists. This knowledge, however, was necessary to develop, adjust and optimise technical fermentation processes.

Furthermore, conventional prejudices from the existing fermentation industry had to be overcome with reason and experiment.

Existing processes are characterised by

- batch-wise procedure
- fermentation in simple vats
- energy wasting raw materials preparation and ethanol distillation
- small plants operating partly seasonally in combination with baker's yeast production, beer brewing, wine making etc.

The choice of raw materials employed depends very often rather on tradition than on an investigation. This traditional industry is legally protected in many countries inhibiting development and progress.

Only in recent years the world wide search for energy alternatives to crude oil has activated investigation into fermentation, and presently many R & D programs deal with this topic in universities and industry. The aims of these have been summarised for a given carbohydrate source as follows(6):

- continuous raw material preparation with recovery of heat where possible
- thermotolerant yeast strains
- continuous fermentation within a simple and cheap reactor
- non-sterile fermentation
- increased ethanol productivity with yields equivalent to batch processes
- large scale realisation
- continuous ethanol recovery with heat recovery

- reduction of slops B.O.D.
- reduction of slops solid content.

A number of continuous fermentation processes have been developed in recent years (7) (8) (9) which, however, to our knowledge are not operating industrially yet, and which do not achieve the major aim stated above, namely increase of productivity within a simplified plant. All technologies operate sophisticated fermentors, partly in series, the control of which appears to afford highly trained shift personel and complicated measurement equipment.

Furthermore it is reported that many of these processes are troubled with infections leading to yield losses and to the necessity to restart frequently.

New continuous fermentation process - theory

Chemical reaction rates and yields display in many cases a behaviour proportional to the physical conditions of the environment of the reactants. Chemical process engineering has developed reactors suitable for these reactions.

Microbiological processes are different in so far as to obtain optimum yields and productivities a certain band width of each physicochemical parameter such as temperature, pH, ionic strength etc. has to be maintained. The actual biochemical conversion of fermentation occurs within each microbial cell, which is separated from its environment by a cell membrane. In the case of ethanol fermentation it can be found that the possible reaction rates are much higher than those achieved in practise, whereas the substrate yields generally reach almost the theoretical value. The former is due to the fact that in a fermentation reactor by far not all yeast cells are treated equally, i.e. subjected to the same physicochemical distribution pattern.

Secondly the yeast cells are considered mainly as inertial catalysts in the main process and not as living cells that have basic requirements of metabolism to be able to perform the fermentation conversion. In conventional batch processes each batch is started with a freshly prepared inocculation culture and disposed of at the end of the batch; in continuous processes discussed so far the yeast is subjected, in a separate stage, to a so called recovery treatment. This separation is responsible for the low productivities and the decline of fermentation activity in continuous processes.

To overcome this it is necessary to find out the basic requirements of the yeast cells and the range where these overlap with the fermentation conditions.

Depending on the yeast strain employed there are

NUTRIENT REQUIREMENTS
TEMPERATURE, pH
OXYGEN TENSION
FREE SUBSTRATE CONCENTRATION
FREE ETHANOL CONCENTRATION
MASS AND HEAT TRANSFER RATES

to be considered.

Finally infections particularly in continuous fermentation have been observed as troublesome. In a large scale process biologically sterile operation appears to be much too expensive. Therefore conditions have to be found where ubiquitously present infectuous germs are suppressed in favour of the fermenting yeast cells.

Possibilities here are a low pH-range which is tolerated by yeast better than by most bacteria.

An elevated temperature which eliminates some further foreign microorganisms. A high active cell concentration of the yeast cultures appear to develop an active protection against other microorganisms if most yeast cells are in a germinative phase; dead cells on the other hand offer an ideal substrate for bacteria.

These considerations taken into account the following process was developed and tested:

Process Description

Supported by the German Federal Ministry of Research and Technologies the companies Hoechst AG and Uhde GmbH have set up a biotechnology project and have developed new continuous processes, equipment and products in this field since 1971, among them an ethanol fermentation process which is characterised by the following items:

CONTINUOUS ONE STAGE OPERATION IN A MIXED LOOP REACTOR
HIGH ACTIVE YEAST CONCENTRATION
LOW RESIDENCE TIME
USE OF AN ADAPTED YEAST STRAIN - ELEVATED TEMPERATURE
SUBSTRATE-CONTROLLED CHEMOSTAT PRINCIPLE
HIGHLY INCREASED PRODUCTIVITY

Raw Material Preparation

Depending on the quality of molasses the following raw material preparation is carried out.

High quality, solids free molasses can be employed without any treatment, in the case of dispersed particles a centrifugation may become necessary.

In tropical areas where cane sugar molasses are used a high degree of infections can be reduced in a continuous stream sterilisation step.

cleaned molasses then is diluted to a fermentable sugar content with water and its pH is adjusted with sulfuric acid. Ammonium phosphate and magnesium sulfate generally is added to meet the nutrient requirements of the yeast.

Continuous Fermentation

This prepared substrate solution then flows continuously, in a controlled manner, into the fermentation reactor.

The fermenter is a simple compact vat with a large stirrer which keeps the fermentation broth in a slow but even defined loop flow mixing the ingoing substrate into the broth.. The fermenter is temperature controlled and aerated with a circular sparger at the bottom. The alcohol content and CO_2-production are automatically monitored from the exit gas.

According to the inflow an equivalent amount of fermented broth leaves the reactor through an overflow device. This enters a sedimentor funnel where the yeast cells are allowed to settle in a downward motion; the supernatant overflows into a second settler where all residual solids sediment to the bottom. They are harvested from time to time and can be used after heat treatment as a protein rich fodder.

The final overflow enters distillation. The settling phase from the first sedimentor is continuously withdrawn at the funnel end and recycled at a high recycling rate to the fermenter.

Thus, two flow systems are superponed within the fermenter: one slow substrate - product flow and a fast yeast recycling flow.

Fermentation data

Sugar content of substrate	14	%
Flow rate of substrate (dilution rate)	0.3	h^{-1}
Residence time in fermenter	3	h
Yeast concentration in fermenter	50-60	g/l dry weight
ethanol concentration of fermented broth	7	%

Substrate yield (based on fermentable sugar)		0.47-0.5	
Aeration rate		0.05	vvm
pH of substrate		4.5-5.0	
ethanol productivity	average	25	ml/l·h.
	max.	50	ml/l·h.
Fermentation temperature		37°	C

Distillation

The fermented worth is conventionally distilled and rectified in continuous operation using heat recovery. It is facilitated by the fact that the worth is solid free.

The outcoming slops therefore have a reduced B.O.D. and can be used as a fertiliser or treated in a biodigester for biogas fermentation.

Pilot-Plant

The described process was developed in laboratory scale where it was operated continuously for more than three months. No infections or depression of yield and productivity occured, although no pretreatment of the beet molasses employed or any precautions were undertaken. It was then operated in technical scale in a 1 m^9 fermenter where the same values were achieved.

Discussion

The described process was developed within a R+D facility using beet molasses.

For commercial application the process appears to be flexible for adjustment to the local and substrate conditions.

The key parameters are the substrate flow control and the recyling of yeast, both very simple and apparent measurements. Extension of the process to starch containing raw materials is under investigation in our laboratories.

It is hoped, therefore, that this new technology may contribute in the future to realisation and economisation of large scale ethanol production.

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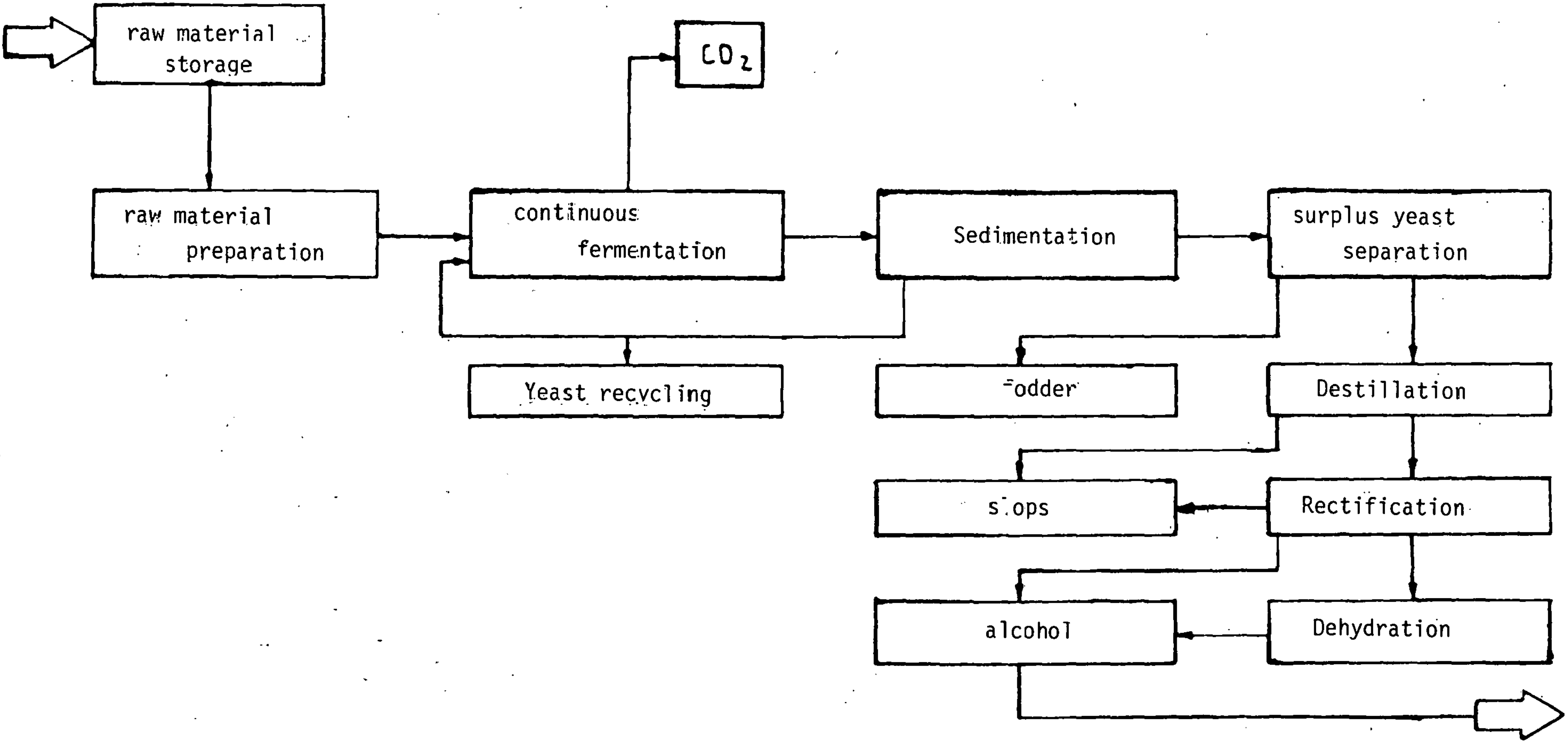
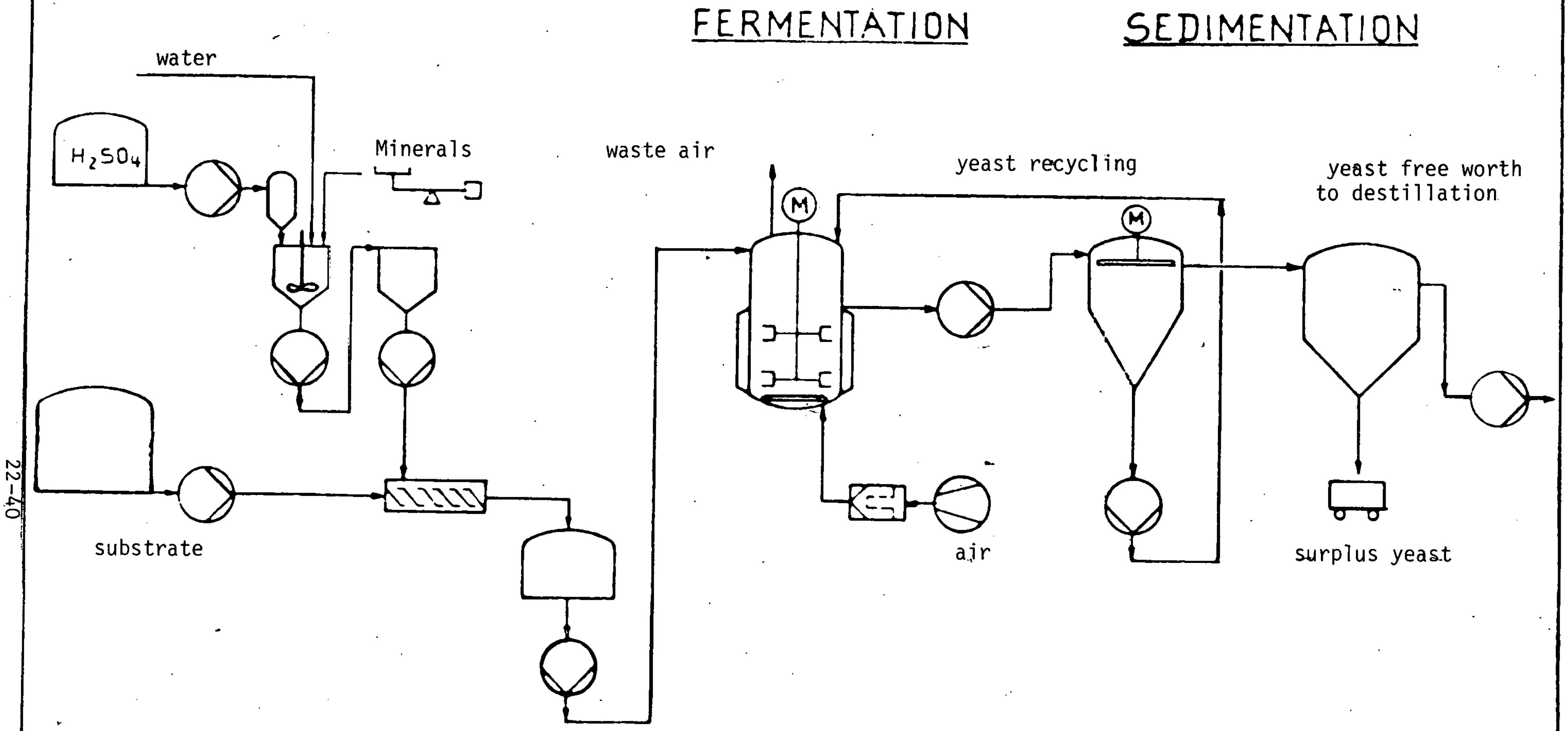


BLOCK DIAGRAM
CONTINUOUS FERMENTATION



22-40

FLOW DIAGRAM
CONTINUOUS FERMENTATION

PRODUCTION OF METHANOL FROM WOOD

by

Stephen M. Kohan, SRI International, USA*

This paper discusses the technology and economics of producing methanol from wood. Comparisons are made to prior work in the field, including the production of methanol from coal and from municipal solid waste.

FEEDSTOCK SELECTION

Many types of renewable resources may potentially be used for the production of methanol. Biomass feedstocks considered to have high potential for this application include woody plants, low moisture plants, and miscellaneous collected residues. For reasons of projected availability and potential conversion economics, woody plants were selected for detailed analyses. Table 1 shows the assumed ultimate analyses of the wood feedstock (typical of pine bark). (1,2,3)** Wood is assumed to be received at the conversion plant with a 50 wt.% moisture content (i.e., green wood). In general, other biomass feedstocks having moisture contents above 50 wt.% are expected to have estimated conversion economics less favorable than those shown here, and conversely.

TECHNOLOGY DESCRIPTION

Gasifier Selection

Candidate gasifier technologies available for or under development for wood or biomass gasification include fixed bed, fluid bed, entrained bed, molten bath, rotary kiln, and other types, with variations of staged gasification, catalytic gasification, and other options. Fixed bed systems have been studied by Battelle Pacific Northwest Division (4), American Fyr Feeder (5), Halcyon Associates, and others. The prediction of the yields and product properties of the condensible organic products from fixed bed gasification is difficult in the absence of experimental data. Entrained gasifiers (e.g., Texaco-type or BIGAS-type) may certainly be used to gasify biomass; however, the extent of required biomass pre-drying and pulverizing is not known. Molten bath technologies (e.g., Atomics International) are currently being considered only for (less reactive) coal gasification. Fluid bed technologies are currently being developed for the

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**Numbers in parentheses (1) designate References at end of paper non-catalytic gasification of biomass (e.g., Texas Tech.); for the catalytic gasification of biomass (Battelle Columbus Division (6) and Battelle Pacific Northwest Division (7));and for the non-catalytic pyrolysis of wood waste (e.g., ERCO) (8).

Many types of gasifiers may be used to gasify wood. Technologies which exploit the greater reactivity of wood as contrasted with coal are under development by the Department of Energy in cooperation with industry. For this analysis, a pressurized, oxygen-blown fluid bed gasifier technology was selected for analysis, using a dry lock-hopper feeding system. The principal reason for this selection was that gasifier yields could be estimated based on thermodynamic limitations and that no condensible by-products would be formed. Pressurized gasification was selected because of potentially favorable economics and energy usage when contrasted with the alternative of atmospheric pressure gasification and syngas compression.

Flowsheet Description

Figure 1 presents a conceptual flow diagram. Table 2 presents the stream flows, and Table 3 shows an overall energy balance.

A feed rate of 2000 short tons per day of wood chips was selected as the base plant size. The green wood chips (2" x 0) are air-dried to remove 40 to 50 percent of the moisture, and are ground to a size of 3/8" x 0 to 1/4" x 0. This size range was selected based on information previously received from Davy Powergas, Inc., regarding the size of coal particles recommended for Winkler (9) fluid bed coal gasification.

Petrocarb-type dry lock-hoppers (10) are used to feed the chips to gasifiers operating at 500 psia. Gasification is assumed to proceed with oxygen (500 short tons per day, preheated to 610°F) and steam, with wood chip residence times in the gasifier being of the order of 1/2 hour or shorter. A large gasifier yield of CO_2 is expected from non-catalytic wood gasification because of the high oxygen content of the wood. Catalytic wood gasification concepts (e.g., as being developed by Battelle) may reduce the gasifier CO_2 yields significantly; however, results from these efforts were not yet available when the present study was undertaken early in 1978. The bottom of the gasifier is assumed to operate in the agglomerating-ash mode to reduce carbon loss (11, 12).

Because of the high temperatures (1900-1950°F) used for the gasification, no condensible organic products are assumed to be formed. Product gases are cooled in a waste heat boiler, further cooled to condense water, reheated, and sent to a high temperature shift converter. The outlet mol ratio of H_2/CO (1.8) is set based on the desired H_2/CO ratio for Chem Systems synthesis (2.0) plus an estimate of CO losses in the cryogenic seperation step.

The shifted gases are cooled to 250-300°F upstream of the hot potassium carbonate unit. In the unit, CO_2 is removed down to 0.02 vol%; 95% H_2S removal is assumed; and 70% COS removal (by hydrolysis) is assumed. The acid gases are sent to a Stretford unit (13) for sulfur recovery. Less expensive Claus sulfur recovery units cannot be used because of the low H_2S content ($<$ 1 mol %) in the acid gas stream.

The synthesis gases are compressed to 735 psia and sent to a zinc oxide bed to remove the final traces of sulfur compounds. The syngases are next sent to a dew point depression unit to permit reasonable sizes to be used for the subsequent cold box feed preparation step (molecular sieves).

The molecular sieves remove the last traces of water and CO_2 from the gases before the cryogenic separation step. Based on information received from Linde and on information contained in a report by the Ralph M. Parsons Company (14), the cryogenic separation step separates the syngas into three streams: a hydrogen-rich stream; a CO-rich stream; and a methane-rich stream. The low pressure CO-rich stream is compressed and combined with the hydrogen-rich stream to form the feed to the Chem Systems synthesis unit.* The methane-rich stream is compressed and used as plant fuel.

The methanol synthesis reaction may be represented as:

$$2H_2 + CO \rightleftharpoons CH_3OH$$

In the Chem Systems synthesis concept, fresh syngas and recycled syngas are combined and passed upward through an expanded catalyst bed which is fluidized by an inert, nonmiscible hydrocarbon liquid. The hydrocarbon liquid serves as a heat carrier, absorbing the heat of reaction and generating steam by being continuously circulated from the reactor top to the reactor bottom. This coolant also permits close, uniform temperature control to be maintained in the reactor.

The reactor product stream is cooled to condense the methanol product as well as any entrained hydrocarbon liquid. The bulk of the noncondensible gases are recycled to the reactor. A small purge stream is continuously withdrawn (and used as plant fuel) to prevent the buildup of nitrogen and methane in the loop. Table 4 shows the estimated composition of the Chem Systems methanol fuel.

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* A small amount of CO_2 is recycled from the Stretford tail gases to obtain the syngas composition specified in the R.M. Parsons report (14).

The material and energy balances for the Chem Systems synthesis loop were ratioed, as appropriate, from the information presented in the R.M. Parsons report (14). Based on the estimated methanol production rates obtainable from wood feedstocks, single-train methanol synthesis units would be used.

Plant power needs are partially provided by high pressure steam from the gasifier waste heat boiler; the fuel gas boiler; and the shift effluent steam generator. High pressure steam is sent to extraction-condensing turbines to furnish 500 psia gasifier steam and low-pressure steam for the Stretford unit. The plant requires about 2.2 MW of purchased electricity since in-plant heat recovery is insufficient to satisfy plant power requirements.

Table 3 shows that the plant thermal efficiency (HHV methanol/ HHV wood + electricity) is 57.1 percent. Heat rejected to cooling (281 MMBtu/hr) represents principally oxygen plant and acid gas removal unit cooling requirements, and the cooling needs of the steam cycle.

Economics

Table 5 shows the estimated capital investment for the production of methanol from wood. Regulated utility financing is assumed with 65 percent debt capital. Wood storage, handling, and preparation facilities consist of wood receiving, handling, drying, grinding, conveying, and dust collection facilities. Wood gasification facilities include two 12-foot 8-inch I.D. gasifiers, lock hopper feed systems and compressors, external cyclones, ash lock hoppers, waste heat boilers, and the equipment for the condensing step. Shift conversion facilities include one shift converter and several heat exchangers. Cryogenic separation facilities include the molecular sieve and cryogenic units (with costs as furnished by Linde), compression (CO_2, recycle, CO-rich stream, and tail stream), and required cooling. Costs for the methanol synthesis unit were obtained from the report by R.M. Parsons (14). Costs for the Stretford unit were based on information in a Bechtel report (13). Utility facilities include such items as the fuel gas boiler, steam turbine and condenser, combustion air blower, a tank of oil for start-up, methanol storage facilities, cooling towers, and similar equipment items.

The plant facilities investment is estimated to be $88.0 million and the total capital investment is $101.5 million.

Figure 2 shows the effect of plant size on plant facilities investment. The plant investment, expressed as dollars per ton per day of methanol, decreases as plant size increases, reflecting economies of scale. The number of gasifiers increases from one to four as the wood feed rate increases from 500 to 3,000 ODT per day.

Table 6 presents the estimated major operating requirements. Operating labor is estimated to be 15.5 men per shift. Plant electricity requirements are estimated at 19.1 MW, about 10 percent of which is purchased. Fresh water requirements reflect the gasifier steam needs as well as boiler and cooling tower makeup.

Table 7 presents the annual operating costs. Based on regulated utility financing, the estimated revenue required from the sale of methanol is $8.85 per million Btu. Wood costs are 27 percent of annual operating costs; labor-related costs, 21 percent; and fixed costs (including depreciation), 38 percent.

Figure 3 presents the effect of plant size on revenue requirements. As plant capacity increases from 500 ODT per day to 3,000 ODT per day of wood, revenue requirements fall by 18 to 26 percent, reflecting economies of scale.

For every 10 cents per million Btu change in wood cost, revenue requirements change by 16 cents per million Btu. As the annual capacity factor drops from 90 to 70 percent, revenue requirements increase by a factor of 1.2. For each 10 percent change in plant facilities investment, revenue requirements change by about 6.0 cents per million Btu.

Comparisons

The methanol costs presented here are generally higher than the levelized costs of $5.18 to $6.44 per million Btu reported by R.M. Parsons (14) for the production of methanol from coal. This may be explained in part by the lower production rates observed here (300 to 1,700 short tons per day), contrasted with the larger (16,400 tons per day) rate used by Parsons. The costs presented here, however, are lower than the $10 to $12/million Btu values described by Lipinsky (17) for the production of 430 short tons per day of methanol from sugar crop residues.

Hokanson (18), using air-blown Moore-Canada gasifiers, reports an overall plant thermal efficiency of 38 percent for the conversion of 1,500 ODT per day of wood to methanol. The tabulation below suggests resulting methanol prices when using a feedstock cost of $19 per dry ton.

Methanol Production Rate		Methanol Price (1975$)	
MMgal/yr	ST/D	¢/gal	$/million Btu HHV
50	492	85¢	$13.30
200	1970	50	7.82

These methanol prices are higher than those evaluated here. By y of explanation, Hokanson used air-blown, atmospheric pressure sification with a cryogenic separation step to remove the nitrogen in the syngas, since the analysis was restricted to the use of commercially-available equipment. This is believed to be energy-inefficient with respect to a design considering oxygen-blown Moore-Canada gasifiers or to the pressurized oxygen-blown gasification concept considered here. Additionally, Hokanson considered the methanol synthesis at 2500 psia. ICI, Lurgi, and others currently offer low pressure synthesis loops operating at 750 to 1,500 psia.

MITRE (19) considered the production of methanol from wood using a Purox-type technology for wood gasification and a 1,500 psia synthesis loop. The Purox technology did not appear to have been integrated into a complete process plant design with the methanol synthesis step. As a result, the estimated selling prices of methanol are lower than those developed here.

Based on information to be presented in another Symposium paper by J. L. Jones, et. al., (20) the cost of producing methanol from municipal solid waste (MSW) may be greater than the cost of producing methanol from wood. Contributing reasons include expensive metals-separation steps for MSW feedstocks, as well as smaller plant sizes (methanol production rates).

ACKNOWLEDGEMENTS

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GLOSSARY OF TERMS

1. Plant facilities investment means the total cost of the plant erected and ready for start-up (in late 1977 dollars).
2. Total capital investment means the plant facilities investment plus land, working capital, start-up costs, and interest during construction.
3. Regulated utility (or regulated producer) financing means a declining rate-base analysis is used, with the following financial parameters: 65% debt; 9% interest rate on a 20-year loan; 15% return on equity capital; 10% interest rate during construction; straight-line depreciation; 52% federal and state corporate tax rate.
4. Nonregulated industry (or nonregulated producer) financing means a discounted cash flow analysis is used, with the following financial parameters: 100% equity financing; 15% DCF return over a 15-year period; sum-of-the-years-digits accelerated depreciation; 52% federal and state corporate tax rate.

Table 1

Ultimate Analysis of Wood

ELEMENT	WEIGHT PERCENT
C	53.8
H	5.7
O	38.2
N	0.2
S	0.1
Ash	2.0
Total	100.0

Higher heating value (millions of Btu/dry ton) 19.1

Table 4

PROPERTIES OF CHEM SYSTEMS METHANOL FUEL

	Weight Percent	Mol Percent
Methanol	95.4	94.48
Ethanol	1.0	
Isopropanol	1.0	1.16
Higher alcohols	0.1	
Water	2.5	4.36
Total	100.0	100.00

Higher heating value, Btu/lb 9,610
Btu/gal 63,930

Source: Reference (14)

Table 3

PRODUCTION OF METHANOL FROM WOOD BY DIRECT GASIFICATION AND CHEM SYSTEMS SYNTHESIS -- OVERALL ENERGY BALANCE

(Basis: 1,000 Dry Short Tons Per Day Wood Feed Rate)

	Millions of Btu Per Hour	Percent
Input		
Wet wood	796.7	99.1%
Electricity	7.5	0.9
Total	804.2	100.0%
Output		
Methanol	458.8	57.1
Heat rejected to cooling	281.2	35.0
Stack	44.4	5.5
Ash and unconverted carbon	7.1	0.9
Insulation losses	8.0	1.0
Miscellaneous losses*	4.7	0.5
Total	804.2	100.0%

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* Because of mechanical inefficiencies.

Table 5

PRODUCTION OF METHANOL FROM WOOD BY DIRECT GASIFICATION AND CHEM SYSTEMS SYNTHESIS

ESTIMATED TOTAL CAPITAL INVESTMENT
(Basis: 1,000 Dry Short Tons Per Day Wood Feed Rate)

	Millions of Dollars
Plant section investment	
Wood storage, handling, and preparation	$ 4.7
Wood gasification	16.7
Shift conversion	1.5
Acid gas removal	5.4
Oxygen plant	11.4
Cryogenic separation	4.1
Syngas compression	1.3
Methanol synthesis	7.7
Sulfur recovery	1.8
Utility facilities	21.9
General service facilities	11.5
Total plant facilities investment	$88.0
Land cost	0.3
Organization and start-up expenses	4.4
Interest during construction (2-year construction period)	6.7
Working Capital	2.1
Total capital investment	$101.5
Depreciable investment	99.1
Debt capital	66.0
Equity capital	35.5

Table 2

PRODUCTION OF METHANOL FROM WOOD BY DIRECT GASIFICATION AND CHEM SYSTEMS SYNTHESIS--STREAM FLOWS
(Basis: 1,000 Dry Short Tons Per Day Wood Feed Rate)

	(1)	(2)		(3)		(4)	(5)		(6)		(7)		(8)		(9)		(10)		(11)		(12)		(13)		Methanol Product
	10^3 lb/hr	10^3 lb/hr	lbmol/hr	10^3 lb/hr	lbmol/hr	10^3 lb/hr	10^3 lb/hr	lbmol/hr	10^3 lb/hr	lbmol/hr	10^3 lb/hr	lbmol/hr	10^3 lb/hr	lbmol/hr	10^3 lb/hr	lbmol/hr	10^3 lb/hr	lbmol/hr	10^3 lb/hr	lbmol/hr	10^3 lb/hr	lbmol/hr	10^3 lb/hr	lbmol/hr	10^3 lb/hr
C	44.88					0.44																			
H	4.74																								
O	31.795																								
N	0.165																								
S	0.08																								
Ash	1.67					1.67																			
H_2O	83.33			60.73	3,371		7.44	413	2.31	128											38.41	2,132	0.01	0.8	
H_2				5.22	2,588		6.16	3,054	6.16	3,054							6.16	3,054					0.19	95	
CO				60.36	2,155		47.34	1,690	47.34	1,690							42.77	1,527	4.56	163			1.29	46	
CO_2				63.24	1,437		83.71	1,902	0.04	1	83.75	1,903	83.40	1,895	0.35	8					14.30	325	0.34	7.8	
H_2S				0.07	2.2		0.07	2.2			0.08	2.4													
COS				0.02	0.3		0.02	0.3																	
N_2		0.73	26	0.90	32		0.90	32	0.90	32							0.64	23	0.25	9	255.51	9,120	0.64	23	
O_2		41.28	1,290																		65.33	2,043			
CH_4				1.80	112		1.80	112	1.80	112							0.45	28	1.35	84			0.45	28	
Methanol																							0.11	2.8	47.76
	165.66	42.01	1,316	192.34	9,697	2.11	147.44	7,205	58.55	5,017	83.83	1,905	83.40	1,895	0.35	8	50.02	4,632	5.16	256	373.60	13,620	3.03	203.4	47.76

Table 6

PRODUCTION OF METHANOL FROM WOOD BY DIRECT GASIFICATION AND CHEM SYSTEMS SYNTHESIS
ESTIMATED MAJOR OPERATING REQUIREMENTS

(Basis: 1,000 Dry Short Tons Per Day Wood Feed Rate)

Operating labor (men per shift)	15.5
Electric power (kWh/hr)	
Plant needs	19,100
Purchased (if any)	2,200
Cooling tower circulation-- ΔT = 20°F (gpm)	28,500
Purchased water (gpm)	1,540

Major compressors:

Service	Operating BHP
Syngas compression	1,580
CO compression	2,580
Methanol recycle compressor	1,340
Oxygen plant - oxygen compressor	2,900
Oxygen plant - air compressor	7,150

Table 7

PRODUCTION OF METHANOL FROM WOOD BY DIRECT GASIFICATION AND CHEM SYSTEMS SYNTHESIS -- ESTIMATED ANNUAL OPERATING COSTS AND REVENUE REQUIRED FOR A REGULATED PRODUCER

(Basis: 1,000 Dry Short Tons Per Day Wood Feed Rate)

	Millions of Dollars Per Year	Dollars Per Million Btu of Methanol
Materials and supplies		
Wood at $9.56/short ton (wet)	$ 6.28	$ 1.73
Catalysts and chemicals	0.62	0.17
Maintenance materials	1.76	0.49
Total materials and supplies	$ 8.66	$ 2.39
Labor		
Operating labor ($8/hr.)	1.09	0.30
Supervision	0.16	0.04
Maintenance labor	1.76	0.49
Administrative and support labor	0.60	0.17
Payroll burden	1.26	0.35
Total labor costs	$ 4.87	$ 1.35
Purchased utilities		
Water ($0.60/1000 gal.)	0.43	0.12
Electric power ($.035/kWh)	0.43	0.12
Total purchased utilities	$ 0.86	$ 0.24
Fixed costs		
G&A expenses	1.76	0.49
Property taxes and insurance	2.20	0.60
Plant depreciation, 20-year	4.95	1.37
Total fixed costs	$ 8.91	$ 2.46
Total annual operating costs	23.30	6.44
Return on rate base and income tax*	8.73	2.41
Total revenue required*	$32.03	$ 8.85
Sources of required revenue		
Methanol at $8.85/million Btu	32.02	8.85
Sulfur at $30/LT	0.01	
Total revenue*	$32.03	$ 8.85
Revenue required (nonregulated producer)	(46.33)	(12.80)

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*20-year average values.

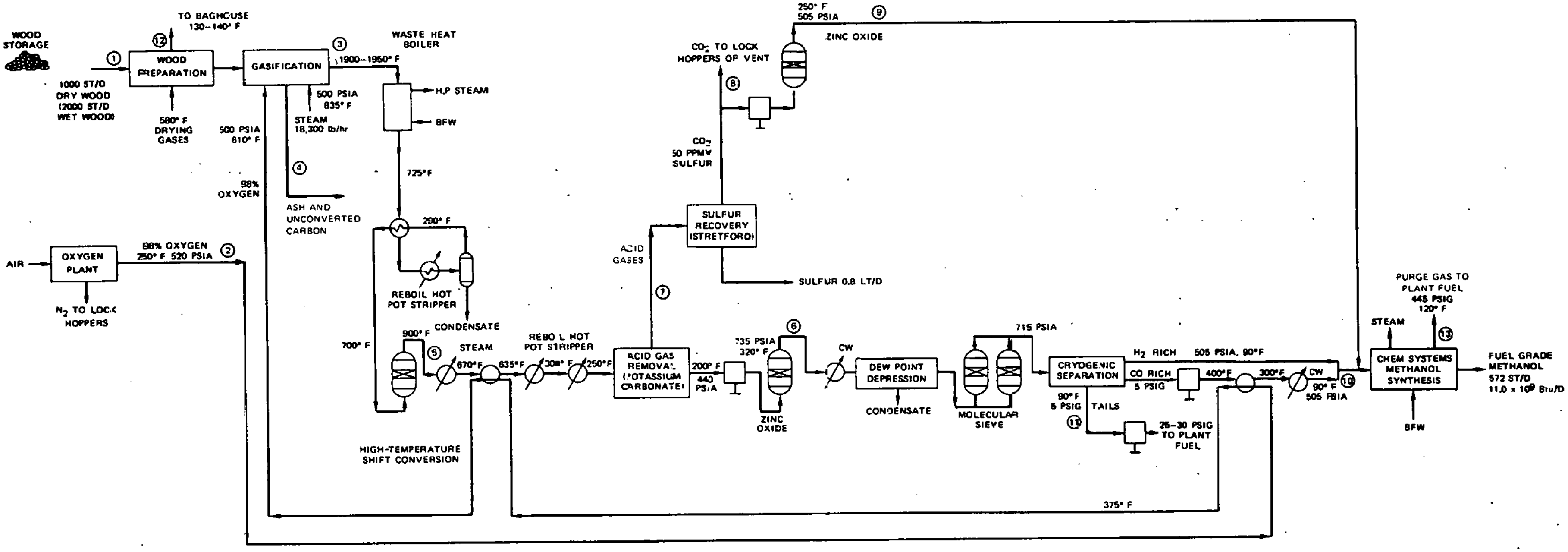

FIGURE 1 PRODUCTION OF METHANOL FROM WOOD BY DIRECT GASIFICATION OF WOOD AND CHEM SYSTEMS SYNTHESIS

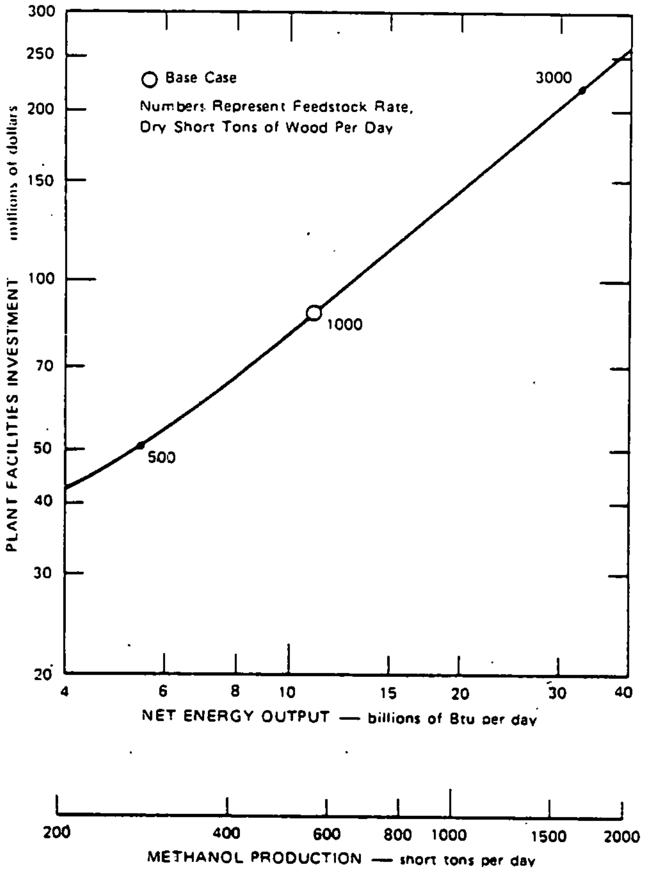

FIGURE 2 PRODUCTION OF METHANOL FROM WOOD BY DIRECT GASIFICATION AND CHEM SYSTEMS SYNTHESIS — EFFECT OF PLANT SIZE ON PLANT FACILITIES INVESTMENT

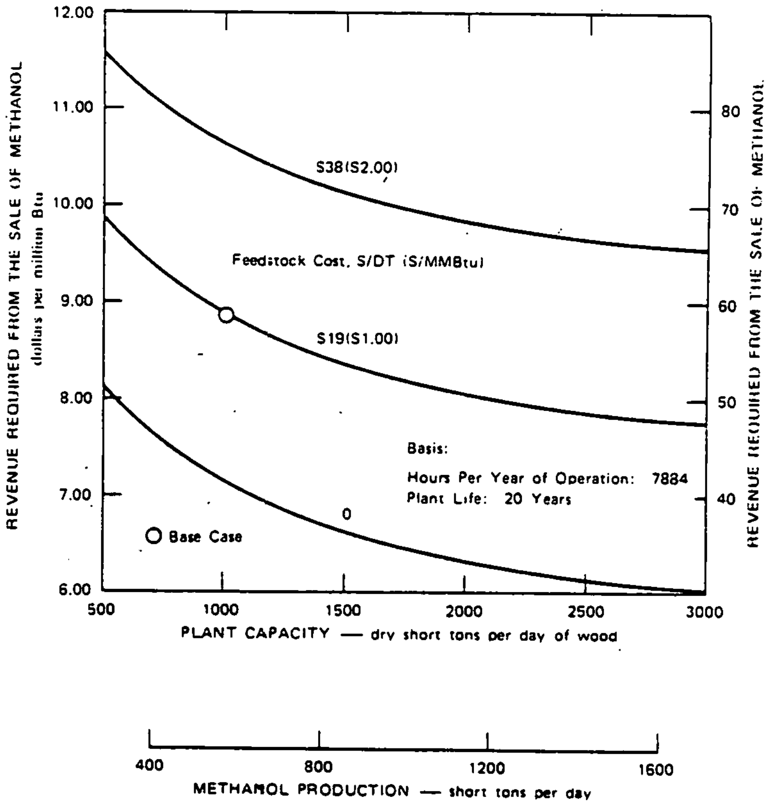

FIGURE 3 PRODUCTION OF METHANOL FROM WOOD BY DIRECT GASIFICATION AND CHEM SYSTEMS SYNTHESIS — EFFECT OF PLANT SIZE ON REVENUE REQUIRED FROM THE SALE OF METHANOL BY A REGULATED PRODUCER

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WHAT DO WE DO WHEN THE WELLS RUN DRY?

by

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California State Legislature

As America passes from the 1970's into the 1980's it also passes from an old energy era into a new one. Energy needs and availabilities of the past must be reassessed in light of the present international situation and its effect upon domestic energy supplies. It is obvious that fossil fuel reserves (natural gas and petroleum) are becoming increasingly scarce. Moreover, those which continue to produce high yields are being exploited at prohibitive pricing scales by those interests which control them. The critical point has been reached with the loss of Iranian oil on the fuel market. OPEC nations are one by one raising their prices on exported petroleum, producing circumstances that will very soon drive consumer prices to unprecedented levels. Additionally, domestic oil companies who purchase the crude, raise the market price even further in the interests of increasing corporate profit.

The governments of the world have issued ominous warnings pointing to the need for oil rationing and conservation measures in the near future. America's dependence upon foreign oil has brought it to the brink of an energy crisis of immense and lasting proportions.

The major oil companies, in conjunction with the U.S. Department of Energy and President Carter, have responded to this impending crisis inadequately. Instead of developing alternatives to non-renewable petroleum-based fuels when it was abundantly clear that an energy crisis was imminent, they chose to continue foreign importation and pass the costs on to the American Consumer, no matter how high those costs go. Instead of pursuing energy programs that domesticate fuel production while boosting the U.S. economy and creating new industries and jobs, the oil companies have increased their own profits while the rest of the country suffered. A recent article in the Wall Street Journal points out that corporate profits for the thirteen major oil companies jumped 70% during the 1974 oil embargo and can be expected to do so again in light of the rising price of crude oil. The OPEC nations themselves recently levied a $1.20 surcharge upon each barrel of oil exported, stating among other things that the oil companies were enjoying sky-rocketing profits by passing price increases on to the consumer, who once again is the big loser.

The oil and gas lobbies have spent millions of dollars influencing federal decisions away from the development of alternative fuels. Importation of foreign oil and gas continues because the oil interests control the market. As gas and oil become increasingly scarce, the consumer will be hit hard by $1.00 to $1.50 gallon prices at the pump. In effect, oil companies are direct contributors to inflationary trends in the country.

Through the U.S. Department of Energy (DOE), President Carter himself has fallen victim to the oil lobby and consequently has not provided any comprehensive energy program which would actually solve the problems the U.S. faces today. Considering the size of the federal budget, our limited reserves of fossil fuels, our extensive technical expertise and the ability of the American people to rise to a difficult situation and to do their best to solve it, the U.S. government should have moved long ago to avoid the trauma of oil and gas shortages by developing synthetic fuels capabilities. Given these factors, the United States should be a world leader in developing alternate fuel production, allocation and utilization systems. Instead, it is the state and local governments which have given impetus to replacing petroleum production with renewable synthetic fuel production.

One effort to create an alternate fuel industry has taken place in California. The State Legislature has moved to create a Joint Committee on Alternate Fuels to address itself to the production and marketing of alcohol fuels on a large scale basis. This effort, along with the "Gasohol" movement in several midwestern states, are the forerunners of new concepts in alternative energy production. The Legislature's goals are expressed by Assembly Bill No. 3555 (1978), Senate Concurrent Resolution No. 4 (1978), and Senate Bill 1395 (1976), which are enclosed as Exhibits A, B and C. A chart is enclosed as Exhibit D to show the general concept of the California synthetic fuels industry which will emerge in the next few years.

In order to promote a synthetic fuels industry in California, additional legislation will be introduced to foster the growth of biomass farming and efficient conversion of biomass into energy. In addition, taxation and financing programs will be initiated to promote construction and operation of conversion plants. These programs will make synthetic fuel production economically feasible in its embryonic stages.

Legislation specifically dealing with programs to set aside land, to allow for the cultivation of biomass on marginal lands, is an essential element to developing the industry. Marshland, "hardpan" secondary lands and areas not suited for tilling would be optimal for biomass farming.

Agricultural waste as well as municipal solid and liquid waste would be utilized extensively in a synthetic fuels industry. SB 1395 (Greene) made it part of California's state policy to initiate an "Energy from Waste" program but additional legislation will be needed to provide facilities to process the more than 40,000 tons of agricultural waste produced daily.

In addition, tax programs to allow the rapid growth of such an industry are an issue which must be addressed in the form of legislation. Prototype plants for the conversion of biomass into methanol fuel must be allowed to demonstrate existing technology and to develop new and more efficient technologies.

As was done with the railroad industry in the early days of California, and as has been done for the last seventy years in the petroleum industry, government subsidies allowing for the establishment of a synthetic fuels industry would be necessary for a period of time. Financial support would be an important part in allowing such an industry to get off the ground. Guaranteed loans for the construction of processing plants are one step government might take. Encouragement of the marketing of alcohol fuels is another step government should take in helping out.

Laws giving exemptions to synthetic fueled autos from current pollution control devices would also effectively provide impetus for the populace to drive such cars. Synthetic-fueled cars are practically pollution-free given the high compression (18-1) ratio and lean burn ratio on which they can run. Therefore, devices required by law for most autos on the roads today would not be necessary on alcohol fueled cars.

In the utilities industry, government might once again take action to foster use of synthetic rather than petroleum fuels. Peaking turbines, used to boost power output in peak-demand situations, could be powered by methanol rather than natural gas and oil based fuels as is currently done. Alcohol turbines would lower emissions from oil based fuels while giving higher performance and lower maintenance costs.

The 1970's has seen the extreme demoralization of the American people. Their faith in the larger institutions, both in the public and private sectors, has eroded to alarming and unprecedented degrees. Such obvious blunders by the federal government such as the senseless war in Vietnam and the Watergate and Koreagate affairs, have made the American populace cynical about institutions which profoundly affect their lives. Similar feelings of resentment have arisen toward private industry because of large corporations pursuing corporate profits at any price. The lack of sensitivity with which many large industries conduct their affairs has turned America off to big business, and rightfully so. In the view of the average wage earner, too many corporate executives have been overly active in making illegal campaign contributions and bribing government officials around the world. Many corporations have been very successful without illegal activities. They know how to see the future needs of the market place and they compete openly to win as many profits as they can by giving the consumer a better bargain. Synthetic fuels will soon prove to be a better product at a lower price, and those oil companies which bring the product to the consumer as the wells run dry, will reap their just profits. Several oil companies are moving hard in this area, and so are a number of other types of companies.

The development of a synthetic fuels industry could significantly affect the ill feeling many Americans currently have toward government and big business. A positive program that touches every person's life could rekindle hope for the future of America. It is possible to provide cheap, abundant, renewable sources of energy by the use of synthetic fuels. In addition, pollution could be reduced and automobiles and industry alike could be run more efficiently. These developments would reach prominently into all our daily lives as we drive to work in automobiles which are quicker and cleaner, less expensive, and free from the threat of stopping as the wells run dry.

It is time for government and citizens alike to protect their interests by supporting the development of synthetic fuels before the energy situation reaches a point of no return. It is up to the American people to control their destiny and protect their energy independence.

Corporate executives need to be more sensitive to the mood of the working American. Continuance of oil policies which are inflationary, excessively profitable and heavily destructive of consumer energy freedoms, will lead to proposals for nationalizing the oil industry. Secretaries Schlesinger and Brown, cannot continue to fail to aggressively support synthetic fuels, and then suggest the use of American troops to protect oil interests in foreign lands. The public will not support President Carter in his "moral equivalent to war" when that equivalent becomes a shooting war. A synthetic fuels industry sponsored by government would be supported by the public - enthusiastically!

Assembly Bill No. 3555

CHAPTER 1192

An act relating to synthetic fuels.

[Approved by Governor September 26, 1978. Filed with Secretary of State September 26, 1978.]

LEGISLATIVE COUNSEL'S DIGEST

AB 3555, Cline. Synthetic fuels: biomass conversion.

Under existing law, the State Solid Waste Management Board is required to determine the economic feasibility of developing a research and demonstration project which would further the development of the concept of conversion of agricultural wastes to synthetic fuel, and, upon determining economic feasibility, to undertake the construction and field demonstration of a system for such conversion.

This bill would declare that it is this state's policy to foster development of a synthetic fuels industry capable of providing fuels by encouraging the utilization of biomass feed-stock, construction of facilities for conversion of biomass into readily usable fuels, development of markets and technologies capable of utilizing such fuels, and appropriate taxes and other prescribed governmental action to aid in establishing a synthetic fuels industry in the private sector in the next decade.

The bill would not alter or supersede (1) existing policies or priorities established pursuant to another statute or (2) the discretionary authority of any public agency carrying out its duties and responsibilities required of such agency by law.

The people of the State of California do enact as follows:

SECTION 1. (a) The Legislature hereby declares that it is the policy of the state to foster development of a synthetic fuels industry capable of supporting the needs of the people of California by encouraging:

(1) The utilization of biomass feed-stock which converts the energy of the sun into solid materials (plant life) which can then be harvested.

(2) The construction of facilities capable of converting the biomass into readily usable synthetic solid, liquid, and gaseous fuels.

(3) The development of markets and technologies capable of utilizing such synthetic fuels in place of natural coal, gas, and oil-based products.

(4) The appropriate taxes, subsidies, variances, special permits, and agency assignments to aid in establishing a synthetic fuels industry within the private sector within the next decade.

(b) This act is not intended and shall not be construed as altering or superseding:

(1) The policies or priorities established pursuant to another statute, or

(2) The discretionary authority of any public agency in carrying out the duties and responsibilities required of such agency by law.

Exhibit A

Exhibit B
6
II-42

AMENDED IN SENATE JANUARY 8, 1979

Senate Concurrent Resolution No. 4

Introduced by Senator Greene

December 15, 1978

Senate Concurrent Resolution No. 4—Relative to the Joint Committee on Alternate Fuels.

LEGISLATIVE COUNSEL'S DIGEST

SCR 4, as amended, Greene. Joint Committee on Alternate Fuels.

Chapter 1192 of the Statutes of 1978 declared that it is the policy of the State of California to foster development of a synthetic fuels industry.

This measure would create the Joint Committee on Alternate Fuels and prescribe the composition, powers, and duties of the joint committee.

The measure would transfer all work of the Joint Committee on Job Development which is related to the synthetic fuels car, biomass, mobile agricultural waste convertor, and methanol or synthetic natural gas activities to the Joint Committee on Alternate Fuels.

The measure would require the joint committee to complete its work and recommendations to the Legislature no later than January 31, 1981, and the joint committee would be dissolved on that date.

Fiscal committee: no.

WHEREAS, The natural gas and oil resources which the people of California consume are finite; and

WHEREAS, These resources are projected to fall short of this generation's needs as well as the needs of future generations; and

WHEREAS, Development of an alternative combustible fuels industry is a long leadtime effort requiring major commitments by both government and industry; and

WHEREAS, The technology for producing synthetic fuels from waste materials and biomass has been demonstrated; and

WHEREAS, The necessary technical and business expertise to develop a synthetic fuels industry resides throughout various California industries; and

WHEREAS, The California Legislature finds and declares that there is an urgent need to develop a synthetic fuels industry to provide alternative combustible fuels to replace natural gas and oil wells as energy sources; now, therefore, be it

Resolved by the Senate of the State of California, the Assembly thereof concurring, That the Joint Committee on Alternate Fuels is hereby created with the following composition, powers, and duties:

(1) The joint committee shall consist of three Members of the Senate, appointed by the Senate Committee on Rules, and three Members of the Assembly appointed by the Speaker of the Assembly. Vacancies occurring in the membership during the existence of the joint committee shall be filled by the appointing power.

(2) The joint committee is authorized to perform research and analysis, hold hearings, publish reports, and sponsor legislation relative to development of a synthetic fuels industry for the people of the State of California in compliance with Chapter 1192 of the Statutes of 1978.

(3) The joint committee is authorized to create an advisory committee, with appointments and duties to be established by the chairman of the joint committee.

(4) The joint committee shall begin its work immediately upon passage of this resolution, and is authorized to act during the 1979–80 Regular Session of the Legislature.

(5) The joint committee shall complete its work and recommendations to the Legislature no later than ~~December 30, 1980~~ *January 31, 1981,* at which time the

joint committee shall be dissolved.

(6) The Joint Rules Committee may make funds available from the Contingent Funds of the Assembly and Senate for the expenses of the joint committee and its members and for any charges, expenses, or claims incurred by the joint committee under this resolution; provided that, in accordance with Joint Rule 36.8, any expenditure of funds shall be made in compliance with policies set forth by the Joint Rules Committee and shall be subject to the approval of the Joint Rules Committee.

(7) All work related to the synthetic fuels car, biomass, mobile agricultural waste convertor, and methanol or synthetic natural gas activities of the Joint Committee on Job Development shall be transferred to the joint committee created by this resolution.

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Exhibit C

8

Senate Bill No. 1395

CHAPTER 1246

An act to amend Sections 66740 and 66745 of, and to add Sections 66786 and 66786.5 to, the Government Code, relating to synthetic fuels, and making an appropriation therefor.

[Approved by Governor September 22, 1976. Filed with Secretary of State September 27, 1976.]

LEGISLATIVE COUNSEL'S DIGEST

SB 1395, Joint Committee on Job Development. Synthetic fuels: solid waste conversion.

(1) Existing law provides for the State Solid Waste Management Board of specified members, including one representative of the public appointed by the Governor who has specialized education and experience in environmental quality and pollution control, and certain state officers or their deputies who serve ex officio. Existing law provides that members of the board receive necessary expenses and $100 per day for meetings of the board.

This bill would increase the board by including three representatives of the public appointed by the Governor, delete the specialized education and experience requirement of such members, and delete the requirement that the member appointed by the Speaker of the Assembly be a registered civil engineer for a specified reason. The bill would provide for a full-time chairman designated by the Governor, subject to the advice and consent of a majority of the members elected to the Senate, and paid a prescribed annual salary. The bill would remove the per diem payment to the chairman and the state officers serving ex officio, for attendance at meetings of the board.

(2) Existing law requires the State Solid Waste Management Board to adopt, by January 1, 1975, the State Solid Waste Resources Recovery Program, which is required to include demonstration projects on the recovery of useful energy from solid wastes.

This bill would require the board to select, not later than July 1, 1977, and, after consulting with interested cities and counties, the State Energy Resources Conservation and Development Commission, the Department of Water Resources, the State Lands Commission, the State Air Resources Board, and the State Water Resources Control Board, one or more sites for the establishment of facilities for the conversion of solid waste into energy synthetic fuels, or for the recovery of materials based upon certain feasibility information. The State Energy Resources Conservation and Development Commission and the California Pollution Control Financing Authority would be required to assist the secretary in identifying sources of funding and developing a plan for financing the facilities.

The board would be required to submit the plan and recommendations to the Legislature by December 31, 1977.

The bill would also require the board to consult with the State Air Resources Board, the State Water Resources Control Board, and the State Energy Resources Conservation and Development Commission and cause construction and operation specifications to be prepared.

The facilities would be required to be operational not later than January 1, 1981, and would be required to be constructed and operated under agreements with the selected cities, counties or other agencies having jurisdiction over the site or sites selected and in accordance with the board's specifications.

The bill would also require the board to determine, after consultation with the State Energy Resources Conservation and Development Commission and the State Air Resources Board, the economic feasibility of developing a research and demonstration project for conversion of agricultural wastes to synthetic fuel, and the bill would require, if economically feasible, the board to undertake the construction and field demonstration of such a system, and to complete such field demonstration by July 1, 1979.

The bill would reappropriate $250,000 to the board for expenditure during the 1976–77 and 1977–78 fiscal years from the sum appropriated by the Budget Act of 1976 for expenditure in support of the board in the 1976–77 fiscal year for such research and demonstration project, and would require the State Energy Resources Conservation and Development Commission to consider an amount, not to exceed $250,000 and as identified by the feasibility study, in their 1977–78 fiscal year budget request for such demonstration project.

The bill would declare state policy and legislative intent regarding the conversion of solid and agricultural wastes into synthetic fuels.

Appropriation: yes.

The people of the State of California do enact as follows:

SECTION 1. Section 66740 of the Government Code is amended to read:

66740. There is in the Resources Agency the State Solid Waste Management Board.

The board shall consist of the following members:

(a) One member appointed by the Governor who is at the time of his appointment a city councilman from a city having a population of more than 250,000 persons as determined by the 1970 federal census.

(b) One member appointed by the Governor who is at the time of his appointment a county supervisor from a county having a population of more than 500,000 persons as determined by the 1970 federal census.

(c) Three representatives of the public appointed by the Governor.

(d) One representative of the public appointed by the Speaker of the Assembly, who shall have specialized education and experience in natural resources conservation and resources recovery.

(e) One representative of the public appointed by the Senate Committee on Rules, who shall be a registered civil engineer under the laws of this state and have specialized education and experience in natural resources conservation and resources recovery.

(f) One member appointed by the Governor from the private sector of the solid waste management industry from southern California.

(g) One member appointed by the Governor from the private sector of the solid waste management industry from northern California.

(h) The State Director of Health or his deputy who shall be a nonvoting ex officio member.

(i) The State Director of Agriculture or his deputy who shall be a nonvoting ex officio member.

(j) The Chief of the Division of Mines and Geology of the Department of Conservation or his deputy who shall be a nonvoting ex officio member.

The Governor shall appoint, subject to the advice and consent of a majority of the Members of the Senate, one of the members of the board as chairman. The chairman shall serve full time and shall receive an annual salary as prescribed by Section 11552.

SEC. 2. Section 66745 of the Government Code is amended to read:

66745. Each member of the board shall receive the necessary traveling and other expenses incurred by him in the performance of his official duties out of appropriations made for the support of the board. In addition, each voting member, except the chairman and state officials serving ex officio, shall receive one hundred dollars ($100) for each day attending meetings of the board. When necessary the members of the board may travel within or without the state.

SEC. 3. Section 66786 is added to the Government Code, to read:

66786. The Legislature finds and declares that effective solid waste management can aid in the development of alternative sources of energy through the conversion of solid waste material into energy, synthetic fuels, and recovery of materials. It is the policy of the state and the intent of the Legislature that a well-coordinated governmental effort be directed toward achieving an efficient process for the conversion of solid wastes into energy, synthetic fuels, and reusable materials. Such policy is specifically designed to encourage the dual objectives of materials recovery and the development of supplemental energy resources. Not later than July 1, 1977, and after consultation with interested cities and counties, the State Energy Resources Conservation and Development Commission, the State Air Resources Board, and the State Water

Resources Control Board, the board shall select one or more sites that are suitable for the establishment of facilities for the conversion of solid waste into energy, synthetic fuels, or for the recovery of materials. This selection shall be predicated upon information that shows the feasibility of the particular process based upon availability of markets, project economics, impact of any such facility on local employment, local needs for new energy sources, conformance with local land use planning, and a guaranteed volume of waste or feedstock.

The State Energy Resources Conservation and Development Commission and the California Pollution Control Financing Authority shall assist the board in identifying appropriate sources of funding and developing a plan for financing the facilities. The board shall submit the plan and its recommendations to the Legislature not later than December 31, 1977.

The board shall consult with the State Air Resources Board, State Water Resources Control Board, and State Energy Resources Conservation and Development Commission, and shall cause specifications for the construction and operation of the solid waste conversion facilities to be prepared. The board may call upon any other commission, board, department, or agency of the state or upon any agency of local government for assistance in selection of the site or sites, preparation of plans, and development of specifications.

The board shall enter into one or more agreements to facilitate the construction and operation of any solid waste recovery and conversion facilities with selected cities, counties, private entities, or with any other agencies having jurisdiction over the site or sites selected for such facilities. However, the board shall not enter into any agreement for the construction or operation of any facility the financing of which requires further action of the Legislature until the Legislature has so acted.

Any such agreements shall provide that the construction and operation of any such facilities shall be done in accordance with the specifications of the board, and that the facilities shall be operational within a period of time determined by the board, but in no event later than January 1, 1981.

SEC. 4. Section 66786.5 is added to the Government Code, to read:

66786.5. The Legislature of the State of California hereby finds and declares that there exists a significant air pollution problem associated with the current practice of the burning of agricultural wastes as a means of disposal. The conversion of agricultural waste to a synthetic fuel might serve to mitigate the air pollution problem and the solid waste disposal problems as well as provide an additional source of energy.

This section shall serve as an expression of the intent of the State of California to actively explore and develop the alternative of conversion of agricultural wastes to synthetic fuels rather than the current practice of burning.

After consultation with the State Energy Resources Conservation and Development Commission and the State Air Resources Board, the board shall determine the economic feasibility of developing a research and demonstration project which would further the development of the concept of conversion of agricultural wastes to synthetic fuel. As a part of this feasibility analysis, the board shall:

(a) Determine whether an adequate volume of wastes would be available to serve such a project.

(b) Complete an analysis of the cost of transporting the agricultural wastes from the fields to the conversion unit.

(c) Determine whether a mobile or stationary system should be developed and demonstrated.

(d) Develop a test program that will result in the construction and demonstration of such a system.

(e) Determine the availability of matching federal funds.

Upon a finding by the board that such a demonstration is an economically feasible solution to problems caused by the burning of agricultural wastes, with the assistance and cooperation of the State Energy Resources Conservation and Development Commission and the State Air Resources Board, the board shall undertake the construction and field demonstration of a system for the conversion of agricultural wastes to synthetic fuel. Such field demonstration shall be completed by July 1, 1979. The demonstration program shall study the various parameters of system performance regarding air pollution emissions, other environmental impacts, the utility of the system on various types of agricultural wastes, the evaluation of the reliability of the process, and an overall economic analysis.

As a result of this demonstration project, the board shall provide for public consumption, documentation regarding the evaluation of the system. Assuming the demonstration is a successful one, the documentation shall be in a form that would encourage commercial development of conversion of agricultural wastes to synthetic fuel.

SEC. 5. Notwithstanding any other provision of law, the sum of two hundred fifty thousand dollars ($250,000) of the appropriation made for support of the State Solid Waste Management Board by Section 10.6 of the Budget Act of 1976 (Chapter 320 of the Statutes of 1976) is hereby reappropriated to the State Solid Waste Management Board for expenditure during the 1976–77 and 1977–78 fiscal years for use by the board for the research and demonstration project for conversion of agricultural wastes to synthetic fuel utilizing a mobile converter in accordance with Section 66786.5 of the Government Code. Such sum may be used by the board for any useful purpose of such research and demonstration project utilizing a mobile converter, including, but not limited to, obtaining matching funds for federal or other public or private funds or grants for such research and demonstration project.

SEC. 6. The State Energy Resources Conservation and Development Commission shall consider in its research and development budget funding request for the 1977–78 fiscal year such amounts, not to exceed two hundred fifty thousand dollars ($250,000) and as identified in the feasibility study, to carry out such demonstration project.

SEC. 7. The Legislature finds and declares that the deletion of the requirement that the representative of the public appointed by the Speaker of the Assembly to the State Solid Waste Management Board be a registered civil engineer is necessary to effect the intent of the Nejedly-Z'berg-Dills Solid Waste Management and Resource Recovery Act of 1972 as adopted by the Legislature.

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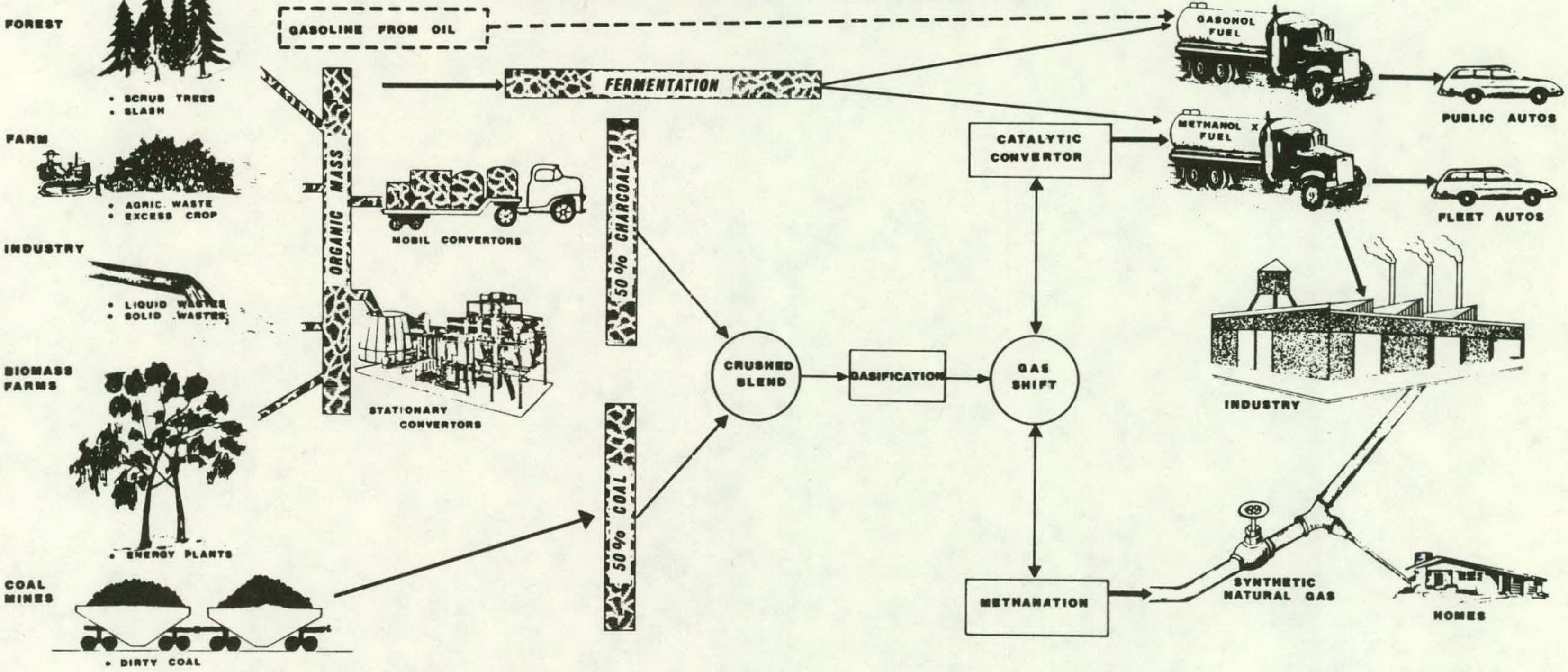
Exhibit D
11

CALIFORNIA SYNTHETIC FUELS INDUSTRY



RESEARCH PROGRAM "ALCOHOLIC FUELS FOR ROAD TRAFFIC" OF THE GERMAN FEDERAL MINISTRY FOR RESEARCH AND TECHNOLOGY DURING THE PERIOD 1979 - 1982

by

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Motor vehicle traffic is of particular importance in the Federal Republic of Germany as it accounts for more than 80% of passenger transport and over 45% of freight transport (data for 1978). A total of 25.3 million motor vehicles (of which 21.6 million are passenger vehicles and 1.3 million are trucks) can therefore be found on our roads today. Our modern automobile industry has provided the essential requirements for this purpose by developing efficient motor vehicles and has expanded to become the second largest automobile exporter in worldwide markets.

Thus motor vehicle traffic and the automobile industry represent a significant economic factor for the Federal Republic of Germany.

On the other hand our motor vehicles are almost solely dependent on the primary energy crude oil, that is to say on the energy resource which, according to all forecasts, will soon be showing distinct signs of scarcity. Our oil deposits in the Federal Republic of Germany are hardly worth mentioning which is why our motor vehicle traffic is particularly susceptible to disturbances and bottlenecks in the supply of mineral oil.

Therefore the imponderabilities and uncertainties connected with an energy structure, which is based mainly on imported crude oil, must be reduced by improved energy utilisation and increased diversification to domestic and other available primary energy carriers whose supply is less problematical. For motor vehicle traffic the alcoholic fuels are a promising alternative for the following reasons:

1. The alcohols which can best be used for engines, namely methanol and ethanol, are liquid fuels. For this reason it would be much easier to adapt not only the engines and automobiles but also the whole supply infrastructure and would involve less expense than if gaseous fuels were to be used as an alternative solution, even considering the lower density of energy compared with gasoline fuels.

2. Alcoholic fuels - methanol in particular - can be extracted directly from the domestic primary energy carrier coal (brown coal, pit coal) using well-known techniques. The

methanol synthesis is practically the first stage of the procedure. Further stages, for example towards producing synthetic petrol, are conceivable, but all involve additional energy losses in the conversion process.

3. Alcoholic fuels are generally well-suited for use as blends in combination with traditional fuels based on crude oil and could thus lead to a direct reduction of crude oil consumption. The adaption measures then required for engines and vehicles in current production are realisable. For blend ratios up to certain limits (15% to 20% or even higher) there is a reasonable compatibility with gasoline fuels and so motor vehicles running on such blends would not be subject to restrictions due to bottlenecks in supply (such as crossing borders).

4. Due to their specific properties straight alcohol fuels can be used advantageously in both gasoline and diesel engines resulting in substantial improvement in their efficiency, i.e. reduction in energy consumption.

5. From the viewpoint of environmental protection the usage of alcoholic fuels also contributes to a further reduction of the harmful exhaust gas components (CO, HC, NO_x, soot). The occurrence of strongly odorous substances can be reduced by technological measures to a permissible level.

6. Alcoholic fuels, especially ethanol, are gaining more and more significance throughout the world. By developing suitable vehicle concepts the conditions for smooth adaptation to changed fuel supplies will be improved.

7. Alcohols are also suitable for other purposes, e.g. industrial and heating combustion etc. They represent an important basic product for the chemical industry. Expansion of the present production capacities could therefore be seen as a contribution - also in terms of the economy - towards guaranteeing the supply of energy. It is particularly true, during a time in which the price of crude oil is increasing rapidly, that fabrication could very soon stretch the limits of economy. This situation could definitely be eased by using the heat gained from the production of nuclear energy.

All these aspects were considered by the German Federal Ministry for Research and Technology in a fundamental investigation into the possibilities of using alternative fuels in 1974. In the following years investigations and intensive development work have been promoted with a view to achieving the following objectives:

- the use of alcohols, especially methanol as a blend with traditional gasoline

- the improvement of fuel quality by adding methanol in dual-fuel operation with gasoline

- dual-fuel operation of diesel engines

- the use of straight alcohol as a fuel in gasoline engines

The results have already been tested and demonstrated in prototype vehicles with success. Finally, by using a fleet of 45 motor vehicles, they have gained initial experience of a blend consisting of 85 parts gasoline and 15 parts methanol. Numerous reports have already been given on this work [1 - 8].*

In view of the increasingly critical energy situation and supported by a vote among the parties represented in the Federal Parliament, the Ministry for Research and Technology put forward the proposal to carry out a 4 year focal point sponsorship program on alternative energy sources for road traffic in the budget debate in 1978. The aim of this program is to reveal the technological potential for future decisions on the basis of present results and findings gained from previous research programs and by concentrated research, development and demonstration.

Now that the necessary financial means have been approved by Parliament the program is in its initial phase.

The focal point project "Alternative Energy Sources for Road Traffic" during the period 1979 to 1982 covers the following partial projects (see Figure 1):

- alcohol technology,
- hydrogen technology
- electric traction and hybrid technology.

The funds amount to a total of 135 million DM of which 65% or 87.75 million DM are for the field of alcoholic fuels, 25% or 33.75 million DM for hydrogen technology and hybrid-technology and 10% or 13.5 million DM for the field of electric traction.

Within this project, of which considerable parts of the testing and demonstration will be carried out in West Berlin, the entire energy chain will be analysed and assessed - from the production through distribution and storage to storage arrangements and application in the vehicle taking into consideration the various conditions of usage. These investigations in the motor vehicle sector will be complemented by extensive funding by the Federal Ministry for Research and Technology who are also promoting the further development and

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* Numbers in brackets 1 - 8 designate References at end of paper

improvement of the methanol production process.

The extent of the work on the partial project "alcoholic fuels" for use with motor vehicles will be described in the following (see Figure 2).

The focal point of the project is the practical testing of the most promising vehicle concepts under realistic road traffic conditions; a definite and sound basis for assessments and decisions can only be founded on the results gained from fleet tests. On the basis of the findings gained from this major experiment, statements can readily be made on weak points of the system which can then be eliminated with the aid of individual investigations.

Although the project was made public only to a limited extent in November 1978, the automobile and mineral oil industries as well as other research organisations have shown great interest in participation. However, not all the ideas and proposals could be included for financial reasons. Having had numerous and lengthy discussions on the structure of the project, the parties involved have begun their work. The project field "alcoholic fuels" has been divided up into the following sections: methanol-gasoline blend fuels for gasoline engines, methanol fuel for gasoline engines and methanol fuel for diesel engines in dual-fuel operation, and alcoholic fuel emulsions for use with diesel engines.

METHANOL-GASOLINE BLEND FUELS

On the basis of the present results gained from research work and the findings from cooperation with working groups abroad, the use of methanol-gasoline blend fuels should, as already mentioned, constitute a possibility - realisable in the short term - for the partial substitution of fuels based on crude oil. For this reason the necessary technological potential is to be revealed in a large scale fleet test.

According to current plans, about 1000 passenger cars of different vehicle categories with different engine types from 6 German automobile manufacturers which have been equipped for operation with methanol-gasoline blend fuels will take part in the major experiment beginning in the Fall of 1979 (see Figure 3). In the initial phase these vehicles will operate on a fuel which contains 15% methanol. The gasoline-based fuel will be a standard premium fuel. This ensures that this blend fuel - with the exception of the vapour pressure - complies in the main with the prevailing specification according to DIN 51600 on carburetor fuels in the Federal Republic of Germany. It will be made available in summer and winter qualities. Accompanying investigations will consider and test further blends with a higher methanol content, for which, however, the optimisation of the gasoline additive is extremely important. All the notable German mineral oil companies are involved in these fuel investigations. The supply infrastructure (see Figure 4) is organised in such a way that, besides the 12 filling stations in the main test centre of Berlin, the vehicles operating on blend fuels can drive through all other areas of the Federal Republic without any difficulties arising in connection with supplies. The M-15 pumps (approximately 30 in total) will be set up at 24-hour filling stations of the companies ARAL, BP, ESSO and SHELL. The production of the blend fuel will be carried out by the companies SHELL and VEBA. GERMAN SHELL, who are also performing so-called storage and distribution experiments, will take charge of the distribution to the filling stations.

All the mineral oil companies mentioned will participate in the essential basic investigations and the accompanying investigations on various types of vehicles.

The newly equipped vehicles made by BMW, Daimler-Benz, Ford, Opel, Porsche and VW will be sold to interested private customers or retailers who will test them in the selected test areas, i.e. beside Berlin, the area around Hamburg, Wolfsburg-Hanover, the industrial area of the Ruhr, Cologne-Bonn, Frankfurt (Rhein-Main), Stuttgart and Munich (see Figure 5).

This widespread scattering of the vehicles should ensure that the fleet tests are carried out under all conceivable conditions and that they are as realistic as possible. At the same time each automobile manufacturer has the possibility of realising the special features and concepts to the company and the vehicle type.

For their special services in conjunction with the fleet tests (such as additional expense for accompanying inspections during servicing, regular reports by means of logbooks, random tests on the vehicles, extra expense and detours for refuelling, etc.), the purchasers of the vehicles will receive financial recompense and the assurance that they will be indemnified generously for any costs incurred for damages resulting directly from operation with the methanol-gasoline blend fuel. The evaluation of all data pertinent to the program will be carried out according to uniform criteria by academic institutions in Berlin.

STRAIGHT ALCOHOL FUELS

The feasibility of using straight alcohol fuels in a form defined as "methanol fuel" will be tested in 4 different variants, namely

1. as fuel for gasoline engines
2. as fuel for diesel engines with ignition accelerating additives
3. as fuel for diesel-alcohol dual-fuel operation
4. as diesel-alcohol emulsion fuel.

In special investigations with individual vehicles ethanol will be included in the program under the same 4 conditions as mentioned.

Firstly the quality of the fuel will be defined for variant 1 which will initially also apply for the other usages. However, in accompanying and further fundamental investigations the optimum quality of the straight alcohol fuel will be sought for the varying purposes. This applies especially for the development of additives designed to accelerate ignition and of emulsifiers for application in diesel engines.

The companies involved in the fuel investigations are ARAL, BASF, SHELL, UK-Wesseling and VEBA. The automobile manufacturers participating in this part of the program are Daimler-Benz, Klockner-Humboldt-Deutz (KHD), MAN and VW. The testing of the vehicles, a total of about 385 passenger cars, buses and commercial vehicles, will be focussed in Berlin. By setting up filling stations, the preconditions necessary for testing the fuels and the vehicles in realistic circumstances will be fulfilled. Contrary to the tests on operation with methanol-gasoline blends, only closed vehicle fleets will be used from commercial, communal or public motor vehicle pools.

This field "straight alcohol fuels" still requires important basic research and development work both on the fuel itself and on the engine and vehicle concepts, the results of which will be included continuously during the course of the project in the actual demonstrative part of the entire program. This will also insure that inclusions and improvements concerning the application in the vehicle can be taken into account throughout (see Figures 6 and 7).

SCHEDULING OF THE PROGRAM

Figure 8 shows in summarised form the current scheduling plan for the most significant phases of the fleet tests of the individual variants for alcoholic fuels. On the basis of the preparatory work and the findings gained from earlier research work and despite the considerably larger total number of vehicles and extent of the infrastructure, the first fleet tests will be able to commence for the field alcohol-gasoline blend fuels with the first vehicles and filling stations in Berlin in August/September 1979. The filling station infrastructure will be completed in quick succession by about March 1980 which means that from then on the fleet tests can take place without restriction. Most of the vehicles will have been supplied by mid-1980 at the latest. Further newer vehicle models will, however, also be included in the test at a later date.

Fleet testing in the sector straight alcohol operation will probably begin for the first passenger cars with engines at the beginning of 1980. Up to then work will have to be completed on the required filling stations. Vehicles with diesel engines operating on straight alcohol will not begin their fleet tests until mid-1980 at the earliest.

For diesel-alcohol dual-fuel operation the first commercial vehicles are planned to start their fleet tests in October/November 1979. But for diesel-alcohol emulsion operation the current fundamental investigations on the fuel and further investigations on the adaptation of the engine will have to be completed before a date for the commencement of the fleet tests can be decided upon. They are planned for mid-1980 at the earliest.

Apart from the actual demonstrative parts of the project, the accompanying investigations and fundamental studies will be carried out simultaneously during the entire course of the program.

SUMMARY

The focal point project "alternative energy sources for road traffic" initiated by the German Federal Ministry for Research and Technology for the period 1979 to 1982 is, in its partial field "alcoholic fuels", the largest known demonstration project in content and scope for this sector. It thus reflects the importance attached to the research and realisation of technologies in using alternative energy sources based on alcohols for the motor vehicle sector. The significance is also underlined by the great interest shown by many organisations, both at home and abroad, in participation in the partial programs for which proposals were invited. The involvement of all the notable German mineral oil companies and automobile manufacturers manifests the attractiveness and necessity of such a program and will assist in the detailed investigations being carried out in the depth and intensity required and including manifold knowledge and experience specific to each branch. The technological potential revealed by this research program should come to be an important foundation for decisions taken on future energy supplies.

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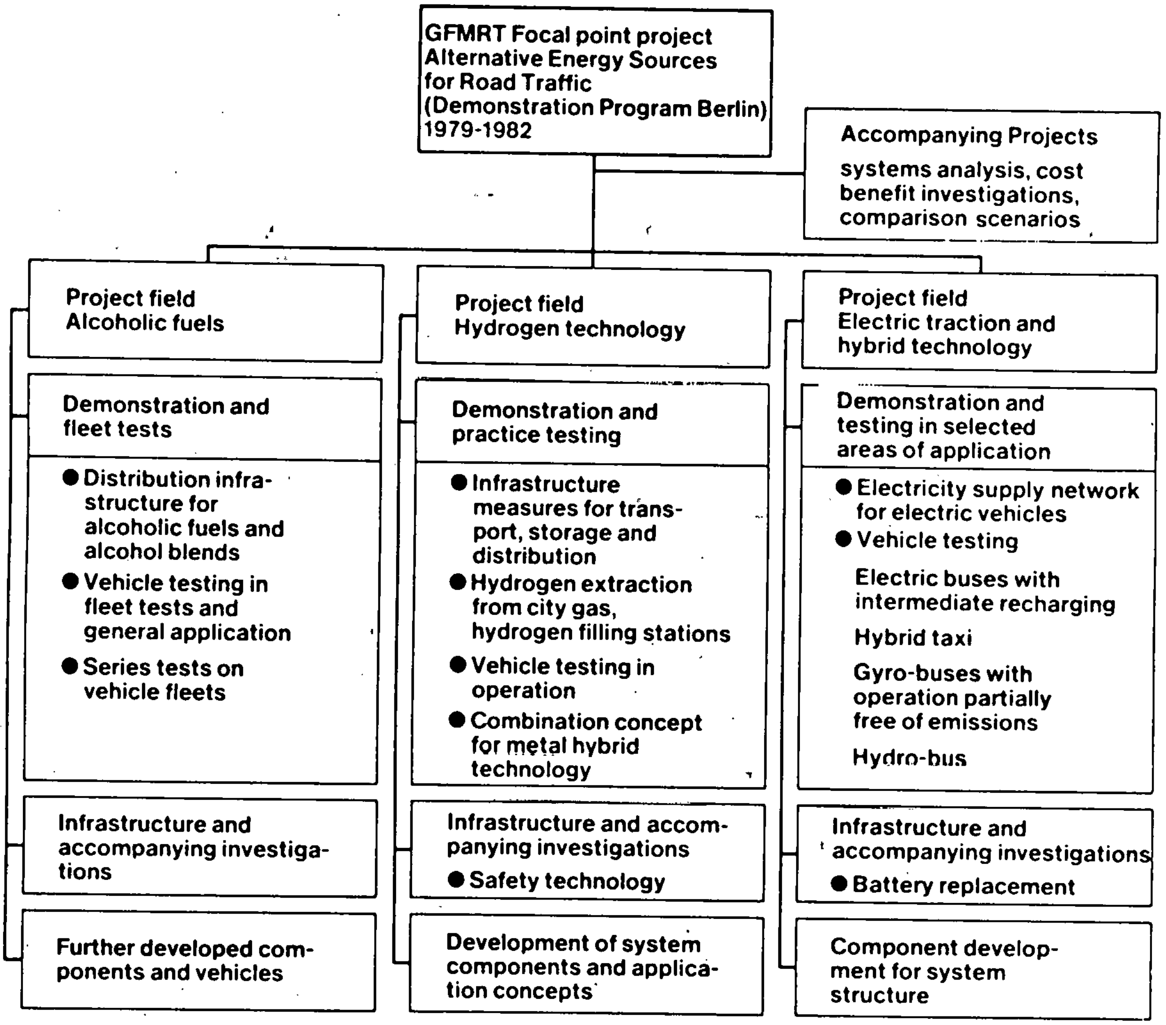

Fig. 1: Outine of the entire GFMRT focal point project "Alternative Energy Sources for Road Traffic 1979 - 1982"

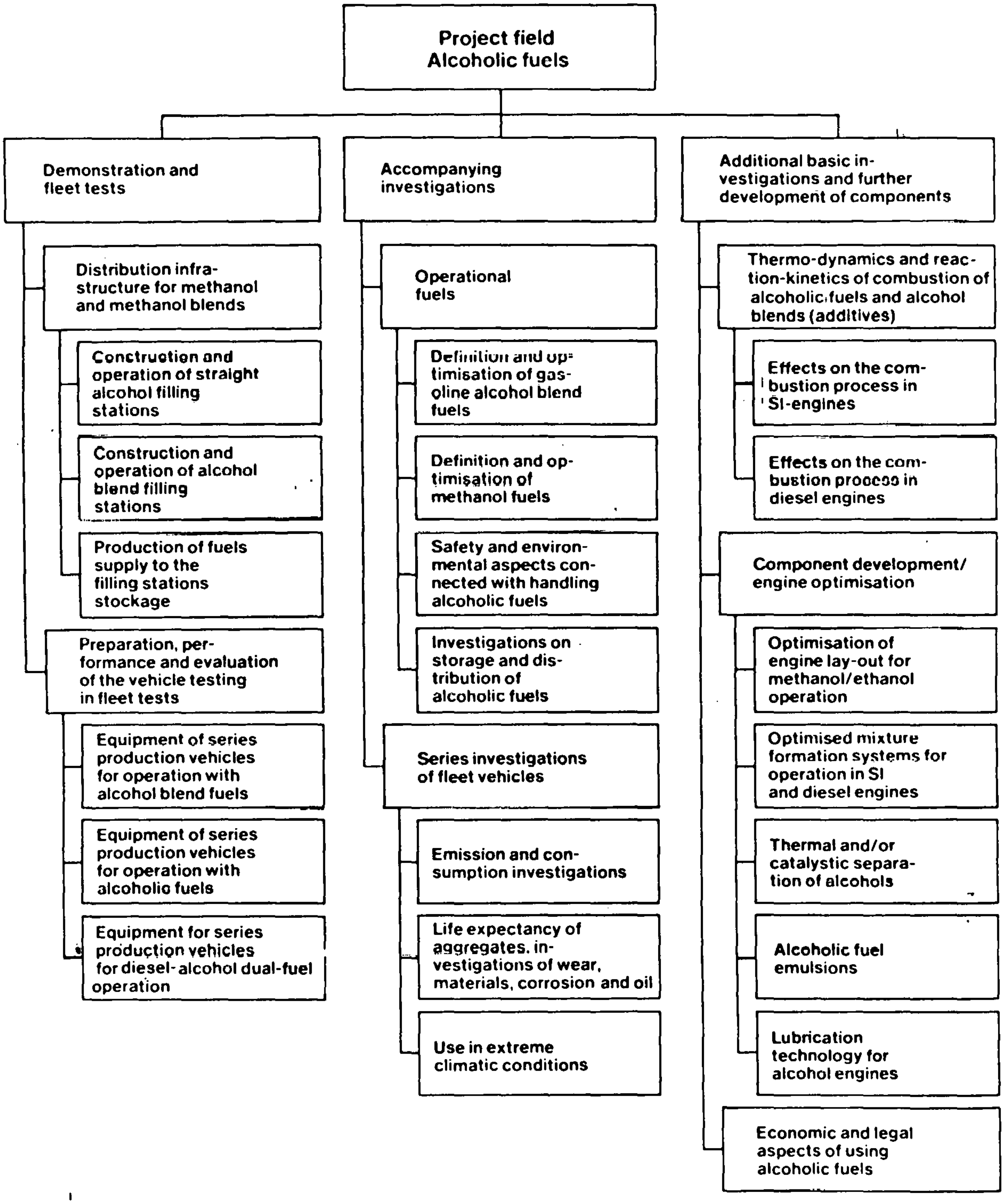

Fig. 2: Focal points of the research work in the project field alcohol fuels within the GFMRT project "Alternative Energy Sources for Road Traffic 1979 - 1982"

Fig. 3: Automobile manufacturers, number and usage variant of the vehicles for operation with alcoholic fuels within the fleet tests of the GFMRT Program "Alternative Energy Sources for Road Traffic 1979 - 1982"

Automobile Manufacturers Involved	Alcohol-gasoline blend fuel operation	Straight alcohol		Diesel-alcohol dual-fuel operation	Diesel-alcohol emulsion operation
		Gasoline engine	Diesel engine		
BMW	1 Demonstration vehicle Type 733 Options on 10-20 vehicles				
Daimler-Benz	30 passenger cars Type 230 20 transporters L 208	30 passenger cars 280 E	20-30 buses S 80		10 passenger cars Type 240 D
Ford	190 vehicles Types Fiesta, Escort, Transit, Taunus, Granada				
KHD				85 comm. vehicles	
MAN			20 buses S 80 10 buses SD 200 F		
Opel	200 passenger cars Type Rekord 2.0 S carburettor 2.0 E injection 100 each				
Porsche	10 passenger cars Type 924				
VW	600 vehicles, Polo Rabbit, Dasher Audi 5000, Microbus light duty truck (LT)	100 vehicles Rabbit, Dasher Microbus			100 vehicles Rabbit, Dasher light duty truck (LT)

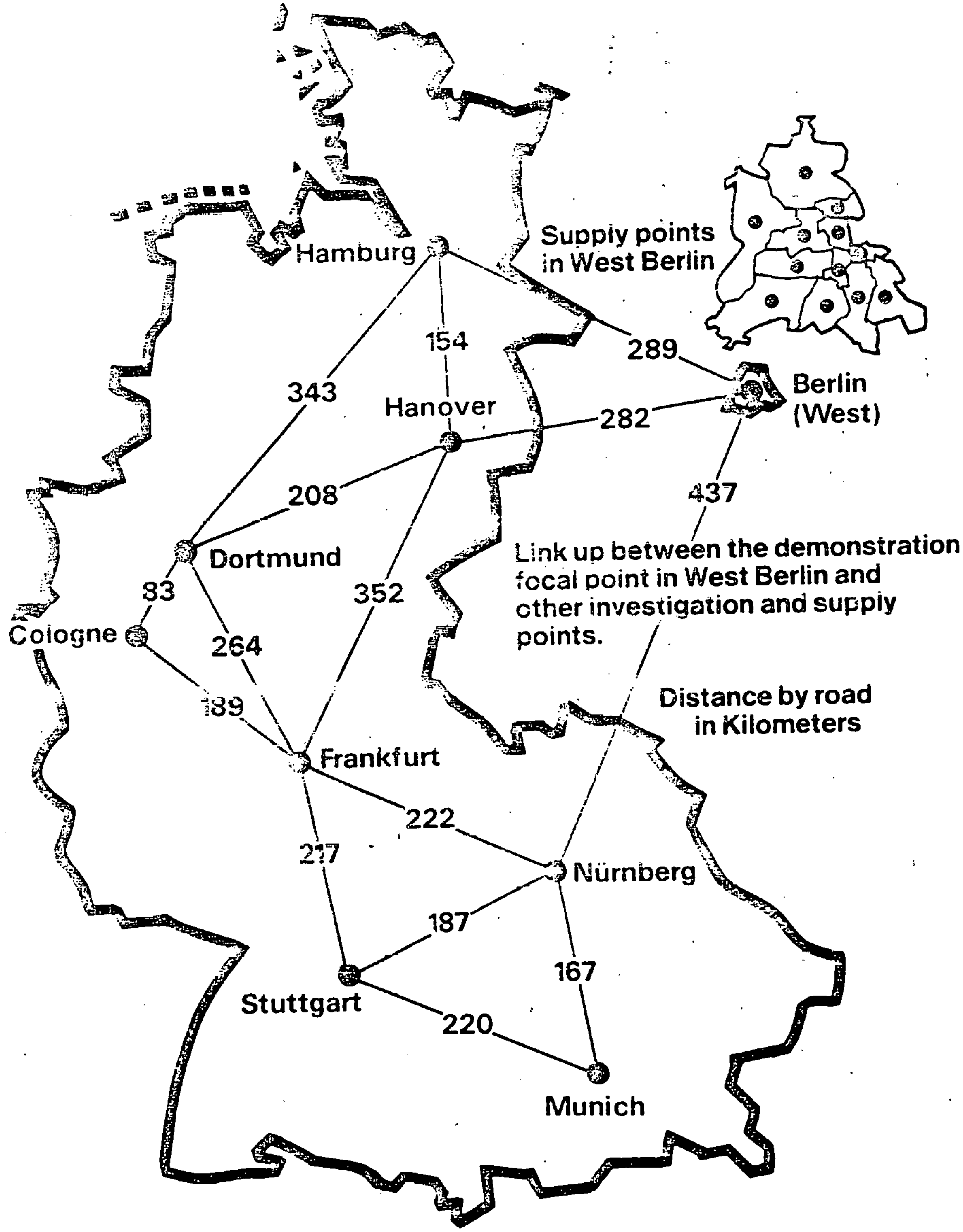

Fig. 4: Outline of the filling station network for alcohol-gasoline blend fuels

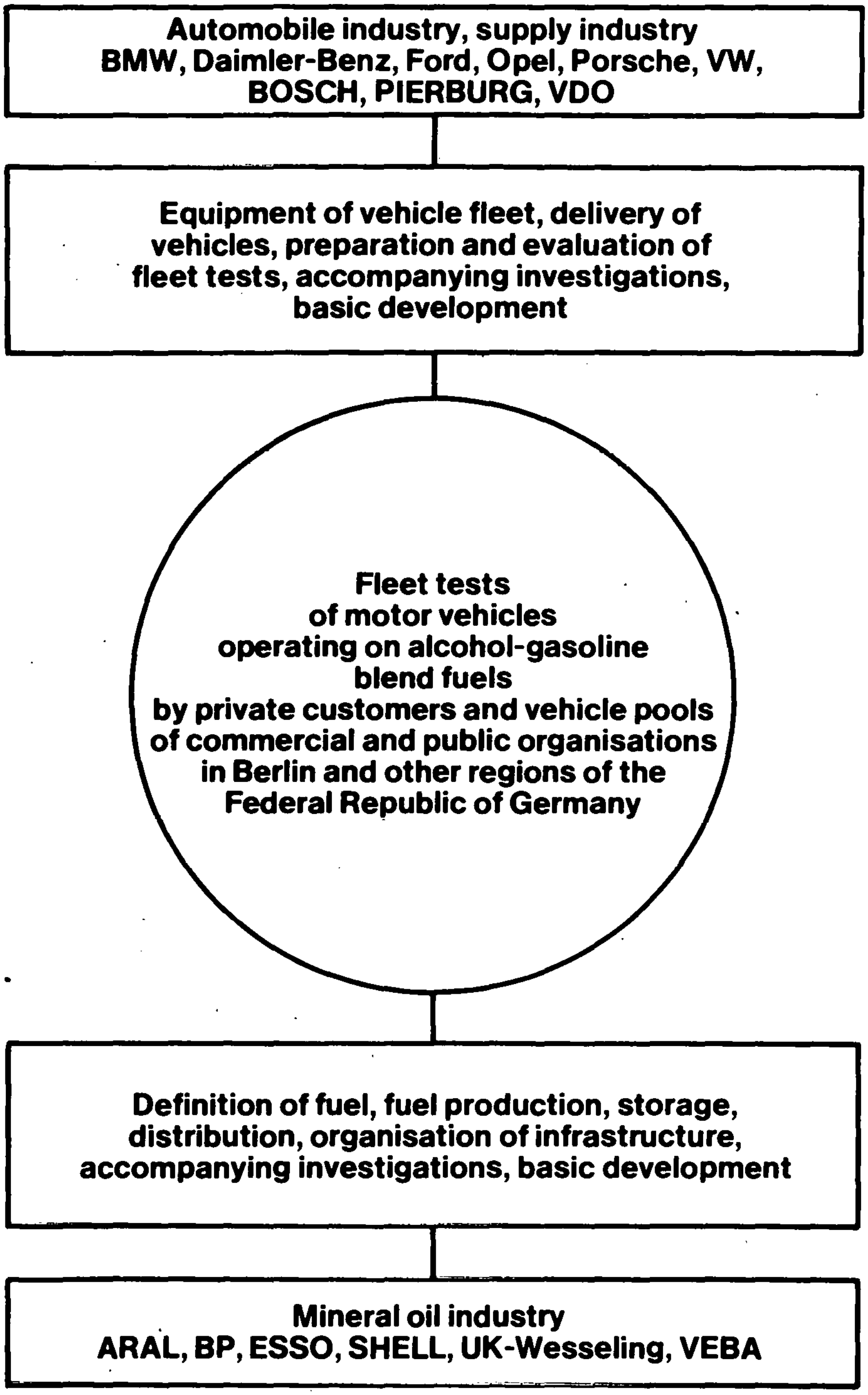

Fig. 5: Participating companies and distribution of activities in the field alcohol-gasoline blend fuels

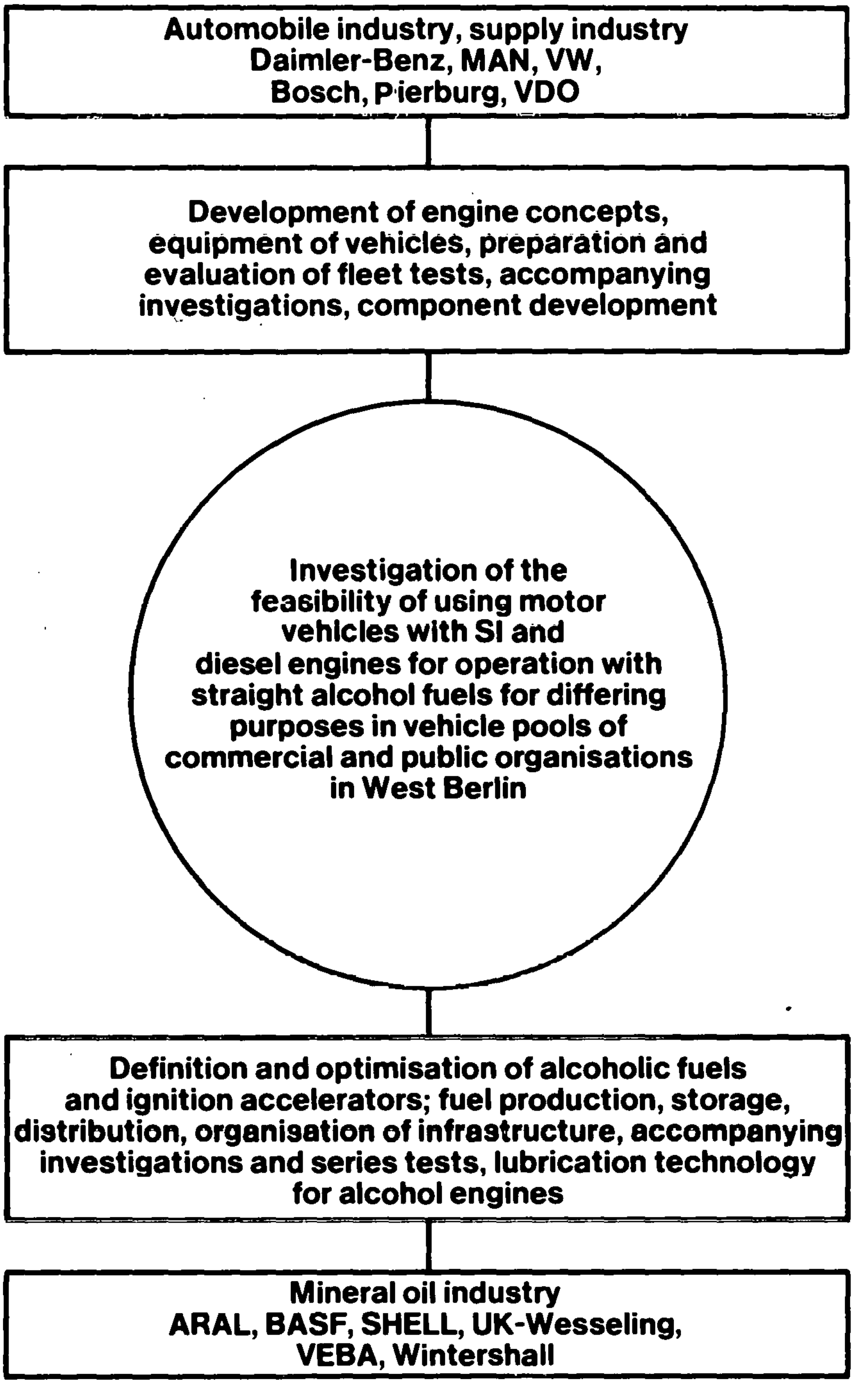

Fig. 6: Participating companies and distribution of activities in the field straight alcohol operation of gasoline and diesel engines

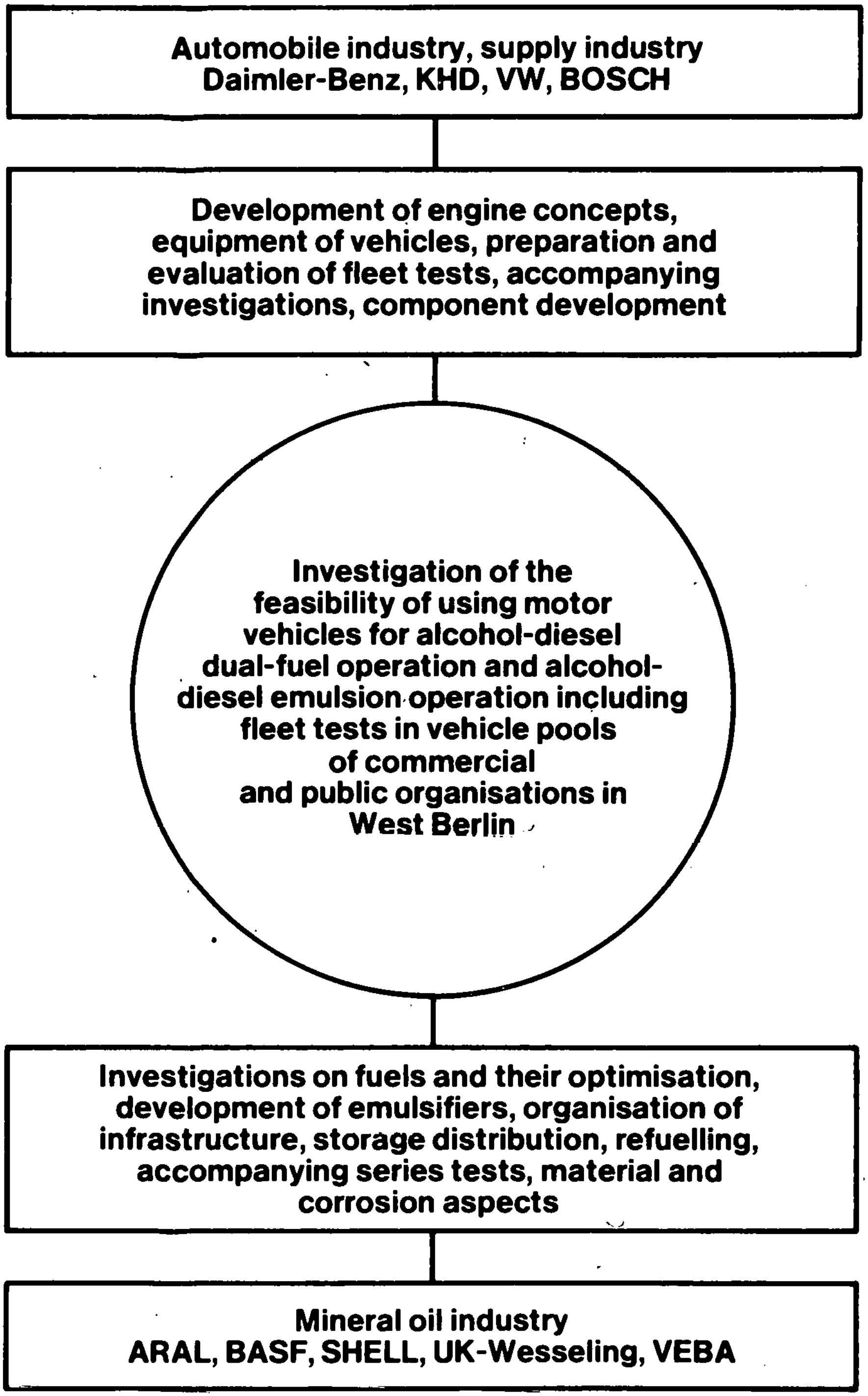

Fig. 7: Participating companies and distribution of activities in the field alcohol-diesel dual-fuel operation and alcohol-diesel emulsion operation

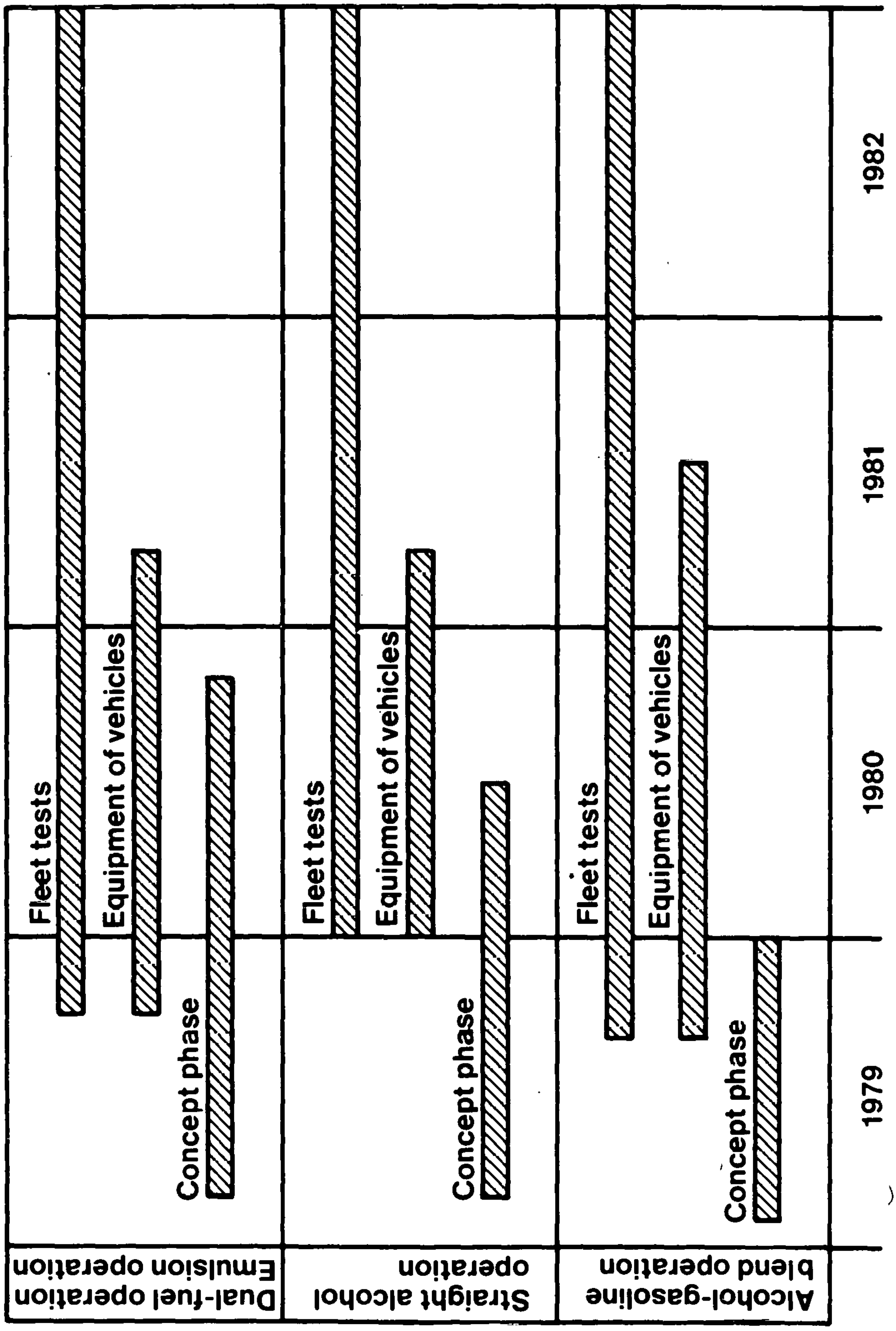

Fig. 8: Scheduling of the program for the project field alcoholic fuels

LEGAL AND REGULATORY INFLUENCES ON ALCOHOL FUELS USE IN THE UNITED STATES

by
E. E. Ecklund, U.S. Department of Energy

ABSTRACT

During the last year, grass-roots interest in Gasohol has resulted in commercial sales going from zero to 6 million U.S. gallons (600,000 gallons ethanol) in January 1979. This started in the Midwest United States on the basis of motorist appeal without benefit of incentives, spread with the benefit in some cases of State incentives and was further encouraged by the waiver of 4 cents-per-gallon Federal excise tax for fuels with 10-volume percent alcohol from renewable resources. Continuation depended on a favorable ruling under the Clean Air Act by the Environmental Protection Agency, which also acted favorably on use of tertiary butyl alcohol and methyl tertiary butyl ether as octane improvers. Other supportive Federal actions include loan guarantee for a processing plant to convert bagasse to ethanol, planned initiation of reliability fleet tests on advanced alcohol/gasoline blend compositions, and establishment of a Congressional National Alcohol Fuels Commission to determine what can and should be done to help alcohol fuels find their appropriate levels in replacing petroleum.

INTRODUCTION

Researchers in the United States, as in many other countries, have worked on alcohol fuels for transportation off and on for many decades. In 1935 an ethyl alcohol fermentation plant was built in Kansas specifically to make fuel. Although the company went bankrupt within a few years, the plant was reopened in 1941 under new ownership.(1)*, and is still one of the largest operating plants in the country. Interest and research activities in alcohol fuels were again rejuvenated in the early 1970's, and Federal vehicular oriented activities were initiated in 1974 following feasibility studies on alternative fuels for highway vehicles. This work on utilization and allied activities on processing of coal and biomass** continued for several years without much special attention, except that the biomass activity benefited to some extent from being part of the larger and popular solar energy activity. However, it was not until early to mid 1977 that alcohol fuels picked up any significant support. Interest of both the public and the Congress has grown steadily, though this has centered on the most costly and energy intensive of the possibilities, ethanol from agricultural commodities.

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*Numbers in brackets ( ) designate References at end of paper.

**U.S. Department of Energy projects, started under predecessor affiliations, include portions of the Alternative Fuels Utilization Program, Coal Conversion Program and Fuels From Biomass Program.

COMMERCIAL USE OF GASOHOL

About January, 1978, Gasohol* went on sale in a service station in Springfield, Illinois. Initiators and supporters of this activity sought and found a source of ethanol and others took up marketing one by one. The word spread rapidly, and despite a lack of incentives other stations took up the cause, and additional supply sources were located. Through interaction between proponents in various States, known to one another and brought together to a substantial extent by organization of the National Gasohol Commission, Inc., additional dealers grew rapidly. Participation of business cooperatives helped considerably. By the latter part of the year, the 200 mark was reached. Most of this occured in the Midwest (Illinois, Iowa, Nebraska, Wisconsin and others), though some occured from the Rocky Mountains to the East Coast.

ENVIRONMENTAL CONTROLS

In 1977 the Congress amended the Clean Air Act, and in so doing added some provisions applicable to automotive vehicles.(2) The use of lead additives had been banned, and the industry was active in use of MMT (methylcyclopentadienyl manganese tricarbonyl) as a prime alternate. As a result, the amendment to the law included the requirement to qualify this and any other additive or fuel not in use as of January 1, 1974, by assuring that the fuel or fuel additive does not cause or contribute to failure of any emission control device or system used to achieve compliance by the vehicle with the applicable emission standards.

The Environmental Protection Agency (EPA) formulated regulations which detailed the requirements for the waiver necessary to permit commercial use, application was made by at least one producer of MMT and the EPA proceeded with deliberations on this.

Included in the amendment to the Clean Air Act was a grace period in which waiver action could be consumated, and which culminated on September 15, 1978. This was apparently overlooked by many, including those selling and/or promoting Gasohol. It was not until the EPA promulgated regulations for generally seeking waivers, that attention was focused on the September 15 deadline. Several waiver applications were made involving Gasohol, methyl-t-butyl ether (MTBE) and higher concentrations of tertiary butyl alcohol (TBA)**. Under the law the EPA has 6 months in which to make a determination to permit or negate use. If no ruling is made, approval of the additive is automatic.

*Gasohol is a mixture of 10-volume percent anhydrous (water free) ethanol and 90-volume percent unleaded regular gasoline (87 octane $\frac{R + M}{2}$)

**Arconol (primarily TBA) had been commercially used in concentrations of up to 5 percent prior to January 1, 1974. Up to 7 percent was later used and application was made for up to 7 percent.

At this point, the stage was set for an ironic, perhaps incredible, outcome. Arriving at a determination within the specified timeframe, EPA banned use of MMT on September 11, 1979.(3) Many in industry had been preparing against this eventuality, recognizing that this would in essence signal the end of using metallic compounds as octane improvers and thereby concentrating their attention on organic additives. On September 15, faced with the legal deadline for use of any unapproved additives not in use on January 1, 1974, EPA announced that in view of considerations in process they would not at the present enforce the illegality of Gasohol and TBA.(4) Since MTBE was not available in the market, its use was noted as illegal until a ruling was made on waiver applications.* The outcome of this, then, was that used of lead was limited and MMT outlawed as octane improvers, and there was no organic octane booster other than toluene clearly satisfactory from a legal viewpoint. Industry was facing spot shortages of unleaded fuel, with satisfactory supplies in the summer of 1979 clearly in doubt, and toluene prices increased sharply. The only obviously open solution was more severe refinery processing, which would produce more aromatic materials with attendant carcinogenic polynuclear aromatics (PNA). This at a time when there was considerable concern about particulates and PNA's from diesel emissions. Thus, at that time there existed the ironic situation that the laws aimed at protecting public health created near term pressures toward more risky solutions.

About this same time, the production of Iranian petroleum was stopped while that country struggled with its political situation, and imports to the United States dropped. Pressures on the public to conserve on petroleum were escallated by a series of interpretations expressed by the Secretary of Energy, Dr. James Schlesinger.

Also, ironically, EPA interpretation of the Clean Air Act indicated that indeed it was technically illegal for commercial chemical producers to sell any unapproved compound for use in a fuel even for test purposes. Thus, a Catch-22** situation existed, in that it was illegal to use fuels for test purposes necessary to apply for waivers which would allow use thereof.

*One of two waiver applicants for use of MTBE was already in construction of a commercial processing plant, which was continued despite the hiatus.

**From the theme of Joseph Heller's book "Catch-22" (Simon and Schuster, New York, 1961), a novel about the military. In this a crazed airman could not be grounded because he had to request such action, but Catch-22 stated that such a concern for one's own safety was the process of a rational mind.

Under cover of the declaration not to enforce the law on these two additives, EPA and others rushed tests to help the decisionmakers. On December 16, 1978, EPA declared that despite insufficient evidence on which to make a proper decision, the use of Gasohol would be allowed as the quantities involved were so small that no significant environment risk was associated with its continued use.(5) Under this ruling EPA stated that the law provides the basis to review the matter at a later date should there be unresolved problems.

On February 6, 1979, EPA ruled that use of 2 percent additional TBA, increasing concentrations up to 7 percent, was satisfactory.(6) Use of up to 7 percent MTBE was approved on February 23, 1979.(7) Thus, faced with a dillema, industry and government combined to set things straight in relatively short order. It is anticipated that by year end about 7500 barrels per day of MTBE will become available out of a potential feedstock sufficient for about 20,000 barrels per day.(8) Use of MTBE provides upgrading equivalent to about one additional barrel of gasoline per barrel of MTBE, so this equates to potentially increasing the fuel supply by 40,000 barrels per day.

One prospect, not yet evaluated, is that if light ends are removed from the base stock gasoline blended with alcohols it may be possible to use much of these for making MTBE.

ALCOHOL PRODUCTION INCENTIVE

In late 1977 the Congress of the United States passed the Food and Agriculture Act of 1977, which included provisions for encouraging the use of biomass for energy. This law authorized the U.S. Department of Agriculture (USDA) to make loan guarantees of up to $15 million for each of 4 pilot projects to produce alcohols or industrial hydrocarbons from agriculture or forest products, providing that a project use less energy from fossil fuel than that available in the products produced.

Following publication of detailed preliminary requirements for loan application and associated public hearings, final requirements were published. Some 30 applications were received by the prescribed October 1978 deadline. Projects included production of solid, liquid and gaseous products. Following review of the proposed projects by USDA with assistance from a Federal interagency advisory committee, the final approval sequence was undertaken by the Commodity Credit Corporation (CCC), a USDA subsidiary responsible for agricultural loans. In the first of 3 successive regular monthly meetings dealing with these applications, 4 applications were considered of which one was approved.(9) That project was for production of mobile pyrolysis units to convert a wide range of forest, crop and sawmill wastes into gas, charcoal and combustible wood oil. Two projects, one for making alcohol from cane and the other for alcohol from beet molasses and milo, were among those considered.

Following this meeting there were published reports of Congressional criticism. One criticism was that the projects discussed did not include any which represented a significant step forward in technology. Whether or not this influenced the next meeting, 2 projects not considered at the first meeting were then approved.(10) One of these involves 2 plants to pelletize forest wastes. The other project approved is for production of about 8 million gallons per year ethanol and butanediol from bagasse, sugarcane tops, and other cellulosic wastes using what is generally termed the Tsao process named for its developer. This process uses a combination of mild acid hydrolysis pretreatment of the feedstock to separate the pentosans, followed by concentrated acid tumbler treatment to separate the lignin and cellulose, then acid hydrolysis conversion to glucose followed by fermentation. The loan guarantee for this project is in two parts; one for extending present research at Purdue University to fully test Florida bagasse, plant design and engineering planning, and the other for construction of a plant to be located adjacent to a sugar mill.(11) About 70,000 tons of dry bagasse will be processed per year out of 165,000 tons available from the sugar mill. Process derived lignin and bagasse will be used for all the required processing energy input. Resources for electrical requirements amount to about 55% of the energy available in the output products.

At the third meeting, approval was granted for the 10-million gallon per year ethanol from sugarcane molasses discussed at the first meeting (17). The sponsor of this project is the owner of the first U.S. alcohol fuel plant, noted earlier. This plant will be located in Texas adjacent to a sugar mill and use excess bagasse fueled steam from the mill about 60 percent of the year. The ethanol will be made for the industrial market, with the option to market for fuel use.

INCENTIVE FOR AUTOMOTIVE FUEL USE

After long and sometimes heated debate, in November 1978, the U.S. Congress passed several energy acts including the Energy Tax Act of 1978.(12) Included in this act is a provision to waive the four cent per gallon Federal excise tax on gasoline if it includes 10-volume percent alcohol from renewable resources. This tax will expire in October 1984. Several states have similar provisions relating to State gasoline taxes. These amount to five cents per gallon on limited supplies in Nebraska and Colorado, and presently equate to 6½ cents per gallon in Iowa. The combination of these Federal and State incentives amounts to an indirect fuel alcohol subsidy of $0.90 - $1.05 per gallon.

The waiver of the Federal exise tax took effect January 1, 1979, following the EPA approval of Gasohol two weeks earlier. Numerous service stations were awaiting the latter decision before taking on Gasohol supplies, and the combination provided considerable incentive for additional marketing outlets. By the end of February, 1979, the number of retail service stations selling Gasohol had increased to about 375.

Since it is common in business planning to amortize the investment over 20 years, it is not clear whether a limited period incentive such as this will encourage construction of a plant to produce alcohol expressly for fuel use. However, there apparently are situations where this incentive may provide positive influences. Most of the ethanol now being sold into the fuel market has come from plants that are an adjunct to other processes. One of these uses cheese whey as the feedstock. This was a waste product which can no longer be disposed of through discharge into waterways. Another uses residue from a corn milling plant as the feedstock. Situations such as this, where processors are faced with requirements and costs for environment equipment or special disposal facilities, provide the basis to take advantage of such incentives. Also, the previously mentioned Energy Tax Act of 1978 provides for additional investment tax credits for energy projects which permits accelerated amortization. Thus, it is quite possible that additional ethanol supplies will become available. Estimates project 20 to 100 million gallons per year additional ethanol supply within the next year.(13)

Although the Tennessee Valley Authority (a Federal electric power operation) has plans for a coal to ammonia plant which uses technology and processing similar to that applicable to methanol, there is no known activity to produce methanol from nonpetroleum resources. Coal is the only nonpetroleum resource which has been used commercially for methanol manufacture using technology which could likely be used under present conditions. However, the National Energy Act excludes this from the alcohol fuel incentive. Use of wood and agricultural residues is basically applicable, but there is presently insufficient data regarding the concentrations of various synthesis gas products at various process conditions to permit engineers to design optimized plants. Thus, it appears that some additional technical work, an extension of incentives or some other initiative is essential as a minimum to initiate fuel methanol production from nonpetroleum resources.

There is no demand for methanol, nor any commercial combustion equipment to utilize it. There is no fuel methanol being produced, so there is no need for such modified equipment. Further, such equipment can be produced in the timeframe required to build a methanol processing plant. Thus, here again is a Catch-22 situation, and there must be a conscious decision made that simultaneously influences both supply and demand if anything positive is to happen. One potential external force is that of extensive use of Gasohol. Should that happen, new vehicle production would likely include appropriate changes, and it would appear prudent to thus accommodate all oxygenated hydrocarbons including methanol. On the supply side, the lower costs of methanol compared to ethanol could be influential in providing methanol. There are several commercial activities in process to plan and assess viability of coal to methanol plants for supply of fuel for electrical generation.

FLEET TESTS OF ENGINEERED FUELS

In early October, 1978, the Congress added funds to the Department of Energy FY 1979 appropriations to plan and initiate reliability fleet tests on alcohol/gasoline blends in Government vehicles during FY 1979

(October 1, 1978 - September 30, 1979). If carried out as planned in the Alternative Fuels Utilization Program (AFUP), this activity would serve as the last step of bringing alcohol/gasoline blends to the state of technical commercial readiness. The sequential developmental action steps in the AFUP are: (a) fuel characterization and engine performance tests to identify and understand the problems related to use of the fuel, (b) seek a variety of solutions to the problems, (c) design a fuel/engine system which incorporates the best solutions, (d) run controlled engineering tests on a limited number of vehicles to assure satisfactory results, and (e) conduct reliability fleet tests to provide statistical proof of performance in typical and representative field use. In actuality, both of the latter two are still to be done. However, it is believed practical to do both essentially in parallel, though appropriately time-phased so the reliability tests can feed on the results of the controlled engineering tests, and this is the approach being used.(14)

Both ethanol and methanol blends will be tested, emphasizing fuels and vehicles representative of what industry would do under widespread commercial use. Although Gasohol will be used in limited tests, the effort will concentrate on formulated blends using a nominal 10-volume percent alcohol.

The controlled engineering tests will primarily involve dynamometer tests of about 15 engine/emission packages representative of anticipated 1982-85 and beyond automobile production. Five ethanol blend compositions will be tested; Gasohol plus four formulated fuels. Work on methanol blends will start with bench tests for screening of some 21 compositions from which 5 will be selected for engine tests. On the basis of tests of the 10 fuel compositions in engines for fuel economy, exhaust emissions and driveability, two fuels will be selected for the larger scale reliability fleet tests. One fuel will be an ethanol/gasoline blend and the other will be either a methanol/gasoline blend or a methanol/ethanol/gasoline blend. Three to nine fleets will be used to assure performance under the various climatic conditions encountered throughout the country.

If typical and extremes are judged sufficient, the smaller number of fleets may be appropriate. The minimum number of fleets essential to satisfy stakeholders will be used. However, the program is set up to take advantage of all the fleets that may desire to participate. The tests will run for at least two years, and preferably three, in order to cover seasonal variations. The number of vehicles in each fleet is yet to be determined, but will be sufficient to be statistically significant.

ENERGY POLICY

In early 1978, the Department of Energy issued an Alcohol Fuels Position Paper and an Alcohol Fuels Program Plan.(15) These included a new Immediate Action Element which consisted of a commercialization study and a related policy action assessment. After unanticipated delay, an Alcohol Fuels Policy Review Committee was established under the direction of the Assistant Secretary for Policy and Evaluation to address the latter portion of this. The input for this was essentially the previously available information, but a broad range of outside experts were used to review and sort out the material, and public meetings were held to obtain as broad a range of input as practicable.

This effort was to provide inputs to a parallel effort on a National Energy Supply Strategy (NESS), which in turn was to provide input to an updated National Energy Plan (called NEP 2). The NESS activity never materialized and inputs to NEP 2 were conducted in a more casual manner.

CONGRESSIONAL ASSESSMENT

After about a year of consideration, the Congress authorized establishment of the National Alcohol Fuels Commission(16) to assess the long- and short-term potential for alcohol fuels from biomass and coal to contribute to meeting the Nation's energy needs, and to recommend those policies, and their attendant costs and benefits, most likely to minimize dependence on petroleum, insure adequate energy supplies, and contribute to the economic health of the Nation. The Commission consists of a Chairman and 5 members from the Senate, a Vice Chairman and 5 members from the House of Representatives and 7 members from the public sector which would provide a broad representation from industrial, labor, agricultural, small business and consumer groups.

The Congressional members equally represent members of standing committees on appropriations, agriculture/forestry, and energy technology/natural resources. A staff director and appropriate personnel will assist the Commission in carrying out its functions.

The final report of the Commission, including its findings and recommendations, is to be submitted to the President and the Congress within one year of establishment, which will be within 60 days of being provided with funds. Funding is awaiting Congressional action on supplemental FY 1979 appropriations now under consideration, and it is anticipated that the Commission will be activated about June 1, 1979.

Summary

In the United States, there is considerable public grass-roots interest and activity in Gasohol, with appreciable support and encouragement by State and Federal Governments including financial incentives. There continues to be controversy over the wisdom and the benefits to using agricultural crops. The crux of this may primarily be related to the extent of such use, and continuation of marketplace activities could be the key to achieving its proper level. In the near term, ethanol fuel use will be limited by availability to perhaps 30 to 50 million gallons per year which is less than 5 hundreths of one percent of the gasoline use.

Use of metallic compounds as octane blending agents appear to have lost favor, and organic compounds will be increasingly used as replacements. Some oxygenated hydrocarbons have been approved for use under the Clean Air Act, and it would appear that any such chemical could be qualified as long as the oxygen content of the resulting fuel composition does not exceed 2 percent. Gasohol exceeds this, and EPA actions under the Clean Air Act if and when its use becomes significant may be a key milestone in U.S. use of alcohols. At the same time, Federally sponsored tests, including proof of performance field fleet tests, will be conducted over the next few years on fuels with oxygen content ranging up to perhaps 4 to 6 percent. Unless there is a significant use of Gasohol, some new pressures toward incorporating methanol, or introduction of methanol into other uses, it appears unlikely that methanol will play a role in the near term.

In parallel with fleet tests, advanced ethanol process development is continuing under Federal sponsorship including partial support for at least one commercial project using cellulosic feedstocks. A special Congressional commission will, in the next year, assess total prospects for use of alcohol fuels and recommend actions to achieve appropriate levels of use.

A concern of many, particularly in the technical and automotive/fuels industry, is that actions on alcohol fuels do not inadvertently shut out other fuel options. It is not clear how this will be kept in perspective, whom will spearhead balanced considerations, and where this will be brought to bear.

REFERENCES

(1) Remarks by Cloud L. Cray, Jr., at Gasohol Seminar, Rio de Janeiro, Brazil, September 26, 1977.

(2) Clean Air Act, 42 U.S.C. 7545(f), 1977, Section 211(f).

(3) Federal Register, Vol. 43, No. 181, September 18, 1978.

(4) EPA Environmental News release, September 15, 1978.

(5) EPA Environmental News release, December 16, 1978.

(6) Federal Register, Vol. 44, No. 36, February 21, 1979.

(7) Federal Register, Vol. 44, No. 45, March 6, 1979.

(8) Private conversation with W. Heglund, March 8, 1979.

(9) Meeting of Commodity Credit Corporation, December 5, 1978.

(10) News release by U.S. Department of Agriculture, January 12, 1979.

(11) Stockholder notification, Savannah Foods & Industries, Inc., January 18, 1979.

(12) Energy Tax Act of 1978, Public Law 95-618, November 9, 1978.

(13) Private conversations with M. E. Card and K. M. Friedman, March 5-9, 1979.

(14) Project Plan for Reliability Fleet Testing of Alcohol Gasoline Blends, U.S. Department of Energy, Office of Transportation Programs, March 30, 1979.

(15) "Department of Energy Position Paper on Alcohol Fuels", April 1978, and "Alcohol Fuels Program Plan", March 1978, U.S. Department of Energy.

(16) Surface Transportation Assistance Act of 1978, also called the Federal-Aid Highway Act of 1978.

(17) Meeting of Commodity Credit Corporation, March 20, 1979.

A U.S. ALCOHOL FUELS POLICY AND THE POLITICAL STATE: ASSESSING DIRECTIONS

by

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INTRODUCTION

The debate on alcohol fuels from biomass has been marked by a preoccupation with the ability of the market to determine the fate of such fuels for transportation and other end-uses. Alcohol fuel proponents view their product as an anxious arrival waiting for the big break, discovered by a growing public but still not having captured the hearts of the moneyed interests. These supporters, then, try to rally the political state to the alcohol fuel's cause. The state is seen as an arbiter between the interests of alcohol proponents and their unenlightened opponents. Buzz words such as "helping hand," "push" and "incentive" have all become the orders of the day.

Alcohol opponents, on the other hand, have not only accepted the terms of the debate, but seem, out of experience, to have mastered the associated rhetoric and style. Those oil companies unfavorably disposed toward gasohol, for example, have relied upon a laundry list of gasohol's alleged disadvantages: its adverse effects on engine components, its increased NO_x emissions, its difficulties in handling and mixing, etc. But these opponents know that the most reliable way to discourage government and lending institution intervention is to challenge gasohol's economics. The alcohol manufacturing process, they contend, can never successfully compete against the efficient and proven petroleum refining process. The state subsidies received by refiners, such as entitlements and allocation programs, remain unmentioned.

Government officials hold varying views on alcohol from biomass. Until recently, alcohol fuels, particularly ethanol, were ignored by the energy bureaucracy because of their "uneconomical characteristics". Methanol was the favored alcohol fuel because of coal industry contentions that it would become cost-competitive as crude oil and product costs increased. All of the advantages of ethanol vis-a-vis methanol were ignored because of the singular concern with market economics.

This concern is no less predominant today, though its focus has shifted somewhat. Those officials acting as friends of the fledging alcohol fuels industry fear that over-subsidization of the product will distort the market, only hurting alcohol fuel's competitive stance in the long-run. Other bureaucratic supporters, like the coal industry spokespeople, are confident that alcohol fuels, regardless of type, will find their place in the energy mix as traditional fuel prices continue to increase.

What emerges from the interaction between parties is a preoccupation with market forces. The market is seen as a clearinghouse, a measure of all efforts. That group with market economics on their side is generally the more persuasive and powerful group. It is unfortunate for alcohol fuels from biomass that opponents to its cause represent entrenched interests, where the economics of processes are easily quantified and where market demand is established. The engy and agricultural bureaucracies continue to aid these interests through subsidies, tax credits, other material supports and symbolic appeal. Also working on behalf of the existing arrangements is bureacratic inertia, that omnipresent, but seldom evaluated force assuring the continued success of established actors.

The real questions behind a commitment to alcohol fuels are inherently political. Economic concerns, while important, serve to obscure and disguise the overriding issues. The public interest is seen as being served solely by the most economical energy mix, while true costs for energy supplies often go unrealized by the consumer. Attempts to improve the economics of alcohol fuels may hurt consumers in the long-run by distorting the fuels' real values.

Little movement toward a national alcohol policy is likely to occur while the controversy continues to be constrained by economic rhetoric alone. The following events are more likely: the level of necessary political commitment will remain unknown; economic barriers will be removed for the short-term, leaving poltical barriers firmly in place; each new wave of government intervention will represent a new piecemeal approach and will result in dissatisfaction and disillusion among alcohol fuel promoters; and, finally, whatever commitment to alcohol fuel from biomass that does emerge will be to the idea of alcohol fuel, but never to alcohol fuel itself.

Some of the major issues surrounding the U.S. debate on biomass-derived alcohol fuels are highlighted below. The discussion demonstrates how an overconcern with economics has overshadowed other questions and contributed to the lack of a coherent U.S. alcohol fuels policy.

NET ENERGY EFFICIENCY

A central thrust of the alcohol fuels debate attempts to quantify the net energy efficiency of gasohol and other fuels. That is, do the Btu's delivered justify the expense of Btu's in crop production and fertilization, harvesting, transportation to alcohol manufacturers, the manufacturing process and distribution? Net energy efficiency is a confluence of a variety of factors: the end-use Btu content, the extent of utilization of by-products of the alcohol manufacturing process, the type of feedstock, the available centralized quantity of that material and the design of the alcohol manufacturing plant. Opinion on net energy efficiency should also be determined by what one considers to be the highest and best use of the agricultural feedstock.

Yet, strangely enough, this abundant list of qualifications and assumptions goes often ignored by policy-makers. It is not that they don't care about the net energy efficiency of alcohol fuels; it is just that they have more predominating thoughts on the subject -- and these thoughts are firmly rooted in economic concerns. U.S. debates on alternative energy technologies have been consistently rich in econometric, feasibility and energy efficiency studies. The primary criterion, though, for government intervention has been how well the technology could compete or penetrate the market on its own.

The debate on alcohol fuels is no exception. The extensive literature on net energy efficiency, which has developed in the U.S. and abroad, is for the large part ignored by bureaucrat and politician alike. Each side of the alcohol fuel debate comes before decision-makers armed with net energy efficiency studies supporting its respective cause. In the end, such studies are forgotten as decision-makers tally up the financial pluses and minuses to their constituents and existing fuel industries. Perfunctory questions may be asked about the methodology of some of the studies, but the central actors ultimately turn inwards and decide according to their view of the market. The accepted opinion argues that net energy efficiency losers will be punished by the market, while net energy gainers will survive and flourish. Policy-makers defer to the natural selecti of the competitive market while there occurs little or no discussion on the merits of the opposing studies.

STATE-LEVEL SUBSIDIES

Gasohol promoters have been unwilling to leave the fate of their product to the capriciousness of the market. They have, with some success, fought for sales tax exemptions in several American states. In doing so, they are not abandoning the market, but rather trying to redefine its terms by giving alcohol an economic boost. Fortunately or unfortunately, depending upon where one sits, the U.S. federal government has removed its $.04/gallon sales tax on gasohol. Thus, consumers in those states with upwards of $.04/gallon exemptions of their own are realizing a total $.08 subsidy. Given that gasohol is ten percent alcohol, we then find an ethanol subsidy, in some states, of $.80/gallon.

Alcohol promoters view these tax exemptions with excitement, hopeful that demand will respond to the lowered price and that a new supply will arise to satisfy the demand. The original arguments on behalf of gasohol regarding its superior fuel qualities, and hence its justified treatment as a premium priced fuel, are becoming less prevalent. Politicians voting for the subsidies do so at the behest of a few of their intensely interested colleagues. The politicians are told, by these colleagues, that the tax exemptions will help publicize alcohol fuel and contribute to generating a demand. Opinion on whether a supply will follow varies according to the individual legislator's perception of the resiliency of the market.

Of course, the alcohol promoter's preoccupation with competitive economics may help demonstrate that the existing energy mix need not be very resilent to resist the penetration of alcohol fuels. Potentially interested lenders for supply projects may see the existing layers of subsidies as resulting in some distortion of demand. Over-subsidizing gasohol with tax exemptions, some fear, may create the spectre of an artificial demand, as well as a ready excuse for refusing investment. Gasohol promoters have seemingly lost the opportunity to sell the product, to potential supply investors, on its superior fuel characteristics. The argument, for example, that gasohol demand will increase as the unleaded gasoline shortage worsens will be, in the minds of such investors, overwhelmed by concerns with the demand influence of tax subsidies and the lasting effect once such subsidies are removed.

THE PROPER ROLES OF THE FEDERAL BUREAUCRACIES

U.S. Department of Energy

The Department of Energy ("DOE") has been quite confused over the direction it should pursue, first in supporting research and development, and second in demonstrating and commercializing new (or reemerging) energy technologies. Generally accepted federal thinking, however, assumes DOE should support R&D of promising technologies even when industry cannot or will not see the full energy and economic potential of such efforts. Demonstration, and especially commercialization, on the other hand, should occur only when the market refuses to accept the risks or externalities associated with such activity, or when government support promises to expedite the market penetration of an alternative technology.

While there are many areas of alcohol fuels technology deserving R&D, it is equally true that some alcohol technologies are at the commercialization stage. But it is when discussing the commercialization of alcohol plants, from agricultural feedstocks for example, that DOE invokes its concept of the government's role in the marketplace. The question is repeatedly asked with respect to alcohol fuels ([illegible]icularly gasohol): why should DOE support a technology that seems capable o[illegible]eating its own demand? If gasohol is economical, and if demand persists, won't the market assure a supply consistent with that demand?

There are a number of conspiracy theories put forth to explain DOE's reluctance, in the past, to talk about alcohol fuels from biomass. One such theory suggests that Secretary Schlesinger has acted as self-appointed guardian of the oil companies' profits. Based upon a history of U.S. energy policy it would be more accurate to suggest that alcohol fuels had been simply forgotten. This is not to say that simple assumptions were at work during the period of inaction and complete neglect. Several years ago, there was no appreciable commercialization activity in the area and, thus, it was easy for DOE to assume that the technology was uneconomic. More recently, the flurry of private activity has supplied federal bureaucrats, protecting their favorite alternative energy projects, with a convenient excuse for delaying support of alcohol fuels.

In November, 1978, DOE announced eight energy technologies that may benefit from government subsidies and commercial marketing plans. Alcohol from biomass was not even considered, though alcohol from solid wastes and coal, both which may be desirable in their own right, were analyzed and rejected for the time being. The exclusion of alcohol from biomass must be symptomatic of the prioriy that fuel received within DOE.

It is hard to suggest what direction DOE policy will take in light of ongoing intra-agency and congressional studies. A real commitment to alcohol fuels and gasohol may develop within DOE or may be created at a higher, congressional level. Observation of DOE behavior to date reveals that, in the absence of such commitment, the economic mentality will reign supreme. DOE has the resources, and may well have the desire, to continually demonstrate the cost-disadvantages of alcohol fuels (1)*. By doing so they place the burden of commercialization on the private sector; yet, risk-taking ventures by private actors, attempting to prove the economic worthiness of their designs, may further convince DOE that its neglect is appropriate. Alcohol promoters, having reduced the many benefits of gasohol, for example, to one of economics, and in accepting the terms of the debate, may be unable to convincingly challenge DOE.

U.S. Department of Agriculture

U.S. Department of Agriculture ("USDA") resistance to alcohol fuels from biomass is less difficult to understand than DOE's resistance. It has been argued that USDA opposed alcohol fuels from agricultural feedstocks because agency economists feared such plants would be uneconomical. Alcohol plants, they reasoned, would be subject to the vagaries of the grain pricing system (2). This, in part, may be a reasonable inference of USDA behavior. More likely, and a root cause of much of USDA policy, is a conditioned fear against any activity that could increase grain prices and jeopardize grain exports.

It is USDA thinking that agripower will generate agridollars that will affect the balance of payments cost of petrodollars (3). This approach, as applied to alcohol fuels policy, creates the impression that the most important issue is one that the average layman -- indeed, the average alcohol promoter -- is incapable of understanding or assessing. Here we enter the arena of world economics and trade, an arena better left undisturbed by the naive farmer, university scientist, or state bureaucrat. This mentality makes it easy to forget or ignore some of the other consequences, for the agricultural community, from an alcohol fuels policy: a market for surplus commodities, an opportunity to buy or trade for a fuel the farmer helps produce, and an opportunity to bring a new industry to rural areas.

The much discussed USDA loan guarantees further reveal the policy direction of this agency. USDA, reacting to pressure from some members of Congress, anr [illegible] ced four $15 million loan guarantees for alcohol plant construction. After much [illegible] y,

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*Numbers in brackets (1) designate References at end of paper.

USDA announced the chosen projects. At time of writing, three of the four projects have been selected, though none of them will be for grain alcohol plants. hether grain alcohol plants should receive public subsidy is a policy question that should be fully and explicitly debated. Instead, USDA, albeit a step ahead of DOE, has decided thats its fear of raising grain commodity prices is justified, and without public debate has acted accordingly.

CENTRALIZED VS. DECENTRALIZED SYSTEMS

The acceptance of the economic terms of debate, by alcohol proponents, is beginning to foreclose the consideration of smaller scale, renewable fuel fired alcohol plants. Many biomass alcohol adherents respond to charges that the fuel is not cost-competitive by citing the benefits of economies of scale. The way to decrease costs, so the argument goes, is to build large $30 million plants, capable of taking advantage of European designs. Yet, competing fuel costs, such as oil, are considerably more expensive in Europe than the U.S., and an incorrect model might be chosen.

Another example of putting economics before appropriateness is provided by these same adherents' responses to the claims of net energy efficiency. The solution is not to use renewables as boiler fuel or for process heat. Nor is a partial solution advocated that would build small, local plants, thus reducing transportation costs and providing a more manageable market for process by-products. Rather the assumption is made that large plants will be able to take advantage of new energy efficient designs, and that an infusion of R&D money will improve upon such designs.

What is being suggested here is that the alcohol from biomass community may be limiting itself by presenting the 20 million gallon/year plant as the sole "state-of-the-art" technology. In doing so, we may gain some formidable rebuttals to refiner's claims that their process is inherently more efficient. But we may, at the same time, develop a paradigm that will win only on the basis of appeals to its monetarily quantifiable outputs, its energy and economic balance sheet. Concurrent with this development, we will lose the opportunity for a national examination of the desirability of smaller scale, locally matched alcohol plants.

COMPARISON WITH SOLAR PROMOTION

Solar heating and cooling advocates are interested in demonstrating the economic reliability of their projects. But they are also cognizant of the disadvantages of using economics as the only argument for a solar future. Solar advocates fare least well when the energy debate becomes solely one of payback periods, comparative capital costs and the outlook for improving cost-competitiveness. Opponents to solar can too easily summon their own "empirical" studies to refute the contentions made on behalf of solar. Policy-makers, faced with a mass of conflicting evidence, vote according to their own perceptions of the desirability of solar.

Solar advocates fare best when they rely upon an overall ethic or philosophy in support of a solar future. Solar, according to this ethic, makes sense not only because its economics will become more favorable as traditional fuel prices increase, but because of a variety of other reasons. Solar increases individuals' and communities' self-reliance, providing protection against supply disruptions. Solar also increases pride in ownership, allowing individuals to play a role in their own energy futures. Solar decreases the environmental hazards inherent in the development of oil, natural gas and coal and nuclear electrical facilities. S[illegible] also symbolizes resistance to exponential energy growth. This philosophy can be used as a mainstay of an argument for solar. Or the philosophy can be treated as an extension of the economic reasons for solar: "Even if you don't believe solar is completely cost-competitive now, there are other compelling reasons for its widespread adoption."

There is another argument that further diffuses the preoccupation with economics. The argument also suggests that whatever cost disadvantages that do exist have been artificially created. Solar, it is reasoned, is forced to compete against traditional fuels that received (and receive) government subsidies, tax credits, insurance, etc. A recent study puts government expenditures for energy production (nuclear, hydro, coal, oil and gas), since 1918, at $123 to $133 billion (4). The market is distorted and solar is forced to compete against traditional fuels that are purposively and implicitly supported by a host of government programs.

These two contentions together demonstrate a realization by many solar advocates that their cause cannot be won on appeal to market economics alone. One solar spokeman summarized the concern (5):

> Preoccupation with costs, especially when it's pretended that they can be given absolute numerical values, obscures the important principle that societies choose technologies for noneconomic reasons, then adopt whatever economic policies are needed to make them float.

SUGGESTIONS

Some alcohol proponents have made the above realization. Admittedly, the portrayal of the biomass alcohol community as one obsessed with market forces, market shares and set upon proving the economic superiority of their technology is an extreme description. There are RD&D activities in many states that are examining the use of renewable fuels in plant boilers. Solar, hydropower and methane from anaerobic digestion are all being considered, as are smaller plant designs. These designs may be capable of standing on their own economically. The designs also contribute to the energy efficiency of the process, as well as help make public support more likely. Furthermore, there are groups, such as the Department of Commerce with its small distillery grant, the National Center for Appropriate Technology and the Domestic Technology Institute, that have supported the cause of decentralized systems. The National Gasohol Commission's conference on small-scale plants is a pleasant break from that group's emphasis on large plants and large subsidies.

The previously described characterization of the alcohol fuels debate does represent a noticeable trend, despite the exceptions. This is not to say that large alcohol plants may not have a place in the U.S. fuel mix. It is to say that little meaningful and widespread support will be forthcoming from government institutions so long as cost-competitiveness is made the hallmark of the alcohol fuel controversy.

Certainly, a number of low interest or guaranteed loans may be made available by federal or state agencies. But these subsidies, for the most part, will be made for large-scale plants. In the absence of any explicit support for alcohol fuels, the subsidies will represent pork barrel payment to a specific constituency. The constituency will be viewed, not as representing a community or all energy users, but as farmers and potential gasohol dealers. Yet, only a limited amount of pork barrel will be allowed before a congressman's peers shout, "No more." Also, not many plants will be built prior to a congressman feeling he has demonstrated sufficient constituency support.

The biomass alcohol community, in order to prevent alcohol fuel activity from being short-lived and limited to a few large plants, needs to develop its owr ethic. Biomass alcohol supporters should continue to improve the competitive position of their product and advance economic arguments when necessary. The alcohol community, though, needs to expand its own conception of the possibilities for and advantages of alcohol fuel development. As alcohol fuel advocates have more interaction with government agencies and their actors, the temptation to reduce the benefits of such fuels becomes stronger. Bureaucratic discussion is couched in economic language, and increased interaction with the government creates the illusion that such languauge is necessary to achieve victories.

An alcohol fuel ethic or philosophy would be a coherent, internally defensible statement that would point to the diverse advantages of the fuel for a variety of audiences. Dispersed, small-scale plants, for example, offer consumers a substitute for premium unleaded fuels, and supply the anti-knock and performance features necessary for such a substitute. The gasohol product from such plants would also provide some local or regional hedge against gasoline product disruptions, or at least make the effects of such disruptions less severe. Consumers would feel they are aiding their own community. Small-scale plants would go some way toward fostering the understanding that petroleum alternatives need to be found. The economic advantage is no less deserving of mention: as world and domestic oil prices increase, gasohol could provide some price impact protection.

Small-scale plants not only provide farmers with an alternative market (which could be their own farm), but allow them to feel less captured by federal policy and world grain movements. The plants would allow the farmers to feel they are contributing to the energy sufficiency of their community, as well as allow them to contribute to the employment of local citizens. As mentioned earlier, locally placed plants provide the farmer more opportunity to buy back some of the alcohol product than would the more removed, larger plants. Small-scale plants would demonstrate to the government that dispersed energy systems can be accepted and supported by communities.

References

1. DOE's desire to demonstrate the capital intensiveness of alcohol production was shown in its Alcohol Fuels Program Plan of March 1978. The treatment of alcohol plants in the report also reveals DOE emphasis on large-scale technology. This emphasis comes, in part, as a response to criticisms from alcohol advocates. DOE states in its report:

> An agressive program to put ten 30-million-gallon-per-year fermentation plants in place by 1985 would provide ethanol from agricultural products in an amount less than 1 percent of the total projected 1985 liquid fuels demand, at a cumulative investment for plants of nearly $500 million. If the number of plants were doubled by 1990, the influence of ethanol would still be very small. (p. 1-5)

DOE does not tell us how it decided upon a $500 million program as representative of an aggresive program. But let's assume that such a program was desireable. DOE discounts the significance of such a program by not mentioning the regional supply consequences of the investment. DOE further discounts the effect of the hypothetical program by ignoring the contribution of the alcohol as a supplement to gasoline, rather than as a replacement as the argument implies.

More importantly, DOE never develops another scenario: what would be the consequences of a $500 million investment in small-scale distilleries? It has been suggested that a 500 gallon/day plant could be built for $250,000; the cost including equipment to use solar to dry the by-product DDGS. If the $500 million were to pay for these plants outright, then 2,000 of the plants could be built. The distilleries would employ several thousand persons and would provide fuel and byproducts for up to as many communties as there were plants.

2. Cf. Hal Bernton, "Alcohol Fuels: A Major Source of Power Only a Few Years from Here", Environmental Action Bulletin, October 29, 1977, p. 5.

3. If anyone has any doubts that this thinking afflicts USDA, they should consult the quotations, by agency officials, as collected in Wendell Berry, The Unsettling of America: Culture and Agriculture (New York: Avon, 1977), pp. 34-35.

4. Batelle, Pacific Northwest Laboratories, An Analysis of Federal Incentives Used to Stimulate Energy Production, March 1978.

5. David Brower, "Introduction", Sun: A Handbook for the Solar Decade, ed. by Stephen Lyons (San Francisco: Friends of the Earth, 1978), p. 2.

CALCULATIONS RELEVANT TO THE FUELING OF ALCOHOLS IN SPARK IGNITED INTERNAL COMBUSTION ENGINES - SIGNIFICANCE FOR ELECTROSTATIC CARBURATION

by

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INTRODUCTION

The significant advantages of alcohols as fuels with inherently high octane numbers and giving rise to improved power outputs in spark ignited internal combustion engines has long been known (1)*. More recently the concern over economy and pollution has prompted the further aspects of lead-free operation, higher thermal efficiency and faster flame speeds of alcohol and alcohol gasoline blends to be considered with respect to the potential for reduced emissions and improved economy at lean air to fuel ratio operation (2 to 6).

However the use of alcohols as automotive fuels can present some unique difficulties associated with atomization and vaporization. This is due to the oxygen atom present in the hydroxyl group (-OH) of alcohol molecules, which means they are partially oxidised (and therefore have a net calorific value lower than a normal hydrocarbon) while hydrogen bonding between these groups, see Figure 1, gives rise to very high boiling points, but, more important, very high values of latent heat of vaporization. If one considers methanol for example and compares it with iso-octane, the relevant data are shown in Table 1, it can be seen that the ratios of calorific value and latent heats are 1:2.23 and 1:3.64 respectively, so that to <u>vaporize</u> (as distinct from atomize) an equivalent energy flux of methanol, to iso-octane, would require 8.11 times as much heat flow into the vaporizing system.

TABLE 1

Fuel	Lower Calorific value at 25°C/MJ kg^{-1}	$\Delta H_{vap}\,\Theta$/kJ kg^{-1}
Iso-octane (C_8H_{18})	44.4	308
Methanol (CH_3OH)	19.9	1120

One can also see from Figure 1 that due to the difference in electronegativity of O and H the -OH group in alcohols is electrically polarised, thus giving them a finite conductivity (typically ≃ 10^{-7} ohm^{-1} cm^{-1}) and making them amenable to electrical atomization. Basically, if one were to produce a spray of small droplets, by electrically charging the surface of the liquid (work against surface tension only) such that these droplets evaporated in the charge air, adiabatically, ie. with no heat transfer across boundaries such as inlet manifold, piston crown etc., would it be possible to achieve, by cooling contraction, a chemical energy density in the charge equal to or greater than that of iso-octane, and in part overcome the calorific value penalty of alco-

mbers in parenthesis (1) designate References at the end of the paper hol fuels. This would in effect be like supercharging the intake, not by pressurizing, but by reducing the temperature.

It had been generally assumed that increased power outputs that are experienced when running on alcohol fuels may in part be attributable to increased volumetric efficiency due to charge cooling on evaporation (7). Some Ricardo work, however, (5) showed that this is not the case and methanol (and blends with petrol) may lead to worse volumetric efficiency compared to petrol. The explanation was that, due to poor carburation of methanol, the fuel lay along the inlet manifold and dribbled into the combustion chamber, where the latent heat of vaporization was extracted from the piston crown, displacing charge in the liquid → gas transition that took place, and thus lowered volumetric efficiency. The relative lowering was, as expected from this explanation, engine speed dependent.

As part of some other electrical atomization work (to be detailed elsewhere) some calculations were performed to see under what conditions one might expect to see improved volumetric efficiencies for adiabatic evaporation, where one has to balance volume expansion due to liquid → gas transition on evaporation, with volume contraction due to absorption of latent heat from the charge air. One therefore has to define a control surface as seen in Figure 2. For practical conditions there will always be sufficient enthalpy in the charge air for the latent heat of vapourization to be extracted from the air (8) and not non-adiabatically by drawing the latent heat from across working surfaces with the resultant lowering in volumetric efficiency and possible 'icing-up' of carburettors and manifolds. Whether this enthalpy is available for evaporation will depend on many factors, including how the fuel is prepared with respect to atomization. This last consideration led to the work on electrostatic carburation while the associated expansions or contractions that could modify volumetric efficiency will be considered next.

THEORETICAL

Consider the following for the constant pressure adiabatic control volume of Figure 2.

N = Number of moles of air
n = Number of moles of fuel evaporated
V = Volume
$\Delta H_{L,n}$ = Molar latent heat of vapourization of fuel (kJ/mole)
$\Delta H_{L,m}$ = Latent heat of vapourization of fuel (kJ/kg)
P = Pressure
R = Gas Constant
T_i = Initial temperature of air
T_e = Exit temperature of charge
ΔT = Temperature change in charge due to evaporation
$\bar{C}p$ = Mean specific heat of charge
$\dot{m}_a$, $\dot{m}_f$ = Mass flow rates of air and fuel respectively (kg/s)
h_i = Specific enthalpy of air at T_i
h_e = Specific enthalpy of charge at T_e
F_a = Actual w/w air to fuel ratio ($\dot{m}_a/\dot{m}_f$)

F_s = Stoichiometric air to fuel ratio
λ = Mixture strength (F_a/F_s)

The main condition for evaporation is:-

$$\dot{m}_a h_i \geqslant \dot{m}_f \, \Delta H_{L,m} \qquad (1)$$

Initially, before evaporation $$V_i = \frac{NRT_i}{P} \qquad (2)$$

Finally, after evaporation $$V_f = \frac{(N + n)R(T_i - \Delta T)}{P} \qquad (3)$$

Enthalpy balance $$n \, \Delta H_{L,n} = (N + n) \, \bar{C}p_{,n} \, \Delta T \qquad (4)$$

Equation 3 may be expressed as $$V_f = \frac{(N + n)R}{P} \left[T_i - \frac{n \, \Delta H_{L,n}}{(N + n) \, \bar{C}p_{,n}} \right] \qquad (5)$$

$$\text{or} \quad V_f = \frac{R}{P} \left[T_i \, (N + n) - n \, \frac{\Delta H_{L,n}}{\bar{C}p_{,n}} \right] \qquad (6)$$

Of direct interest is how V_f varies with the amount of fuel evaporated, therefore differentiating we have

$$\frac{\partial V_f}{\partial n} = \frac{R}{P} \left[T_i - \frac{\Delta H_{L,n}}{\bar{C}p_{,n}} \right] \qquad (7)$$

Equation (7) gives a very interesting result and shows there are three regimes of volume change on evaporation of the fuel under adiabatic conditions depending on the value T_i (eg. inlet manifold temperature) and the ratio $\Delta H_{L,n}/\bar{C}p_{,n}$. It is convenient to work in specific units and define $\beta = \Delta H_{L,m}/\bar{C}p$ as a constant having units of temperature.

if $T_i > \beta$ .... an expansion
$T_i \simeq \beta$ .... no change $(\frac{\partial V_f}{\partial n} = 0)$
$T_i < \beta$ .... a contraction

β is not strictly a constant, but to a good first approximation may be treated as one since $\Delta H_{L,m}$ varies only slightly with temperature, while $\bar{C}p$ is more of a problem since it will vary with temperature, and the amount of fuel evaporated. (A more rigorous treatment puts $\bar{C}p$ in terms of T and n and modifies equation (7) accordingly - this adds complication which adds nothing of real value to the general results presented here.) However, if we use the fact that under combustion conditions $N > n$ we can approximate $\bar{C}p$ to that of air, ie. $\bar{C}p \simeq 1000 \text{ J kg}^{-1} \text{ K}^{-1}$. Table 2 shows the values of β for a number of fuels and water. One then compares the values of β for different liquids with the initial values of temperature to see if the volume change is positive or negative on adiabatic evaporation. The value of β for iso-octane at ≃ 35°C is very interesting.

TABLE 2

Liquid	β/K
Iso-octane	308
Diethyl Ether	350
Toluene	350
Ethanol	850
Methanol	1120
Water	2260

% Change in charge volume

To calculate the % change in the volume of charge on evaporation, ie. V', where

$$V' = \frac{V_i - V_f}{V_i} \times 100 \qquad (8)$$

we obtain V' in terms of β, which is a linear function.

$$V' = 100\,\frac{n}{N}\left[\frac{\beta}{T_i} - 1\right] \qquad (9)$$

V' may be plotted as a function of mole ratio fuel to air (n/N) for different values of T_i. Obviously from the way equation (8) is defined the gradient of this plot indicates whether a contraction (+ve gradient) or expansion (-ve gradient) occurs. From the point of view of volumetric efficiency a contraction is desirable. So far the calculations apply generally to any fuel, however considering specifically methanol (and alcohols in general) then:-

For an alcohol of general formula $C_xH_yO_z$ the stoichiometric w/w air/fuel ratio, F_s, may be calculated as

$$F_s = \frac{137.33M}{w} : 1 \qquad (10)$$

where $M = x + y/4 - z/2$, $w = 12x + y + 16z$ for Methanol $F_s = 6.44$ and$(n/N)_s = 0.173$

V' has therefore been plotted as a function n/N for different likely initial temperatures as shown in Figure 4. As we would expect from Table 2, provided the inlet air temperature is below 1120K a contraction on adiabatic evaporation of methanol is possible with resulting increased charge density and improved volumetric efficiency.

Temperature drop on evaporation

Various detailed methods of calculating the temperature drop (ΔT) associated with the adiabatic evaporation of methanol have been attempted. The estimated values for stoichiometric methanol/air range from 122K (9), 125K (10), 142K (11), with increasing levels of complexity. What is detailed below is a simple method of calculating ΔT which easily gives values in as good agreement as the most complicated methods. Again it is written for general application to any fuel.

For combustion purposes $N > n$ therefore assume $\bar{C}p \simeq 1.0$ kJ kg^{-1} K^{-1}

On enthalpy balance

$$\Delta T = \frac{\dot{m}_f \, \Delta H_{L,m}}{\dot{m}_a \, \bar{C}p} = \frac{\beta}{F_a} \qquad (11)$$

$$\Delta T = \beta / \lambda F_s$$

Consider the three fuels shown in Table 3; Table 4 was constructed using equation (11).

TABLE 3

Fuel	β/K
Ethanol	850
Methanol	1120
15% MeOH/85% Iso-octane	430

It should not be forgotten that a decrease in temperature may still be associated with an increase in volume, subject to the conditions of β and T_i.

TABLE 4

	ΔT		
λ	MeOH	EtOH	15% MeOH/85% iso-octane
0.8	217	119	39
1.0	174	95	31
1.2	145	79	26
1.4	124	68	22
1.6	108	59	19
1.8	97	53	17
2.0	87	47	16

Table 4 gives some idea of the temperature drop one would expect; we see that for stoichiometric methanol/air a value of ΔT of 174K is calculated which is within the same range as the more complicated methods of calculation. Again, rigorous calculation for iso-octane gives 18K drop at $\lambda = 1$ (12). Using equation (11) and the value of F_s for octane at 15.06 gives ΔT as 20K.

ELECTROSTATIC CARBURATION

All the calculations presented are based on thermodynamic equilibrium being established, and an assumption that the initial temperature is arbitrary. Nevertheless they indicate the best that could possibly be achieved, given sufficient time for evaporation. The atomization and evaporation of these fuels in the fuel handling system, would not allow these steady state conditions to be realised in practice unless sophisticated controlled atomization (tending to very small droplets) and mixing systems could be devised. It is for that reason that electrostatic methods were considered.

Electrostatic atomization of fuels is not new (13) and complete burners have been made operating electrostatically on kerosine fuel (14). With most hydrocarbon fuels the conductivity is far too low for them to be perturbed by an applied electric field (although it is possible to spray charge from corona sources onto the surface of hydrocarbons and cause them to subsequently atomize) hydrocarbon fuels are made conducting therefore by the addition of an anti static agent.

The potential for electrostatic carburation of alcohol fuels is unique, in that the hydroxyl group that leads to the problems associated with lowered calorific values and high latent heats, also provides the handle whereby these fuels may be atomized electrostatically - due to the conductivity of the functional group as described earlier, thus enabling the possibility of improved economy and combustion characteristics to be obtained.

Most mechanical methods of atomization (including piezoelectric) put nearly all of their energy input (typically of excess of 90% see also ref. 13) into kinetic energy of the droplets once formed. For carburation this is disadvantageous for at least two reasons, firstly, it corresponds to an energy input to the fuel which serves no useful purpose (in contrast to a diesel injector or gas turbine fuel spray) and, secondly, any energy input of this sort gives rise to an unnecessary (however small) increase in the negative area of the indicator diagram.

For pressure jet atomizers the size distribution function of the fuel spray is not readily variable (15) and tends to be very wide (from 7 to 560 microns) for the spray of Figures 8g & h. Whereas for electrostatic atomization within certain ranges of flow the size distribution function may be varied by varying the applied field intensity. Conventional venturi carburation fails badly at low throttle openings and has led people to consider piezoelectric (16) and sonic (17) carburettors. However since electrostatic carburation involves no moving parts nor does it rely on air movement directly to produce droplets it has non of these drawbacks.

Mechanism and power requirements

There are many theories of how droplets are formed electrostatically when stressed by an applied electric field, depending on liquid properties such as conductivity, viscosity, surface tension as well as the charging environment (18, 19 and references therein). Basically if the surface of a liquid becomes charged then forces are established (an electrical pressure) on the surface opposing the surface tension forces of the liquid holding it together. The excess charge is removed from the surface by it disrupting and emitting streams of charged droplets. The apparatus to do this is very simple and is shown in Figure 3, while the kinds of spray readily obtained by the application of a DC field are shown in Figures 8b to 8d. The exact details are given under the experimental section.

In any situation where a highly ordered energy form such as electricity is to be interacted in a combustion situation attention is always paid to the power requirements. For a DC application the power is the direct product of operating voltage and current drawn, ie. $P_{actual} = V_{op} \times i$, the powers used for electrostatic atomization are small, although the voltage was high (20 → 30kV) the currents drawn were always small 100 μA to 1 mA. It should be stated here that one of the powers supplies used to generate the sprays shown in Figures 8h to 8d was an automotive electronic ignition circuit modified with a television rectifying diode.

It is possible to calculate a minimum power requirement for electrostatic carburation based on the fact that, independent of the droplet producing mechanism, the net result in forming the spray is work against fuel surface tension (the power then being the rate at which that work is done). If unit mass flow rate is considered, then the minimum work required to go from a condition such as Figure 8a, condition 1, to condition 2 such as Figures 8b to d can be calculated as follows:-

E_1, E_2 = Surface energies in conditions 1 and 2 respectively

A_1, A_2 = Areas bounding unit mass under conditions 1 & 2 respectively

γ = Surface tension

Then $E_1 = A_1\gamma,\ E_2 = A_2\gamma$

$$\Delta E_{Elect} = (A_2 - A_1)\,\gamma \simeq A_2\gamma \text{ since } A_2 >> A_1$$

$$P_{min} = \gamma\frac{dA_2}{dt} = N_s a_2\gamma = \frac{6x\gamma}{d} \qquad (12)$$

Where N_s = number of droplets generated per second with surface mean diameter d and droplet surface area a_2 at flow rate x. With x in m^3/s and d in m this gives power directly in Watts. γ for MeOH was taken as 22.6 mNm^{-1}, some results are shown in Figure 5.

This calculation represents an absolute minimum, obviously when charged particles move in an electric field gradient and with ionic winds known to be present further power is being utilised above the P_{min} level. The total power used will be of the form $P_t = P_{min} + P_{kinetic}$ however it is expected that $P_{kinetic}$ could be made small.

EXPERIMENTAL

Space constraints preclude a detailed discussion of the experimental arrangements, these will be discussed in more detail in the presentation. For Figures 8a to 8d the fuel feed (Methanol) was earthed with a column of fuel acting as a limiting resistor to prevent a spark discharge. DC fields were generated by applying either a +ve or -ve potential (in the range 20 to 30kV) to a variety of electrode configurations either a single point corona (Figure 8b) a multicorona source (Figure 8c) or a standard plate electrode (Figure 8d). Figure 8a represents the free fall case. For each of these figures the fuel flow rate was 1cc/s. Spray size distribution functions were obtained between 10 to 50 microns (depending on conditions) using a Malvern Instruments diffraction system (20).

The potential for improving atomization of existing atomizers was considered. A study was made by applying photographic analysis to an intermittent injector (a CAV single hole nozzle as seen in Figures 8e to 8h). This analysis could have been done using high speed cine, however a novel photographic technique was developed as shown in Figure 6. The instant the spray emerges from the nozzle it attenuates the laser beam, a rapid response photodiode detects this and generates t_o as shown in Figure 7. It is possible to freeze the spray with a flash at any point (t_f) during the spray duration t_d or beyond. If the flash duration is 100 microseconds say, this is equivalent to choosing one frame from a 10,000 fps film at will, with better resolution and at a fraction of the cost.

Figures 8e and 8f are with t_f = 5 ms, Figures 8g and 8h, t_f = 46 ms, Figures 8i and 8j t_f = 109 ms. The first figure in each case is without an applied field, and the second with 30 kV (-ve) applied to the ring electrode. The fuel in each case was Methanol.

The most interesting shots from a practical point of view are the early shots (note the change in penetration and width) both from the point of view of an ignition delay modification (for diesel engines) and that the system could be regarded as an air-dielectric capacitor being discharged by the fuel emerging from one electrode and receiving a substantial initial discharge current. Naturally once a flame is established the flame ions would dictate the discharge. For carburation of a spark ignited engine these considerations would not apply. Detailed spray analysis for later times confirmed what is seen in Figures 8e to 8j, ie. that the outside of the spray is charged while the inside core remains uneffected. This is not unexpected for the ring electrode configuration.

CONCLUSIONS

Calculation has shown alcohol fuels can improve volumetric efficiencies of spark ignited engines, provided the evaporation is adiabatic. Electrostatic carburation of alcohol fuels is ideally suited to this purpose, offering the potential for high atomization efficiency at low throttle openings as well as overcoming the unique difficulties that low calorific value and high latent heat alcohol fuels present.

Increasing awareness of how the constraints of economy and emissions are influenced by burning rate (21, 22) how size distribution function may effect this (23) and that optimum spray sizes for propagation rates (23) and pollutant emissions may exist (24), leads to consideration of electrostatic carburation as an engine research tool. That homogeneous mixtures (on a molecular scale) are not optimal for engine operation has been shown (25) that advantages may exist with a fuel air mixture that is aerodynamically stratified into a uniform mist are at present under study. If one envisages it as a dust or mist suspension then wider 'flammability limits' will certainly exist. The fact that optimum sizes for propagation and emissions may exist prompts further study for engine research using electrostatic carburation. The detailed electrode configurations and charging criteria for practical application have yet to be established.

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The author is indebted to Mr. R.W. Wheeler of Ricardo & Co., England for the loan of apparatus and providing research facilities, as well as helpful comments. Mr. M.W. Wedd of Malven Instruments is thanked for the loan of the ST 1800 analyser. Some of this work was done as part of the Ph.D. requirement of the author at Imperial College, London, with research advisor Prof. F.J. Weinberg.

I would particularly like to thank Wayne State University for meeting all the preparation and travel costs, and my wife for typing the manuscript.

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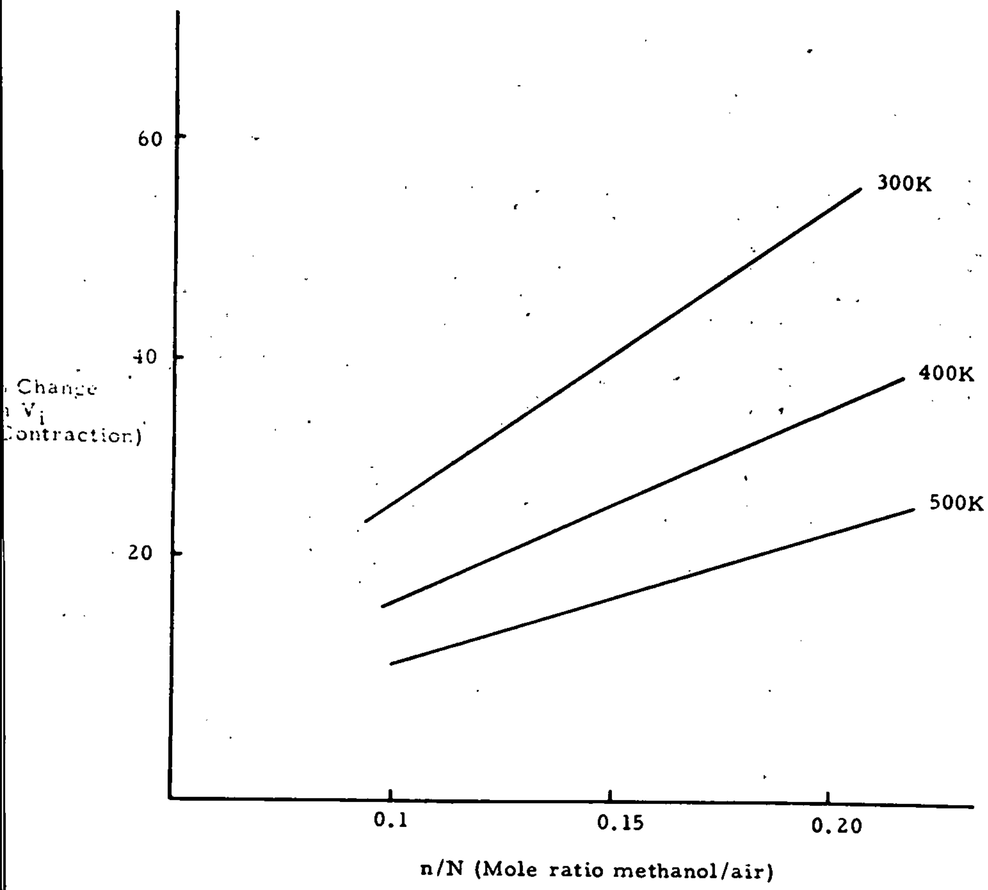


Figure 4 - % Change in volume as a function of mole ratio for different initial values of T_i, less than β.

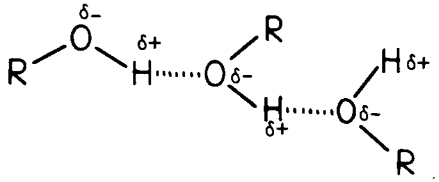


Figure 1 -Schematic of intermolecular hydrogen bonding (·········) between alcohol molecules in the liquid phase.

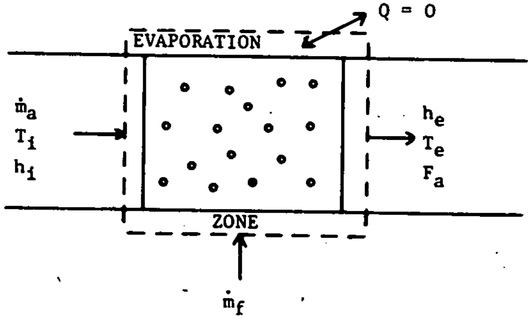


Figure 2 - Control Surface used for adiabatic evaporation.

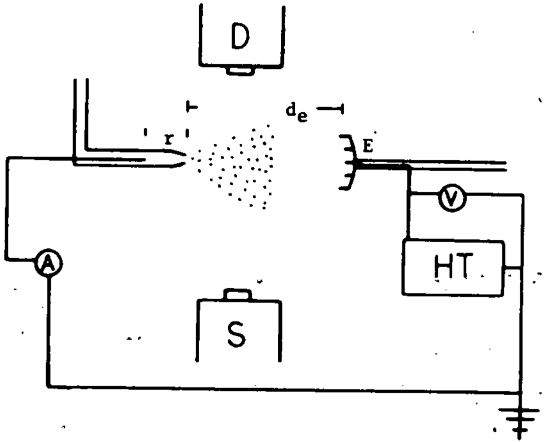


Figure 3 - Diagramatic of apparatus used to obtain photographs shown in Figures 8a to 8d; S and D - the Source and Detector of the size distribution analyser, r = limiting resistor column of Methanol (≃ 3 cms). d_e ≃ 10 cms. E - electrode. (ie. Corona or plate).

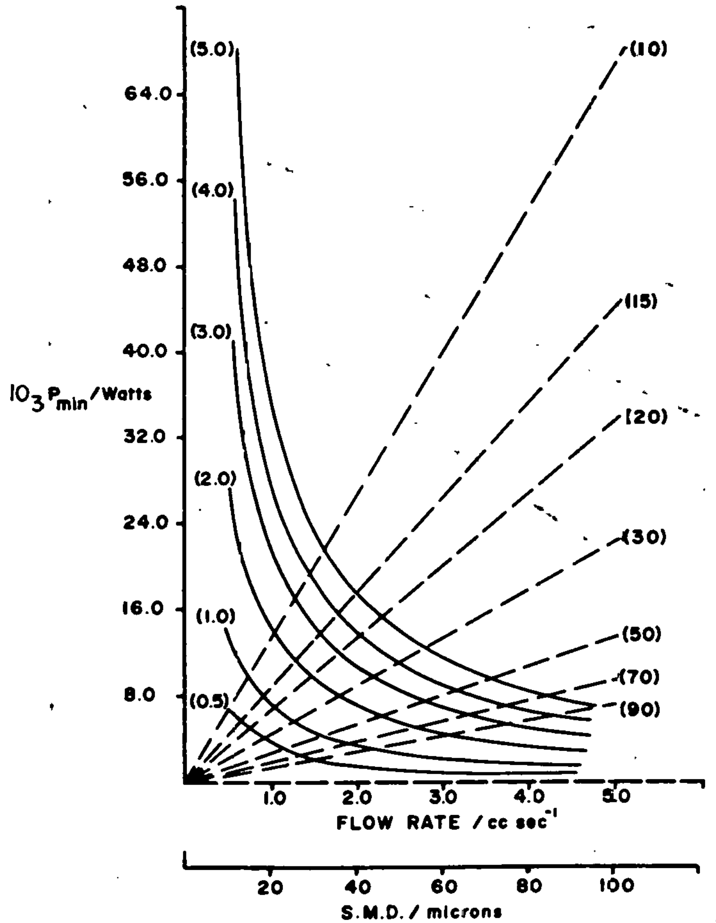


Figure 5 - Minimum calculated powers for electrostatic carburation as functions of i) flow rate ii) size distribution function. Numbers in parenthesis te i) fuelling rate 0.5 → 5.0 cc/sec of Methanol ii) Surface mean meter of droplets formed 10 → 90 microns. (as SMD => 0, power => ∞)

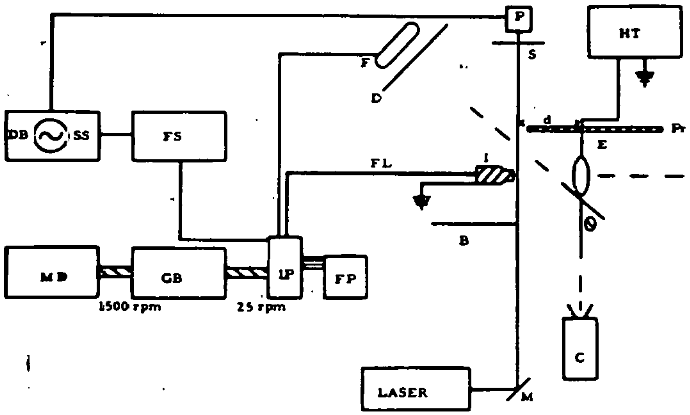


Figure 6 - Diagramatic of spray apparatus used to obtain pictures shown in Figures 8e to 8j. DBSS - Dual beam storage oscilloscope, FS - Flash synchroniser, MD - Motor drive (input 1500 rpm), GB - Gearbox (as torque converter to 25 rpm), IP - Injector pump, FP - Fuel pump, FL - Fuel line, I - Injector, B - Blind, M - Mirror, D - Diffuser, F - Flash tube, S - Slit, P - Photodiode, HT - High tension unit, Pr - Perspex rod, E - Ring Electrode, C - Camera, θ - Scatter angle (40°).

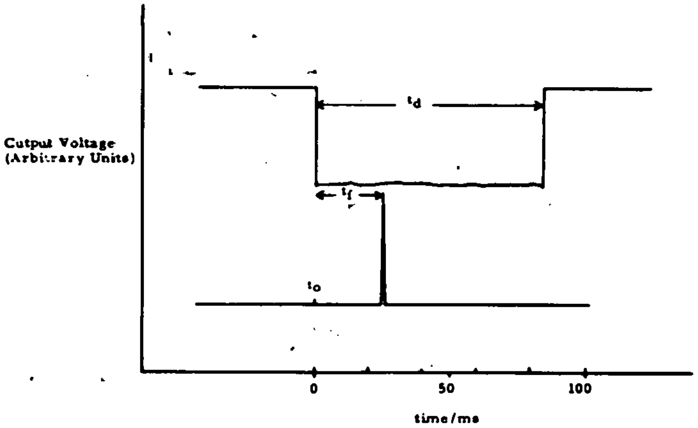
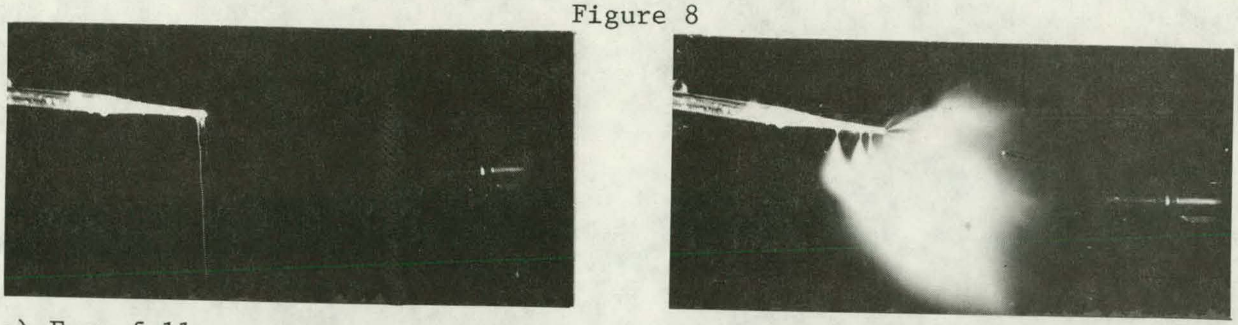


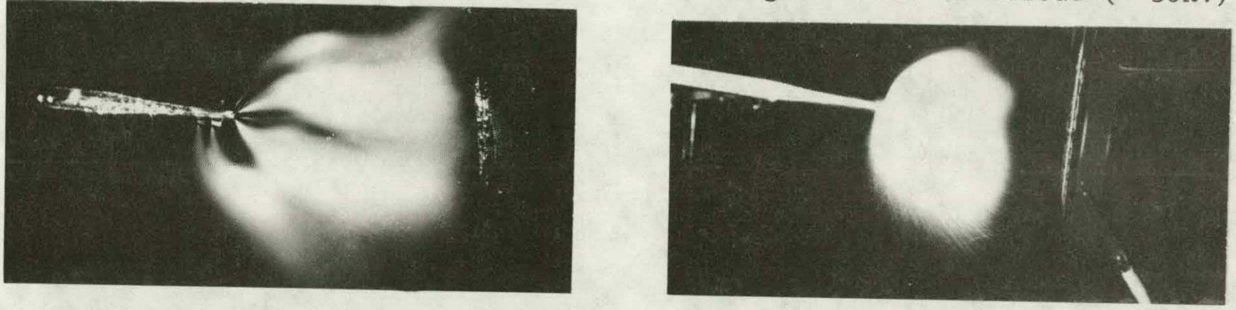
Figure 7 - Typical storage scope output trace, $t_d = 96$ $t_f = .5$ → 109 ms for conditions shown in Figures 8e to 8j

Figure 8



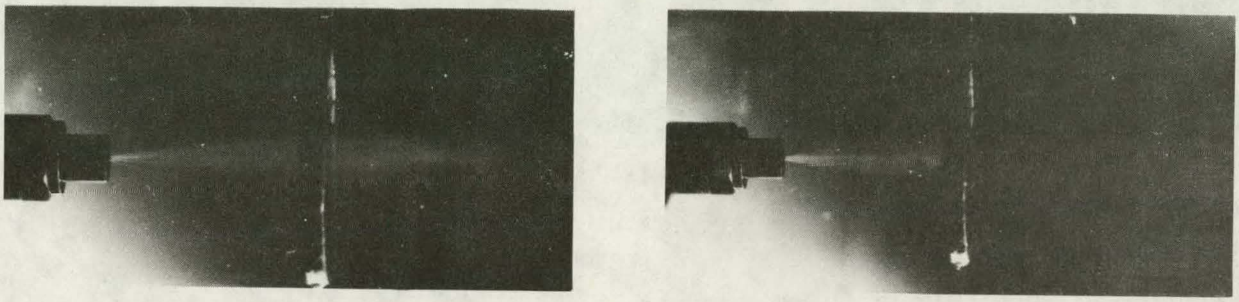
a) Free fall

b) Single-corona electrode (- 30kV)



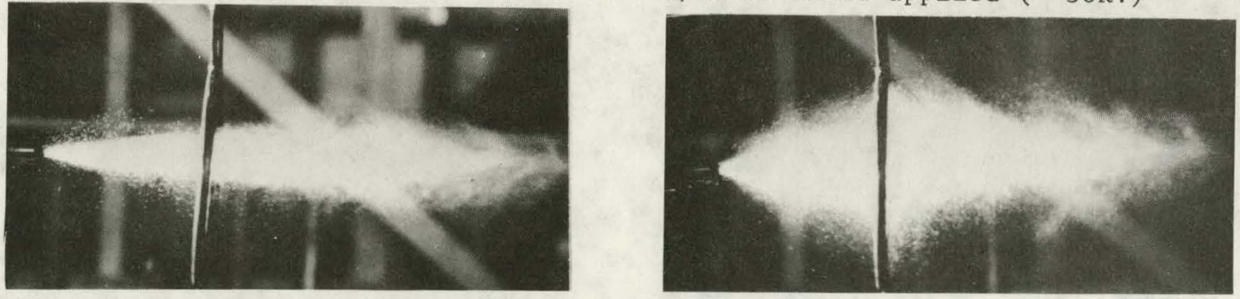
c) Multi-corona electrode (- 30kV)

d) Plate electrode (- 30kV)



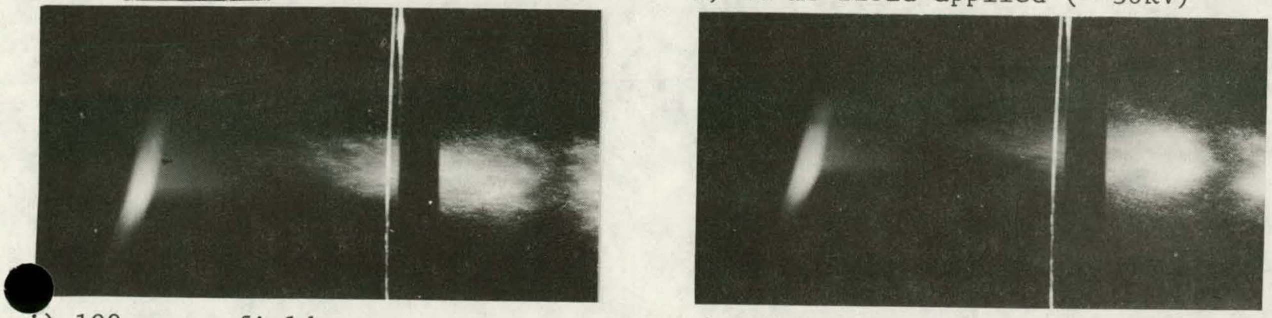
e) 5 ms no field

f) 5 ms field applied (- 30kV)



g) 46 ms no field

h) 46 ms field applied (- 30kV)



i) 109 ms no field

j) 109 ms field applied (- 30kV)

COMBUSTION AND EMISSION OF GASEOUS FUEL FROM REFORMED METHANOL IN AUTOMOTIVE ENGINE

by

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INTRODUCTION

Since the energy crisis in 1973 many studies have been made on the problem of dveloping an energy source which could substitute for those based on petroleum. These studies were prompted by the anticipated shortage of petroleum-based fuels, as well as political instability prevalent in some oil-producing countries as evidenced by recent events in Iran.

Various automotive fuels other than those which are petroleum-based have been actively researched, and recently methanol has received widespread interest as the most promising of all available substitutes.

We have made an experimental study of the applicability of methanol to the automotive engine. Our study was concerned with using reformed methanol as an automotive fuel, which is considered to be one of the most effective methods of utilization.

The reformed gas was obtained by converting methanol into hydrogen and carbon monoxide by using a catalyst. The heat of exhaust gas from the engine was used to accomplish the reformative reaction. Since the reformed gas contains hydrogen, the engine offers similar combustion characteristics to those of the hydrogen engine. Therefore, use of methanol reformed gas may lead to the realization of a clean burning engine which provides excellent thermal efficiency.

In our study, we first clarified the properties of the methanol reformed gas and experimented with it using an Otto cycle engine to obtain the most effective results. We have developed a reformer, and have confirmed that the engine possesses superb characteristics in respect to thermal efficiency and exhaust emission. We have estimated the potential for a methanol reformed gas engine and have conducted its basic evaluation.

PROPERTIES OF METHANOL REFORMED GAS

Methanol reacts on the catalyst at about 300°C, and decomposes into a gas made up of hydrogen (H_2) and carbon monoxide (CO). As shown in Fig. 1, this is an endothermic reaction, in which the low calorific value of the reformed gas is about 20% greater than that of methanol. That is, in this reaction heat energy is converted into chemical energy. The heat of exhaust gas from the engine can be utilized as the heat source for recovering the engine's energy. The following paragraphs describe the advantages of the methanol reformed gas.

Complete Combustion

As a fuel, hydrogen (H_2) has excellent properties such as fast burn, small ignition energy, short quenching distance, etc. In addition, the combustion properties of CO demonstrate similar tendencies, therefore making it easier for the reformed gas to burn completely, leaving less combustible components in the combustion gas.

Combustion of a Lean Mixture

The reformed gas has a wide range of inflammability, allowing a lean air-fuel mixture to burn stably. This is made possible by the combustion properties of H_2 and CO.

Superior Anti-Knock Feature

Owing to its high temperature of spontaneous ignition and other qualities, the reformed gas offers a superior anti-knock properties, which enable the selection of a large value for the compression ratio of the engine.
In addition to those stated above, the reformed gas has other advantages such as a small radiation loss at combustion and less frequent occurrence of abnormal combustion of H_2. Utilization of the reformed gas as fuel in the Otto cycle engine will produce geater thermal efficiency and a better exhaust emission through the combustion of all of these advantages.
One drawback of the methanol reformed gas as a fuel is low calorific value of combustion per unit volume of the theoretical air-fuel mixture, which is 88 percent of that of gasoline. Another drawback is that the number of mols of the theoretical mixture decreases by 15 percent due to combustion. This second drawback causes a drop in thermal efficiency, but its effect decreases as the mixture becomes leaner (see Table 1).

Table 1 - Physical properties of methanol reformed gas (theoretical value)

Composition of gas	H_2 67 vol. % CO 33 vol. %
Mean molecular weight	10.68
Low heating value	5,720 Kcal/kg
Theoretical air-fuel ratio	6.51
Theoretical mixture calorific value	820 Kcal/Nm^3
Rate of decrease of theoretical mixture mole	15%

OUTLINE OF EXPERIMENTAL EQUIPMENT

The engine used in these studies was a 4-cylinder, reciprocating engine, and its major specifications are given in Table 2. The composition of the engine is explained below in Fig. 3.
Methanol flows past the fuel strainer to the fuel pump, which delivers it to the reformer. The reformer consists of an evaporative unit and a reformative unit filled with catalysts. Methanol reacts with the catalytic bed and is converted into a reformed gas. The catalytic temperature is 300 - 350°C, and the reactive heat is completely supplied by exhaust gases. Reformed gas comes out of the reformer at a temperature of about 300°C and at a pressure of 1 - 4 kg/cm^2G. The temperature and pressure of the gas is lowered by the gas cooler and pressure regulator to about 150°C and the atmospheric pressure is then metered by the gas valve and supplied to the engine.
This gas valve is interconnected with the air valve, controlling the excess air ratio. The safety valve operates in the event of an emergency. The piping and connectors use SUS 304 as their material. During the engine test, industrial methanol was used as a fuel, and the reaction rate and compositic of the reformed gas was measured by using gas chromatography.

Table 2 - Specifications of the methanol reformed gas engine

Type of engine	L20B (4-cycle, reciprocating)
No. of cylinders	4 cylinders (in-line)
Piston displacement	1,952 cc
Bore x stroke	85 x 86
Cpmpression ratio	8.5
Shape of combustion chamber	Wedge type
Reformative catalyst	Pt type 3.8 ℓ
Fuel	Industrial methanol, 100%

REFORMER

There are three methods of reforming methanol; (1) reformation of the methanol alone, (2) reformation by adding steam, and (3) reformation by burning part of the methanol. Although methods (2) and (3) permit easy reformation of methanol, they have their own disadvantages such as the complicated construction of the reformer, the small increase in fuel calorific value, etc. Therefore, here we will deal only with method (1). This method is an endothermic reaction and it increases the fuel calorific value by about 20 percent through reformation. In experiments, however, it is accomplished by some sub reactions (exothermic reactions), producing such byproducts as dimethyl ether (CH_3OCH_3), methane (CH_4), etc. Furthermore, if the reaction is insufficient, the resultant reformed gas will contain non-reacted methanol.

Main reaction (endothermic reaction)

$$CH_3OH \longrightarrow 2H_2 + CO$$

Sub reaction (exothermic reaction)

$$2CH_3OH \longrightarrow CH_3OCH_3 + H_2O$$
$$CH_3OH + H_2 \longrightarrow CH_4 + H_2O$$
$$CO + 3H_2 \longrightarrow CH_4 + H_2O$$

Although the degree of sub reactions is very small compared to the main reaction, these sub reactions affect the engine adversely by causing a reduced recovery of exhaust heat, and an increase in HC emission.

Reformative Catalyst

The performance of the reformative catalyst greatly influences engine performance. The important properties which the reformative catalyst must have are (1) low-temperature activity, (2) selectivity, and (3) durability. Comparative experiments were performed on Cu, Zn, Cr, Pt, Pd, and Rh, and a Pt catalyst was selected from the standpoint of durability. The carrier used alumina. Fig. 4 shows the reaction rate and the composition of the reformed gas. With the temperature of the catalytic bed over 310°C, the methanol almost completely reacted, and the composition of the gas produced showed a value close to the theoretical value.

Reformer

The reformer is required to be compact, lightweight, and extremely durable. herefore, close investigation must be conducted concerning (1) heat exchange performance, (2) corrosion resistance, and (3) heat resistance. In addition, easy assembly and simple replacement of the catalyst are important requirements for the reformer. We have developed the following reformer after careful considering all of these factors.

(1) The heat exchanger employs a plate-fin type construction using SUS 304.
(2) The reformer withstands a pressure test of 20 kg/cm^2G at room temperature.
(3) The reformer case is comprised of an insulated structure which reduces the loss of heat resulting from radiation.
(4) The rated flow of methanol is 10.8 kg/h.
(5) The amount of catalyst needed is about 3.8 liters, and the weight including the reformer case is about 50 kg.

ENGINE CHARACTERISTICS

Excess Air Ratio and Indicated Thermal Efficiency

An experiment was performed on the excess air ratio by using a cylinder gas made up of the theoretical reformed composition and utilizing a single-cylinder engine. The experimental results obtained are as follows:

(1) Combustion of a lean mixture resulted in an improvement in indicated thermal efficiency (see Fig. 5).
(2) The experimental value of the lean mixture combustion limit was an excess air ratio of 6.0 - 7.0. When it was over 4.0, however, the engine provided unstable performance.

Excess Air Ratio and Exhaust Emission

An experiment using a 4-cylinder engine was performed to determine what results the use of a lean mixture would have on exhaust emission. Fig. 6 gives the experiment's results.

The amount of CO and HC emission is very small compared to that of the base engine (gasoline), and the reformed gas is known to be a fuel which is easy to burn completely. In addition, NO_x shows a considerable decrease as the fuel becomes leaner.

When the cylinder gas was used, CO emission decreased to about half as much as that of the reformed gas, and the amount of HC emission was extremely small. This seems to have resulted from irresolvent material or byproducts such as CH_4 and CH_3OCH_3 contained in the reformed gas.

Compression Ratio and Indicated Thermal Efficiency

A high compression ratio was presumed to be applicable to the methanol reformed gas, for the reasons stated below.

(1) H_2, CO, and methanol have a high temperature of spontaneous ignition.
(2) Fast burning.
(3) Knocking is unlikely to occur, because a lean mixture is used. In addition, the engine's thermal efficiency is not significantly affected by ignition timing. This facilitates the prevention of knocking by retarding the ignition timing.

To verify this, a test was conducted on the compression ratio. Fig. 7 gives the test results. In this situation, the engine set at a compression ratio of 14.0 is capable of operating at a nearly stable level. With a compression ratio of 16.0, the engine begins to knock in MBT. Knocking can be prevented by retarding the ignition timing; however, this measure brings about a more narrow range setting for ignition timing. When the compression ratio was increased from 8.5 to 14.0, the indicated thermal efficiency showed an improvement from 36.5% to 42.5%. The recovered exhaust heat was not included here. Furthermore, the brake thermal efficiencies at these settings were 26.5% and 30.0%, respectively.

Compression Ratio and Exhaust Emission

Fig. 8 shows the relation between compression ratios and exhaust emission. As the compression ratio increases, CO and HC increase. NO_x is hardly affected by a change in the compression ratio.

A high compression ratio is not advantageous in terms of CO and HC. However, reducing CO and HC is possible by improving the reformer. Accordingly, a compression ratio of 14.0 is considered desirable for this engine.

Operating Experiment in Practical Driving Range

In this paragraph we describe our experiment regarding a system which recovers the exhaust heat from the engine. The engine's operating range was a 10-mode region (inertial weight: 1,250 kg), and the experiment was performed using a compression ratio of 8.5. Moreover, the excess air ratio was set as shown in Fig. 9, so that the engine satisfied the 1978 regulations in Japan and offered maximum thermal efficiency. In the slow acceleration range, the excess air ratio is approximately 1.7. The excess air ratio becomes smaller because the amount of stowed air is saturated under a heavy load. In order to prevent a drop in engine exhaust temperature at low speed under a light load, the excess air ratio is set at a low value. The ignition was timed 5 degrees behind MBT so as to reduce NO_x emission.

Fig. 10 shows the thermal efficiency. The recovery of exhaust heat, coupled with the effect of lean-mixture combustion resulted in very high brake thermal efficiency. When the brake torque with wide open throttle was 8.0 kg-m at an excess air ratio of 1.7, the brake thermal efficiency showed the maximum value, which was about 34% as compared to 24% for a gasoline fuel. Calculating from the reaction rate and the composition of the gas, this 10-% difference was possibly attributed to (1) 5% obtained by recovering exhaust heat and to (2) another 5% obtained through improved combustion and lean combustion. Further, the rate of improvement in efficiency is greater as the load is reduced when compared to that of the base engine.

In addition, the indicated thermal efficiency in a brake-torque range of 4.0 - 8.0 kg-m is approximately 44%. It seems possible to further increase the brake thermal efficiency by utilizing the effect of the compression ratio or by improving the crack per pass.

Fig. 11 shows the brake specific fuel consumption. The best fuel consumption can be obtained at an excess air ratio of 1.7 with a wide open throttle.

While the engine is running at high speed, the exhaust temperature rises high and improves the reformer's performance such as in the reaction rate.

Thus, in contrast to the base engine, the point of the optimum fuel consumption is at a somewhat higher speed. Furthermore, similar measurements were taken when cylinder gas was used as the fuel. These measured values were about 50g/psh smaller than those of the reformed gas over the whole range of operation.

Figs. 12 through 14 depict the exhaust emission. CO increases almost in direct proportion to an increase in the engine output. However, CO decreases in the range where the excess air ratio is small under a heavy load. Although the excess air ratio is small when the engine is running at low speed under a light load, the exhaust temperature drops, reducing the reformer's performance, so that CO will decrease only slightly. HC shows a tendency similar to that of

CO. One notable fact is that 60 - 80% more HC is detected in the exhaust port. This is considered to have resulted from the effect of the reformer's reactor. NO_x emission is very small where the brake torque is below 8.0 kg-m, which increases at an intensified rate as the excess air ratio becomes smaller under a heavy load. Moreover, 10-mode exhaust performance was calculated, by extrapolating from these exhaust properties. The results satisfactorily meet the 1978 emission control standards in Japan.

The optimum excess air ratio was about 2.1 when cylinder gas was used as the fuel. Compared to the reformed gas, CO and NO_x were almost at the same level, while HC emission was approximately one-fifth. Formaldehyde (HCHO) emission was roughly one-fourth of HC, which was a smaller value than that ejected from the methanol engine.

CONCLUSION

The advantages of methanol reformed gas and the related performance of the engine may be summarized as follows:

(A) The methanol reformed gas provides the following advantages as an automotive fuel.
  (1) Its calorific value as a fuel can be improved about 20% through reformation.
  (2) Facilitates complete combustion.
  (3) Combustion of a lean mixture is possible. (Excess air ratio for lean combustible limit: 7.6)
  (4) Greater anti-knock properties. (Limit compression ratio: about 14.0)

(B) From the advantages described above, it is evident that methanol reformed gas is an ideal fuel for the Otto cycle engine, and that by using it the engine will provide high thermal efficiency and excellent exhaust emissions.

(C) We have developed a reformer for a 4-cylinder engine, and have tested it in the practical operating range. The test results are as follows:
  (1) Brake thermal efficiency is improved compared to the base engine (gasoline).
  (2) Exhaust emissions are so excellent that they satisfy the 1978 emission control regulations in Japan without using an EGR or an exhaust catalyst.

(D) An especially notable characteristic is the high thermal efficiency of the engine. It can be improved even further by utilizing the effects of recovering exhaust heat, lean-mixture combustion, and a high compression ratio.

From the facts described above, we have concluded that reformation of methanol makes the most of its properties as an automotive fuel, and the methanol engine has the greatest potential from the standpoints of thermal efficiency and exhaust properties. Furthermore, this engine can be regarded as a hydrogen engine using methanol as a medium.

It retains the advantages of a hydrogen engine while it recovers exhaust heat and solves the problem of storing hydrogen.

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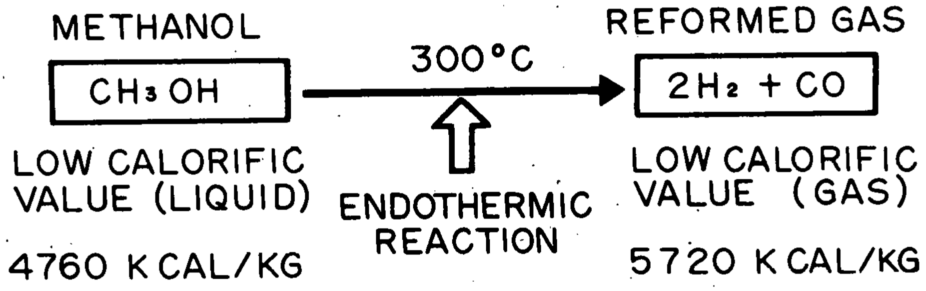
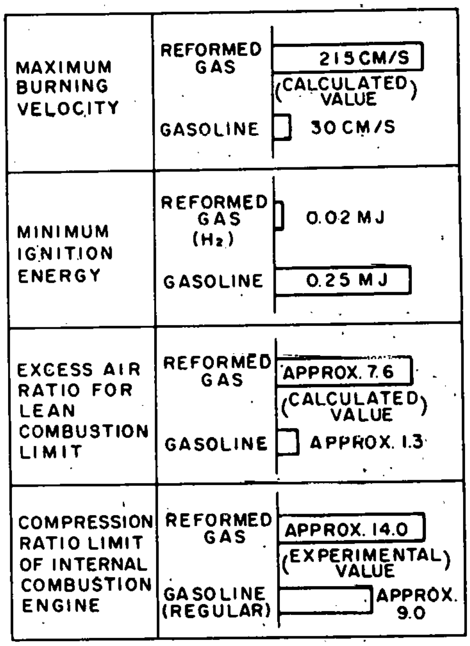


FIG.1 METHANOL REFORMING



MAXIMUM BURNING VELOCITY	REFORMED GAS	215 CM/S (CALCULATED VALUE)
	GASOLINE	30 CM/S
MINIMUM IGNITION ENERGY	REFORMED GAS (H_2)	0.02 MJ
	GASOLINE	0.25 MJ
EXCESS AIR RATIO FOR LEAN COMBUSTION LIMIT	REFORMED GAS	APPROX. 7.6 (CALCULATED VALUE)
	GASOLINE	APPROX. 1.3
COMPRESSION RATIO LIMIT OF INTERNAL COMBUSTION ENGINE	REFORMED GAS	APPROX. 14.0 (EXPERIMENTAL VALUE)
	GASOLINE (REGULAR)	APPROX. 9.0

FIG. 2 CHARACTERISTICS OF REFORMED GAS

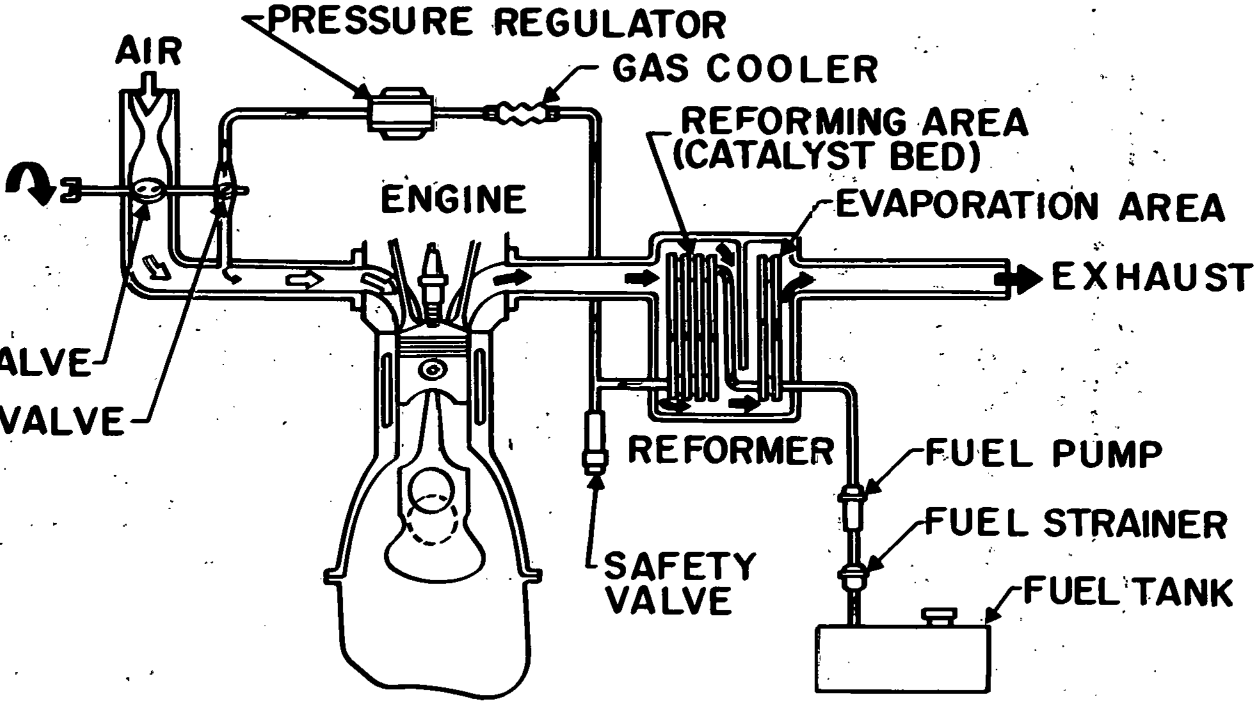


FIG. 3 METHANOL REFORMED GAS ENGINE

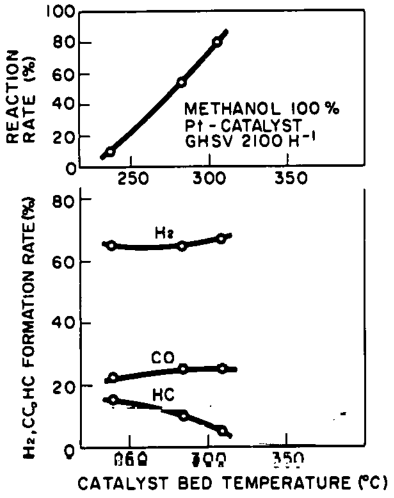


FIG.4 COMPOSITION OF REFORMED GAS

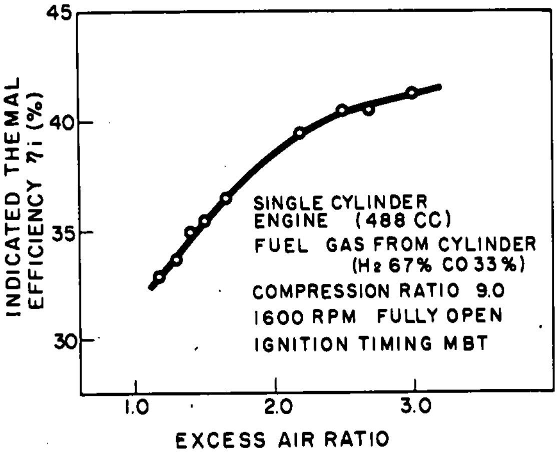


FIG. 5 INDICATED THERMAL EFFICIENCY VS. EXCESS AIR RATIO

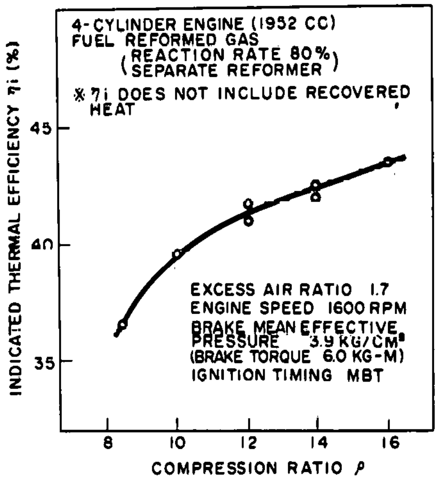


FIG.7 INDICATED THERMAL EFFICIENCY VS. COMPRESSION RATIO

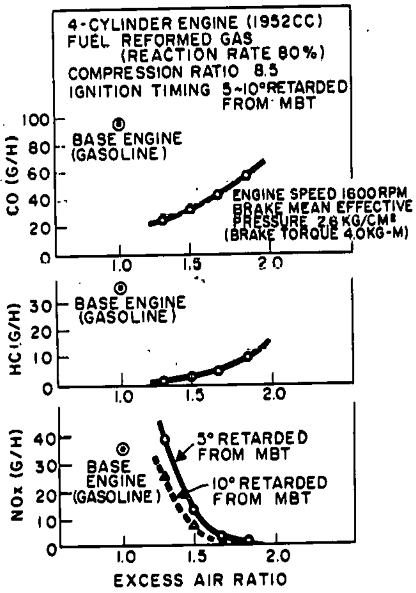


FIG.6 EXHAUST EMISSION VS. EXCESS AIR RATIO

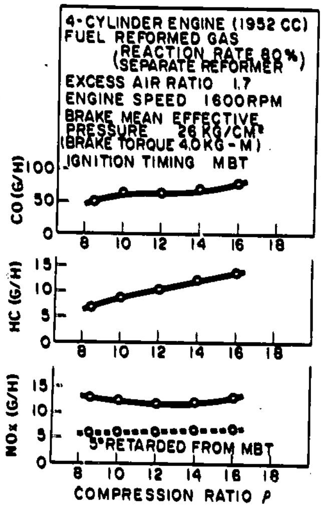


FIG.8 EXHAUST EMISSION VS. COMPRESSION RATIO

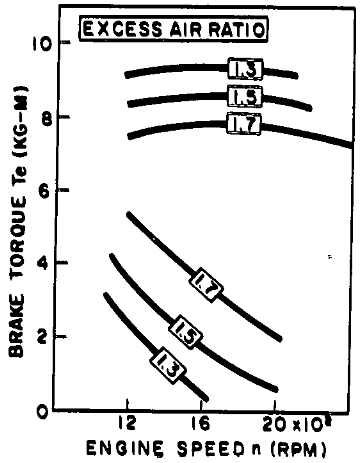


FIG.9 CHARACTERISTICS OF EXCESS AIR RATIO

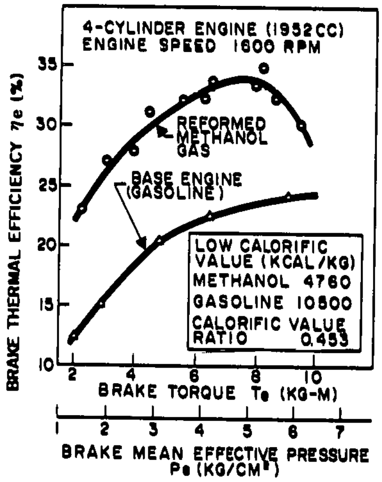


FIG.10 BRAKE THERMAL EFFICIENCY

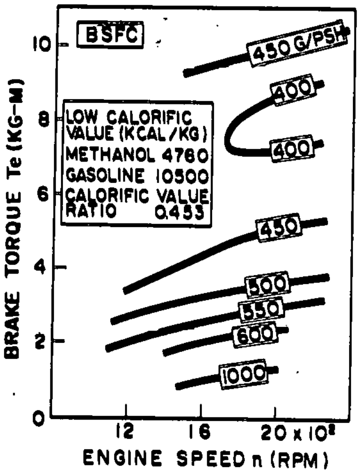


FIG.11 BRAKE SPECIFIC FUEL CONSUMPSION

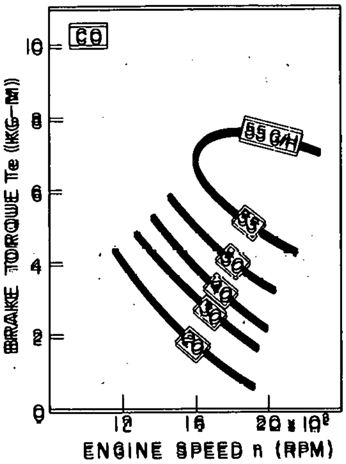


FIG.12 CO EMISSION

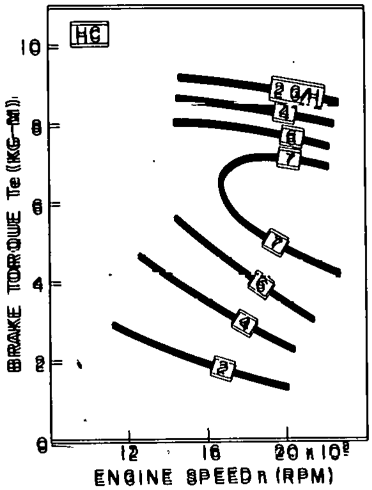


FIG.13 HC EMISSION

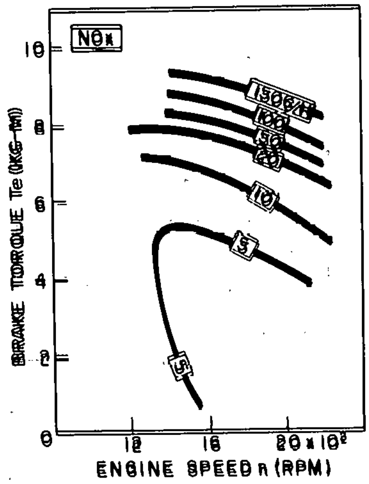


FIG.14 NOx EMISSION

Dup

DRIVING CYCLE COMPARISONS OF ENERGY ECONOMIES AND EMISSIONS FROM AN ALCOHOL AND GASOLINE FUELED VEHICLE

by

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ABSTRACT

A late-model vehicle was converted to operate using methanol, gasoline, or ethanol as fuel and experimental work was done to obtain energy economy and exhaust emissions data for each of the three fuels. Results are compared at equal equivalence ratios both with and without an oxidation catalyst in the exhaust system.

Using a catalyst for emissions control, unburned (hydro)carbon emissions were lowest during lean operating conditions and were nearly the same for all three fuels under those conditions. Oxides of nitrogen emissions typically were reduced by over 50% in changing from gasoline to methanol or ethanol.

Detailed composition of the exhaust hydrocarbons was determined from analysis via gas chromatography. These data were used for calculating photochemical reactivities and comparisons were made among the fuels during cold start and FTP weighted tests. Gasoline exhaust was often calculated to have the lowest total reactivity during the FTP, however, methanol exhaust reactivity was lowest for the stoichiometric condition with catalyst. Aldehydes accounted for large fractions of the reactivity calculated for methanol and ethanol exhausts. Cold start emissions were of about equal reactivity for gasoline and methanol.

INTRODUCTION

The technical feasibility of using alcohols to replace hydrocarbons as fuels for current internal combustion engines has been established. [1,2,3,4*]. Moreover, of the several options for using alcohols, the use of neat alcohol appears to be one of the most attractive.

The results of several studies suggest that the different gasoline compositions blended for satisfactory performance in conventional spark-ignition internal-combustion engines yield very similar exhaust gas species and compositional characteristics. However, the exhaust gas from vehicles fueled with neat alcohol is markedly different from that of the exhaust from hydrocarbon fuels and in order to determine possible adverse effects from neat alcohol exhaust gas, its composition must be studied.

The fuels used in the study were methanol, ethanol, and a gasoline. Exhausts for comparative study were produced using a 1976-model vehicle with a spark-ignition, four-stroke cycle engine. The vehicle was operated on a chassis dynamometer following the 1975 Federal test procedure (FTP). The experimental objectives were: first, to provide energy economy and emissions data for

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*Numbers in brackets designate References at end of paper.

the fuels at equal equivalence ratio; second, to assess the effect of the addition of isopentane and a high-vapor-pressure gasoline to methanol on the cold-start behavior of a vehicle; and third, to generate a data base from which to plan photochemical smog chamber experiments. Such information should help determine whether any adverse environmental effects may occur if methanol or ethanol is used as a fuel for passenger vehicles.

EQUIPMENT AND TEST PROCEDURE

The vehicle used was a 1976-model (4500 lb. inertia weight) with 8-cylinder engine and 3-speed automatic transmission. Engine displacement was 318-cu.-in. (5.2 liter) with a compression ratio of 8.5:1. The combustion chamber was of wedge-type construction in conjunction with flat-top pistons. These specifications are those of the engine as it came from the manufacturer with no modifications.

The fuel-induction system used with the engine was specially constructed to handle the high heat of vaporization of methanol, ethanol, or other alcohols and to provide operation at nearly constant equivalence ratio during a driving cycle test. The system was controlled electronically using various inputs such as engine speed, intake air flow, intake manifold vacuum, barometric pressure, engine coolant temperature, fuel temperature, and throttle position. Our aim was to have a constant equivalence ratio during a driving cycle regardless of the fuel used. (The system, however, was capable of being programmed to follow any equivalence ratio program.) Spark timing was also controlled by the electronic unit and the same program was used for all fuels tested.

A major feature of the fuel-induction system was the intake manifold which was an aftermarket item modified for this application. The manifold was designed especially to provide superior air/fuel (A/F) ratio distribution between the cylinders. Under steady-state operation (1500 RPM, 40 ft-lb torque) the A/F ratio sample standard deviation was measured to be 0.22 from a mean of 16.84. (This was measured when using gasoline as a fuel.) An aid to good distribution was the conical design of the throttle body which uncovered slits as the throttle was opened. This shape of the slits and conical section of the throttle provided some swirl to the air and fuel as they entered the intake manifold. Heavy water jacketing of the manifold provided enough heat to adequately vaporize methanol and provide A/F distribution similar to that obtained with gasoline. The fuel/air equivalence ratios (Φ) studied were lean ($\Phi = 0.8$), stochiometric ($\Phi = 1.0$), and rich ($\Phi = 1.2$).

An oxidation catalyst of monolithic-type construction was used on additional runs made at equivalence ratios of 0.8 and 1.0. Since there was no air pump, the catalyst had little effect at $\Phi = 1.0$ due to the small amount of free oxygen present at this condition. Exhaust gas recirculation (EGR) was made operative according to intake manifold vacuum; maximum EGR valve opening was obtained under conditions of high vacuum.

The fuels used were methanol, a gasoline, and denatured ethanol. The gasoline was a low octane, lead-free, summer-grade gasoline with hydrogen/carbon (H/C) ratio of 2.04 and a specific gravity of 0.718. The denaturants used in the ethanol were (by volume percent): 4.5% methanol, 0.9% ethyl acetate, and 4.5% methylisobutylketone. Emissions calculations from ethanol exhaust were made assuming neat ethanol fuel.

In addition to the driving cycle tests the cold-start behavior of another vehicle was studied using blends of methanol with isopentane and methanol with a high-vapor pressure gasoline. The cold start vehicle had a 350 CID (5.7 liter) engine with 13:1 compression ratio and standard carburetion modified to meter methanol. The equivalence ratio during fully warmed, steady-state operation with methanol was 0.9.

Cold-start tests were made by soaking the vehicle in a room for 8 hours before attempting to start it. If the start was successful, the engine was run for a short period of time and then stopped and allowed to soak at a temperature 10°F lower than before. This procedure was repeated until a temperature was reached where starting would no longer occur. Testing was then resumed at temperatures staggered from the previous group to allow "zeroing-in" on the temperature where starting would not occur.

FTP DRIVING CYCLE RESULTS

The emissions from the driving cycle were weighted by phase accoring to the 1975 FTP.

Exhaust hydrocarbons were measured in accordance with the FTP-CVS procedures using a flame ionization detector (FID). The FID measured the amount of ionizable carbon present in the exhaust sample and was calibrated by referencing its response to a known concentration of propane. However, in the FTP calculations it is assumed that all of the ionizable carbon comes from unburned fuel molecules with a predetermined hydrogen to carbon ratio.

On that basis, using the H/C ratio of the fuel, the response of the FID was used to calculate the mass amount of unburned fuel present in the exhaust gas.

The FTP prescribed method of calculation presents some problems when comparing exhaust hydrocarbon mass emissions from substantially different fuels. The gasoline used in this study had a H/C ratio of 2.04 which resulted in the calculated exhaust hydrocarbons consisting of 85% carbon and 15% hydrogen (mass basis). Methanol, however, is only 37.5% carbon-the rest being hydrogen and oxygen - while ethanol is 52% carbon. To eliminate this arbitrary mass calculation difference, only the FID measured mass of ionizable carbon in the exhaust from each fuel will be reported in this section.

It should be noted that the photochemical reactivity effects of an exhaust hydrocarbon mixture are more closely associated with the mass of carbon present in specific chemical classes rather than the total mass present. Thus it is a reasonable simplification to compare only the mass of FID exhaust carbon among these fuels.

An additional problem with the exhuast hydrocarbon measurements results directly from using the standard propane calibration technique. The FID does not respond equally to a carbon atom in an alcohol and to a carbon atom in the alkane class of hydrocarbons.

The response of the FID (Beckman Model 402) to methanol has been determined to be only 73% as great as the FID response to propane on a parts per million carbon (PPMC) basis [5]. Similarly, the response of the FID to ethanol was found to be 83% of its PPMC response to propane. Thus, the FID response could be corrected for the amount of alcohol in the exhaust only if the exhaust hydrocarbon to alcohol ratio were reliably known. This adjustment procedure appears trustworthy in the present case of methanol exhaust where over 99% of the non-aldehyde mass of total hydrocarbon emissions are methanol (see Table 1). However, the denatured ethanol exhaust gas was found (by gas chromatography) to contain variable amounts of light hydrocarbons as well as unburned ethanol (see Table 1).

Ethanol mass emissions ranged from 77% to 88% of the non-aldehyde total hydrocarbon FTP emissions. Therefore, no single correction factor could be relied upon throughout the ethanol tests.

Through GLC analysis of each phase of the cycle, the ratio of hydrocarbons to ethanol were determined. The FID response of each phase of the driving cycle was corrected according to the percentage of hydrocarbons and ethanol - the hydrocarbons assumed to have 100% response from the FID. Accurate determination of ethanol exhaust gas carbon content depends on analysis of the hydrocarbon species present and FID response to ethanol.

Unburned carbon results (Fig. 1) showed the lowest mass output (without a catalyst) at stoichiometric operating conditions. At stoichiometric and fuel lean conditions, methanol resulted in increased carbon relative to gasoline which in turn was higher than the amount from ethanol. No explanation is readily available for these results. The gasoline gave higher unburned carbon results than methanol at the fuel rich condition but carbon monoxide (CO) measurements (shown in Fig. 2) suggest a slightly richer setting occurred when using the gasoline.

Use of the oxidation catalyst caused large reductions in unburned carbon at the fuel lean condition (Fig.1). The differences between the fuels appear insignificant and suggest no apparent difficulty for the oxidation catalyst when using alcohol fuels. Some reduction in unburned carbon was observed at the stoichiometric condition limited by the fact that no additional oxygen was provided to the exhaust gas.

The unburned carbon results from the "best" condition (fuel-lean with catalyst) are higher than were permitted for 1976-model vehicles sold in the United States. This is the consequence of a fuel induction/emission system tailored to provide a direct comparison between different fuels rather than optimum emission control. This will apply to the CO and oxides of nitrogen (NO_x) emissions as well. The focus of this study was on evaluating these fuels under conditions of equal stoichiometry and fuel preparation. The reported tests should be inferior in terms of emissions and efficiency to a system optimized for a given fuel.

Carbon monoxide emissions are mainly a function of equivalence ratio (Fig.2). Little difference in CO output between the fuels is seen at the fuel-lean condition. High CO from the fuel-rich condition is expected and is much higher than the other conditions.

The test conditions using the oxidation catalyst show reduced CO output at the fuel-lean condition. The CO emissions at stoichiometric with oxidation catalyst are about the same as without catalyst due to the lack of excess oxygen available at this condition.

Measurements of NO_x(Fig. 3) show the alcohols to have a distinct advantage over the gasoline at the fuel-lean and stoichiometric conditions. This difference is inherent to the alcohols due to reduced peak flame temperatures and less favorable concentration of the species necessary for NO_xformation [6] in the reaction zone. The NO_x output with the gasoline at the fuel-rich condition is lower than that of methanol but with the penalty of very high CO emissions. This is in accordance with the idea postulated that at the fuel-rich condition, the gasoline tests were run at an equivalence ratio slightly higher than was used for methanol. Addition of the oxidation catalyst had little effect on NO_xoutput.

Exhaust aldehyde measurements were made during all the cycle tests by the methyl benzothiazolinone hydrazone method. Total aldehydes, in gm/mi, over the driving cycle were calculated using the same procedure as for the other exhaust emissions measured. (All the aldehydes measured were assumed to be formaldehyde.) The results show that approximately twice the amount of aldehydes were generated from the alcohols as compared to the gasoline (Fig. 4). The trend of increasing aldehydes from rich to lean equivalence ratios is in agreement with most published work. [4,7] The addition of an oxidation catalyst greatly reduces the total mass of aldehydes emitted. A larger relative reduction of aldehydes occurred at the fuel-lean condition than at the stoichiometric conditions. This is probably due to the oxygen available at the fuel-lean condition enabling the catalyst to function. With an oxidation catalyst, the concentration of aldehydes in the exhaust was greatly reduced during the stabilized and hot transient phases. Without oxidation catalyst, the concentrations of aldehydes were nearly the same during all phases of the driving cycle.

Comparison of energy economies (Fig. 5) shows fuel-lean and stoichiometric conditions to have an advantage over fuel-rich operation. Methanol seems to have a good tolerance for operation at varying equivalence ratios; its energy economy changed little between the conditions tested. A large drop in energy economy occurred at the fuel-rich condition for gasoline. Operation with methanol at the fuel-lean condition resulted in the best energy economy obtained.

Cold-start tests using methanol/hydrocarbon blends were conducted to show the effect of the addition of high Reid vapor pressure (RVP) hydrocarbons to methanol. Neat methanol alone allowed cold starting down to around 55°F. The addition of 10% (volume) isopentane (Fig. 6) allowed cold starts to be made down to the range of 25° and 30°F. Starts were increasingly difficult between 30° and 25° F, and starts below 25° F were not possible with this system. Cold-start tests were also conducted using a blend of methanol and a high RVP gasoline (Fig. 7). The gasoline was a 50/50 mix of two commercial w er-grade brands obtained locally. The RVP of this mix was measured as 12.4 psi. It was thought that possibly a gasoline used as a blending component with methanol would yield better results than a single component hydrocarbon. No such advantage was noted since the results using these two blends were virtually identical.

COMPOSITION AND REACTIVITY ANALYSES

A gas chromatograph featuring liquid nitrogen sub-ambient temperature control and a capillary column was used to obtain detailed analyses of dilute exhaust samples [8]. Total aliphatic aldehydes were measured during each phase using the MBTH wet chemistry technique [9]. Formaldehyde measurements were also made using the chromotropic acid wet chemistry technique [10]. Methanol and ethanol analyses were made on a second gas chromatograph using a packed column technique [5].

The mass emission rates of seven separate classes of exhaust hydrocarbons are presented in Table 1. Methanol, ethanol, and total aldehydes which are all oxygenated hydrocarbons are herein included among the "total hydrocarbon" emission rates presented. The seven classes were chosen for their qualities as photochemically reactive precursors of urban oxidant. Methane and ethane are of negligible reactivity in class I. the C_{3+} alkanes are of low-to-moderate reactivity in class II. Total alkene emissions are of moderate-to-high reactivity in class III. Total aromatics range from low to high reactivity in class IV. The alcohol class V includes the low reactivity methanol and ethanol. Class VI alkynes are generally of low reactivity. Total aliphatic aldehydes, which are calculated as formaldehyde, have a unique quality and are considered to be of high reactivity in class VII. Aldehydes can be photolysed by ultraviolet light and, therefore, aldehydes may enhance the photochemical reactivity of other hydrocarbons in a non-linear way.

Composition and Reactivity of Exhaust Not Subjected to Catalyst Treatment

The FTP weighted non-catalyst gasoline tests show a variety of characteristic patterns. Methane, ethane, and alkyne emissions are directly but nonlinearly proportional to the fuel-air equivalence ratio. The remaining classes produce U-shaped curves in which mass emissions are lowest during stoichiometric conditions and higher at both rich and lean operating conditions. It is important to note that these classes with U-shaped curves are the hydrocarbon classes which also have the highest photochemical reactivities [11,12,13,14]. Calculated total mole weighted reactivities, normalized to the reactivity of ethylene, are presented in Fig. 8.

$$\text{total reactivity} = \Sigma n_i R_i$$

Also included are total reactivity per gram and total reactivity per mole of carbon comparisons for each of the 13 test configurations.

$$\text{total reactivity per gram} = \frac{\Sigma n_i R_i}{\Sigma m_i}$$

$$\text{total reactivity per mole carbon} = \frac{\Sigma n_i R_i}{\Sigma n_i C_i}$$

Where: n_i= FTP weighted moles of the i^{th} species.
R^i= photochemical reactivity normalized to ethylene.
m_i= mass of the i^{th} species.
C_i= carbon atoms per molecule of i^{th} species.

The non-catalyst gasoline case in Fig. 8 indicates that the total exhaust hydrocarbon reactivities follow the same U-shaped pattern as determined by the mass emission rates of their reactive constituents shown in Table 1. The alkene and aldehyde class emissions from gasoline fuel produced the largest contributions to total reactivity. Alkenes accounted for 44% and 60% and aldehydes for about 43% and 30% at lean and stoichiometric conditions, respectively.

Non-catalyst methanol exhaust hydrocarbon mass emissions were over 95% unburned fuel in composition. Aldehyde mass emissions, calculated as formaldehyde, were less than 4.4% of the total and the remaining small mass was the sum of alkanes, alkenes, alkynes, and aromatics. Total mass emission rates in Table 1 increase directly with fuel-air equivalence ratio. Fig 8 indicates a slight U-shaped total reactivity trend for methanol. This pattern is a result of the inverse relationship between the mass emissions of highly reactive aldehydes and the fuel-air equivalence ratio. Methanol accounts for less than 22% of the lean, non-catalyst total reactivity. The small mass of formaldehyde produces the remaining 78% of the total reactivity. However, at stoichiometric and rich conditions the decreased mass emission rates of formaldehyde produce progressively smaller contributions to the total reactivity--53% and 35% respectively.

Non-catalyst ethanol exhaust hydrocarbon mass emissions were generally over 63% unburned fuel, but with as much as 17% aldehyde by weight. Methane and ethane were nearly 12% and the remaining sum of alkanes, alkenes, alkynes, and aromatics totalled about 5%. Total weighted ethanol exhaust reactivity was dominated by the mass emissions of aldehydes which produced over 75% of the calculated reactivity.

Composition and Reactivity: Catalyst-Equipped Vehicle

When the test vehicle was equipped with an oxidation catalyst, but no air pump, the mass of hydrocarbon emissions from FTP testing was generally decreased compared to FTP testing without oxidation catalyst. The total mole weighted reactivity also decreased for all three fuels when using an oxidation catalyst. Among the seven hydrocarbon classes the composition was also shifted towards lower reactivity hydrocarbons. For example, gasoline exhaust alkanes and alkynes appeared to significantly increase their relative mass fractions from 55% and 54% to 68% and 59% for lean and stoichiometric conditions, respectively. Concurrently, the highly reactive alkenes and aldehydes were decreased in mass fraction from 35% and 36% to 22% and 29% for the lean and stoichiometric cases, respectively. The changes in exhaust composition among reactive and unreactive hydrocarbon classes is conveniently expressed on the basis of total reactivity per gram or total reactivity per mole of carbon atoms. These mass and mole-carbon specific reactivities are included in Fig. 8 for comparison among the 13 test configurations.

The lowest FTP weighted hydrocarbon mass emissions were observed in this catalyst-equipped test series for the gasoline fueled, lean configuration. Lean methanol and lean ethanol tests produced the next lowest mass emissions.

The lowest total reactivity was also calculated for the lean gasoline condition. Stoichiometric and lean methanol tests were next lowest in total mole-weighted reactivity. The very low total reactivity of gasoline exhaust was primarily th result of low mass emissions since the mass-specific reactivity was comparable with methanol exhaust.

The lowest mass-specific reactivity was calculated for the stoichiometric methanol with catalyst condition. This resulted from the very low reactivity of unburned methanol emissions, the moderate-to-low formaldehyde emissions, and the high molecular weight of methanol which carries 130% more mass per carbon atom in comparison with gasoline exhaust hydrocarbons.

The lowest carbon-mole specific reactivity was calculated for the stoichiometric methanol with catalyst condition. This low specific reactivity is expected to be an important factor in ongoing smog chamber experiments in which total ppm carbon to NO_X ratios will be controlled.

COLD START COMPOSITION AND REACTIVITY

An experimental cold-start test was added during the first 163 seconds of the cold transient phase of the FTP. A separate bag sample of dilute exhaust was analyzed for its detailed hydrocarbon composition. Total aldehydes and formaldehyde measurements were also taken during the cold start. This extra test phase was included in order to assess the aldehyde emissions during routine or difficult starting conditions. The total mass emissions per cold start test are presented in Table 1. The vehicle travels about 2/3 of a mile during the first 163 seconds; results are reported in grams per cold-start test rather than grams per mile.

The experimental carburetion system enriched the mixture during cold starts and has therefore increased the average cold start equivalence ratio above what is nominally reported. Total hydrocarbon mass emissions appear to reflect this shifted baseline towards richer operation. During non-catalyst gasoline operation the cold start hydrocarbon mass emission rates were higher than during FTP averaged driving conditions.

Cold start aldehyde mass emissions were generally highest during non-catalyst operation; however, the lean methanol tests yielded 0.8 gram of aldehyde per catalyst equipped cold start while the non-catalyst cold start yielded only 0.6 gram. This observation needs further verification since each case is the average of only two tests.

Cold start total reactivity comparisons are reported in Fig. 9 the cold start total reactivity of methanol is very similar to that calculated for gasoline at all lean and stoichiometric conditions. Ethanol cold start emissions were slightly higher in calculated reactivity.

Large quantities of unburned methanol fuel accounted for the majority of the cold-start exhaust hydrocarbon reactivity except in the lean, with-catalyst case. Alkene emissions produced the majority of gasoline cold-start exhaust reactivity. Aldehyde emissions produced the majority of the ethanol cold-start reactivity.

Composition and Reactivity Discussion

y vehicle which just meets the 1981 FTP light-duty vehicle emission standards 0.41 gram per mile hydrocarbons and 1.0 grams per mile NO_X will generally not produce a photochemically reactive exhaust mixture. This is due to the low hydrocarbon-to-NO_X ratio which this standard represents. Dividing by the molecular weights specified for hydrocarbons and NO_X, one obtains 0.0296 moles of carbon as hydrocarbons and 0.0217 moles of NO_X. This results in a ratio of ppmC-to-NO_X equal to 1.36/1. This low ratio of hydrocarbons-to-NO_X is not able to fully convert the primary emissions of nitric oxide into nitrogen dioxide. Thus, no substantial buildup of ozone can result from such mixtures without help from additional sources of reactive hydrocarbons. The present experimental carburetion system and exhaust treatment technique has resulted in excessive hydrocarbon emissions. None of the test configurations could meet the Federal emission standards for hydrocarbons. Therefore, all the present FTP weighted emissions range from moderate-to-very-high in photochemical reactivity. All of the cold-start emissions are of very high reactivity due to their very high mass emission rates and high ratios of hydrocarbons-to-NO_X.

The increased mass emission rates of aldehydes could eventually merit their own emission control standards; however, in the present tests the total reactivity contribution of the highly reactive aldehydes was often surpassed by the sheer mass emissions effects of lower reactivity species.

It is clear from the present experiments that the use of alcohol fuels may produce reactive exhaust emissions which are better than, equal to, or worse than gasoline emissions depending upon the hardware details and set-up of a particular vehicle carburetion/exhaust system. Further tests and system optimization efforts are underway to improve both energy economy and reactive hydrocarbon emissions.

Photochemical smog chamber tests are also being conducted to directly compare the reactivities of typical FTP weighted hydrocarbon emissions from gasoline- and alcohol-fueled tests. The linear summation of mole weighted reactivities may not adequately represent the special photolysis qualities of aldehydes as reactive hydrocarbons.

CONCLUSIONS

- Methanol provides energy economy equal to or superior to gasoline at a wide range of equivalence ratios.
- Both methanol and ethanol NO_X emissions are less than half those of gasoline.
- The minimum temperature for cold-starting of methanol is reduced to approximately 30°F (-1°C) through the addition of 10% hydrocarbon fuel.
- The photochemical reactivity of hydrocarbon emissions during lean operation were lowest for gasoline, however, during stoichiometric tests methanol exhaust hydrocarbons were lowest in total reactivity.
- Aldehydes accounted for large fractions of the reactivities calculated for methanol and ethanol, particularly during lean operation.
- Cold start hydrocarbon emission reactivities were comparable between methanol and gasoline exhausts.

ACKNOWLEDGEMENT

Appreciation is expressed to Mr. Lou Browning for his valued assistance in preparing the data reduction program.

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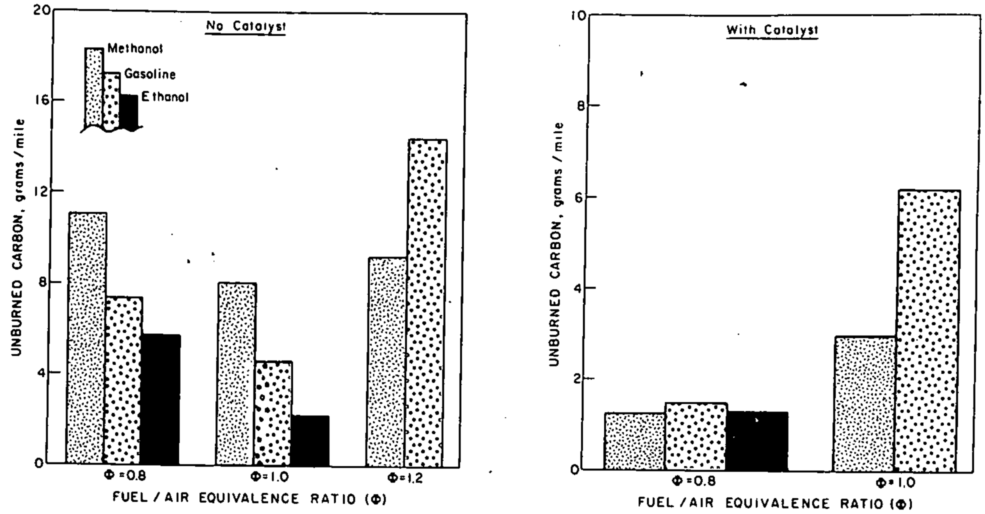

Fig. 1. - Unburned Carbon as a Function of Fuel and Equivalence Ratio

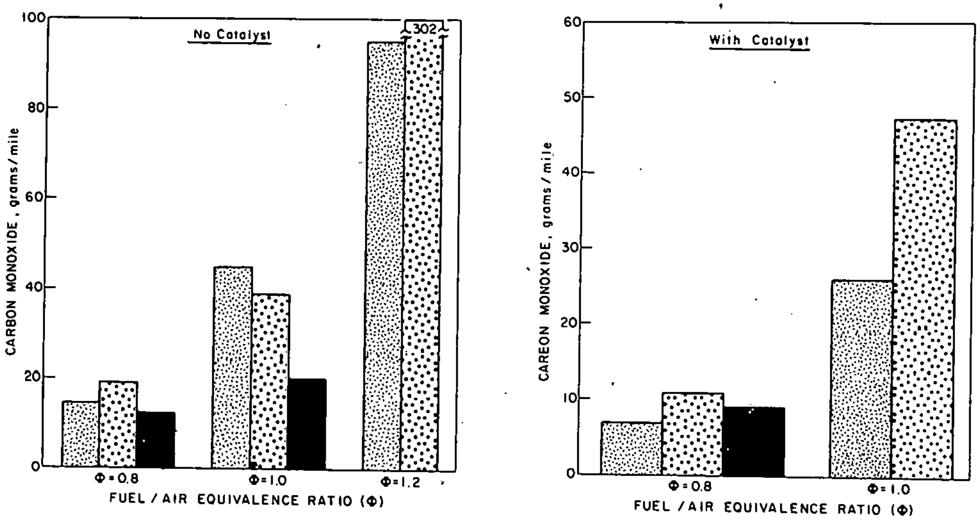

Fig. 2. - Carbon Monoxide FTP Driving Cycle Results

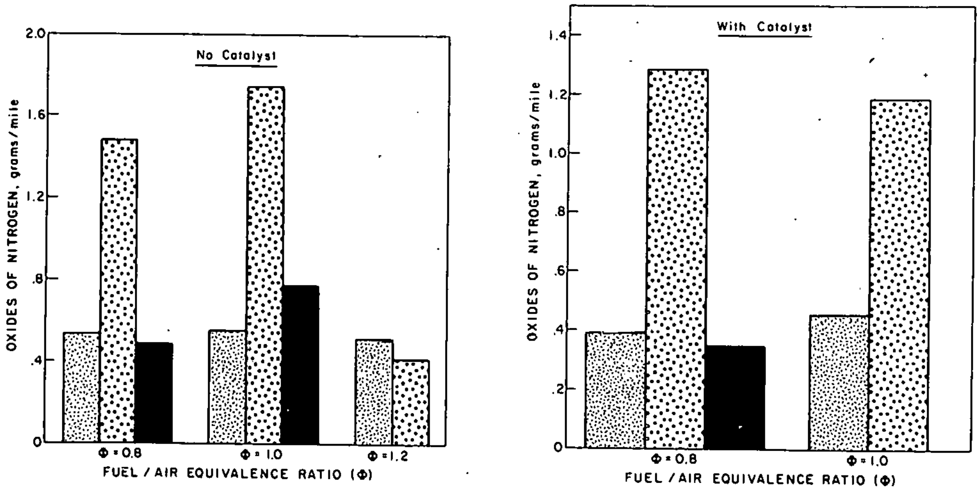

Fig. 3. - Oxides of Nitrogen According to Fuel and Equivalence Ratio

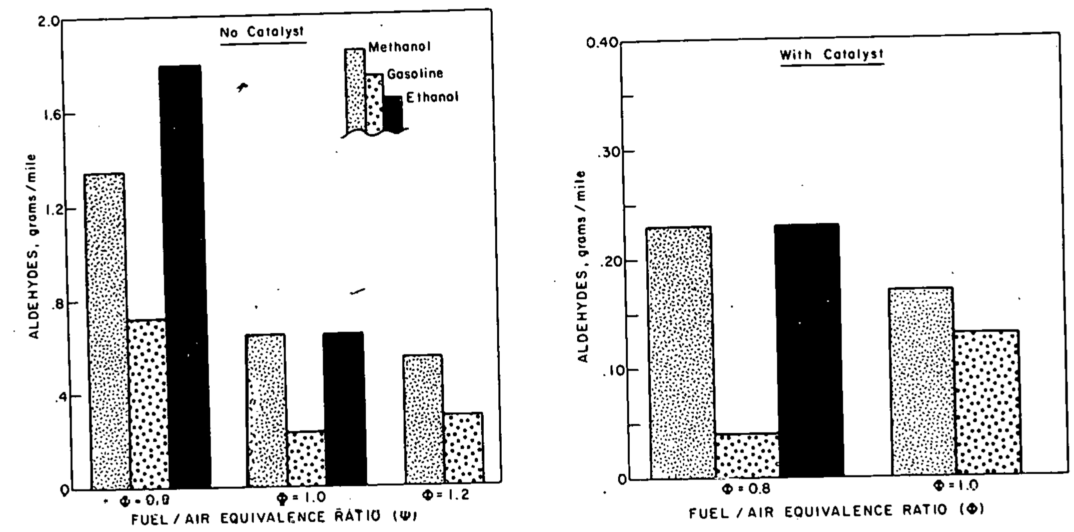

Fig. 4. - FTP Driving Cycle Aldehyde Emissions

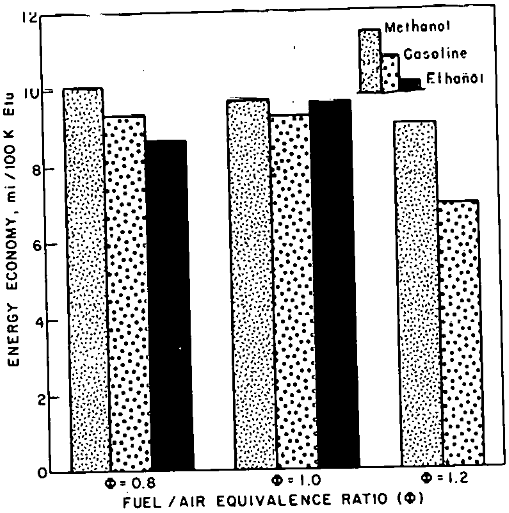

Fig. 5. - Energy Economy--with and without Catalyst

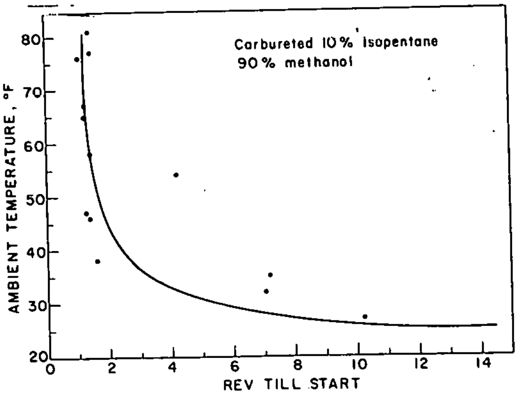

Fig. 6 - Cold-Start Results from the 10% Isopentane/90% Methanol Blend Using Carburetion Modified for Methanol

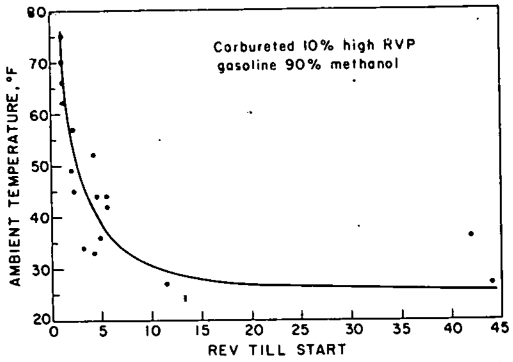

Fig. 7. - Cold-Start Results from the 10% Gasoline/90% Methanol Blend Using Carburetion Modified for Methanol

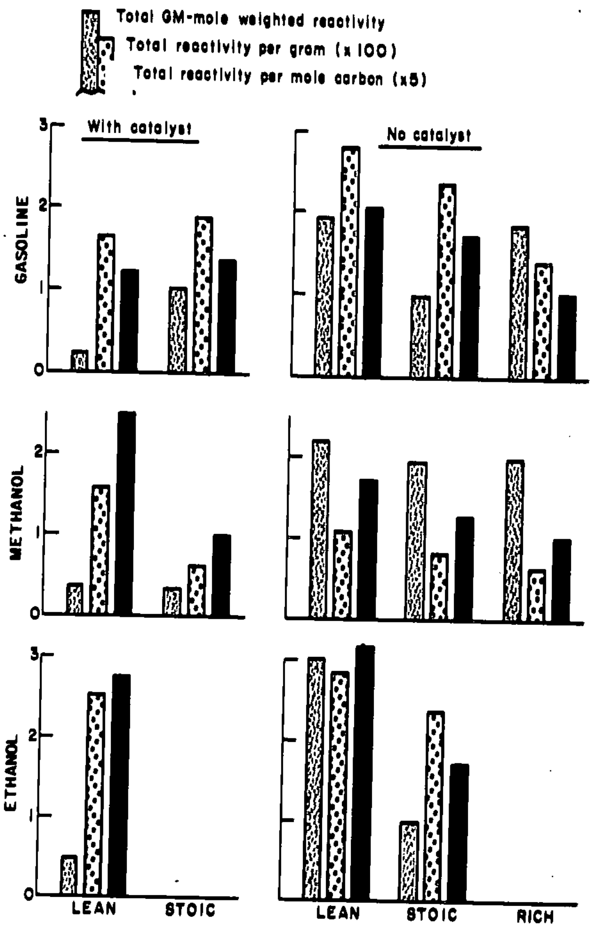

Fig. 8 Calculated FTP Reactivities

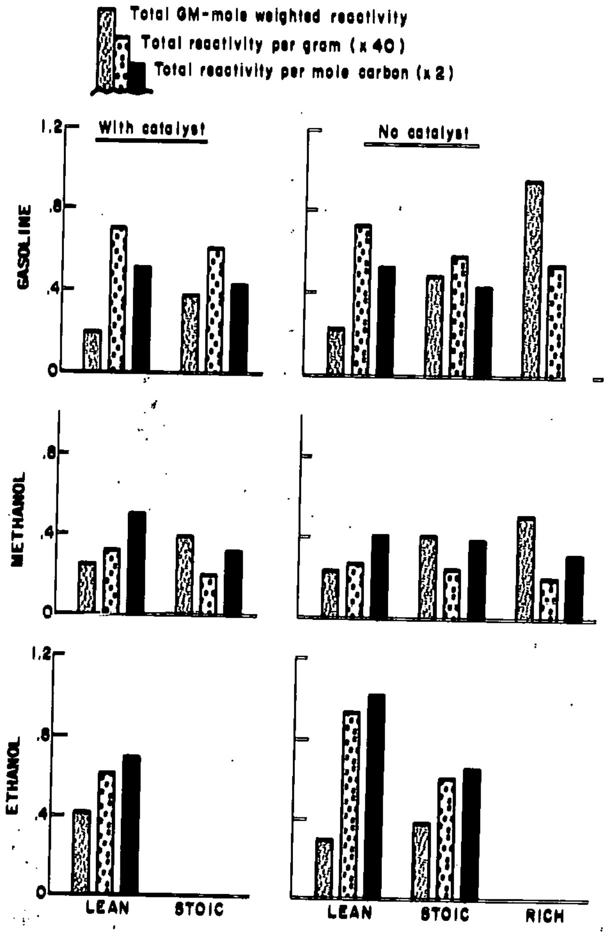

Fig. 9 Calculated Cold-Start Reactivities

TABLE 1. - FTP Weighted and Cold-Start Composition Comparison

Fuel	Catalyst	φ	Methane Ethane	Alkanes	Alkenes	Aromatics	Alcohol	Alkynes	Aldehyde	Total
					FTP, grams/mile					
Gasoline	Yes	0.8	0.31	0.75	0.36	0.15	0.030	0.11	0.036	1.73
Methanol	Yes	0.8	0.034	0.001	0.001	0.0003	2.8	0.0001	0.23	3.04
Ethanol	Yes	0.8	0.29	0.002	0.083	0.0008	1.8	0.039	0.28	2.52
Gasoline	Yes	1.0	0.81	2.5	1.7	0.65	0.097	0.38	0.093	6.17
Methanol	Yes	1.0	0.087	0.005	0.003	0.002	6.9	0.003	0.12	7.07
Gasoline	No	0.8	0.43	4.3	2.6	0.84	0.18	0.37	0.68	9.31
Methanol	No	0.8	0.037	0.003	0.003	0.002	26.	0.012	1.2	27.1
Ethanol	No	0.8	0.35	0.005	0.87	0.007	11.	0.10	1.7	14.2
Gasoline	No	1.0	0.66	1.8	1.8	0.61	0.061	0.68	0.25	5.76
Methanol	No	1.0	0.12	0.005	0.014	0.002	33.	0.004	0.83	34.0
Ethanol	No	1.0	0.27	0.012	0.43	0.009	2.6	0.12	0.61	4.0
Gasoline	No	1.2	3.5	4.7	3.8	1.6	0.17	3.8	0.29	17.8
Methanol	No	1.2	0.20	0.004	0.020	0.002	46.	0.032	0.56	46.7
					COLD-START, grams/test					
Gasoline	Yes	0.8	1.6	4.9	2.6	0.86	0.19	0.87	0.12	11.1
Methanol	Yes	0.8	0.13	0.005	0.010	0.0006	30.	0.010	0.79	31.2
Ethanol	Yes	0.8	1.1	0.011	0.94	0.036	23.	0.43	1.1	26.5
Gasoline	Yes	1.0	4.8	9.1	5.5	2.0	0.37	3.7	0.094	25.6
Methanol	Yes	1.0	0.24	0.035	0.030	0.011	76.	0.066	0.64	77.1
Gasoline	No	0.8	1.4	5.3	2.7	1.2	0.23	1.4	0.23	12.5
Methanol	No	0.8	0.15	0.004	0.011	0.006	35.	0.021	0.58	35.9
Ethanol	No	0.8	0.61	0.006	0.62	0.009	10.	0.31	1.1	12.6
Gasoline	No	1.0	4.8	13.	5.6	2.7	0.56	5.7	0.44	33.2
Methanol	No	1.0	0.19	0.012	0.024	0.005	69.	0.025	0.93	70.2
Ethanol	No	1.0	1.4	0.12	0.99	0.043	21.	0.81	1.1	25.0
Gasoline	No	1.2	12.	25.	11.	7.2	1.1	15.	0.67	71.5
Methanol	No	1.2	0.29	0.009	0.021	0.006	106.	0.052	0.73	106.

CONGRESSIONAL CONCERNS ABOUT ALCOHOL FUELS - A TECHNICAL ADVISOR'S PERSPECTIVE

by

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INTRODUCTION

During the calendar year 1978, as a Congressional Fellow sponsored by the Institute of Electrical and Electronic Engineers, I served as a technical advisor to Senator Dale Bumpers of Arkansas. He is a member of the Senate Committee on Energy and Natural Resources and the Committee on Appropriations. He is one of the many members of the U.S. Congress who consider our dependence on imported petroleum to be at an unacceptable level and strongly feels that our gasoline consumption must be decreased to avoid increasing imports. As a matter of fact, Senator Bumpers is so concerned about deteriorating trade imbalance that he has been willing to sponsor and advocate legislation to ration gasoline - a measure perceived by the Congress to be very unpopular with the public. Naturally, any source of domestic alternate fuel, particularly from a renewable resource, is of great interest to him. I had the opportunity to analyze and evaluate the testimonies of numerous witnesses before the various Congressional Committees and study a number of technical papers(1)** written on the subject. This paper is intended to present my perspective of the issues and concerns facing those members of the U.S. Congress who are enthusiastic about alcohol fuels, yet are unable to initiate or support any major legislation to commercialize the application of alcohol as a motor fuel.

CONGRESSIONAL TESTIMONIES

The number of Congressional Committees that hold hearings on alcohol fuels attest to the widespread interest among Congressional members and their constituents on this subject. Most legislators need no convincing that our petroleum imports cannot be permitted to continue to increase. There is no question that it is politically profitable for legislators to support alternate domestic fuel. Yet, a number of witnesses have tended to dwell heavily on the need to curtail imports and on the attractiveness(2) of alcohol fuels that can be produced from agriculture products and residues. There might be some advantage, from the point of view of drawing public attention, in repeated enunciation of the merits of alcohol fuels; but it does little to address the real concerns of those legislators who are

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* The opinions expressed herein are solely those of the author and do not necessarily represent the positions of The MITRE Corporation, Senator Dale Bumpers or the IEEE.

** Numbers in brackets(1) designate References at end of paper.

trying to formulate practically feasible and economically sensible legislation to promote the widespread use of alcohol fuels. Some proponents have implied that sinister forces are undermining the acceptance of alcohol fuels and spreading erroneous technical information. The proponents of alcohol fuels, I believe, will be doing their cause a great disservice by quickly dismissing legitimate concerns. Certainly, there are groups with vested interests who may view alcohol fuels as an economic threat. But the sincere concerns of those who are interested in the promotion of alcohol fuels should not be and cannot be dismissed so casually.

The major issues associated with the commercialization of alcohol fuels can be grouped, for convenience, into four categories:

(a) Application Problems

(b) Supply and Resource Availability

(c) Energy Balance

(d) Cost and Economics

These issues, the available data (and the associated confusion) and their importance are discussed below.

APPLICATION PROBLEMS

Much of the discussion in testimonies has centered around application problems(3) such as carburization, vapor lock, engine starting, separation etc. However, these problems do not seem to be insurmountable and the technology to solve or alleviate them appears to be within reach(4). Many constituents and even legislators have demonstrated(2) many times vehicles that run on straight or blended alcohol fuels. These demonstrations seem to be popular, probably, because they are easy and not very expensive. They do focus media attention but do little, in my opinion, to promote substantive legislation. Some alcohol fuel enthusiasts have used such demonstrations to claim that alcohol has higher octane number and therefore results in better performance and even fuel economy. One entrepreneur implied that his automobile running on straight methanol (with half the BTUs per gallon compared to gasoline) yielded the same number of miles per gallon as with gasoline. Most engineers, I am sure, will agree that such an improvement in efficiency is improbable and certainly cannot be attributed to the higher octane. At this point, even the claim(5) that ethanol blends can yield the same fuel economy seem largely unsubstantiated.

Another major advantage claimed for straight alcohol is the lower emissions of particulates, carbon monoxide and nitrous oxides. Methanol vapors have less atmospheric reactivity (therefore, create less "smog"). However, there seems to be a reluctance to recognize that alcohol fuels produce higher aldehyde emissions that may cause greater physical discomfort and that methanol vapor is toxic. It may be true that these problems are not severe enough to prevent commercialization of alcohol as a motor fuel but sooner these problems are recognized and resolved, the easier the acceptance will be.

SUPPLY AND RESOURCE AVAILABILITY

The major new sources for alcohol production can be loosely classified into two groups, namely, methanol from fossil fuel (coal) and mostly ethanol from renewable sources (biomass). The production of methanol from coal does not appear to be constrained by the availability of coal but rather by the cost and the environmental acceptability of the technology. In the prevailing enthusiasm for the production of ethanol from biomass, methanol production from coal has received less attention. The possibility that the commercialization of methanol from coal might pave the way for public acceptance of alcohol fuel and therefore accelerate ethanol production from biomass has been overlooked by proponents.

The present energy requirement in the form of gasoline is approximately 14 quads per year. A five percent blend (by volume) of ethanol represents(6) about 0.5 quads. It appears reasonable(6) that the biomass resources in the form of surplus grains, sugar and residues can supply this requirement within a decade. The major difficulty, other than economics, appears to be the construction and the necessary capital to build the plants to produce about 30 times the current production rate of ethanol. Some recommend(2) that the U.S. Department of Energy should "get plant construction underway". If private industry does not see a profit incentive to build these plants, the wisdom of the government launching such an enterprise on a commercial scale should be questioned. The U.S. Congress has already appropriated(7) funds for construction of demonstration plants and has also authorized USDA to permit the production of energy crops from set-aside acres. The available information on technologies and economics does not seem to warrant the U.S. Government going beyond the demonstration stage at this point.

Though it does seem likely that sufficient biomass resources can be available for a five percent blend, I must point out the exaggerated figures used by alcohol proponents. Most of them seem to assume that the best way to use all the forest and agricultural wastes and surpluses, and the municipal solid wastes is to produce alcohol. They ignore the fact that there are other more appropriate and energy efficient uses(7) for these resources. For example, direct combustion of lumber waste can replace petroleum fuels under certain situations in a competitive manner. Hence, the assumption that all lumber waste can be used for alcohol production is not fully justified.

ENERGY BALANCE

The most controversial and confusing issue is the question of whether alcohol fuels are energy efficient. The critics and the proponents have indulged in extensive, and what I consider irrelevant, discussions on energy conversion ratio. The critics claim that the energy(8) in the produced alcohol is less than what is in the feedstock and what is required for processing. The proponents(1) point out that electricity generation is only about 30 percent efficient. Just as electricity is the only form of energy that certain applications (e.g. computers) can use, liquid fuel is the only form that automobiles (with some exceptions) can use. The production or conversion efficiency is immaterial when there is a requirement for the conversion.

The attractiveness of alcohol fuels is its potential to replace imported petroleum fuel. Hence, the real issue is whether a BTU of alcohol can be produced with substantially less than a BTU of petroleum or natural gas. The energy contents of all other input materials are hardly relevant as long as the materials are available for this application and the objective is to replace petroleum. Nor does it matter whether there is added energy in the byproducts unless the production of those byproducts by other processes involve petroleum based energy. Certainly, the conversion efficiency will affect the cost of production but the energy balance equation as frequently discussed merely confuses the issue.

The meaningful way to look at the energy savings can be depicted(6) by the example of ethanol production from corn and residues as shown in Figure 1. It is not the intention here to substantiate or refute the numerical values of the energy components shown in the diagram. The net energy gain clearly is negative; but, the important fact is that for every 2.1 MMBTU of petroleum that is used to produce the corn, we can produce 4.1 MMBTU of ethanol. There is, thus, a net saving of 2 MMBTU of petroleum fuel assuming that the ethanol will be used in applications that use petroleum now. By the same token, it must be recognized that the 4.1 MMBTU of ethanol can replace only 2 MMBTU of imported petroleum. Of course, an important assumption here is that the process heat can be provided by coal or sources other than petroleum or natural gas. It is rather surprising that this simple fact has not been emphasized in all the testimonies before the Congress. Instead, witnesses have resorted to unsubstantiated claims(5) that a BTU of ethanol produces more work (miles per BTU) than a BTU of gasoline. What, therefore, needs to be demonstrated in this case (ethanol from corn grain and residues) is that a practical economic process can be developed to produce ethanol with 5.1 MMBTU of non-petroleum (e.g. coal) source. Let us hope, we will see such results from the demonstration projects about to be funded(7) by the USDA.

The conventional energy conversion efficiency, indeed, is meaningful when comparing alcohol production against other possibly more appropriate uses, such as direct burning, of the same resources. All of these conversions will, of course, yield a ratio less than unity. Nevertheless, such a comparison very likely will put alcohol production at a distinct disadvantage. It then becomes a subjective decision whether such a penalty is worth paying considering the savings in petroleum imports.

If the non-petroleum fuel for the 5.1 MMBTU in Figure 1 is coal, the logical question arises whether it is more energy efficient to produce methanol from this coal. If so, the use of coal to produce ethanol will be entirely unjustified since the cost(8) of ethanol per BTU is at least two to three times as high as methanol produced from coal. If it can be shown that the needed coal is of a quality to satisfactorily produce 2 MMBTU (net petroleum gain in Figure 1) of methanol, then it becomes necessary to find other sources to supply this 5.1 MMBTU to demonstrate a petroleum gain from producing ethanol from corn grain and residues.

COST

Though there is considerable controversy on the cost of production of alcohol, there is general agreement that alcohol, particularly ethanol s considerably more expensive to produce per BTU (and even per gallon) than gasoline under present technologies. The testimonies(5,7,9) before the Congress indicate general agreement that ethanol from biomass costs a little over a dollar per gallon (about $11 or more per million BTU depending upon the feedstock), methanol from biomass about 35 cents a gallon (about $5 per million BTU), methanol from coal 20 cents a gallon* (about $3 per million BTU) compared to gasoline production cost of 3 to 4 dollars a million BTU. The higher cost of alcohol fuel has been compared to the higher cost of air travel in early days. It is argued that just as the public progressively accepted the higher air travel cost to a point it has become quite ordinary and therefore comparatively inexpensive, alcohol will also find acceptance if only the government will encourage it. The simple fact is air travel got the passenger to the destination in a shorter time thereby making the higher cost worthwhile in time and comfort. Alcohol fuel offers no such advantage over gasoline to the user. Alcohol as a motor fuel clearly will not be economically attractive to the consumer without some form of government subsidy to equalize its cost to gasoline. Such subsidy, however, is not entirely new in the U.S. The petroleum depletion allowance, for example, represented about $2 billion a year(1). The question, then, is how much of a subsidy is it sensible for the government to pay in order to commercialize alcohol and reduce the petroleum import.

A meaningful way(6) to evaluate the necessary subsidy is to convert it into cost per barrel of petroleum saved. Such computation, however, has to be done with care with consideration to the actual petroleum gain discussed earlier.

Suppose we wish to evaluate the government cost of commercializing ethanol use to an extent of 5 percent. Let us also suppose this ethanol will cost $11.8 per million BTU ($1 a gallon). In order to make the cost equivalent to gasoline ($3.5 MMBTU), the subsidy must be $8.3 per MMBTU. The 5 percent ethanol represents about 0.5 quads at our current rate of gasoline use and the subsidy is $4.15 billion. If this ethanol is produced from corn grain and residues (assuming the resource exists), the half quad will replace only 0.244 quad (Figure 1) of petroleum or 42 million barrels of petroleum. Thus the subsidy of $4.15 billion represents a cost of $98.8 to avoid each barrel of import. Not being an economist, I cannot tell you whether it will be in the national interest for the government to spend $98.8 to avoid importing a barrel of petroleum that costs $14. However, as a member of the fuel consuming public, such a proposition does not sound sensible and is highly unpalatable. Let me hasten to add that this example is based on a very expensive source of ethanol. Other sources and technologies might represent a lower cost. In particular, methanol from coal could be attractive, if the technology can be demonstrated.

The claim has been made that though ethanol is not cost competitive at today's cost of petroleum, it could become attractive as the petroleum shortage and price increase. Unfortunately, there is every likelihood that alcohol cost will increase as rapidly as petroleum cost. It is interesting to note that exactly such speculation was made by the U.S. Department of Agriculture in 1936 when petroleum was perhaps half as expensive.

These costs for alcohol are probably optimistic.

Those who favor production of ethanol from grain have made the claim(5) that if the subsidy for the "diversion" acres is used to reduce the price of grain that could be produced on that land, the ethanol will become attractive in cost. Such an approach, it is estimated, could supply about 1.5 percent or 0.21 quads of our gasoline use. The diversion subsidies in 1978 for corn, sorghum, barley, wheat and cotton are estimated to be about $630 million representing about 3.7 acres. If the ethanol costs $11.8 per MMBTU, the 0.21 quads will require $1.74 billion to equalize the cost of gasoline; that is, 1.11 billion in addition to the "diversion" subsidy. The 0.21 quad will, as shown earlier, replace only 0.1 quad or 17.6 million barrels of petroleum. So even with the diversion subsidy, the equalizing cost becomes an additional $63 a barrel of import saved.

It is possible that with other sources and technologies, a much more favorable picture could emerge. But, unfortunately, there has been no such evidence presented to the Congress so far. If the current state-of-the-art is such that no better economic case can be presented in support of alcohol, then we must be content with programs in support of research, pilot and demonstration plants. It would be futile to press for legislation to commercialize alcohol under such economics.

CONCLUSION

Though there is a vast segment of the public and the Congress that would like to see alcohol fuel replace even a small part of our petroleum consumption, convincing information has not been presented to the U.S. Congress to enact legislation to commercialize alcohol fuels. Much of the promotion of alcohol fuel has been oriented towards ethanol production from grain resources. Unfortunately, this resource seems to be one of the most expensive and least likely to be economically competitive. The objections against alcohol on energy balance seem to be based on misleading analysis and not entirely justified. Most testimonies ignore the fact that the available biomass resources could have more appropriate uses than producing alcohol.

Methanol produced from coal appears to have a great immediate potential in terms of cost and supply but this path is overshadowed by the enthusiasm for agriculture based ethanol, even though methanol from coal has the greatest possibility of generating public acceptance of alcohol as a motor fuel from the point of view of cost.

In order to promote the cause of alcohol fuel several things are necessary. First, the proponents must recognize the issues, particularly the economics and petroleum replacement, as the legislators and the public see them. If satisfactory answers are not available, one must be content with research and developments to solve them and not try to rush into commercialization. Second, the credibility must be enhanced by avoiding exaggerations and by presenting a realistic picture of the issues, problems and potential solutions. Third, the emphasis on problems that are not serious or for which solutions are at hand must be minimized. Only then there can then be a hope of establishing alcohol as a viable alternate fuel.

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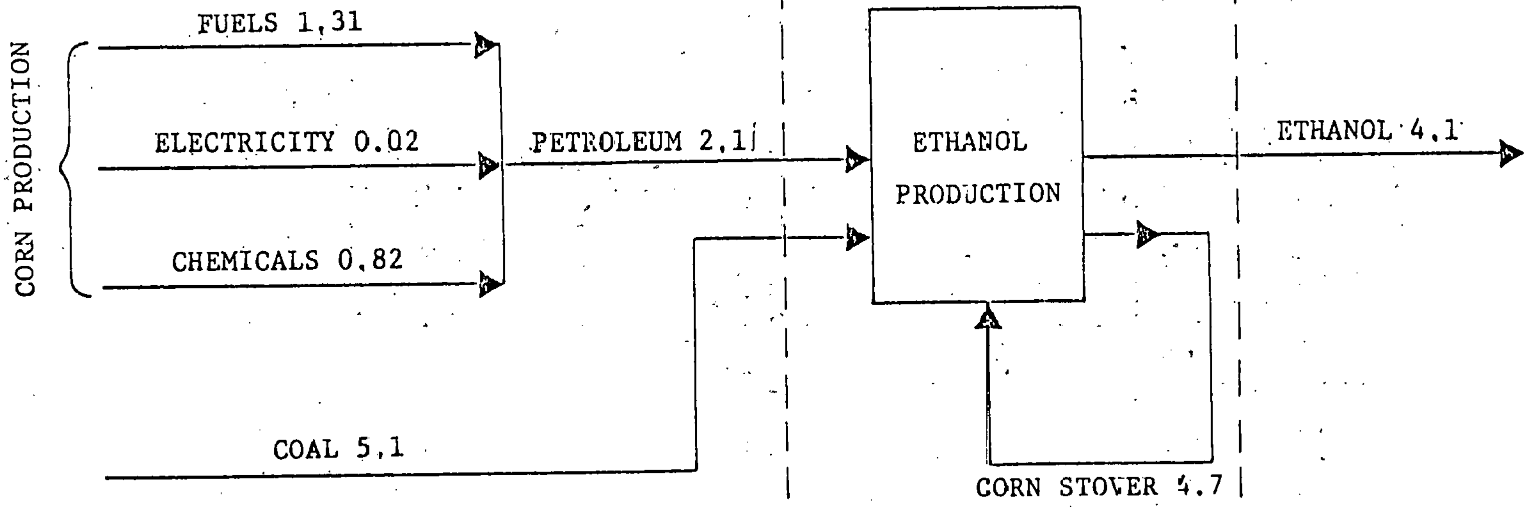

- NET ENERGY GAIN = -3.1
- NET PETROLEUM GAIN = 2.0

FIGURE 1
ENERGY BALANCE FOR PRODUCING ETHANOL FROM CORN GRAIN AND RESIDUES

All figures in MMBTU/Ton of Corn Grain and Residue Processed
Source: Reference 6.

ENGINE COLD-START WITH DISSOCIATED METHANOL

by

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SUMMARY AND CONCLUSIONS

Preliminary studies are reported on means to thermally decompose methanol to products that include hydrogen in order to start an internal combustion, passenger-car engine using that fuel at very low temperature. Methanol was properly decomposed on passing through tubes heated as shunt to the automobile battery. However, excessive battery current was required to provide sufficient gases for engine start. A small methanol-air combustor has been developed to supply the thermal energy. The related decomposition tubes become coated with carbon after repetitive operation and lesser amounts decompose. Water dissolved in the methanol decreases carbon buildup, but also lessens amounts decomposed. This problem requires further attention. An engine cooled to -13°F was rapidly initiated by a synthetic mixture of the gaseous decomposition products. Transition from this gas mixture to liquid methanol as fuel required exessive times, and needs further study.

INTRODUCTION

Internal combustion engines fueled with methanol are difficult to start in cold weather. Methanol, however, may be thermally decomposed to products that include hydrogen, viz.: $CH_3OH(l) = 2H_2(g) + CO(g)$, and hydrogen rapidly ignites in a very cold engine. Thus, means are being studied to thermally decompose the initial flow of methanol, prior to injection of fuel into the engine. The studies are constrained to devices which appear adaptable to a passenger car, with respect to hardware simplicity, rapid action, reliability, acceptible detrimental side effects, and so on.

In preliminary studies, methanol is passed through tubes heated as shunt to the battery. Subsequently, the thermal energy is supplied to the tubes by a low-pressure enclosed burner; and a considerable effort is devoted to the development of the latter. Problems due to carbon formation in the related decomposition tubes are reported. A cold engine was found amenable to rapid start using the types of gases formed on decomposing methanol, and problems are noted in subsequently transferring to operation with liquid methanol.

BACKGROUND

Theoretical equilibrium products vs. temperature for the elements within methanol (i.e.: CH_4O) at one atm total pressure are given in Figure 1. At the highest temperatures shown, a consider-le proportion of hydrogen is formed. Also shown are heat effects when the equilibrium products are formed from liquid methanol, originally at 77°F. Below about 710°F, heat is liberated (i.e., methanol can, in theory, decompose exothermally), while above that temperature heat must be provided. Consequently, the data suggest that methanol should be heated with a considerable thermal input to effect its decomposition to hydrogen. At all but the highest temperatures, solid carbon may also form.

In addition to equilibration, other product mixes satisfy free energy consideration, if, for example, $H_2O(g)$, $CH_4(g)$, $CO_2(g)$ and/or C(s) can be prevented from forming. Thus, CO(g) and 2 H_2 (g) could be the exclusive products, even at low temperatures. Such a desireable circumstance probably requires special catalysts, whose development would be time consuming. Possibly, too, the hardware would be relatively costly and complex, and longer initiation times would be required. For such reasons, these preliminary studies were limited solely to thermal decomposition at high temperature.

The means to decompose the methanol should be small,light, reliable, fast-acting, not comprimise other engine parts, utilize existing components, etc. It was tentatively assumed that engine start should be accomplished 10 to 15 seconds after "turning the key." Very preliminary calculations indicated that .3 to .6 g/sec of decomposition products would be needed over a time period of 4 to 7 seconds. Complete decomposition of liquid methanol at high temperatures (see Figure 1) requires thermal input in the range of 2000 BTU/lb. However, useful amounts of hydrogen are produced with a thermal input as low as 500 BTU/lb, corresponding to equilibria in the range of 1000°F.

BATTERY SHUNT STUDIES

The battery already present in an automotive engine qualifies as a tentative source of energy to supply the necessary thermal input. For the minimal need of 500 BTU/lb and minimal flow rate of .3 g/sec. the required battery output at 12 volts is 38 amps. For 4 to 7 sec, this seems within its capacity. However, if 2000 BTU/lb and .6 g/sec are needed, the required battery output of 230 amps is at the outskirts of acceptibility.

An intriguing means to effect decomposition is to pass the methanol through a tube that is made a shunt to the battery. The tube preferably should achieve maximum allowable temperature rapidly, before methanol flow is initiated. The temperature reached depends on the weight of metal in the tube and its heat capacity, while the effective current that supplies the thermal input increases with frontal area and decreases with length. Ramifications of these conflicting effects are indicated in Table 1 for the pessimistic case of 300 amps input. As shown, times required to heat the stainless steel tubes to the maximum safe temperature of 1800°F vary from .3 to almost 20 sec. Heating for only .3 sec results in a low margin of safety before the tube might self-destruct, while the much longer times would not be acceptible in starting a passenger automobile. Taking about 1 sec as optimum, a tube of about .25-in diameter, .010 wall thickness and 12-in length appeared satisfactory.

Tests of various tubes were made by initially shunting across the battery for given intervals, and subsequently flowing methanol at selected rates through the tube, while still operating as a shunt. In many cases, a small air flow was also passed through the tube, though this practice was discontinued after it was found of doubtful value. The effluent from the tubes was passed into a small can containing water, whose gain in weight was subtracted from the total methanol flow to estimate the amount decomposed to water-insoluble gases.

Table 2 has typical results. Only a small portion of the methanol was decomposed, and when tube length exceeded about 16 in, none was decomposed. In test no. 10, the tube was heavily insulated with glass wool, which resulted in increased amounts decomposed. Despite the scatter in the tests, they do show that methanol may be decomposed by this method, but the amount is less than 25%.

The greater amount decomposed in the insulated 16-in tube, probably was due to a longer staytime in the hot environment, since this tube's temperature is less than those of the smaller-length tubes. For this reason, a reverse-flow decomposition tube set was fabricated consisting of 1/16-in by .010 wall tube within a 3/16-in by .010 wall tube. The incoming liquid first passes through the 1/16" tube and is subsequently directed through the annulus between tubes. The tubes were electrically connected at each end. Together, the tubes have electric and thermal capacity properties equivalent to those of the .25-in by .010 wall tubes of the previous tests. When the tube set was subjected to test, 50 to 60% of the methanol was found to decompose. The gaseous effluent contained about 40% H_2, 17% CO and 15% CH_4. The analysis procedure does not respond to CO_2(g), H_2O(g) or more complex hydrocarbon molecules. To achieve these results a battery input of 260 amps was needed.

The current requirement for the above tests was considered excessive, and succeeding tests were performed with battery input restricted to 50 amps. With this lower current, 1/16" by .010-in wall by 12-in length tubes were used, which rapidly heated to redness. Methanol passed through such tubes at rates greater than .05 g/sec produced virtually no non-condensible gases. At flows in the range of .035 g/sec between 40 and 60% was decomposed. These flow rates were considered insufficient to effect cold-engine start.

METHANOL COMBUSTOR STUDIES

A methanol-air combustor liberates about 8600 BTU per pound of fuel. This is sufficient to decompose about 4 times its flow of methanol, assuming a need for 2000 BTU/lb. For a combustor-decomposer to be acceptable in engine cold-starts, the overall device must be small, fast-acting, reliable, not interfere with the engine, etc.

A present design is illustrated in Figure 2. It evolved from the battery studies, and after preliminary experiments showed that an open burner does not provide satisfactory heat-transfer properties. It comprises four sections: pilot, main-burner, decomposition and vaporization. The pilot initiates burning. The main-burner plus the lesser input from the pilot supply the required thermal energy. A separate flow of methanol is thermally decomposed in the decomposition section, and another flow is used to provide vapors from the vaporization section to assist in the start process.

Both the pilot and main-burner are fed premixed air-fuel vapors. This technique provides a homogeneous flame front that improves later heat transfer and stabilizes the flame shortly after ignition. To ignite the pilot even in very cold weather, the fuel passes first through a thin tube that is located partially within the combustor. The tube is momentarily shunted across the battery at start, which draws about 50 amps and rapidly vaporizes the incoming fluid. The vapor is led into the air stream just before entry into the burner, and the mixed vapor-air is ignited, on entry, by a spark. After ignition, the energy for continuous vaporization is supplied by heat exchange from the flame and battery input is not used. The pilot flame subsequently passes over a series of main-burner tubes, and supplies energy to effect vaporization of the main-burner fuel that is passed through the tubes. The latter vapors are led into the air stream just prior to its entry into the main-burner air ports, and the incoming air-vapor mixture is ignited by the flame. The overall scheme achieves ignition and effective heat evolution in seconds. The combined flame from pilot and burner next pass over the decomposition-tube set, where the methanol is decomposed. Finally, the flame passes over similar tubes that vaporize another flow of methanol.

The entry-air cylinder and the burner tubes were fabricated from tin cans--the latter from a tennis-ball container. The interior of the burner is protected with a ceramic coating. The experimental unit is fabricated in sections to facilitate study. Its length is about 13" and the outside diameter of the burner is about 2 3/4". Despite the fact that operation is close to stoichiometric because of the transient character of the start system, the present pilot-burner combination has undergone thousands of 20-sec runs without failure.

Ignitability of the combustor at low temperatures was tested by filling the pilot with dry ice, cooling the methanol fuel in a dry ice-alcohol slurry, and simultaneously cooling the air by passing through a radiator chilled with dry-ice cooled methanol. Under these conditions, the methanol and pilot hardware temperature measured close to -70°F and the incoming air, -50°F. Suc cooling increased the requirement for ignition from .5 sec of battery shunt at normal temperatures to .9 sec, which is considered satisfactory.

The burner efficiency was tested by measuring the oxygen content at its effluent. Generally, this was found to be below 3%, which implies excellent reaction. The various methanol flow rates were determined using rotometers. Because of the transient nature of the flows and their relatively low rates, this procedure is probably no more accurate than 10%, which is considered acceptible. The effluent from the decomposition tubes was often passed into a water bath in which the methanol was dissolved, and the change in weight subtracted from the total flow was taken as the amount of decomposed (i.e., water-insoluble gases) material formed. The water-insoluble gases then were passed either through a wet-test gas meter or used to displace water from a large tank, and the measured volume of gases converted to weights, to check the previously determined value. From time to time, the latter gases were analysed in an appropriate absorption column: generally, the approximate ratio of 40 H_2, 20 CO and 5 - 15 CH_4 was found. The analysis procedure was insensitive to CO_2, H_2O, other C-H-O compounds, or to components of air which might have been present. For reasons of safety, every effort was made to exclude air, but nitrogen was often used to displace unwanted gases. Finally, the effluent from the vaporization tubes was often collected in water to determine flow rates, or simply burned. The flow at which the effluent from these tubes converted from vapor to liquid was estimated by relating to the temperature determined at its outlet by means of a thermocouple. For values below 175°F (methanol boils at 149°F), the emission was considered to be primarily liquid. The amount of vapors formed when the decomposition tubes were simultaneously operating was variable: between about 1.5 and 4 g/sec.

As shown in Figure 2, the decomposition section presently contains 16 coils of 1/16" by .010" wall tube, each 4' long. These dimensions were selected after considerable experimentation: larger diameter tubes are less effective,as were both longer and shorter lengths of the 1/16" tubes. The maximum flow through each tube that resulted in notable decomposition was about .05 g/sec, where 75 to 80% (sometimes more) was decomposed. These correspond to about .8 g/sec total flow for the 16 tubes, and .6 g/sec of decomposition products. To achieve the latter, over 1 g/sec of methanol is needed to fuel the burner, which is far greater than the amount (.15 g/sec) which is theoretically needed. For experimental purposes (though perhaps not optimum) a standard test comprises 2-sec pilot before initiating burner flow, 11-sec pilot plus burner before initiating decomposition flow, 7 additional seconds of pilot, burner and decomposition methanol (often with vaporizer also running), and a final 1 sec with only pilot flow. Usually, air flow and pilot plus burner fuels are kept constant, while decomposition and vaporizer ows may be varied. A ratio of about 4 to 1 is maintained be-
een burner and pilot flow rates.

Problems in achieving reproducibility in amount decomposed were traced to a decrease with the number of runs made in a given decomposition tube assembly, as indicated in Table 3. Substituting various steel alloys, such as 300 and 400 series stainless, and Inconel, had little effect. However, carefully heating the tubes by intermittently operating the burner while passing air through them, between runs using methanol, appeared to eliminate this degradation, as indicated in Table 4. These and related experiments showed that deposition of carbon within the tubes was responsible.

Preliminary tests are underway to note the effect of water addition to the methanol on carbon formation, through either a reformation or oxidation reaction. Recent results are gathered in Figure 3 for 13% water addition. The data were determined with the same 13% solution used to fuel the burner, which operated very well at its lower temperature. While the results indicate little degradation with time, the penalty is a decrease in the amount of fluid that can be decomposed from .05 g/sec per tube with pure methanol to about .03 g/sec with the water added, and a further decrease in proportion decomposed from more than 75% to about 50%. As a consequence, the flow rate of decomposition products with 16 tubes has decreased from about .6 g/sec to .25. Apparantly, more work is needed to solve the carbon problem.

Since catalytic means may diminish the effect of carbon formation, decomposition tubes with larger inside dimensions, which may be readily coated, are presently being investigated. Apparantly, dimensions to ½" in diameter may prove satisfactory.

COLD ENGINE IGNITION TESTS

Only very preliminary tests have been begun related to starting an actual engine with decomposition products. In these, a Ford Pinto 2.3-liter, 4-cylinder engine was used. It became available after completion of strenuous experiments, including 1000 hours of dynometer testing and other cold-start work. By locating methanol fuel injectors on the manifold plenum and on the intake manifold near each cylinder, and adjusting the choke to achieve a manifold vacuum of about 12 in of mercury during cranking, good starts were obtained with liquid fuel at temperatures as low as 46°F. Subsequently, a 2-to-1 molar ratio of a mixture of hydrogen and carbon monoxide gases, to simulate decomposed methanol, was injected at the manifold plenum at flow rates of .5 g/sec. Under these circumstances, ignition and continuous run was achieved with the engine cooled to -13°F. However, subsequent transition from this gaseous fuel to liquid methanol required many seconds of gas mixture operation, as indicated in Figure 4. Further studies to ellucidate this time interval are needed, including the effect of simultaneous injection of vaporized methanol.

TABLE 1. APPROXIMATE SHUNT TIME TO REACH 1800^{O}F VS TUBE DIMENSIONS

Material: Stainless Steel, Heat Capacity .11 BTU/lb-^{O}F,
Density 490 lb/ft^3
Electrical Input: 12 Volts, 300 Amps

Tube Dimension (in) Diameter	Wall Thickness	Length	Shunt Time (sec)
.125	.010	6	0.3
.125	.020	12	1.2
.125	.030	18	2.8
.1875	.010	9	0.8
.1875	.020	18	2.8
.375	.010	18	2.8
.250	.010	12	1.2
.250	.020	24	5.0
.250	.032	38	12.7
.500	.010	24	5.0
.50	.020	48	19.8

TABLE 2. DECOMPOSITION TESTS WITH .250" O.D. BY .01" WALL TUBE.

Methanol Flow Rate: .55 g/sec
Air Flow Rate: 6 SCFM
Results Given Are Average of Several Consecutive Runs

Run No.	Tube Description Length (in)	Configuration	Preheat (sec)	% Gas Produced
1	12	Straight	0.5	10
2	14	Straight	2.5	12
3	14	S-Shaped	2.5	9
4*	14	S-Shaped	2.5	9
5	16	Straight	2.5	16
6	16	Straight	2.5	19
7	16	Straight	0.5	13
8	18	Straight	2.5	0
9	18	Straight	2.5	0
10**	14	Straight	2.5	22

* No air flow.

** Very heavily insulated.

TABLE 3. AMOUNTS DECOMPOSED IN CONSECUTIVE RUNS, WITHOUT CLEANING

Each Datum: 5 Runs, 7 Sec. Each, 35 Sec. Total
Fuel: Methanol To Burner and To Decomposition Tubes
Number of Tubes: 2

Datum	Condition	Weights Collected, g. Gas	Weights Collected, g. Methanol	Decomposed %
1	Clean Tubes	2.5	0.6	81
2	After Above	2.0	1.8	53
3	After Above	1.7	1.6	52
4	After Above	1.4	2.1	40
5	After Above	1.3	2.6	33
6	After Above	1.1	2.3	32
7	After Above	0.8	2.8	22
8	After Above		Tubes Clogged	

TABLE 4. AMOUNTS DECOMPOSED IN CONSECUTIVE RUNS, WITH CLEANING

Tests As Described In Table 3.

Datum	Condition	Weights Collected, g Gas	Weights Collected, g Methanol	Decomposed %
1	Tubes as Rec'd	1.3	3.0	30
2	After Above	1.7	2.7	39
3	Clean With Hot Air	2.7	0.4	87
4	Clean With Hot Air	3.4	0.3	92
5	Clean With Hot Air	3.4	0.7	83
6	Clean With Hot Air	3.3	0.3	92

FIGURE 1. COMPUTED EQUILIBRIA FOR THE ELEMENTS COMPRISING METHANOL AT ONE ATM. ALL PRODUCTS CONSIDERED.

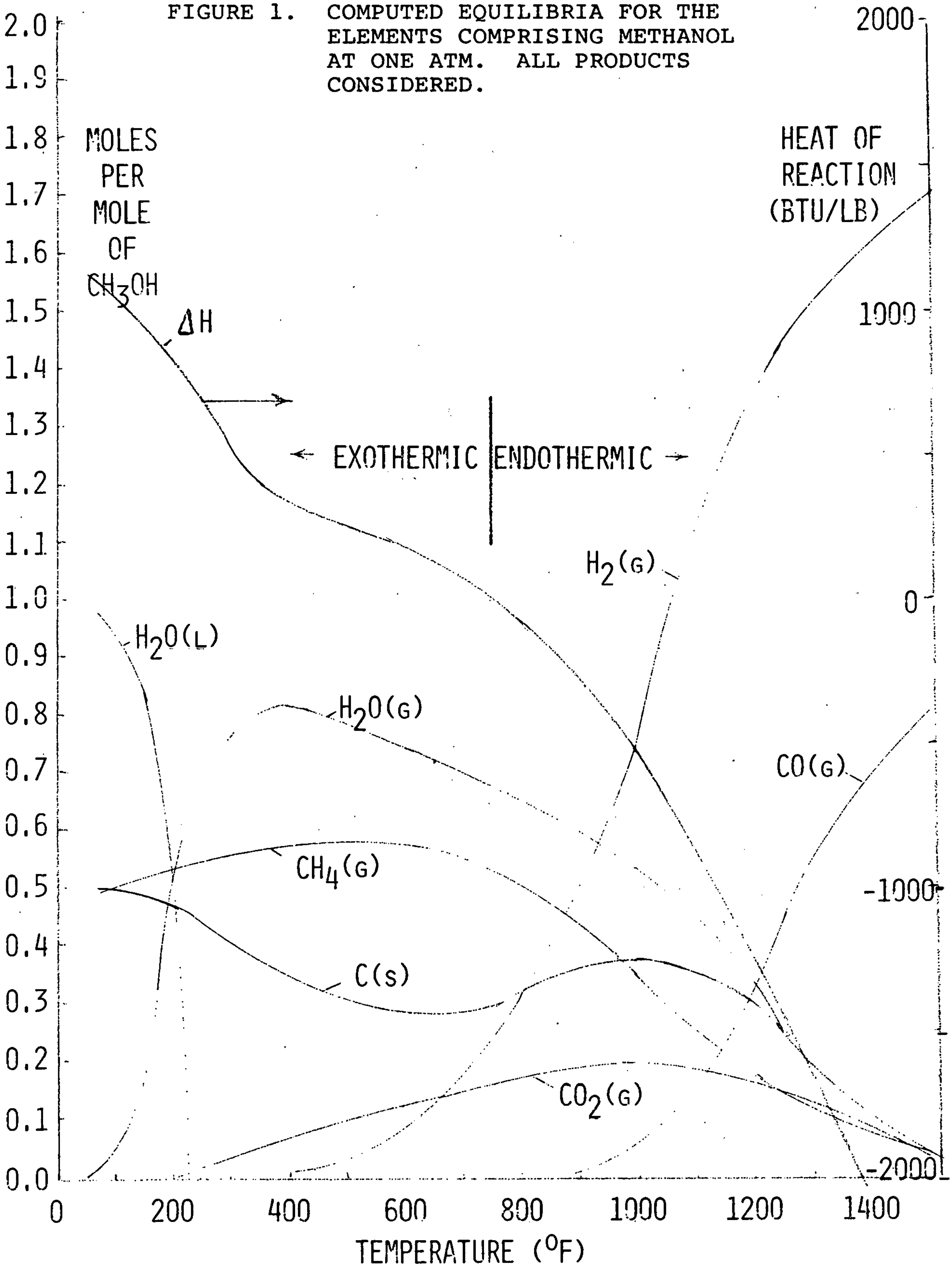
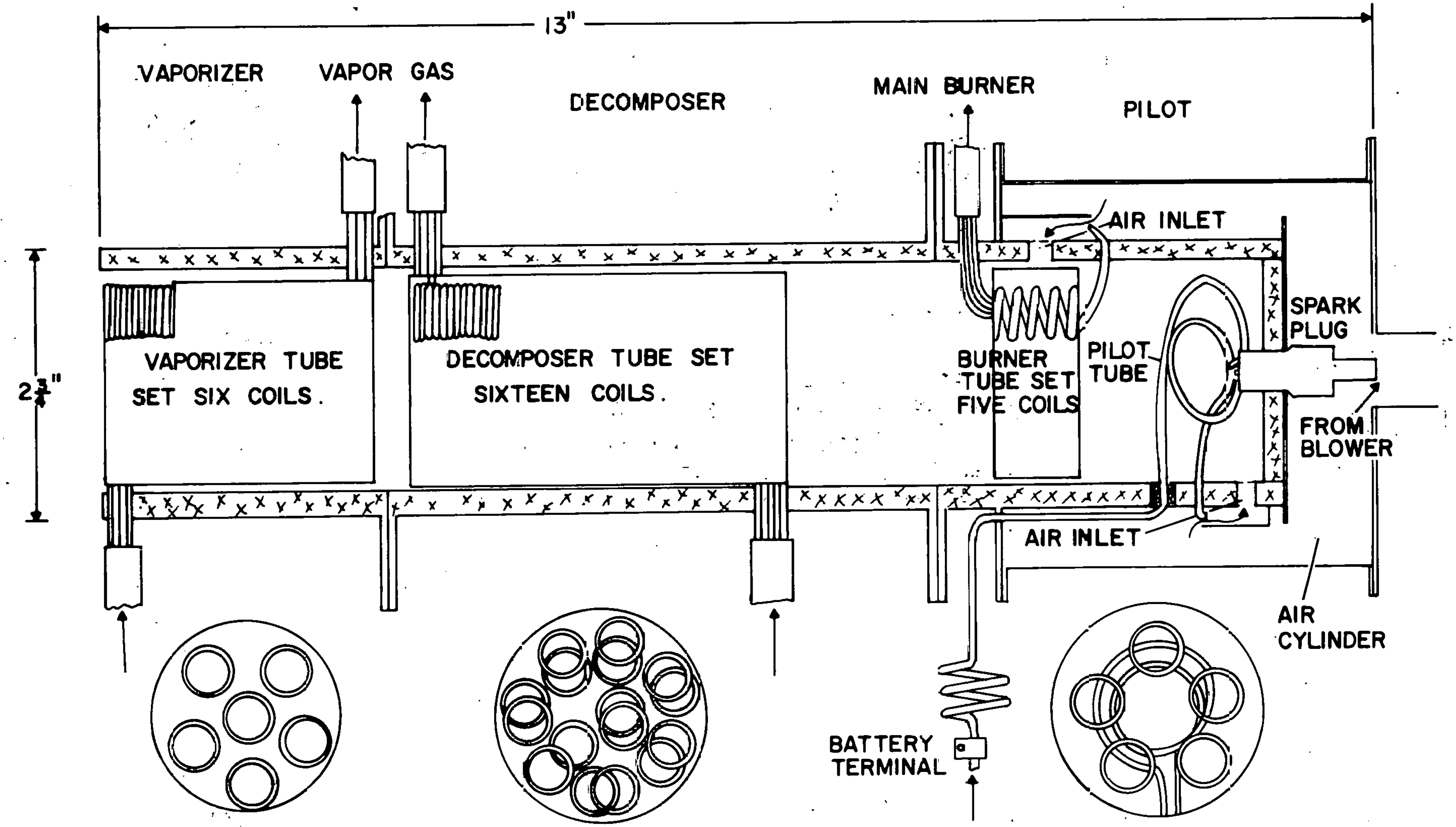


FIG. 2 : SCHEMATIC OF COMBUSTER - DECOMPOSER - VAPORIZER



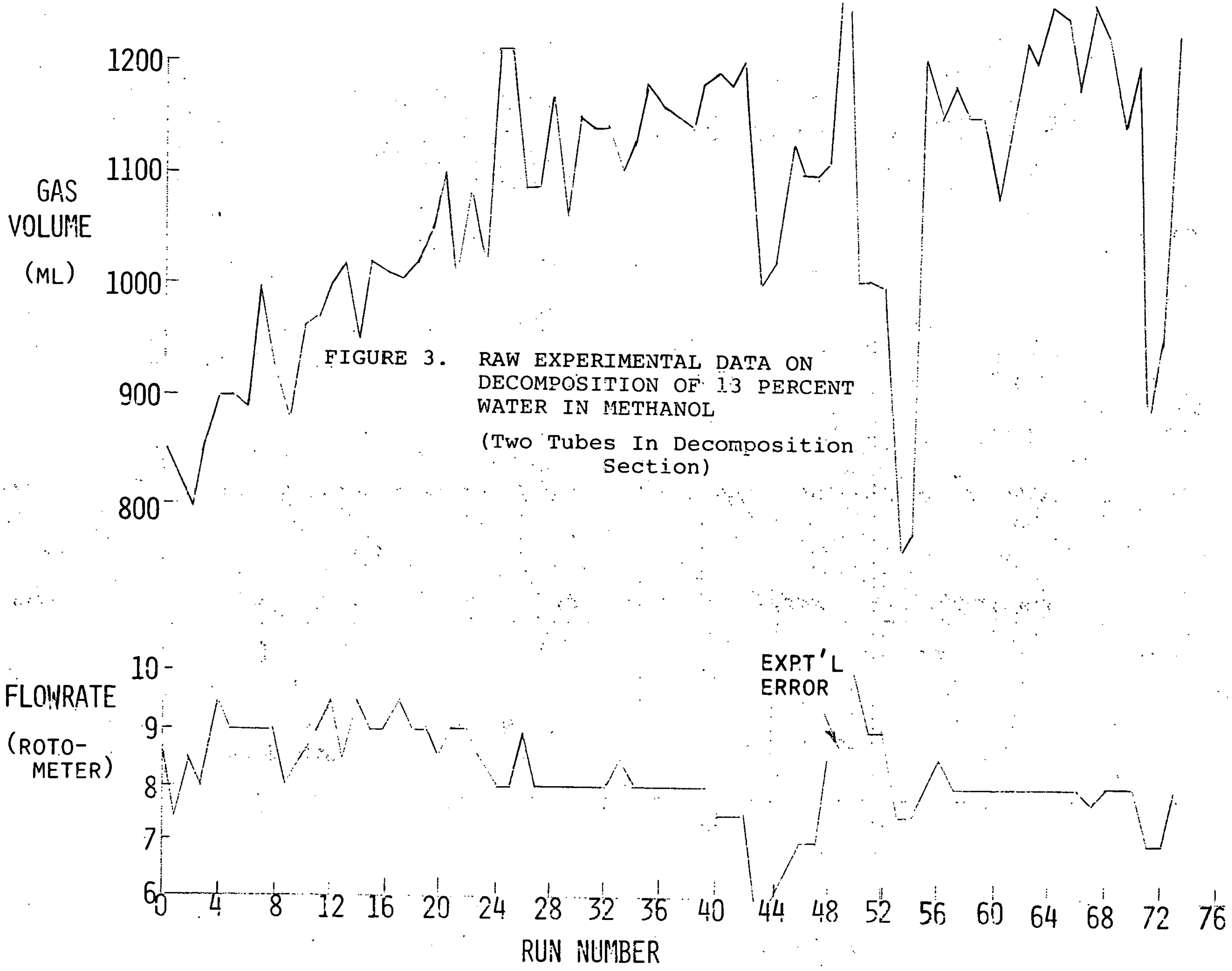


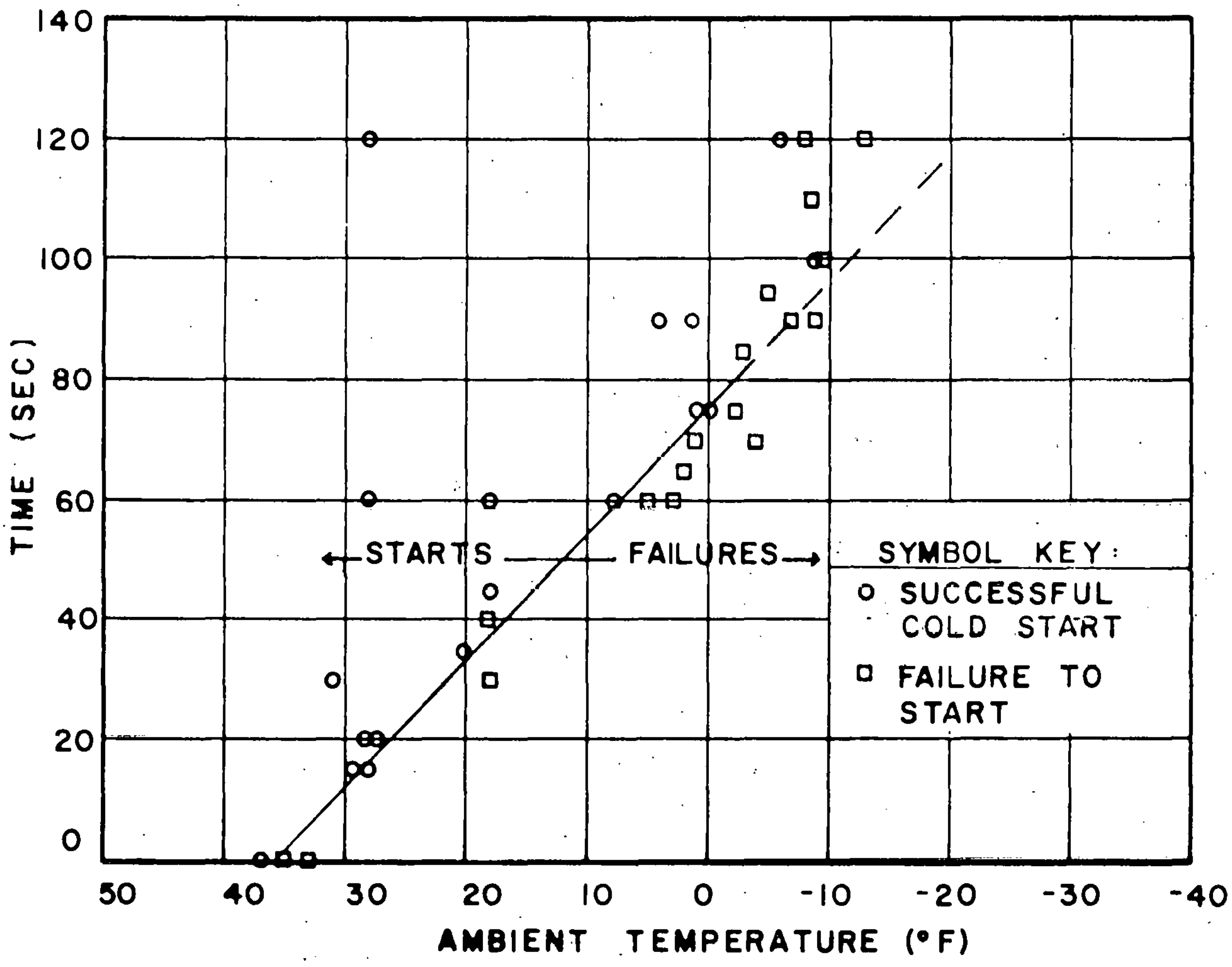
FIGURE 3. RAW EXPERIMENTAL DATA ON DECOMPOSITION OF 13 PERCENT WATER IN METHANOL

(Two Tubes In Decomposition Section)

FIGURE 4

COLD START RESULTS USING DISSOCIATED MEOH AT VARIOUS AMBIENT TEMPERATURES.

2300 C.C., 4 CYL. ENGINE
8.5 : 1 C.R., ELECTRONIC FUEL INJECTION
AVERAGE FUEL FLOW = 0.5 GRAMS/SEC.



ENGINE EXPERIMENTS WITH ALCOHOL/DIESEL FUEL BLENDS

by

C. A. Moses, Southwest Research Institute

SUMMARY

A single-cylinder CLR engine with an open-chamber diesel head has been run on alcohol/diesel fuel blends. Preliminary results are compared on 20% blends of methanol/DF2 as an emulsion and ethanol/DF2 as both a solution and an emulsion. Instabilities in the emulsions made operation erratic and limit the conclusions. Results on higher concentrations of the ethanol/DF2 solution show good combustion on as high as 30% ethanol at all load/speed conditions; 50% concentrations could be used at low speeds. Resultant savings in diesel fuel justify further studies, especially into micro-emulsions of alcohol and diesel fuel.

INTRODUCTION

Worldwide petroleum reserves are a nonreplenishable commodity. The rate of depletion depends primarily on the economic growth rates of all the countries of the world and the production rates allowed by the oil producing nations.

Although the oil producing countries have been generally meeting the world's demand, recent events in Iran show how tenuous even this supply can be. At some time in the future, the OPEC will have to decide whether to limit production and extend their supplies or to continue to meet the demand as long as possible. Regardless of the choice, at some point in time we, and the world in general, will be faced with supplementing our petroleum production with alternate domestic energy sources.

The transportation sector consumes large volumes of fuels and is a national target for the conservation of petroleum energy. Petroleum fuels can be conserved by substituting hydrocarbons from other sources, e.g., oil shale and coal, or by blending them with nonhydrocarbon as well as hydrocarbon components from nonpetroleum sources. This is likely to result in the use of unorthodox fuels and some hardware changes may be necessary in order to accommodate fuels in their most economical and abundant compositions.

Hybrid fuels are finished fuels derived from combinations of different energy sources. Such fuels can be slurries, emulsions, and homogeneous solutions; the supplementary component would necessarily come from a renewable source, e.g., alcohol, or an extremely abundant one, e.g., coal. The use of hybrid fuels to extend the supplies of petroleum-derived fuels is not only a viable alternative in the short to mid-term, but will also apply to hydrocarbons from oil shale and/or coal as they become available in significant quantities. Some hybrid fuel concepts could also permit the utilization of lower quality fuels thus reducing the refining cost of fuels from syncrudes; this can be accomplished by tailoring the supplement(s) to achieve certain combustion characteristics such as lean combustion, cleaner burning, or reduced emissions.

Alcohols, primarily methanol and ethanol, are receiving considerable attention as alternate fuels or hybrid components with gasoline for use in spark ignition engines because of their high octane numbers and boiling points which are amenable to carburetted systems. Blends of 10-15% methanol in gasoline present no serious performance problems and can be used in current automobiles without hardware changes. Blends of 10% methanol in gasoline are being marketed in several mid-western states although all of the vehicle/engine system problems have not yet been resolved.

Alcohols have been tried in compression-ignition engines but primarily as dual-fuel systems where the alcohol and diesel fuel are not pre-mixed but introduced into the combustion chamber by separate delivery systems. The people at Riccardo carburetted methanol into the intake air [1]*. The pilot charge of diesel fuel was required to be quite large to overcome the quenching of the evaporating methanol; inlet heating and amyl nitrate were found to be helpful as ignition improvers but brought the quench and knock limits too close together for practical operation. Volvo got around this problem by injecting the methanol during the ignition delay period of the pilot charge; efficiency was the same while smoke and exhaust temperatures were lower. Road tests were conducted on as much as 91% methanol by volume (82% by energy) at high loads and speeds. Endurance tests showed anticipated problems with some gaskets in the fuel system and unexpected injector faults caused by a lower damping performance of the methanol when the needle hit the seat—both correctable [2]. Ethanol has been tested in a dual-fuel system at the Indian Institute of Technology in Madras with similar results: as much as 70-80% of the energy requirement could be obtained from the ethanol over most of the speed and load range [3].

Very little work has been reported on the use of alcohol blended with diesel fuel either as a solution or an emulsion. Methanol has very limited solubility in diesel fuel unless the aromatic content is abnormally high and would therefore have to be emulsified into the diesel fuel. Dry ethanol is completely soluble in diesel fuel but separates with as little as 1/2% water present. Here, too, an emulsion may be more practical. Ontario Research Foundation has conducted some cursory tests of emulsions of 20% methanol in diesel fuel in a Deutz engine. They found a 5-6% reduction in power which is equivalent to a 5-10% increase in thermal efficiency when heat content is considered [4]. The Army has found similar results with no effects on ignition delay, complete combustion of the alcohol, and some reduction in smoke; there was also some preliminary indication that thermal cycle efficiency was improved [5]. The author is not aware of any work reported on engine studies with ethanol in diesel fuel either as a solution or an aqueous emulsion.

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*Numbers in brackets designate References at end of paper.

A study of the combustion and performance of alcohol/diesel fuel blends has been undertaken in the Mobile Energy Division of Southwest Research Institute as part of a larger program for DOE on hybrid fuels to determine the potential for this fuel concept to save petroleum in the transportation sector and to identify the problems of utilization. This paper discusses some of the early results of this program.

EXPERIMENTAL PROGRAM

A CLR single-cylinder research engine with an open-chamber, compression-ignition head was used for preliminary evaluations of alcohol/diesel fuel blends. Engine performance tests were run at the following load-speed conditions:

% full load	speed, rpm
100	1000,1500,2500
75	1000,1500,2500
50	1000,1500,2500

The engine was coupled to an eddy-current dynomometer and instrumented for cylinder pressure as well as load, speed, and fuel flow rate. An AVL pressure transducer was used to measure cylinder pressure; pressure data were acquired digitally every crank angle degree. The main purpose of the digital pressure data is to calculate heat release rates from the following equation derived from the 1st law of thermodynamics [6]:

$$\frac{dQ}{d\Theta} = \left(\frac{k}{k-1}\right) P \frac{dV}{d\Theta} + \frac{1}{k-1} V \frac{dP}{d\Theta}$$

In this work, the ratio of specific heats, k, was given a constant value of 1.35 for the cycle as well as among fuels. This is not correct since k is a function of temperature which not only changes during the cycle but probably among fuels due to some charge cooling by the alcohol which has a much higher heat of vaporization than diesel fuel. Also the gas composition would be different which would affect k. Heat transfer to the cylinder walls is also not accounted for in this analysis; the heat transfer should be about the same for all fuels at a given speed and load condition and therefore should not bias any comparison.

Four fuel types were compared:

1) DF2
2) methanol/DF2 as an emulsion
3) ethanol/DF2 as an emulsion
4) ethanol/DF2 as a solution

A solution of methanol in DF2 was not included because of the limited solubility. Comparative engine tests were performed with these fuels using 20% alcohol by volume in each case; the two emulsions contained 1.75% water to make the alcohol insoluble and 3.25% surfactant to stabilize the emulsion.

It should be noted that these were macro-emulsions and did not have good stability; they were circulated through an ultrasonic cavity to maintain the dispersion. Tests were also conducted with concentrations as high as 50% ethanol/DF2 as a solution. The solutions required special handling to minimize their contact with air as they would absorb moisture and separate; laboratory tests showed that 1/2% water was sufficient to destroy the solution.

Brake specific energy consumption, BSEC, is necessarily used to compare engine performance rather than fuel consumption, BSFC, because of the significant differences in heat content of the fuels.

$$\mathrm{BSEC} = \mathrm{BSFC} \cdot H_{net}$$

The net heats of combustion for the fuels tested are given below:

Fuel	Net heat of combustion, H_{net}
DF2	18270 BTU/lb
E* - 20% Methanol/DF2	15789 BTU/lb
E - 20% Ethanol/DF2	16367 BTU/lb
S - 20% Ethanol/DF2	16988 BTU/lb
S - 30% Ethanol/DF2	16335 BTU/lb
S - 40% Ethanol/DF2	15672 BTU/lb
S - 45% Ethanol/DF2	15337 BTU/lb
S - 50% Ethanol/DF2	15000 BTU/lb

For reference, the following cetane numbers were measured:

Fuel	Cetane Number
DF2	49
DF2 plus surfactant and water	45
20% methanol emulsion	30
20% ethanol emulsion	43
20% ethanol solution	33

Note that the emulsified ethanol had very little effect on Cetane number as compared to the solution. This is thought to be due to the shielding effect of the emulsion structure, whereas in the solution, the ethanol is free to evaporate immediately.

RESULTS

Figure 1 compares the relative specific energy consumptions for the three 20% alcohol/DF2 blends and the pure DF2. Here a value of 1.0 means the same amunt of energy was used to generate a unit of work for a test fuel as would

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*E - emulsion
S - solution

be for DF2. The data are for only one test per fuel at each engine operating condition so the conclusions will be limited.

There is very little pattern to the results with the emulsions except to say that generally the performance was less efficient than with pure DF2 as more energy was almost always required. The scatter in the data is believed to be mainly due to variations in the emulsions leading to variations and uncertainties in the actual heat content of the fuel.

Such was not the case with the 20% ethanol solution which was stable and uniform. Energy consumption was essentially the same as for pure DF2 with some indication of improved efficiency at lower loads and higher speeds.

The engine had been set up for full load at 20:1 air-fuel ratio on diesel fuel. No adjustments were made to injection timing from that used for diesel fuel. The ethanol solution produced considerably more knock than the emulsions or the DF2; however all three alcohol blends had essentially the same increases in ignition delay—about 2^{o} at 1000 rpm and 4^{o} at 2500 rpm.

Figures 2 and 3 compare the pressure data and calculated heat release rates for the DF2 and 20% ethanol/DF2 solution at 75% load and 1500 rpm. This represents typical comparison for all the blend types: about 4^{o} longer ignition delay for the test fuel and faster and higher pressure rise which calculates to higher heat release rates. A complete presentation is not provided here because of space limitations but will be reported at a later time when better data are obtained on emulsions.

Further tests were conducted on higher concentrations of the ethanol/DF2 solutions. Figure 4 compares the engine performance as a function of ethanol concentration. Some changes were tried in injection timing but satisfactory operation seemed to be limited to between 30 and 40% ethanol. It was found that energy efficiency could be improved by varying the timing but a systematic evaluation has not been done.

Figure 5 shows the savings in diesel fuel that were realized in these tests for concentration. Here only the diesel fuel used is accounted for and the relative brake specific diesel-fuel consumption is the diesel fuel used in the test fuel divided by the amount of pure diesel fuel required for the same condition. Some sensitivity to load and speed is evident at low load. On the average, every 10% of alcohol produced about an 8% savings in diesel fuel with a potential of between a 25 and 30% savings.

CONCLUSIONS

If the ethanol/diesel fuel solution can be considered indicative of the performance potential of alcohol/diesel fuel blends, then further studies of these fuels are justified from this preliminary data. The ethanol solutions do not appear to be practical because of the affinity for water which leads to separation. The emulsions do not share this problem, however, and therefore further work is justified at finding a surfactant which will give satisfactory physical stability. Perhaps even a micro-emulsion can be formed which will be thermodynamically stable.

ACKNOWLEDGEMENTS

This work was conducted for the U.S. Department of Energy, Division of Transportation Energy Conservation under Contract No. EM-78-C-04-4240; the contract monitor was Mr. Eugene Ecklund, Chief, Alternative Fuels Utilization Branch. The author wishes to thank Dr. Dave Naegeli for his help in making the alcohol emulsions, Mr. John Tyler for directing the engine experiments, Mr. Milan Maymar for his excellent work in running the engines and his contributions to the fuel system, and Mr. Ed Owens for his help in the analysis.

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FIGURE 1. RELATIVE ENERGY CONSUMPTION FOR ALCOHOL/DF2 BLENDS

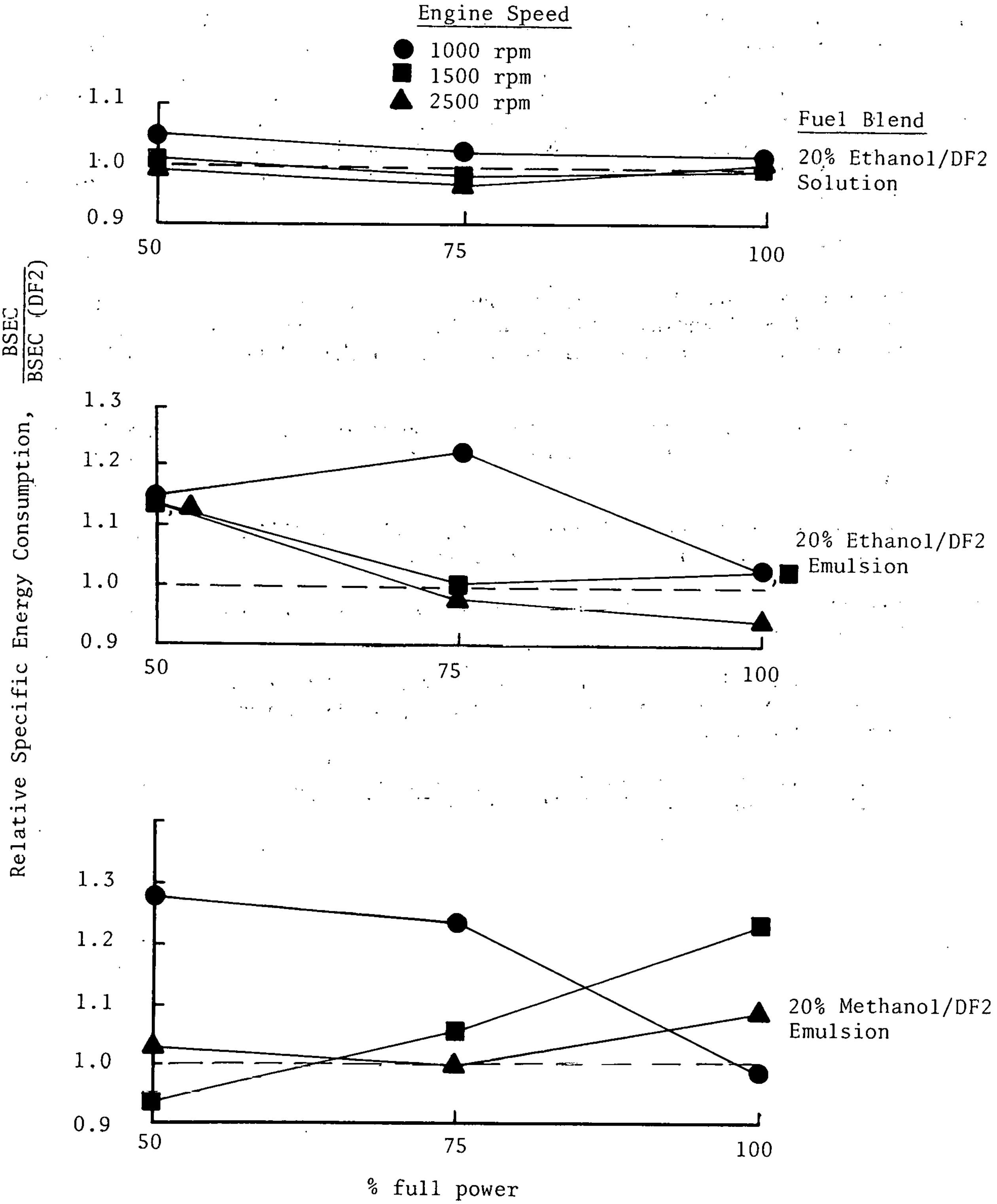


FIGURE 2. COMPARISON OF CYLINDER PRESSURE DATA

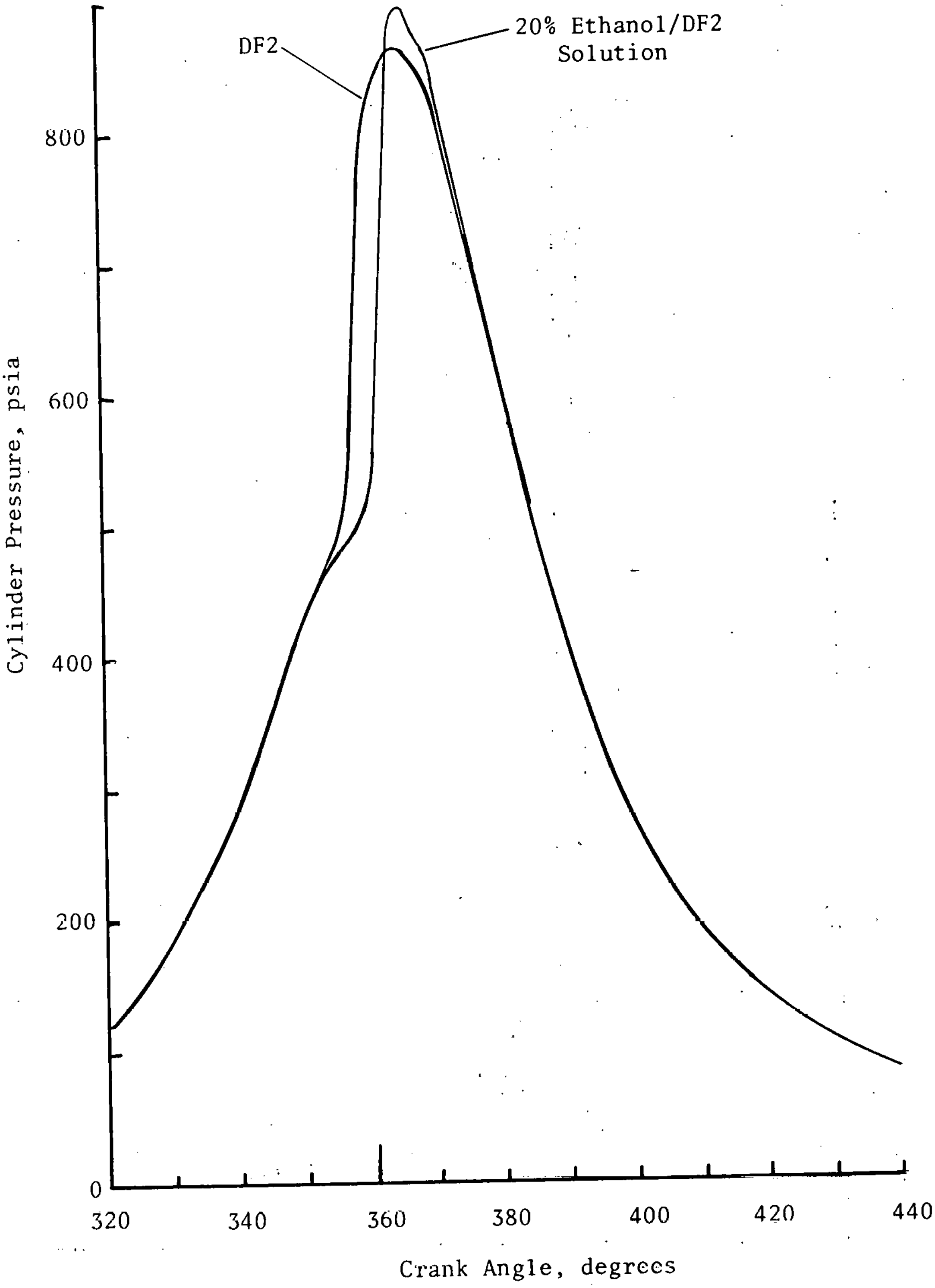


FIGURE 3. COMPARISON OF HEAT RELEASE RATES

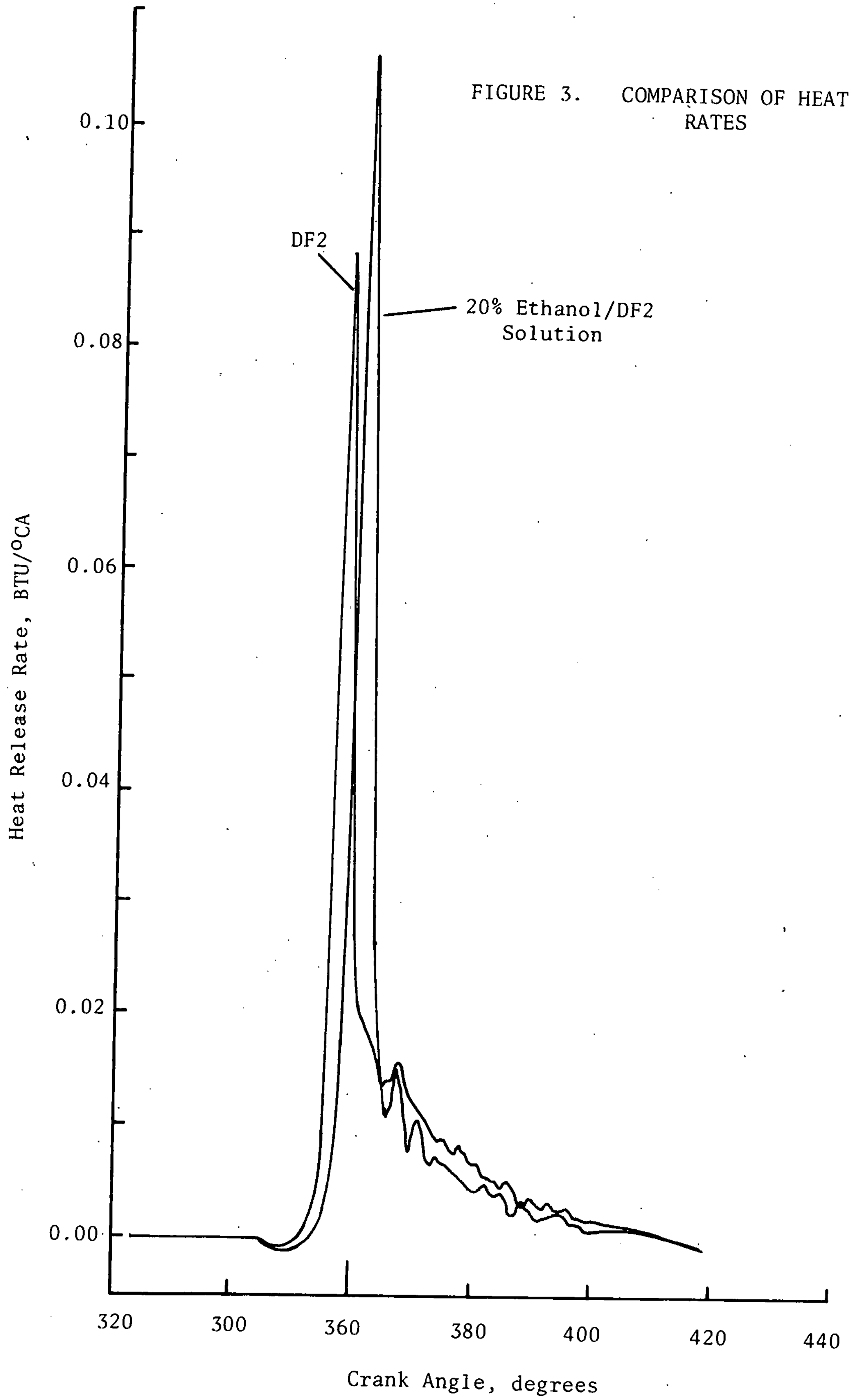


FIGURE 4. EFFECT OF ETHANOL CONCENTRATION ON SPECIFIC ENERGY CONSUMPTION

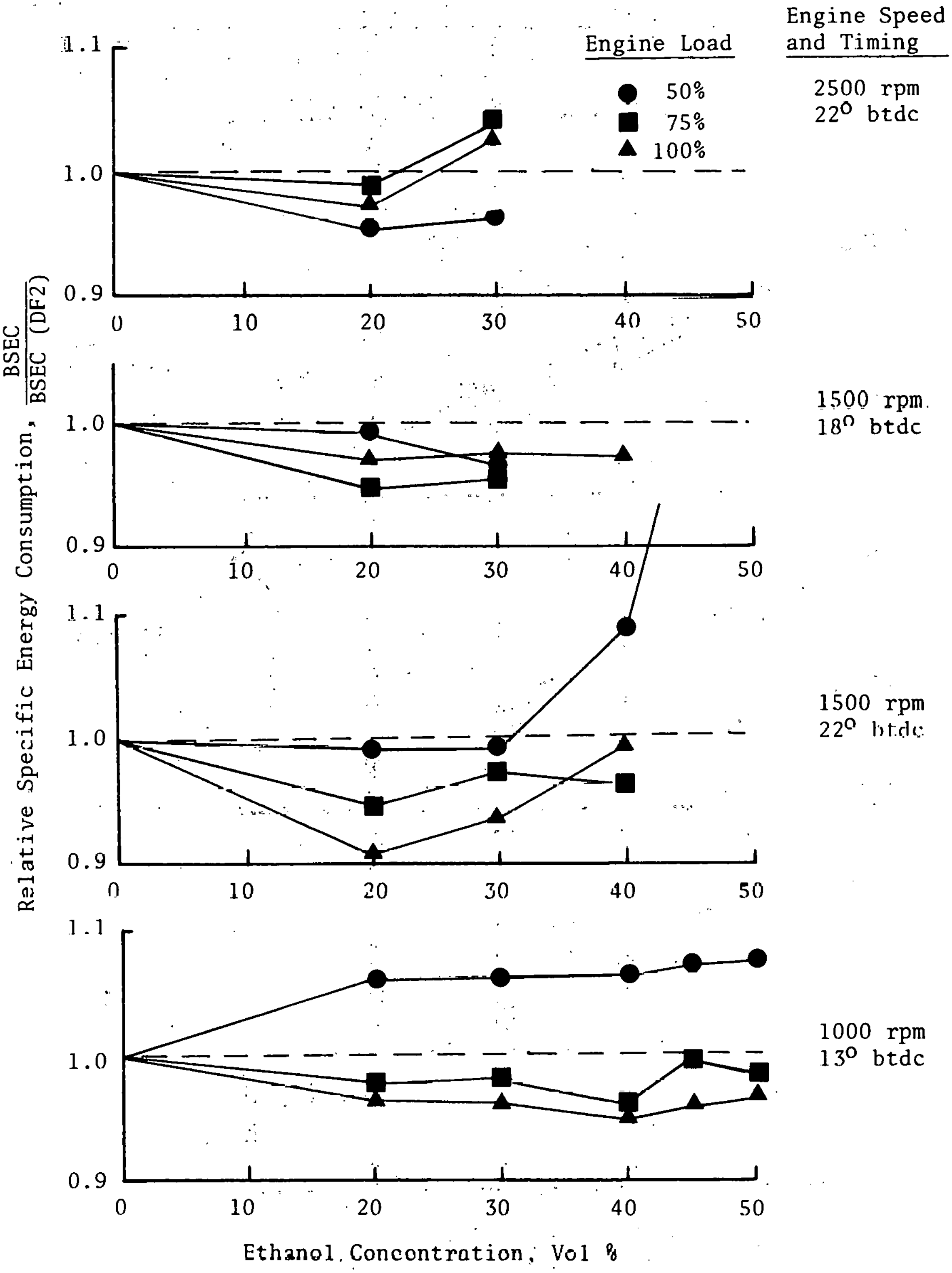
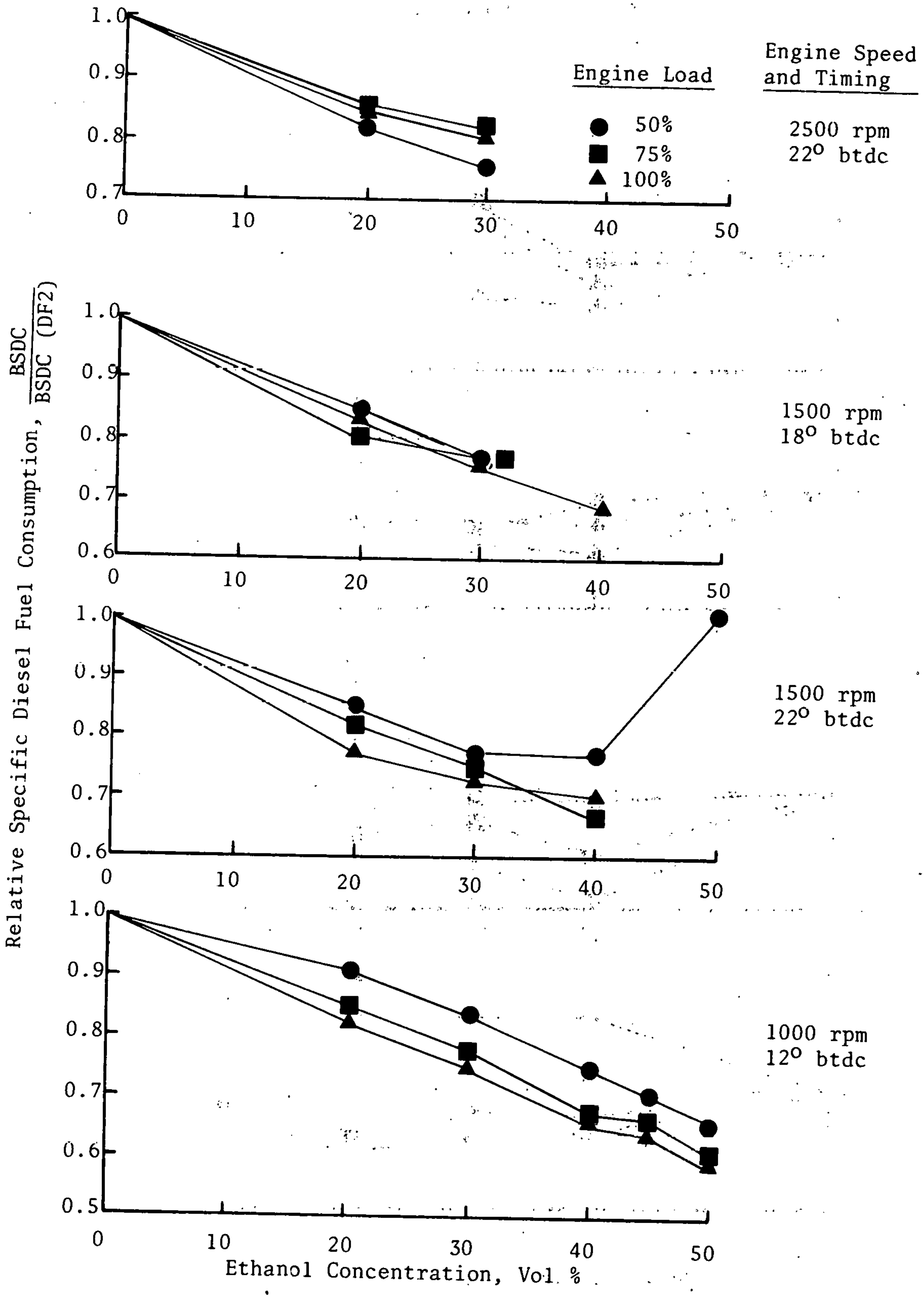


FIGURE 5. RELATIVE CONSUMPTION OF DIESEL FUEL FOR ETHANOL/DF2 SOLUTIONS



AN ASSESSMENT OF ALCOHOL FUELS FOR STATIONARY GAS TURBINES: TECHNOLOGY OF UTILIZATION AND PROSPECTS FOR MATCHING FUTURE ENERGY DEMAND

by,

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ABSTRACT/SUMMARY

This paper is derived from reports prepared by Mueller Associates, Inc. for the U.S. Department of Energy's Alternative Fuels Utilization Branch under contract number EX-76-C-01-2098. [1,2]*

Addressed is the prospect of utilizing alcohols to fuel electric utility peaking gas turbines. Gas turbines require a relatively high quality fuel in order to meet Federal and state emission requirements** as well as for engine protection; alcohol fuels could satisfy both of these requirements. Electric utility personnel are technically oriented which tends to minimize educational requirements. Also, fuel distribution problems may be minimized as there are relatively small numbers of electric utility generating stations compared to other potential users of alcohol fuels (e.g., the highway transportation sector). Perhaps the most "favorable" reason for considering introducing alcohol fuels into the electric utility sector is that electric utilities are heavily regulated by the Federal government (and state governments); thus, any government mandate requiring the introduction of alcohol fuels may be easily implemented. Finally, introduction of alcohol fuels into the electric utility sector may meet less resistance since a relatively small number of people would be "directly" affected.

The paper discusses the current state of technology regarding the use of alcohols for fueling stationary gas turbines. A full scale methanol fueled---- stationary gas turbine test is in progress. To date, an operational 12.5 hour methanol-fueled utility stationary gas turbine test and a 100 hour bench endurance test of the fuel supply system (the combustion system also was tested) from an industrial scale gas turbine engine have been completed. Further, two combustor tests, one each for methanol and ethanol, utilizing combustors from existing stationary gas turbine engines have been completed. Additionaly, work has been conducted involving alcohols to fuel smaller scale gas turbine engines and combustors (including automotive applications) which should be applicable to the larger scale stationary type gas turbine engines with respect to providing a "baseline" for further work.

Also discussed are projections of peaking gas turbine energy requirements to the year 2000. These projections are then assessed against the potential supply of alcohol fuels as provided by a reasonable commercialization scenario.

The overall objectives of this paper then are to present an assessment of:

1. The sufficiency of work performed to establish the feasibility of alcohol as a fuel for stationary gas turbines.
2. Whether or not the status of alcohol fuels utilization technology is defined sufficiently to detail the conversion of existing gas turbines.

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*Numbers in brackets designate references at end of paper.

**Currently, the U.S. Environmental Protection Agency (EPA) regulates only oxides of nitrogen (NO_x) and sulfur dioxide (SO_2) for stationary gas turbines. Alcohols contain no fuel-bound sulfur and generate significantly less NO_x than ventional liquid fuels for gas turbines.

3. Whether or not the status of alcohol fuels utilization is defined sufficiently to detail requirements for the design of new product offerings.
4. How well a reasonable commercialization scenario for alcohol fuels production would match projections of future electric utility peaking gas turbine energy demand.

ALCOHOL FUELS FOR STATIONARY GAS TURBINES: TECHNOLOGY OF UTILIZATION

Overview of Basic Technological Problems Associated with the Utilization of Alcohols in Gas Turbine Engines

Before attempting to define the status of alcohol fuels utilization technology for stationary gas turbines, it is worthwhile to review the basic problems associated with the use of alcohols as compared to conventional liquid fuels for gas turbines:

- Heat Content - Methanol contains only about 50% and ethanol about 65% of the energy, on a volume basis, of conventional liquid fuels for gas turbines. For equal power output, approximately twice as much alcohol must be burned in the combustor(s). Fuel delivery system components must be sized accordingly. Among the components affected are the fuel pump(s), valves, lines/manifolds and nozzles.
- Other Thermal Properties - The alcohols possess flash points significantly less than and flammability limits significantly wider than conventional liquid fuels for gas turbines. These properties become important during engine start-up and shut-down and require that the engine be explosion proof.
- Lubricity - Methanol and ethanol display poor lubricity compared to conventional liquid fuels for gas turbines, thus fuel pumps must be modified and/or lubricating additives mixed with the alcohol fuel.
- Corrosivity - Alcohols are generally more corrosive, especially with respect to aluminum alloys, casting alloys and some plastics, elastomers and sealants.

Engine Modifications

1. Methanol - As indicated by Table 1, the "state of the art" for methanol fueled stationary gas turbines is defined by the only operational stationary gas turbine test conducted to date, the Florida Power Corp. test (completed December, 1974). All engine modifications were conducted using available technology and hardware. The engine converted was a FT4C-1-LF gas generator ($\sim$26 MW). For operation on methanol, larger capacity, dual-fuel manifolds and nozzles(modified previously to accommodate water injection for NO$_x$ control)were installed to account for methanol's lower heat content. Due to the starting characteristics of the fuel nozzles, gas assist starting was required (i.e., the fuel nozzles, designed for No.2 oil, may not atomize the methanol fuel properly). A larger fuel delivery pump was installed due to the increased fuel flow requirement. Finally, lubricating oil was injected into the methanol fuel to lubricate the engine-driven fuel pump (SAE 30 non-detergent oil), although effectiveness was not conclusively established due to the limited test time (i.e., 12.5 hours). Excellent engine performance and emissions were obtained, although full system capacity was not realized (a maximum of 19.2 MW was generated). Full capacity would have been met had a larger capacity fuel modulating control valve and engine-driven fuel pump been installed. [3]

The Southern California Edison test (which ultimately will accumulate 500 hours of simulated peak load firing time) totaled 38 hours of methanol firing time as of the writing of this paper. The test consists of two FT4C-1 gas turbines powering a single generator. One engine burns methanol while the other burns Jet A fuel, thus allowing for performance and emissions comparisons under identical operating and environmental conditions. The only engine hardware modifications were the installation of a larger fuel modulating valve and a larger fuel pump incorporating special seals and seal materials. Testing to date has utilized a Mobil oil additive to the methanol fuel in order to lubricate the fuel pump . However, after inspecting the methanol fuel pump, current plans are to suspend use of the additive for the duration of the test. The test program is expected to be completed in October 1979 and a final report available by the end of the year. A more detailed description of the test program may be found in Reference 1.

2. Ethanol - Although no "operational" utility scale stationary engine tests have been performed in the U.S., significant progress has been made. A 100-hour bench endurance test of the fuel supply system from the Garrett Corp.'s IE831-800 Industrial gas turbine engine (800 HP) was performed during 1976. Garrett also successfully tested the combustion system (fuel nozzle and combustor). The ethanol fuel tested consisted of 84.6 wt.% completely denatured ethanol (formula No. 19) and 15.4% distilled water. The original fuel pump failed due to ethanol's poor lubricating characteristics and was replaced with a redesigned fuel pump. The original fuel valve developed corrosion problems resulting from galvanic action between a steel washer and the aluminum bypass valve. Fuel pump gearshafts and carbon bearings were redesigned to improve bearing fatigue strength, shaft hardness, and lubricating qualities. All fuel bypass valve parts were fully anodized. The fuel supply system then successfully completed 100 hours of durability testing. No modifications were necessary to the combustion system.

The above-described modifications were recommended by the Garrett Corp. for use on their IE831-800AE alcohol fuel engine (two engines were subsequently loaned to the Brazilian government for further testing). [4,5] Two ethanol-powered gas turbine tests have (or are) been conducted in Brazil (apparently in addition to the testing of the two Garrett machines); although, very little information has been published in the U.S. literature. Interested parties may be able to obtain further information through Brazilian government agencies. [6]

Engine Component Design

1. Issues - Tests completed and in progress indicate that existing stationary gas turbine engines may, after minimal engine conversions, be successfully operated on alcohol fuels. However, in order to realize maximum efficiency of operation as well as lowest possible emissions, various engine components should be redesigned. Among the major engine components affected are fuel pump(s), fuel nozzles and combustion chamber(s). To date, components for the larger scale electric utility engines have not been designed explicity for alcohols, except for the Southern California Edison test which is utilizing a specially designed fuel pump.

Fortunately, work has been conducted involving alcohols fueling smaller scale gas turbine engines/combustors (including automotive applications). Although significant differences in scale exist, the basic problems of design/selection of fuel supply systems as well as the mechanisms involved in emissions formation are common to larger gas turbine engines. Thus, much of this work should be applicable with respect to providing a "baseline" for further work. Also, various results of work involving the use of alcohols fueling reciprocating I.C. engines may have applicability to stationary gas turbine engines.

2. Fuel Pump Selection/Lubrication - There are basically two types of fuel pumps: centrifugal and positive displacement. Generally, positive displacement pumps receive lubrication from the fuel itself; centrifugal pumps are often lubricated externally. Many gas turbine fuel pumps are of the positive displacement type.

For the Florida Power Corp. test, SAE-30 non-detergent oil was injected into the methanol fuel to lubricate the engine-driven fuel pump. No problems were evident; but, since methanol is not miscible with oil and the test was of short duration, it is unclear if the oil was an effective lubricant from a durability viewpoint. However, a Belgian utility has used a conventional lubricating oil as an additive in naphtha (naphtha also has poor lubricating characteristics) and there also is a report of castor oils being used for lubricating purposes in methanol. [7,8]

The Southern California Edison test is employing a fuel pump designed for methanol use by the Sundstrand Corp. (sized larger, featuring special seal design and materials). To date, a Mobil lubricant has been utilized as an additive; however, the remainder of the test will employ no additives.

The Union Oil Co. of California tested several additives for anti-wear characteristics and found all but one to be ineffective. Texaco's TFA-431, a lubricity additive for turbine fuels, was found to be effective (with methanol) at concentrations of 500 and 1000 mg/l, but not at 100 mg/l. [9]

With respect to ethanol, no design work has been conducted for fuel pumps for larger utility size engines. However, the Garrett Corp. has successfully redesigned the fuel pump from an 800 HP industrial size engine for operation on an ethanol/water fuel mixture. After two identical fuel pump failures, Garrett redesigned the pump by increasing the radius at the step in the floating bearing outside diameter (to improve fatigue strength), machining a lubricating groove lengthwise in the journal of all four bearings (to enhance lubrication of the journals), and the gearshaft material was changed to increase hardness to RC 60 minimum. One hundred hours of durability testing was then successfully completed.

3. Fuel Nozzle Types: Effects on Emissions

Gas turbine fuel nozzles are designed for optimum utilization of the chemical/physical characteristics of conventional liquid fuels. Thus, consideration of alternative fuel nozzle types seems appropriate.

Fuel droplet size and thus fuel nozzle design strongly influence emissions. Results of the University of Santa Clara test (60 HP) show lower NO_x and CO emissions for methanol for simplex type fuel nozzles with increasing injection pressure, thus smaller fuel droplets. Additionally, utilization of an air-assist-atomizing nozzle (thus, smaller fuel droplets) results in lower relative NO_x emissions; from 96% of the distillate fuel emissions (the best simplex type nozzle results) to only 32%. Correspondingly, CO emissions dropped from 87% to 77%. The University researchers concluded that at low combustor inlet temperatures initial fuel droplet size is important in achieving the low NO_x levels predicted by earlier work (limited ethanol testing yielded similar results). [10]

The effectiveness of air-assist-atomizing fuel nozzles in reducing emissions has a strong dependence upon the air-atomizing pressure drop for a given engine power setting. Results from the University of Santa Clara's work with an air-assist-atomizing fuel nozzle operating with methanol show CO emissions to decrease with increasing air-atomizing pressure, NO_x emissions to first decrease and then increase while HC emissions are shown to first decrease and then level off. Thus, there appears to exist an optimum air-atomizing pressure drop for a given engine power setting in order to "optimize" the engine emissions. In general, with ethanol the same relative trends occurred only with NOx; although, an "optimum" air-atomizing pressure drop does seem to exist. Data for both alcohols were obtained at 75% of engine rated load.

Researchers at GM found the atomizing-air pressure drop for methanol to have a significant affect on CO emissions while NO_x and HC emissions varied only slightly. Increasing the atomizing-air pressure drop caused CO emissions to drop rapidly while NO_x emissions increased slightly. Again, there appears to exist an optimum air-atomizing pressure drop for the given engine power setting in order to "optimize" the engine emissions. Also, it was discovered that use of a modified air-assist-atomizing nozzle (i.e., enlarged fuel passages) provides a significant reduction in CO emissions as compared to the standard air-assist-atomizing nozzle for the same atomizing-air pressure drop. [11]

It is important to note that neither CO nor HC is currently regulated by the U.S. EPA for stationary gas turbines. Thus, it appears NO_x emissions (which are regulated) may be reduced even further with the use of an air-assist-atomizing fuel nozzle.

4. Combustion Chamber Design: Effects on Emissions

Gas turbine combustion chamber design is dictated largely by: (1) proper mixture ratio, (2) temperature of reactants, (3) turbulence for good mixing, and (4) time for burning. Although no work has been reported involving gas turbine combustors designed specifically for alcohols, the above-mentioned design factors indicate that modifications could be made.

Work completed by researchers at Ford Motor Co. indicates appropriate combustor design could have an affect on ultimate emissions from a gas turbine combustor burning methanol. The Ford work shows that NO formation is completed in the immediate vicinity of the fuel nozzle in a regenerative combustor and that the $CO \rightarrow CO_2$ reaction continues until quenched by the secondary dilution ports.* Thus, the researchers indicated that CO emissions from methanol may be reduced (with no apparent adverse influence on NO_x) by moving the combustor's secondary air-dilution ports somewhat further downstream. [12]

Status of Utilization Technology: Systems Approach

Serious efforts to utilize alcohols for fueling utility stationary gas turbines require careful consideration of many factors including technical, economic, legal, and environmental-social. From a systems approach many issues have not been addressed. Table 2 illustrates an attempt to delineate the issues surrounding the utility stationary gas turbine system as a user of alcohols.

In reference to Table 2, the consideration of methanol as fuel for utility stationary gas turbines has centered on the issues contained in the first block under the columns titled "STATIONARY GAS TURBINES MANUFACTURING" and "STATIONARY GAS TURBINE USE". The present status of these issues are as follows:

Stationary Gas Turbine Manufacturing:

- Patents - no reported work.
- Lube Development - SAE 30 non-detergent oil, Texaco's TFA-431 turbine fuel additive, a Mobil lubricant and castor oil may be satisfactory additives for lubrication of fuel pumps.
- Fuel Specs - no reported work.
- Material Compatibility - As a result of automotive studies aluminum, some alloys (primarily of Al, Mg, Zn), plastics, elastomers and sealants are susceptible to corrosion or swelling. Special seals and seal materials have been identified for fuel pumps.

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* Ford work involved analyzing gas samples obtained from within the combustor.

- Explosion Proofing - no reported work; however, many engines are rated as explosion proof for volatile fuels such as naphtha.
- Fuel Nozzles - no reported work.
- Fuel Pumps - Sundstrand Corp. has designed a pump (currently being tested).
- Combustors - no reported work.

Stationary Gas Turbine Use:

- Start-up/Shut-down Requirements - Engines employing dual-fuel water-injection type fuel nozzles may require gas assist starting.
- Conversion Vs. Replacement - not established; however, tests indicate conversion may be possible.

Serious efforts to introduce and utilize methanol as fuel for utility stationary gas turbines should address all of the issues indicated in Table 2. Some of the issues contained in the first five columns have begun to be addressed as a result of interest in methanol as an automotive fuel.

Consideration of ethanol is not as advanced as for methanol due to the lack of any utility scale operational tests. However, as was the case with methanol, some of the issues contained in the first five columns of Table 2 have begun to be addressed as a result of interest in ethanol as an automotive fuel. Also, work conducted by the Garrett Corp. on their 800 HP industrial engine fuel/combustion system may be suggestive of some viable solutions to the engine-related technical problems. In addition, the status of ethanol fuel technology may be altered as a result of work presently being conducted in Brazil.

PROJECTED PEAKING GAS TURBINE ENERGY REQUIREMENTS VERSUS POTENTIAL ALCOHOL FUELS SUPPLY: 1980-2000

This discussion is based upon a study conceived to determine if a reasonable commercialization scenario for alcohol fuels production would match future elecctric utility peaking gas turbine energy demand from the year 1980 to 2000. [2] Addressed are projections of peaking gas turbine energy demand and a plausible scenario for the future production of alcohol fuels. Net energy and overall systems economics considerations are not addressed; however, the affect of fuel cost on electricity rates is discussed briefly. Unfortunately, there are inherent difficulties in predicting both future peaking gas turbine energy requirements and potential alcohol fuels supply due to uncertainties in predicting future electric utility energy requirements in general and the fact that a widespread alcohol fuels industry does not yet exist in the United States.

Projected Peaking Gas Turbine Energy Requirements

The Oak Ridge Associated Universities Institute for Energy Analysis (ORAU) and the General Research Corp. (GRC) have projected peaking gas turbine energy requirements to the year 2000. [13, 14] In 1976, ORAU published projections of peaking gas turbine energy requirements based upon an estimate of the 1973 energy consumption and an assumed average energy growth rate of 7% per year to the year 2000. Our adjustment of the base energy value using the actual 1973 energy generated data and an average net efficiency value of 24% [15] resulted in the projected energy requirements as illustrated in Fig. 1. The GRC projections utilized data obtained from the Department of Energy's Inventory of Power Plants for pre-1985 estimates and information received from the regional offices of the National Electric Reliability Council (NERC) for post-1985 estimates. Utilizing the GRC projected capacity/capacity-factors and the DOE-EIA average net efficiency of 24% we obtained the energy requirements as illustrated in Fig. 1. The other projections illustrated in Fig. 1 were derived from estimates/information obtained from studies and/or information obtained from the Petroleum Industry Research

Associates, Inc.(PIRINC), the Edison Electric Institute (EEI) and the National Electric Reliability Council (NERC). Reference 2 should be consulted for details of assumptions and methodologies employed.

Projected Potential Alcohol Fuels Supply

Projections of alcohol fuels availability were obtained from the Mitre Corporation and the U.S. DOE. [16, 17] Mitre projected methanol from wood (forest products) and ethanol from agricultural crops/residues that could supply a 5% blending stock for automotive gasoline by 1990. All projections assume that a concerted effort is made to produce alcohol fuels.

The DOE projection reflects a production scenario which entails ten coal-to-methanol plants, each producing approximately 1.9 million gallons per day of methanol, that could be on-stream by 1990, followed by one plant per year to the year 2000 (see Fig. 1). The Mitre Corp. methanol from wood projection involves ninety plants, each producing approximately 65 million gallons per year of methanol, to be on-stream by 1990 at a rate of introduction as indicated by Fig. 1 (we assumed the rate of introduction for the 1990-2000 time frame to be equivalent to the DOE projection, on an equal energy basis). Finally, the Mitre Corp. ethanol from agricultural crops/residues projection involves eighty-six plants, each producing approximately 67 million gallons per year of ethanol, to be on-stream by 1990 at a fixed rate of introduction as indicated by Fig. 1 (again, we assumed the 1990-2000 time frame rate of introduction to be equivalent to the DOE projection, on an equal energy basis).

Peaking Gas Turbine Energy Requirements Vs. Potential Alcohol Fuels Supply

In reference to Fig. 1, if the ORAU energy requirements are considered as more indicative of a limiting boundary and not characteristic of future trends, the resultant energy value of projected alcohol fuels production could supply all of the projected utility peaking gas turbine energy requirements as early as 1987, nearly three times the projected energy requirements for the year 1990, and about four times the projected energy requirements for the year 2000. Any one of the three alcohol fuel/resource combinations could supply all of the projected peaking gas turbine energy requirements by about 1990. Alcohols from agricultural crops/residues and forest products together could provide about 45% to 55% of the projected 1985 peaking gas turbine energy requirements. Methanol form coal is not projected to be available until 1986.

Electricity Production Costs: Alcohols Vs. Conventional Fuels (1975)

The methodology involved in deriving electricity rates due only to peaking gas turbines is complex. However, it is possible to examine the affect of fuel cost variability on the cost to produce electricity generated by peaking gas turbines (i.e., exclusive of transmission costs and return on investment). As a baseline, we examined the ten electric utility systems with the largest gas turbine capacity as of 12/31/75, representing 30.4% of the total 1975 net generation and 41.9% of the total capacity for U.S. electric utility peaking gas turbines. [15] We performed a weighted average analysis (weighted to the net generation by fuel type) to obtain representative values of electricity costs due to fuel per kilowatt-hour (net) of generated power (by fuel type). These values are illustrated in Fig. 2 as the solid vertical lines, for oil and gas, on the left ordinate scale. The weighted average cost for the alcohols (see Fig. 2) w based on "average" prices of $0.50 and $1.10 per gallon for methanol and ethanol, respectively and the MAI-calculated weighted average heat rate of

14,597 BTU/Kwh (net). The range of costs were obtained utilizing the maximum and minimum prices for oil and gas in conjunction with the weighted average heat rate (irrespective of fuel type). Maximum and minimum alcohol prices were those stated in Reference 17.

We derived the total electricity production costs (the right ordinate scale on Fig. 2) utilizing a 1976 Federal Energy Adminstration study which indicated that capital costs amount to 50% of the total production cost with the remainder composed of fuel and operating and maintenance costs (O & M). [18] The DOE-EIA reported that 1975 fuel and O&M costs (for the utilities represented) were related to each other as a ratio of 77 (fuel) to 23 (O&M). Thus, total production costs break down as 50% capital, 38.5% fuel and 11.5% O&M. We varied only the relative fuel costs to obtain the results shown in Fig. 2.

Therefore, based on 1975 fuel cost data and using the lowest price for alcohol, the total cost of electricity produced by peaking gas turbines would be about 65% higher than if this electricity were produced from using the highest price fuel oil (110.1 mills per kilowatt-hour versus 67.2 mills per kilowatt-hour).

CONCLUSIONS

- It appears that methanol is a feasible fuel for utility stationary gas turbines. No operational tests on ethanol have been conducted to demonstrate its feasiblity.
- Results of the Florida Power Corp. test imply that utility stationary gas turbines can be successfully converted for operation on methanol. The results of the Southern California Edison Co. test may confirm this. No utility scale engines have been converted for ethanol; however, the Garrett Corp. work with their 800 HP engine suggests viable solutions.
- Little or no work has been initiated for designing <u>new</u> electric utility gas turbine engines for operation on alcohol fuels.
- It appears that should a concerted effort be made to produce alcohol fuels they could supply all of the projected electric utility peaking gas turbine energy requirements as early as 1987; however, the final electricity production costs will probably be higher than with conventional liquid or gaseous fuels.

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Table 1. GAS TURBINE ENGINE/COMBUSTOR/FUEL SYSTEM TESTS

TYPE	ORGANIZATION	TESTS	RESULTS/FINDINGS
Full Scale, Utility, 26.9 MW (methanol)	Southern Calif. Edison Company	• Emissions • Durability • Operation	In Progress
Full Scale, Utility, ∼26 MW (methanol)	Florida Power Corporation	• Emissions • Operation	• NO_x 74% less, CO 100% greater than No. 2 oil. • Larger capacity fuel manifold/nozzles of type for H_2O injection result in satisfactory operation • Gas generator temperature lower than No. 2 oil. • Larger capacity fuel pump/modulatino value required to develop full power potential.
Single Combustor Test from GE MS7001B, 65 MW (methanol*)	General Electric Company	• Emissions • Operation	• NO_x 60% less; CO 300% greater than No. 2 Distillate. • Predicted 6% gain in power output and 2% gain in thermal efficiency. • Some fuel system components must be redesigned
Full Scale 60 HP Solar T-45M-13 (methanol & ethanol)	University of Santa Clara - California	• Emissions • Operation	• Best simplex fuel nozzle methanol NO_x 4% less and CO 13% less than Jet A Fuel. • Best air-assist-atomizing fuel nozzle methanol NO_x 68% less and CO 23% less than Jet A Fuel. • Equivalent power output with methanol achieved at 40°F lower exhaust temperature than Jet A Fuel. • Best air-assist-atomizing fuel nozzle ethanol NO_x 62% and CO 1% less than Jet A Fuel.
IE-831-800 Industrial Engine 100 Hour Fuel System Test and Combustion System Test (ethanol/water blend	The Garrett Corporation	• Fuel System Durability • Combustion System Operation • Emissions	• Fuel pump modification added/lubrication capabilities and fuel value annodization required for successful operation. • Combustion system (fuel nozzle & combustor) successfully completed rig test, excellent light-offs obtained, no metal temperatures above 1350 F indicated. • NO_x 76% less than liquid fuel.
Full Scale, Utility, 2 tests, 2 Garrett machines on loan (ethanol)	Brazilian Government	Unknown	Unknown
Combustor, Industrial, From W-21 1800HP engine (ethanol)	Westinghouse Electric Company	• Emissions • Operation	• NO_x 0.7 No. 2 oil, CO slightly less than No. 2 oil, HC significantly less. • No signs of coking or excessive wall temperatures indicated. • No operational problems.
Full Scale, Automotive, GT-225 experimental engine (methanol)	General Motors Corporation	• Emissions • Performance	• Passages of air-assist-atomizing nozzles enlarged, gear-type fuel pump replaced with swash-plate piston pump & diaphragm (fuel valve) material changed. • Air-atomizing pressure drop found to have significant effect on emissions. • Under transient operation, methanol produced 73% less NO_x, 30% less CO and 60% more HC than kerosene. • Under transient operation, little fuel economy differences observed.
Combustor, Automotive (methanol)	Ford Motor Company	• Emissions	• NO production is effectively completed in immediate vicinity of fuel nozzle. Differences in emissions due to details of droplet burning process and associated heterogeneous chemistry. • NO_x 70% less than No. 2 oil, CO 240% greater than No. 2 oil.
Full Scale, Automotive (ethanol & methanol)**	Chrysler Corporation	• Emissions	• Under engine idle conditions, methanol & ethanol CO is 6.6 and 1.06 times greater than No. 1 Diesel; methanol and ethanol NO_x is 0.17 and 0.37 times No. 1 Diesel. Under acceleration conditions, NO_x is 0.34 times No. 1 Diesel for methanol and ethanol.
Full Scale, and Combustor, Automotive (methanol)	Volkswagenwerk AG	• Emissions	• Combustor tests showed HC and CO the same as kerosene and No. 2 Diesel with NO_x 4 to 5 times lower. • Engine tests demonstrated no loss of driving power after enlarging x-sections of fuel regulator and increasing injection pressure for the fuel nozzles.

*Also tested were 25% methanol/75% No. 2, 80% methanol/20% H_2O and No. 2 with H_2O injection.

**Also tested were isopropanol, 40% methanol/60% gasoline, 40% isopropanol/60% Diesel, 40% denatured ethanol/60% gasoline, 150° proof rum.

Table 2. THE ISSUES SURROUNDING THE STATIONARY GAS TURBINE SYSTEM AS A USER OF ALCOHOLS

MAJOR FACTORS AFFECTING SYSTEM TRADE-OFFS	SUBDIVISIONS OF MAJOR FACTORS	RAW MATERIAL	RAW MATERIAL TRANSPORT	FUEL MANUFACTURE	FUEL DISTRIBUTION	FUEL RETAILING	STATIONARY GAS TURBINES MANUFACTURING	STATIONARY GAS TURBINE USE	STATIONARY GAS TURBINES MAINTENANCE
TECHNICAL FACTORS	R & D	EXTRACTION PROCESSES; HARVESTING	SLURRY TRANSPORTATION; SLASH HARVESTING	PATENTS; PROCESSING AND/OR CONVERSION TECHNIQUES, FUEL SPECS/DENATURANTS	PUMPS PIPELINES-MATERIALS	PUMPS, STORAGE TANKS	PATENTS, LUBE DEVELOPMENT, FUEL SPECS; MATERIAL COMPAT., EXPLOSION PROOFING, FUEL NOZZLES/PUMPS; COMBUSTORS	START-UP/SHUT-DOWN RQ'MTS; CONVERSION VS REPLACEMENT	SPECIAL INSTRUMENTS & INSPECTION REQUIREMENTS/PROCEDURES
	PROOF OF CONCEPT (DEMOS)	PILOT PLANTS	DEMO PIPELINE & OTHER TRANSPORT SYSTEMS	DEMONSTRATION PLANTS; FUELS COMPOSITION	DEMONSTRATION DISTRIBUTION SYSTEMS	DEMO/TEST MARKETING	AVAILABILITY OF FUEL SUPPLY AND HARDWARE FOR DURABILITY, RELIABILITY, LARGE SCALE/DURATION TESTS; GOV'T SUPPORT	LARGE SCALE/DURATION TESTS-ENGINE CONTROL	LARGE SCALE TESTS
	PRODUCTION DESIGN	SPECIAL EXTRACTION/HARVESTING EQUIPMENT	PUMPS, SEALS, VALVES, FITTINGS, ETC...	PROCESS OPTIMIZATION PATENTS	ASSESS DELIVERY EQUIPMENT, SAFETY PROVISIONS	FIRE FIGHTING EQUIP.	FUEL TANKS, INCORP. NEW MATERIALS, FUEL PUMPS, FUEL FLOW SYSTEMS, COMBUSTORS/NOZZLES	OPERATION MANUAL	NEW EQUIPMENT DESIGN; RE-WRITE MAINTENANCE MANUALS
	PRODUCTION	AG., FOREST, & MINING TECHNIQUES	SPECIALIZED TRANSPORT VEHICLES/SYSTEMS	CONSTRUCTION OF FACILITIES			TOOLING DESIGN, OEM SUPPLIERS	USE OF ENGINES FOR BASELOAD OPERATION	MANUFACTURE OF EQUIPMENT
	END USE & INFRASTRUCTURE		DEVISE MEANS OF SUPPORT IF NEEDED			SERVICE PERSONNEL TRAINING	SUPPLIES TO TURBINE MFG. FACILITIES	CONSUMER EDUCATION	DEVELOP SERVICE CAPABILITIES
ECONOMIC FACTORS	CAPITAL REQUIREMENTS	NEW MINES, CROPS/HARVEST EQUIP., LEASE ACQUISITION	MORE HOPPER CARS, PIPELINES, BARGES & HARVESTING TRANS. VECH.	NEW SYNGAS/PROCESS PLANTS, GOV'T SUPPORT	MORE TANK CARS, TRUCKS, PIPELINES	MORE TANKS PUMPS, PIPELINES	REVISED MFG. PLANTS	NEW/EXPANDED STORAGE TANKS; RETRO-FIT Vs. NEW MACHINES	INVEST IN NEW EQUIPMENT AND PERSONNEL TRAINING; RETROFIT RQ'MTS
	OPERATING COSTS	REGIONAL LOGISTICS; AG. SUBSIDIES/PRICE SUPPORT	RAIL VS. PIPELINES; RESOURCE CONVERSION PLANT LOCATIONS	FUEL SPECS., SUPPLEMENTAL PRODUCTS	NATIONAL VS. REGIONAL DISTRIBUTION; BATF RQ'MTS	BATF REQUIREMENTS	COST OF NEW MATERIALS AND THEIR USE	FUEL PRICE CHANGE, TAXES;	CHARACTERISTICS OF NEW EQUIPMENT
	ENERGY UTILIZATION (NET ENERGY)	SHOVELS, MINERS, DRAG LINES, FARM EQUIP.	ENGINES, PUMPS	INCREASED USE OF BOILERS, HTRS & EQUIP.	INCREASED USE OF ENGINES, PUMPS	INCREASED USE OF PUMPING SYSTEMS		. BTU'S/GAL. CHANGE	
	EMPLOYMENT	MINING & AG. PERSONNEL & TRAINING NEEDS	RAIL, PIPELINE & BIOMASS HARVEST PERSONNEL & TRAINING NEEDS	MFG'G, INDUS., & BATF., SUPPORT PERSONNEL & TRAINING NEEDS	INCREASED RAIL PIPELINE TRUCK AND BATF PERSONNEL NEEDS	BATF PERSONNEL	MFG. PERSONNEL & TRAINING NEEDS	PERSONNEL TRAINING	QUALIFIED PERSONNEL
	INSTITUTIONAL DISLOCATIONS	COMPETITION FOR OTHER RAW MATERIAL AND LAND USE	RIGHT OF WAY ACQUISITION EFFECTS	PLANT SITE LOCATIONS; NATIONALIZATION	RIGHT OF WAY ACQUISITION EFFECTS				
	SECONDARY IMPACTS	MINE SUPPORT SERVICE, NEW TOWNS		PLANT SUPPORT SERVICES; OTHER FUEL USE COMPETITION	PIPELINE, TANK-CAR & TANK MANUFACTURE	DEMAND FOR PUMPS, TANKS, & EQUIPMENT	OEM SUPPLIERS	USE OF ENGINES FOR BASELOAD OPERATION; LOCAL TAX CHANGE	AFTER MARKET SUPPLIERS FOR CRITICAL MATERIALS
LEGAL FACTORS	LAND & RESOURCE MANAGEMENT	ACQUIRE FEDERAL COAL LEASES, H_2O RIGHTS; COMPETING LAND USES	ROUTING OF WATERWAYS, PIPELINES & RAIL	LOCATION OF PLANTS AND SUPPORT FACILITIES	INCREASED FUEL STORAGE REQUIREMENTS			ENGINE SITING RQ'MTS	
	REGULATORY	AG. SUBSIDIES/PRICE SUPPORT	RIGHT OF WAY ACQUISITION EFFECTS	TREASURY DEPARTMENT ETHANOL CONTROL; FOREIGN COMPETITION		EMISSION & BATF RQ'MTS	UNIQUE WARRANTY REQUIREMENTS; EMISSION RQ'MTS	PRICE CONTROL, MANDATORY USE; EMISSION & SITING RQ'MTS	SERVICE PERSONNEL CERTIFICATION
	TAXATION	NATIONAL AND [illegible] TAX UNIFORMITY	INTERSTATE TRANSPORTATION	INVESTMENT INCENTIVES, ALCOHOL TAX BONDS		THERMAL VS. VOLUMETRIC		PURCHASE INCENTIVES, SPECIAL TAX ON ALCOHOL	
	DIVESTITURE	ANTITRUST CONSIDERATIONS							
	MISCELLANEOUS	INDIAN RIGHTS	CONTAINMENT OF RESOURCE MATERIALS, EFFLUENTS, AND WASTE PRODUCTS	ETHANOL DENATURANTS, ENTITLEMENTS	SPECIAL LABELING		UNIQUE LIABILITY CONSIDERATIONS		
ENVIRONMENTAL/SOCIAL FACTORS	ENVIRONMENTAL	LOCAL LAND CONTOUR, WATER COMPETITION		AIR, WATER	VAPOR EMISSIONS, SPILLS		NON REGULATED EMISSIONS - AIR QUALITY (UNBURNED ALCOHOLS, ALDEHYDES, PNA'S); USE OF ENGINES FOR BASELOAD OPERATION		
	HEALTH & TOXICOLOGY			INHALATION/ABSORPTION; INGESTION EFFECTS & DENATURING					
	SAFETY	MINE SAFETY IMPROVEMENT		OSHA REQUIREMENTS FOR SAFE FUEL HANDLING PROCEDURES					SERVICING TECHNIQUES
	IMPACTS	NEW TOWNS, DISLOCATIONS; EFFECTS OF LABOR STRIKES	EFFECTS ON WILDLIFE	WATER USAGE	COMPETING USES; AVAIL. OF FUEL TO DISTRIBUTORS	INDUSTRY ADAPTATION; JOB DISPLACEMENT		COMPETING USES; AVAILABILITY OF FUEL	SERVICE AVAILABILITY

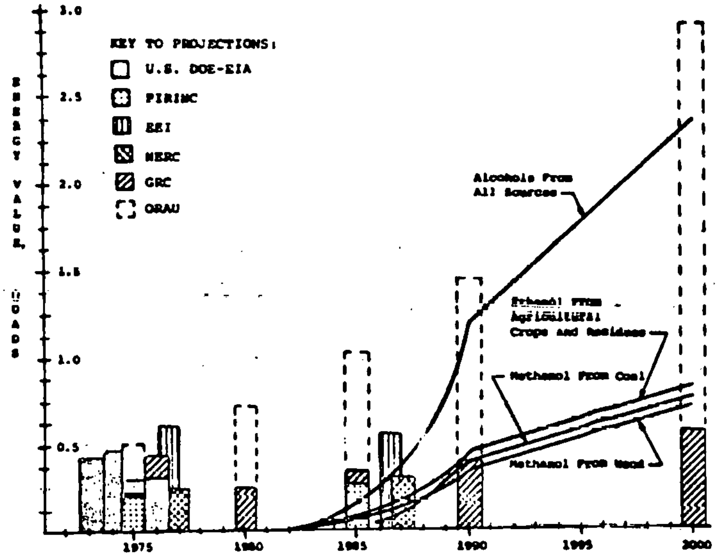

FIGURE 1, COMPARISONS OF GAS TURBINE ENERGY REQUIREMENTS WITH POTENTIAL ALCOHOL FUELS SUPPLIES

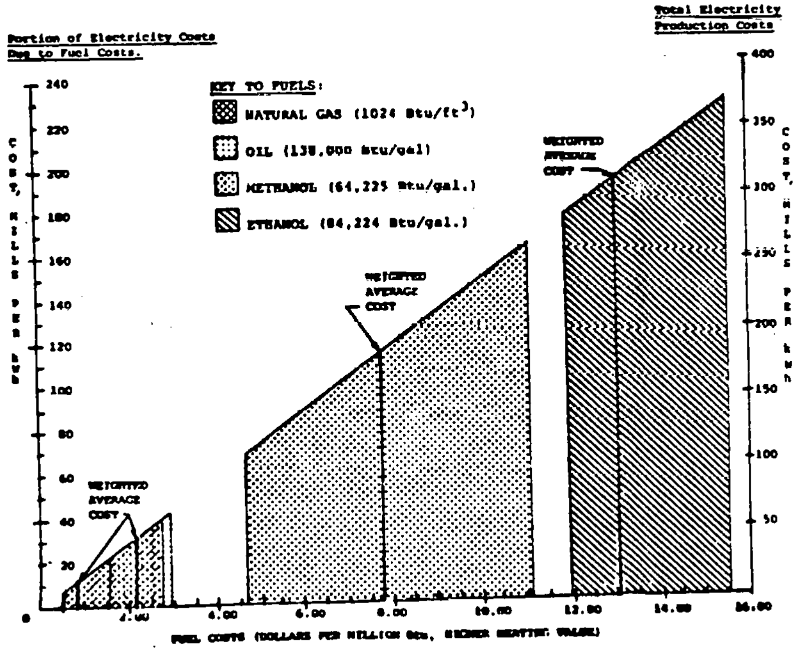

FIGURE 2, ELECTRICITY PRODUCTION COSTS VERSUS FUEL COSTS

EVALUATION OF METHYL-TERTIARY BUTYL ETHER AS A GASOLINE BLENDING COMPONENT

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ABSTRACT

The use of methyl tertiary butyl ether (MTBE) as a gasoline blending component was studied in laboratory bench tests, with dynamometer engines and in vehicle chassis dynamometer tests. Octane studies have determined MTBE blending RON values to be between 110 and 130. Fuel system materials compatibility evaluations indicated a slight swelling of some elastomeric materials with 20 percent blends in comparison with gasoline. Studies to identify individual HC constituents in engine exhaust gases showed that gasoline and MTBE-gasoline blends yield the same types of hydrocarbons. Multi cylinder engine dynamometer studies with a 20 percent blend and with Indolene Clear alone gave equal exhaust emissions at equal spark timing, equivalence ratio, speed and load. Fuel consumption for the blend was determined to be 4 to 6 percent higher at the same equivalence ratio. MBT spark timings for 20 percent blends were within 2 degrees of gasoline values, indicating a minimal effect of MTBE on burn rate.

Vehicle tests confirmed the engine dynamometer observations. Exhaust emission changes were consistent with a lean shift in equivalence ratio. Volumetric fuel consumption increased when an exhaust air-fuel sensor was used with a feedback carburetor to adjust equivalence ratio back to stoichiometric. However, when the equivalence ratio was allowed to shift lean, the improved engine efficiency offset the lower fuel heating value so that fuel consumption was equal to that of the base gasoline test. Cylinder-to-cylinder air-fuel mixture distribution was not affected by the addition of MTBE.

INTRODUCTION

Methyl tertiary butyl ether (MTBE) has been shown to be an effective octane blending component (1-7)*. Because of this and because its properties are fairly close to those of other gasoline components, MTBE provides a convenient way to utilize methanol, one of the starting materials for its production, as a gasoline component. The use of MTBE retains the octane advantage of methanol, but lessens disadvantages such as tendency to phase separation, enhancement of corrosion of some materials, and increased fuel front end volatility. MTBE is made from methanol and di-isobutylene (8) and therefore could also supplement petroleum fuels to the extent of isobutylene availability. The primary use of isobutylene is as an alkylation feedstock. The

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* Numbers in parentheses designate References at end of paper.

resulting alkylate RON blend value is 94 to 96. If the isobutylene is diverted to MTBE production, the RON blend value is upgraded to about 120. Since the fuel cost depends primarily upon material cost rather than additional processing, the cost per volume of MTBE will be about equal to the alkylate it replaces, but the cost per road octane unit improvement is one-fourth the cost of alkylate (9).

The blend characteristics of various oxygenates can be significantly different and must be considered in the selection of an octane blending component. A number of difficulties have been demonstrated with methanol blends (10). One specific concern with methanol blends as a gasoline extender is the increased volatility. Volatility can be lowered by removing light hydrocarbons from the blend, however this results in a net loss in available transportation fuel energy (11). MTBE has less effect on blend volatility so that removal of petroleum components should not be necessary.

Considering the desirable blend characteristics compared with alcohols and a reasonably competitive anticipated cost, MTBE blends must be included as one of the means to supplement transportation fuels from non-petroleum sources now being developed. Accordingly, a test program was conducted to confirm the literature on octane value, exhaust emissions, performance and fuel consumption of MTBE-gasoline blends. Studies reported on MTBE blends have shown that HC and CO emissions were decreased by the addition of MTBE, while NOx emissions and fuel economy were not significantly affected. Fuel octane quality was improved, however, hot driveability depreciated slightly due to the tendency of the blend to cause vapor lock under high ambient temperature conditions. No problems with material compatibility or phase stability have been reported. Additional measurements were made in this program of fuel system material compatibility. Three-way catalyst activity and exhaust gas unburned fuel constituents were also measured.

LABORATORY STUDIES

FUEL PROPERTY CHARACTERIZATION The commercial application of MTBE is expected to be in the range of 5 to 10 percent with an expected upper limit of 20 percent. Laboratory tests involved use of 20 volume percent MTBE (European commercial grade) in Indolene Clear gasoline. A qualitative analysis of the MTBE based on a combined gas chromatography mass spectrometry survey showed the sample to contain methanol, butene and di-isobutene, isobutanol and butyl methyl ether along with MTBE. The MTBE-gasoline blends were volumetric mixtures with no modification made to control blend properties. Fuel properties are given in Table I and Figure 1. The gasoline distillation curve is affected over the 20 to 65 percent evaporation region, Figure 1a; MTBE addition at the 20% level causes a 14 C reduction in temperature for evaporation over the region. Measurements on vapor to liquid ratio, Figure 1b, show V/L of the blend to be higher than for gasoline at temperatures above 52 C. These changes in volatility are consistent with reports of improved cold start warm-up behavior and an increase in vapor lock tendency (1). Other properties of the fuels are only slightly different, indicating a small influence of MTBE. Research and motor octane values for 20% MTBE blends in Indolene Clear were increased by 2.5 and 1.2 units due to MTBE, corresponding to blending RON and MON values of 110 and 95.

CATALYST EFFECTIVENESS Catalyst activity determinations were made for CO, NOx and unburned fuel. A laboratory "pulse flame apparatus" commonly utilized for catalyst testing (12) was used. The device was operated with a three way catalyst using isooctane and a 10 percent MTBE isooctane blend. Measurements were made to determine MTBE effects on catalyst activity and to identify the catalyst effluents. Concentrations of exhaust constitutents were determined at the catalyst inlet and outlet using the two fuels, Table 2. The ratio of outlet to inlet concentrations is also given in Table 2. Gas analysis was based on application of Fourier Transform Infra Red Spectroscopy (FTIRS) (13). Comparison of results with the two fuels shows no strong fuel effects on distribution of exhaust consituents or overall concentrations. With MTBE, the concentrations of iso-butene and formaldehyde at the catalyst inlet were higher as were NO and NO2. At the catalyst outlet NO and NO2 levels were reduced to about the same values however several of the hydrocarbons were higher with the blend; these include ethylene, propylene and Iso butene. Total HC values at the catalyst outlet were somewhat higher with the blend even though catalyst inlet values were nearly the same. This pulse flame result indicating lower HC activity with the blend was not supported in subsequent vehicle testing which involved a different three-way catalyst, therefore this result is not considered representative. The only explanation for the apparent lower efficiency is that the baseline test, conducted substantially before the blend test, was not fully equivalent in all operating conditions.

A chemical analysis of neat fuel grade MTBE did not reveal the presence of known catalyst poisons.

MATERIALS COMPATIBILITY Studies to assess compatibility of MTBE with materials comprising fuel systems involved submersion of the materials in gasoline (Indolene Clear), a 20% MTBE-gasoline blend and neat MTBE. Materials tested are listed below.

MATERIAL	APPLICATION
zinc	carburetor body
aluminum	carburetor body
brass	fuel jets
nitrile	float bowl gaskets
neoprene	fuel lines
epichlorohydrin	choke control diaphragms
cellular rubber	carburetor floats
viton	fuel inlet valve seats
flourosilicone	accel. pump diaphragms

submersion period was about four months at a temperature of ut 20 C. During this interval, measurements of fuel color change, precipitate formation and change in weight and volume were made.

Most material changes occurred rapidly and were essentially complete after the first 40 hours of submersion. Changes in weight and volume measured at 1100 hours are summarized in bar-graph form in Figure 2. Metals such as aluminum, zinc and brass were not affected by MTBE however with water present in the blend brass was corroded. Elastomeric materials varied in their response to MTBE; cellular rubber exhibited less swelling in MTBE than in gasoline alone. Neoprene had a substantial weight and volume change with all three fluids. The other elastomers (viton, flourosilicone, epichlorohydrin and nitrile) exhibited an increase in swelling and/or weight as MTBE content of the fuel was increased, however their response was small at the 20 percent blend level. Coloration of all liquids generally changed from an initial water clear color to a slight yellow as submersion period increased. With cellular rubber there was a slight yellowing of liquid with MTBE but a very pronounced yellowing with gasoline alone. With neoprene there was a slight yellowing with gasoline and the 20 percent blend and a very deep yellowing with neat MTBE. This could reflect leaching of matter from the elastomers.

Present observations did not indicate any serious material swelling or weight change problems with MTBE use at levels below 20 percent in gasoline. It should be noted however that this study represents an initial attempt to identify materials problems with MTBE blends and that studies involving additional materials and measurements on properties important to failure mode are needed.

ENGINE DYNAMOMETER TESTS

OCTANE STUDIES The octane quality of MTBE blends was determined by rating the blends on a 2.3L 4 cylinder engine using full boiling range reference fuels. This was believed to be a better representation of road octane than the Research and Motor methods. Blends consisting of 10 and 20 volume percent MTBE in 85, 91 and 97 RON reference fuels were used. The blends could not be rated directly, however, because of the shift in equivalence ratio. A procedure was developed to rate the blends using manual control to match equivalence ratio.

The engine was operated at 1700 and 2450 rpm with the intake manifold depression set at 1.5 in-Hg and with fuel-air ratio set 10 percent rich of stoichiometric. Knock limited spark advance was determined for each of the reference fuels and blends. Spark timing was dynamically advanced at a rate of about 0.5 degrees per minute from TDC to a point where knock, as indicated by individual cylinder combustion pressure records, was observed. Emissions, torque and engine temperatures were monitored as a function of spark timing during each "spark scan". The blend was assigned the octane value of the reference fuel with the same knock-limited spark timing. Blend research octane values, Figure 3, increased linearly with MTBE content at each speed and with each of the fuels. Blending RON values for operation at 1700 rpm are near 130. At 2450 rpm, blending octane values are near 11 These results are consistent with the literature (1-7).

In obtaining knock limited spark advance data, a measure of MBT spark timings was also made. MBT spark timings were obtained from spark scans using fuels with a sufficiently high octane that the knock limit was more advanced than MBT. The presence of MTBE at the 20 percent level in gasoline had essentially no effect on MBT spark timing. At 1700 rpm MBT spark timing was changed from 23 BTDC for gasoline to 25 BTDC with the blend; at 2450 rpm the shift was from 26 BTDC to 24 BTDC. With such small changes in MBT and the apparent reversal in trend, it was inferred that the burn characteristics of gasoline and the blends were the same.

EMISSIONS AND FUEL CONSUMPTION Emission and fuel consumption measurements were made on the 2.3L engine using Indolene Clear gasoline and a 20 percent MTBE blend. Test points were chosen on the basis of importance in the CVS engine operating range. Speed/brake-torque values were 1400 rpm/27 Newton Meters (N-m), 1800 rpm/34 N-m and 1800 rpm/68 N-m. Spark timing settings were referenced to a 2.3 litre engine in a manual transmission vehicle. Spark timing was adjusted ±5 and ±10 degrees from this reference. At each spark setting, air-fuel equivalence ratio was dynamically scanned from rich to lean while torque output of the engine was held constant to within ±2 N-m. During scanning, exhaust emissions and engine temperatures were monitored. Results obtained in consecutive tests with the two fuels were compared at common operating conditions and equivalence ratios to determine MTBE effects. Representative results are shown in Figure 4. Both fuels exhibited the same emission response to changes in speed/load, equivalence ratio and spark calibration. The HC, CO, NOx and exhaust temperature are almost identical at each common value of speed/load, spark timing and equivalence ratio. This indicates the lack of adverse effects on regulated emissions of an engine using blends containing up to 20 percent MTBE provided that mixture stoichiometry is maintained.

During mixture ratio scanning tests at the three speed/load points, relative fuel consumption rates of the engine with the blend and with gasoline were also determined. Fuel consumption of the blend was 4 to 7 percent higher than with gasoline at common operating conditions and equivalence ratios, with the largest difference being at lean equivalence ratio and retarded spark timing. Based on the relative heat content of a 20 percent blend and of gasoline, a 4 percent increase in fuel consumption was expected.

Unburned fuel exhaust constituents due to MTBE were also identified during the dynamometer tests. The engine was operated at a fixed speed, load, spark and equivalence ratio while bag samples of exhaust gas were collected for analysis by Fourier Transform Spectroscopy methods. Results of one set of measurements with the two fuels are given in Table 3 which lists the exhaust constituents and their concentrations. MTBE causes an increase in nitrous acid, iso-butene, formaldehyde and Methyl alcohol. The increase in iso-butene and formaldehyde is consistent with the "pulse flame" results of Table 2. The same types of exhaust constituents are present with gasoline and 20 cent MTBE blends.

VEHICLE TESTS

A 1977 Federal vehicle with a 2.3 litre engine and manual transmission and a 1978 California vehicle with 2.3 litre engine and automatic transmission were used to compare Indolene with a 20% MTBE blend. The 1977 vehicle was was tested with standard carburetion and with the oxidation catalyst removed to determine effects of direct fuel substitution on engine emissions. The 1978 vehicle was tested in its production configuration with exhaust air-fuel sensor, feedback carburetor, three-way-catalyst and downstream oxidizing catalyst to determine the overall effects of MTBE on tailpipe emission levels with equivalence ratio adjustment.

DIRECT SUBSTITUTION Engine exhaust emissions and fuel consumption were measured over the CVS-C/H test cycle with the 1977 vehicle. Overall equivalence ratio and cylinder-to-cylinder distributiion were determined at idle and cruise up to 50 mph. No carburetor adjustments were made to accommodate differences in properties of the blend. Fuel economy determinations were based on a carbon balance as outlined in the Federal Register but with MPG values adjusted to account for fuel oxygen content.

Test results are given in Table 4, which shows individual bag mass emissions along with CVS-H and CVS-C/H emissions. Test repeatibility was poor, however the directional effect of the blend on emissions can be seen. The 20% MTBE blend decreased HC and CO and increased NOx values as indicated by the ratio of average results listed at the bottom of the table. The HC decrease is 20 to 30 percent, the CO decrease is 40 to 50 percent and the NOx increase is between 12 to 22 percent. The emission ratios are about the same for CVS-H and for CVS-C/H tests. These emission changes are expected based on mixture leaning. The stoichiometric A/F of the blend is about 4 percent lower than that of Indolene. Based on information such as shown in Figure 4, an equivalence ratio shift from 0.95 to 0.99 could account for the observed emission changes. The emission results agree with published information on MTBE blend substitution effects.

Along with emissions, fuel consumption was measured with both fuels. Results, in Table 4, show fuel consumption to be about the same with the blend and gasoline. The fact that fuel economy was not compromised by MTBE addition was unexpected since the 20 percent blend has 4 percent less heating value than gasoline. The reduced heating value apparently was offset by improved efficiency at the leaner mixture ratio. Others also have reported this type of fuel economy effect in direct fuel substitution tests with standard carburetion (1,3,5).

Results of steady state tests to determine individual cylinder and overall air-fuel equivalence ratios are shown in Table 5. Mixture distribution was unaffected by the fuel change while the the lean shift with the blend was about as expected. Individual cylinder measurements of equivalence ratio at idle and at 50 MPH deviate from overall average values by about 0.02 units with both fuels. Mixture leaning at idle was near 6 percent and at 50 MPH was about 1.3 percent, compared with the expected percent shift in equivalence ratio if metered mass fuel fl rates are identical. The fact that the measured leaning effect exceeds 4 percent at idle and is less than 4 percent at 50 MPH indicates that carburetor metering characteristics with the blend deviate from those with gasoline.

FEEDBACK CARBURETION WITH CATALYSTS The 1978 California vehicle was also operated over the CVS-C/H test cycle with a 20% MTBE blend and with gasoline. Results from the cold start portion were not consistent due to hardware difficulties unrelated to the test fuels. Observations made during hot portions of the tests showed that all three emission constituents were lower with the blend that with gasoline, Table 4. Since the engine measurements showed no differences in emissions at the same equivalence ratio, these vehicle differences are believed to be due to the non-feedback operating modes, idle and power enrichment. Fuel consumption was determined by the feedback modes. A 3 to 6% increase was observed, corresponding with the 4% loss in heating value.

CONCLUSIONS

Based on laboratory, engine dynamometer and vehicle chassis dynamometer tests, the following conclusions regarding MTBE use in gasoline are drawn:

- MTBE is an effective octane booster for unleaded gasolines with blending research octane numbers in the range of 110 to 130.
- Addition of MTBE to current gasolines at levels up to 20 volume percent causes increased fuel midrange volatility. The effects on driveability under extreme temperatures must be determined.
- Laboratory bench tests indicate HC activity of a three way catalyst to be reduced slightly when 10 percent MTBE blends replace gasoline. Vehicle results do not indicate a reduced HC activity. The laboratory results may reflect differences in test conditions and are not considered to be representative.
- Compatibility tests on selected fuel system materials showed that blends with up to 20 percent MTBE cause no serious swelling, weight change or corrosion problems but significant swelling of some elastomers is observed with neat MTBE. Further materials testing is needed.
- Chemical analysis of exhaust gases with blends and gasoline shows both fuels to produce the same products in similar concentrations. Therefore, health effects are expected to be similar to gasoline exhaust. However, these tests were not comprehensive regarding worst case operation.
- Based on MBT spark timing, MTBE blends have combustion rate characteristics equivalent to gasoline.
- Exhaust emissions with blends and gasoline in multi cylinder engine dynamometer tests are the same when speed, load, spark timing and mixture equivalence ratio are the same.
  Exhaust emissions for vehicles with non-feedback carburetion reflect mixture leaning effects in direct blend substitution

tests.

- Cylinder-to-cylinder mixture distribution in the engine is the same with gasoline and a 20 percent MTBE blend.

Results of this study show that combustion characteristics are acceptable for MTBE in gasoline at blend levels up to 20 volume percent. Regulated emissions with blends and with gasoline are essentially the same when adjustments are made for the shift in equivalence ratio. This would involve recalibration of carburetors or use of feedback carburetion. Additional work in the area of unregulated emissions and materials compatibility is needed along with further vehicle testing under more extreme environmental conditions.

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Table 1 Selected Properties of Fuels

Property	Ind. Clr.	20 MTBE Blend	Neat MTBE(*)
Specific Gravity (15 C)	0.739	0.741	0.746
Vapor Pressure (38 C, kPa)	64.1	62.1	x
Hydrocarbon Content (FIA) Vol. Percent			
Aromatics	25.8	25.9	x
Olefins	3.9	4.2	x
Saturates	70.3	69.9	x
Research Octane	97.7	100.2	117.0
Motor Octane	89.0	90.2	101.0
Stoich. A/F	14.55	13.99	11.74
Net Heat Content (cal/gr)	10600	10100	8394.
Boiling Point (C)	FBR (**)	FBR	55.00
Latent Heat of Evap. (cal/gr)	FBR	FBR	76.7

(*) From Ref. 9
(**) FBR refers to full boiling range fuel

Table 2 Pulse Flame Study of MTBE Effect on Three-Way Catalyst Activity

Compound	Concentration* w/Isooctane Cat In	Cat Out	Cat Out / Cat In	Concentration* w/Blend** Cat In	Cat Out	Cat Out / Cat In
1 H_2O (%)	1.13	2.38		1.06	1.38	
2 CO_2 (%)	14.47	15.28	1.06	12.91	14.58	1.13
3 CO	13685	4768	0.384	12600	5632	0.447
4 HC	-	-	-	-	-	-
5 NO	313	77	0.246	347	77.3	0.222
6 NO_2	66	5.7	0.086	91	2.7	0.030
7 N_2O	1	1.8	1.818	1.1	.7	0.636
8 HONO	9	3.5	0.386	5.0	1.1	0.220
9 HCN	14	4.7	0.330	11.3	3.6	0.327
10 NH_3	1.8	1.2	0.663	1.7	0.5	0.286
11 SO_2	11.9	6.6	0.560	5.2	4.2	0.795
12 CH_4	577	396.2	0.686	448.	405.3	0.904
13 C_2H_2	140	14.0	0.100	120.	10.3	0.090
14 C_2H_4	529	78.7	0.149	465	139.3	0.299
15 C_2H_6	66	32.9	0.500	55.	35.5	0.636
16 C_3H_6	348	84.6	0.245	351.	108.3	0.309
17 IC_4H_8	416	103.4	0.248	478.	122.5	0.255
18 CH_2O	10.5	1.6	0.152	15.	1.4	0.100
19 HCOOH	3.	3.0	1.000	1.9	1.0	0.474
20 CH_3OH	5 5	17.1	3.110	5.6	.9	0.160
TOT HC (PPM C)	4774	1337	.280	4716	1595	.338
TOT NOx	389	86.2	0.222	438.	81.2	0.182

* Concentration expressed in PPM unless otherwise indicated.

** Blend is 10% by vol. MTBE in isooctane.

Table 3 Influence of MTBE Addition to Gasoline on Composition of Exhaust Gases with a 2.3L Four Cylinder Engine

Speed: 1400
Load: 27.1 N•M Brake
$\varnothing_{FA}$: Lean ∿ 4.0% O_2

Compound	Amt in Gasoline*	Amt in 20% MTBE Blend*
H_2O (%)	11.36	10.69
CO_2 (%)	10.75	10.42
CO	1116	1104
HC	554.4	481.2
NO	232	144.1
NO_2	258	248.5
N_2O	4.7	4.9
HONO	8.3	11.2
HCN	-2.5	-0.9
NH_3	.7	.6
SO_2	2.9	3.2
CH_4	39.7	41.0
C_2H_2	57.3	50.2
C_2H_4	138.3	123.0
C_2H_6	3.5	2.7
C_3H_6	130.6	120.5
IC_4H_8	65.0	106.8
CH_2O	65.5	84.2
HCOOH	5.7	5.1
CH_3OH	5.3	10.9
TOT HC	1065.3	1025.5
TOT NOx	497.9	403.7
O_2 EXH (%)	3.8	4.1

*Concentration expressed in PPM unless otherwise indicated

Table 4 Vehicle Emission Test Results

		CVS-CH, gm/mi			CVS-H, gm/mi			Fuel Consumption L/100 km	
Fuel	Test	HC	CO	NOx	HC	CO	NOx	CVS-CH	CVS-H
I. 1977 Federal 2.3L, Non-Feedback Carburetor, No Catalyst									
Indolene	1	3.3	23	2.5	2.9	21	2.5	10.5	10.3
	3	-	-	-	3.8	52	1.9	-	10.9
	6	-	-	-	3.2	19	2.3	-	10.0
	7	3.6	41	1.9	3.1	37	1.9	11.1	10.7
Avg.		3.4	32	2.2	3.2	32	2.2	10.8	10.5
20% MTBE in Indolene	2	-	-	-	2.3	19	2.3	-	10.5
	4	-	-	-	2.5	16	2.6	-	10.5
	5	2.9	20	2.4	2.8	18	2.4	10.6	10.4
Avg.		2.9	20	2.4	2.5	18	2.4	10.6	10.5
Avg. Ind. Cl. / Avg. 20% Blend		.85	.62	1.1	.78	.56	1.1	.98	1.00
II. 1978 California 2.3L, Feedback Carburetor Three-Way + Oxidation Catalysts									
Indolene									
Avg.	1-5	-	-	-	.11	.11	.94	-	12.1
Avg.	10-12	-	-	-	.09	.08	.89	-	12.0
20% MTBE in Indolene									
Avg.	6-9	-	-	-	.06	.05	.72	-	12.8

Table 5 Individual Cylinder and Overall Air-Fuel Mixture Ratio (λ)

A) Fuel - Indolene Clear

Test Condition	λ (1)	λ (2)	λ (3)	λ (4)	λ Overall
Idle	.983	.942	.936	.909	.949
10 MPH	-	-	-	-	.915
20 MPH	-	-	-	-	.976
30 MPH	-	-	-	-	1.003
40 MPH	-	-	-	-	1.077
50 MPH	1.124	1.070	1.057	1.097	1.090

B) Fuel - Indolene Clear with 20% MTBE

Test Condition	λ (1)	λ (2)	λ (3)	λ (4)	λ Overall
IDLE	1.030	.989	1.003	.976	1.010
10 MPH	.989	.956	.956	.936	.962
20 MPH	1.023	.983	.962	.956	.989
30 MPH	1.057	1.010	.983	.983	1.010
40 MPH	1.111	1.063	1.050	1.063	1.097
50 MPH	1.145	1.084	1.070	1.084	1.104

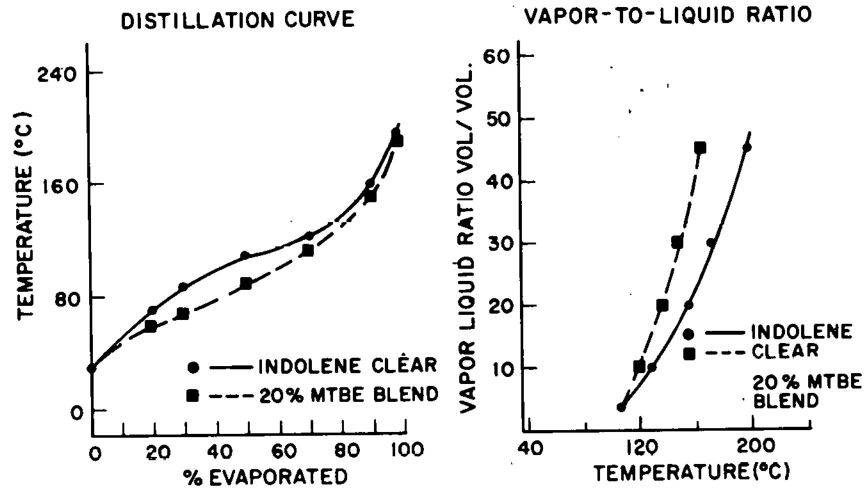

FIGURE 1 - DISTILLATION AND VAPOR/LIQUID CURVES FOR INDOLENE CLEAR AND 20% VOLUME PERCENT MTBE BLEND

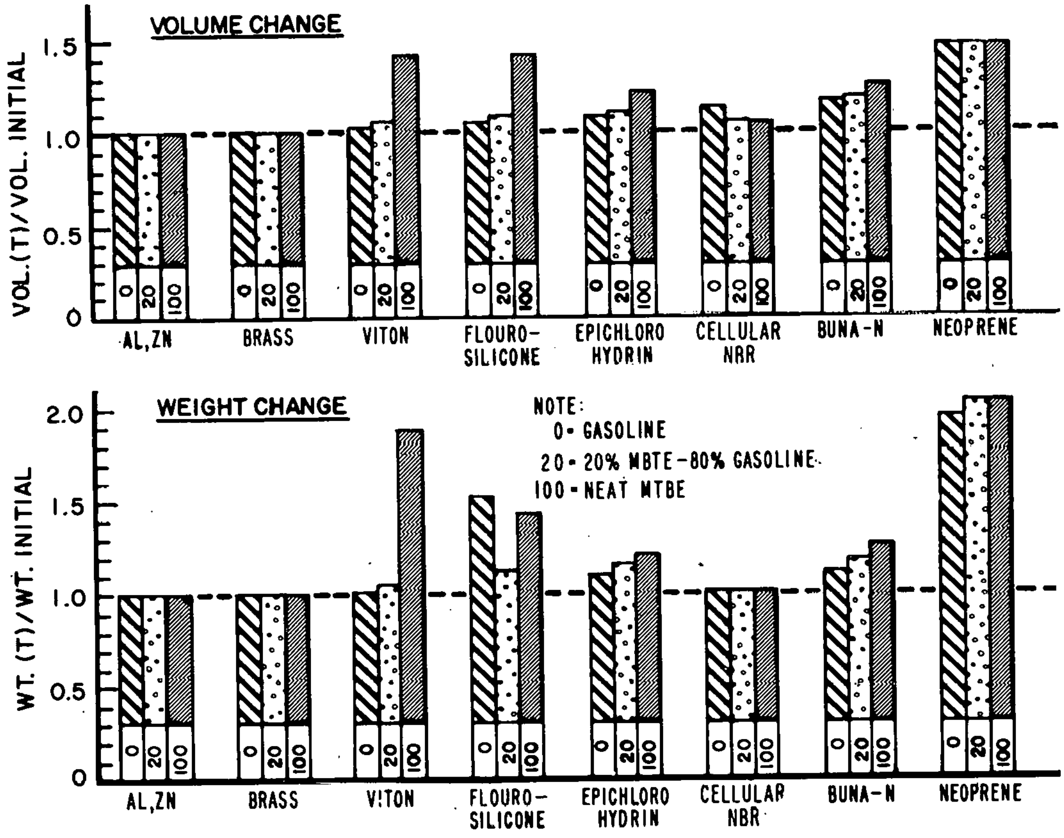

FIGURE 2 - VOLUME AND WEIGHT CHANGE OF MATERIALS AFTER 1100 HRS. SUBMERSION IN MTBE - GASOLINE BLENDS

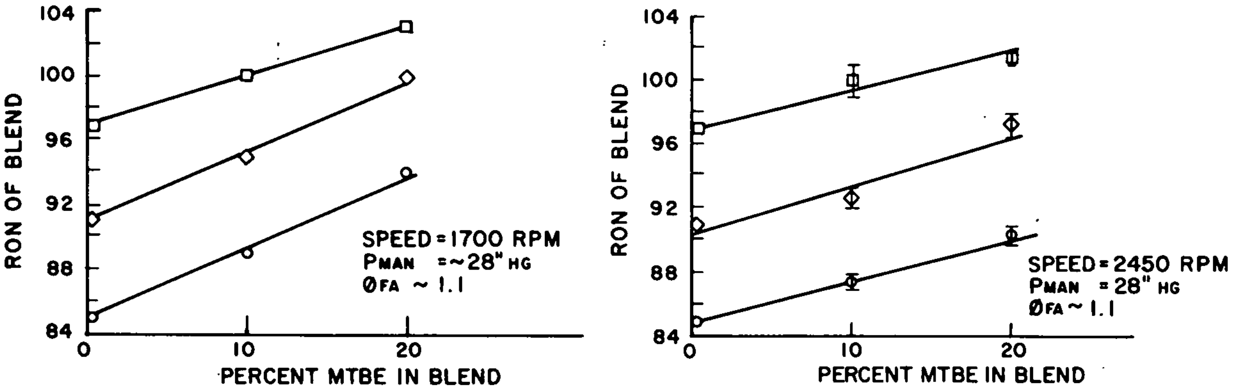

FIGURE 3 - INFLUENCE OF MTBE CONTENT ON BLEND OCTANE VALUE

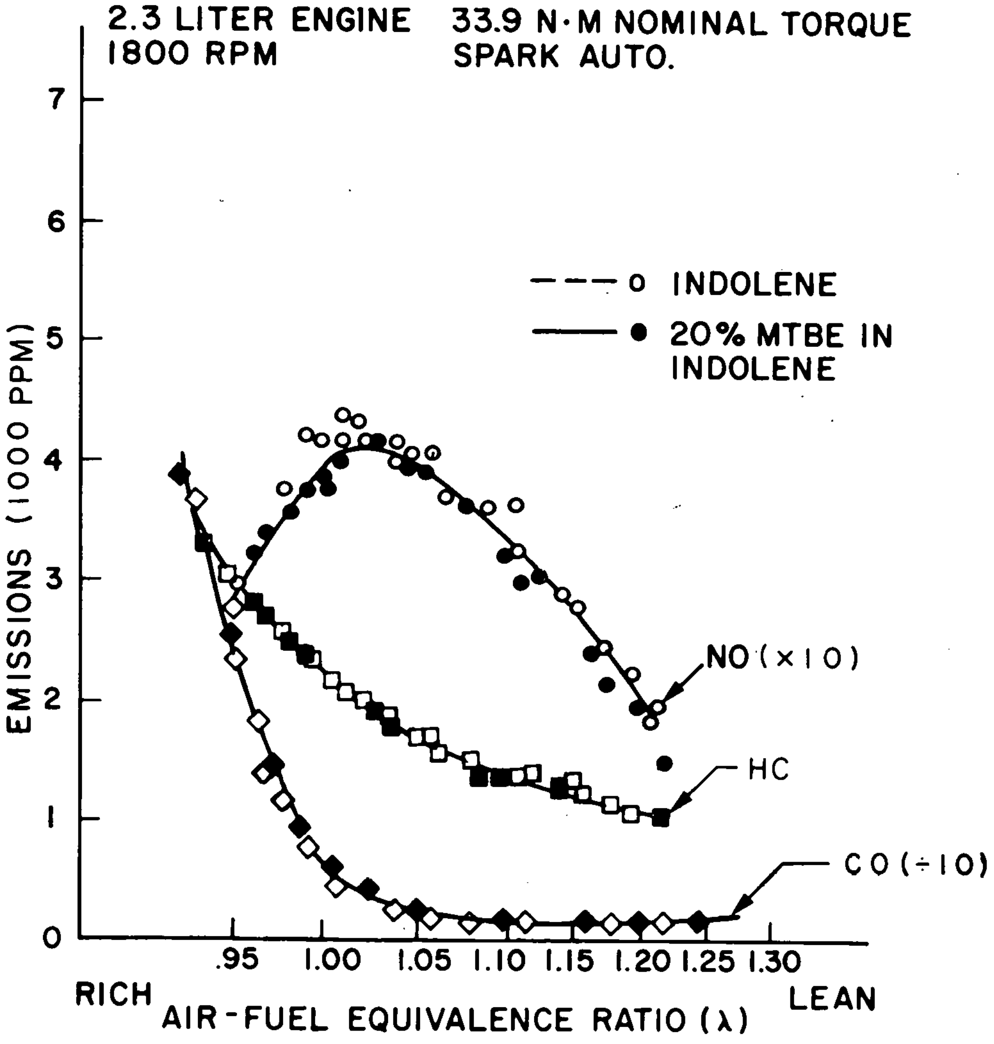

FIGURE 4 - EMISSIONS VARIATION WITH MIXTURE RATIO FOR GASOLINE AND MTBE BLEND

HARDWARE/SOFTWARE STRATEGIES FOR FUEL ECONOMY OPTIMIZATION WITH EXHAUST EMISSION CONSTRAINTS IN METHANOL FUELED AUTOMOBILES

by

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ABSTRACT

An experimental investigation of 4-cylinder 2.3L spark ignition engines was undertaken to examine steady-state power, thermal efficiency (fuel economy), and exhaust emissions while operating on methanol at three compression ratios. The effects of camshaft modification, exhaust system modifications, and fuel type are evaluated in terms of both steady state and simulated driving cycles relative to a 'baseline' established at 8.5:1CR on Indolene. Some possibilities for lean engine operation on methanol are discussed in light of possible engine control strategies. Three engine control stratgeies are introduced for evaluation of current and future engine hardware-carburetion configurations. One of these strategies is based on a constrained mathematical optimization of fuel economy with exhaust emission constraints in an urban driving cycle.

INTRODUCTION

In the search for viable alternative fuels for transportation systems, methanol and ethanol are emerging as attractive candidates to supplement (in the near term) or replace perhaps (in the long term) petroleum derived fuels in both compression and spark (SI) ignition multicylinder engines. A U.S. Department of Energy sponsored research program [1] at this institution is currently investigating the end use of pure methanol in SI engines, with emphasis both on engine optimization and on assessment of environmental impact. Engine optimization for methanol operation is being approached from analytical, engine-dynamometer, and fleet vehicle perspectives. Environmental impact is being assessed in terms of comparative photochemical reactivity of methanol and gasoline exhausts, and in terms of biological disruptions resulting from both marine and terrestrial spill situations.

The purpose of this paper is to review progress in the experimental arena of multicylinder SI engine modification for methanol usage, in reference to our results which were presented at a previous symposium [2], and to introduce some empirically based computer simulation methods for assessing engine control strategy (a constrained mathematical optimization procedure). It is this interaction of an empirical engine data base with a mathematical procedure, which describes techniques to minimize exhaust emissions while maximizing fuel economy, that leads to the concept of engine control strategy as a combination of hardware and software considerations.

Prior Work and Scope of Current Engine Studies

The prior work [1,3] concentrated on establishing a data base of Indolene baseline and comparative methanol fuel economy and emissions results for a 2.3L four-cylinder engine. A variety of fuel-air mixture preparation systems were described, and in the current work, all have been retained with the exception of an electronically controlled fuel injection system. At constant Φ* and 8.5:1 CR, both steady state and simulated driving cycle results for all the methanol systems showed improvements in energy-based fuel economy, when contrasted with the Indolene baseline results. In a simulated hot start urban driving cycle (U.S. FTP), a sonic carburetor predicted improvements in fuel economy ranging up to 30% over the Indolene results for the idealized case of constant Φ. Geometric maldistribution (cylinder-to-cylinder variation in Φ), hereafter termed simply maldistribution, at steady state was identified as a major impediment to the full realization of methanol's lean burning potential. Two fueling systems which eliminated this detrimental phenomena were described, and on the basis of 'engine out' (as opposed to 'tailpipe out') emissions at fixed Φ, it was postulated that at very lean Φ (0.7) the NOx standard of 0.4 gm/mi could be met without the need of exhaust gas recirculation or a reduction catalyst. However, these 'hot' FTP simulation results indicated that an oxidation catalyst for control of unburned fuel (UBF) would be required for this lean burning condition. Driveability and emission constraints imposed by real engine behavior for cold start, warm-up, and transient behavior were not addressed in these predictions.

The scope of the current program has expanded the data base, by obtaining results at 10:1 and 11.3:1 CR in the 2.3L four-cylinder engine. Extension to the more efficient compression ratios (CR) is made possible through methanol's high octane number. Improved camshaft and exhaust system designs have also been evaluated in terms of steady state mapping (and subsequently driving cycle simulations) in an attempt to gain additional exhaust emission and fuel economy benefits while meeting emission standards with methanol, the scope has been expanded to include optimization schemes in the simulation of the U.S. FTP. This type of study is currently receiving much attention with regard to gasoline powered vehicles as a first step in the search for possible engine control systems [4,5,6]. In a similar fashion, the intent of these studies is to explore the tradeoffs among fuel economy, NO_x, UBF, and CO emissions for methanol data bases. This software strategy is an attempt to provide a predictive model, a diagnostic package, and a design tool based on engine maps toward the ultimate goal of optimized vehicles which, by definition, are vehicles which meet emission standards in the urban cycle, while maintaining maximum fuel economy in both urban and highway driving cycles.

HARDWARE, MODIFICATIONS AND TESTING METHADOLOGY

Carburetion

Four of the five fuel-air induction systems described in an earlier paper [2] were retained for steady state testing of modified 2.3L (squish-type combustion chamber) engines. Two of the carburetion systems utilize the stock venturi

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*Φ - Fuel-air equivalence ratio = $A/F_{stoich} \div A/F_{actual}$.

carburetor modified for Φ control; one for Indolene and a rejetted version of the same for methanol operation. Control of Φ, in both, was attained through pressurization of the fuel bowl. The third system investigated was a sonic carburetor, mounted directly on the stock intake manifold. Using only methanol, Φ control was attained by the positioning of a variable flow area, slotted fuel bar. The fourth system was an individual cylinder acoustic fuel metering system, designed for methanol operation. Use of the electronically controlled EFI system was abandoned due to the lack of control over air flow induced maldistribution which was experienced during and after speed and load changes.

Camshaft

The stock overhead camshaft in these engines was of relatively high lift (0.397 in.), and long duration (263 CA degrees for intake at 0.005 in. lift), with a relatively long valve overlap period (67 CA degrees at 0.002 lift). A modified cam was designed which incorporated lower lift (0.368 in.), and shorter duration (252 CA degrees for intake at 0.005 in. lift), with a shorter valve overlap period (45 CA degrees at 0.002 in. lift). This new cam was utilized in the higher compression ratio engines after comparison of results with the stock camshaft in an 8.5:1 CR engine. Substantial low speed improvements in power and thermal efficiency were observed (see Experimental Results).

Compression Ratio

Two stock 8.5:1 CR engines were modified through slabbing of the head to provide compression ratios of 10:1 and 11.75:1. Milling of the heads by 0.085 inches and 0.125 inches, respectively, attained the desired goal; however, the structural integrity of the latter was diminished to the point where the thin special copper gasket could not seal the combustion chambers, even at moderate loads. This was manifested by an apparent boiling of the coolant, as combustion gases forced their way past the gasket and into the coolant system. The use of the thicker stock gasket resolved the problem, however, this reduced the compression ratio to 11.3:1. Browning has shown in modeling studies [7] that squish-type combustion chambers, in contrast to flat-head chambers for the same CR, can significantly affect the production of NOx emissions. Though a geometry factor which predicts the effect on NOx for increasing CR is not known, the non-squish to squish volume at TDC can be used as an indicator of chamber dissimilarity. For the stock 8.5:1 CR engine, this ratio was 18.75, while the 10:1 and 11.3:1 engines had values of 16.5 and 19.9, respectively.

Exhaust System

Two modified exhaust systems: a low back pressure muffler and resonator using the stock tailpipe, and a tuned exhaust system, were utilized in the investigation of the 10:1 and 11.3:1 CR engines. The low back pressure system provided a nominal 3% indicated power benefit across a 10 point speed and load range, and a corresponding 1% gain in indicated thermal efficiency for the same carburetor. The tuned exhaust system was used on the 10:1 CR engine for testing of the acoustic carburetor, and on the 11.3:1 CR engine for testing of the sonic carburetor. This exhaust system provided improved high speed power, which offset the slight drop experienced by both engines, when the improved camshaft was installed only.

Test Methodology

The testing methodology for evaluation of compression ratio, camshaft, and exha system modifications consisted of engine mapping with Φ as the principal independent variable. Engine speed, load (defined by either manifold vacuum or throttle position), and spark advance (SA) were the other independent variables. Even though EGR is known to significantly reduce NO_x emissions for both methanol and gasoline, it simultaneously penalizes fuel economy at lean Φ [8]. Though this penalty is small,methanol combustion without EGR shows signficantly reduced NO_x emissions relative to gasoline anyway, and thus the evaluation of the EGR effect with methanol was not undertaken. SA was usually limited to mean best torque conditions (MBT), however, this automatically provided individual cylinder non-MBT (retarded and advanced) spark conditions for those systems in which maldistribution was present (stock and sonic systems). Recorded engine data included torque, intake air temperature, oil and coolant temperatures, speed, manifold vacuum (throttle position in the case of the acoustic system) and SA.

Exhaust emissions were measured near the exhaust valve of each cylinder and also downstream in the exhaust pipe. This latter measurement position was referred to as the composite or "tailpipe" sample position. Measured emissions included CO, O_2, NO_x, UBF, and to a limited degree,aldehydes. All other exhaust species (CO_2, H_2O, H_2, and N_2) were deduced through carbon and nitrogen balances, and by the use of the water gas reaction ($CO_2 + H_2 \rightleftarrows CO + H_2O$ with $K_{eq} = 3.5$). "Wet" NO_x and UBF emissions were measured with heated chemiluminescent (150°F) and FID (300°F with a measured response factor for methanol of 0.85) analyzers, respectively, while aldehydes were determined by the MBTH method (total aldehydes expressed as formaldehyde).

EXPERIMENTAL RESULTS

Fuel, Compression Ratio, and Camshaft Effects at WOT

A total of eight hardware fuel configurations (not counting exhaust system variations) were tested under steady state conditions on a laboratory dynamometer. Four of these systems (stock carburetor-Indolene, stock carburetor-Indolene with improved camshaft, stock carburetor-Indolene with improved camshaft and 10:1 CR, and sonic carburetor-methanol with improved camshaft and 10:1 CR) are compared in Figure 1. Engine conditions were wide open throttle (WOT) for a Φ of 1.14 with speed as the variable. Maldistribution is highest at WOT conditions and the effect is quantified by use of a maldistribution index (MI).* The lower two curves show the effect of camshaft replacement alone as seen in the first and second columns of the table. The low speed improvement in brake thermal efficiency was as high as 15% while at higher speeds (3500 RPM) the gain was only 2%. The corresponding power curves (not shown) actually indicated losses in power above 3000 RPM. This result could be anticipated directly from the shortened duration and the lower valve lift of the improved camshaft. With the change to 10:1 CR using Indolene an additional gain of 7% was realized at 1500 RPM; however, this benefit vanished at the higher speeds, and spark limiting knock occurred at all speeds thus precluding attainment of MBT spark timing.

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*$MI \triangleq (\Phi_{richest} - \Phi_{leanest})/2\Phi_{ave}$

With a change of carburetion and fuel, the 10:1 CR engine experienced an additional 5% gain in brake thermal efficiency at 1500 RPM, relative to the knock limited Indolene operation with stock carburetor. At 3000 RPM, an 18% relative gain was achieved with methanol.

It can be concluded that improvements in brake thermal efficiency at low speeds resulted primarily from camshaft change, with CR change and methanol/carburetion change providing smaller but nearly equal gains. However, at the higher speeds the methanol/carburetion change provides the primary benefit while octane rating and carburetor limits Indolene fuel performance.

Equivalence Ratio and Maldistribution Effects

Figures 2 and 3 display indicated power and thermal efficiency, respectively, for six hardware configurations at 2000 RPM and WOT conditions. Again, Indolene 'baseline' results appear for comparative purposes. The WOT condition provided worst case maldistribution for both the stock and sonic carburetors, but the acoustic carburetion provides virtual Φ matching among cylinders (MI = 0.02). Insight into the limitations placed on lean engine operation on methanol are visualized through comparison of the various systems in the Φ plane. With respect to the power curve (Fig. 2), some observations yield the following conclusions:

A. At fixed CR - 8.5:1

1) Methanol provides improved WOT power with simple rejetting of the stock carburetor.

2) Maldistribution doubles with methanol as the fuel.

3) Improved carburetion (sonic) provides additional power.

4) When significant maldistribution exists, MBT spark timing for methanol is retarded relative to Indolene: an effective reversal of single cylinder evidence in which faster burning characteristics of methanol are clearly demonstrated [9].

B. At increased CR's

1) Power increases with increasing compression ratio for methanol even with increased maldistribution (sonic carburetor).

2) At 11.3:1 CR, a more stable lean combustion is displayed by the diminished sensitivity of the power to Φ changes in the lean region (compare 11.3 with 8.5:1 CR sonic carburetor results where MI values are equal).

3) Maldistribution is seen to be a function of fuel type but only a weak function of CR.

4) The 10:1 CR results show higher maldistribution in comparison to the 11.3:1 CR results, yet MBT spark advance shows the reverse from the expected trend.

The indicated thermal efficiency plot in Figure 3 provides some additional information. Note that the acoustic carburetor results (for the limited range of Φ va permitted by its jetting configuration) at 10:1 CR also appear. Some additiona comments follow:

1) Thermal efficiency at all CR's is more sensitive to maldistribution effects especially in the far lean region in comparison to the relative effects displayed by the power curves.

2) Higher CR's in general provide more stable lean combustion (compare 8.5 and 11.3:1 CR sonic carburetor results) and provide higher thermal efficiency (11.3:1 CR results).

3) The acoustic carburetor which eliminates maldistribution shows thermal efficiencies approaching 41% at $\Phi = 0.9$ (a 22% gain in energy based fuel economy relative to the 8.5:1 CR Indolene results).

4) Methanol's lean misfire limit for 8.5 and 10:1 CR engines was found to be in the range $0.56 \leq \Phi \leq 0.58$, while the Indolene baseline results indicated closer to $\Phi = 0.7$. Though the lean limit in the 11.3:1 CR engine wasn't established within a range, it was found to be lower than $\Phi = 0.6$.

Some Aspects of Exhaust Emission Behavior with Methanol Fueling

a) NO_x emissions at three CR's - Figure 4 displays NO_x emissions at $\Phi = 0.9$ (peak NO_x) as a function of indicated horsepower for three compression ratios. These specific emission results (gm/Ihp-hr) were obtained from individual cylinder measurements taken near the exhaust valve. Interpolation of data in the Φ plane was required in order to get MBT spark timing results when maldistribution was high. The evidence tends to support the model of Browning [7] at WOT conditions where NO_x emissions actually decrease with increasing compression ratio for the squish chamber design. Data shows the 10:1 CR results lower than the 8.5:1 CR results but the same (within measurement uncertainty) as the 11.3:1 CR results. Maldistribution and/or the non-squish volume to squish-volume ratio differences are the probable causes of the disagreement between model and experiment.

b) UBF emissions at three CR's - Figure 5 displays UBF emissions corresponding to the NO_x emission plot of Figure 4. Upstream values measured near the exhaust valve are termed "engine" emissions, while downstream measurements (2 to 6 ft down the tailpipe) are termed "tailpipe" emissions. The differences in values of UBF across the speed range are a strong function of CR, but absolute values are greatly attenuated when viewing the results after downstream oxidation has occurred. Note that similar to the NO_x results, UBF emissions at the driving cycle loads (22.5 and 24 Ihp) are nearly the same for all three compression ratios. Though not shown, "engine" UBF for the stock-Indolene results at 8.5:1 CR fell above the methanol results at 8.5:1 CR, but below 10:1 and 11.3:1 CR results. Combining these UBF emission results with the cycle simulation (next section) indicates that UBF for the methanol engines will have to be controlled through the use of an oxidation catalyst.

DRIVING CYCLE SIMULATION AND OPTIMIZATION

imulation

Simulations of driving cycles found in the U.S. Federal Test Procedure (urban driving) and Highway Fuel Economy Test (highway driving) by use of steady-state engine maps of fuel economy and exhaust emissions and a digital computer have been presented in earlier reports and papers [1,2]. The flexibility of such computer codes is seen in the many ways in which vehicle hardware and engine operating variables can be altered and subsequently evaluated in terms of effect on vehicle fuel economy and exhaust emissions. Factors such as vehicle weight, aerodynamic drag, rolling resistance, drive train efficiency, transmission gear ratios, rear axle ratio, carburetor behavior (ability to control Φ), and the steady state map of fuel economy and exhaust emissions itself can all be treated as variables. In the study of alternative fuels such as the alcohols, it is appropriate to fix all the vehicle characteristics so that the effect of fuel change alone (as reflected in the steady state maps of fuel economy and emissions) can be evaluated. Subsequent to this, engine hardware modifications (such as higher CR, improved camshaft, alternative carburetion systems) can be evaluated in terms of the driving cycle requirements which weight particular portions of the engine maps. The previous work evaluated the fuel and alternative carburetion advantages for methanol in a 3000 lb vehicle. The results presented here for CR and camshaft modifications are also for the idealized case of constant Φ operation based on the fully warmed-up engine maps of steady state engine performance. Twenty-five engine speed-load points at MBT spark timing were used at each Φ in the simulations, and identical vehicle characteristics were used.

Constant Φ Cycle Simulation Results

In the earlier work, results of urban and highway cycle energy fuel economy (mi/10^{6}Btu or Km/10^{6}KJ) for an 8.5:1 CR engine showed substantial improvements (relative to the Indolene baseline) for methanol fueling and alternative carburetion. The sonic carburetor operating on methanol attained energy fuel economies (at $\Phi = 0.8$) which were 30% higher than Indolene baseline results at $\Phi = 1.0$. Lean engine operation at $\Phi = 0.7$ reduced that benefit to roughly 26% in the urban cycle but at the same time the NO$_x$ standard of 0.4 gms/mi was attained. CR and camshaft changes modify these previous results as is seen in Figures 6 and 7.

a) Fuel economy - constant Φ simulations comparing 8.5:1, 10:1 and 11.3:1 CR engines for both urban and highway (except the 11.3:1 CR results) cycles predict the following:

1) An apparent improved fuel economy at the higher compression ratios, but the benefit is primarily derived from the camshaft modification, not the CR. (In comparison to Indolene at $\Phi = 1.0$, the 10:1 CR results at $\Phi = 0.8$ show a 37% improvement in urban fuel economy.)

2) Poorer fuel economy at most Φ values for the 11.3:1 CR engine in comparison to the 10:1 CR engine while operating on methanol.

3) A decrease in average cycle maldistribution with increasing compression ratio in the urban cycle.

4) A slight decrease in fuel economy in the highway cycle for the 10:1 CR engine in comparison to 8.5:1 CR engine operating on methanol, and higher maldistribution for both 8.5:1 and 10:1 CR engines in comparison to the urban cycle.

b) Exhaust Emissions - The fully warmed-up engine emissions appear in Figure 8 for the urban driving cycle. These results predict the following:

1) Increasing UBF emissions with increasing CR and mixture leaning.

2) Peak values of NO_x for methanol in the range of 3 to 3.5 gm/mi (at $\Phi = 0.9$), but at $\Phi = 0.7$ the higher CR's more than double the results at 8.5:1 CR.

3) CO emissions virtually the same for all CR's (except for $\Phi \geq 1.0$), and at lean Φ well under the 3.4 gm/mi standard.

Discussion

While methanol, sonic carburetion, lean engine operation, and camshaft change, provide substantial fuel economy benefits over Indolene, driving cycle simulation results indicate that increased CR doesn't provide additional improvements in either energy fuel economy or urban cycle emissions. However, benefits in driveability, cold starting, acceleration, and improved transient response are expected at the higher CR's and these factors were not addressed in the cycle simulation. The lack of any substantial fuel economy improvements in the urban cycle most likely results from the increased pumping losses at higher CR. Since driving cycle power requirements remain the same at each point in time, this suggests that perhaps a smaller engine should be used to take advantage of the higher thermal efficiencies attained when approach WOT operation. Assessments of such changes in engine size or other vehicle parameters is not currently a part of this study.

The lean operating capability of methanol, suggests a strategy of engine operation in this region since fuel economy maximizes there. The 11.3:1 CR results indicate that there is a lean combustion stability there which is less sensitive to maldistribution effects than at lower CR's. UBF emissions, in this type of strategy, will still have to be controlled with an oxidation catalyst. If the higher CR's are to be used the NO_x emission results indicate that operation near $\Phi = 0.6$ may permit the meeting of the 0.40 gm/mi standard. The CO emissions predicted in the simulation are well below the 3.4 gm/mi standard. In contrast, our results indicate cold transient bag CO emissions of 4.5 to 12 gm/mi for a methanol fueled Pinto at 9.0:1 CR (with O_2 feedback carburetor). Testing of cold starting and fuel nebulization aids will determine how well both UBF and CO emissions can be controlled.

These comments reflect the conflicting requirements that plague engineers in their search for the "best" engine operating scheme but a systematic approach to the problem can be found by viewing it as an engine control problem suited to a mathematical optimization theory approach.

Optimization Study Methodology

Stated simply, the optimization problem consists of defining engine 'control' variables (such as Φ, SA) which, through a mathematical optimization procedure, maximize the fuel economy while maintaining the exhaust emissions of UBF, CO, and NO_x at levels defined by emission standards. This procedure is performed over a driving cycle similar to the FTP. The use of Φ as a control variable is suggested by the strong sensitivity of emissions to this variable, as depicted in the maldistribution and cycle 'transient free' emissions of Figure 7. SA significantly effects NO_x emissions in both gasoline and methanol fueled engines [9], while simultaneously - but to a lesser degree - it effects fuel economy and UBF emissions. Thus it is also selected as a control variable. Figure 8 displays a comprehensive optimization strategy flow chart, which systematically takes into account all the factors effecting both the control strategy itself and the final results of fuel economy and exhaust emissions.

This computer based study will contrast three different engine operating scenarios with the baseline scenario (the constant Φ/no control strategy results presented in Figures 6 and 7). The first scenario involves lean Φ operation at wide open throttle, with fuel enrichment used only to meet power demand (no constraints on emissions). The second is a maximum fuel economy case but with no emission constraints. The third scenario is the ultimate optimization problem, where the objective is to maximize a function (fuel economy) while subject to one or more constraints (allowable emissions of UBF, CO, and NO_x). The effects of cold starting, transient carburetor behavior, maldistribution, and exhaust after-treatment will be added following the preliminary strategies which exclude these 'real' effects.

Scenario 3 has been treated in the literature with several unique algorithms for gasoline data bases [4,5,6]; however, no methanol data bases have been treated, to date. Two aspects of methanol fueled engine operation are important to note in this optimization. First, methanol, in contrast to gasoline, displays higher maldistribution and thus it may effect engine control strategy significantly. Second, methanol's lean burning capability provides a far wider engine map in the Φ plane, and thus a control strategy may have far more flexibility than current gasoline data bases allow. For example, the Φ range for the optimization of Rao et al. was $0.78 \leq \Phi \leq 1.62$ [5]. With methanol, values of $\Phi \leq 0.6$ are possible without misfire when there is no maldistribution. It is anticipated that improved ignition, the use of high swirl combustion chambers [10], and hydrogen enrichment via decomposition of methanol [11], will extend the lean limit to the point where power demand can be achieved by Φ modulation with the throttle wide open. The intention of the optimization study is to exploit the demonstrated and potential benefits of methanol toward the end of defining an implementable control system for methanol fueled vehicles.

CONCLUSIONS AND FUTURE WORK

Steady state and simulated driving cycle energy fuel economy results for methanol fueled engines at 10:1 and 11.3:1 CR have shown improvements relative to Indolene and methanol results in an 8.5:1 CR engine. These improvements were primarily due to camshaft modification and not CR, however, the cycle simulation results did not reflect the extended Φ range, cold starting, driveability, and transient carburetor response improvements that would be expected at higher CR.

Peak steady state NO_x emissions at WOT went down as CR was increased in the methanol fueled engines, but driving cycle NO_x values increased with the effect being more pronounced at very lean Φ (0.7). 'Engine' UBF emissions were a strong function of Φ in the lean region and increased substantially with CR increase (except near the lean limit). UBF 'tailpipe' emissions were reduced substantially at all CR's due to oxidation effects in exhaust manifold and tailpipe.

Simulated driving cycle results for the idealized case of a fully warmed-up engine operation at constant Φ provided the baseline scenario for an engine/vehicle optimization strategy. This 'software' approach to final optimal controls for various hardware configurations is being approached through three engine operation scenarios. The last of these is a constrained optimization problem where fuel economy is maximized while constraints are placed on the exhaust emissions of UBF, NO_x and CO.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy under contract EC-78-C-03-1737. The authors thank the Ford Motor Company for the generous donation of two 2.3L engines, and Dresser Industries for the loan of the sonic carburetor.

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% IMPROVEMENT IN BRAKE THERMAL EFFICIENCY
OVER STOCK CAM - INDOLENE.

SPEED	STOCK CAM	IMPROVED CAM		
	8.5:1 (I)	8.5:1 (I)	10:1 (I)	10:1 (M)
1500	0	13	21	26
2000	0	14	15	20
2500	0	6	7	16
3000	0	4	2	20
3500	0	2	3	—
CARB	STOCK	STOCK	STOCK	SONIC

2300 CC - 4 CYL.
MBT SPARK TIMING
$\Phi = 1.14$ (RICH)
METHANOL AND
INDOLENE

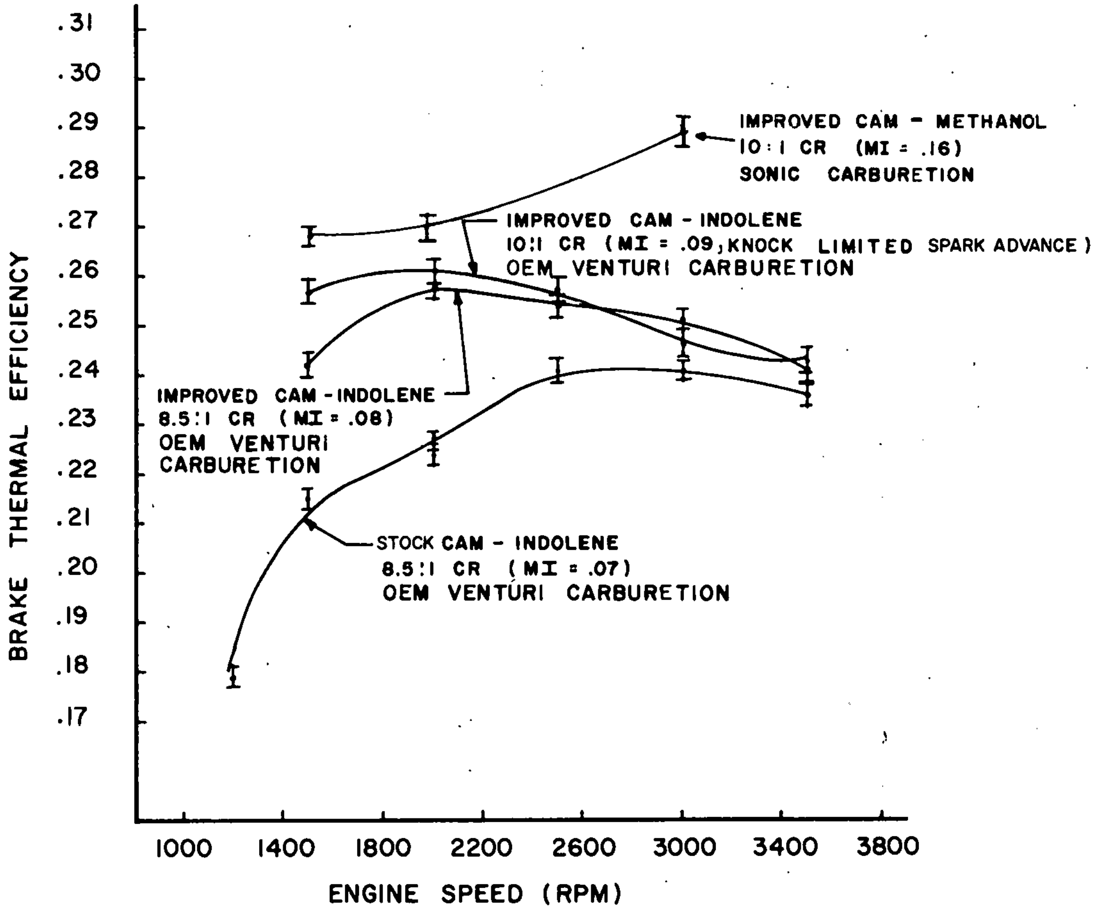


FIGURE 1 EFFECTS OF COMPRESSION RATIO, CAMSHAFT MODIFICATION, FUEL AND CARBURETION ON ENGINE BRAKE THERMAL EFFICIENCY

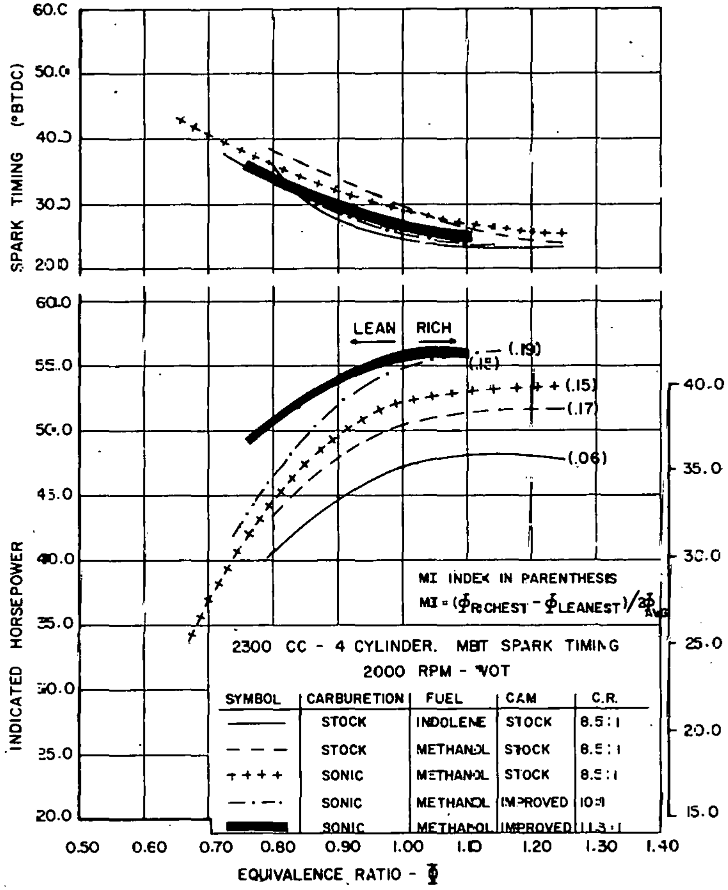


FIGURE 2 COMPARATIVE INDICATED POWER AND MBT SPARK TIMING FOR 8.5:1, 10:1, AND 11.3:1 CR ENGINES

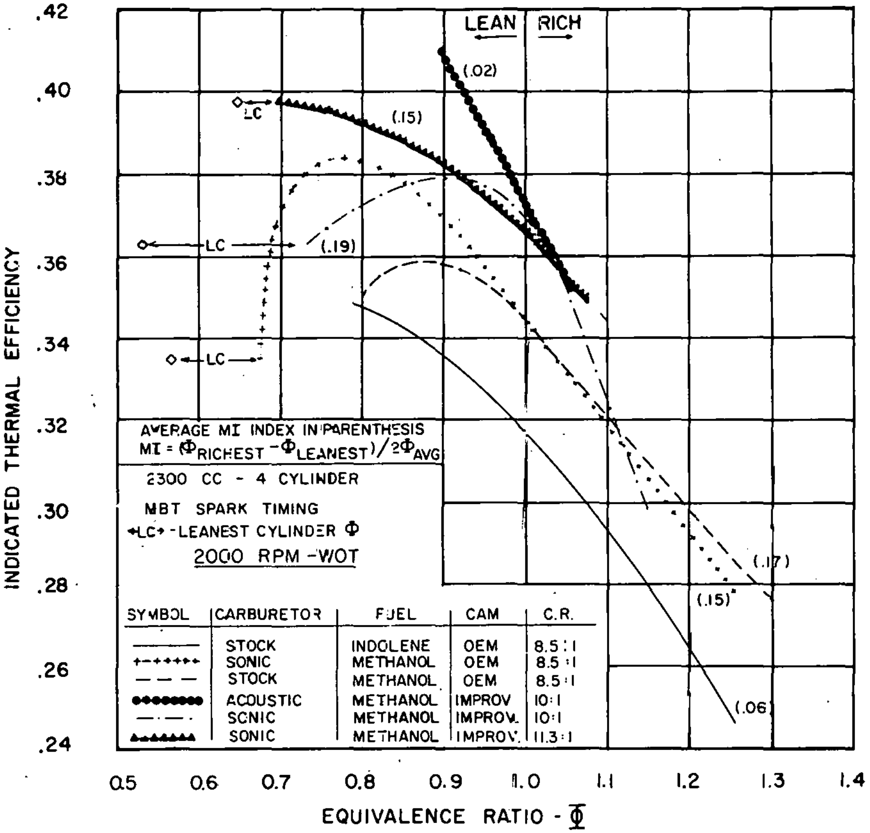


FIGURE 3 COMPARATIVE INDICATED THERMAL EFFICIENCY FOR 8.5:1, 10:1, AND 11.3:1 CR ENGINES

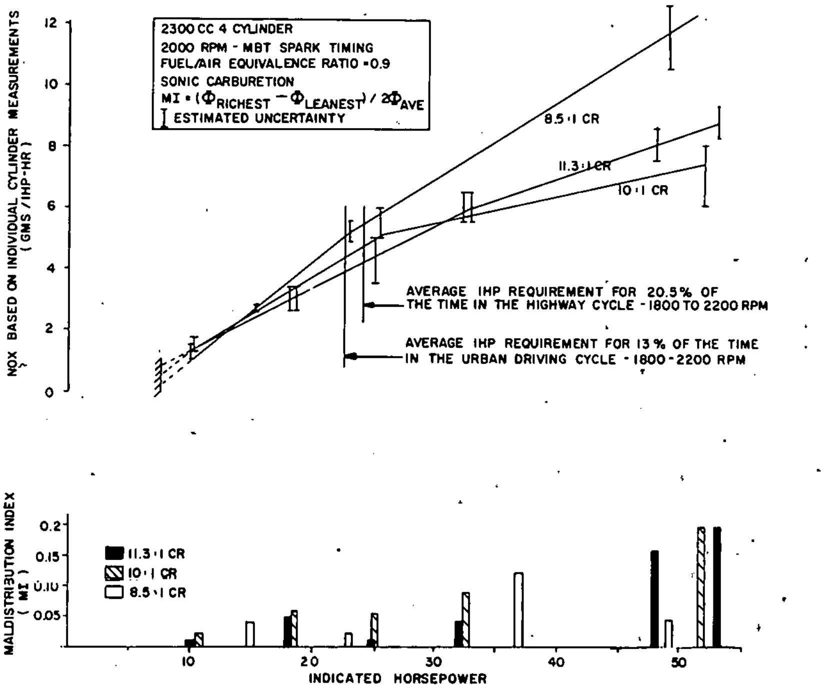


FIG. 4 INDICATED SPECIFIC NO_X EMISSIONS AND MALDISTRIBUTION AT THREE COMPRESSION RATIOS.

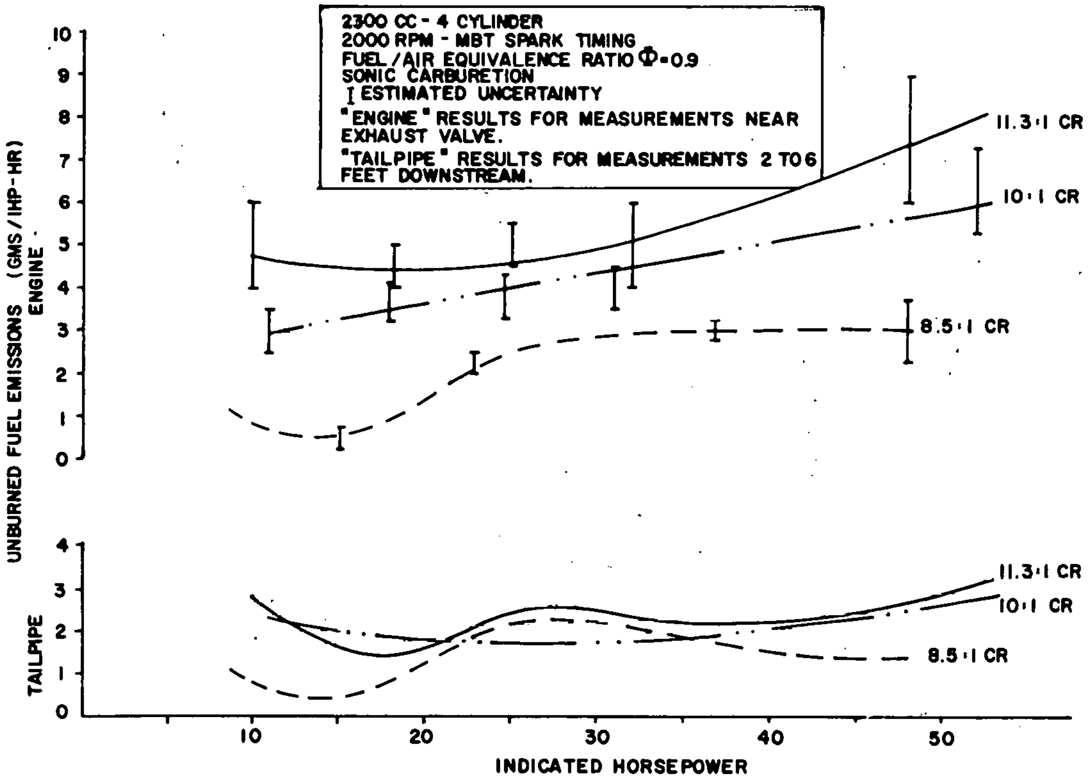


FIGURE 5 ENGINE AND TAILPIPE INDICATED SPECIFIC UBF EMISSIONS AT THREE COMPRESSION RATIOS.

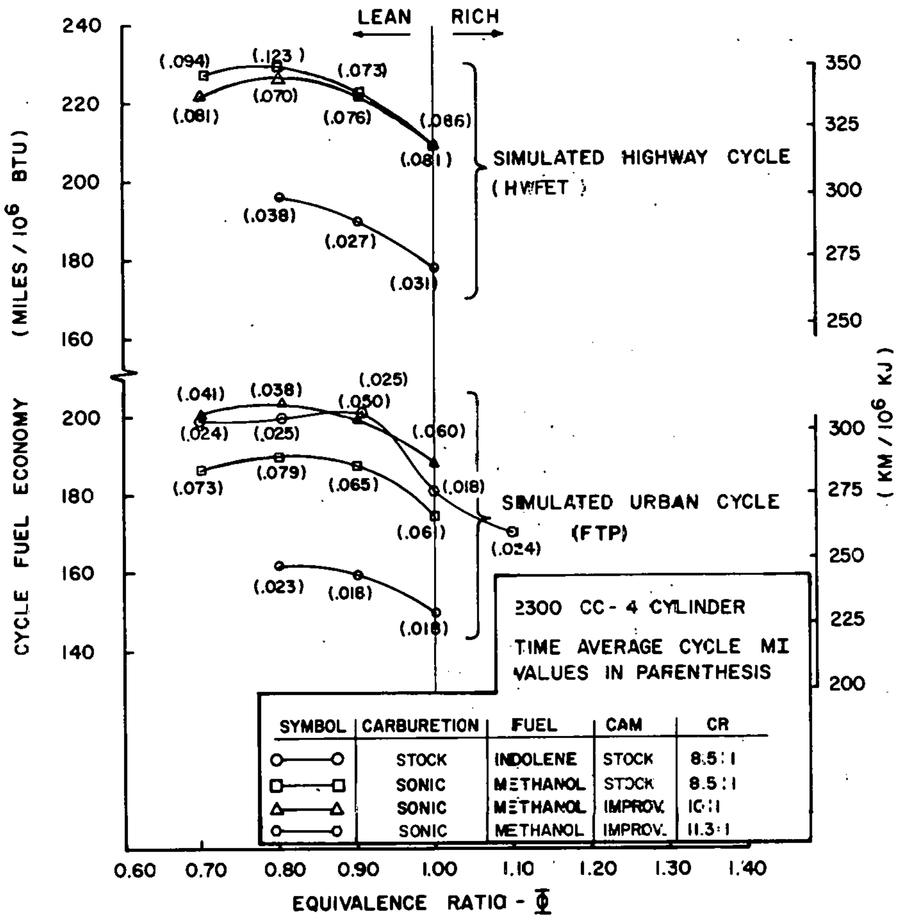


FIGURE 6 | COMPARATIVE SIMULATED URBAN AND HIGHWAY FUEL ECONOMY FOR 8.5:1, 10:1 AND 11.3:1 CR ENGINES.

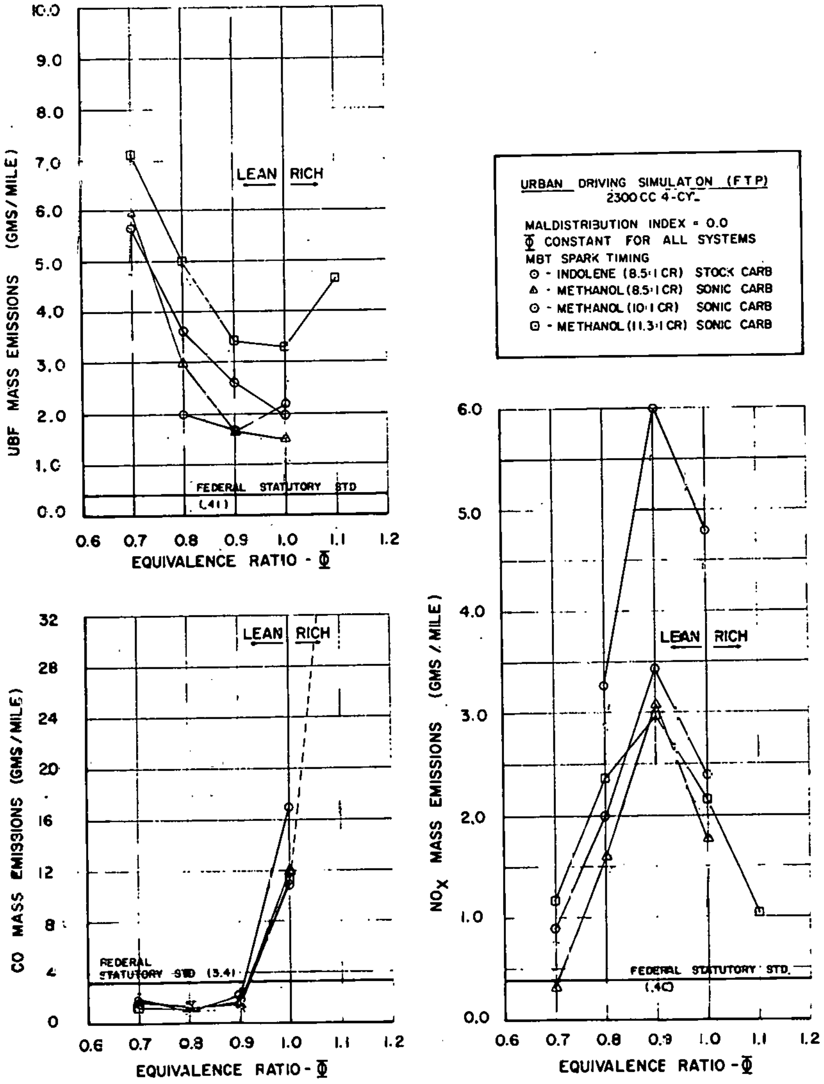
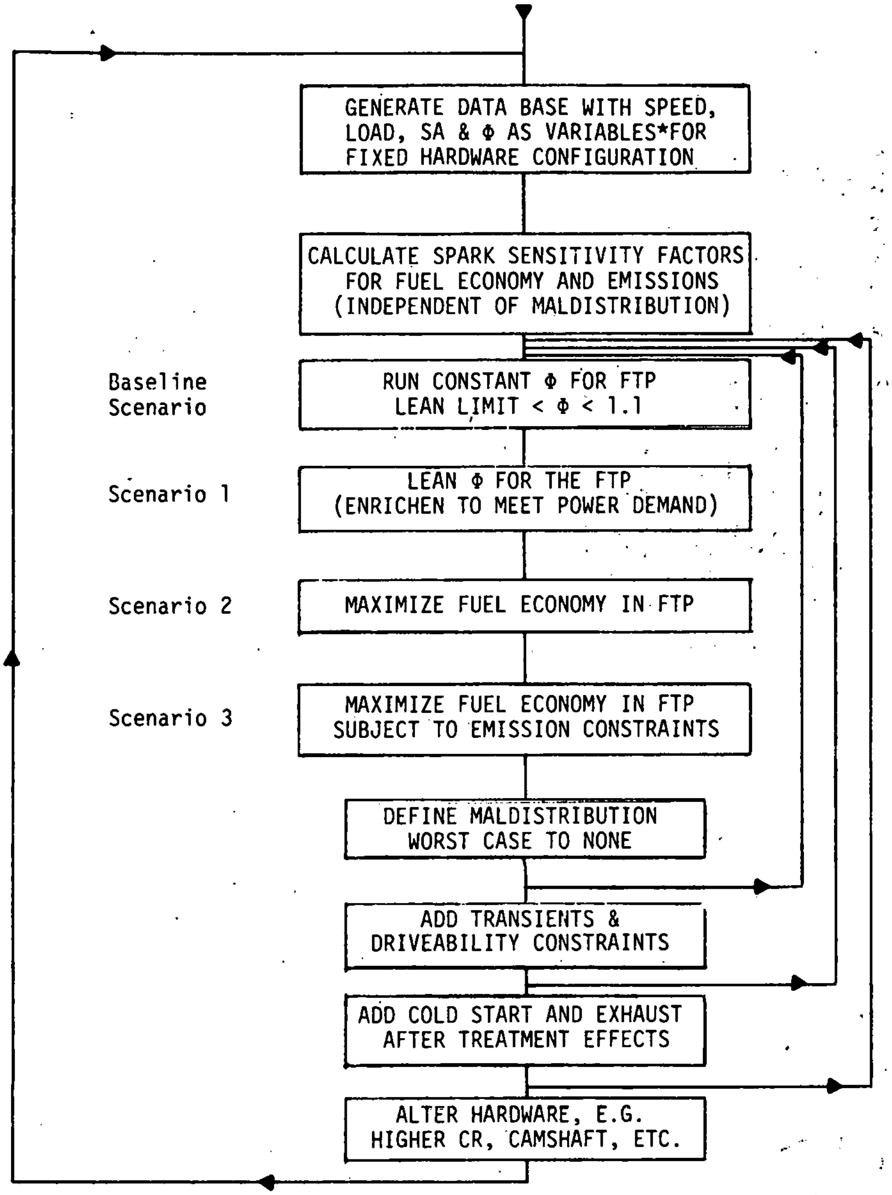


FIGURE 7 METHANOL, AND INDOLENE EXHAUST EMISSIONS FOR SIMULATED URBAN DRIVING.



*EGR, coolant temperature, inlet temperature, etc., can be added.

FIGURE 8: OPTIMIZATION STRATEGY FLOW CHART FOR A SIMULATED URBAN DRIVING CYCLE (FTP) - METHANOL FUELED VEHICLES

CHARACTERIZATION OF ALCOHOL/GASOLINE BLENDS AS A STRATIFIED-CHARGE ENGINE FUEL: PERFORMANCE AND EMISSIONS

by

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1. INTRODUCTION

Alcohol has been promoted as a motor fuel for almost 70 years. Most of the early work was concerned with the use of ethyl alcohol (ethanol), which could be produced by fermentation of grain and other farm products as well as synthetically. The impetus behind these studies was the desire to develop new outlets for farm produce and to develop energy sources other than those based on petroleum. Excess cost and the absence of technical advantages to justify a higher cost prevented the general use of ethanol as a motor fuel (1)*.

Recent concern about environmental problems and the eventual shortage of conventional petroleum-based fuels coupled with the potential of obtaining alcohols (both methanol and ethanol) has brought about a recent interest in the use of methanol as a fuel.

In order to assess the feasibility of using an alcohol as a motor vehicle fuel, either alone (neat) or as a blend in gasoline-type base stocks, its performance, emissions and practical use characteristics must be ascertained. To this end, the authors and their colleagues are conducting a series of experiments which will determine alcohol blend-fueled engine characteristics information found to be lacking during their preparation of Reference 3. This report contains some of the results obtained to date. Other results, concerned mainly with a carbureted, homogeneous-charge, spark ignited engine, have been presented in References 4-10. This report focuses on the results obtained during testing of a stratified-charge engine.

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* Numbers in parentheses designate References in Section 6.

2. PRESENT INVESTIGATION

2.1 OBJECTIVES

The objective of the present investigation was the determination of the effect of alcohol addition to gasoline on performance and emissions characteristics of a stratified-charge, spark ignition engine when it is operated at the same as gasoline-fueled operation engine speed and torque (unequal manifold vacuum) with no alteration to the controllable engine parameters other than the throttle setting and with the fuel-air equivalence ratio being determined by the stock carburetor and the spark advance equal to the stock value corresponding to the engine speed and manifold vacuum.

The motivation behind establishing said objective is that the results thus obtained allow for an estimation of what would happen to its performance and emissions characteristics if the above-described engine were to power an automobile traveling at constant speed while being fueled by the various blends of alcohol and gasoline. To achieve the objective of the study, the engine was fitted with its stock, as delivered from the manufacturer, carburetor. The spark advance was also stock. The speed of the vehicle being simulated during the tests determined the engine speed and torque requirement.

2.2 FUELS

Indolene H. O. Clear Motor Fuel III was used as the base stock representative of unleaded gasoline. Mixtures of Indolene and commercial grade methanol and ethanol were used to represent methanol-gasoline blends. Blend levels of up to 30 volume percent of methanol in Indolene and 20 volume percent of ethanol in Indolene were tested as well as the base stock, Indolene. An X volume percent blend was formed by taking X volume units of alcohol and combining them with (100-X) volume units of Indolene. In this report, Indolene is also referred to as I and X volume percent methanol blend as MX and X volume percent ethanol as EX. Fuels tested were I, E10, M10, E20 and M30.

2.3 ENGINE

The four cylinder engine used in this study was manufactured by the Honda Motor Company, Ltd., Tokyo, Japan and donated to the University of Miami by the American Honda Motor Company, Inc. It is normally used in the Honda Accord CVCC automobile; the engine number is EF1-3537455. Table 1 gives some engine specifications. The engine was not modified in any way other than to replace the radiator and fan with a cooling tower. This tower utilized fresh city water and a thermostat to maintain constant coolant inlet temperature.

2.4 MEASUREMENTS

e various measurements that were made during testing are described in Reference 8. Included are the methods used to make the measurements along with an estimate of the precision (6) of the instruments. These estimates were determined either from manufacturers' specifications and/or calibrations performed during the investigation. In Reference 8, the methods used to estimate experimental uncertainty of the various measurements are given.

2.5 TEST PROCEDURES

All testing was carried out under steady-state conditions with the engine connected to a water brake dynamometer. The tests performed, designed to achieve the objective of the project, are termed Type II tests and are described below.

2.5.1 Calibration Check

Prior to performing any tests, the necessary daily instrument calibrations were performed. The instruments were also recalibrated between each test.

2.5.2 Type II Tests

During the Type II tests, the engine was adjusted to a predetermined engine speed and torque, corresponding to 30, 40, and 50 mph (48, 64, 81 km/hr) cruise conditions with a Honda Accord (see Table 2), while using Indolene fuel with the stock metering jets in the carburetor and the ignition timing adjusted to manufacturers' specifications. Subsequently, the alcohol blends were substituted. This substitution resulted in a decrease in engine speed and torque. The procedure was to lower the manifold vacuum by opening the throttle until the Indolene-fueled-operation engine speed and torque were regained. The spark advance was set by the stock vacuum- and centrifugal-advance mechanisms.

The engine speeds selected were 1400, 1900 and 2400 RPM and corresponded to vehicle speeds of approximately 30, 40 and 50 mph (48, 64 and 81 km/hr).

The torque values selected approximated the torque (same mean effective pressure) requirement of a Honda Accord cruising at 30, 40 and 50 mph (see Table 2).

3. EXPERIMENTAL RESULTS

3.1 Manifold Vacuum

In order to achieve the same torque and engine speed with the blends as had been measured during Indolene-fueled operation, it was necessary to open the throttle. Figure 1 shows the resulting manifold vacuums. As the blend level is increased, increasingly greater manifold pressure (less vacuum) was needed to achieve equal-to-Indolene-fueled power output.

3.2 Blend Leaning Effect

One consequence of adding alcohol to gasoline is the blend leaning effect. This effect is illustrated in Figure 2 where the fuel-air equivalence ratio is plotted as a function of fuel type. As the blend level increases, the equivalence ratio is seen to decrease.

3.3 Brake Thermal Efficiency

Figure 3 illustrates the brake thermal efficiency data. It is observed that there is a slight increase in brake thermal efficiency when blends up to and including M20 are used for the 50 mph simulation tests. For the other speeds, there is a general tendency for the efficiency to decrease. This result is unlike the one obtained with the uniform-charge engine where a general increase in BTE was observed with increasing methanol blend level (8).

3.4 Oxygen Emissions

As a result of the blend leaning effect, oxygen emissions increase as the methanol blend level is increased. To illustrate this increase, Figure 4 is presented.

3.5 Carbon Monoxide Emissions

Carbon monoxide emission data for the Type II tests are shown in Figure 5. Except for the 30 mph simulation, the CO emissions increase when the alcohol blends are used even though the Φ of the mixture delivered by the carburetor decreases (becomes leaner; Figure 2). This result is unlike that obtained when a uniform-charge engine is subjected to Type II testing. For the uniform-charge engine, the blend leaning effect results in a decrease in CO (8). The reasons for this behavior is not, at present, known. But an increase of CO emissions with decreasing Φ is not unexpected; Turkish (12) found similar results while using gasoline as a fuel.

3.6 Nitric Oxide Emissions

Nitric oxide (NO_x) ppm emission data for the Type II tests are illustrated in Figure 6. It is observed that, except for the 50 mph simulation with E10, there is a decrease in NO_x emissions as the alcohol blend level is increased. Alcohol blends are similarly found, in general, to decrease NO_x emissions in homogeneous-charge engines.

3.7 FID Total HC Emissions

FID total HC emission data for the Type II tests are shown in Figure 7. The E10 blend has a small affect on FID HC emissions with a favorable affect being noted for the 30 mph simulation. Going to higher than 10% blend levels adversely affects HC emissions for the 30 and 40 mph simulation. For the 50 mph simulation, HC are not strongly affected by blend level until the M30 blend is reached. There, lean mixture misfire is suspected of causing the FID HC to rise. As the blend level increases past the 10% level, the emissions are seen, in general, to increase. This result is dissimilar to the uniform-charge engine Type II test results. There, the HC emissions were found to decrease with increasing blend level - provided the level was not sufficiently high to cause lean-limit misfire. When said misfiring occurs, HC emissions increase (8). Some of the test points in Figure 7 are noted to exhibit relatively large HC emissions. During engine operation to obtain these points, the stratified-charge engine was observed to produce sounds in its exhaust similar to those heard during misfiring with a premixed engine (9).

The HC emissions characteristics with increasing blend level with the stratified-charge engine, while different than those of the premixed engine, are not unexpected. As with the CO emissions, Turkish (12) found HC emissions to increase with lean mixtures ($\Phi < \approx 0.85$) during gasoline-fueled operation of a Honda CVCC engine.

4. SUMMARY AND CONCLUSIONS

During the present study, experiments (Type II tests) were performed to determine the effect of alcohol addition to unleaded gasoline (Indolene) on the performance and emissions characteristics of a three-valve, carbureted, stratified-charge engine if it were in a stock condition and used to power an automobile. Engine torque and speeds selected simulated 30, 40 and 50 mph cruise (48, 64 and 81 km/hr). The results of these experiments showed the following:

(1) When the alcohol blends were substituted for gasoline with no engine adjustments, the torque and engine speed decreased.

(2) In order to regain the Indolene-fueled operation values of torque and engine speed, it was necessary to lower the manifold vacuum by opening the throttle (Figure 1).

(3) The fuel-air equivalence ratio with the blends was found to be lower than that found during Indolene-fueled operation (Figure 2).

(4) The brake thermal efficiency during blend-fueled operation was found to be, in general, lower than that during Indolene-fueled

operation (Figure 3).

(5) CO emissions were found to either decrease (30 mph simulatio or increase (40 and 50 mph simulation) depending on the cruising speed being simulated (Figure 4).

(6) Nitric oxide (NO_x) emissions were, in general, found to decrease with increasing methanol blend level (Figure 5).

(7) FID hydrocarbon emissions were found, in general, to increase with alcohol addition (Figure 6).

The results obtained during the Type II tests differ in many respects from those obtained with a uniform-charge engine (8). From a practical point of view, both E10 and M10 blends have a small effect on performance and emissions characteristics.

5. ACKNOWLEDGMENTS

There are a number of individuals whose assistance is greatly appreciated:

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Table 1. Honda CVCC Engine Specifications*

Engine Number	EF1-3537455
Type	Water cooled 4 stroke-cycle OHC, CVCC
Cylinder Arrangement	4-cylinder in line
Bore x Stroke mm (in.)	74 x 93 (2.91 x 3.66)
Displacement cc (cu in.)	1600 (97.63)
Compression Ratio	8.0:1 (Max. 8.2:1, Min. 7.8:1)
Carburetor Type	Downdraft
Carburetor, Ventury Dia. P/S/A** mm (in.)	22/29/8.5 (0.866/1.142/0.335)

Table 2. Nominal Values of Operating Parameters for Type I and II Tests with Indolene Fuel.

Vehicle Speed, mph (km/hr)	30 (48)	40 (64)	50 (81)
Load Level	Cruise	Cruise	Cruise
Engine Speed, RPM	1400	1900	2400
Torque, ft lb_f (n:m)	13.0(17.65)	17.0(23.1)	23.0(31.2)
$P_{manifold}$, in. Hg (kPa)	18.5(61.6)	16.9(56.3)	14.7(49.0)

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* From: Honda Accord CVCC 1978 Shop Manual, Published by Honda Motor Co., Ltd., Tokyo, Japan.

** P = Primary, S = Secondary, A = Auxiliary

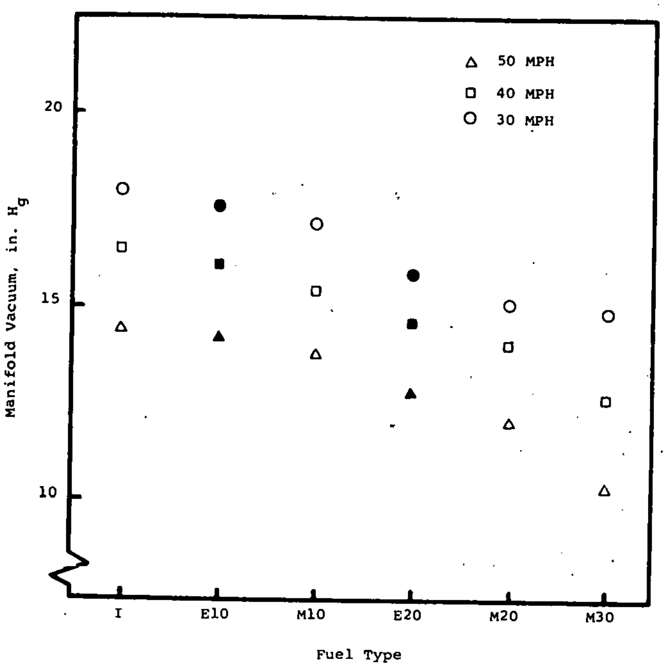

Figure 1 - Illustrates the Reduced Manifold Vacuum Required for Alcohol Blends to Attain the Same Torque and Engine Speed as Found with Indolene (Type II Tests)

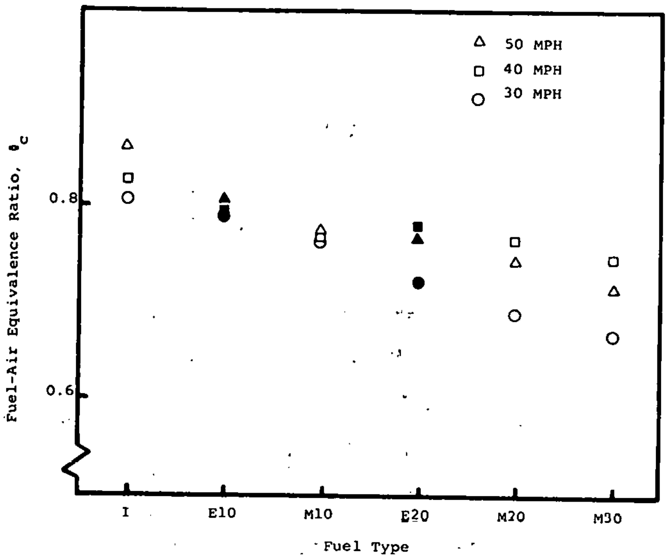

Figure 2 - Illustrates the Fuel-Air Equivalence Ratio Decrease (Blend Leaning Effect) as a Function of Alcohol Blends for Type II Tests

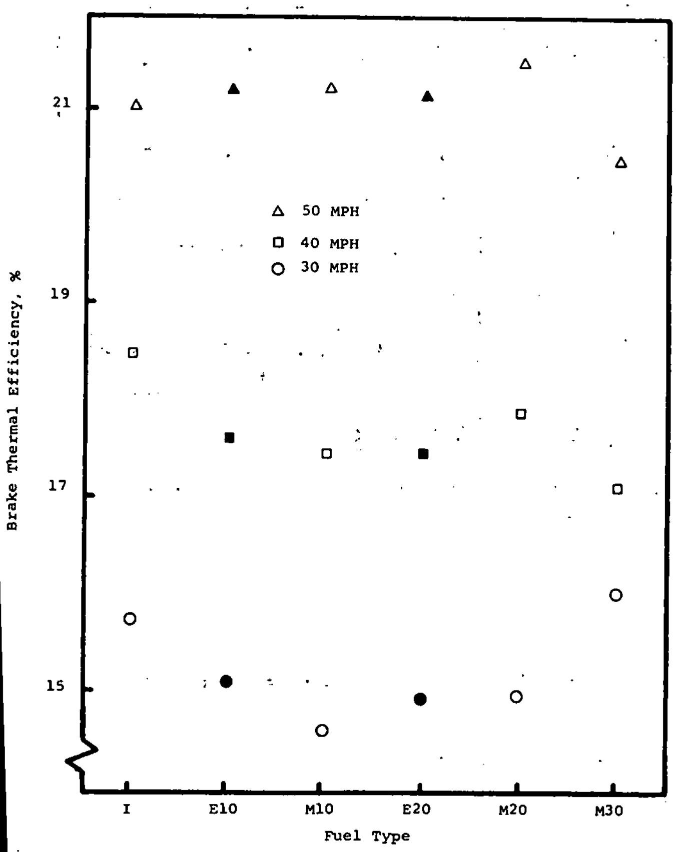

Figure 3 - Illustrates the Brake Thermal Efficiency obtained with Alcohol Blends at Equal-to-Indolene Torque and Engine Speed Operation (Type II Tests)

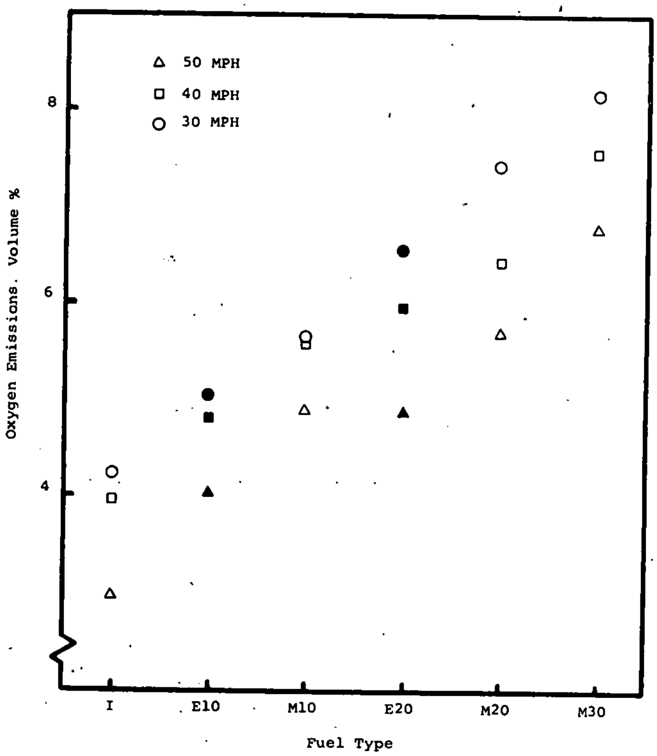

Figure 4 - Illustrates the Oxygen Emissions as a Function of Alcohol Blends for the Type II Tests

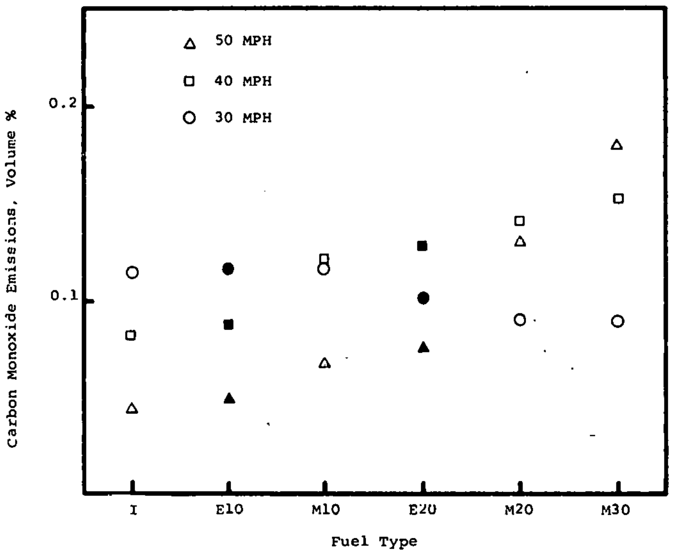

Figure 5 - Illustrates the Effect of Alcohol Blends on CO Volume Emissions at Equal to Indolene Fueled Torque and Engine Speed (Type II Tests)

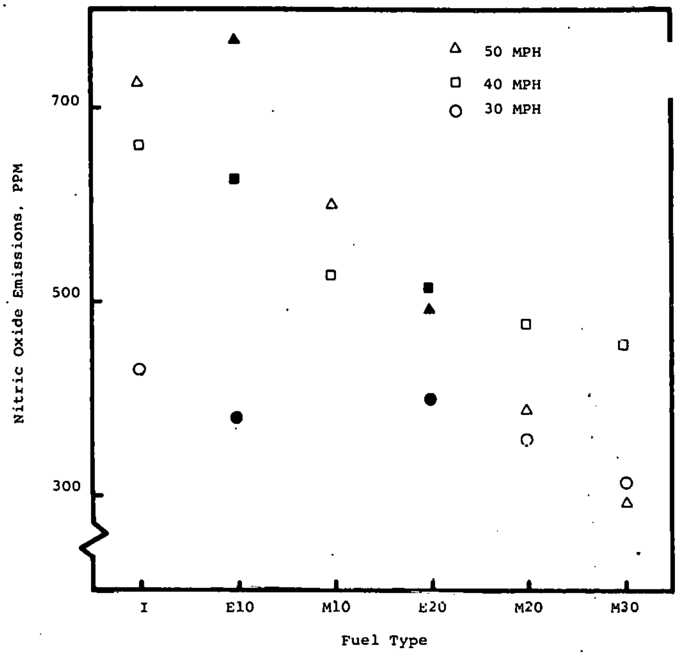

Figure 6 - Illustrates the Effect of Nitric Oxide Emissions with Alcohol Blends at Equal-to-Indolene Torque and Engine Speed Operation (Type II Tests)

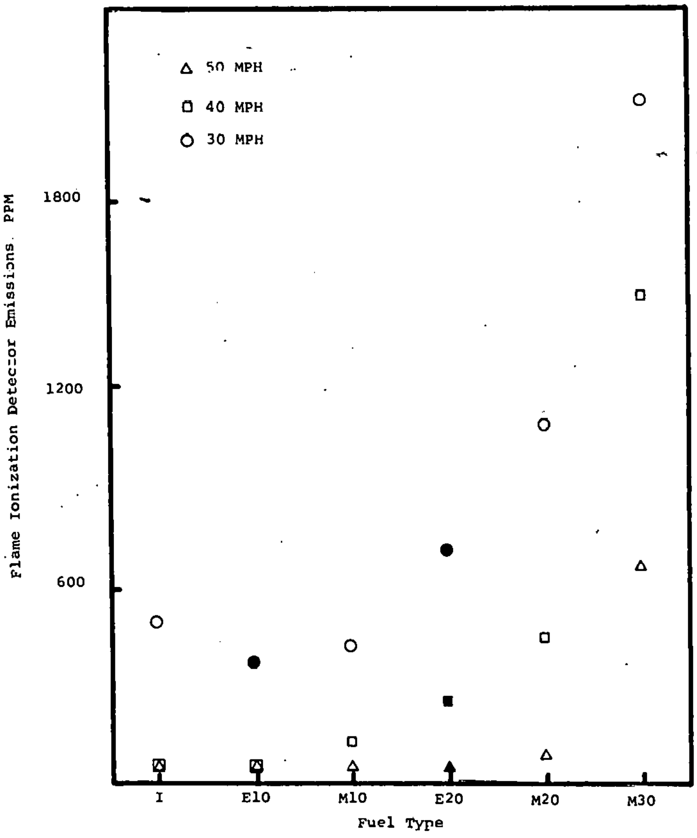

Figure 7 - Illustrates the FID HC Volume Emissions With Alcohol Blends at Equal-to-Indolene Torque and Engine Speed Operation (Type II Tests)

NEW ZEALAND'S METHANOL-GASOLINE TRANSPORT FUEL PROGRAMME

by

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INTRODUCTION

The situation existing in New Zealand makes it an ideal country for the early introduction of a blend of methanol-gasoline as a transport fuel. It has no crude oil reserves of its own and must import nearly all of its transport fuel either as crude oil for the refinery or as refined transport fuels. At present this amounts to $270 million a year for gasoline alone which equals about 10% of the country's total yearly export receipts.

On the other hand the country has very large reserves of natural gas due to come on shore next year, well in excess of current and predicted demands. The gas fields were originally developed to meet predicted increased demand for electricity. This demand no longer exists and even allowing for extensive reticulation of the natural gas economical alternative uses for the natural gas are highly desirable. Methanol production for use as a blended fuel with gasoline offers one of the most attractive alternatives. Current estimates show that methanol could be produced from natural gas in New Zealand economically at prices about 40% less (on a volume basis) than the imported price of gasoline. When used as a blend (10-15% methanol) in the existing transport fleet it will be shown that this represents a very economical and efficient use of New Zealand's natural gas.

In addition New Zealand has a moderate climate which reduces considerably the problems of phase separation and vapour lock often associated with the use of blends of methanol and gasoline.

The main emphasis of this paper will be to present the results of road tests using blends of methanol and gasoline up to 25% methanol in a wide range of vehicles currently operated in New Zealand. An historical approach will be adopted starting with the earlier single vehicle trials which have been underway over the last four years. Much of this work has been funded by the New Zealand Research and Development Committee. This will be followed by results of larger fleet trials which were started about one year ago. These trials are being continuously extended to cover as wide a range of vehicles and conditions including distribution, as possible. By-and-large this work has been organized and funded by the Department of Scientific and Industrial Research and now through the Liquid Fuels Trust Board, a body set up to investigate alternative transport fuels financed by a levy on gasoline sales. In conclusion, tests planned on high methanol blends will be presented as an option for the more distant future. Details of earlier studies providing economical analysis of the use of methanol in New Zealand, laboratory studies on phase separation etc. and stationary engine tests are available (1)*(2)(3)(4).

SINGLE VEHICLE STUDIES

Over the last four years a total of about forty different single vehicle road tests have been conducted with blends of from 0-25% methanol in gasoline. These tests have been conducted at the Department of Scientific and Industrial Research, the University of Canterbury and the University of Otago with the assistance of a number of oil companies and car manufacturers.

In general the aim of these trials was to look at the performance of the blends in individual cars keeping records of drivability, fuel consumption, changes in water tolerance and any mal-functioning or obvious material wear. In all cases the cars used were initially either taken as received from the car manufacturer or in the case of older cars, tested by the Automobile Association on gasoline to ensure the car was within the specifications of compression, timing and carburation set for each car. Fuel consumption was measured by measuring the volume of fuel put into the car and the volume removed at the finish of a given test. Distance travelled was recorded from the vehicle's odometer. The fuel used was in general changed more or less at random such that the driver of the vehicle did not know what fuel was being tested. The driver was asked only for comments on drivability and any problems such as hard starting.

Three types of road tests are reported here.

(1) Standard Test Driving Pattern: In these tests a fixed course was used which represented a mixture of town, hill and open road driving. The distance was approximately 185 km. Care was taken to ensure that, as far as possible, the driving technique was kept constant with strict observance of all road signs being kept. For any given vehicle a single driver was used. Climate and traffic conditions were uncontrollable but in the latter case, careful selection of the time of the run tended to give very similar traffic conditions for each test.

(2) Uncontrolled Long Runs: The vehicles were taken out and driven under normal traffic conditions over long distances usually in excess of 200 km. Different drivers were used but where possible each driver was asked to do two comparable runs, one on petrol and one on 15% methanol/petrol.

(3) General Use: Vehicles were driven under normal traffic conditions over routes mainly involing town driving. The driving pattern was generally the normal day-to-day routine of the driver. No controls at all were applied.

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* Numbers in brackets (1) designate References at end of paper

The above tests all involved close study of single vehicles operating in the manner indicated. In some cases the vehicles were modified to compensate for impaired drivability caused by the methanol addition resulting in excessive leaning of the fuel mixture. These modifications, when necessary, involved the enlarging of the carburettor fuel jet. Fuel consumption data was obtained before and after modification.

Details of the vehicles used and the fuel consumption results are given in Table 1. Only data for 0% methanol and 15% methanol is given but full data for all blends may be obtained from the authors (4).

Fuel Consumption

The fuel consumption data is reported as ℓ/100 km. As can be seen the volumetric fuel consumption in general increases slightly but in a few cases decreases slightly and in other cases increases drastically. By-and-large this is related to the initial tune of the engine with the effect of the addition of 15% methanol being to lean off the original tune by about 9%. If the engine is originally tuned slightly rich as for maximum power, the leaning effect of the methanol will be to put the engine operation into a more efficient range of combustion, while if the engine is already tuned to its lean limit, the addition of methanol will make the engine operation too lean for efficient combustion.

To investigate the question of the efficiency of combustion of the blend it is useful to calculate either a specific fuel consumption based on the energy or heat value of the fuel or as is done here, calculate the gasoline or fuel equivalance of the methanol component of the blend. This is the litres of gasoline necessary to give the equivalent fuel consumption as would be obtained from a litre of methanol as determined by its performance in the blend. This may be calculated from the following relationship:

$$1\ \ell \text{ of methanol} = \frac{\dfrac{(\ell/100\ \text{km})\text{gasoline}}{(\ell/100\ \text{km})\ \text{blend}} - x}{1 - x}$$

where x is the volumetric fraction of gasoline in the blend and (ℓ/100 km)blend and (ℓ/100 km)gasoline are the fuel consumption for the blend and gasoline respectively.

Since methanol has just about half the calorific heat or heating value as gasoline (0.45 based on lower calorific values) it would be expected that if the engine were operating the same for the blend as for gasoline that the fuel equivalence of the methanol would be 0.45. It can be seen however that in general, the fuel equivalence of the methanol in these tests was well above 0.45. In fact a simple average of all the fuel consumption data available from our tests gives a fuel equivalence of the methanol of 0.82. This indicates an improvement in engine efficiency of over 80% for the methanol when used as a 15% blend. Or put another way, an average only 1/0.82 = 1.2 litres of methanol would be needed to replace a litre of gasoline (when used in a 15% blend) rather than 1/0.45 = 2.2 litres as predicted from calorific values only.

This improvement in efficiency is thought to be largely due to th leaning effect of methanol as discussed before. It is apparent that the majority of cars tested, which is gradually building up to be a fairly representative picture of the current car pool in New Zealand, are tuned on the rich side. This is in agreement with an independent study on vehicle exhaust emissions (5) in which it was found that from 65-75% of the cars tested were tuned too rich at idle to meet reasonable levels in carbon monoxide emissions (3.5% - 4.5%).

It is worth noting that often variables including the driver and his driving habits affect the relative comparison between gasoline and the blends. Tests number 6 and 7 clearly show this where two different drivers driving the same car over the same route consistently obtained very different results, one driver averaging a fuel equivalence of only 0.47 while another obtained a fuel equivalence of 0.93.

Clearly much more road testing is required which was one of the reasons for starting the fleet trials discussed in the next section.

Drivability

Along with fuel consumption one must also consider drivability. Our experience with single vehicle road tests would indicate a slight deterioration in drivability with the blends. At the 10% level of addition of methanol however the deterioration was very minimal with only the smallest or most leanly tuned engines showing any deterioration in performance. At the 15% level a significant number of vehicles showed noticeable loss in performance and at the 20% level a majority of vehicles showed noticeable loss in performance. The Toyota Corolla however showed no significant deterioration in drivability even at the 25% level of methanol. Also no differences in acceleration were found in controlled acceleration tests between gasoline and the blends using both the Corolla and a Holden Belmont.

The two common complaints on performance were a need for increased choking and/or idle speed until the car was fully warmed up and a flat spot in low speed acceleration. In the extreme cases the car would stall frequently at intersections and/or give "lumpy" driving unless extra choke was used.

The deterioration observed in drivability is clearly due to the leaning effect of the methanol but is is actually surprisingly minimal at the 10-15% level of methanol addition. This is no doubt due in part to the relative richness of the tune of most cars in New Zealand as discussed previously. However it is felt that the fact that blends can operate under such lean conditions is due in part to more efficient combustion with the blends and a higher volumetric efficiency. These results have been substantiated by single cylinder test engine results showing significant improvements in power and thermal efficiency with 10% nd 20% methanol-gasoline blends over straight premium gasoline nder lean conditions (2)(3).

In summary it is felt that at the 10% level of methanol addition the effect on drivability would be minimal for cars in New Zealand without any modifications. For leaner tuned cars at high methanol concentrations (15-20%) some minor carburettor adjustments might be needed to make the performance acceptable. In these tests for example with the Mini 1000, a change in the carburettor jet costing about $3.00 was required to make the performance acceptable at 15% methanol. It is felt that similar or even simpler modifications could be made to allow most cars to operate with blends of up to 20% methanol.

Vapour Lock

We experienced no definite cases of vapour lock which could result from the higher vapour pressure of the blends when a standard premium gasoline is blended with methanol. This is perhaps not surprising when one considers the mild climate of New Zealand; the mean temperature varies from 9°C in the South to 15°C in the North, with a mean low temperature of -8°C and a mean high temperature of 32°C.

Fuel System Compatibility

Extensive tests on all components in the fuel system, both metallic and non-metallic, have been made. Details of these studies are available but in short no metallic parts have been found to be adversely affected by the blends. One type of plastic fuel line currently used in a very few cars in New Zealand (polyurethane), is dissolved by the methanol in the blends and would not be acceptable for use with the blends. Also the lead-tin alloy, terne plate, used as a coating in the pressing of some fuel tanks is dissolved by the methanol but this has given rise to no serious problems in our road tests.

Paint Finishes

Certain paint finishes are susceptible to damage by the blends. In New Zealand the paint finishes most affected have been shown to be a reflow acrylic lacquer and to a lesser extent nitrocellulase lacquer. In some cases any damage done can be repaired by cutting and polishing but with the acrylic lacquer the damage is essentially irreversible, with fine craze lines developing in the paint finish after being exposed to direct contact with a blend after about five short periods (a few minutes during which the fuel evaporates). On the other hand the most common paint finish on new cars in New Zealand, an acrylic enamel, shows excellent resistance to attack by methanol or blends of methanol. Clearly however special techniques of filling will have to be ir [illegible]duced for the blends.

Improved Octane Rating

Due to the high octane rating of methanol, especially when used as a blend with gasoline, it should be possible to reduce the amount of lead compounds added to gasoline to improve the octane rating. In New Zealand the lead additives are one of the highest in the world (0.8 g lead per litre) and tests using a single cylinder Ricardo test engine (2),(3) indicate that the lead additive level could be reduced by about fifty percent for a 15% level of addition of methanol and still maintain the same octane rating as the present premium gasoline in New Zealand.

Confirmation of improved octane rating for the blends was obtained during the controlled fuel economy runs. The course included a steep hill and invariably 'pinking' was found on going up the hill in top gear using premium gasoline alone. Under similar conditions with blended fuel 'pinking' was completely absent.

FLEET TESTS

Description

During the year from February 1978 to February 1979 a fleet trial was conducted in Auckland, New Zealand.

The principal aims of the trial were to obtain information on fuel consumption and drivability obtained when operating on methanol blends. A number of other aspects of blend use were also observed during the trial.

The fleet used was that operated by the Ministry of Works and Development, a large Government organisation. It comprised approximately sixty vehicles, approximately because normal scheduled replacement of vehicles occurred throughout the trial. The composition of the fleet early in the trial is shown in Table 2.

The fleet formed a vehicle pool for MOW personnel and was mainly used for inspection and service duties in and around Auckland City, a radius of approximately sixty kilometres. Occasionally longer runs were made. Generally drivers were not allocated to a specific vehicle.

The topography of Auckland is mainly flat with a few hilly areas, although the hilly parts are generally modest and gently rolling. A fair proportion of the runs would be on motorways when the vehicles would achieve speeds of 80 km/h (the allowable speed limit) for much of the time. The balance would be normal city/suburban driving with the speed limit of 50 km/h applying.

The climate of Auckland is mild with average temperatures of 20°C in summer and 10°C in winter. The recorded extremes are 32.4°C and -0.1°C (100 years observations). Average rainfall is 1268 mm/y spread reasonably well throughout the year. Typically the relative humidity is 70-80% during the summer months and 80-85% during the winter months.

Two fuels were used during the trial, normal premium petrol and a blend of 10% methanol:90% premium petrol. Each fuel was used in rotation for a nominal six weekly period. During the year there were thus four six weekly periods on the blend and the same on petrol. It should be noted that when fuels were changed the storage tank was drawn down to the lowest practicable level before introducing the new fuel in order to minimise cross contamination. Relevant data for the fuels is shown in Table 3.

The methanol blend was prepared by BP (NZ) Ltd and delivered to the fuelling point by conventional road tanker. Storage of the fuel was in an underground tank (4 500 ℓ capacity) and was drawn off through a conventional dispensing unit into the vehicle tank. The fuel dispensing unit was in an enclosed garage area. The fleet was serviced by MOW mechanics.

Test Preparations

Prior to the commencement of the trial the storage tank was removed and a new one installed. The original one was found to contain quantities of black sludge which caused separation of a blend due to entrained water.

The vehicles in the fleet were inspected and new fuel lines were put into two of the vehicles to replace existing polyurethane lines. This material had been previously shown to be attacked by methanol. No other precautions were taken. It is interesting to note that none of the vehicles had sufficient water in the fuel tanks to cause separation of the initial fill of blend.

Data Collection

As noted the primary aims of the fleet trial were to obtain fuel consumption and drivability data. In the former case this was achieved by recording fuel volumes used and distance travelled. These were recorded in a running book that accompanied the vehicle. At each fuelling operation the vehicle tank was filled to an automatic pump cut-out. Volumes were recorded from the pump head meter. Distance was taken from the vehicle odometer. This information allowed calculation of the fuel consumption for each tank of fuel and also the fuel consumption for the full six weekly period.

At the fuel changeover point the vehicle fuel tanks were run down to the lowest practical level before introducing the new fuel in order to minimise cross contamination.

In the latter case drivers were asked to complete a questionnaire which was collated to obtain an indication of drivability. In addition to these main aims information was collected on a number o ther relevant points.

The mechanics servicing the vehicles were asked to comment on any unusual mechanical faults and also to make visual observations, and reports if necessary, of the vehicle during normal maintenanc The opportunity was also taken to measure the concentrations of methanol and petrol components in the atmosphere around the fuelling point. This was done by the Department of Health and involved the use of personal sample tubes worn by the refuellers.

The water content of the blend in the storage tank was monitored to obtain an indication of the amount of water naturally entering into the tank.

Results

For the period of the trial noted, the total distance travelled on the blend was 354 994 km and on petrol 345 205 km.

Gross average fuel consumptions i.e. based on total distance travelled and total fuel used are 9.32 ℓ/100 km on petrol and 9.22 ℓ/100 km on the blend. This represents a slight improvement in fuel economy on a volume basis.

With the exception of one particular vehicle make, drivability was not particularly impaired. Occasional comments from the drivers were made to the effect that

- engine harder to start when cold
- vehicle slower to warm up in the morning
- engine hard to start when hot
- vehicle hesitates at slow speed, i.e. city traffic
- slight but regular hesitation or staggering at steady speed, i.e. motorway driving

However the majority of the drivers could not detect any difference between the fuels. The vehicles noted previously performed poorly on petrol as well as on the blend. Increasing the diameter of the main jet by approximately 5% eliminated the problem.

No adverse comments (or otherwise) have been made by the service mechanics. The vapour concentrations of methanol and petrol components around the fuelling point increased when a methanol blend was being dispensed but in all cases the concentrations were well below the TLV values applying in New Zealand. Bearing in mind that the fuelling point is enclosed this indicates that in a normal exposed fuelling situation no toxic hazard is likely to arise.

Water content of the fuel in the storage tank averaged about 600-700 ppm. A maximum water level of 850 ppm was recorded over the test period.

Conclusions

1) For the fleet in question and with a 10% methanol/petrol

blend, fuel consumption on a volumetric basis shows an improvement of about 1% corresponding to an improved energy consumption of about 6-7%.

2) Drivability problems are minimal.

3) No corrosion or untoward mechanical problems occurred during the course of the trial.

4) Based on limited data obtained from this test the toxic hazard is not effectively increased with a 10% blend.

5) Accumulation of water in storage tanks and vehicle fuel tanks is minimal and insufficient to promote phase separation.

FUTURE WORK

More large scale fleet trials are currently underway and will be conducted at various locations throughout New Zealand. All aspects of introducing a methanol-gasoline blend will be considered and the conclusions reached above will be investigated carefully for as wide a range of cars and climatic conditions as possible.

Preliminary studies on high methanol blends (50% to 100% methanol) have highlighted a number of potential problems, and a very extensive testing programme has been planned for the next year to look at performance, car modifications etc. necessary to use high methanol blends efficiently and safely. This is considered to be an option for New Zealand only in the more distant future.

ACKNOWLEDGEMENTS

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TABLE 1: Single Vehicle Road Test Results

Test No.	Vehicle	Comments	Averaged fuel Consumption		Fuel Equivalence for 15% methanol ℓgas ≡ 1ℓ methanol
			0% methanol	15% methanol	
1	Holden Belmont	as received, standard test run	9.35	9.16	1.14
2	Holden Belmont	as above but mod'fd	9.34	9.58	0.83
3	Ford Cortina 2000	as received, standard test run	9.98	10.07	0.94
4	Mazda 323	" " "	6.50	6.98	0.54
5	GM Sunbird	" " "	8.58	9.60	0.29
6	Toyota Corona (1.6ℓ)	" " "	7.57	8.22	0.47
7	Toyota Corona (1.6ℓ)	as above but different driver	8.25	8.34	0.93
8	Toyota Corona (1.6ℓ)	as above but mod'fd	8.68	8.57	0.75
9	Datsun 180B	as received, standard test run	7.25	7.79	0.54
10	Mitshubishi Lancer	" " "	6.84	7.24	0.63
11	Mitshubishi Lancer	as above but mod'fd	6.90	7.07	0.78
12	Toyota Corolla	as received, standard test run	7.21	7.06	1.14
13	Hillman Hunter S/W	" " "	7.81	7.94	0.89
14	GM Chevette	" " "	6.87	7.12	0.77
15	Holden Belmont	as received, uncontrolled long runs	10.76	12.35	0.14
16	Ford Cortina	" " "	12.40	12.04	1.20
17	Toyota Corona (1.6ℓ)	" " "	8.75	9.12	0.73
18	Datsun 180B	" " "	8.82	8.99	0.87
19	Mitshubishi Lancer	" " "	8.01	8.63	0.52
20	Chevette	" " "	7.51	8.05	0.55
21	Toyota Corolla	" " "	9.57	9.44	1.09
22	Cortina 2000	as received, general runs	14.02	13.35	1.33

Test No.	Vehicle	Comments	0% methanol	15% methanol	Fuel Equivalence for 15% methanol
23	Toyota Corona (1.6ℓ)	as received, general runs	10.20	10.54	0.78
24	Datsun 180B	" " "	10.76	11.61	0.51
25	Mitshubishi Lancer	" " "	11.14	10.43	1.45
26	GM Chevette	" " "	9.42	9.09	1.24
27	Holden Belmont	" " "	11.28	13.10	0.07
28	Rover 2000 (1970)	AA tested, general runs	12.16	13.77	0.22
29	Chevy Nova (1967)	" " " "	16.12	16.12	1.00
30	Mini 1000 (1973)	" " " "	7.25	7.25	1.00
31	Mini 1000 (1973)	" " " "	7.44	7.41	1.03
32	Marina (1.3ℓ) (1974)	" " " "	9.33	9.74	0.72
33	Zephyr-MkII (1961)	" " " "	12.15	12.50	0.81
34	Zephyr-MkII (1961)	" " " "	13.35	12.71	1.33
35	Maxi (1.7) (1975)	" " " "	10.45	10.20	1.16
36	Datsun 180B (1976)	" " " "	8.62	8.70	0.94
37	Holden Belmont (1966)	" " " "	17.12	18.22	0.60

TABLE 2: Fleet Composition

Car Make	No.	1971	1972	1973	1974	1975	1976	1977
Toyota Corolla	12	5	1		6			
Toyota Corona	9		9					
Holden	1	1						
Mini	1				1			
Mazda 1000	3							3
Mazda 1300	7					4	2	
Mazda 616	2						2	
Honda	2				2			
Hillman Avenger	3						2	1
Hillman Hunter S/W	1					1		
Cortina	3							3
Corolla Van	1				1			
Bedford Van	2		1					
Mazda Pick-up	4		2					
Hi-Ace Van	2				1			
Austin Pick-up	1							
Thames 1500 Pick-up	1							
Transit Van	2							
Totals	57	6	13		11	5	6	7

TABLE 3: Blend Properties

Distillation Characteristics

% Recovered	°C
IBP	32
5	39½
10	44
20	48
30	52
40	56
50	88
60	102
70	114
80	130
90	150
RBP	188

Reid Vapour Pressure 78.6 kPa

ALCOHOL BLEND USE IN STRATIFIED CHARGE ENGINES

by

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The California Energy Commission (CEC) is required by legislation to carry out numerous activities in alternative fuels research. The Commission's Synthetic Fuels Office primarily directs its efforts toward biomass conversion to energy. Biomass is not viewed as the dramatic, obvious and ultimate "solution" to the energy dilemma; it can, however, add many critical parts to the solution. The biomass program's basic goal is to maximize bio-energy contribution by encouraging production of clean fuels and developing waste-to-energy conversion technologies. Fuel cycle efficiency, technological maturity, ability to produce clean fuels and the immediacy of energy and economic return have been used as the criteria for establishing priorities in this area.

Subsequently, in the order of their ability to utilize biomass over the near term (through 1990), the sectors able to use bio-energy are:

INDUSTRIAL

Solid and gaseous fuels for process heat, steam and electricity.

UTILITY

Solid and gaseous fuels to produce electricity or natural gas substitutes.

RESIDENTIAL

Direct combusion for space heat and water heating.

TRANSPORTATION

Liquid fuel supplies.

Due to the relatively high production costs, biomass derived liquid fuels for transportation cannot be viewed as a significant contributor in the near future without substantial government subsidies. However, direct utilization of biomass via direct combustion and gasification is economical today in many instances and this is the area of major emphasis within the CEC Synthetic Fuels Office.

With this emphasis, biomass is being used to supply energy at stationary sources. This results in the displacement of conventional fuels which can then be converted to transportation fuels.

In the near- or mid-terms, this displacement strategy will not totally lead to a reliable transportation fuel supply. Californians use 12 x 10^9 gallons/year of gasoline. Obviously alternative sources of transportation fuels must be secured to meet projected demand. Coal and shale oil can be used as sources of alternative transportation fuels and methanol from coal is one of the attractive alternatives. In addition, alcohol/gasoline blend fuels are being considered as an option to extend the nation's gasoline supplies. While this may not be the preferred choice when compared to the use of alcohols in stationary turbines or captive fleets, research is required to quantify the potential economic and environmental impacts of implementing blend fuels in the transportation sector.

Experimental investigation of the effects of alcohol blends in conventional engines is currently being conducted by numerous organizations. However, the affects of blend fuels in stratified-charge engines has not been thoroughly investigated. The California Energy Commission has contracted with the University of Santa Clara for the purpose of experimentally investigating the effects of alcohol blends in stratified charge vehicles.

The study consists of three distinct test phases in order to provide adequate information to characterize the use of alcohol blend fuels on the operation and performance of the stratified charge vehicle. These consist of emissions and fuel economy tests performed on a chassis dynamometer, driveability and performance evaluation during road use and a materials wear study performed by way of periodic engine oil analysis.

The stratified-charge vehicles used in this test are four 1978 Honda Civic CVCC Hatchbacks. The vehicles are being run on 5, 10, and 15 percent methanol/gasoline fuel blends for three-month test intervals on each blend percentage. One of the vehicles is operated on the base fuel (unleaded gasoline) in order to provide a comparative base throughout the test period. The identity of the vehicles is not known to the drivers.

During each test period, each vehicle is expected to accumulate from three to six thousand miles while being driven for short trips only. The driver base consists of approximately three hundred CEC personnel. This will expose the vehicles to a wide variety of drivers and driving conditions. Each driver is required to complete a vehicle evaluation sheet. This allows vehicle characterization with regard to hot and cold start operation and general vehicle performance en route. The trends will be displayed as a function of equivalence ratio. Fuel physical properties will be contrasted between base and blend fuels. This analysis will help to quantify some of the vehicle performance characteristics, especially startability.

Intermittent to the three-month driveability test periods the vehicles will be tested on a chassis dynamometer in accordance with the Federal Test Procedure. Emissions consisting of total unburned hydrocarbon, aldehydes, oxides of nitrogen, and carbon monoxide and fuel economy will be recorded. The gasoline vehicle will provide a basis for comparison to conventional vehicle operation.

The vehicles are unmodified and have completed dynomometer and field testing at a 5% blend. The dynomometer testing at a 10% blend is complete and the vehicles are currently undergoing field testing with this blend. Briefly, the results to date show that with a 5% blend there is a:

Negligible change in CO
10-20% increase in HC
30% decrease in NO_x
20% increase in aldehydes
Negligible change in mi/mBtu

There is no indication of any driveability problems and oil sample test results indicate no unusual wear. All results being normalized to the gasoline-fueled vehicle. The emissions of the gasoline-fueled baseline vehicle, from which representative blend emissions can be extracted, are the following:

3.14 (9.0) gm/mi CO
0.280 (0.41) gm/mi HC
1.00 (1.5) gm/mi NO_x
0.02 (no std) gm/mi aldehydes
250 mi/mBtu

The numbers in parenthesis are 1978 California emission standards.

At 10% alcohol in the blend, the vehicles required carburetor adjustment to meet emission standards and dynometer results show a:

Negligible change in CO
40-50% increase in HC
30% decrease in NO_x
200% increase in aldehydes
5% decrease in mi/mBtu

To date there have been no driver complaints with the performance of the vehicles in the field.

Comparison of the results for 5 and 10% blends show that there is a significant increase in HC and aldehyde emissions and a 5% energy fuel economy penalty with the 10% blend. There are slight increases in HC and aldehydes, a substantial reduction in NO_x, and no change in energy fuel economy with a 5% blend. Note that at 5% blend, all regulated emissions are within the 1978 standards. However, at 10% blend, HC emissions are generally in excess of the 1978 standards.

It is concluded that the optimal blend for this particular engine (with no modifications) is around a 5% methanol, 95% gasoline.

The final phase of this experiment will include the identification of the optimal blend ratio for this engine. Originally, it was planned to test the vehicles with a 15% blend; however, the results at 10% indicate that there is little to gain by increasing the blend ratio.

Follow-on to this study will include dual fueling of the vehicles to allow independent fueling of the two combustion chambers on any desired blend percentage or in the pure form. Ethanol, in addition to methanol, is being considered for the follow-on research activity.

FUTURE SCENARIOS OF ALCOHOLS AS FUELS IN BRAZIL

by

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ABSTRACT

An updated account of the Brazilian National Alcohol Program achievements, both on production and utilization of fuel ethanol, is presented. A recently proposed program on methanol from wood (eucalyptus) is also briefly described. These programs are utilized as a basis for the establishment of scenarios for fuel alcohols production and utilization in Brazil, in the near future, with the overall objective of a gradual displacement of the oil barrel by fuel alcohols. An attempt is then made to evaluate the impact of the scenarios in order to prevent shortages/surpluses of fuels while avoiding possible decreases in alcohol production and consumption. As a result, various coherent and integrated energy mixes may be identified.

INTRODUCTION

Up to now the utilization of fuel ethanol as gasoline substitute has contributed to an increase in gasoline surpluses. This resulted from high increases of Diesel and fuel oil demand (about 11.0% and 7.5% per year during 1973-77, respectively) as compared with smaller growth of gasoline demand, against a relatively inflexible refining scheme.

Brazil's present energy supply is heavily dependent on imported petroleum; hence, the great concern existing in this country with developing domestic sources of energy to reduce dependence on foreign supplies. Imports in 1977 accounted for about 90% of total Brazilian energy oil consumption, and 40% of its total primary energy [1] *.

Brazil's primary energy demand has grown at a high annual growth rate of 7.2% over the last 10 years. Oil demand increased at higher annual rates (9.5%), with stagnant domestic oil production at the same level in 1977 as it was 10 years ago [1] . The recent escalating price of oil in the international market has strained the balance of payments of Brazil. It is estimated that in 1978 approximately 1/3 of the exports were spent with petroleum imports.

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* Numbers in brackets [ ] designate references at end of paper.

The "Programa Nacional do Álcool - ProÁlcool" is an ongoing Federal Program established in November 1975 to promote most rapidly an increase of fermentation ethanol production. The ProÁlcool subsidizes the investment required for new ethanol plants and expansion and revamping of existing distilleries.

Methanol is also being considered as an alternative fuel in Brazil. Depending on the market and future policies, methanol could possibly be produced in coal gasification complexes, in addition to wood gasification.

A methanol program based on 2,000 ton/day methanol plants based on gasification of wood has been proposed by CESP - São Paulo State Energy Utility. Secondarily, methanol could be potentially recovered as a byproduct in the production of charcoal for blast furnaces.

EXPERIENCE OF ALCOHOLS AS FUELS IN BRAZIL

Otto Engines

Alcohol Blends

The mandatory utilization of ethanol-gasoline blends in Brazil goes back to 1931, when, by law, 5% of imported gasoline had to be obtained as ethanol in the domestic market to be blended with gasoline [2] . During World War II, a great deal of cane sugar was converted into ethanol to meet fuel demand. During most of the first three quarters of this century anhydrous ethanol was used to hedge the sugar industry against international sugar price fluctuations. Therefore, the addition of ethanol to gasoline followed an irregular pattern. A major departure from this policy occured in November 1975 when ProÁlcool was launched. Ethanol addition to gasoline became a mechanism aimed at decreasing Brazil's dependence on imported energy. The history of anhydrous ethanol addition to gasoline on a national basis and in the State of São Paulo, the major ethanol producer in the country, is shown in Table I.

As of September 1978, 195 new or expanded ethanol distilleries supported by ProÁlcool will add a new capacity of 3.6 million m^3 of alcohol/year within 2-4 years. Official estimates [3] indicate that 55 of those 195 new or expanded distilleries have already produced 33% of the total ethanol production in the 1977-78 harvest year (total production of 1.5 million m^3), which represented an increase of 124% over the previous period. In 1977, about 1.4 million m^3 of ethanol were produced, 46% of which was distributed through blending centers for the anhydrous ethanol (20%) - gasoline (80%) blends.

Estimates for the harvest year 1978-79 indicate a production of 2.5×10^6 m^3 of ethanol.

Two types of automotive gasolines (A and B) are currently marketed in Brazil. Type A is the regular gasoline with a specified 73 MON minimum rate. Such octane rating is compatible with Brazilian Otto engines designed with a compression ratio of about 7:1. Type B is the Brazilian premium automotive with a 82 MON minimum rating. This gasoline is quickly disappearing from the market.

As a whole climatic conditions in Brazil favor the use of alcohol-gasoline blends. Ambient temperatures are seldom below freezing. Most Brazilian engines still operate with a rich carburation. Therefore, driveability and fuel-economy are not greatly affected with alcohol additions up to 20% vol.. However the optimum ethanol content in gasoline for Brazilian Otto engines was found to be in the range of 12% to 15% based on the lowest fuel volumetric consumption [6] .

Also, 2600 m^3/month of methanol (produced from natural gas), are being diverted for blends with ethanol and gasoline in the State of Bahia (6% methanol + 14% ethanol + 80% gasoline). This addition is temporary and local. It should cease as the chemical market for methanol develops further in Brazil.

Plans for coal gasification plants in Southern Brazil led to studies on the feasibility of methanol as fuel for Otto and Diesel engines, gas turbines and boilers [7] . Road and lab data are presently being collected by PETROBRÁS to compare the performance of Otto engines fueled both with ethanol-gasoline and methanol-gasoline blends.

Straight or Neat Alcohol

Early investigations on the use of straight ethanol fuel by E. Sabino de Oliveira, L.B. Siciliano and H.S. Mattos [7,8,9] deserve special attention. After 1975, the interest on straight ethanol engines increased. CTA (The Brazilian Air Force Technical Center) has conducted investigations with several currently manufactured Otto engines fueled with straight ethanol.

As of October 1978, 10 different commercial fleets operating on straight ethanol fuel were testing the technical-economic feasibility of this fuel in 725 vehicles, with a cumulative kilometerage of 2 million km [3] .

On the other hand, the use of straight methanol as a fuel in Brazil has been limited to a few experiments in car racing and isolated tests supported by CESP.

Diesel Engines

Although the 1977 Diesel oil consumption for transportation was similar to that of automotive gasoline (see Table II), limited attention has been given to the use of alcohols in Diesel engines in Brazil until recently. This was due to the price policy for oil-derived fuels, which holds Diesel oil price relatively low in comparison with gasoline, thus discouraging penetration of non-conventional fuels competitors(see Figure 1). However, due to the high increase of Diesel oil consumption this situation is changing.

Several experiments with both methanol and ethanol are now under way be the automotive industry and research institutes, including the following approachs: fumigation technique, engine conversion to Otto cycle, fuel additives to increase cetane number, individual and simultaneous direct injection of alcohol-Diesel oil and alcohol (methanol) dissociation [3, 10, 11] . Alcohol performance varies for each approach and there is no general consensus about the best solution to use alcohol fuels in Diesel engines up to this date.

Investigations about Diesel-vegetable oils blends have also been done, but most likely vegetable oils will not be available in as large quantities as alcohols in the near future.

Gas Turbines and Boilers

Past experience of fuel alcohols in Brazil with gas turbines have been limited to the Cações and São José dos Campos stations and lab experiments. In 1976, the Cações plant [12] equipped with a 55 kW ethanol-fired Lucas turbo generator began supplying eletricity to a small fishermen village in the State of Bahia to investigate its technical feasibility.

PROFILE OF OIL - DERIVATIVES CONSUMPTION

Over the last four years only about 30% of total ethanol production [5] was used as fuel in gasoline blends and a minor portion was used in the neat ethanol fleet cars and a negligible amount in gas turbines. Most of it was used for industrial purposes (approximately 60%) and exports (approximately 10%).

The Brazilian consumption profile of oil-derived fuels over the last decade (see Figure 1) indicate that, if substantial savings in oil imports are to occur,action should be taken to reduce consumption of the three main products with roughly equal volumetric demand in 1977: fuel oil, Diesel oil and gasoline.

Gasoline consumption has been kept relatively constant in the past years due to price increase and new conservation measures, such as reduced maximum speed in highways (now at 50 mph) and reduced operating hours of gas stations. However, Diesel oil and fuel oil consumption have not decreased (see Figure 1). Diversion to heavier crude oils and changes in the current refining schemes have been employed to adjust to the new situation. There are indications, however, that large investment would be necessary to avoid major surpluses of derivatives hard to move over national borders.

Gasoline and Diesel oil, as expected, are consumed mainly in transportation. Despite the large distances involved in Brazil -- 8,500,000 km^2 (i.e., larger than the continental U.S.A. or the whole of Western Europe), highway transportation growth was considerable over the last decade (15% annually). Railway and ocean transportation were responsible respectively for only 20% and 10% of total transportation in 1974. Air transportation had a negligible contribution of about 0,2%. Highway transportation, employing Otto and Diesel engines [3] , was responsible for the balance (approximately 70%).

Fuel oil is used essentially in industry (cement manufacturing, steam generation, industrial furnaces), since elecricity in Brazil is mostly hydro. Space heating is not needed in most of the country. However, Diesel and fuel oil supply most small-scale electricity generation in certain remote areas of Brazil, mainly in the Amazon region.

SCENARIOS OF FUEL ALCOHOLS

The scenarios are analysed with the help of a simple optimization model which, for the time period under study, minimizes the global consumption of petroleum barrels, while preventing fuel oil shortages/surpluses. Thus, the overall objective is a "gradual struggle against the barrel" in the sense that barrel consumption is going to be gradually penalyzed over the years.

Inasmuch as the range of feasible fuel substitution depends on the utilization technologies that are available, the model is constructed around these technologies.

The model was designed to incorporate endogenously the following features:

- cracking flexibility of the three major petroleum derivatives;
- technological fixes and bounds for alcohol mixtures, e.g. when added to gasoline, the mix can contain, at most, one part of ethanol in 4 parts of gasoline;
- different alcohol performances depending on its application; and
- stability in alcohol production, i.e., production and utilization shall not decrease over the years.

Other parameters that are policy-related are left as exogenous inputs, such as: automotive production, neat alcohol engine production capacity, demand from industrial and transportation sectors, and investment required.

The model identifies possible gasoline or Diesel oil shortages, thus outpointing demand inbalances or insufficient alcohol availability. Shortages of gasoline or Diesel oil are strongly penalyzed which occur when alcohol availability is exhausted, if alcohol uses are at their technological bounds or will not lead to reductions in the total amount of oil derivatives consumption. so, the model has imbedded a preference rule for alcohol uses: for example, under limited supply, ethanol may save more gasoline as a gasoline blend component than as a straight fuel. Among the alcohol fuels in Brazil, ethanol from sugar cane and mandioca is already being used in large scale, and most probably will be responsible for more oil savings than the use of methanol in the short run (5-10 years). Methanol from wood has recently been proposed by CESP and appears as an additional opportunity to be exploited.

Three scenarios were developed as an attempt to evaluate the impact of methanol and ethanol availability, over the next ten years. A simplification was introduced which considered ethanol to be employed only to displace gasoline and Diesel oil, whereas methanol could be used for Diesel oil and fuel oil substitution (as blend component or as a straight fuel with additives when necessary). The maximum availability of ethanol corresponds to official estimates [1] during 1979-1980 whereas figures from 1981 on correspond to a 30% increase over the official estimates. Methanol maximum availability corresponds to the introduction of one 2000 tons of methanol/day plant every two years, beginning in 1982. Therefore, annual alcohols availability by 1988 would be about 3.0 million m^3 of methanol and 6.5 million m^3 of ethanol.

Oil derivatives and alcohol fuels consumptions for the main applications and for three scenarios developed are shown in Figure 2. Scenarios I and II corresponds to a relatively low increase in annual demand: 3% for gasoline, 3% for Diesel and 1% for fuel oil. Scenario III corresponds to a somewhat larger annual demand: 5%, 8% and 3.5% respectively for gasoline, Diesel and fuel oil. Due to the limited flexibility of the refining schemes assumed, both scenarios generate gasoline surpluses in the first years and Diesel oil deficits in the last years. Scenario III, with higher demand, leads to excessive Diesel oil deficits. The deficit of Diesel oil could be met by either of the following: Diesel oil imports, increased crude oil imports and export of corresponding surpluses, additional modification of existing refineries to cope with the new situation or even a higher availability of fuel alcohols.

Scenario II differs from Scenario I in the sense that all methanol plants production should have to be consumed (as Diesel oil substitute, up to a limit, and as fuel oil substitute) leading to increasing Diesel oil deficit.

Automotive Production

One of the conclusions of Scenarios I and II is that about 760,000 light vehicles should be operating on neat ethanol (Otto engines) by 1988, requiring production of such vehicles to reach a peak of about 15% of total automotive production, during 1979-1987. Also, the number of neat alcohol buses or trucks (using methanol or ethanol as Diesel substitute) by 1988 would be around 55,000 vehicles. This corresponds to an annual increase of about 5,000 - 7,000 vehicles i.e., about 5% of total heavy vehicles production in 1978. However, if the Diesel oil deficits showed Figure 2 for Scenarios I and II are met by neat methanol vehicles, about 140,000 - 180,000 heavy vehicles shall be operating on neat alcohol fuels, requiring an annual increase of about 30,000 - 40,000, which is almost one third of heavy vehicles production in 1978. In Scenarios I and II, amounts between 0.25 and 0.50 million m^3 of ethanol per year would be employed as a Diesel oil blend component (up to 10% volume).

Return on Investment and Petroleum Savings

In Brasil, large eucalyptus-based methanol plants, with a 2,000 ton/day methanol production capacity are expected to cost about US$ 250-300 million, per plant [14,15] and correspond to 0.3% of the country primary energy consumption in 1978.

To evaluate the capital recovery as a function of petroleum savings, it was considered the fuel-mix obtained from Scenario II, which requires the implementation of a methanol plant every two years, up to a total of 4 plants by 1988. Plants take two years to be constructed; production in the first year of operation reaches 1,000 ton/day with full capacity in the second year, producing about 2.2 million barrels/years of crude oil equivalent (Scenario II). Three possibilities of petroleum price increases (P_I P_{II} and P_{III})were considered, with yearly price increases of 8%, 11.5% and 14% respectively (i.e. US$30, US$40 and US$50 per barrel by 1988 based on US$15 per barrel in 1979). The amortization period was 10 years, with a 2-years maturity and capital costs taken as 15% per year (including inflation).

Despite the large investments required, in a few years a positive cash-flow can be reached, as shown in Table III for Scenario II, based on amortization payments and oil imports reduction. For instance, assuming US$250 million for the plant cost and annual increase of 11.5% for the crude oil prices, a positive cash-flow would be reached in 4 years. Furthermore, by the end of 1997 all 4 plants of Scenario II would have been fully paid, with a present worth value of about US$2 billion of crude oil displacement. This amount is equivalent to more than twice the corresponding capital investment, assuming that crude oil price would be kept constant after 1988.

With respect to ethanol plants, a total of US$ 2.7 billion would be necessary as additional investment, relative to 1978 ethanol production, to reach the total production of about 6.5 million m^3/year by 1988, assuming a typical investment of US$610/$m^3$/year of ethanol from sugar cane and US$360/$m^3$/year of ethanol from mandioca based on distilleries of 150 m^3 of ethanol/day [16,17], and that 10% and 90% from the total 1988 ethanol availability would be produced respectively from mandioca and sugar cane.

Fuel Costs

As of February 1979, anhydrous ethanol price as established by the Government was US$290/$m^3$ (US$14.5/$10^6$ BTU). It has been claimed that methanol from wood in Brazil could be produced at about $US\$100/m^3$ ($US\$6.5/10^6$ BTU) [14] . Considering $US\$120/m^3$ ($US\$3.5/10^6$ BTU) as the price of the average oil-derivatives fuel at refinery in Brazil (where about 80% corresponds to crude oil cost [18]) both alcohols are not competitive with petroleum as yet. However, as of February 1979, regular gasoline price at gas stations is $US\$430/m^3$ ($US\$13.0/10^6$ BTU) including high taxes and transfer price from fuel oil, Diesel oil and other petroleum derivatives. On the other hand, it is important to build and test alcohol production and utilization in large scale in order to be prepared for the increasing crude oil prices and for security reasons. Also, it seems evident that a country with difficulties in the balance of payments could pay more for its domestic energy sources with greater potential in social benefits than short term cheaper imported energy.

Area Requirement

The assumed methanol availability (about 3 million m^3/year) corresponds to a total of 0.8 million hectare utilization by 1988, i.e., 0.1% of total Brazilian surface area. Requirements for ethanol production (about 6.5 million m^3/year) correspond to a total of 1.8 million hectare utilization by 1988. These figures correspond to productivity figures equivalent to 3.6 m^3 of alcohol/hectare-year [15] .

CONCLUSIONS

An attempt was made to help determine strategies for displacement of petroleum barrels by alcohol fuels in Brazil, while avoiding shortages or surpluses of fuels. The analysis of different scenarios have shown evidence of the strong sensitivity of the fuel energy economy to factors such as petroleum cracking structure, automotive production, technological fixes, etc. Despite high investments and initially higher costs, alcohol fuels seems to show interesting prospects, recovering the capital in term of savings in trade balance.

ACKNOWLEDGEMENTS

Thanks are due to Boris Enrique Utria and Ney Mauricio Carneiro da Cunha from Centro de Tecnologia Promon-CTP, for their contribution to this article.

TABLE I - Addition of Anhydrous Ethanol to Regular Gasoline, 1967 - 1978

Year Ethanol	67	68	69	70	71	72	73	74	75	76	77	78
Volume ($10^3 m^3$)	437	191	32	184	254	391	309	190	162	171	639	1.43
Brazil (% vol.)	6.2	2.3	0.4	1.9	2.5	3.5	2.5	1.4	1.1	1.2	4.6	9.4
São Paulo (% vol.)	13.5	5.1	0.4	4.6	5.8	8.6	7.0	3.1	2.4	2.6	-	20.0

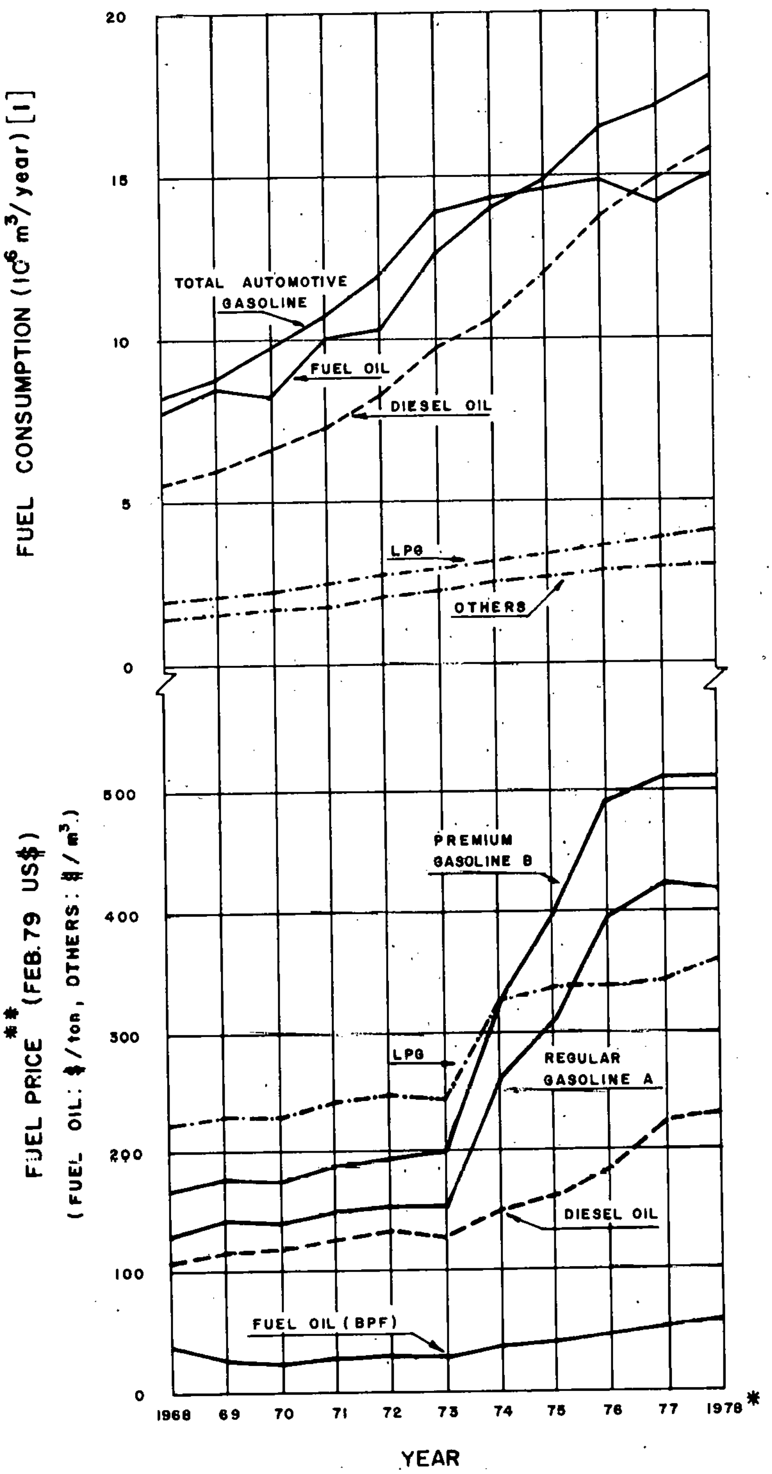
Sources: 1967 - 1976 [4]; 1977 [5];

TABLE II - Utilization of petroleum fuels [1,13] (% of total oil-derivatives on volumetric basis), 1977.

Fuel		Utilization			
Type	% vol.of total	Land Transportation	Industrial	Electricity Generation	Other
Gasoline	27	25	1	-	1
Diesel oil	28	21	3.5	0.5	3
Fuel oil	32	1	27	2	2
Total	87	-	-	-	-

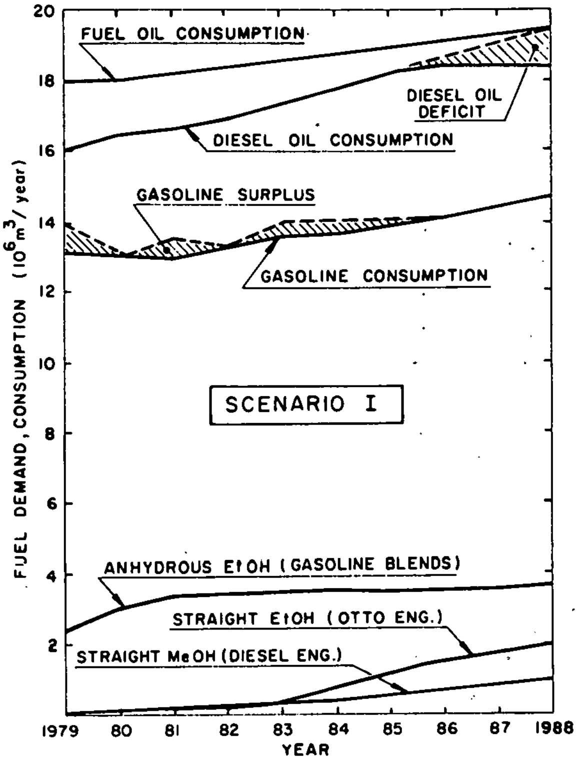
TABLE III - Years for positive cash-flow as a function of annual price increase of oil (Basis: methanol, Scenario II)

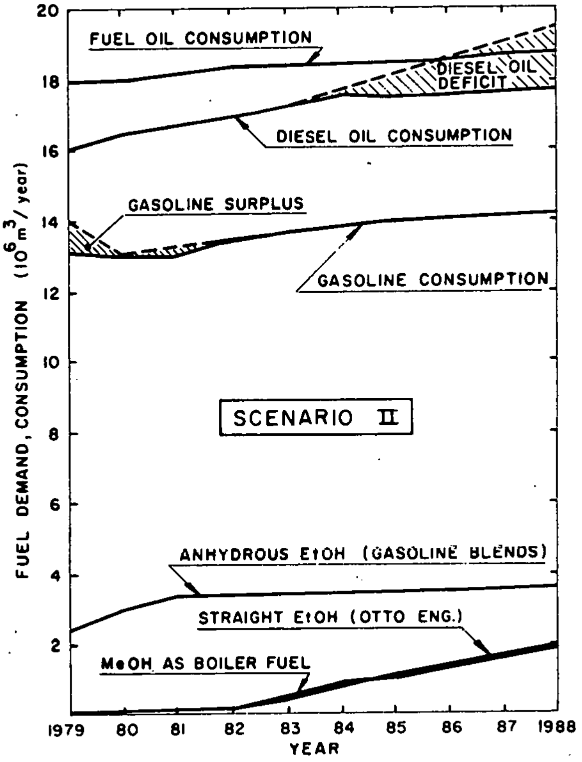
Plant Cost Case		250 million US$ (years)	300 million US$ (years)
P_I	(8% p.a.)	5	8
P_{II}	(11,5% p.a.)	4	6,5
III	(14% p.a.)	3	5

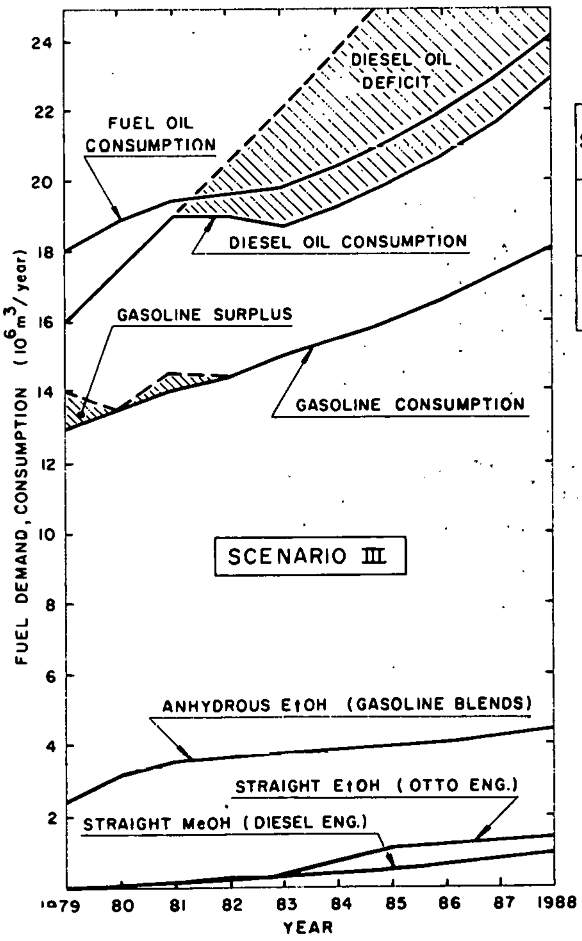


NOTES:
* ESTIMATE
** TO CONSUMER

FIG. I - FUEL CONSUMPTION AND PRICE, 1968-1978







	ALCOHOL	GASOLINE ($10^6 m^3$)	DIESEL OIL ($10^6 m^3$)		FUEL OIL ($10^6 m^3$)	TOTAL SAVINGS ($10^6 m^3$)	
			*	* *		*	* *
SCENARIO I	MeOH	—	2.0	4.0	—	2.0	4.0
	EtOH	40.0	3.0	3.0	—	43.0	46.0
SCENARIO II	MeOH	—	2.0	6.7	3.3	5.3	12.0
	EtOH	40.0	3.5	3.5	—	43.5	43.5
SCENARIO III	MeOH	—	2.0	38.0	—	2.0	38.0
	EtOH	42.5	1.5	1.5	—	44.0	44.0

OIL-DERIVATIVE VOLUMETRIC SAVINGS IN THE PERIOD

NOTES:

* WITHOUT ATTENDING THE PROJECTED DIESEL OIL DEFICIT.

* * METHANOL ATTENDING THE PROJECTED DIESEL OIL DEFICIT.

FIG. 2 - EXAMPLES OF ALCOHOL FUELS SCENARIOS, 1979-1988

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CANADIAN SCENARIO FOR METHANOL FUEL

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INTRODUCTION

This paper outlines a Canadian scenario to displace significant amounts of gasoline and diesel fuel with methanol fuel during the next two decades. A long term opportunity exists in Canada to achieve large scale methanol production by the late 1990's, based primarily on Canada's renewable forest biomass resources. In the next decade, the transition scenario outlined here would use near term Canadian natural gas surpluses as a joint feedstock along with renewable resources to produce methanol fuel. This scenario would promote the methanol fuel market development and methanol supply technology optimization needed to achieve, by the late 1990's, Canada's longer term forest-related alcohol fuel production opportunities.

The Canadian transition scenario outlined here reflects the findings of a consultant's study recently completed for Canada's federal government (1). The major conclusions of this and another recent Canadian study (2) are summarized in a separate paper presented to the Third International Symposium on Alcohol Fuels Technology (3). Other summaries of the consultant's report to the federal government are noted in the references (4).

No specific transition scenario has been adopted at this time by the Canadian government. As outlined in a separate paper (3), Canadian governments are actively investigating areas of forest biomass growth and production, forest biomass harvesting, gasification of forest biomass suited to methanol production, and various transportation end-uses for alcohol fuels to displace gasoline and diesel fuel. The government of Quebec has also recently announced a commitment to build a pilot plant for the conversion of wood to methanol fuel.

THE CANADIAN SITUATION

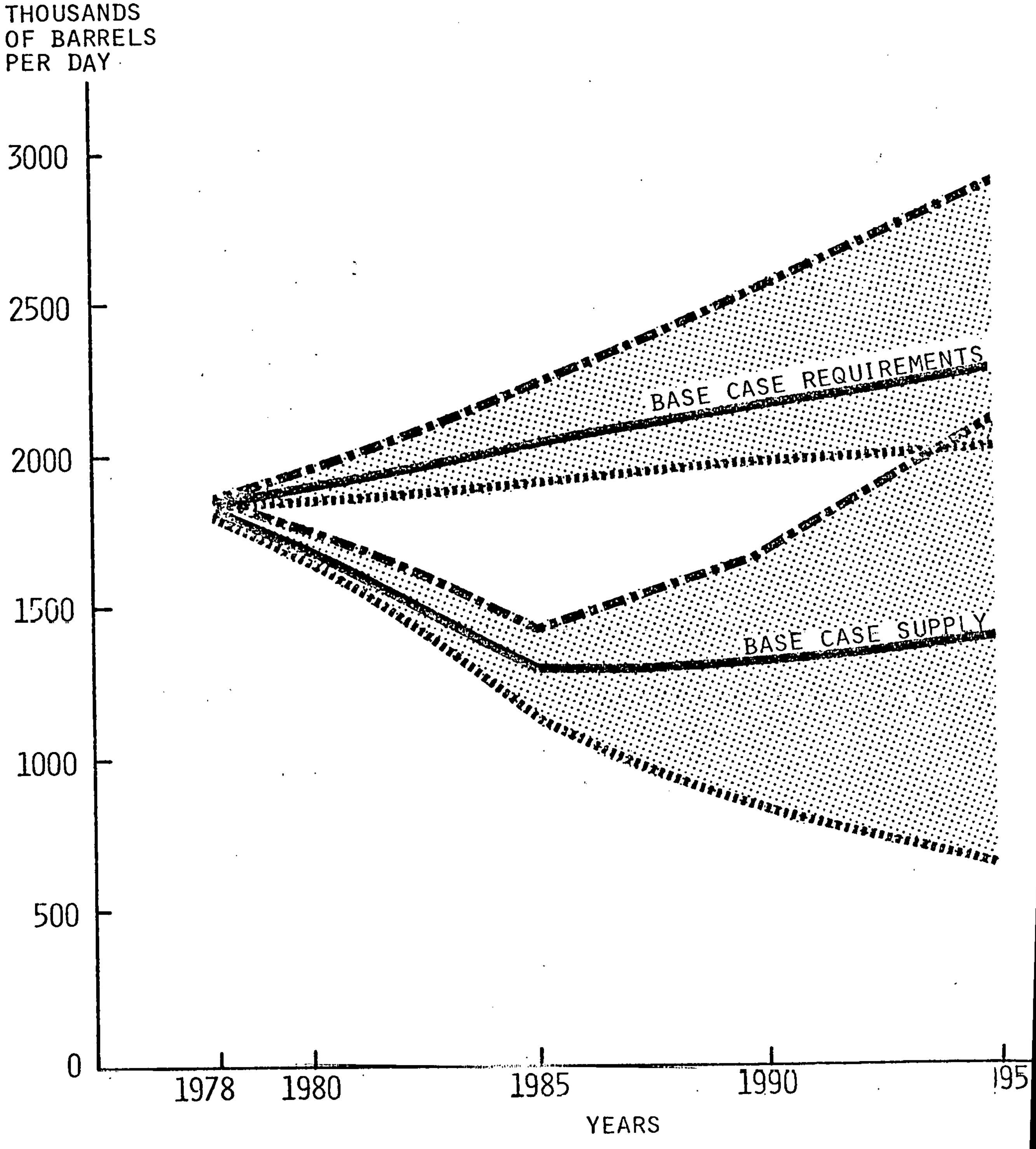
Oil Imports

Canada will need greatly increased oil imports at the very time (i.e., the mid-1980's to mid-1990's) when oil import constraints and escalating real (constant dollar) oil import prices are likely to emerge on a permanent basis due to a world shortfall in oil supplies relative to oil requirements. Figure 1 outlines ranges for Canada's oil requirements and supplies up to

FIGURE 1

CANADIAN SUPPLY AND REQUIREMENTS - CRUDE OIL AND EQUIVALENT

(SOURCE: 1978 NATIONAL ENERGY BOARD REPORT)



1995, taking into consideration the impacts of conventional inter-fuel substitution programs, energy conservation programs, higher oil prices, and maximum feasible near term development of Canada's heavy oil, frontier oil, and western region oil sands supplies. Figure 1 indicates that Canada is likely to need imports to meet almost 40 per cent of the nation's oil requirements by the mid-1980's. Canada's oil import needs may well exceed 700,000 barrels per day throughout the 1985-1995 period unless new unconventional non-petroleum liquid fuel supplies are made available.

International oil scarcities marking the end of the petroleum era are anticipated to create escalating real world oil prices. At present, Canada's oil imports cost over $15 per barrel ($1977 Canadian) landed at Montreal. A minimum Canadian import price ($1977 Canadian) of about $20 per barrel appears to be prudent for planning purposes for the mid-1980's and beyond, and prices may in fact (stated in $1977) exceed $30 per barrel by the 1990's (ignoring the very relevant risks associated with war or other possible sources of disruption affecting world oil supplies).

Liquid Fuel Options

Methanol fuel is a cost competitive and environmentally attractive near term option to enhance Canada's future liquid fuel supply security (1). This option would also create a major new long term resource and technology development opportunity throughout Canada's vast forestry sector, and would permit each Canadian region to enjoy significant industrial development benefits associated with new alcohol fuel supply development.

Other forms of alcohol fuel (e.g., ethanol) as well as possible synthetic petroleum products are indicated to be inferior options for Canada relative to the methanol fuel option during at least the next decade, and probably thereafter (1).

Aside from renewable resources, Canada's coal resources are reasonably plentiful in the two most western provinces -- however, rapid and extensive development of these coal resources for large scale liquid fuel use (e.g., methanol) would be constrained by environmental and political factors. In the long term, beyond the 1990's, coal offers far less potential than renewable forest biomass for large scale Canadian methanol production.

In the short and medium term, Canada is expected to have significant surpluses of natural gas which could potentially be used to meet Canadian liquid fuel needs. In some markets, e.g., home heating, natural gas could help to reduce oil requirements through simple direct substitution. In the gasoline and diesel fuel markets, methanol derived at least in part from natural gas could work towards the same objective. In all cases, however, the effects at best would be focused primarily within the next two decades. In the longer term, natural gas feedstocks cannot provide a viable basis for meeting Canada's liquid fuel needs.

Accelerated and extensive development of Canada's vast tar sands potentials located in Alberta could provide cost competitive liquid fuel supplies adequate to meet Canadian needs sometime beyond the mid-1990's. This fact alone, however, does not preclude the long run potential relevance of methanol fuel for Canada. Socio-economic, environmental, political and other factors underline the possible long run significance of a renewable resource based methanol fuel option for each Canadian region. Moreover, the methanol fuel option need not restrict development of Canada's tar sands and frontier oil potentials, i.e., the nearby United States markets should be able to absorb any oil surpluses made available by Canada.

LONG TERM METHANOL DEVELOPMENT: POSSIBLE TARGETS FOR CANADA

This paper's Canadian transition scenario for methanol fuel is designed to be consistent with specific long term (late 1990's and beyond) methanol development targets appropriate for Canada. These targets are established in light of Canada's domestic demand and supply factors pertaining to sustained long term methanol fuel production and use. Targets related to possible export sales of methanol are not considered.

Long Term Methanol Market Targets

The most promising large scale, long term methanol fuel market option for Canada involves widespread displacement of gasoline and diesel fuel oil in transport and industrial end-uses. In total, this market option would require over nine billion Imperial gallons (IG) of methanol fuel per year by the mid-1990's, i.e., an amount of alcohol fuel equivalent to the displacement of roughly 480,000 barrels per day of crude oil energy. Slightly larger amounts of methanol fuel would be required at later time periods, e.g., about eleven billion IG by the year 2005.

Methanol fuel would be used in the gasoline market in a variety of "pure" alcohol fuel uses (e.g., alcohol cars, "flexible fuel" vehicles able to use either alcohol or gasoline fuel, etc.) as well as in various "blend" fuel uses. The blend uses would tend to represent a residual rather than a major long term application in Canada. In contrast, the "pure" alcohol fuel uses would clearly constitute the dominant share of the methanol fuel market. Restriction of methanol marketing to blend fuel applications would imply long term methanol markets in Canada well below 2 billions IG per year; for this reason, the blend fuel end-use option is not emphasized in the following development scenario.

Methanol fuel would also be used in dual fuel applications with diesel fuel, constituting at least 40 per cent of the dual fuel volume consumed in such applications. (Canadian research on emulsifier technology for blend and dual fuel uses of methanol is described in a separate paper to this Symposium,written by Dr. T. Last and Dr. A. Lawson).

The gasoline and diesel fuel displacement option is attractive because it provides large scale displacement of oil products while utilizing end-use technologies readily available within the time periods needed to build up large scale methanol supplies. Within this market,conventional equipment replacement facilitates almost complete equipment turnover within ten or eleven years. The technical marketing and distribution problems associated with this use of methanol should also not provide any significant barriers to its adoption. Finally, potential market values for methanol fuel under this option are significantly higher than the market values estimated for other possible large scale Canadian uses of methanol fuel, e.g., retrofitted domestic oil furnaces, synthetic gasoline production, other light fuel oil displacement, etc.*

Long Term Methanol Supply Targets

Canada's renewable resources could easily sustain the long term methanol supplies needed to meet the gasoline and diesel fuel displacement market option outlined above. Canada's forest biomass alone could be used to sustain up to 15 billion IG per year of methanol fuel in the long term; coal resources could also be used to provide significant methanol supplies. (In contrast, Canada's agricultural wastes and municipal wastes could probably each sustain less than one billion IG per year of methanol production.)

As outlined in a separate paper (3), methanol produced using Canadian forest biomass alone as the feedstock could be economical in each Canadian region for supplying the target market when oil import prices reach about $25 per barrel ($1977 Canadian) and higher; methanol produced from western Canadian coal could be economical at slightly lower oil import prices of about $22 per barrel. It is considered quite likely that such average prices could in fact be achieved over a full 20 year economic life for Canadian methanol plants built in the late 1990's. In addition, the "break-even" oil import price required for such plants will certainly be clarified (and may indeed be reduced) by any methanol development and research activities conducted during the next decade.

Long term methanol supply targets for Canada therefore assume the use of forest biomass resources (without the use of any joint feedstocks) in each region to produce the volume of methanol needed to meet long term market targets.

Long Term Institutional Development Targets

Canada's long term methanol market and supply targets are not expected to be achieved simply through the unaided workings of "normal" market forces. Commercial feasibility for any entrepreneur will require clearly defined and integrated federal and provincial government regulatory and other policies designed to encourage a Canadian methanol fuel market supplied by indigenous renewable resources.

At present no Canadian market actually exists for methanol fuel, no significant sales of methanol fuel are being made in Canada, and no private

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*"Market value" here refers to a commodity value of methanol at its production site. Overall consumer costs for energy use are assumed to be unaffected by the choice of alcohol versus petroleum fuels; at any given oil price level, methanol production site values take into consideration all relevant end-use costs, distribution and marketing costs, relative conversion efficiencies, etc. for methanol relative to petroleum fuels. Methanol market values therefore vary among different end-use markets.

or government industrial entity has emerged as a leading force promoting methanol fuel development in Canada.

Methanol development will present very large investment requirements for each plant. Private investors, however, face the risk of low profit margins on such investments. Moreover, their profit margins will in all probability be largely determined by future government policies affecting relative fuel taxes, fuel price regulation, environmental regulations, crown taxes and royalties in each province for forest resource use, fuel use regulation for domestic and export markets, etc.

Under these circumstances, methanol fuel development in Canada will be affected by associated long term institutional development targets. Assuming that private rather than Crown corporations are required to play the leading role in developing future Canadian methanol supplies (1), it is essential that federal and provincial governments jointly establish a clearly defined policy framework within which private sector corporations can work to promote long term methanol development targets. A variety of such policy frameworks could be envisaged, ranging from utility-style regulation for "captive" franchise methanol markets to the integrated use of oil and methanol fuel tax policies, fuel use regulations, vehicle standards and emissions regulations, etc.

A critical result flowing from any near term transition scenario will be the resultant removal of uncertainties affecting the institutional framework for Canadian methanol development. In this context, a highly desirable near term objective is simply to establish large scale methanol fuel markets and major methanol fuel suppliers throughout Canada, using whatever options are most appropriate for the near and mid term time periods. This objective is, of course, greatly enhanced by the fact that such "transitional" methanol developments could be economically feasible on their own merits.

TRANSITIONAL SCENARIO FOR CANADIAN METHANOL FUEL DEVELOPMENT

Canada has the option, during the next decade, to pursue a "natural gas hybrid" methanol development transition scenario. This approach would facilitate viable and profitable development of methanol fuel markets, supplies and institutions while simultaneously advancing all of the technologies required to meet long term methanol market and supply targets appropriate for Canada.

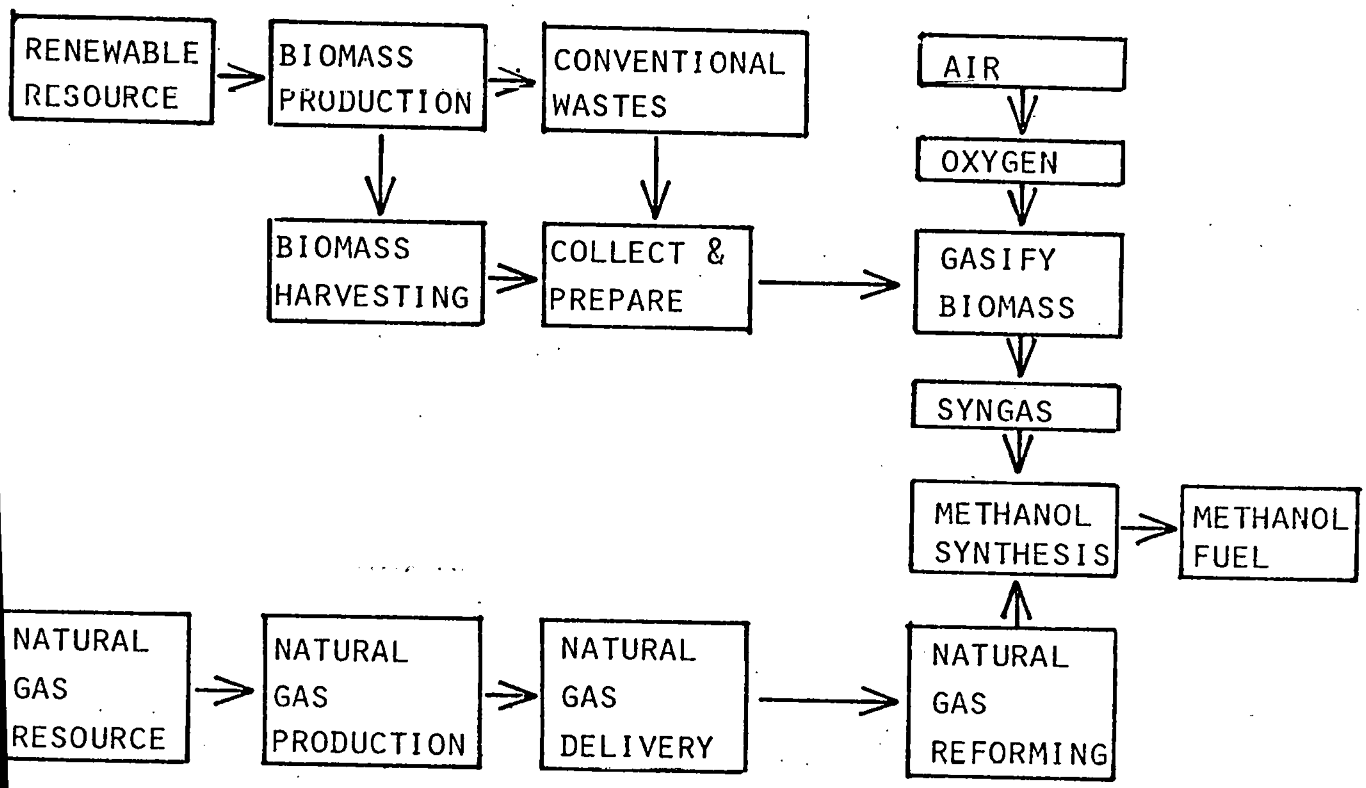
Natural Gas Hybrid Supply Option

The natural gas hybrid process would involve the joint use of natural gas and renewable resources (primarily forest biomass) to produce methanol. As outlined in Figure 2, this option requires reforming of the natural gas plus oxygen-fed gasification of the renewable resource in order that an optimal gas stream is provided for methanol synthesis. Renewable resource biomass and natural gas feedstocks complement each other for methanol production purposes -- gasified biomass is hydrogen deficient and too rich in carbon monoxide, while the reverse is true for reformed natural gas used to produce methanol.

The overall natural gas hybrid process using forest biomass is estimated to have an energy conversion efficiency of about 65 per cent with about 23

FIGURE 2

METHANOL PRODUCTION PROCESS: NATURAL GAS HYBRID OPTION



cent of the energy inputs being wood biomass and the balance being natural gas. One billion IG of methanol would thus require about 1.4 million oven dry tonnes (ODt) of wood (the ODt measurement is for convenience only since wood used would actually have significant moisture levels) plus about 91 billion cubic feet (Bcf) of natural gas.

The natural gas hybrid supply process is the least-cost Canadian option for methanol fuel supply until oil import prices ($1977) exceed about $25 per barrel, i.e., until such time as it is feasible to utilize longer term methanol supply options relying exclusively upon renewable resources. The technology needed for this option is readily producible, i.e., all components are now in commercial use except for the gasification unit using wood biomass. It is estimated that appropriate gasification units can be tested and finalized within two years. The gasification unit is a relatively small element within this specific methanol supply option. Improvements gained in this technology (along with forest biomass production and harvesting technologies) would, however, be of major importance to longer term methanol production which must rely exclusively upon biomass gasification without any joint use of natural gas feedstocks.

Large scale natural gas hybrid methanol plants would probably produce from 1,000 to 3,000 tonnes per day (91 million IG to 273 million IG per year) of methanol fuel. Canadian natural gas feedstocks appear to be sufficient to sustain up to at least four billion IG per year of methanol production for twenty years.

Economic Feasibility

Figures 3 and 4 outline, for 91 million and 273 million IG per year plants respectively, the economic feasibility of methanol production jointly using natural gas and forest biomass feedstocks to displace gasoline and diesel fuel products. "Average market values" indicate methanol commodity values at production sites (see earlier note); these demand values vary depending upon whether existing fuel tax revenues are maintained (the "Gasoline Tax Rate" option) versus having methanol fuel bear similar Federal and provincial fuel and sales tax rates per Btu purchased as presently apply for diesel fuel (the "Diesel Tax Rate" option). "Average production costs", in contrast, indicate methanol supply costs at production sites, incorporating all opportunity costs for the resources used (including valuation of natural gas purchases at 83 per cent parity values per Btu with oil import prices) plus a ten per cent real (net of inflation) rate of return on capital resources used over a twenty year economic plant life. Methanol supply costs vary among the different regions, reflecting variations in assumed natural gas feedstock costs.

Economic feasibility is clearly indicated for 273 million IG per year natural gas hybrid plants in all areas west of Quebec whenever Canadian oil import prices ($1977) averaged over a plant's twenty year life exceed about $18 per barrel; adoption of "Diesel Fuel Tax Rate" marketing options would cause these larger plants to be viable in all Canadian regions whenever oil import prices ($1977) exceed about $15 per barrel. The same "Diesel Fuel Tax Rate" option would cause even the smaller 91 million IG per year plants to be viable in each Canadian region whenever oil import prices ($1977) exceed $20 per barrel. Moreover, in all cases a natural gas hybrid plant economic feasibility would be enhanced by rising oil import prices.

FIGURE 3

ECONOMIC FEASIBILITY OF METHANOL PRODUCTION NATURAL GAS HYBRID USING FOREST FEEDSTOCKS

(GASOLINE AND DIESEL FUEL DISPLACEMENT MARKET PRODUCTION FROM A 91 MILLION GALLON/YEAR PLANT)

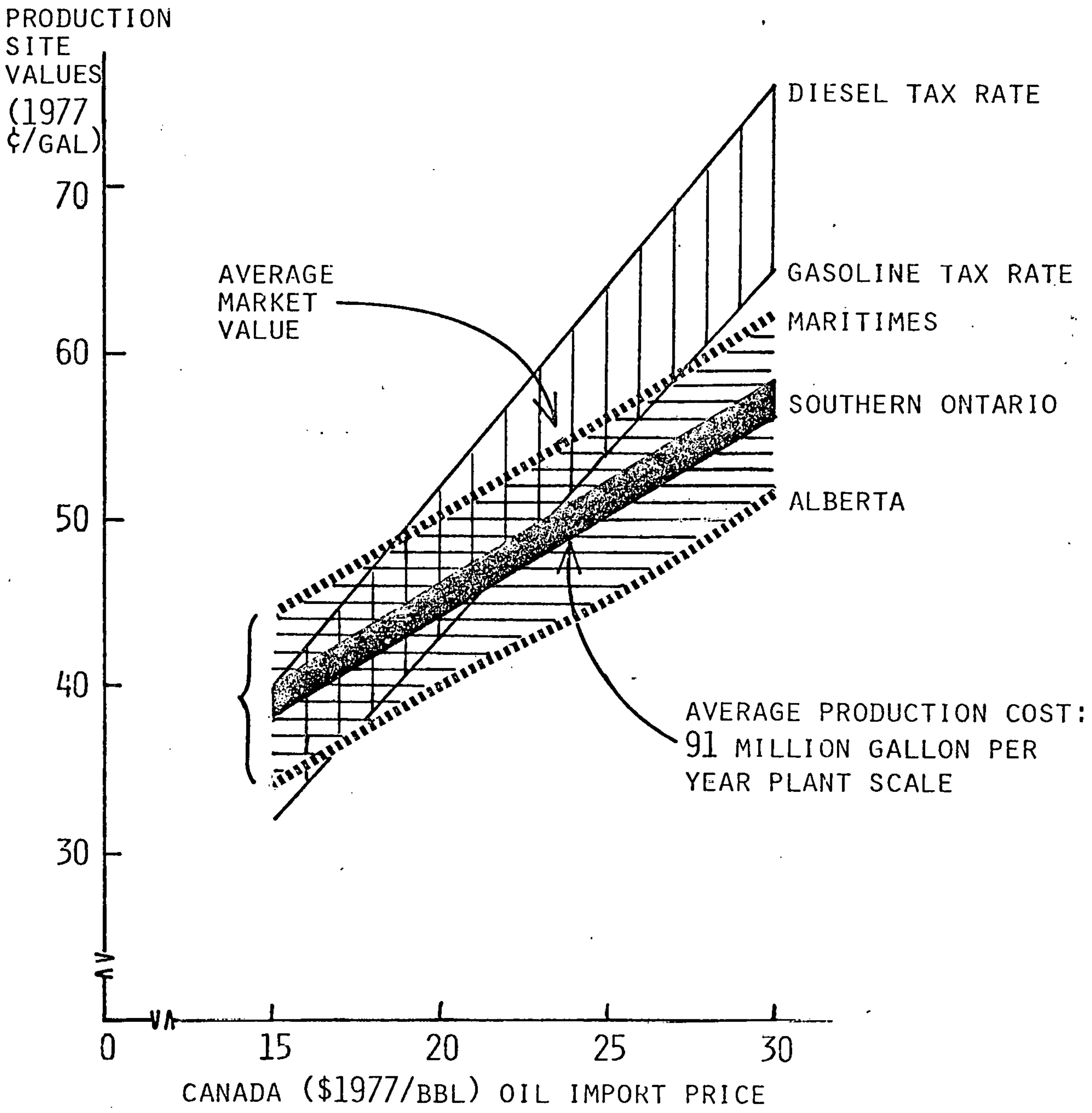
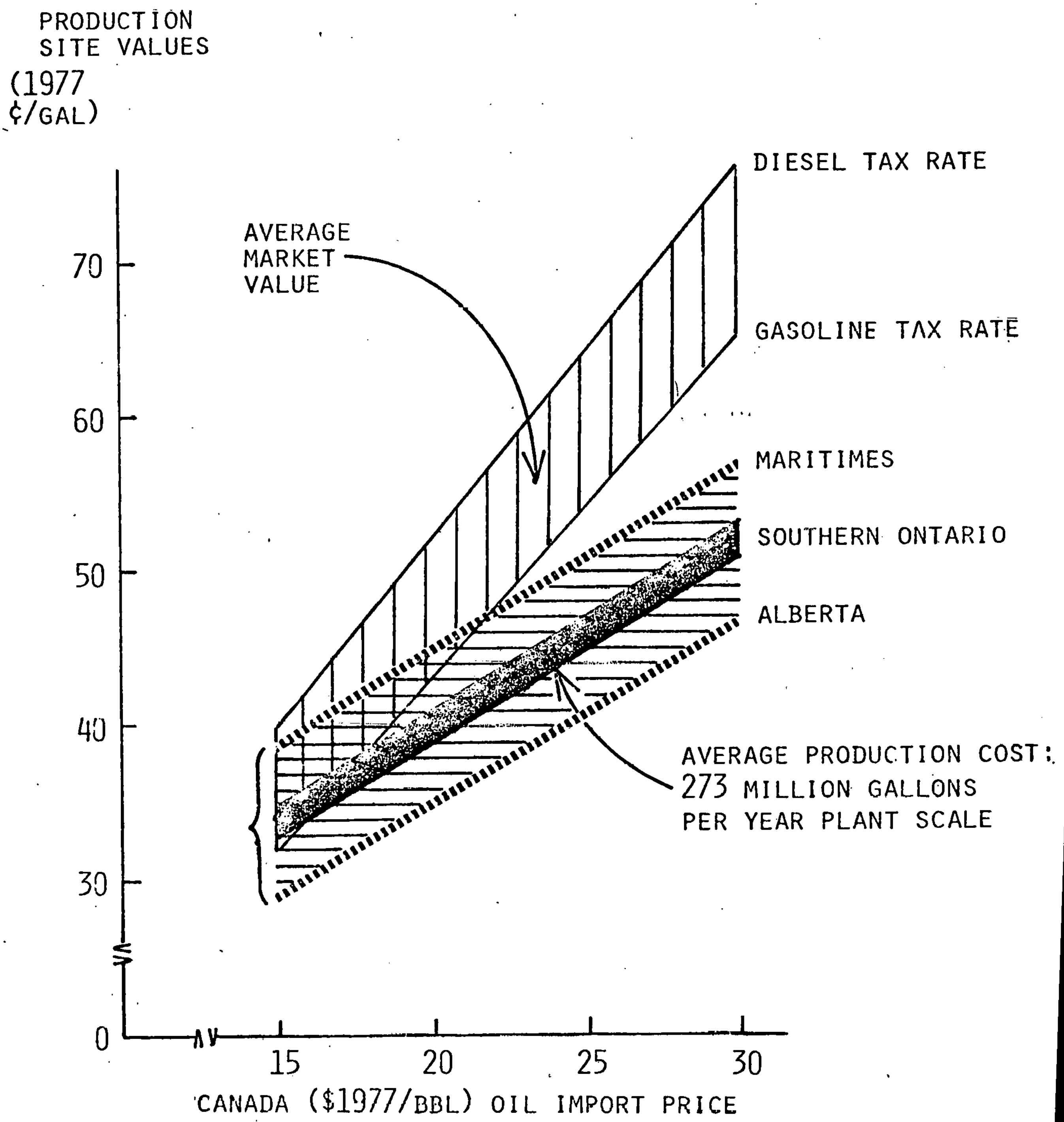


FIGURE 4

ECONOMIC FEASIBILITY OF METHANOL PRODUCTION NATURAL GAS HYBRID USING FOREST FEEDSTOCKS

(GASOLINE AND DIESEL FUEL DISPLACEMENT MARKET PRODUCTION FROM A 273 MILLION GALLON/YEAR PLANT)



In summary, given a prudent minimum planning price of $20 per barrel ($1977) for Canadian oil imports for the mid 1980's and beyond, it is economically viable at the present time to proceed with a natural gas hybrid methanol development scenario throughout most areas of Canada.

Methanol Transition Scenario

The natural gas hybrid process could permit Canada to produce from two to four billion IG per year of methanol fuel within five to six years. Production could continue to be expanded throughout the next ten years.

Production of two billion IG per year would require between 7 and 22 separate plants throughout Canada, a capital investment between $1.7 and $2.0 billion ($1977 Canadian), direct construction employment between 14 and 20 thousand man-years, and displacement of petroleum energy needs equal to the output of about one tar sands plant producing 125,000 barrels per day.

Development of the "first generation" of Canadian methanol plants to operate by the mid 1980's could proceed through three distinct phases in each region:

(a) Phase One: Phase One would require about 1 to 1½ years. The key objective for this phase is to specify plant sites, scales, processes, feedstocks, and markets for mid 1980's full scale operation. The key decisions at the end of Phase One are the approval of these specifications, the commissioning of engineering design work for the initial plants, and the approval of activities for Phase Two. Phase One activities would include testing and finalizing gasifier designs for the initial plants, testing of end-use technologies, demonstration test planning for various end-use markets, the identification of market priorities for each plant's fuel output, and the identification of optimal renewable resource feedstocks for each plant. Phase One would also involve setting up appropriate overall institutional frameworks suited to ongoing methanol development.

(b) Phase Two: Phase Two would require about 1½ years. The key objective is to complete engineering designs for the initial plants, to complete all requirements associated with delineating markets and regulations for those initial plants, and to begin planning a second set or "generation" of methanol plants. The key decision at the end of Phase Two is the approval to proceed with actual construction of the initial plants plus approval to begin design work on the next set of plants. It is noted that these decisions occur some 2½ to 3 years after the initial decision was made to begin the program, i.e., this amount of time is available before full scale investment and construction decisions are finalized.

(c) Phase Three: Phase Three would require about 2½ years. The key objective is to complete construction and start-up of the initial methanol plants including all associated implementation activities required for end-use marketing. This phase could also include activities related to second and third sets of plants to be constructed in a region.

The above transition scenario does not include as a pre-requisite the completion of extensive and costly non-commercial pilot plant activities. It i pected that a decision to proceed with large scale development would c private operators to pursue a wide range of research and testing activities with the expectation that such costs would be borne by future product sales. An essential requirement, however, is that all parties have reasonable confidence that stated methanol volumes will in fact be produced and sold within planned time periods, cost ranges, and price levels. Detailed review of the different activity phases for constructing any one methanol plant simply confirms the planning periods associated with different decisions.

Adoption of the above methanol transition strategy would create opportunities for planning ongoing methanol marketing and renewable resource development activities in each region. It is expected that alcohol vehicles, flexible fuel vehicles, and dual fuel (diesel fuel and alcohol) applications would all participate in the market from the outset along with blend fuel uses. It would also be relevant to consider planned use of a variety of forest biomass feedstocks sources in each region in order to facilitate longer term development of these feedstock supplies (this type of activity being assisted by the fact that natural gas methanol costs are relatively insensitive to renewable resource feedstock costs).

In short, the above transition scenario offers the prospect for Canada to occupy a leading position in liquid fuels technologies and biomass related energy systems appropriate for the post-petroleum era expected to emerge within the next two to three decades. Without appropriate government policy frameworks and entrepreneurial leadership within major Canadian businesses, however, the large scale aspects of this option could well preclude Canadian efforts until technologies and markets have clearly emerged in the United States and other areas outside of Canada.

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METHYL FUEL AND ITS EFFECT ON CRUDE OIL CONSUMPTION

by

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ABSTRACT

The study reported in this paper is part of a project on energy saving sponsored by the Italian National Council for Research.
The impact of methyl fuel use on oil consumption is examined in two energy scenarios characterized by different fuel oil demands.
Two possible uses have been considered:
- methyl fuel as a component of gasoline
- methyl fuel (or straight methanol) as a fuel oil substitute.

The bigger advantages in terms of oil and investment savings are obtained using methyl fuel as a gasoline component having a very high octane rating.

INTRODUCTION

It will take many years to switch from petroleum based fuel to non-petroleum fuels.
In the critical transition phase the availability of methanol from coal or from natural gas could play a key role; methanol is in fact the most likely choice among the potentially viable fuels for broad application either as such or as a petroleum extender.
In the near to mid-range term straight methanol can be used in place of fuel oil particularly in large scale electric utilities as no special problems are anticipated in this type of application.
On the contrary, the use of straight methanol in the automotive application requires major modifications of the present engines or even the design of totally novel engines.
Instead, the use of methanol as a gasoline component in a concentration up to 20% does not require any substantial engine modification.
Its use as a gasoline component does, however, pose many technical problems such as the low temperature phase separation in the presence of water and a large increase in vapor pressure, etc.
One of the solutions presently investigated in Italy for overcoming or at least minimizing the effect of the problems mentioned consists of using methyl fuel which is a blend of methanol and higher alcohols.
As a first step a number of laboratory tests have been performed in order to evalutate the chemical, physical and anti-knock properties of the gasoline-methyl fuel blends.
A 12 car road test has been subsequently run with a blend of gasoline-methyl fuel (80/20 by volume).
results so far obtained seem to indicate that the use of me-
l fuel in place of methanol is extremely attractive.

The main objective of this study is to determine the impact of methyl fuel availability on crude oil consumption and on the Italian refining system.
Methyl fuel for the Italian market must, in fact, be imported due to the lack of cheap raw materials available locally.
It is, therefore, necessary to quantify the replacement ratio between crude oil and methyl fuel with regard to both the fuel application (gasoline and fuel oil) and the future scenarios of oil products consumption including the foreseeable quality variations.
Another important aspect of this study is the evaluation of the impact of methyl fuel availability on the required investments to adapt the present refining system to the future market demand.
These elements as well as the cost of the methyl fuel will be the likely elements on which a realistic evaluation of the validity of this alternative fuel will be based.
The results of this study will, therefore, influence any future decision concerning the opportunity for building methyl fuel production plants.

THE CHOICE OF METHYL FUEL

The use of pure methanol as a gasoline component poses several problems relative to its use (vapor lock, corrosion, safety) and preparation of blends (volatility).
The most critical aspect is, however, the low temperature phase separation of the blend in the presence of water which is always present in the gasoline delivery system, even if its concentration is low.
A special survey conducted in Italy has shown that the storage tanks of refineries and depots and the delivery tanks of the filling stations are the most critical parts of the system.
The fuel tank of the car does not seem to be critical for water up-take but at low temperature it could be a problem.
The use of methyl fuel, which is a blend of methanol and C_2-C_4 higher alcohols, could solve all these problems because the higher alcohols greatly increase* the water tolerability of the alcohol-gasoline blends (1) (2) ; other advantages offered by the use of higher alcohols consist in their lower volatility and their higher heat content per unit volume.
Based on the available information concerning the possibility of producting methyl fuel on an industrial scale, the following alcohol composition has been selected for evaluating the performance of the methyl fuel

Methanol	80% vol.
Ethanol	4% "
n- Propanol	6% "
iso- Butanol	10% "

The methyl fuel to gasoline volume ratio of 20 to 80 by volume

*Numbers in brackets (1) (2) designate References at end of pa has been selected because lower alcohol concentrations do not offer satisfactory energy savings (3).

A comparison between methanol and methyl fuel in terms of stability of the alcohol-gasoline blends is shown in Fig. 1, where the cloud points of the blends are plotted versus the water content.

The improvement shown by the methyl fuel is considerable; for example, at 2000 ppm water content, the cloud point is +14°C with methanol and -16°C with the methyl fuel.

By reading the diagram in a different way, Fig. 1 shows that at 0°C 900 ppm of water are sufficient to generate haziness using methanol, while more than 3000 ppm of water are required to initiate haziness in the gasoline-methyl fuel blend.

A specific project has covered the evaluation of the blending performance of methyl fuel compared to methanol.

The most relevant results obtained are reported below:

- The blending octane numbers of methyl fuel are slightly lower compared to methanol, however the differences become smaller the higher the requested RON of the blend.

  For example, the data in Tab. 1 show the same base gasoline is suitable as a component of a 20/80 alcohol-gasoline blend with a RON of 98-99.

  The blending RON and MON of the methyl fuel are lower by only 2 and 1 unit respectively.
- Compared to methanol, the blending RVP of methyl fuel is lower; for example, at 20% concentration a blending RVP of 1.4 to 1.5 kg/cm^2 for methyl fuel compares to the corresponding value of 1.8 to 1.9 for methanol.
- The increase in volatility (% evaporated at 70°C) shown by the methyl fuel is lower compared to methanol, however, the increase at 100°C is greater.

  These phenomena depend on the lesser tendency shown by the higher alcohols to form azeotropes with hydrocarbons.

Overall, methyl fuel as a gasoline blend component practically offers the same octane advantages as methanol with fewer problems due to volatility.

IMPACT OF METHYL FUEL ON CRUDE OIL CONSUMPTION

General approach and key assumptions

The forecast of oil products demand in the years 1985 and 1995 is given in Table 2.

Distribution of oil products in 1985 is practically the same as today, being still characterized by the high share represented by fuel oil consumption (51.2% compared to the present 53.9).

The data for 1995 show a decrease in fuel oil demand (37.7% of the total consumption) as a consequence of the increasing exploitation of alternative energy resources (coal, nuclear power, etc.)

This estimate should be regarded as an optimistic expectation on account of the time required for implementing changes especially Italy where the use of non-renewable energy sources is not supported; it is, however, generally recognized that the petroleum products market will in future resemble the one outlined above. The Italian refining structure will, therefore, require an increased capacity of conversion of the bottom of the barrel to medium and light distillates.

The motor gasoline demand is expected to increase from 12.5 to 15.7 10^6 metric T per year (MTpY) in the time period 1985-1995.

The gasoline lead content in Italy is presently 0.6 g/l; it will be 0.4 g/l by 1981 and it is very likely that in future Italy, as well as other E.E.C. Countries, will take the same attitude as West Germany and will gradually reduce the lead level; this move will require additional investments and increase crude oil imports.

The impact of methyl fuel availability in this perspective will be now examined.

Our study has been carried out with a comprehensive refinery LP model on the basis of the following key assumptions:

- Alternative use of a methyl fuel-gasoline blend in the ratio of 20 to 80 by volume in place of conventional Premium gasoline. Experimental research has shown that the engine fuel consumption with this blend increases by 10% weight due to the lower energy value of methyl fuel as compared to gasoline:

	Conventional	Blend	Fuel consumption
Gasoline	1	0.87	-0.13
Methyl fuel	-	0.23	+0.23
Total	1	1.10	+0.10

  As a consequence, as shown in Table 3, the methyl fuel to gasoline replacement ratio is 1/0.57 by weight and 1/1,17 energy units.

  In the case of methyl fuel or methanol replacing fuel oil, the replacement ratio has been assumed to be 1/1 in energy units and, consequently, 1/0.5 by weight.
- The RON and RVP specifications of the methyl fuel gasoline blend has been considered equal to those of the conventional Premium gasoline; no limits have been set to either volatility (% ASTM evaporated) or Motor octane number.

  The experimental work done on the stability of the methyl fuel-gasoline blends has suggested setting a 25% vol. miniumum limit for the aromatic content of the base gasoline (1) (2).
- The lead content of the blends has been set equal to 0.4, 0.15 and zero g/l.
- For comparison purposes, it has been assumed that the availability of methyl fuel as a fuel oil substitute be equal to that considered for its use as a gasoline blending component.
- The objective function set in the Refinery LP Model has been to minimize the crude oil requirement necessary for meeting the anticipated 1985 and 1995 demand.

  No limits have been set for LPG, this being a process by-product.

Discussion of the results

The quantity of methyl fuel required amounts to 2.6 x 10^6 MTpY in 1985 and 3.1 x 10^6 MTpY in 1995.

The following considerations apply to the use of methyl fuel as gasoline component:

- The crude oil savings in 1985 and 1995 are reported in Table 4 and 5 respectively. The crude oil processed in 1985 is anticipated to be 118.4 x 10^6 MTpY for producing conventional Premium gasoline at 0.6 g/l Pb while it increases to 120 x 10^6 MTpY should the Pb be completely eliminated (Table 4).

  The production of methyl fuel-gasoline blends results in crude oil savings definitely higher than the methyl fuel/premium gasoline replacement ratio of 1/0.57 by weight and 1/1.17 in energy units; these increase to 1.02 T/T methyl fuel for a lead level of 0.4 g/l, to 1.05 T/T for 0.15 g/l and to 1.14 T/T for clear fuel. In energy units, the amount of crude oil saved is practically double (2 to 2.3 kcal per kcal of methyl fuel added).

  The quantity of crude oil saved is higher in the year 1995 (Table 5); it increases from 1.02 to 2.07 T/T methyl fuel added (from 2 to 4.1 kcal/kcal) when the lead content decreases from 0.4 g/l to zero.

  The availability of methyl fuel largely reduces the refinery energy consumption (Table 6) due to the high octane rating of this fuel component; the reduction of the processing fuel consumption is, in 1985, 0.9 to 1% of the processed crude oil and even higher, 1 to 3.1%, in 1995. It is interesting to note that in the case of production of a clear blend, the refinery fuel consumption is even lower than that presently needed for producing conventional gasoline with 0.6 g/l lead.
- The crude oil saving is broken down into lower gasoline production and lower refinery energy consumption in Table 7.

  The refinery fuel consumption saving is definitely higher in the year 1995 because, as has been already mentioned, at that time the need is anticipated for a larger capacity of residue to light fractions conversion units compared to 1985; the capacity of the conversion plants is higher the lower the lead content of the conventional premium gasoline to be produced.

  By reducing the quantity and the octane rating of the base gasoline, the availability of methyl fuel greatly lessens the need to utilize these high energy requiring processes.
- The impact on additional plant capacity, divided into octane improvement and conversion processes, is shown in Table 8.

  At 0.15 and zero g/l Pb the savings in capacity and then in investment costs are considerable with the use of methyl fuel.

The use of methyl fuel as a fuel oil substitute results, instead, in crude oil savings equal to or even lower than methyl fuel/fuel oil replacement ratio of 1/0.5 by weight and 1/1 in energy units as shown in Table 9 where a comparison between the two possible uses of the methyl fuel are reported. There are, in fact, no advantages in terms of either processing energy savings or additional plant capacity requirements of octane improvement or conversion units.

CONCLUSIONS

In the coming 10 to 15 years the advantages offered by the likely

availability of methyl fuel will be greater the lower the gasoline lead level required by law.
The estimated benefits, in terms of crude oil savings and less plant investment, are rather attractive.
For a complete evaluation of the benefits in terms of cost, it is essential also to know the cost differential between methyl fuel and crude oil. This point is at present still not well defined.
The use of methanol or methyl fuel as a fuel oil substitute is, instead, less attractive; the crude oil savings are lower and there are no advantages in terms of plant capacity requirements.

ACKNOWLEDGMENT

Thanks are due to the Italian National Council for Research (CNR) for their kind permission to publish this work.

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TABLE 1

CLEAR OCTANE RATING : COMPARISON BETWEEN METHANOL AND METHYL FUEL

BLEND COMPOSITION				
Base gasoline	%v	100	80	80
Methanol	"	-	20	-
Methyl fuel	"	-	-	20
OCTANE RATING				
RON		89.7	98.6	98.2
MON		81.4	84.9	84.7
Sensitivity		8.3	13.7	13.5

BLENDING O.N.	METHANOL	METHYL FUEL
RON	134.2	132.2
MON	98.9	97.9
Sensitivity	35.3	34.3

Note: METHYL FUEL is composed of 80%v methanol and 20%v higher alcohols (4%v ethanol, 6%v n-propanol, 10%v i-butanol)

TABLE 2

FORECAST OF DOMESTIC OIL PRODUCTS CONSUMPTION IN ITALY

	10^6 MtpY			% OF TOTAL		
	1975	1985	1995	1975	1985	1995
LPG	2.1	1.4	1.6	2.3	1.2	1.5
Premium gasoline	10.1	11.2	13.3	11.3	9.9	12.7
Regular gasoline	1.0	1.3	2.4	1.1	1.2	2.3
TOTAL GASOLINE	11.1	12.5	15.7	12.4	11.1	15.0
PETROCHEM. FEEDSTOCK	4.7	8.5	12.4	5.3	7.5	11.8
KEROSENE, JET FUEL	3.4	4.5	5.2	3.8	4.0	5.0
Diesel gasoil	5.8	10.0	12.2	6.5	8.8	11.6
Heating gasoil	14.1	18.3	18.3	15.8	16.2	17.4
TOTAL GASOIL	19.9	28.3	30.5	22.3	25.0	29.0
FUEL OIL	48.1	57.8	39.6	53.9	51.2	37.7
TOTAL	89.3	113.0	105.0	100.0	100.0	100.0

TABLE 3

USE OF METHYL FUEL AS ALTERNATE FUEL

METHYL FUEL SUBSTITUTING FOR	METHYL FUEL/OIL PRODUCT REPLACEMENT RATIO	
	Wt/Wt	Kcal/kcal
- Premium gasoline (1)	1/0.57	1/1.17
- Fuel oil (2)	1/0.5	1/1

(1) 1 Mt of premium gasoline replaced by 1.1 MT of methyl fuel/gasoline blend 20/80 vol/vol.

(2) 1 Mt of fuel oil replaced by 2 Mt of methyl fuel.

Note:	Lower Heating Value
- Methyl fuel	5000 kcal/kg
- Premium gasoline	10250 " "
- Fuel oil	9800 " "

TABLE 4

CRUDE OIL SAVING BY USING METHYL FUEL/GASOLINE BLENDS-YEAR 1985

(10^6 MTpY)

LEAD CONTENT IN GASOLINE g/l	0.6	0.4	0.15	0
CRUDE OIL CONSUMPTION				
- Without methyl fuel	118.4	118.96	119.53	119.96 (1)
- With methyl fuel	-	116.28	116.78	117.01
CRUDE OIL SAVING	-	2.68	2.75	2.95
METHYL FUEL INPUT	-	2.63	2.62	2.59
CRUDE OIL SAVED PER METHYL FUEL UTILIZED T/T (2)		1.02	1.05	1.14
kcal/kcal		2.0	2.1	2.3

Note:

(1) Crude oil input-Virgin naphtha surplus

(2) Lower heating value of crude oil = 10,000 kcal/kg

TABLE 5

CRUDE OIL SAVING BY USING METHYL FUEL/GASOLINE BLENDS-YEAR 1995

(10^6 MTpY)

LEAD CONTENT IN GASOLINE g/l	0.6	0.4	0.15	0
CRUDE OIL CONSUMPTION				
- Without methyl fuel	112.3	112.98	113.65 (1)	118.35 (1)
- With methyl fuel	-	109.82	109.92	111.92
CRUDE OIL SAVING	-	3.16	3.73	6.43
METHYL FUEL INPUT	-	3.10	3.10	3.11
CRUDE OIL SAVED PER METHYL FUEL UTILIZED T/T	-	1.02	1.20	2.07
kcal/kcal (2)	-	2.0	2.4	4.1

Note:

(1) Crude oil input-Virgin naphtha surplus

(2) Lower heating value of crude oil = 10,000 kcal/kg

TABLE 6

REFINERY ENERGY CONSUMPTION AS % OF THE TREATED CRUDE OIL

LEAD CONTENT IN GASOLINE g/l	0.6	0.4	0.15	0
YEAR 1985				
- Without methyl fuel	4.6	4.8	5.1	5.5
- With methyl fuel	-	3.9	4.1	4.4
YEAR 1995				
- Without methyl fuel	6.5	6.7	7.4	9.2
- With methyl fuel	-	5.7	5.9	6.1

TABLE 7

BREAKDOWN OF CRUDE OIL SAVING

(10^6 MTpY)

LEAD CONTENT IN GASOLINE g/1	0.4	0.5	0
YEAR 1985			
- Petroleum gasoline	1.51	1.50	1.47
- Refinery energy consumption	1.17	1.25	1.48
TOTAL SAVING	2.68	2.75	2.95
YEAR 1995			
- Petroleum gasoline	1.77	1.77	1.78
- Refinery energy consumption	1.39	1.96	4.65
TOTAL SAVING	3.16	3.73	6.43

TABLE 8

REQUIREMENTS OF ADDITIONAL PLANT CAPACITY COMPARED TO THE 0.6 g/1 CASE (10^6 MT)

LEAD CONTENT IN GASOLINE g/1	0.4		0.15		0	
METHYL FUEL USE	NO	WITH	NO	WITH	NO	WITH
YEAR 1985	-	-	-	-	-	-
- Octane improvement	-	-	3.1	0.2	12.0	1.2
- Conversion	-	-	-	-	-	-
YEAR 1995						
- Octane improvement	-	-	0.9	0.7	4.8	1.5
- Conversion	1.3	-	3.0	-	12.4	-

Note: Octane improvement processes: Cat. reforming, C_5/C_6 Isomerization, C_5/C_6 Molecular sieve, C_3/C_4 Alkylation, Cat. reformate Splitter

Conversion processes: Vacuum, Cat. cracking, Hydrocracking (with H_2 synthesis)

TABLE 9

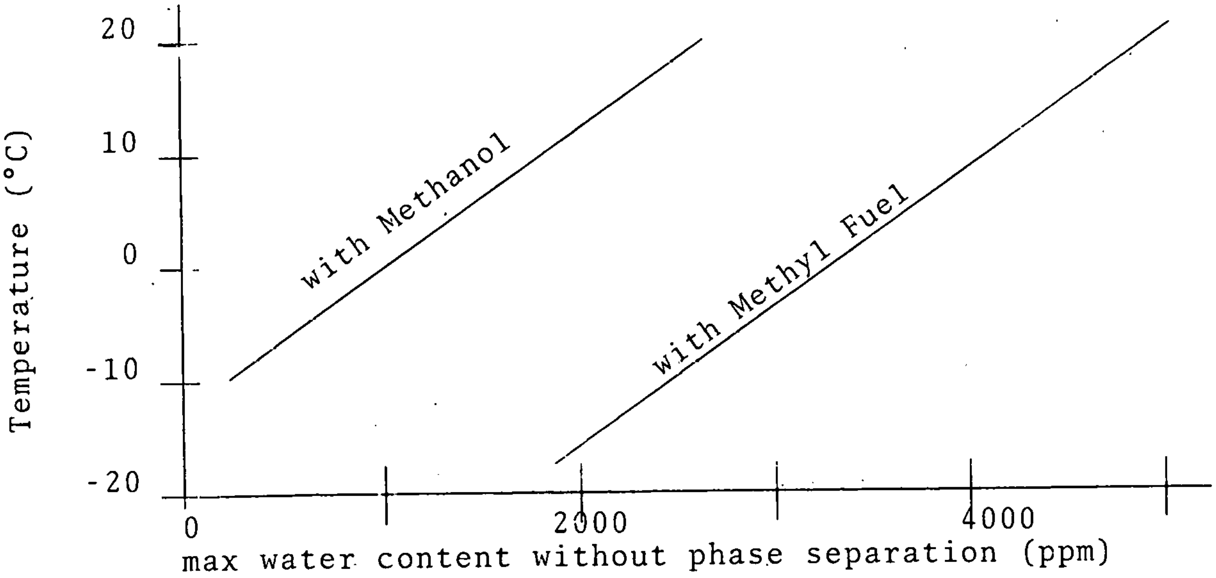
CRUDE OIL SAVINGS BY USING METHYL FUEL AS GASOLINE COMPONENT OR FUEL OIL SUBSTITUTE

LEAD CONTENT IN GASOLINE g/l	0.4		0.15		0	
METHYL FUEL as a substitute for	G.	F.O.	G.	F.O.	G.	F.O.
CRUDE OIL SAVED per METHYL FUEL utilized T/T						
- YEAR 1985	1.02	0.51	1.05	0.50	1.14	0.42
- YEAR 1995	1.02	0.48	1.20	0.44	2.07	0.32

Note: G = Gasoline

F.O. = Fuel oil

Fig. 1 - COMPARISON BETWEEN METHANOL AND METHYL FUEL USING BLENDS COMPOSED OF 80%v HYDROCARBONS AND 20%v ALCOHOL (Base Fuel composition: A = 29%, O = 6%, S = 65%)



Methanol, its precursors and/or derivatives in different scenarios, its testing and development of hardware required for alcohol fuels.

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Summary:

In different areas of the world it is possible to produce methanol at costs, where it can economically be used as a motorblending component at normal conditions. If for example 15 vol% would be added, additional capacity should be constructed. During exceptional conditions of embargo's, calamity, this capacity of methanol can increase the degree of autarchy for transportation of basic human needs. For USA, EEC and the Netherlands possible scenarios are demonstrated.
Adaptions of fuels and/or engines may be required, as well as development of auxiliaries especially when they can be retrofitted to ease introduction. Also possible is the use of raw materials and/or derivatives of methanol can be considered, of which fuel cells may be a promising example.

At the Wolfsburg symposium of November 1977 the work in the Netherlands with respect to the testing and development of hardware required for the application of methanol in cars and vans was reported. In the second part of this paper the work carried out since then is reported. This work has been concentrating on further development of transducers for alcohol fuels versus petrol. Next a description is given of the development of retrofittable hardware for a relatively simple system to enable diesel engines to run with about 40% alcohol fuel in the air intake. A description is given of the hardware development of retrofittable hardware to enable cars and vans to run on all mixtures(between 0-100%) of ethanol and petrol with automatic adaption via a transducer. It is stated that retrofittable kits help to move to alcohol fuels, bearing in mind that the results are not so good as from specially manufactured alcohol engines.

This paper consists of 2 parts:

Part 1 : Methanol, its precursors and/or derivatives in different scenarions
Gerrit Hovestreydt

Part 2 : Testing and development of hardware required for alcohol fuels
- Jouke van der Weide

Introduction

To try to predict possible future scenarios, a high number of variables are present, such as:

technical possibilities

consequences of technical actions on the environment

economical aspects

somatical aspects, etc.

The paper will only treat what a future scenario could be, mainly based on the economical situations for the USA and EEC. Technical and environmental aspects will be touched upon only. Other aspects will be disregarded in this paper.

Economical aspects

It is the aim of this paper to try to determine what the value of methanol as a blending compound for motor fuel can be and then to confront the value of methanol with the costs to produce it.
In the first instance all data will be based on a fuel-mix containing 15 vol % of MeOH.

Our definition of value of MeOH is based on the assumption that the final consumer of motor fuel, whether buying unmixed (hydro carbon) gasoline or a mixed gasoline, will have the same fuel costs per unit driven in the same way in the same car.

Several aspects will appear when determining this value, to know:

1. The combustion value of methanol is about half of that of gasoline. Since normally the state levy taxes on volume, the use of methanol would be penalized.
Two alternatives are approached:

- taxes on volume

- taxes on energy content

2. The quality of methanol as a motor fuel.
Methanol shows a relative good octane-number combined with a low boiling point.
So RON, MON and FON are affected favourably. This means that in the refining operations, the costs can be reduced.
The hydro carbon part now costs 64.4 ¢nts/gln instead of 78.8 x 0.85 = 66.98 ¢nts/gln, so a reduction of about 3½% to 4%.

3. The thermal efficiency of the Otto-motor when consuming a mix as fuel. This is a debatable point, which some institutions will not take into account.
However, statistical data by Volkswagen, as well as data derived from American sources and also the Dutch National Institute for Road Vehicle Research (TNO) are available. Although adjustments of the combination and other technical aspects will play their roles, it is assumed that enough theoretical and statistical considerations will be present to accept an increase of the thermal efficiency. In the calculations this increase is taken as 2½% if 15 vol % of methanol is added (graph 1).

If tax will be based on energy content of the motor fuel an optimum value of the methanol will appear when 15 vol % of methanol is added.
As in all the countries different tax systems are existing, it now will be shown for the Dutch conditions what the calculated values of methanol will be if 15 vol % is added for different tax systems and for cases where the final consumer will not have the same fuel bill, but will pay the same price per volume (fig. 1).

Fig. 2 is an approach to the costs of production for methanol in 1982, starting from different types of raw materials and assuming new production units to be built.
For European conditions the costs will be about $ 170/t excl. ROI and about $ 215 incl. ROI.
For US conditions this may be the same or lower, depending on the premisses used.

Possible scenario's

Having demonstrated that under certain conditions methanol can be an economically justified fuel as a blending component into gasoline under normal economic conditions, it can be calculated what the impact can be if exceptional conditions will exist, caused by embargo's, calamities etc. having the methanol capacity available. The degree of self-sufficiency, the level of autarchy will depend on the volume of methanol apparent in the gasoline on a national (USA) or regional (EEC) scale. Since it is not very probable that at one stroke of the pen 15 vol % MeOH will be added, calculations are made how the situation will be for 5, 10 and 15 vol %. Three scenario's for 1982 are set up for different area's, to know: USA, EEC and the Netherlands. It appears that if through unexpected causes no import of crude-oil to the USA will be available, the transportation and distribution of basic human needs can be continued. This will not be the case for the EEC-area, where the level of self-sufficiency will be decreased to 52%, if under normal conditions an extra capacity of 13.5 mln tons of methanol will have been constructed. Sufficient raw materials will be available to produce this quantity of methanol. It might even be extended for example by production of MTBE. For the Netherlands the situation can be worse if under normal conditions 15 vol % of methanol will be present in the gasoline. A level of about 40% will only be reached and extension with MTBE seems, strictly speaking, not possible.

Other fuels and/or power sources

Mostly production of methanol takes place via synthesis based on hydrogen and carbon monoxide. Hydrogen can very well be used as a motor fuel. However, if hydrogen should be considered, the fuel cell should be taken also in consideration. The following costs are approached, for fuel only and for fuel plus fixed costs of the power source:

		¢nts per kwh	
otto-engine	- gasoline	22,4	24,4
otto-engine	- gasoline, 15 vol % MeOH	22,4	24,4
otto-engine	- methanol	29,3	31,3
otto-engine	- hydrogen	26,0	28,0
diesel-engine	- diesel oil	11,0	11,3
diesel-engine	- methanol	24,0	24,3
fuel cell	- hydrogen	12,7	15,6 ÷ 18.1

Ways of introduction

While introducing, the governments should care for at least two important aspects, to know:

- control of environment
- control of energy consumption

As far as can be foreseen this can be realised on two ways only:

- introducing alcohol in motor fuel on a national base at a given level, so engines can be adjusted for a longer period.
- using auxiliary equipment for control of air/fuel mixtures flowing to the engines, so the required emissions and thermal efficiences of the engines are reached. This area has been searched by TNO.

1 Gradual introduction to the desired concentration of methanol should be contemplated

1982

(texes based on 1978)	H.C. motor fuel	blends with 15 vol.% MeoH, 0,15 gr lead/l				
		taxes on volume	taxes on energie content	taxes on volume	taxes balanced	taxes balanced
density, kg/l	0.756	0.7583	0.7583	0.7583	0.7583	0.7583
combustion value MJ/l	32.5	30.47	30.47	30.47	30.47	30.47
cost price, ex refinery in D ¢nt/l						
- hydrocarbons	39.4	32.2	32.2	32.2	32.2	32.2
- methanol	-	3.05	6.1	7.2	4.95	9.81
distrubution, retail, D ¢nt/l	20.0	20.0	20.0	20.0	20.0	20.0
taxes	48.6	48.6	45.55	48.6	46.7	45.99
	108.0	103.85	103.85	108.0	103.85	108.00
ATV 18%	19.4	18.69	18.69	19.4	18.69	19.4
total D ¢nt/l	127.4	122.54	122.54	127.4	122.54	127.4
relative consumption (on volume)	1	1.04	1.04	1.04	1.04	1.04
relative costs to final consumer per unit driven	1	1	1	1.04	1	1.04
relative proceeds to government	1	1.03	0.983	1.04	1	1
relative proceeds on production of hydrocarbons						
value of methanol D Fl/mt		256	512	604	415	822
value of methanol $/mt		128	256	302	207	411

fig. 1

fig. 2

Methanol production costs

In constant money from 1982

8.000 hrs./a
1 $ = ƒ 2,00

raw material	nat. gas	nat. gas	vac. resid	coal
capacity, mt/d	1.000	2.500	1.000	1.000
investment, $ 10^6				
- WBL	75	140	110	140
- OBL	20	40	25	35
capital related costs:				
- depreciation	10%			10%
- labour	1%			2%
- maintenance	1,5%			3%
- overhead	2%			3%
- deferred costs	1%			3%
	15,5%	17%	19%	21%
capital related costs per ton:	44,20	36,70	77,00	110,30
variabel costs:				
- electricity			±5	±15
- steam				
- BFW				
- cat. + chem.	±2	±2	±3	±4
raw material:				
- spec. consumption GJ/mt unices to $/GJ	37,5	37,5	42	45
N.W.-Europe 1982	$ 3,25	$ 3,25	$ 2,10	1,85
N.W.-Europe 1990	$ 3,75	3,75		1,95
USA 1982	$ 2 - $ 3	$ 2 - $ 3	$ 1,75	0,40 - 0,70
USA 1990	$ 2,20 - $ 3,10	$ 2,20 - $ 3,10	$ 2,00	0,40 - 0,70
total costs, excl. ROI:				
N.W.-Europe 1982	168	160	173	212
N.W.-Europe 1990	187	180		217
USA 1982	121 - 159	113 - 151	159	147
USA 1990	120 - 170	121 - 162	169	147

fig. 3

1982 scenario's	normal conditions			exceptional conditions		
	USA	EEC	the Neth.	USA	EEC	the Neth.
Demand for transport:						
- gasoline, total, t/a	360	90	5			
- gasoline for trucks, t/a	120	9	0,2			
- diesel oil (1) , t/a	55	4 5	4,5			
Production from indigenous sources:						
- gasoline, t/a				190	15	-
- middle distillates, t/a				105	30	-
Methanol requirement, if concentration will be 15 vol %:						
- new capacity to be constructed, mln t/a	54	13,5	0,8			
- existing capacity, mln t/a	4	3	0,8			
- potential available, mln t/a	58	16,5	1,6			
Required for transport of basic human needs:						
- gasoline				50 (3)	3,5	0,1
- diesel oil				22	16	2,0
Required for domestic heating, middle distillates, mln t/a				80	120	-
Level of self-sufficiency, % (2):						
- on existing MeOH capacity				100	10	20
- on potential available MeOH				100	52	38
Ability of diesel engine to run on MeOH, or derivatives				preferentially partial	partial	total
Indigenous raw materials				natural gas, oil, coal	natural gas, oil, coal	natural gas

1 assumed to be for transport of goods

2 for transportation

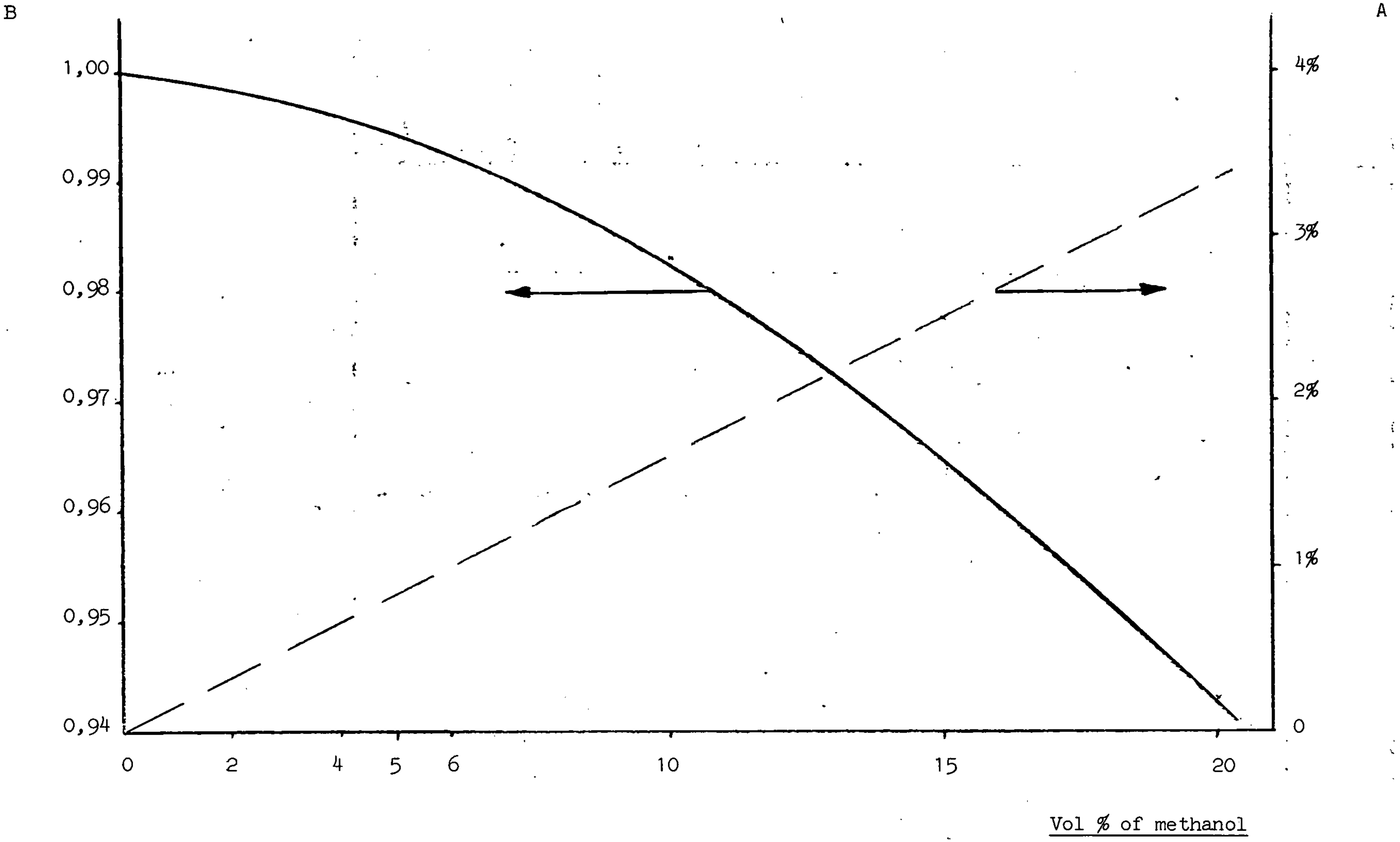
3 disregarding requirements for commuting etc.

6

Assumed relation between the methanol content of the mix and

A. The increase of the thermal efficiency of an otto-engine

B. The fraction of the costs of $\frac{\text{hydro-carbon part in mix (vol)}}{\text{premium gasoline (vol)}}$



Graph 1

Part 2. Testing and development of hardware required for alcohol fuels.
Jouke van der Weide

2.1 Introduction

Related to the above mentioned scenarios the progress since the Wolfsburg symposium in November 1977 with respect to the testing and development of required hardware is reported. Already at that symposium (1) statements were made with respect to the advantages of retrofittable hardware for engines to enable these to run on alcohol fuels. It will be clear that in the long term the advantages of specially developed engines for alcohol fuels are superior (2)(3). There is however still a long way to go before an engine manufacturer can decide to take such engines in full scale production. This is due to:
- a failing infrastructure for dispenser and bulk transport
- no guarantee for sufficient fuel during the whole year.

On the other hand it is difficult for a fuel industry to start to create such an infrastructure and guarantee for the fuel as long as alcohol engines are not put on the market on a large scale. The case of LPG as an engine fuel may provide an example. Although the use of LPG is widely increasing in Western Europe due to its future availability, car manufacturers have still not decided to sell cars ready for the use of LPG straight from the factory. It has reached the stage now, where importers of cars in various countries retrofit LPG kits authorized by their factory (6). That cars manufacturers still not fit the kits in production is due to still insufficient number and homologation problems, mainly because of different homologations in different countries.

Also because in various countries the infrastructure for dispensers and bulk transport is insufficient, the cars are adapted such, that switching to 100% petrol is still possible.

All this experience has shown a steady growth of the number of cars running on LPG together with an infrastructure, but on a retrofit base. For that reason the opinion in the Netherlands is, that is is probable that for a certain period of say 10 years, a rather similar system will be necessary for those countries which have the alcohol fuels available or locally available. These retrofittable systems should be such that the engines can also run on their original fuel, either by automatic switching or handswitching, or by a minimum of fitters' work for those cases where during a period of the year the fuel is not available sufficiently, or when the vehicle moves to areas where no dispensers of the alcohol are available.

For this reason the work is concentrated on retrofittable kits for existing petrol cars and vans and the more heavy diesel engines for trucks and buses. Although this does not give optimal results with respect to the fuel consumption and the exhaust emission, it may well be better enabling the move to the use of alcohol fuels.

This part of the paper has to be regarded as a status report with respect to the testing and development of hardware required for alcohol fuels in the Netherlands.

In summary this work concerns:
- the development of transducers for the detection of the petrol/alcohol fuel ratio for alcohol fuel percentages between 0-100%, also for inhomogeneous fuel mixtures
- the development of retrofittable hardware for dual fuel systems with about 40% alcohol fuel in the air intake in diesel engines
- the development of retrofittable hardware for cars and vans with petrol engines to enable them to run on ethanol by automatic control through a petrol/alcohol fuel transducer

2.2 Transducers for the detection of the petrol/alcohol fuel ratio for alcohol fuel percentages between 0-100%, also for inhomogeneous fuel mixtures.

The target for a transducer is to create a reliable electrical signal depending on the alcohol/petrol ratio for all ratios between 0 and 100% alcohol, also in inhomogeneously mixed condition. After the Wolfsburg symposium (1) the work was continued on that base. Different frequences in the resistant-capacity measurements were tested. The 160 kHz line was chosen for further application due to its most significant and relatively linear signalling. After that work was done on a similar base for ethanol-petrol ratios, because it was felt that in various more tropical countries the application of ethanol would come in the picture on a shorter term basis. For reasons of compactness of the paper all these graphs are not presented.
This transducer was used in test vehicles as further described in section 4 of this part of the paper. It was found that in more practical use it was not sufficiently accurate. Further work taught that in particular the following parameters were influencing the transducer: the temperature of the fuel, the flowspeed in the transducer, the kind of petrol, the quality of the ethanol. Especially the influence of the fuel temperature is important, see for this (5).
Work is continued to improve the transducer by sensing the parameters mentioned and combining the different signals by electronic control. Also the internal sizes as well as the chosen materials under consideration. Because of the increasing complexity of the transducer it was decided to enlarge this work by trying to find transducers based on other physical parameters such as:

- other electromagnetic characteristics, such as eddycurrent or changes of impendance
- the application of optical methods, such as the measurement of transmission and/or reflection in the infrared spectrum
- the application of other physical characteristics such as the heat of evaporation or the specific heat

2.3 The development of retrofittable hardware for dual fuel systems with about 40% alcohol fuel in the air intake in diesel engines.

In the past TNO has carried out a lot of work in the field of dual fuelling of diesel engines with about 35% of LPG in the air intake. This type of work was also published recently. (6)(7). This experience with LPG dual fuelling was used in creating an alcolhol dual fuelling system in which it can be expected that 40% of the diesel fuel can be replaced by atomized alcohol in the air intake. This 40% diesel fuel replaced applied for the full load curve. At no load of the engine no fuel should be given in the air intake, because of insufficient combustion. At part load a value of 50% can be expected to be the maximum. In fig. 1 such a system is shown (see also (6)(7).

In a diesel engine the amount of fuel has to be controlled in relation to engine speed and engine load. For the atomisation of the fuel, compressed air is used. When the engine speed increases, the amount of air from the separate air compressor increases too, resulting in the atomisation of more alcohol fuel. When the engine load increases the rack of the injection pump moves to another position. To control the amount of alcohol in relation to engine load a special controlling device is developed for direct control of the amount of alcohol by the rack. A more detailed drawing of this device is given in fig. 2. This system is ready for engine performance testing now. A lot of effort has been put in creating an atomizer which creates sufficient atomisation at different engine speeds and loads with a limited amount of compressed air and with sufficient self-sucking characteristics to avoid a special fuel pump.

2.4 The development of retrofittable hardware for cars and vans with petrol engines to enable these to run on alcohol by automatic control through a petrol/alcohol 1 transducer.

Shortly after the Wolfsburg symposium work was started to enable petrol cars and vans to run on ethanol-petrol mixtures between 0-100% ethanol. This was, because it became clear that application of ethanol as a motorfuel could arise in a shorter term than methanol. This in particular with respect to more tropical countries. Furthermore it is to be expected that retrofittable hardware for ethanol is more simple than for methanol, due to the smaller amounts of fuel and better evaporation characteristics (1). A system was built for a VW Passat and a VW 1302. A system like that is given in fig. 3. Essential in such a system is a transducer (see section 2 of this paper and (1)).

In this case the system was applied to a single barrel constant venturi carburator. This carburator is adapted with a needle in the main jet and a needle in the idle jet. These needles are each governed by a small close loop servo motor; see fig. 4. Through the electronic control box these needles are governed in accordance to the alcohol/petrol ratio, thus adapting the fuel flow orifice to this ratio. Furthermore some preheating,and for the VW 1302 air preheating,was applied.

Rollertestbench results of the VW Passat are e.g. shown in average figures:
- at 100% petrol an increased fuel consumption of 3,0% by volume and accordingly normal exhaust emission
- at 50% ethanol an increased fuel consumption of an average 27% (volume) with a rather similar exhaust emission as with 100% petrol
- at 100% ethanol an average increase of fuel consumption of 51%(volume) with an improved exhaust emission with respect to CO and NO, and some increased power.

Practical tests further showed:

- less accurate transducer control, as further mentioned in section 2 of this paper
- resulting in sometimes poorer engine performance and an increased fuel consumption up to 65% volume base (on energy base this is at about 7% more).
- cold starting capabilities to -10°C when 20% of petrol was mixed in the ethanol. In such cases however a 2-3 minute engine running was necessary before the vehicle could move with a poor performance in the first 5 minutes. At 100% alcohol cold starting was possible to roughly 0°C. It became clear that further transducer work is necessary as stated in section 2 of this paper.

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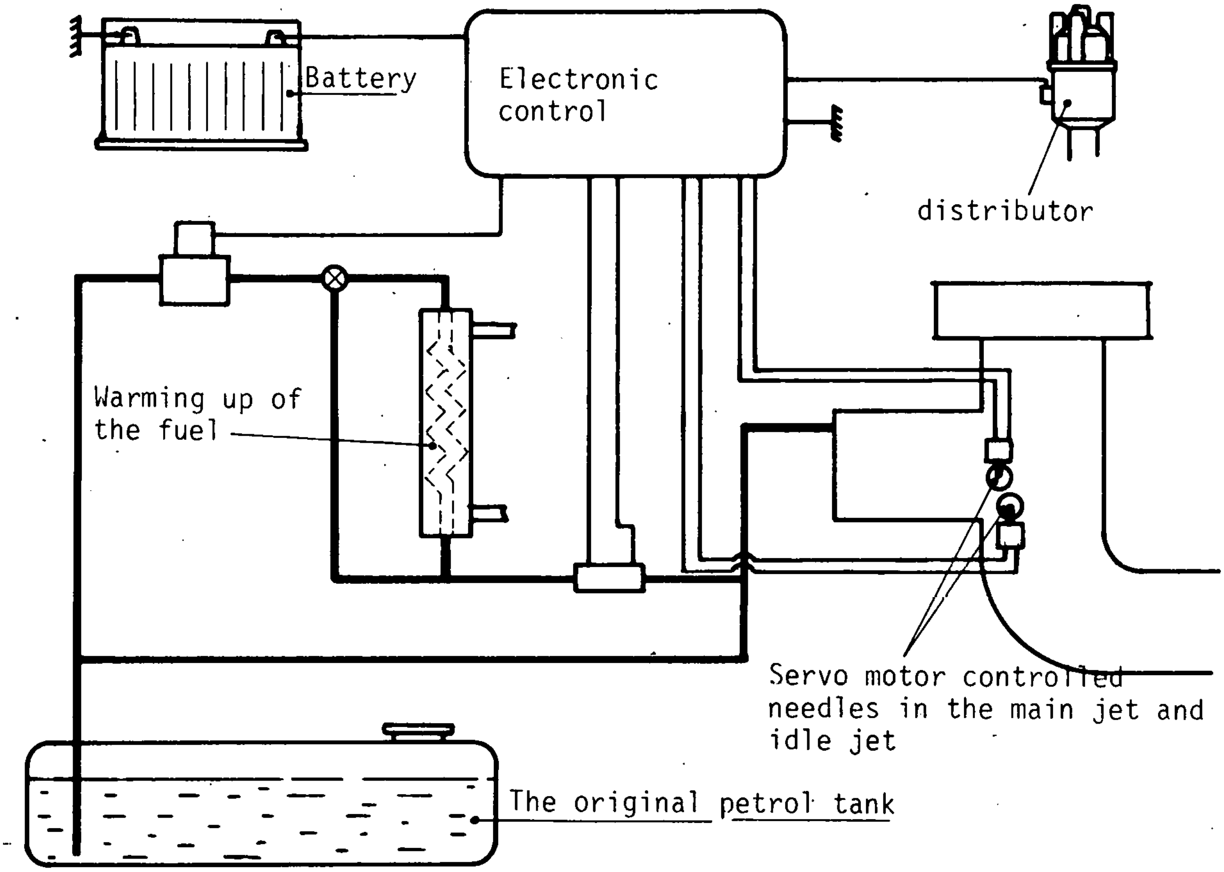

Fig. 1 Retrofittable system which enables petrol engines with carburator to run on ethanol or petrol and its mixtures

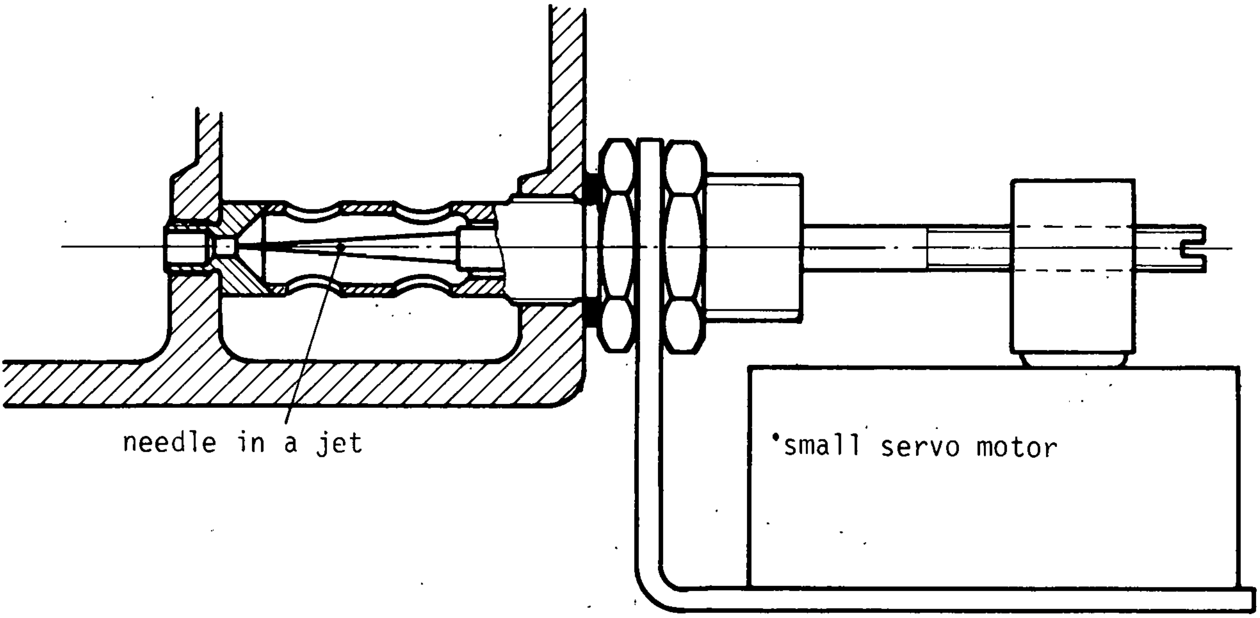

Fig. 2 Small servo motor control for a needle in a jet of a carburator

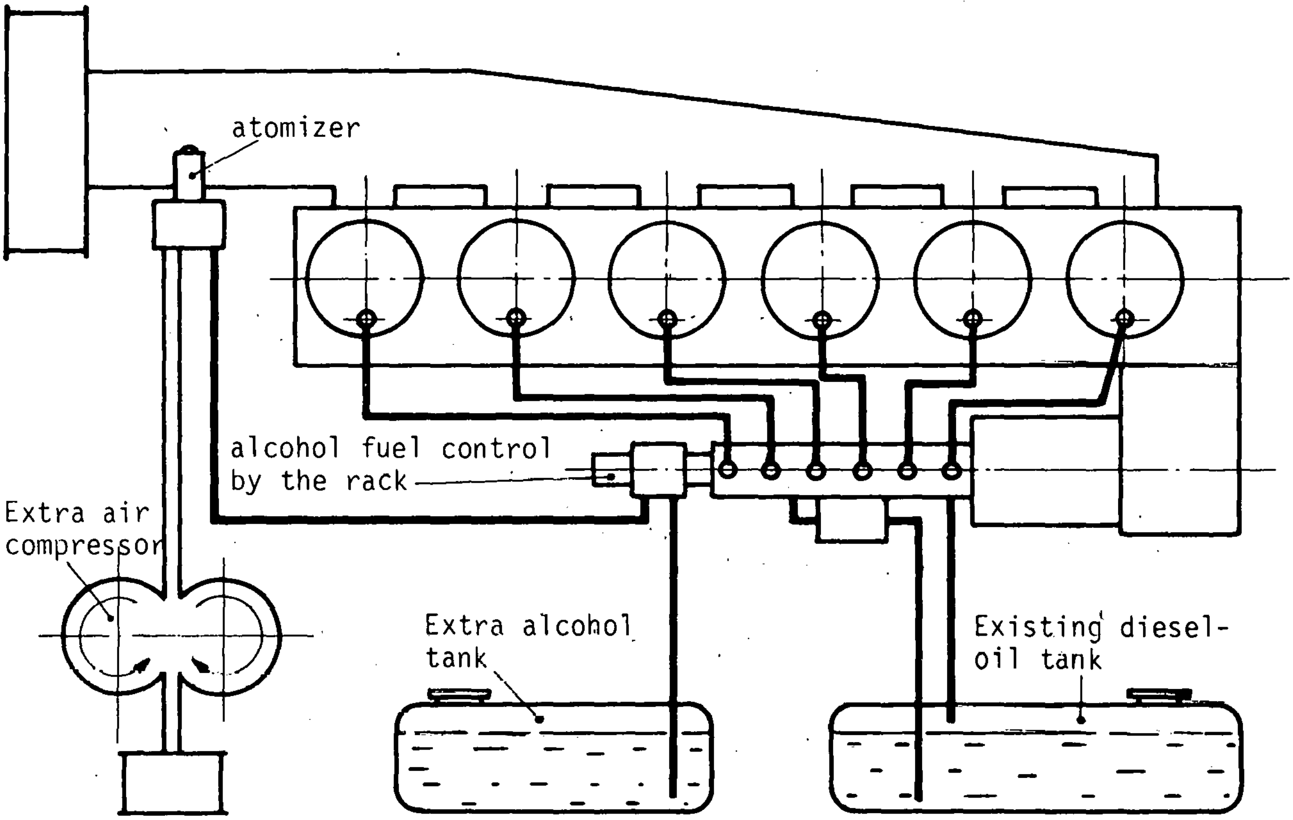

Fig. 3 Retrofittable system which enables diesel engines with in line injection pumps to run partly on alcohol fuel in the air intake (aiming at 40% dieseloil replacement in the full load curve)

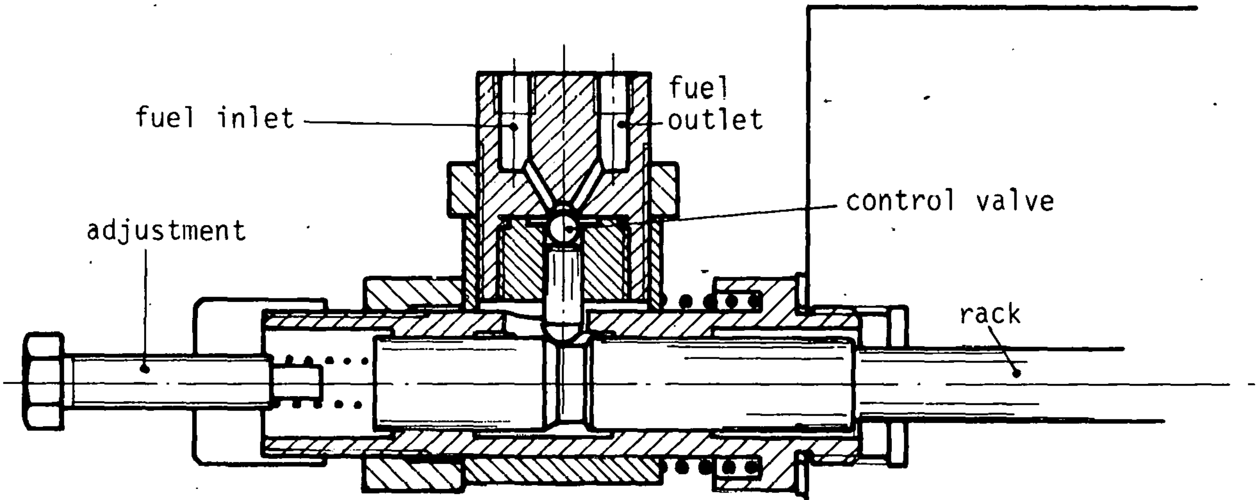

Fig. 4 Control of the amount of alcohol fuel by the rack of the diesel injection pump

ALCOHOL FUELS AND AGRICULTURAL SYSTEMS

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An effort has been made in this paper to look at some factors which point to a positive pursuit of biomass conversion as a significant source of energy. The development of new energy sources combined with the need of additional market channels for farm production were the leading motives in starting this project.

Biomass provides an energy alternative to a portion of the petroleum fuels market that is flexible with respect to the forms it can be used and that is renewable. Energy presently is utilized in one of four forms: solid, liquid, gaseous fuels, and electricity. Of proposed energy alternatives to replace petroleum products and natural gas, only coal and converted biomass can provide energy in a mobile form (liquid or gaseous) which is essential to present technical and social operations.

Forestry and agricultural products have traditionally been basic sources of energy. As cheap petroleum products became available, energy dependence transferred from biomass to petroleum products and the number of functions that could be economically mechanized grew, creating a greater dependence upon petroleum products. Since 1974 the economics and availability of petroleum-based energy has caused an exploration into new energy sources including a move back to significant use of biomass as energy.

National/International Factors

Involved in the proposition of energy crops production are questions on the social responsibility of using land for purposes other than food production when millions are hungry and the world population is continuously increasing.

Nations import food to improve the nutrition of the population. Food is exported, however, because of monetary considerations. Food is just another trade commodity on the world market. All major food exporting countries are dependent upon energy imports while the market for food export is limited by the fact that the poorest countries, where the majority of the world's population lives, lack funds for the import of food commodities. The developed countries cannot indefintely distribute food surpluses freely, as they need energy and other resources to produce the next crop; therefore, no international effort has been successful in creating sufficient food transfers from food surplus to food deficit countries. Developing countries may have suitable land and environment conditions for increasing agricultural production, yet aid has too often come mainly in the form of a transfer of food surpluses. Developing countries can be greater helped through aid in developing the infrastructure necessary to support a modernized agricultural sector rather than the minimal (maintenance) program that food transfers have been. It should be also realized that crops utilized for energy conversion are not completely removed from the food channels, e.g., high protein feed or food is obtained as a by-product of corn conversion into ethanol or a residual product of molasses-ethanol conversion can be mixed with the pulp and utilized as a livestock feed.

Developed countries have a nearly permanent problem of agricultural overproduction, and governments are regulating acreages of cultivated cropland, supporting minimum commodity prices, making payments for not planting crops, and purchasing/storing the surplus commodities to keep the farming sector economically stable. Additionally, this situation involves energy wastage as significant amounts of (imported) energy are used in the production drying, storing, and handling of surplus food commodities.

Through the development of a biomass conversion industry, a market can be developed for new agricultural products that contributes to a sound agricultural economy. At the same time, a positive benefit accrues to society through an elimination of, or decrease in, cost shifting through storage, support prices, etc., as a means to stablize the agricultural sector. Rather than wasting resources that have gone into commodities that exceed market demand or ability to distribute, resources should go into producing a needed commodity.

Additionally, an interesting situation of food exports and energy imports should be considered. While the price of imported crude oil is continually and rapidly increasing (Table 1) the export price of agricultural commodities fluctuates with only slightly increasing trends. Consequently, it can be realistically projected that the ratio of acre-equivalent of oil imports (value of exported commodity produced on one acre of land, applied to the import of crude oil) to acre-equivalent of food exports will be continuously decreasing. The expected trend is well documented by analysis of data for the years from 1960 to 1977 (Figures 1 to 5).

Consequently, the efficiency of the U.S. foreign trade is continuously decreasing as progressively less oil can be imported for the export of agricultural commodities. This situation is well illustrated in Table 2.

In the case when food is considered just another trade commodity, the economic considerations may lead, at a given time, to the production of energy crops instead of maintaining the traditional policy of exporting food to pay for oil imports.

Cropping/Production Factors

Realizing that different types of biomass can be utilized as sources for energy generation, two specific types are crop residues and energy crops and will be discussed in the following paragraphs.

Crop residues are essential for maintaining the optimum soil structure, but they seem also to be ideally suitable for energy conversion being "just" a by-product. Several factors, however, may reduce the usefulness of crop residues as potential energy sources: (1) The residues are not free; a significant amount of dollar and energy expenditures is needed to collect, transport, and handle the residues; (2) the availability of residues is dependent upon the market conditions for the main crop; (3) the availability of crop residues has highly seasonal characteristics; and (4) the priority orientation in the development of new crop varieties may reduce the potential amount of by-products (e.g., high yield of grain versus short stem crop).

Energy crops can supply a dependable flow of biomass for energy conversion. Various studies estimate that this renewable resource can provide from 5 to 15 percent of national energy requirements. Biomass can be utilized for the production of ethanol, methanol, gas, or as a fuel for direct burning. Typical crops presently considered for energy conversion are corn, sorghum, cassava, sugarcane, sugar beet, and trees.

The question of energy gains is being frequently discussed in converting biomass into energy. Technologies exist to make this conversion energy efficient, e.g., in utilizing molasses for ethyl alcohol production. A well managed R&D effort should result in the increase of energy conversion efficiencies. Also, it is very important to realize that mainly farm commodities grown traditionally for their nutritional values have been considered as potential sources for energy conversion; obviously, their net energy productivity has not been a major goal of the past plant breeding. A new orientation of agriculture science is needed for the development of specialized high-yield energy crops.

Conclusion

The production of energy sources and chemicals from agriculture crops is technically and economically feasible. Agricultural crops can become a part of a diversified energy system in the national economy. Their usage as an energy source will contribute not only to the energy supply, but also to the establishment of a sound farm economy and international agricultural development. In the future, agriculture can be developed as a system of food, fiber, and energy crops.

TABLE 1

BARREL VALUE OF IMPORTED CRUDE PETROLEUM *
1960-77

Year	$/bbl.	$/bbl. (1967 dollars)
1960	2.52	2.84
1961	2.57	2.87
1962	2.52	2.78
1963	2.51	2.73
1964	2.51	2.71
1965	2.48	2.62
1966	2.45	2.52
1967	2.40	2.40
1968	2.38	2.28
1969	2.36	2.14
1970	2.30	1.98
1971	2.62	2.16
1972	2.75	2.19
1973	3.41	2.56
1974	11.11	7.52
1975	11.66	7.23
1976	12.35	7.24
1977	13.04	7.18

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* Statistical Abstract of the United States, US Dept. of Commerce, 1969-78 editions.

TABLE 2
IMPORTED CRUDE OIL

(bbl. per crop-acre equivalent, selected years)

Crop	1965	1966	1967	1975	1976	1977
Wheat	14.42	17.50	14.94	9.35	6.70	5.42
Rice	84.58	87.32	93.95	32.67	26.51	32.58
Corn	34.66	37.00	34.38	18.78	15.30	14.13
Cotton	62.41	42.61	49.73	19.93	24.14	20.61
Soybeans	25.09	28.51	25.42	12.15	14.39	13.14

EXAMPLE

The value of corn produced from one acre and exported provided revenues for the import of 34.66 barrels of crude oil in 1965, but only 14.13 barrels of crude oil in 1977.

FIGURE 1

Cotton Crop Value and BBL/acre Equivalent Trends
1960 - 1977

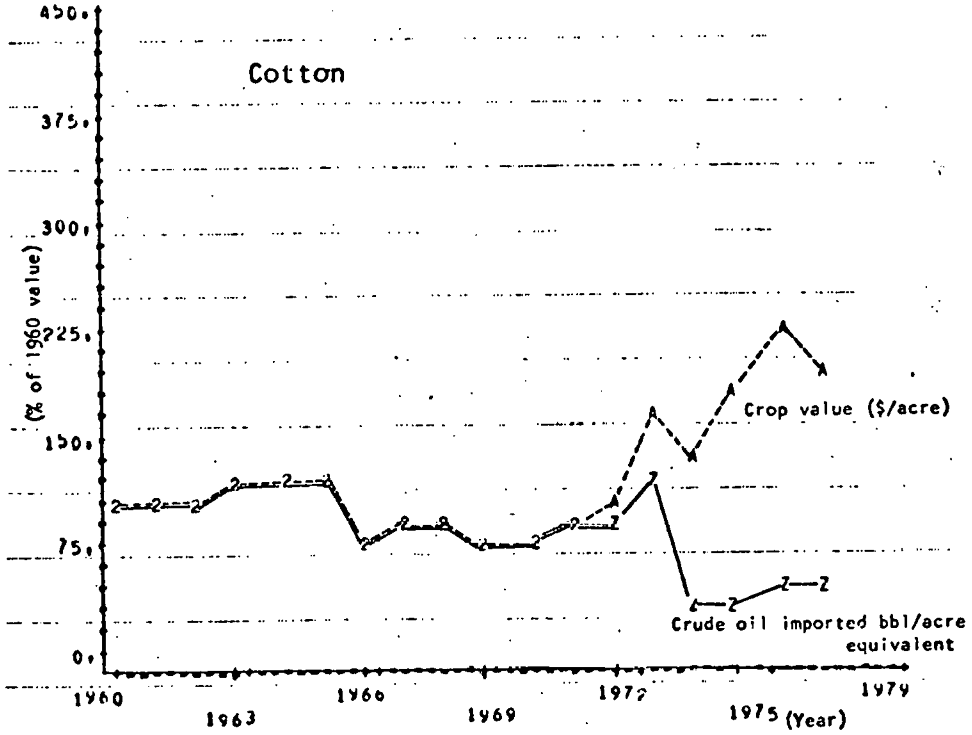


FIGURE 2

Soybeans Crop Value and BBL/acre Equivalent Trends
1960 - 1977

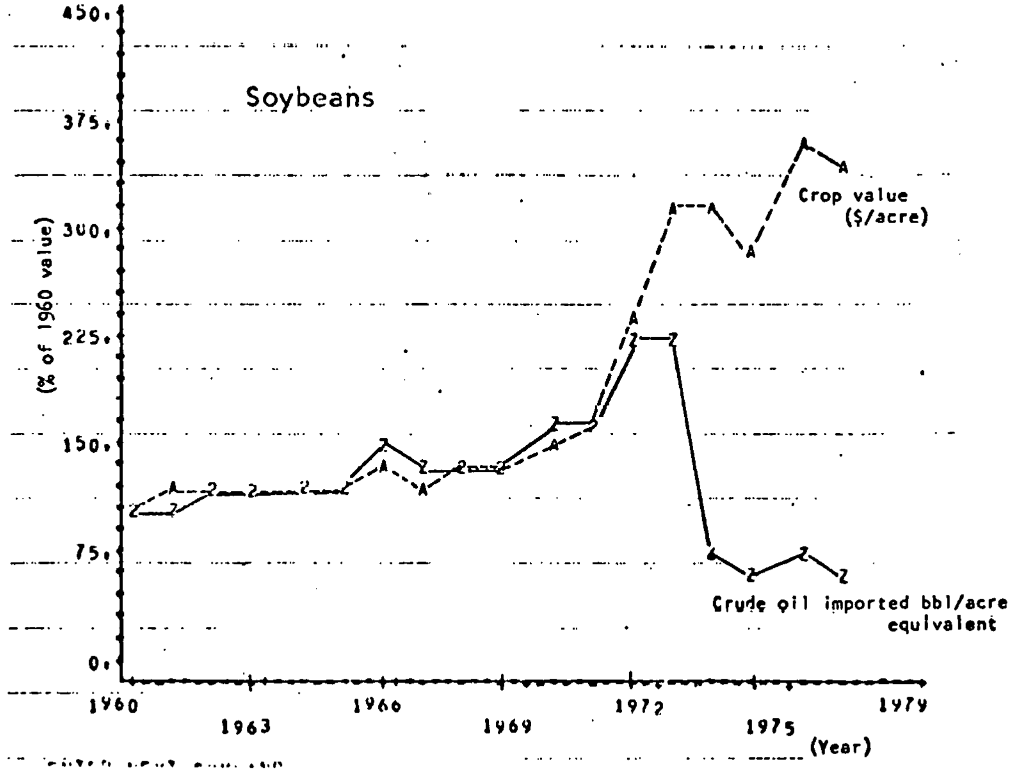


FIGURE 3

Rice Crop Value and BBL/acre Equivalent Trends
1960 - 1977

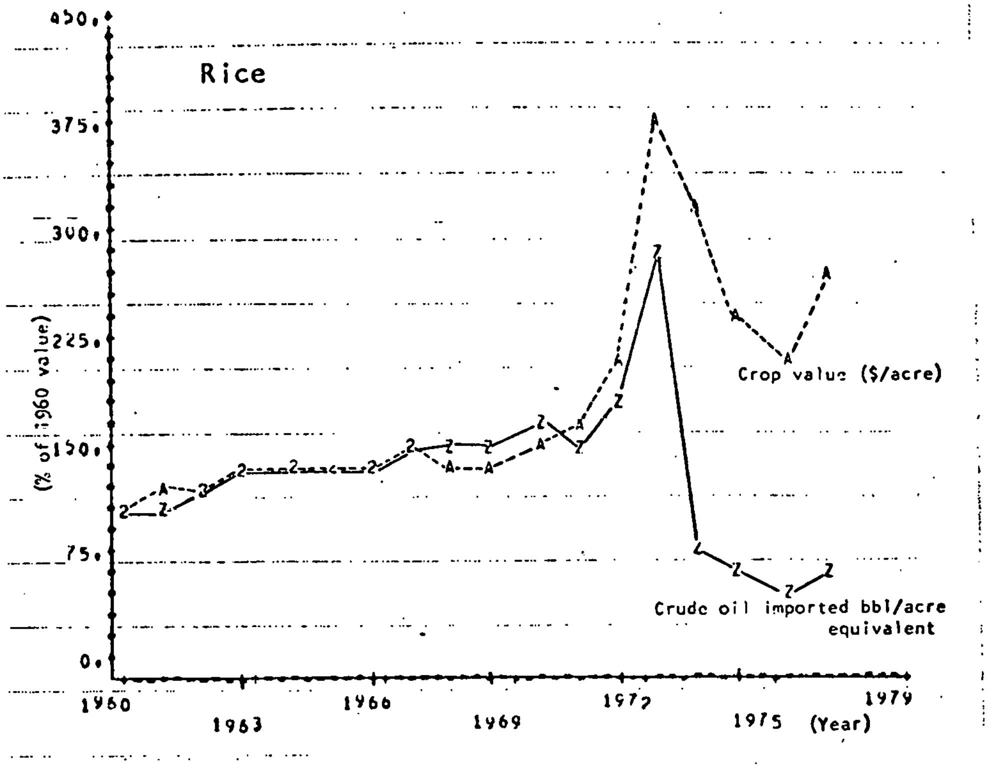


FIGURE 4

Corn Crop Value and BBL/acre Equivalent Trends
1960 - 1977

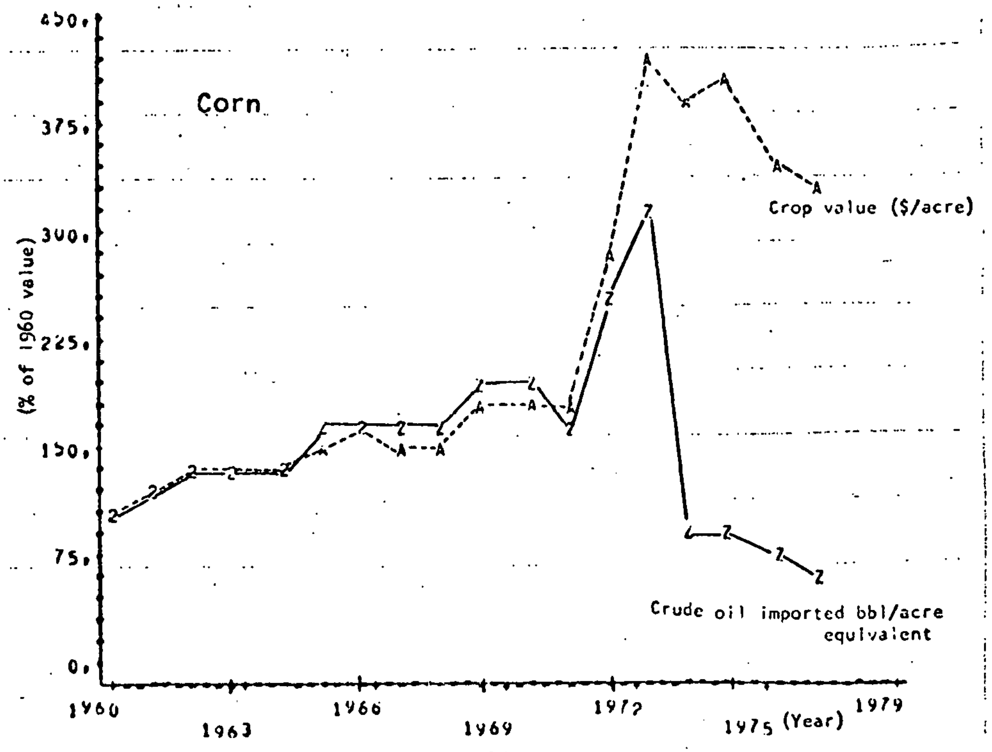
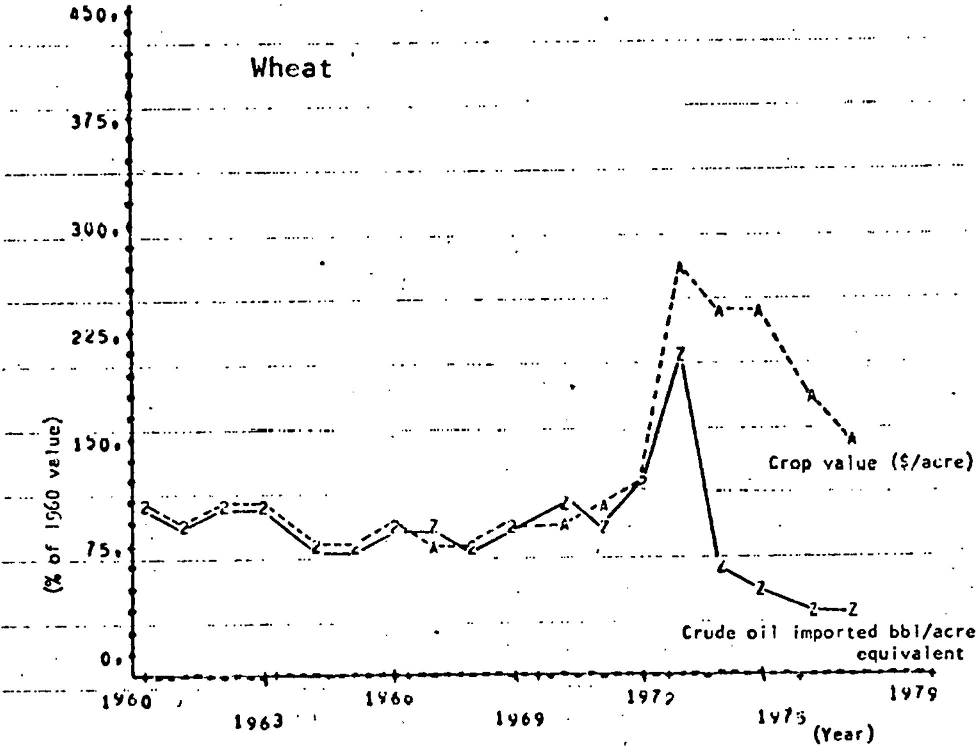


FIGURE 5

Wheat Crop Value and BBL/acre Equivalent Trends
1960 - 1977



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ALCOHOL FUELS: THE MOST OFTEN ASKED QUESTIONS

A Political and Technical Overview of the "American Alcohol Issue"

By Scott Sklar Washington Director

In the United States, alcohol fuels have been used by the low income in our society in most recent times to supplement their energy needs. The uncertainties of supply of conventional energy have driven up gasoline prices. The failure of the Federal government to embrace an effective/assertive energy policy has created an atmosphere of uneasiness in the more vulnerable urban and rural areas throughout the country.

Thus members of the agricultural community, the inner city and the forested areas of the nation have begun to look for energy sources using community resources. Sewage, urban wastes, agricultural residues, paper pulp, cheese whey and wood slash have taken on an added significance in these times of rising fuel costs. What appeared uneconomical before, making fuel from these wasted materials, now is viable in many regions of the country. As a result, over two hundred gas stations now sell gasohol (10% ethanol blended with no-lead gasoline) in over fifteen states. Alcohol entrepreneurs are appearing everywhere even without the blessing of the Federal energy establishment. However state policymakers have been in the forefront in promoting the use of this long forgotten fuel. State governments have not only turned to alcohols as a means to extend their regional gas supplies, but as a means to increase employment, preserve the small farmer, utilize pollutants in a positive way, and keep local capital at home.

The public has embraced the alcohol fuel issue in a most enthusiastic manner. Because of the uncoordinated role of government in the energy issue, many people have turned to sources of energy which they can produce themselves. The lure of energy self-sufficiency through the use of local resources and the use of "low capital" technology has made steady gains among the population. In terms of alcohol fuels, methane and solar, which can be tied to conventional energy systems easily, public usage, support and experimentation will increase and the nation as a whole will greatly benefit.

QUESTION 1: What are the benefits of using gasohol/alcohol fuels?

CONSUMER ACCEPTANCE AND COMMUNITY PARTICIPATION: Over 150 gasohol stations have sprung up across the country. Gasohol and alcohol groups include such diverse groups as: the American Automobile Association, Americans for Energy Independence, WIFE, State Economic Development Offices, and farm and urban development groups. Such enthusiastic promotion of an energy option from such diverse economic and regional groups was heretofore unknown in the 1970's. The benefit of alcohols in this context is to promote and enhance public support of non-conventional energy forms, support community self-help programs, and integrate these energy forms in the conventional system.

EXTEND GASOLINE FUELS: Assuming alcohols are not produced from gasoline, or gasoline is not used in producing alcohol, our domestic gasoline supply can be extended at least 10% in the automotive sector and much more in the turbine and industrial chemical applications. This 10% extension can offset imports, which would comply with the President's goals in this area. Additionally, balance of payments would be offset positively in our favor.

ALLEVIATE THE FUEL VERSUS FOOD QUESTION: Methanol from coal or ethanol or methanol from urban wastes or timber are not involved in this problem. However, with many other technologies, the use of grains or agricultural residues could pit fuel markets against food markets. This is not so with fermentation or hydrolysis technologies advocated by most alcohol proponents. Fermentation does not destroy the nutritive value of the food feedstock. Only the sugars and carbohydrates are converted to fuel, while the fermentation leftover (stillage) is a high protein human food supplement or animal feed or fertilizer. Stillage today is used by Seagrams and, locally, Virginia Gentleman, for cattle feed.

ECONOMIC, EMPLOYMENT AND ENVIRONMENTAL BENEFITS: Increased domestic employment would ultimately result from a domestic alcohol industry. Such problems as strip mining, boom towne, severe water usage, are not faced in ethanol production. Use of contaminated grains such as aflatoxin, a carcinogenic mold, that has affected up to 40% of our crops in recent years, along with cheese whey, etc., all can be kept out of the public food and water supplies. Positive uses for our wastes of industry, food processing and cities can only have a positive effect. And, of course, the multiplier effect of dollars kept at home will expand the economy, thus creating jobs.

QUESTION 2: What are the preferred feedstocks for producing alcohol fuels and what are the available quantities?

AVAILABLE QUANTITIES: Cellulose is the most plentiful resource in the world. If cellulose can be converted to sugars, as evidenced by the Gulf Chemical Company's one-ton-per-day demonstration plant in Kansas, and then fermented into alcohol, this country has the opportunity to make a significant impact on our liquid fuel needs.

T. Alston's summary table on supply availability is attached and is the same table that was dispensed to Congressional staffers during our working sessions. Whatever the real possible supply for alcohol production is, either higher or lower, there is no question that there are enough cellulose resources available to meet a significant portion of our liquid fuel needs.

PREFERRED FEEDSTOCKS:

SUGAR--Currently, domestic sugar producers cannot compete internationally. In addition, synthetic processes will severely cut into the domestic sugar market. As in Brazil's program, this sugar can be easily made into ethanol and the bagasse, the sugar sheath, can be burned as the primary plant fuel. Not only do we halt a depression in this industry, but produce alcohol using non-conventional fuels.

TIMBER--Certain timbers have the best proclivity for being converted to fuel. Eucalyptus trees, for instance, which require little water, have the highest conversion rates to energy, and can be clearcut and will regrow, make an ideal energy crop. Entrepreneurs are already investing in eucalyptus land in California. There is enough timber, milling wastes and pulp to make a significant fuel impact without destroying the renewability of our forests.

MUNICIPAL URBAN WASTE AND SEWAGE--These wastes are easily collectable and are an ideal energy source. These wastes can undergo several processes, each with its own attributes and problems. The direct burning of waste not only prevents other important by-products being recovered, but has severe health and pollution drawbacks. On the other hand, hydrolysis of waste can not only produce alcohol, retrieve the metals and glass, but produce fertilizer and wash to use as a fuel for the conversion plant. Experiments with algae, grown on sewage sludge, then converted to ethanol, are also being staged at this time. With the use of membrane technologies and other sophisticated techniques, these so-called "exotic" processes may become a reality. Gulf Chemicals and US Army Natick Labs have accomplished exciting results in this area.

FOODSTUFFS, SURPLUSES, RESIDUES, AND CONTAMINANTS: Surplus grains and other crops and contaminated feedstuffs: Although seasonal, these feedstocks can be successfully used in small plants across the country. At this time, we have no positive options for disposing of contaminated grains. Thus, highly toxic crops are winding up in the black-market used for animal feeds and in processed foods. This would be one way to protect the public.

Although 50% of the agricultural residues must be put back into the soil, we now have a tremendous quantity of feedstock eligible for energy conversion. The energy from these sources is now burned or inadequately disposed of and should have greater attention.

There is a world pretein deficiency, not a grain or carbohydrate deficiency. Surplus grains should be converted into alcohols and then some system developed to regulate its use as an animal feed, a human protein food supplement used at home or exported abroad or as a fertilizer.

COAL: Methanol from coal is not new and does have a positive application as an industrial turbine fuel, a peak-utility turbine fuel and an industrial chemical. Also, methanol is an excellent pure motor fuel, as evidenced by the automobile built for the California legislature by Charles Stone.

Caution to this option should be made if large quantities of water must be used. Most cases will not follow the Wentworth experience using North Dakota lignite, where 90% of the water needed is found within the coal. We cannot endure a situation where water resources for energy compete with food production needs.

NATURAL GAS: CONOCO and Mitsui of Japan have advocated the conversion of foreign natural gas into methanol for shipping to the U.S. Alcohol transport would be less expensive than LNG tankers, as well as safer. Additionally, the liquid methanol could be used for a variety of end uses, including use as a coal slurry medium. These techniques are being studied very carefully by several companies in the U.S., Japan and Germany.

QUESTION 3: What would be the impact of utilizing set-aside acreage for the production of ethanol?

THE LAW: In the emergency farm act signed this year by President Carter, set-aside acreage may be used for energy farming as long as the crops are different than the set-aside crops planted by the particular farmer. This was done in order to promote energy crops while at the same time assuring that farmers are complying with the farm set-aside program.

WILL THIS HELP FARMERS? Of course, because the set-aside payments will still be paid whule the farmer can get additional monies from his energy crops. This practice will promote energy farming and particularly help the economic situation of the farmer-family business.

ENERGY FARMING: Energy farming will be enhanced by this program. Additionally, this endeavor will promote research and field experience desperately needed for energy farming. Hopefully, agriculture geneticists will be able to develop specialized energy crop species that will have high yield and high cellulose or sugar contents. Species of cassava (manioc root), eucalyptus, sugar beets, corn, sweet sorghum, Jerusalem artichokes, etc. can all be effectively adapted to productive energy farming.

One of the most famous experts on energy farming, Dr. Edward Lipinsky from Columbus Batelle Labs, promotes sweet sorghum as the ideal energy crop. The sorghum is resistant to most diseases and bug infestations, needs very little water or fertilizer and can be harvested with conventional farm machinery.

We need some vision and experimentation in this area very badly.

QUESTION 4: What technologies are available or under development for producing alcohol fuels from renewable resources and coal?

COAL TECHNOLOGIES: There are very many coal technologies available for methanol and related coal liquids. Pyrolysis, Lurgi, etc. are but a few. Hydrogenation of coal was used by the Germans during World War II. I. G. Farben and Standard Oil of New Jersey cooperated before the war in this area. Wentworth Bros. of Cincinnati, CONOCO, Methacoal from Texas, etc. have all been actively involved in this area.

RENEWABLE RESOURCE TECHNOLOGIES: There are four major processes generally talked about in producing ethanol and methanol from biomass.

PYROLYSIS: A destructive distillation process used to make methanol from wood or urban waste. Essentially, the feedstock is crushed and burned and the burn-off gas condensed, washed and stored. The leftover is recycled and burned with the residue usually quenched in water , forming beads coated with glass. Union Carbide, among others, is in the forefront of this technology and has a demonstration plant in Charleston, West Virginia. This process makes alcohol in the most inexpensive manner, from 40-80¢ per gallon. Drawbacks are mostly environmental.

FERMENTATION: A five-thousand-year-old process that uses yeasts which turn carbohydrates to sugar. This sugar solution is then distilled (burned), with the gases going up a column. Ethanol results. The fermentation leftover, stillage, is high in protein and used as an animal feed in this country and as a food supplement in Haiti and other countries. In this country, fermentation from foodstuffs ranges around $1.00 per gallon. The greatest attribute, as mentioned above, is that the food value of the feedstock is not destroyed. Also, ethanol has a higher BTU value then methanol, 84,000 BTU/gallon vs. 62,000 BTU/gallon, respectively, and has a greater proclivity to blend with gasoline.

ENZYME HYDROLYSIS: A relatively new technology which uses enzymes in bacteria to break down cellulose to sugars. Yeast and milldews are types of enzymes. Cellulose, which includes wood, vegetable matter, etc., is an abundant resource. The sugar solution produced then goes through fermentation and distillation. This is an environmentally sound way to produce fuel, but the major problem is the efficiency of the enzyme to turn the cellulose into sugar (about 20%). Gulf Chemical Company has had the greatest success.

ACIDIC HYDROLYSIS: Another kind of cellulose-to-sugar conversion process which uses acid (sulfurous acid) to break down the cellulose. Dr. Tsao from Purdue and the Solar Fuel Company from Mankato, Minnesota are in the forefront with the technology--however, still in the lab stage. Eighty cent per gallon ethanol is currently talked about by Tsao. Urban waste and vegetable residues can be turned into ethanol by both hydrolysis processes.

WHAT NEEDS TO BE DONE: If fermentation times could be speeded up, thus pushing the output and lowering the energy input, the economy of ethanol would be enhanced. Also, with the use of membrane technology such as developed by Professor Gregor of Columbia University, less energy input and greater efficiency could be achieved. Also, the stillage, which sometimes has a high salt content, could employ membranes to filter the salt. Thus, a greater amount could be sold for cattle feed, enhancing the economics. (High salt stillage causes diarrhea in cattle.)

QUESTION 5: What are the economics of producing alcohol? What are the means for reducing production costs?

At the present time, ethanol blended in a 10% solution with no-lead regular gasoline--GASOHOL--will generally cost the following:

	CURRENT	GASOHOL	
No-lead gasoline	34.7	32.8	(low octane)
Anhydrous ethanol	--	11.8	
Fuel transportation	3.3	3.3	
Retail station mark-up	9.3	9.3	
State tax	8.5	8.5	(except Colorado, Iowa)
Federal tax	4.0	0.0	(waived until 1984)
	59.8	65.7	
TOTAL	59.8	61.7	(with partial state tax waiver 4¢)

Under the Federal Energy Tax Act of 1978, a 4¢ federal waiver became effective January 1, 1979 for ethanol or methanol blended in a 10% solution minimum with no-lead gasoline. The ethanol or methanol must be made from renewable resources.

Because ethanol is an octane booster from 1.5 to 4 octane, depending on the gasoline, automobile and scientific study, a lower octane gasoline can be used. Note that with any State tax incentive whatsoever, gasohol could easily undercut regular no-lead's price.

The February 13, 1978 editorial in Business Week supports the use of ethanol as a fuel and urges its immediate use with other liquid energy technologies.

COSTS PER GALLON

Methanol:			Ethanol:		
	42¢	Natural Gas		1.32	ethylene
	25-60¢	Coal		1.10	grain
	67¢	Garbage		1.30	cellulose
	80¢	Agriculture/timber		1.05	sugar

However, these costs are probably misleading due to the fact that although ethanol has two-thirds the BTU's and methanol has one half the BTU's of gasoline, they have greater thermal efficiency than gasoline. This means a BTU of ethanol will take you further (1.3-1.6 times) than a BTU of gasoline.

DOE ENTITLEMENT PROGRAM

Alcohol fuels are also eligible to this special subsidy program for liquid fuels that can displace petroleum. The subsidy is $2/barrel of petroleum equivalent.

Wentworth is quoted in a September 16, 1977 Wall Street Journal article stating that his methanol produced from North Dakota lignite would cost $3 per million BTU's compared with $3.35 per MMBTU's for propane gas; $3 per MMBTU's of No. 1 turbine fuel. "The costs of equipping a coal-fired generating plant with precipitators, stack scrubbers and cooling towers to keep the environment clean make methanol (which doesn't emit sulphur, heavy metals or particulates and emits just low levels of NO_x) cheaper in the long run," says Andrew L. Freema Manager of Minnkota Power. Thus, a pure turbine fuel, or even pure automotive fu methanol has the best chance in this regard.

Ethanol has the best proclivity for blending with gasoline because it is more resistant to phase separation in the presence of water. Additionally, ethanol has more BTU's per gallon, which is important.

RESEARCH AND DEVELOPMENT

The following breakthroughs are needed to make alcohol the major fuel in the nation:

A. Cutting fermentation times and energy input through the use of:
    1. Membranes
    2. Catalysts and enzymes
    3. Solar and process heat incorporation and cogeneration
    4. Solvent process (acidic hydrolysis breakthroughs)

B. Farming and waste treatment
    1. Plant genetic development to yield plants that are hearty and have high energy yields.
    2. Better waste separation, collection and treatment models must be developed.
    3. Development of on-the-farm small energy technologies.

C. Total resource development
    1. Coal, timber, agricultural resources, municipal waste, sewage, timber and pulp all must be singled out for optimum experimentation and demonstration facilities before 1980. We must have this frontline experience.
    2. Real think-tank work with cellulose conversion, algae, clean pyrolysis and other technologies.

Frankly, it is not so much that these technologies can't be developed; they can. Rather, it is to develop these processes in a timely manner so that we can get them into the commercial sector at the earliest possible time.

QUESTION 6: What is the energy balance associated with alcohol fuel production, and how can it be improved?

The best three papers on this issue are:

SILVA, Jose Gomes da. Energy Balance for Ethyl Alcohol Production from Crops. Science. Vol. 201. September 1978, p. 903.

SKLAR, Scott. Alchohol Fuels and Energy Efficiency. PAPER, May 18, 1978, U.S. Senate.

CHAMBERS, R. S., et al. Gasohol: Does It or Doesn't It Produce Positive Net Energy? PAPER, University of Illinois at Urbana, November 1978.

All the papers show that practically ethanol and methanol can be made with a positive energy balance. The Chambers paper states:

> "If one analyzes the petroleum energy balance, then gasohol unambiguously produces positive net petroleum energy. This is a consequence of the fact that except for some inputs to agriculture and transportation, all energy inputs to the gasohol process can be provided from non-petroleum sources such as coal; hence consideration of the various options has little effect on this conclusion."

In my own paper, I state:

> "In most instances the by-products need not be dried or treated. Thus, energy inputs can be cut substantially. As I mentioned earlier in this paper, the stillage used for cattle feed or fertilizer can be stored and dispersed in liquid form.... In addition, if the base fuel used in fermentation or pyrolysis utilizes a substance that would not be used as a fuel in another context (i.e., bagasse, cornstalks, cogeneration, etc.), then this, too, should be noted and some kind of allowance in our energy calculations should be made."

As long as we do not use more of the precious fuels (gas and petroleum) to make alcohol than we will produce in BTU's, then there is absolutely no real problem, no matter what the energy balance. This whole problem has been made a major issue by the alcohol antagonists and is not a real issue.

<u>QUESTION 7</u>: What are the preferred end uses for gasohol and other alcohol fuels?

Gasohol sould just be used as an automotive fuel. Alcohol in gasoline has been used by over twenty-five countries throughout the world in varied percentages in order to extend their gasoline supplies.

Ethanol can be used as a blend with gasoline, as an industrial chemical base, as proposed by Gulf Chemical Company, and as a turbine fuel.

Methanol is not good in blending with gasoline but it can be blended with ethanol in gasoline more satisfactorily. Methanol, in the pure form, makes an excellent turbine fuel and automotive fuel.

<u>QUESTION 8</u>: Can gasohol be used in existing vehicles without modification?

Gasohol, without question, can be used in any vehicle without modification.

I have converted a 1964 Rambler Classic to pure ethanol for under $60.00. I have not experienced coldstart, vapor lock or corrosion that others claim would inhibit the use of pure alcohol fuels.

The use of gasohol would keep out other less environmentally sound additives such as lead and MMT, while still improving octane and driveability.

QUESTION 9: What are the environmental impacts of utilizing gasohol and other alcohol fuels?

Clearly, the impacts are no worse than other fuels and significantly better than coal, direct burning of wastes, shale oil, etc.

Care must be taken that farming practices are performed wisely so that the integrity of our land is preserved. However, no problems with boom towns, sulphur, carcinogens, or particulates plague alcohol as a fuel.

Auto emissions for gasohol are: CO goes down at least 30% compared to gasoline; HC remains the same; NO_x goes up slightly but still falls under the EPA limits. Evaporative emissions with idolene are below the proposed standards, with summer grade are slightly above these standards.

The results on pure methanol from Charles Stone's care are as follows:

	GASOLINE	METHANOL-X	
NO_x	4.9	0.4	GM/MI
HC	2.2	0.3	
CO	16.7	3.5	
Particles	1584	1060	

As you can see, pure alcohols surpass gasoline in all regulated emissions by a significant degree.

One last note on environmental benefits of alcohols. Cheese whey, urban waste, sewage, aflatoxin and other contaminated foodstuffs are all very difficult to process and keep out of our environment unless some economic stimulus is directed to make these wastes into positive end products. What better idea than to make these materials into energy? Liquid energy is in great need and alcohol from these sources is the best answer.

QUESTION 10: What state programs are under way or planned for producing or marketing gasohol? What state subsidies exist or are planned for encouraging gasohol use?

Nebraska--Had one gasohol station, Gas Plus, operated by Jim Lustgarten. Nebraska also put on the 2-million-mile gasohol test. This test was the foremost in the nation and further information can be gotten from Randy Fricke or Bob Soleta at the National Gasohol Commission.

Iowa--Doug Getter at the Iowa Development Commission put out a gasohol marketing study. Iowa has a six-month state tax waiver for gasohol as a test on its marketability and has some 70+ stations in operation.

Illinois--Al Mavis of the Illinois Farm Energy Program states that over 70 stations are operating in the state, with more to come. Illinois gets its alcohol produced from cheese whey in Wisconsin.

Wisconsin--Has two stations operating, with more to come. Don Weiner at the State Energy Office states that Wisconsin has some subsidy program for waste producers to convert and market these wastes. Thus, Milbrew, a cheese manufacturer, receives benefits for turning its cheese whey into ethanol.

California--The California Legislature is developing alcohol car No. 2. Charles Stone should be contacted in this regard.

New York--Just passed a gasohol bill requiring that gasohol be tested and then used in its State fleet. New Jersey is following New York in this area.

Colorado--Has passed a four-cent State tax waiver for gasohol. There are no gasohol stations in Colorado at this time.

The above summary is incompete, but should give readers a general idea of the scope of gasohol across the country.

<u>QUESTION 11</u>: What is the current excess alcohol plant capacity? What is the lead time associated with construction of new alcohol plants?

From general statistics, approximately one billion gallons of alcohol could be made in all of our nation's distilleries without cutting their regular production.

Within two years, alcohol plants using standard technology could be completed. Ethanol plants would take less construction time over coal methanol plants because there are less environmental impediments associated with ethanol than with coal.

The real issue is whether the assorted materials needed for ethanol production could be collected if a crash program were initiated. In my opinion, we could meet the requirements with careful planning.

<u>QUESTION 12</u>: What is the feasibility of attaining a 10% nationwide gasohol program of 90% gasoline/10% alcohol blend by 1990?

Of course, the question becomes moot if there is a severe gasoline shortage. Alcohol is the only liquid fuel that can feasibly be brought into the market in a very short time--within two years.

There is no question that a nationwide blending program can be attained by 1990 with positive and assertive DOE support. If DOE remains unexcited about the program, the time period needs to be lengthened. In terms of balance of payments and employment, such a program would have a great positive impact on the nation.

However, action must be started in this direction by 1979 if we are ever to reach the 10% goal by 1990. In some regions of the country, this goal could be reached within five years, assuming our agricultural and technical know-how stay as good as they are.

<u>QUESTION 13</u>: What are the constraints to the commercialization of alcohol fuels? How can these be overcome?

The constraints are:

a. The lack of a national policy regarding the use of renewable resources for energy.

b. The artificially low price of conventional fuels.

c. The petroleum industry's resistance to competing fuels.

d. Utility resistance to community energy projects and energy self-help programs.

e. Non-support by the scientific community of "exotic" technologies.

f. DOE patent policy regarding financial support of small inventors.

g. A clear hesitation by Federal and Industry policy makers to consider environmental, employment, economic (balance of payments) security and other issues as part of any energy policy decision.

These constraints could be overcome by the Department of Energy if energy planning were done in closer cooperation with the EPA and social service agencies, among others, who have a large stake in what happens to our energy future.

Tax incentives to industries that assist national goals would also be helpful. Clearly, support of regional initiatives regarding community self-help programs is paramount. I could go on for pages and pages--the issue is too complex to address adequately in this kind of paper.

<u>QUESTION 14</u>: What is the projected impact of the recently enacted exemption for gasohol from the Federal 4¢ excise tax on gasoline?

The tax will profoundly assist gasohol in the private sector. If State tax programs are also initiated, gasohol will be more than competitive with no-lead gasoline.

<u>QUESTION 15</u>: What is the most appropriate role for the Federal Government to take with respect to gasohol and other alcohol fuels? Should the Department of Energy take steps to encourage the commercialization of such fuels?

Yes, most emphatically, the Department of Energy SHOULD take steps to
h the commercialization of alcohol fuels form all resources, particularly
using on renewable resources.

The most appropriate role for the Federal Government with respect to alcohol fuels is as follows:

a. Establishing an energy extension service for technical assistance in producing alcohol and methane fuels.

b. Developing a program plan to extend no-lead gasoline reserves in the short term if the gasoline marketers are unable to supply the public with no-lead.

c. Creating some kind of data input so that other issues such as environment, employment and balance of payments can be analysed during energy policy making.

d. Actively supporting and encouraging community energy self-help programs.

e. Linking the waste issues to the energy problem; also, agriculture to the energy problem.

f. Forgetting the idea of quads as a concept and thinking in terms of best possible rather than best practical.

Obviously, there are many ways to push alcohol fuels, but they are too numerous to elaborate in this paper and the above examples are more process" suggestions than real policy initiatives.

TABLE 1

U.S. RENEWABLE RESOURCES FOR ALCOHOL MANUFACTURE
TOTAL AVAILABILITY OF SIGNIFICANT CROPS, RESIDUES AND WASTES

	1975/76(1)				1990			
	Million Dry Tons	Percent	Quads(2)	Percent	Million Dry Tons	Percent	Quads(2)	Percent
WOOD:								
Surplus Growth	184		3.1		67		1.1	
Forest Residues	102		1.7		124		2.1	
Mortality	87		1.5		94		1.6	
Non-Commercial	87		1.5		87		1.5	
Mill Residues	13		0.2		6		0.1	
Other	51		0.9		51		0.9	
TOTAL WOOD	524	40	8.9	44	429	27	7.3	32
GRAINS:								
Corn	145		2.2		213		3.1	
Wheat	57		0.9		78		1.2	
Soybeans	41		0.6		89		1.3	
Sorghum	19		0.3		29		0.4	
Other	18		0.3		14		0.2	
TOTAL GRAINS	280	21	4.3	21	423	27	6.2	28
SUGARS:								
Cane	9		0.1		31		0.2	
Beets	10		0.1		17		0.1	
Sweet Sorghum	-		-		106		0.6	
TOTAL SUGARS	19	2	0.2	1	154	10	0.9	4
RESIDUES:								
High Moisture	115		1.7		150		2.3	
Low Moisture	239		3.6		260		3.9	
Trash/Hulls	6		0.1		8		0.1	
Manures	47		0.6		65		0.8	
TOTAL RESIDUES	407	31	6.0	30	483	30	7.1	32
MSW(3)	75	6	0.7	4	99	6	0.9	4
TOTAL RESOURCES	1,305	100%	20.1	100%	1,588	100%	22.4	100%

(1) Grains, residues and MSW (municipal solid waste) data are for 1975. Wood and sugar data are for 1976.
(2) Quads of contained (not net) energy based on high heating value.
(3) Data aggregated for those states which produce major concentrations of MSW. The data represent about 75% of total U.S. MSW.

T. Alston's summary, 1978

ALCOHOL ENGINE EMISSIONS
- Emphasis on Unregulated Compounds -

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ABSTRACT

Characteristics of alcohol engine emissions were studied on gasoline-methanol and gasoline-ethanol fuels by changing the ratios of their constituents with main emphasis on such unregulated compounds as hydrocarbons, aldehydes, formic acid, acetic acid, hydrogen cyanide, and ammonia. It was found that nitrogen compound emissions such as NOx, hydrogen cyanide, and ammonia decrease and the photochemical reactivity of hydrocarbons also decrease as a whole as the ratio of alcohol increases. Effects of after-treatment by catalyst were also studied for unburned methanol and formaldehyde, and it was found that they can be eliminated catalytically. The HC analyzer (FID) is not sensitive to formaldehyde, and it must be monitored separately to determine the effect of a catalyst on formaldehyde.

INTRODUCTION

While the petroleum consumption in the world is ever increasing every year, its production is expected to taper off in the near future and the problem of energy shortage is a matter of serious concern throughout the world as a foreseeable energy crisis. Existing automobiles use gasoline or light oil, which are petroleum products, as their fuel, and it is getting to be an important problem for our motorized society and automobile industry to develop alternative fuels and engines for the future.

It is said that methanol and ethanol are two of the most hopeful future fuels, and intensive researches have already been undertaken on these alcohols in such countries as the United States, West Germany and Brasil [1]*. In Brasil, especially, the State of São Paulo has already enforcing to mix 20% of ethanol into gasoline for automobiles since 1977, and the use of ethanol as a fuel for automobiles has become a matter of reality.

We have been studying alcohol engines for automobiles since 1973 [2][3]. We have shown through the investigation that these engines, with some improvements in the method of starting and the fueling system, demonstrate such characteristics as the

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*Numbers in brackets [1] designate References at end of paper.

energy efficiency and reduction of Nox emissions which are comparable to those of conventional gasoline engines and can be actually used for automobiles.

The feasibility of alcohol as a new fuel for automobiles, on the other hand, must be determined not only by its technical background but also by the integrated judgement which takes economic aspects and effects on the environment into consideration. It is necessary, as for the effects on the environment especially, to collect detailed information about emission characteristics of unregulated compounds which include trace harmful components, and their suspected ecological influences additional to those of regulated compounds.

There have been several reports on hazardous substances in exhaust emissions from methanol engines, but formaldehyde is the only harmful compound of which emission characteristics have become mostly clear. Few reports have been published on other aldehydes, lower fatty acids which are oxides of aldehydes, hydrogen cyanide and ammonia which show high biological influences, and hydrocarbons which have strong photochemical reactivities, and the information about these compounds is getting imperative.

The objectives of this study are to grasp the emission levels and characteristics of these trace harmful components, which have been unknown heretofore, and to provide basic information for assessing alcohols as alternative fuels from environmental aspects.

The fuel specimens used in this study are methanol, ethanol, and their gasoline mixtures which are more practical as an intermediate step in introducing alcohols as fuel alternatives. Changes in emission characteristics are observed for each component while changing the mixing ratio. As for unburned methanol and formaldehyde, after-treatments by catalyst are also studied, and some important results are also included in this report.

EXPERIMENTAL

Specifications of the test engine are given in Table 1. The fuel specimens are unleaded gasoline (RON 91.4) and methanol (99.9%) or ethanol (99.0%) and their mixtures. The gasoline-alcohol mixtures used in the experiment are of 0, 30, 70, and 100 % (volume percent of alcohol). Operating conditions of the engine are given in Table 2. The excess air ratio λ was chosen to be 1.2 because aldehyde is generated more in the lean zone than in the rich zone and methanol engines are more likely to be operated in the lean zone for the purpose of reducing NOx emissions.

Concentrations of nitrogen oxides (NOx), total hydrocarbon (THC), and carbon monoxide (CO) in the exhaust gas were measured by using a chemiluminescent analyzer, a flame ionization detector (FID), and a non-dispersive infrared analyzer respectively. The methods used for measuring concentrations of other trace components are given in Table 3 [4][5][6][7]. The sampling port was placed at about 2.5 m from the engine in the exhaust pipe.

RESULTS AND DISCUSSION

NOx, CO, and THC

Fig. 1 shows the relations between the alcohol contents of fuels and the NOx, CO, and THC concentrations in the exhaust gas. Including some expected tendencies, we can draw the following results from the figure:

- The NOx concentration in the exhaust gas decreases as the alcohol content of the fuel mixture increases.
- The CO concentration does not depend on the alcohol or the mixing ratio.
- The THC concentration tends to get lower as the alcohol content in the fuel increases.

Hydrocarbons

Photochemical reactivities and biological effects of hydrocarbon compounds in the exhaust gas vary greatly from one to the other. We therefore separated and analyzed each hydrocarbon compound of C1 to C20 to study the characteristics of each component.

The bar graphs in Fig. 2 show how hydrocarbon components in exhaust gas change with the alcohol content of fuels. A bar graph for gasoline fuel itself is also included for reference. Concentrations of components exceeding 100 ppmc are indicated by their numerical values in these figures.

The hydrocarbon compounds were identified by gas chromatograph-mass spectrometer (GC-MS). The identified components amount to more than 93% of all detected hydrocarbons, and hydrocarbon emission patterns can fairly be represented by these identified compounds.

Data on photochemical reactivities of hydrocarbons studied by Yanagihara et al. are shown in Table 4 for reference [8]. As seen in the table, there are many indices for photochemical reactivity, but methanol and ethanol do not show photochemical reactivity for any of these indices.

For methanol-gasoline fuels, hydrocarbons of C1 to C4 decrease
ersely proportional to the methanol content with exception
butenes. Hydrocarbons of C5 to C20 also decrease in a

similar manner. They are hardly detected for 100% methanol, and 98% of the THC value is due to unburned methanol. Judging from the data shown in Table 4, this indicates that the photochemical reactivity will be considerably lower compared with exhaust emissions from conventional gasoline engines, and it can be said as far as hydrocarbons are concerned that the problem with methanol-gasoline fuels is not the photochemical reactivity of exhaust gas but the level of unburned methanol and its harmfulness.

Methanol is poisonous by itself [9]. It was often said that impurities of industrial methanol were the cause of poisonous character of methanol and methanol itself was not poisonous. This is not true. Chemically pure methanol shows specific poisonous characters. The MAK (Maximal Arbeitsplatz Konzentration) for methanol is 200 ppm and the TLV (Threshold Limit Value) is 260 mg/m^3. It can hardly be said that gasoline is not poisonous. It is not possible at this time to clearly state which is more poisonous, gasoline or methanol, because of the lack of data.

Fig. 3 shows the experimental results on elimination of unburned methanol by catalyst. As seen in the figure, methanol itself can be eliminated relatively easily. However in incomplete combustions, at cold starts in particular, a great amount of formaldehyde is generated, and it is necessary to consider measures which also takes care of formaldehyde. See the paragraph on aldehydes for more details.

For ethanol-gasoline fuels, it is conspicuous that ethylene emissions increase as the ethanol content increases, and the level of ethylene concentration exceeds 400 ppm for 100% ethanol. Hydrocarbons of C5 to C20, on the other hand, decrease as the ethanol content increases. Hydrocarbons are hardly detected for 100% ethanol, and 86% of the THC value is due to unburned ethanol.

Ethylene is a material of high photochemical reactivity. Emission levels of ethylene in the exhaust gas from ethanol engines, however, are as same as in those from gasoline engines and there are many other compounds of photochemical reactivity in the exhaust from gasoline engines. Therefore, it can be said as far as the photochemical reactivity is concerned that emissions from ethanol engines is rather harmless compared with those from gasoline engines.

Comparing with methanol engines, however, exhaust gas from ethanol engines can be more reactive photochemically considering the percentage of unburned alcohol in the apparent THC and high ethylene concentration in the exhaust gas.

Aldehydes

Aldehydes are generally known for their high reactivity and harmfulness to living things, and lately, they are also drawing attention as materials which are related to photochemical smogs [10][11] and smells [12] of exhaust gas from automobiles. There have already been some reports [13][14] on formaldehyde emitted from methanol engines, but no report has apparently appeared on its emission characteristics for mixed alcohol-gasoline fuels.

We analyzed carbonyl compounds from an engine using alcohol-gasoline mixtures as fuels by means of the DNPH derivatives-GC method. Carbonyls detected are formaldehyde, acetaldehyde, acetone, acrolein, propionaldehyde, buthylaldehyde and methylethylketone (not separated), crotonaldehyde and valeraldehyde (not separated), benzaldehyde, and tolualdehyde.

An example of measured result is given in Table 5. The general tendency is that the overall aldehyde emission increases as the alcohol content of fuel increases. Changes in concentration of several aldehydes with methanol and ethanol contents are shown in Figure 4.

Formaldehyde emissions increase for both methanol- and ethanol-mixed fuels as the alcohol content increases. For 100% methanol, the level of formaldehyde concentration is more than 100 ppm. This level of formaldehyde concentration is extremely high considering its irritations to the eye and mucus membrane, and after-treatment of exhaust gas is necessary and essential. For reference, MAK of formaldehyde is 5 ppm.

As for acetaldehyde, its emission increases for ethanol-mixed fuels as the ethanol content increases, but its concentration for methanol-mixed fuels is fairly low. The MAK for acetaldehyde is 200 ppm, and the harmfulness of acetaldehyde emissions to the health is not as serious as that of formaldehyde in the context of the present results.

Aromatic aldehydes detected are benzaldehyde and tolualdehyde. As it can be expected, these emissions decrease as the alcohol content increases for both methanol- and ethanol-mixed fuels. Their concentrations are fairly low, and their contribution as irritants is considered to be negligible.

Acrolein deserves an attention as an irritant among the aldehydes of molecular range of C3 to C5. The MAK for acrolein is 0.1 ppm. The acrolein concentration recorded in the experiment is on the order of 1/100 of that of formaldehyde for 100% gasoline. Acrolein as an irritant however is considered about 10 times as strong as formaldehyde [15], and it is a compound which, along with formaldehyde, can not be ignored. The present experimental result, however, indicates that the acrolein concentration decreases inversely proportional to the alcohol contents of the fuel, and it is rather a harmful component of gasoline engine emissions than that of alcohol engine emissions.

From the discussions given above, it is apparent that formaldehyde is the aldehyde compound of highest concern because of its high concentration in the exhaust gas and its influence to the health, and it is most important to find out a measure for reducing the formaldehyde concentration in exhaust emissions.

Emission characteristics of formaldehyde were studied, therefore, taking excess air ratio, ignition timing, engine load, cooling water temperature, evaporation ratio, and water content in fuel as parameters. The reduction-FID method [16] was employed to analyze formaldehyde because the ordinary FID is not sensitive to folmaldehyde. In the reduction-FID method, formaldehyde is first reduced to methane by a Ni catalyst connected to the separation column of the GC, and the reduced methane is then detected sensitively.

Although detailed discussion of the results is not presented here, it is found that an extremely high correlation exists at a constant excess air ratio between the unburned methnaol concentration and formaldehyde concentration as shown in Fig. 5.

The experimental results of elimination of formaldehyde by an oxidizing catalyst are summarized in Fig. 3. The catalyst is not one which is special for formaldehyde but a platinum-paradium catalyst of honeycomb type, which is commercially available. The engine was operated in the lean zone, which means that oxygen is more than required, and no secondary air was supplied.

As seen in Fig. 3, the conversion saturation temperature of formaldelyde approximately coincides with that of CO, and conversion of formaldehyde tapers off at 82%. Considering that formaldehyde is a material of relatively high reactivity, the result can be attributed to an equilibrium between the oxidizing rate of formaldehyde and the generation rate of formaldehyde from unburned methanol. This means that conversion of unburned methanol monitored only by FID might overlook generation of formaldehyde to which the FID is not sensitive. It should be noted that evaluation of catalyst performance necessarily dictates not only the measurement of the THC concentration by FID but also monitoring of associated by-products such as aldehydes.

Fig. 6 shows formaldehyde conversions as a function of space velocity (SV). As seen in the figure, SV must be less than $1x10^4 hr^{-1}$ to completely convert formaldehyde. This means that the catalyst for converting formaldehyde must be considerably larger than those for converting CO and unburned methanol.

Lower Fatty Acids

Formic and acetic acids of which existence in the exhaust emissions from methanol and ethanol engines are easily suspected are measured. Fig. 7 shows relations between the alcohol content in fuels and these acids concentrations in the exhaust emissions.

For methanol-mixed fuels, the formic acid concentration in exhaust gas increases rapidly as the methanol content in the fuel increases. The acetic acid concentration, on the contrary, shows a slight decrease. These tendencies correspond to those of formaldehyde and acetaldehyde concentrations respectively.

For ethanol-mixed fuels on the other hand, the acetic acid concentration in exhaust gas increases as the ethanol content in the fuel increases in a good correspondence with that of acetaldehyde. The formic acid concentration in exhaust gas, however, shows a reverse tendency to that of formaldehyde. A relation which is similar to that of unburned methanol and formaldehyde of Fig. 5 is generally expected, but the result indicates that such correlation does not necessarily exist, and we are still to investigate the cause of this result.

Formic acid is the most irritative and corrosive compound among the lower fatty acids. It is said that the acid shows the same level of harmfulness to the health as formaldehyde [17], and the MAK for formic acid is 5 ppm. Acetic aicd is not as harmful to the health as formic acid, and the MAK for acetic acid is 25 ppm. It is said however that it is impossible to work eight hours a day exposed to an atmosphere with more than 10 ppm of acetic acid for a long period [18].

The results of this experiment indicate that lower fatty acid concentrations in exhaust emissions for alcohol-mixed fuels are not much different from those for conventional gasoline fuels except for the increase in the formic acid concentration for methanol-mixed fuels. Taking the irritative and corrosive characters of these acids into consideration, however, concentrations of lower fatty acids in exhaust emissions are not at all of ignorable levels irrespective of fuels, and deserve a close attention.

Hydrogen Cyanide and Ammonia

Hydrogen cyanide in combustion gases is getting to be of academic interest as a by-product of a NO generation reaction mechanism or the prompt NO generation reaction mechanism in the fuel-rich side [19]. Hydrogen cyanide in the exhaust gas from automobile engines is very little, but is intensive harmfulness to the health has been drawing much attention lately, and more than a few reports [20][21] have been published on characteristics of hydrogen cyanide emissions from automobile engines.

Ammonia, on the other hand, is generally known as a compound which causes smells, and has been drawing much attention lately because it has become known that highly concentrated ammonia is emitted under specific conditions of the after-treatment equipment for exhaust gas.

The MAK for hydrogen cyanide is 10 ppm and that for ammonia is 50 ppm.

Hydrogen cyanide and ammonia concentrations in the exhaust gas for methanol- and ethanol-mixed fuels as a function of alcohol content are shown in Fig. 8. As seen in the figure, emission levels of these compounds are fairly low, and their concentrations do not certainly reach harmful levels in the context of the experiment in which emissions from engine under a normal operating condition were tested.

Furthermore, the fact that hydrogen cyanide and ammonia concentrations in exhaust gas decrease as the alcohol content increases is a matter of interest, along with similar characteristics of NOx emissions, as an advantage of mixing alcohol in gasoline.

CONCLUSIONS

One of the purposes of this study is to provide data for evaluating alcohols as automobile fuel alternatives from the viewpoint of their effects to the environment, and the main emphasis was placed on the measurement of emission levels of potentially harmful components and their evaluation.

Compounds studied in this report were discussed in reference to their photochemical reactivities and using MAKs as indices. These values, however, are not much more than references, because the allowable concentrations like MAKs for example are different from country to country and the background for determining these values is different from one compound to the other. The MAKs for some compounds have been determined by levels of irritations they cause to the eye and mucus membrane, and those for other compounds have been determined on the basis of levels of chronic poisoning they might cause. It is therefore impossible to use these values as standards of reference.

In addition, some compounds, formaldehyde, for example, show synergitic effects [22] when mixed with certain solvents, and it is an extremely diffcult task to evaluate a compound as to its influence to living things. We believe, however, that intensive studies must be carried out on the effects of alcohol engine emissions to the health before they are emitted in a great amount to the atmosphere.

As for unburned methanol and formaldehyde, we demonstrated a possibility of eliminating them by the use of catalyst, and we intend to carry out similar investigations also on other compounds.

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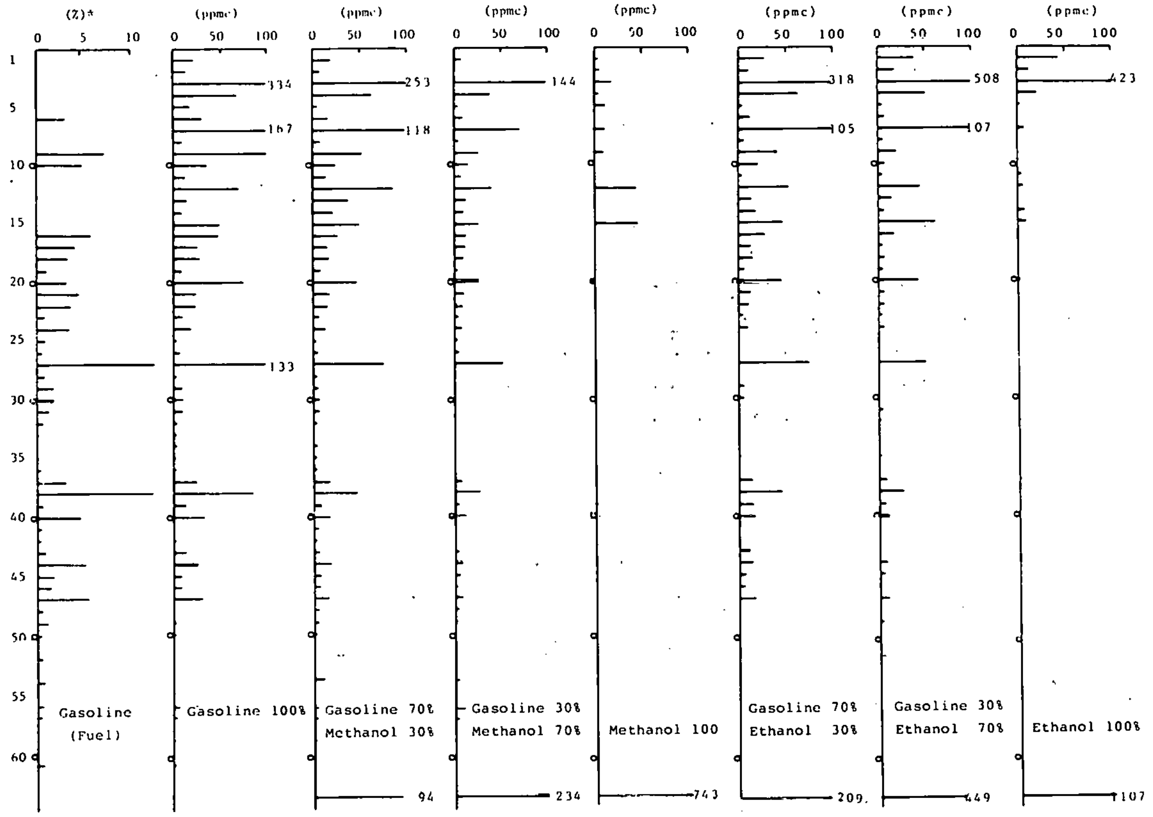
Table 1 Specifications of test engine

Type	4-Cycle Spark Ignition
Number	1
Bore and Stroke	95x72mm
Piston Displacement	510cc
Valve Arrangement	O.H.V
Compression Ratio	8.0

Table 2 Engine operating conditions

Engine speed	1800rpm
Ignition timing	MBT
Charging efficiency	43%
Intake air	3.83g/sec
Excess air ratio	1.2



1) Methane
2) Ethane
3) Ethylene
4) Acetylene
5) iso-Butane
6) n-Butane
7) Propylene
8) Unknown
9) iso-Pentane
10) n-Pentane
11) Unknown
12) iso-Butene, 1-Butene
13) trans-2-Butene
14) cis-2-Butene
15) 1,3-Butadiene
16) 2-Methylpentane
17) 3-Methylpentane
18) n-Hexane
19) Methylcyclopentane
20) Benzene
21) 2-Methylhexane
22) 3-Methylhexane
23) 1-trans-2-Dimethylcyclopentane
24) n-Heptane
25) Methylcyclohexane
26) 2,3,3-Trimethylpentane
27) Toluene
28) 2,3,4-Trimethylpentane
29) 2,5-Dimethylhexane
30) 3-Methylheptane
31) n-Octane
32) 1,2-Dimethylcyclohexane
33) 2,5-Dimethyl-2-hexene
34) 2,3,5-Trimethylhexane
35) 2,6-Dimethylheptane
36) 3,5-Dimethylheptane
37) Ethylbenzene
38) m,p-Xylene
39) 2-Methyl-1-octene
40) o-Xylene
41) n-Nonane
42) 1-Methyl-4-ethylbenzene
43) Propylbenzene
44) 1-Methyl-3-Ethylbenzene
45) 1-Methyl-2-Ethylbenzene
46) 1,3,5-Trimethylbenzene
47) 1,2,4-Trimethylbenzene
48) Decane
49) 1,2,3-Trimethylbenzene
50) 2,3-Dihidroindene
51) Diethylbenzene
52) *Methyl-n-propylbenzene
53) *Methyl-n-propylbenzene
54) *Methyl-n-propylbenzene
55) *Methyl-n-propylbenzene
56) 1,3-Dimethyl-5-ethylbenzene
57) 1,4-Dimethyl-2-ethylbenzene
58) 1,3-Dimethyl-2-ethylbenzene
59) 1,2-Dimethyl-4-ethylbenzene
60) Undecane
61) 1,2-Dimethyl-3-ethylbenzene
62) 5-Methylindene
63) 4-Methylindene
64) Methanol
65) Ethanol

Hydrocarbons identified by GC-MS, *The position of methyl group is unknown.

Fig 2 The change of hydrocarbon components in the exhaust with the alcohol contents of fuel mixtures

Table 3 The methods used for determination of unregulated compounds

Objects	Sampling Methods	Analytical Methods
Detailed HC		
C_1— C_4	Heated Syringe	GC—FID
C_5— C_{20}	Column Sampling	GC—FID, Capillary Column
Alcohol	Heated Syringe	GC—FID
Aldehydes	Bubbler	GC—FID
Acids	Cold Trap(Liq.O_2)	GC—ELCD
Ammonia	Bubbler	Specific Ion Electrode
Hydrogen Cyanide	Heated Syringe	GC—TID

Table 4 Photochemical reactivities of organic materials [8]

	Mean Carbon Number —	NO D.R. ppb/min	NO_2 t-max min	NO_x · NO max ppm	t-max min	F.R. ppb/min	Dosage ppm. min	O_3 max. ppm	t-max min	F.R. ppb/min	Dosage ppm/min	sp.HC D.R. 5h %	HCHO 4h ppm	PAN 5h R.R.	NO_x D.R. 5h %
Motor Gasoline (37.5% Ar.)		12.0	90	0.78	90	10.8	165	0.47	300	1.5	65	----	0.15	0.600	0.61
1,3-Butadiene		23.4	45	0.88	45	23.1	117	0.79	105	7.7	155	100	1.14	0.030	0.72
Ethylen		9.6	150	0.77	120	9.7	171	0.44	300	1.2	49	56.5	----	0.141	0.60
Methanol		1.4	300	0.33	285	1.4	60	0.00	300	0.0	0	not	0.06	0.000	0.10
Ethanol		2.3	300	0.54	300	2.2	94	0.00	300	0.0	0	20.0	0.06	0.013	0.17
Paraffins (13samples)	5.00	5.1	246	0.64	255	4.8	137	0.13	300	0.33	13.5	29.5	0.12	0.100	0.29
Olefins (9 samples)	4.78	21.1	77	0.81	149	19.0	149	0.58	220	6.0	104	92.6	0.70	0.390	0.60
Naphthens (5 samples)	6.20	5.4	231	0.69	237	5.1	156	0.11	300	0.24	9.0	38.7	0.11	0.000	0.27
Aromatics (15samples)	7.67	9.9	127	0.69	125	8.4	127	0.33	239	1.1	47.9	54.0	0.17	0.210	0.61
Mixed Hc (8 samples)	6.29	8.1	154	0.70	161	6.8	144	0.29	276	1.0	41.7	32.2	0.08	0.080	0.50

D.R.;Depletion Rate,F.R.;Formation Rate,sp.HC;measured with G.C.,O_3data are in 5h,
---;not measured ,not;not exact,Inital Condition;HC:2ppm,NOx:1ppm

Table 5 Aldehydes and ketons in alcohol engine emissions

Alcohol content Vol.%	Form-aldehyde	Ace-aldehyde	Acetone	Acrolein	Propion-aldehyde	Methyl-ethyl-ketone Buthyl-aldehyde	Croton-aldehyde Valer-aldehyde	Benz-aldehyde	Tolu-aldehyde	Total aldehyde
Gasoline	35.8	3.14	0.53	0.39	0.05	0.32	0.03	0.66	0.28	41.2
Methnol 30%	20.0	1.22	0.25	0.07	0.003	0.15	0.01	0.27	0.10	22.1
Methnol 70%	65.8	1.00	0.23	0.12	——	0.68	——	0.33	0.12	68.3
Methanol 100%	113	——	——	——	——	0.83	0.003	——	——	114
Ethanol 30%	55.0	16.1	0.53	0.36	0.05	0.27	0.03	0.65	0.27	73.3
Ethanol 70%	89.9	41.3	0.29	0.27	0.09	0.49	0.05	0.39	0.12	133
Ethanol 100%	81.6	71.1	0.07	0.07	0.07	0.90	——	——	——	115

—— : < 0.001

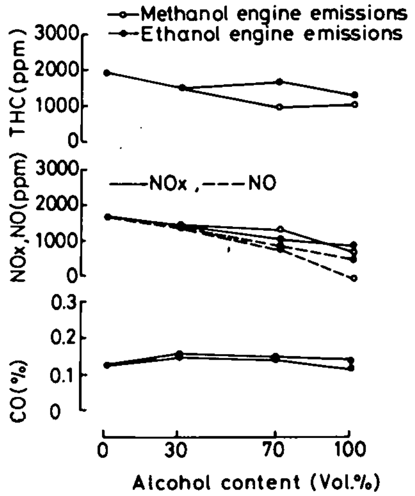


Fig.1 Relations between the alcohol content of fuels and the NOx, CO and THC concentrations in the exhaust gas

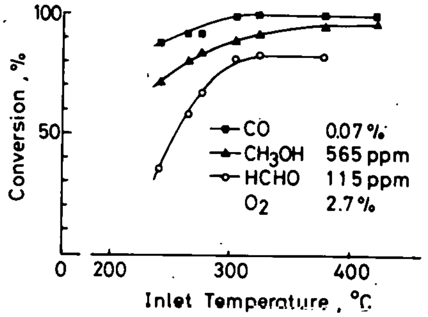


Fig.3 Effects of inlet temperature on conversion

Catalyzer: Engelhart 513 II B, SV: 1.95x10^4

2000 rpm, λ: 1.17

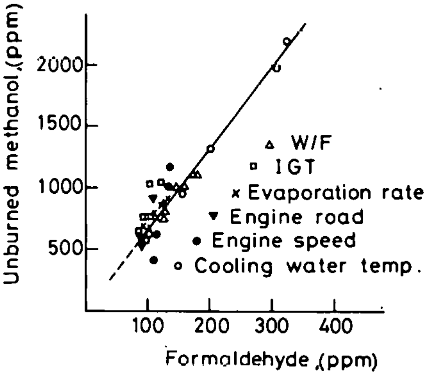


Fig.5 Relations between formaldehyde and unburned methanol

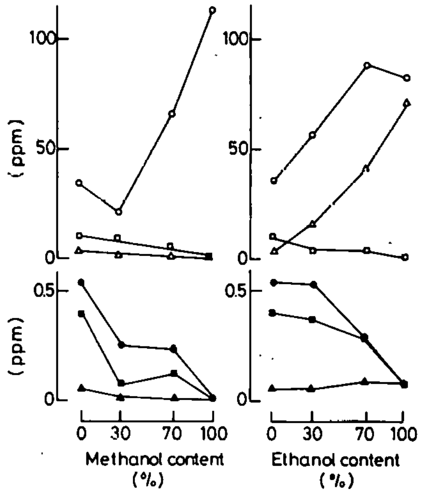


Fig.4 Relations between the alcohol content of fuels and the concentrations of carbonyl compounds in the exhaust gas

-o-Formaldehyde, -△-Acetaldehyde, -△-Benzaldehyde and Tolualdehyde, -•-Acetone, -•-Acrolein, -+-Propionaldehyde

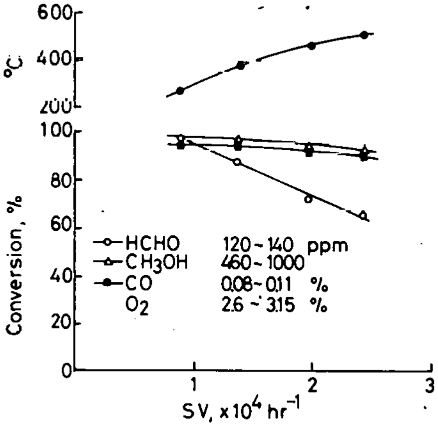


Fig.6 Effects of space velocity on conversion

W/F: 0 %, 2000 rpm, λ: 1.16~1.18

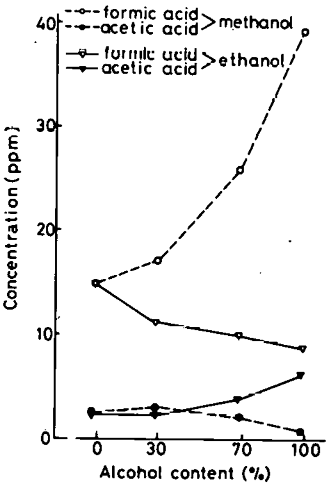


Fig.7 Relations between the alcohol content of fuels and the lower fatty acid concentrations in the exhaust gas

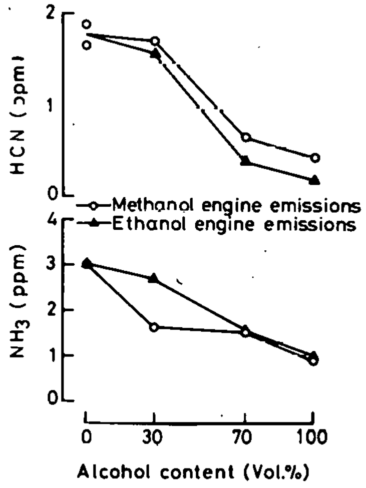


Fig.8 Relations between the alcohol content of fuels and the HCN and NH_3 concentrations in the exh gas

TOXICITY OF METHANOL/PETROL MIXTURES

by

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If methanol is to be introduced as an alternative or supplementary transport fuel, as seems very likely in New Zealand and several other countries, it is essential that the extent of the hazard it may present be accurately defined. As an initial measure it is proposed in New Zealand to introduce a 15% methanol/petrol mixture ("M15"). The sinister consequences of methanol ingestion have induced a somewhat emotive attitude towards methanol exposure by any route. The immediate risks of acute intense exposure to a methanol/petrol mixture are probably no greater than that to petrol alone (McQueen 1978). The most important hazards are likely to be those of exposure to the vapour via the respiratory tract and of skin contamination as a result of spillages of liquid fuel. There is a large amount of information on the risks of exposure to the vapour of methanol on its own as a widely used solvent in industry but there are very few toxicological data on the effects of exposure to the vapour from mixtures of methanol and petrol. Similarly there is no information to date on the absorption of methanol from mixtures with petrol via the skin.

The potential dangers of methanol and of petrol to human subjects permits exposure only to very restricted amounts and there is thus an urgent requirement for satisfactory animal models. This requirement is complicated by the substantial differences there are in the metabolism of methanol by the usual laboratory species from that in human subjects who are peculiarly susceptible to the toxic effects of methanol and it has been suggested that it is necessary to go to primates to obtain a satisfactory model (Martin et al, 1977).

As a more practical alternative for us we have been using sheep for studies on respiratory absorption. Sheep should provide satisfactory uptake data from the respiratory viewpoint and if their rate of methanol metabolism could be shown to be comparable to that of humans, uptake of methanol by sheep could serve as a satisfactory kinetic index even if the netabolic pathways are not identical those in man.

We have therefore studied the elimination by sheep of methanol given by intravenous administration and compared this with its elimination by human subjects. Having confirmed that these are comparable we have observed the rate of uptake of methanol by sheep from M15 vapour and also contrasted this with uptake from straight methanol vapour.

Exposure of the skin to methanol is quite tolerable and quantitative estimations of methanol absorption via the skin from straight methanol have been made in human subjects by Tada et al (1975). However cutaneous exposure of human subjects to M15 is highly irritating to the skin and therefore the dermal absorption of methanol from M15 was studied in anaesthetized rats in which it was compared with that from straight methanol.

METHODS

Kinetic observations

Two human subjects ingested 1.5 and 3.0 ml methanol (40 and 20 mg/kg respectively) in the fasting state in the morning and had multiple blood samples taken over the remainder of the day. Four sheep were given methanol intravenously, two in dosage of 160 mg/kg and two, 45 mg/kg. Multiple blood samples were taken over a 12 hour period.

Respiratory exposure

A number of sheep were exposed to different concentrations of M15 and methanol vapour given via an anaesthetic mask and venous blood methanol measured at regular intervals during and after exposure.

Dermal absorption

Liquid methanol and M15 were applied to the skin of two human subjects over an area of approximately 75 cm^2 on the volar aspect of the forearm under an occlusive dressing and blood taken from the opposite arm for methanol estimation. Rats weighing 250 - 300 g, anaesthetized with pentobarbitone, had an area on their backs closely clipped. A cottonwool pad approximately 32 cm^2 in area saturated with either M15 or methanol was applied to this and left in place for 1 minute. Venous blood was taken from a jugular vein at ½ hourly intervals for up to 2½ hours, care being taken to avoid concomitant inhalation of methanol vapour.

Analyses of blood methanol concentrations and of petrol/methanol mixtures and vapours were undertaken using flame ionisation gas chromatography. Detector and injector temperatures were 250° and 200°C respectively. The gas flow rates were: oxygen-free nitrogen carrier gas 30 ml per min; hydrogen 25 ml per min; air 300 ml per min. "Head space" techniques were used to determine blood methanol concentrations on a 1.8 m x 2 mm id glass column packed with 60/80 mesh Tenax GC at 110°C. Petrol methanol mixtures and vapours were separated on a 2 m x 2 mm id glass column packed with 100/120 chromosorb 102 starting at 160°C for 3 min followed by temperature programming at 4°C per minute to 200°C.

RESULTS

Elimination kinetics

Elimination of methanol following oral administration to the two human subjects showed a linear relationship between the logarithm of the decremental plasma concentration and time (Fig 1). This shows that from the levels achieved by these relatively small amounts of methanol (40 and 20 mg/kg) elimination followed first order kinetics. Elimination of methanol in the sheep also followed the same pattern after completion of the distribution phase (Fig 2). First order kinetics appeared to prevail at least up to levels of 200 μg/ml. Kinetic indices are shown for both humans and sheep in Table I. The half lives for both s :ies were comparable, tending if anything to be longer in the sheep.

Respiratory exposure

Blood levels in the sheep during respiratory exposure rose rapidly at first and then more slowly over the period of exposure. Blood concentrations in two sheep exposed to between 7,000 and 8,000 p.p.m. methanol in M15 or straight methanol vapour are shown in Table II during the incremental phase. There was no obvious difference between uptake from M15 vapour and from straight methanol. Quite marked fluctuations in blood levels occurred associated with the considerable variations in the ventilation rate of the sheep that were observed in the course of the experiments. A plateau which appeared to be reached in previous experiments with M15 may well have been due to partial narcosis of the sheep with reduction in their respiratory exchange.

Following cessation of exposure blood levels of methanol fell rapidly and then, from about an hour afterwards, exponentially with a half life approximating that found in earlier experiments.

Dermal exposure

After application of M15 to human skin a marked sensation of heat became apparent after about 1 minute and by 5 minutes the experiment had to be terminated. The inflammation of the skin was evident for about 3 days but there was no blistering. Barely detectable levels of methanol were observed in the blood as was also the case after application of methanol which however was readily tolerated.

In contrast to the experiments involving respiratory exposure of sheep in which no difference was apparent in methanol levels after either M15 or straight methanol, dermal absorption of methanol by rats was considerably greater after M15 than after methanol (Table III). Methanol levels in some rats after cutaneous exposure for 1 minute were comparable to those after 15 minutes of respiratory exposure in the sheep.

DISCUSSION

Apart from the serious toxic effects of methanol, manifest at levels of about 350 µg/ml and above, a feature of its metabolism that tends to engender anxiety is its relatively low maximum elimination rate. At toxic blood levels elimination is zero order i.e. unrelated to concentration and only about 1/5 that of ethanol. This gives rise to fears that with repeated exposure it is likely to be cumulative. Since there would inevitably be substantial occupational exposure, e.g. by filling-station attendants it is essential that the magnitude of the risk of accumulation be assessed.

Our studies indicate that at low plasma methanol levels elimination in human subjects is first order. The latter findings confirm, on the basis of blood levels, the results of Leaf and Zatman (1952) who similarly found first order kinetics in 2 human subjects as estimated using urinary concentrations.

The half lives of 1.9 - 6.9 hours we have found in the sheep were furthermore reasonably comparable with the human data (3½ as calculated from the data of Leaf and Zatman (1952), 2 and 2.25 for ours). The sheep thus seems to be an appropriate animal in which to study methanol kinetics.

There are considered to be adequate data on the uptake of methanol vapour for the setting of a threshold limit value for industry of 200 p.p.m. However this has related to methanol vapour per se and in relatively stable factory environments. The situation with regard to methanol/petrol mixtures such as the M15 requires to be evaluated de novo particularly because the formation of azeotropes with the various components of petrol considerably enhances the volatility of methanol. The respiratory uptake may similarly be modified by the presence of particularly the light components of petrol. The extent of exposure from the inevitable minor spills at filling stations presents a degree of complexity that virtually precludes theoretical assessment.

The experimental results on sheep are in fact reassuring. Methanol levels after exposure to M15 vapour have been substantially the same as those after exposure to comparable concentrations of straight methanol. Levels attained after exposure to concentrations more than 35 times the TLV for an hour have not induced blood levels so high that they would constitute an apparent hazard in themselves or would suggest the likelihood of cumulation. Blood levels fell rapidly after cessation of exposure with redistribution and elimination.

However the results of dermal exposure at least in rats show a quite marked difference between M15 and straight methanol. As can be seen from the results in Table III methanol levels after M15 were about 3 times as high after M15 as after methanol alone. It is difficult to assess the risks of dermal exposure to M15 directly in human subjects because of the highly irritant effects of the combination which make it impossible to tolerate the mixture on the skin for more than a few minutes. However the experiments in rats suggest that contamination of a substantial area of skin with M15 might lead to absorption of significant amounts of methanol. Tada et al (1975) showed that at least as estimated by urinary methanol concentrations quite toxicologically relevant amounts of methanol could be absorbed from relatively small areas of skin at least when left in contact for a period of 4 hours. Tada et al concluded that cutaneous absorption can be the major route of methanol absorption in man. Absorption of methanol from M15 is likely to be even greater because the de-fatting effect of the petroleum distillate would probably enhance skin permeability to methanol with its non-lipophilic nature. In fact the appearance of human skin after a 5 minutes exposure to M15 provided visual evidence of alteration of the physical character of the epidermis. However there is little danger that unwitting exposure via saturated clothing etc. might be allowed to continue for any length of time at least in the conscious subject because of the irritant effect of the mixture.

The likelihood of accumulation of methanol from any tolerable exposure to M15 seems small. Blood levels observed in the experimental animals employed for the respiratory and dermal exposure measurements were within the range at which elimination kinetics are first order. Hence blood levels of methanol absorbed as a result of repetitive exposure to M15 would fall exponentially at a rate determined at any moment by the concentration after each episode, thus promoting the prompt reduction to minimal levels.

SUMMARY

Methanol elimination from levels likely to be attained as a result of occupational exposure has been shown to be a first order process. The sheep has proved to be a useful model for studying respiratory exposure to a 15% methanol/petrol mixture (M15). Blood levels attained by exposure to M15 vapour with methanol content 7000-8000 p.p.m. for up to one hour produced levels well below those likely to be associated with methanol toxicity and no different from those attained with comparable vapour concentrations of methanol alone.

M15 was severely irritant to human skin. Studies in rats showed that methanol absorption was some 3 times greater from M15 than from straight methanol.

Cumulation of methanol from occupational exposure seems unlikely.

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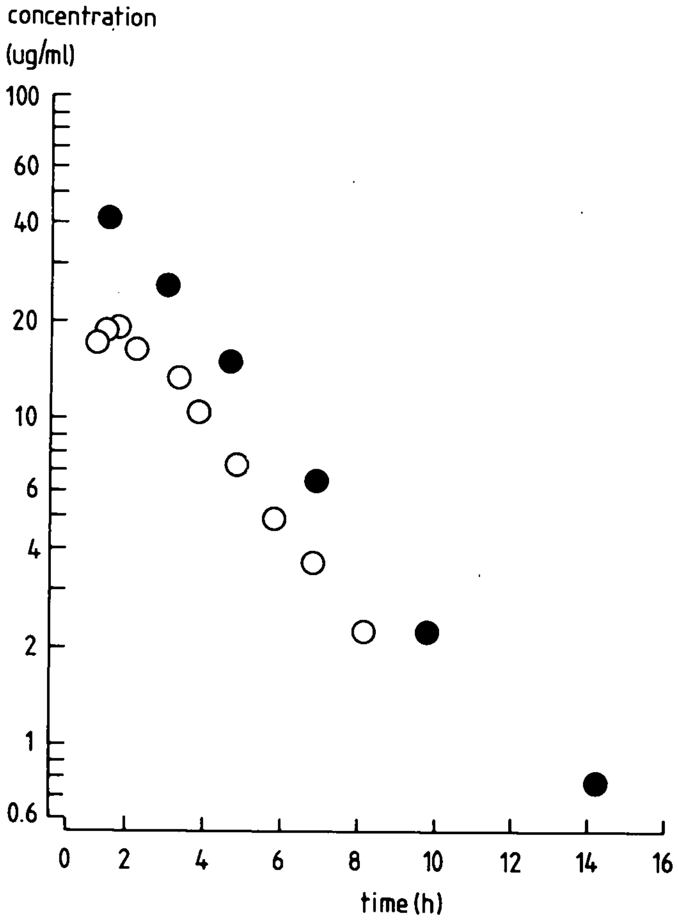

Fig 1. Blood levels in two human subjects who ingested methanol orally in dosage of 40 mg/kg (filled circles) and 20 mg/kg (open circles)

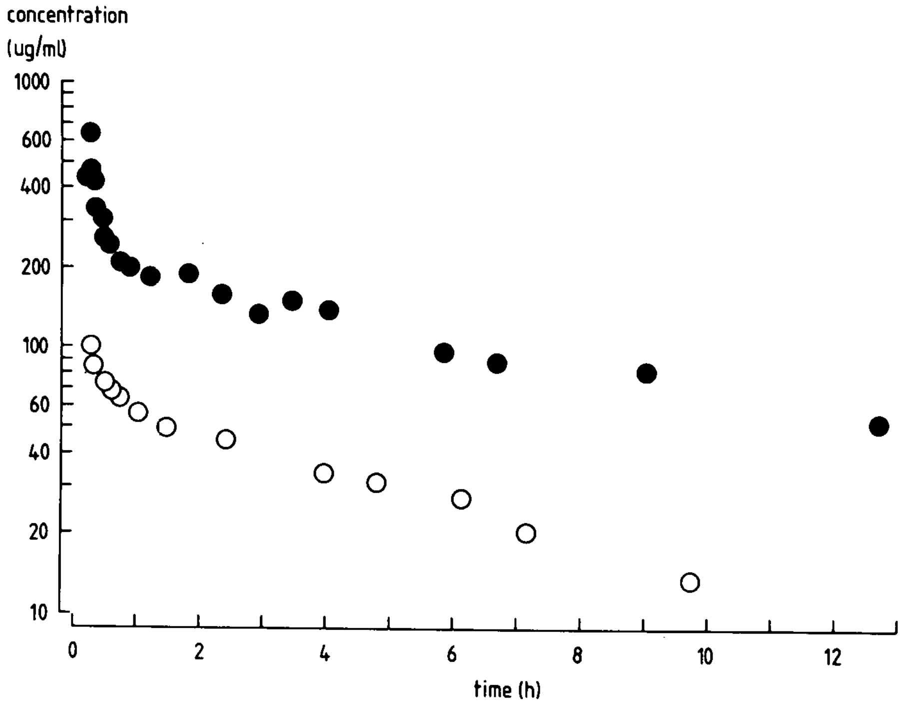

Fig 2. Date from two sheep which received methanol intravenously in dosage of 160 mg (closed circles) and 45 mg/kg (open circles)

TABLE 1

Elimination half life of methanol after oral administration to 2 human subjects and intravenous administration to 4 sheep

	Dose (mg/kg)	t½ β(h)
Human 1	40 Oral	2.25
Human 2	20 "	2.0
Sheep AB 260	160 IV	3.0
" " 262	160 "	6.9
" " 261	45 "	4.5
" " 263	45 "	1.9

TABLE II

Methanol blood levels (μg/ml) in two sheep breathing concentrations of 7105 p.p.m. methanol as M15 vapour or 7816 p.p.m. as straight methanol vapour

Minutes of Exposure	Sheep 359		Sheep	
	M 15	Methanol	M15	Methanol
5	13.2	19.3	13.4	13.6
10	16.1	27.8	15.6	19.7
15	13.3	22.7	14.3	17.5
20	18.8	20.0		
30	28.3	28.5		
40	28.1	31.9		
50	39.3	29.5		
60	37.4			

TABLE III

Blood levels of methanol in rats following dermal exposure to methanol or to M15 (μg/ml)

	30 mins	60 mins	90 mins	120 mins	150 mins
Methanol					
Means	6.7	6.7	6.0	5.0	
Nos.of samples	4	3	4	3.0	
Range	5.0-9.8	4.2-9.0	3.6-8.0	3.6-6.6	
M15					
Means	19.9	24.0	12.4	9.9	8.1
Nos.of samples	4	2	4	3	4
Range	8.8-26.6	14.2-33.8	3.8-24.0	3.4-20.0	2.0-18.6

FORMALDEHYDE EMISSIONS FROM A SPARK IGNITION ENGINE USING METHANOL

by

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ABSTRACT With the aid of derivative spectrophotometry, emission characteristics of formaldehyde from a S.I. engine using methanol were obtained. The single cylinder, water cooled 4 stroke cycle engine was operated with wide open throttle at engine speed of 1500 rpm. Formaldehyde, unburned methanol and other trace species were measured at several distances along the exhaust tube for various equivalence ratios and ignition timings. The results indicate that formation of formaldehyde from unburned methanol already begins in the cylinder or within the exhaust port, and then, formaldehyde accumulation occurs at the temperature ranging roughly 400-500 °C in the exhaust tube.

INTRODUCTION

Aldehyde emission in exhaust gases from a spark ignition engine using methanol as a fuel is almost understood to be higher than from an engine operation on gasoline [1,2]*. Formaldehyde (HCHO) is the main intermediate product in the methanol combustion process and is one of the pollutant species because it is known to be odorous and is believed to be a cause of eye irritation in photochemical smog.

It is necessary to examine the emission characteristics and the formation mechanism of HCHO before putting a methanol fueled engine to practical use. But, as is well known, because of high temperature in exhaust system, unburned fuel or total hydrocarbon (THC) in a gasoline fueled engine is reduced considerably in the exhaust manifold, which acts as a reactor for THC, so that, THC concentrations decrease with increasing residence time of exhaust stream in the manifold. Therefore, measured THC concentrations at a distance, for instance, at the tail end of the exhaust tube, from the exhaust valve indicate over all characteristics including the resulting THC oxidation during the exhaust movement.

To clarify the formation mechanism of HCHO, a reliable measurement of it as well as unburned methanol (UBM) in an exhaust system is needed, and then, according to the results obtained, the emission characteristics of HCHO should be evaluated.

In this study, the emission characteristics as well as the behavior of HCHO in an exhaust system are examined correlating to emission and oxidation of UBM emissions.

EXPERIMENTAL APPARATUS AND PROCEDURES

Test Engine

A water cooled, single cylinder, four stroke cycle spark ignition engine equipped with a wedge type cylinder head was

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* bers in brackets [1] designate References at end of paper.

used. Bore and stroke of the engine were 74 and 75 mm respectively. The rated power with gasoline fueled operation was 12.0 PS at 5500 rpm. A mixture was fed to the engine through a carburetor which had an adjustable metering jet to control the air-fuel equivalence. The lower part of the carburetor was heated to about 80 °C. The specification of the tested engine is shown in Table 1.

During the test program several engine variables were held constant for all test runs. The engine speed was selected at 1500 rpm with a wide open throttle (WOT), lubricating oil temperature and coolant water temperature were 80 ± 2 °C. Air-fuel equivalece ratio, $\varnothing_{AF}$, used in this study is defined as

$$\varnothing_{AF} = (\text{ Actual A/F }) \, / \, (\text{ Stoichiometric A/F }).$$

The fuel used in this work was commercial graded one. The results of the performance tests are shown in Figure 1.

Exhaust Tubing

The exhaust tube fitted to the tested engine was 3000 mm long and made of common materials. Figure 2 shows the exhaust tubing with the location of gas sampling holes. The exhaust valve was located at 70 mm inside the exhaust port.

Gas sampling for measuring the unburned components, such as HCHO or UBM, was taken at six locations, beginning at the exhaust port ($\ell = 0$) and ending ($\ell =$) 2500 mm along the exhaust tube. The exhaust tubing was exposed in room air so that the temperature of the exhaust gas in the tube decreased exponentially as the distance from the port increased. Exhaust gas temperature in the tube was measured by CA thermo-couples fitted at opposite sides against the gas sampling holes.

Gas Analysis

Determining concentration of CO, CO_2, O_2, NO and NO_2 in the exhaust gases is common place in most equipped laboratories. For the common gas monitoring system, sample stream was branched off to the gas analyzer at 100 mm from the exhaust port.

Formaldehyde Determination

For the purpose of this study, determination of HCHO emission had to be carried out employing a rapid and accurate method in comparison with wet chemical procedures, such as the MBTH procedure or the DNPH procedure. An in-situ, rapid analysis for HCHO emission was accomplished by use of a derivative spectrophotometer (YANACO UO-1) equipped with a gas sample cell. In second order derivative ultraviolet absorption, HCHO has a distinctive spectrum within the 270-330 nm wave range.

Figure 3 shows a typical derivative spectrum of the HCHO absorption band. This spectrum was obtained from an exhaust gas from the engine operated with methanol. And also, the spectrum was similar to a spectrum obtained from air containing only pure formaldehyde. Therefore, the presence of any emission component, such as unburned fuel, HC and NO_x, was not considered undesirable when the derivative spectrometry was selected in measuring the HCHO emission of methanol combustion.

In the case of gasoline operation or methanol/gasoline blends operation, the formaldehyde spectrum was slightly deformed in the low wave range because of interference of high molecular hydrocarbons. Then, in this study, a 284 nm band absorption was selected as one of the wave bands which had less interference from HC emission.

Also, it is difficult to provide a reference gas containing HCHO, which concentration was known, for a calibration of the spectrometer. Because gaseous formaldehyde is easily converted to para-formaldehyde at temperatures under 150 °C.

As a consequence, the derivative spectral signals of the instrument were calibrated carefully using the DNPH procedure. Good correlation was obtained between the derivative spectrometry and the wet chemical measurement ranging 0-300 ppm of HCHO in exhaust emissions. On the other hand, sensitivity correction of the instrument was made by a NO reference gas using a wave range of 200-230 nm, in which NO had three sharp signals on the derivative spectrum.

Sampling Line

Gas sampling system for the spectrometry consisted of quartz probes and teflon tubing with flexible silicone connecting tube. In the sampling, the exhaust gas was passed through a sampling line for a distance of about 2.0 m before entering the sample cell of the spectrometer. The sampling line was electrically heated at over 150 °C and the temperature of sample cell was kept at 170 °C to prevent the formation of para-formaldehyde which was not detected by the derivative spectrometry. The sample gas was pulled by means of a pump with a flow rate of 1.5 l/min.

Oxygenized compounds, except for formaldehyde, and hydrocarbons in exhaust emissions were determined with a gaschromatograph which is equipped with FID and two columns in parallel. One column was packed with PEG 400 determining the UBM and the oxigenized hydrocarbons, and the other was packed with Porapack Q for HC of low carbon number.

A gas sample for the chromatograph was collected in a heated syringe at the same sampling holes for the spectrometry.

EMISSION CHARACTERISTICS NEAR EXHAUST PORT

HCHO Emission Characteristics

Figure 4 shows the results of HCHO emission tests for varied air-fuel equivalence ratios and ignition timings using methanol as a fuel. These results were obtained from the exhaust stream sampled at a distance of 75 mm from the engine exhaust port. The resulting HCHO emission characteristics clearly turn at about this position. This phenomenon will be described later on.

It can be seen that in the range of fuel rich mixture, HCHO concentrations in the exhaust vary little with air-fuel equivalence and also with spark timing advance. For lean mixure with advanced timing, HCHO emissions increase steadily with ncreaseing air-fuel equivalence ratio.

However, in the case of TDC operation, HCHO emissions rise sharply after a while and then decrease as equivalence ratio increases. Thus, at retarded ignition timing, HCHO emission characteristics have a maximum value between ϕ_{AF}= 1.1-1.2. This tendency can be seen still at about ignition timing of -20 or -15 °CA.

If the engine was operated with MBT condition, the HCHO emission dependence on equivalence ratio would be clear at a leaner mixture as shown in the figure.

Generally, from these data it is apparent that HCHO emissions are a strong function of the equivalence ratio and influenced by ignition timing, especially for leaner mixture.

UBM Emission Characteristics

One of the most important parameters in determining HCHO emissions is unburned methanol emission [3] corresponding to THC emission for gasoline exhaust constituent. Figure 5 shows the results of measurement of UBM emission at the same sampling position, under the same engine operating condition, with the case of HCHO shown in Figure 4.

Most conditions demonstrate increased UBM emission for the retarded ignition timing, higher UBM emission for both fuel rich and fuel lean mixtures and minimum UBM emission at equivalence ratios on the lean side of stoichiometric.

In general, THC for gasoline exhaust is lower for higher temperature of exhaust. As shown in the figure, however, UBM emission for the operation with retarded timing, for example, of TDC is relatively higher than that for advanced timings, although the exhaust temperature at TDC is extremely high in comparison to the other timing operations as shown in Figure 1.

The fact mentioned above is to be explained as follows; most of the UBM is formed in the quenching layer in the cylinder. In retarded timings the quenching area becomes larger, in addition, the period of UBM oxidation with burned gases from the ending of the flame propagation until the opening of the exhaust valve is shorter than the advanced timings. Then the concentration of UBM near the exhaust port becomes higher than that for retarded timings.

Correlation between HCHO and UBM Emissions

To make clear the effect of UBM emission on HCHO emission property, the correlation between the two emission is reduced.

Plotted points in Figure 6 include all the data for varied air-fuel equivalence and ignition timing. As may be clearly seen in the figure, those data are roughly classified into two groups. One is a group in which UBM is proportional to HCHO and the other has an independent trend for UBM change. The former group is of leaner mixture and the later for richer mixture. But, there are points left out of the groups. Those were obtained with TDC operation, especially, at leaner mixture.

But, the correlation may be incomplete to explain the formation property of HCHO as a function of UBM emission. This fact suggests that the formation of HCHO is partly based on the UBM emission, in addition, there may be unknown factors in connection with the oxidation of UBM.

Effects of Oxygen Concentration on HCHO Emission

It is well known that the oxygen concentration in exhaust stream is determined by air - fuel equivalence ratio and is hardly influenced by ignition timing. Consequently, it is difficult to find a good relation between O_2 and HCHO for all operating conditions. However, if the engine operation was limited at MBT conditions, a linear proportionality would be found between O_2 and HCHO as shown in Figure 7. It may be thought that this property with O_2 is practically useful for estimating HCHO emission in methanol exhaust.

CH_4 Emission

One of the remarkable constituents in hydrocarbons from a methanol exhaust is CH_4 emission. As shown in Figure 8, CH_4 concentrations decrease rapidly with increasing air-fuel equivalence, and it can be recognized that there is no significant effect of the spark timing on CH_4 emissions.

Since CH_4 formation occurs at engine operation with a richer mixture, the fact suggests that the residence time as well as the exhaust temperature has a little effect on CH_4 emission. Therefore, the results imply that CH_4 is formed mainly under the combustion process in flame propagation, and also the quenching layer in the cylinder and the quantity of UBM are of less magnitude for the CH_4 formation.

Consequently, there is no strong relation between the formation of HCHO and CH_4.

Other Trace Species in Methanol Exhaust

Besides the determination of UBM and CH_4, C_2H_4, C_4H_8, acetone, acrolein and methyl-nitrite (CH_3ONO) were detected by the use of gaschromatography. Magnitudes of CH_4, C_2H_4, C_4H_8, acetone and acrolein emissions formed by polymerization were smaller than 5 or 10 ppm in a wide range of operating conditions.

On the other hand, the methyl-nitrite emissions shown in Figure 9 are noticeable because of higher magnitude than the other trace species and dependency to the NO_x emission. The highest value of methyl-nitrite concentration is shown to occur the range of $\phi_{AF} = 1.1-1.2$ and tends to decrease before and after this peak range. The emission characteristics are very similar to the case of NO_2. The formation reaction of CH_3ONO from NO_2 and CH_3OH is already known in a field of chemistry. If the CH_3ONO was formed by the reaction between NO_2 and UBM in the methanol exhaust, the results mentioned above would be reasonable.

HCHO AND UBM CONCENTRATIONS IN EXHAUST TUBE

Figure 10 shows the HCHO and the UBM concentrations in the exhaust tube under the various engine operating conditions, and also, the gas temperature distribution along the tube are shown in the figure.

HCHO Concentrations

In the case of rich mixture, $\phi_{AF}=0.8$, the HCHO concentrations at the engine exhaust port, $\ell = 0$, are about 40 ppm regardless of ignition timing, and stay almost the same along the tube.

For the stoichiometric mixture shown in Figure (B), there is no significant change in HCHO concentration. A typical behavior of HCHO concentration distribution in the exhaust tube can be seen in the operating condition of leaner mixture, $\emptyset_{AF} = 1.2 - 1.4$ (Figures 10 (C) and (D)).

The minimal value of HCHO concentration is shown to occur for a distance between the engine exhaust port and 200 mm from it. After this location, HCHO gradually increases with increasing distance from the engine, namely, increasing the residence time of the exhaust stream in tube. This phenomenon is emphasized when the engine is run with retarded timing, especially at the operation of $\emptyset_{AF} = 1.4$.

The signs of this trend can be already recognized in the former cases of $\emptyset_{AF} = 0.8$ and 1.0. It is obvious that an increase in HCHO is caused by an accumulation due to the formation reaction of HCHO in exhaust tube.

UBM Concentrations

On the other hand, it can be seen clearly that the UBM concentrations show the highest value at the begining of the exhaust tube and then decrease rapidly with increasing distance from the engine. The tendency of marked reduction of UBM is weakened after a while, and then, the reduction is restrained and UBM concentrations remain the same.

This fact suggests that the oxidation of UBM takes place in the exhaust tube, especially near the exhaust port where the gas temperature is higher. Rapid oxidation can be seen in the range of temperatures higher than 400 °C as shown in the figures. Ignition timing produces a substantial effect on the UBM oxidation, for each case of air fuel equivalence. In general, the amount of oxidation becomes greater as the ignition timing retards, because the exhaust temperature rises. Besides, the active radicals exist in the exhaust which are released at retarded timing operation. But the exhaust gases from advanced operation, contain less radicals.

These considerable radicals at initial stage of methanol oxidation within the temperature ranging 300 - 700 °C may be OH and HO_2 [4,5]. For example, the maximum reduction of 75 % over is reached at $\emptyset_{AF} = 1.2$ with TDC operation. Moreover, this operating condition gives the maximum emission of HCHO in this study as shown in Figure 4. Even if the oxygen concentration is a low of 0.8 % at $\emptyset_{AF} = 0.8$, reduction in UBM is over 40 %.

Relation between HCHO and UBM

Figure 11 shows a relation between HCHO concetration at a distance of 75 mm from the exhaust port and the amount of reduced UBM due to the oxidation occuring between the port and the distance of 75 mm along the exhaust tube.

The resulting amount of oxidation is proportional to the HCHO concentration for each air-fuel equivalence ratio, except the case of $\emptyset_{AF} = 0.8$. It is noticed that the figure gives a g correlation even at engine operation with $\emptyset_{AF} = 1.4$ and ignitio timing of TDC. As described in Figure 4, HCHO emission for a retarded ignition timing has the highest value at about $\phi_{AF}=1.2$, and for a leaner mixture after this ϕ_{AF} tends to decrease. This phenomenon can be explained by a decrease in the initial oxidation of UBM due to a low flame temperature in cylinder and a reduced radical concentration

Therefore, the results imply that the exhaust gas temperture, the initial UBM concentration and also radical concentration become variations determining the amount of UBM oxidation.

In a sense, HCHO emission should be understandable as an intermediate product in the oxidation of UBM during a residence time of exhaust stream in an exhaust system. However, in the case of the rich mixture, $\phi_{AF} = 0.8$, neither UBM concentration nor UBM oxidation rate depends on HCHO emission characteristics. Then, it is assumed that there are some different mechanism in the formation of HCHO for a richer mixture. Consequently, HCHO emission characteristics in an exhaust tube must be considered as follows;

1) the region in which HCHO decreases and a rapid oxidation occurs.
2) the region in which HCHO accumulation occurs.

The boundary between the two regions gives the lowest HCHO concentration in the exhaust streams. In this boundary, the temperature of the gases are roughly 500 °C in those experiments.

HCHO Formation from an Exhaust Gases in a Reactor Tube

The effect of the gas temperature of the HCHO formation was also examined by using a reactor tube through which a part of exhaust gas was passed. For this purpose, an electrically heated quartz tube, length of 800 mm and diameter of 6 mm, was employed as a reactor tube. It was connected to the gas sampling hole at $\ell = 75$ mm. When the rate of sampled gas was of 1.5 l/min, then the residence time in the reactor was about 1.1 seconds. The experiments were carried out in a temperature range of 200-600 °C.

Figure 12 shows the effect of reactor temperature on the concentrations of HCHO for varied air-fuel equivalence ratios. It appears that the concentrations of HCHO change with reactor temperature. The concentrations remain the same in the temperature range of 150- 350 °C, but, after 400 °C it increases rapidly and reaches the highest value at about 500 °C, and then the concentrations decrease with increasing reactor temperature. The resulting phenomena indicate a good agreement with the behavior of HCHO characteristics in the exhaust pipe. In the temperature range of 400-500 °C, HCHO accumulation takes place in exhaust stream, in a higher temperature of over 500 °C, HCHO decrease because of a fast oxidation of HCHO.

CONCLUSIONS

The results derived in this study may be summarized as follows;

1) A second order derivative ultraviolet spectrometry was applied to a rapid and continuous analysis of HCHO emission.

Reliable determination of HCHO concentration is achieved by selection a 284 nm derivative band for an exhaust from a methanol fueled engine.

2) From the results obtained at a distance of 75 mm from the engine exhaust port, typical characteristics are described; in rich mixture, HCHO varies little with air-fuel equivalence and also with spark timing advance, and ranges 50 ppm or lower. For stoichiometric and fuel lean mixture with advanced timings, HCHO increases steadily with increasing air-fuel equivalence ratio. However, with retarded timing such as TDC, HCHO increases rapidly and decreases with higher air-fuel equivalence with a maximum emission of about 180 ppm. If the engine is operated at MBT conditions, HCHO emission increases with increasing oxygen concentration in exhaust gases.

3) HCHO concentrations vary in exhaust tube during exhaust movement. It decreases a little after the engine exhaust port, and then, increases with a minimum concentration. This is remarkable in leaner mixture, for example, the HCHO concentration becomes 1.7 times the initial levels. In a test using a reactor tube, HCHO increases in temperatures ranging 400-500 °C and decreases at over this range. Consequently, it is obvious that HCHO is formed by the oxidation of the unburned methanol and accumulated in the exhaust stream.

4) Therefore, HCHO formation and oxidation already begins in the cylinder or in the exhaust port, and then, formaldehyde accumulation is accelerated by the oxidation of unburned methanol at about 500 °C in the exhaust system. Consequently, the characteristics of HCHO emission is very different from that of unburned methanol emission.

5) Dominant oxidation of unburned methanol is obtained at a temperature about or above 400 °C. An amount of unburned methanol oxidation is proportional to the HCHO concentration in lean mixture including stoichiometric. But, in rich mixture, we can not find a correlation between HCHO and unburned methanol emission.

ACKNOWLEDGEMENT

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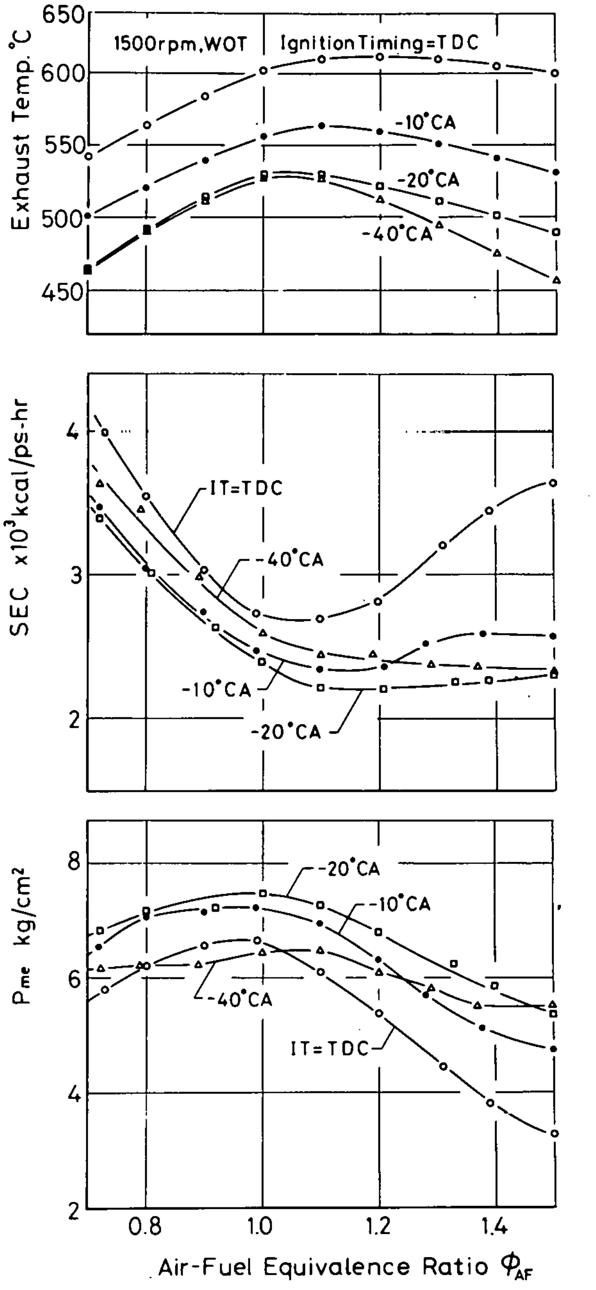


Figure 1. engine performance; brake mean effective pressure, specific energy consumption and exhaust gas temperature versus air-fuel equivalence ratio. -methanol fueled operation-

Table 1. The Specification of Test Engine

engine type	4 cycle OHV
chamber type	wedge type
bore/stroke	74mm/75mm
compression ratio	8.71
carburetor	sigle barrel
max. Pme*	8.5kg/cm^2/2000rpm
max. power*	12.0PS/5500rpm

*gasoline fueled operation

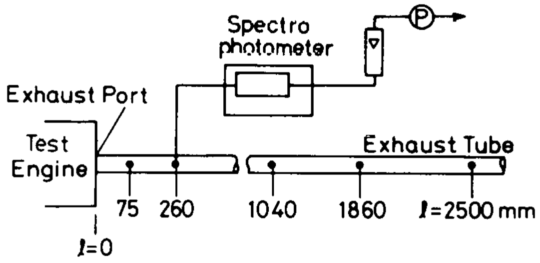


Figure 2. exhaust tubing and locations of sampling holes

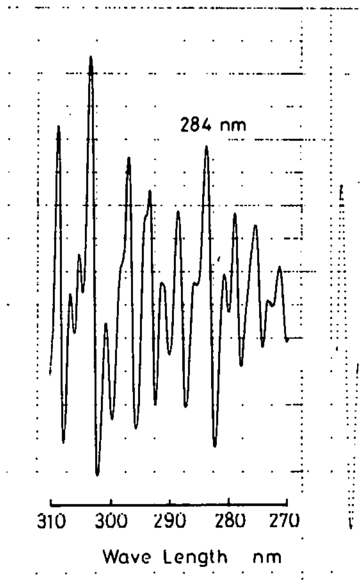


Figure 3. typical second order derivative spectrum ranging 270-310 nm

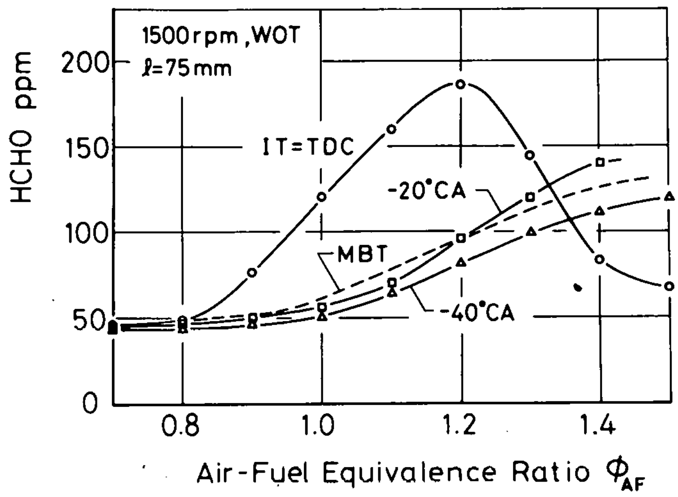


Figure 4. HCHO emission characteristics near exhaust port, l = 75 mm.

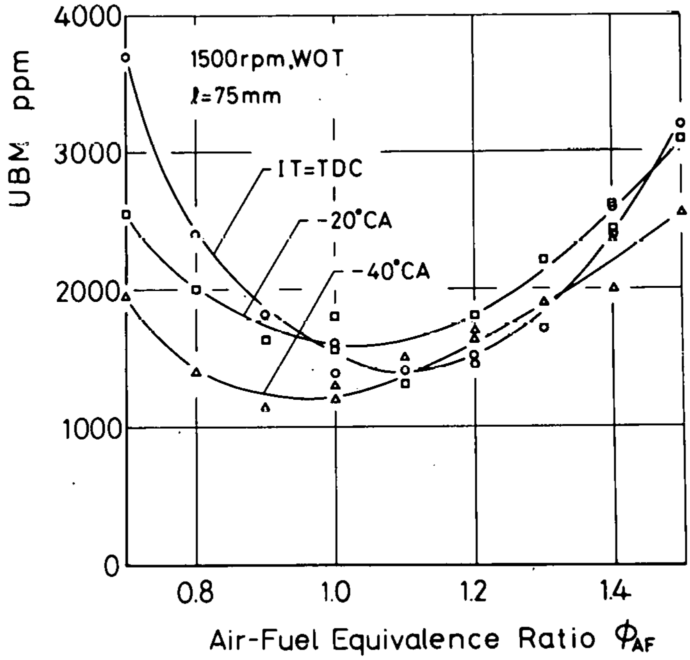


Figure 5. unburnd methanol emission characteristics near exhaust port, l = 75 mm.

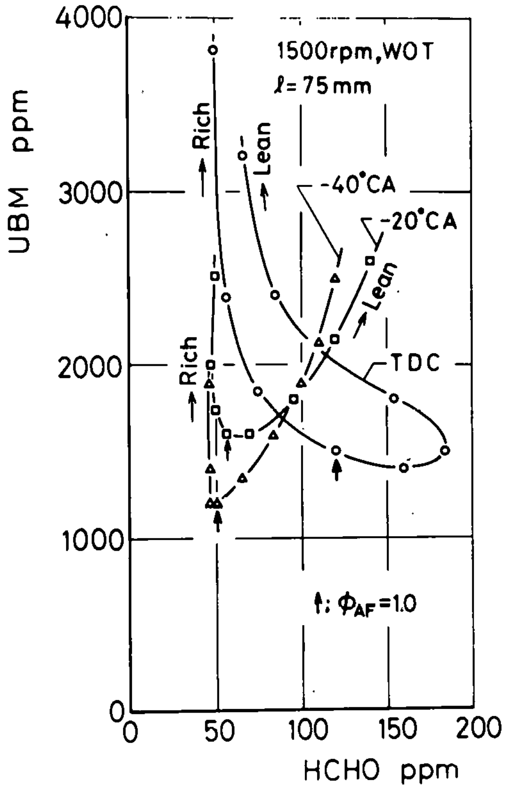


Figure 6. effects of unburnd methanol on HCHO emission

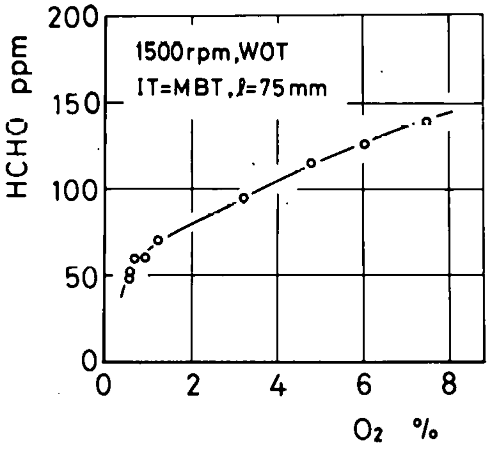


Figure 7. effects of oxygen concentration on HCHO emission at MBT operation

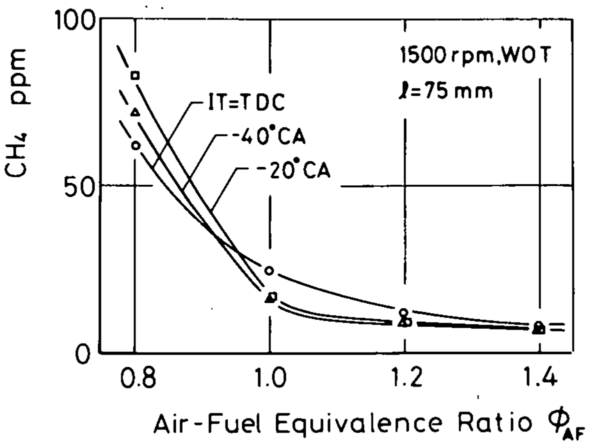


Figure 8. CH_4 emission versus air-fuel equivalence ratio

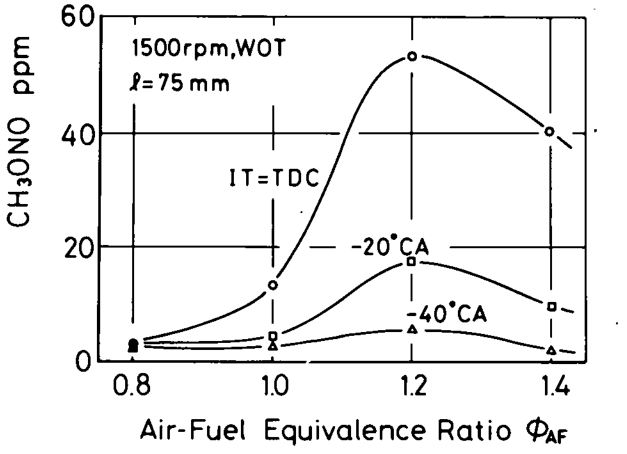
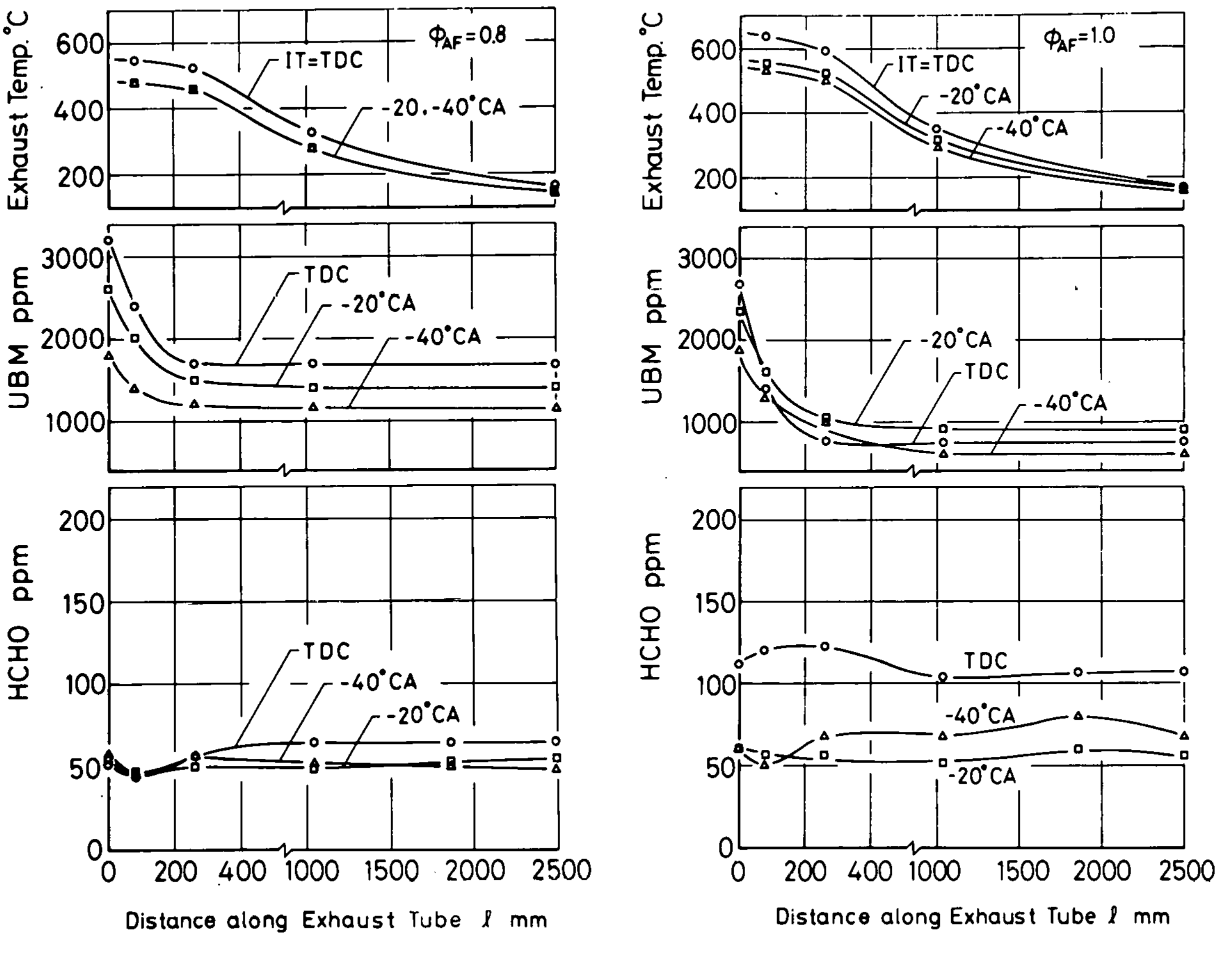


Figure 9. methyl-nitrite emission versus air-fuel equivalence ratio



(A) $\varnothing_{AF} = 0.8$ (B) $\varnothing_{AF} = 1.0$

Figure 10. emission characteristics along the exhaust tube for air-fuel equivalence ratio and ignition timing

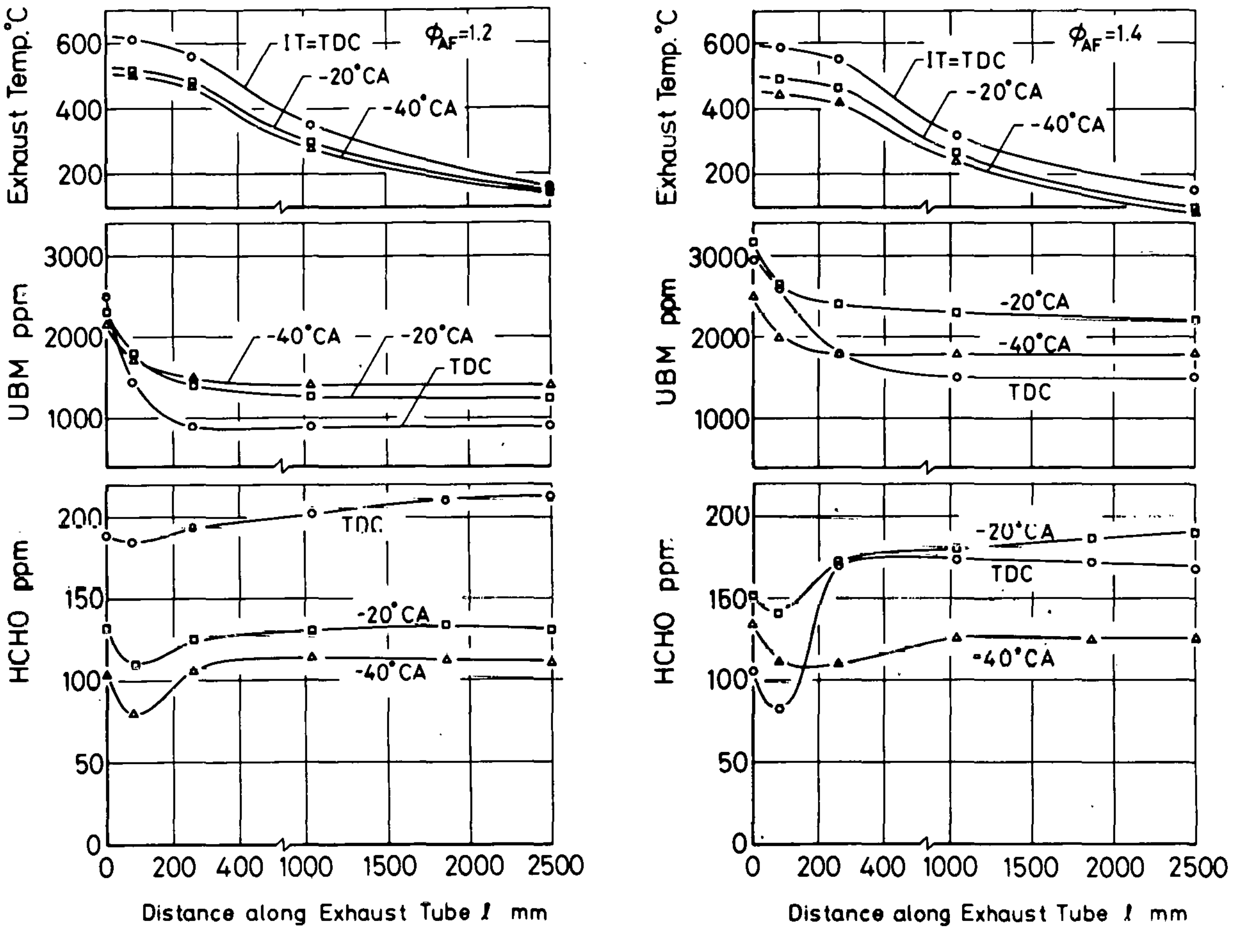


Figure 10. (C) $\phi_{AF} = 1.2$ (D) $\phi_{AF} = 1.4$

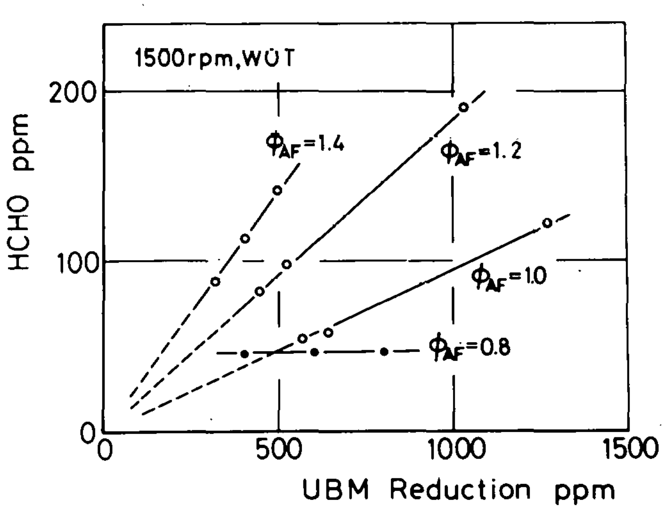


Figure 11. relation between HCHO emission at ℓ =75 mm and unburnd methanol reduction near exhaust port (ℓ = 0 - 75 mm)

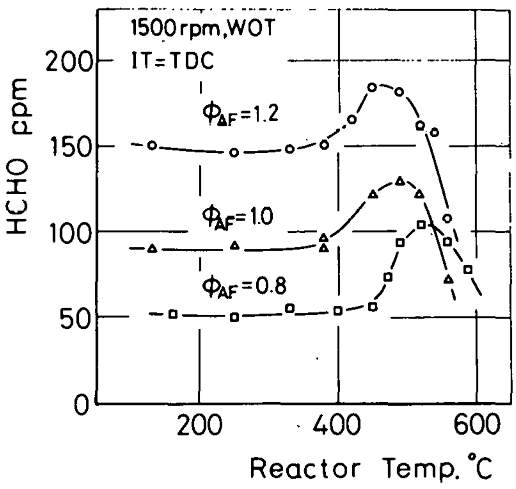


Figure 12. effects of reactor temperature on HCHO concentration for varied exhaust gases

METHANOL CONTAINING FUELS - EVALUTATION OF ENVIRONMENTAL AND HEALTH CONSTRAINTS

by

Britt Marie Bertilsson
Swedish Methanol Development Co, Sweden

INTRODUCTION

All production and utilization of energy carriers involve a certain risk to the human safety and health and to the environment. Prior to the introduction of a new energy carrier a risk assessment should be made.

Risk is the term for unpredictable events that will cause undesirable effects such as a traffic accident may result in injury or death. A risk as well as the actual accident also means different things to different people. An air plane crash with hundreds of people being killed has a greater impact on the public than the annual figure on the road toll, though the latter is much higher. Risk, as the word is normally used today, does not imply an absolute value but a subjective appraisal.

As long as there are no reliable tools available to help estimating what human injuries and deaths, polluted air and water will mean in dollars and cents, it is a question of working with acceptable levels of risk as defined by regulations and public opinion represented by the politicians.

Methanol, introduced as an alternate fuel for the transportation sector, will affect each part of the system: feedstock supply, fuel production, transportation, distribution,handling, consumption and eventually emission of combustion products. (Figure 1) When comparing fuels for the near future it is necessary to make an overall assessment of environmental and health implications. Every step in figure 1 will involve indisputable risks for man and his environment. The risk must be assessed, preventive measures to lower the risk identified, and cost estimated. Thereafter, considering the cost and the risk society is willing to take for the advantage of having the possibility to use a synthetic fuel, a decision can be made.

When discussing current fuels used in the transportation sector it is generally agreed that automobile exhaust emission is a great threat to society causing lung cancer, chronical bronchitis and other respiratory diseases, allergies, leadpoisoning etc. An alternative to gasoline and diesel oil should preferably improve the situation with respect to air pollution. It is essential not to solve one problem creating another. A duction of the present automobile exhaust emissions must not lead to increased air pollution or other adverse effects when producing or distributing a novel fuel.

To evaluate the system raw material - exhaust emissions shown in figure 1 the impact of each step must be considered. The choice of feedstock will determine the kind of ecological interference as well as occupational health risk that must be studied. Production of methanol involves occupational risk, solid waste handling and discharge to water and atmosphere. Produced methanol is transported by pipe-line, tanker, railway etc and potential accidents may result in large spills.

Depending on the storage technique, this will result in evaporation of methanol. Distribution of the fuel involves minor spills and possible accidents. The consumer may use methanol not only as a fuel but for other purposes creating yet another risk. The combustion in an automobile produces harmful exhaust emissions.

How safe is methanol as a fuel? Only an overall assessment of the risk to human health and environment can answer the question. The calculations should proceed from the feedstock to the exhaust emissions. This paper will highlight a few areas along this route that need attention.

EXHAUST EMISSIONS

The highly desirable, complete combustion of diesel oil and gasoline would give only carbon dioxide and water in the exhaust gas. In reality the combustion is not that perfect and alcohols cannot be expected to be totally different. Unburnt fuel, partially oxidized fuel, carbon monoxide and nitrogen oxides will also result from the burning of alcohols. Published data indicate a broad range of results due to the many parameters varied.

In order to obtain information about the impact on exhaust emissions when replacing conventional leaded gasoline by a lead free methanol-gasoline blend, comparative emissions data were generated (1). This was necessary before a larger fleet test could be launched.

Four vehicles of 1976 model, two Volvo 244´s equipped with carburetors and two Volvo 264´s with fuel injection, were used for tests with conventional, leaded gasoline followed by tests with a methanol-gasoline blend (80% lead free gasoline, 18% methanol, 2% isobutanol). The vehicles were not equipped with catalytic converters. No attempt was made to reoptimize the engines for best utilization of the methanol. When running on gasoline the vehicles were adjusted according to the manufacturer´s specifications. When running on methanol-gasoline blend the carbon monoxide content at idling was adjusted to the same as requested for gasoline in order to compensate for the leaning out effect when using a methanol blend. For the fuel injection system and carburetor used, the compensation is more noticeable at idling and low speed than at high speed.

The same simple adjustment has been done in vehicles used in the fleet test for long time testing of the methanol-gasoline blend.

The emission tests were made on a chassis dynamometer according to the 1975 Federal Emission Test Procedure, also the European Test Procedure. Carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and fuel consumption were measured. In addition, total aldehydes, formaldehyde and polynuclear aromatic hydrocarbons (PAH) were analysed. Table 1 shows the mean values from the four vehicles tested with the two fuels.

The following conclusions were derived from the study of the four Volvo cars where a methanol-gasoline blend was substitued for a standard gasoline:

- CO, HC and NO_x tend to slightly decrease (provided that the carburetor and fuel injection system are carefully maintained).
- Total aldehydes increase, formaldehyde being responsible for most of the increase.
- PAH emissions are about the same, no significant difference could be detected.
- Fuel consumption on an energy basis is the same.

In addition tests were made with one Volvo 244, 1977 year model, equipped with fuel injection. Exhaust emissions were measured at constant load (40 and 80 km/h). The same fuels as in the test described above were used. The exhaust emission system was changed prior to change of fuel and subsequent test. To obtain equilibrium as regard to soot deposits the vehicle was driven 60 km before testing.

The emission of PAH was found to be lower for the methanol-gasoline blend compared to gasoline (2). Also the emission of CO was significantly lower, which is to be expected with the vehicle used as there was little compensation at high speed for the leaning out effect caused by methanol.

It has been reported that there is a positive correlation between the emissions of CO and PAH. In an attempt to verify this correlation the amount of CO emitted when using gasoline at 80 km/h was reduced (driveability at low speed was not investigated). Lowered CO gave a decrease in PAH emissions.

Unburnt methanol was analysed at constant load. Sampling was made by means of evacuated glass ampoules. The amount of emitted methanol was 2-3% of the amount of hydrocarbons in the exhaust gas at constant load. The percentage of methanol was higher at idling.

To evaluate the impact of a new fuel it will not be sufficient to investigate the exhaust emissions only with respect to the components regulated today. The amount of carbon monoxide, total hydrocarbons and nitrogen oxides will give a very limited picture of the potential hazards.

Growing concern about nitrogen containing exhaust components has called upon special analysis. Methanol and nitrogendioxide (i e nitrogen tetroxide) can react to form methylnitrite (=nitrous acid methylester), a possible precursor to N-nitroso-amines.

Samples were taken close to the exhaust pipe and after the dilution with air in the FTP 1973 test. Methylnitrite could be detected in small amounts close to the exhaust pipe, much less or none at all after dilution with air. When using an oxidative catalytic converter methylnitrite could not be detected.

It is still not clear whether methylnitrite is part of the exhaust gas or a product of the sampling technique. The chemical reaction when methylnitrite is formed is favoured by low temperature and the reaction is also reversible. The high temperature in the exhaust gas probably inhibits the formation of methylnitrite. When cooled by dilution with air the concentration of methanol and nitrogendioxide are lowered and the conditions for a reaction will be less favourable.

This is an example showing the very complex and difficult task to investigate exhaust emissions. Considering also the chemical reaction in the atmosphere outside the exhaust pipe the possibilities of a total characterization of the exhaust emissions diminish rapidly.

A methanol-gasoline blend with 20% methanol or less cannot be expected to produce exhaust emissions much different from what is produced from gasoline. For the specific conditions in Sweden where lead free gasoline will be required within five years, methanol may be used as an octane improver and thereby help eliminating lead in the exhaust gas. This will also provide the possibility of using catalytic converters.

Exhaust emissions from straight methanol are different (3).Hydrocarbons are hardly detectable which means that aromatic compounds like benzene are absent as well as olefinic hydrocarbons, the latter known to be active in smog formation. Instead there is unburnt methanol and formaldehyde to be taken care of by an oxidative catalyst. These oxygenated hydrocarbons are more easily oxidized than ordinary hydrocarbons.

The fate of methanol and formaldehyde in the atmosphere should be further investigated. Methanol is not supposed to be very active in photochemical reactions forming smog.Formaldehyde in duces the photochemical oxidation of nitrogenoxide to nitrogen dioxide being as potent as olefinic hydrocarbons(4).According to the same reference formaldhyde does not give rise to the amount of oxidants as originates from higher aldehydes and hydrocarbons. This indicates that the combustion of methanol instead of gasoline would not increase the premises for photochemical smog. Other reactions should, however, be investigated.

A methanol-gasoline blend may be used together with catalytic converters of latest design. It has been shown that blends containing up to 20% methanol provide excellent vehicle operation and low HC, CO and NO_X exhaust emissions using a three-way conversion (TWC) catalyst system with exhaust oxygen sensor (lambda sond) (4). The control system also automatically compensates for a variation in the amount of methanol added to the gasoline.

To evaluate the impact on human health when replacing gasoline with methanol or a methanol-gasoline blend it will be necessary to use biological testing in addition to analytical chemistry. This is something that will be required in the near future for current fuels, gasoline and diesel oil, and should be done with proposed alternatives as well.

There is a controversy about the biological test systems available: the outcome of the testing and its extrapolation to humans. The testing is time-consuming and expensive. Even short term tests like the well known one using bacteria, invented by Bruce Ames, are costly. When working with automobile exhaust emissions, a mixture of hundreds of chemical substances from gasoline combustion and less from straight methanol, the sampling technique will prove extremely important. Hence it would be most wellcome if the same procedures for sampling and testing could be used to permit comparison.

HANDLING AND CONSUMPTION

Methanol intoxications are not unusual. The accidents are in most cases caused by intentional ingestion, methanol being mistaken for ethanol. Methanol is not labeled "poison" but "dangerous" in Sweden. Accidents have occured mainly due to the misuse of windscreen washer fluids and carburetor de-icing fluids. Fluids based on either methanol or ethanol could be found on the market. Measures were considered necessary and a regulation was enforced in 1978. Methanol containing fluids of the kind mentioned above are not to be sold unless containing 95% ethanol or more. This regulation does not affect the use of methanol as a fuel.

Still methanol implies a hazard to the public. It is necessary to clearly distinguish between ethanol and methanol. To call em both alcohol will cause confusion and should be avoided public.

Methanol and ethanol blends with gasoline would never be considered potable. There is, however, a possibility of having the methanol or ethanol separated from the gasoline by adding water. The upper phase will contain most of the gasoline and the bottom water phase will contain methanol or ethanol and small quantities of aromatic hydrocarbons. Aromatic hydrocarbons are more water soluble than paraffinic hydrocarbons and will to some extent dissolve in an alcohol-water mixture.

Table 2 shows the composition of the methanol-water and ethanol-water phases depending on the amount of water used for the phase separation. Benzene, toluen and xylene have been quantified. When separating an ethanol or a methanol blend (80% gasoline containing 50% aromatics, 18% alcohol, 2% isobutanol) with a small amount of water the alcohol-water phase will also contain benzene and other aromatic hydrocarbons.

The presence of isobutanol gives the alcohol-water mixture an unpleasant smell and also improves the solubility of hydrocarbons. The absence of isobutanol in the fuel will probably reduce the amount of hydrocarbons in the alcohol-water phase and the latter would become more attractive despite the content of benzene and other aromatics. An ethanol-water mix containing benzene and other hydrocarbons might be consumed without immediately resulting in acute toxic effects like a methanol-water mix would.

The fact that an alcohol-gasoline blend can be intentionally phase separated is worth attention particularly in societies where ethanol containg fluids are abused.

It is considered necessary to add denaturating agents when using straight ethanol as a fuel. Also methanol, when used neat, should contain suitable denaturants and/or emetics to avoid fatal mistakes.

Physical properties of methanol-gasoline blends relevant for estimating risks when handling should be determined. Below three physical data relevant to fire hazards and explosion are shown. The data were determined experimentally for a methanol-gasoline blend (15% methanol, 2% isobutanol, 83% gasoline containing 50-55% aromatic hydrocarbons, balance paraffins).

Flash Point		$< -50^{\circ}C$
Auto Ignition Temp		$475^{\circ}C$
Flammability Limits,	lower	3% weight
	higher	23% "

The flash point is about the same as for ordinary gasoline. The auto ignition temperature is increased from $\sim 250^{\circ}C$ for gasoline to $475^{\circ}C$, which is the same as for straight methanol. The flammability limits for the blend are also very much influenced by the methanol content. No standard procedure for determining flammability limits exists which makes comparison with published figures for methanol and gasoline difficult.

STORAGE AND DISTRIBUTION

The path from the production plant to the filling station involves transportation and storage at depots. There is always a possibility of contaminating the environment by small chronic spills or larger ones as a consequence of an accident. There is an occupational health risk and the public may be in danger in case of larger accidents.

The situation is essentially the same as for gasoline and diesel oil. The difference is that the knowledge about current motor fuels is well established and many data empirically found.

The pattern for transportation and storage of motor fuels might be changed if methanol is introduced as production plants not necessarily will coincide geographically with refineries.

Due to the lower energy content of methanol compared to gasoline higher volumes of methanol will be transported and stored. This fact could mean an increased frequency of accidents where alcohol fuels are involved, however, the increase may not be very significant as these accidents are fairly rare. It is still not certain which is the most fatal: a damaged truck carrying gasoline or methanol. The same question should be asked with respect to a wrecked tanker in the sea. The consequences of a wrecked methanol tanker should be evaluated. Methanol leaked from a tanker will "disappear" by means of two mechanisms: evaporation of methanol to the atmosphere and the dissolving of methanol in the sea water. One may anticipate that the methanol would easily dissolve in the sea due to its complete miscibility with water but the evaporation should not be neglected. This will be studied more in detail.

It has been shown that organisms in tidal waters tolerate methanol much better than gasoline under the same conditions (5). The Baltic, an inland sea with brackish water, is very sensitive to spills. Two organisms common in the Baltic, one crustacean (Nitocra spinipes) and one fish (Alburnus alburnus), were exposed to methanol, ethanol, butanol and heptanol (6). Methanol was well tolerated by the fish (LC 50 >26,000 ppm, 96 h exposure) and also by the crustacean (LC 50 12,000 ppm). The tolerance for alcohols decreases with increased hydrocarbon chain of the alcohol, i.e tolerance diminish in the order methanol, ethanol, butanol, heptanol. The fact that methanol is less toxic to these organisms than ethanol, while the contrary is true for humans, is probably due to the utilization of another metabolic pathway.

Fuel spills occuring at depots when unloading tankers and loading trucks have to be taken care of. Tankers are requested to leave their ballast water for treatment before loading at the depot. Sewage water at depots is normally treated in purification units where water and oil (hydrocarbons) are gravimetrically separated. This procedure does not work with a methanol-water or ethanol-water mixture. A sewage treatment plant can normally handle methanol better than hydrocarbons. Plants using a biological step in the treatment will tolerate methanol fairly well provided the quantities are small.

Unless the methanol concentration of the water is negligeable before discharge into the recipient it will be necessary to develop other procedures for the treatment of sewage water and ballast water when dealing with methanol at depots.

The use of water permeable "molecular sieves" or other new technology might be used for purification if cost is not deterrent.

PRODUCTION

The risk of fuel production should be assessed. This relates to feedstock supply and production process. Conscivably, all organic materials can be used for the production of methanol. Natural gas, residual oil, coal, shale, peat and biomass are considered feasible as raw materials. Depending on the choice of feedstock the occupational risk will vary considerably.

No work has been done on the estimation of risk for feedstock supply and production of liquid fuels where different feedstocks have been compared. The interest is most often focused on the production of one unit electric energy from nuclear power and alternatives. Few studies have included methanol. When methanol has been compared with other energy carriers the occupational risk has been considered high (8). In the calculations wood (timber) represents the feedstock and logging has a high rate of accidents. Other biomass would claim a lower toll.

Waste wood would need to be brought together but the trees are by then already cut and the initial risk should be attributed to another end use.

Short rotating forests, almost a bush vegetation, might be collected by means of harvesting machines, a procedure that would be much safer than traditional logging. Short rotating forests would demand heavy fertilizing which could be reduced somewhat if harvesting is done after defoliation. The ecological impact of this kind of "energy forest" has not yet been fully evaluated.

With respect to occupational risk gathering peat can be compared with biomass other than full grown trees. The ecological consequences are not fully known and will depend on how fast the peat is extracted.

The mining of coal is considered one of the more dangerous industrial occupations with well known risks. Risks with oil and natural gas are familiar and much lower. It is, however, not likely that oil and gas will be so extensively used in the near future as in the recent past.

Independent of feedstock the methanol production process will be virtually the same involving gasification of feedstock to synthesis gas and the following methanol synthesis. The methods for preparation of raw material will vary somewhat with respect to feedstock. The emissions from the production plant will depend on the composition of the feedstock.

Synthesis gas is carbon monoxide and hydrogen but will also contain impurities like carbon dioxide, methane and other hydrocarbons, sulfur compounds and heavy metals. Ash formed during gasification will have to be deposited. When purifying the synthesis gas sulfur dioxide and hydrogen sulfide will be released and can be converted to sulfur with known technique. Other impurities will be separated as sludge.

The ash and the sludge may have to be treated to avoid excessive leaching of harmful components when deposited. Reliable technique for deposition is not yet fully developed.

The occupational risk at a methanol plant can be compared with that for a refinery.

CONCLUSIONS

Methanol production from various raw materials involves known and surmountable problems. Ecological effects of "energy forests" and heavy peat extraction should be studied further. Reliable depositing technique for ash and sludge needs to be developed.

Transportation of methanol will pose few specific problems. Effects of large spills should be evaluated to give authorities information how to prevent and cope with accidents.

Introduction of methanol as a fuel should be accompanied by massive information to the public about the hazards. Methanol must not be confused with ethanol.

Based on available information methanol may be used straight or blended with gasoline in automobiles, also with catalytic converters, without deterioration of the air quality. However, the exhaust emissions from methanol, blends or gasoline are far from being completely characterized. Additional analytical work should be done together with biological testing of the exhaust emissions. The fate of unburnt methanol and formaldehyde in the atmosphere should be further studied.

Acknowledgement

Exhaust emission tests have been carried out in a joint project with Karl-Erik Egebäck, Vehicle Exhaust Gas Laboratory, the Swedish Environment Protection Board. Ulf Stenberg, Department of Analytical Chemistry, University of Stockholm, Arrhenius laboratory, has done the analytical work on PAH. Sven Berg and Anders Jonsson of the same department performed the analyses of methanol and methyl nitrite.

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Figure 1 THE PATH FEEDSTOCK - FUEL CONSUMPTION

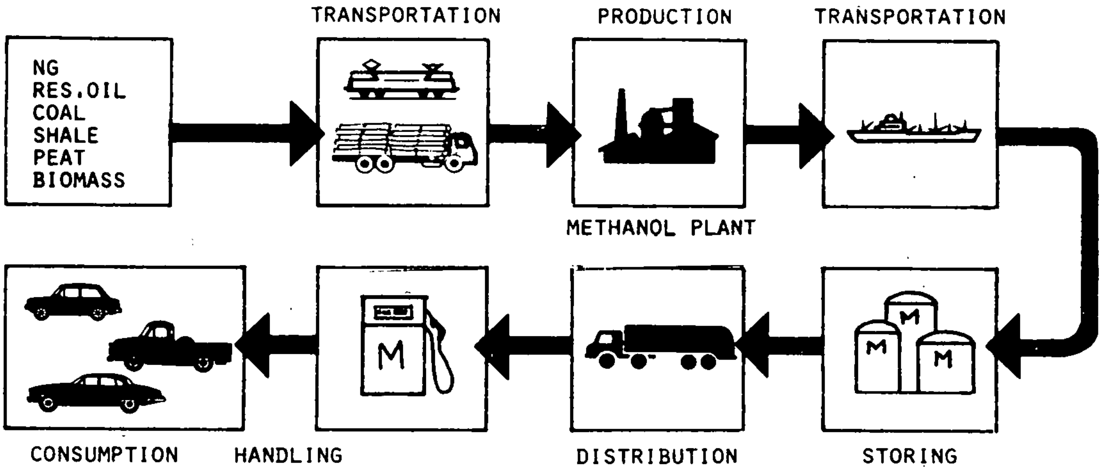

Table 1 EXHAUST EMISSIONS (g/km) WHEN COMPARING GASOLINE AND A METHANOL-GASOLINE BLEND (18% methanol, 2% isobutanol, 80% gasoline).

Four Volvo cars tested according to the Federal Test Procedure of 1973.

	Gasoline	Methanol Blend
Carbon monoxide, CO	15,8	12,8
Hydrocarbons, HC	1.8	1.6
Nitrogen oxides, NO_x	1,6	1.5
Aldehydes, R-CHO	~0,04	~0,05
Methanol, CH_3OH	0,001^{x}	0,016^{x}
Polynuclear aromatic hydrocarbons, PAH	0.0002-0,0005	0,0002-0,0005

^{x} Weighted average (20% idling, 70% 40 km·h^{-1}, 10% 80 km·h^{-1}) from test with constant loads. This figure would be 2-3 times higher measured over a FTP driving cycle if corresponding to the emissions of hydrocarbons.

Table 2 AROMATIC HYDROCARBONS IN THE ALCOHOL-WATER PHASE OCCURING WHEN BLENDS ARE CAUSED TO PHASE SEPARATE

100 ml blend +water added, ml	Water phase, ml	Content of water phase, mg·ml^{-1}					
		Methanol	Ethanol	Isobutanol	Benzene	Toluene	Xylene
E + 2	7	-	524	58	22	53	58
E + 10	24	-	430	30	3,8	7,4	6,0
M + 1	16	497	-	67	26	63	76
M + 10	27	460	-	38	2,8	4,7	2,6

E = 80% gasoline, 18% ethanol, 2% isobutanol
M = 80% gasoline, 18% methanol, 2% isobutanol

Environmental Consequences of Methanol Spills and Methanol Fuel Emissions on Terrestrial and Freshwater Organisms

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Abstract- Organismic responses, habitat degradation, and community-population consequences of methanol and methanol emissions contamination are variable, and in many cases, reversible. Few soil or freshwater organisms can tolerate chronic exposure to 500 PPM of this fuel. Organismic responses include disrupted gametogenesis, desynchrony of biological clocks, disorientation, neuromotor changes, breakdown of adhesive and respiratory surfaces, pheromone degredation, narcosis, and other physiological disorders. However, many organisms show reversible effects at low chronic exposures. In addition, short term pulse, acute exposures are tolerated by many components of the macrobiota. Some soil and aquatic organisms are tolerant to acute exposures to methanol at the 1-10%-vol level for several hours under ambient conditions. Tolerance limits for formaldehyde emissions in chronic exposure are in the range of 100-500 PPM for all but a few species of plants, animals, algae, and microorganisms. Tolerance is related to several factors, including life stage, previous exposure, resistant stage formation, and others. A preliminary evaluation of emissions effects of both aldehydes and unburned fuels on important soil and flying arthropods shows variable tolerance levels. Radioisotope tracing of food-web dynamic exchange, individual metabolism, and residence time show many eutrophic soil and aquatic organisms to be very tolerant to methanol contamination. Normal levels of alcohols and their metabolites in these habitats may contribute to this relative tolerance. Soil community succession rates and species diversity steps in natural recovery from fuel exposure are correlated with interrelated physical, chemical, and biological factors. Preliminary analyses of potential mechanical, chemical, and biological modes of clean-up for methanol-disrupted habitats are favorable. Cost comparisons of methanol versus existing fuels for some soil and water recovery operations are available for some situations. Potential movements of stored or spilled methanol into soil, sub-soil aquifers, and surface waters is assessed.

Biological and environmental consequences of methanol fuels in freshwater and terrestrial habitats are both variable and significant. While the disruptions and recovery of marine ecosystems is dependent in large part upon sessil, canopy-forming organisms (1,2,3), interactions with methanol in freshwater-terrestrial systems is more dependent on alterations of cyclic and seasonal community dynamics. Controlled spills and monitoring in field and laboratory situations indicate wide ranges of organismic tolerance, and differential succession community recovery. In addition, laboratory assessment of methanol exhaust toxicology demonstrated variable ranges of tolerance for soil and flying arthropods.

Freshwater

Methanol impacts on both lotic and lentic aquatic systems are correlated with several physical and biological factors. While tolerances vary among organisms (Table 1) the potential disruptions of populations or communities depend on amount and duration of spill, water volume and flow-rate, temperature, oxygen tension, seasonality or temporality of affected species, and the life stage of organisms with larvae, resistent spores, or motile instars. While few freshwater organisms can tolerate long-term exposure to even 500 PPM methanol, many can survive acute exposures of 1% vol. Some adult crustacea may even tolerate 10% for several hours. In general, aquatic insect larvae are subject to narcosis at concentrations as low as .5%. In particular, lotic fish prey species of Odonata, Plecoptera, Ephemeroptera, and Diptera are killed at 1% concentrations at ambient temperatures. However, recolonization of experimental spill sites involving these larvae is very rapid. Apparently, the rapid dispersal and dilution of the alcohol in moving water systems allows reoccupation of disrupted habitats through immigration from upstream populations. Insect larvae exposed to, but not killed by alcohol generally recover from the narcotic effects in several hours. However, behavioral disputions during this recover period, including disorientation, phototactic and thigmotactic reversals, and color changes make them more vulnerable to predators and physical disruptions.

Terrestrial - Direct Exposure

Macro- and microbiota components in soil exposure experiments have wide ranges of tolerance in methanol. Soft bodied organisms such as oligochaete and enchytraeid worms, nematodes, and soil protoza are quickly eliminated in surface saturation experiments. Arthropod populations dependent on surface canopy vegetation are also drastically reduced, as grasses, masses and other plants are killed by surface saturation of methanol. However, arthropods at lower soil depths, or that are very mobile in the soil are not as affected (Table II). Monitored plots of soil surface saturation spills in oak forest habitats indicate rapid recolonization of surface horizons. Animal populations below 20 cm in these plots were little affected by saturation spil

In addition, fungal and bacterial populations show great tolerance a recolonization of surface horizons exposed to methanol. Preliminary data ow about 60% of initial fungal activity recovers in horizons 10-30 cm deep one week after surface saturation. 90% recovery is noted in similar plots and depths three weeks after saturation. Bacterial activity at 10-30 cm horizons is 85% of initial after three weeks. The rapid recovery or recolonization of these important agents of nutrient cycling is probably due to the very resistant spores and resistant stages produced by many species. Surface nitrates in experimental plots were nearly stable, also indicating the rapid recovery of the microfauna. Laboratory assessment of lateral and verticle movement of methanol in soil shows both rapid initial penetration and degredation of C^{14} labeled spills. In oak forest soils penetration and movement is limited to the immediate spill area. Methotrophic soil bacteria become labeled in a few hours at the perimeter of such tracer sites.

Emissions

Preliminary evaluation of the toxicity of some methanol-automobile emissions shows minimal organismic effects of the major exhaust components. Flow chamber experiments indicate little disruption of plant or animal physiology at anticipated levels of formaldehyde and methanol. Reversible narcosis occurs in many flying insect species at 500 PPM methanol or 100 PPM formaldehyde for 1 hr exposures. The LD50 for several adult Lepidoptera and Hymenoptera is 850-1000 PPM formaldehyde for 1 hr exposure. These important pollinators may be adversely affected by methanol exhaust components under chronic or massive exposure, but further work is needed to determine the extent of direct and indirect disruptions.

Summary

The consequences of terrestrial and aquatic spills of methanol appear to be minimal and of short duration. Recolonization of disrupted habitats is rapid in both soils and freshwater. While further assessment is needed, the direct effects of some methanol emission components on plant and arthropod populations are temporary and occur only at concentrations above anticipated levels.

TABLE 1

Freshwater Organisms - Methanol Toxicology

ORGANISM	LD50 (15°c) (%, 3 hrs)	Disorientation, Narcosis or Color Change (at 500 PPM, 3 hrs.)		
Salmo trutta	.5	+	+	
Salmo clarkii	.5	+	+	
Salmo gairdnerii	.75	+	+	
Gambusia affinis	.75	+	+	
Pomoxis sp.	.75	+	+	
Lepomis sp.	.75	+	+	
Micropterus salmoides	.75	+	+	
Cyprinus sp.	1.0	+	+	
Pacifasticus 3 spp.	3.0 -5.0	+	+	
Procambarus sp.	3.0		+	+
Apus sp.	1.0	+	+	
Asillus sp.	.75	+	+	
Neuroptera (larva)	.5	+	+	
Plecoptera (larva)	.5	+	+	
Ephemeroptera (larva)	.5	+	+	
Odonata (larva)	.5	+	+	
Trichoptera (larva)	.5	+	+	
Diptera (larva)	.5	+	+	
Coleoptera (larva)	.5	+	+	
Coleoptera (adults)	1.5			
Spongilla 2 spp.*	1.0		+	
Sphaerium 3 spp.	3.0			
Anodonta sp	3.0			
Physa 3 spp.	1.5			
Pisiduim casertanum	2.0			
Oscillatoria sp.	1.0			
Nostoc sp.	1.0			

* choanocyte activity

TABLE II
Organismic Recolonization of Surface Saturated Soils - Methanol Toxicology

ORGANISM	% initial population loss (5% intervals)	POST EXPOSURE 1 week (% below initial)	POST EXPOSURE 3 weeks (% below initial)
Lipidoptera (larva) 5 spp.	100	100	100
Diptera (larva) 2 spp.	90	90	90
Collembola 4 spp.	100	50	5
Nematoda 4 spp.	85	30	15
Enchytraeid 2 spp.	85	25	20
Oligochaeta	90	30	10
Coleoptera (adult)	90	20	0
Coleoptera (larvae)	90	90	90
Mites 5 spp.	95	40	15
millipedes 3 spp.	70	40	10
centipedes 2 spp.	10	10	0
Orthoptera 3 spp.	100	100	100
bacteria	90	40	15
fungi	70	60	10

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ENVIRONMENTAL PLANNING AND ASSESSMENT FOR HIGHWAY VEHICLE USE OF ALCOHOL FUELS

by

Martin J. Bernard III and Oreste M. Bevilaqua*

ABSTRACT

Argonne National Laboratory (ANL) is assisting the Office of Transportation Programs (OTP) of the U.S. Department of Energy in performing the required enviromental planning and assessment for highway vehicle alcohol fuel commercialization in accordance with the National Environmental Policy Act of 1969 (NEPA). In this presentation the process for planning and assessment is given, specific documents resulting from the process are explained.

NEPA requires an environmental impact statement (EIS) for every major federal action that may have a significant impact on the quality of the human environment. The EIS is subject to public review, according to DOE's guidelines. The environmental assessment process, as described in the DOE guidelines and as implemented by OTP will result in environmentally sound demonstration and commercialization of alcohol fuels. The term environment is defined very broadly to include the ecosystem, resource, physical environment, health, safety and socioeconomic subsystems.

Three types of environmental documents record this process: the Environmental Development Plan (EDP), the Environmental Assessment (EA) and the Environmental Impact Statement (EIS). The transportation EDP describes the energy conserving technologies; identifies and ranks environmental concerns; outlines strategies to resolve the concerns on a priority basis; and proposes a research program to implement the strategies. This is done annually for the division. In addition, environmental documentation is scheduled for each technology as it reaches different stages of development. One major document is the EA, prepared when it is not clear whether an EIS is necessary. The information to make such a decision is collected in one detailed assessment of the technology or program. An EIS may then be written if impacts are expected to be significant.

An EA is being performed for alcohol (neat and blends) fuels for highway vehicles by ANL.

INTRODUCTION

This paper describes the environmental planning and assessment process used by the Department of Energy (DOE) Office of Transportation Programs (OTP) and in particular its use in the Alternative Fuels Utilization Program, the alcohol fuels for highway vehicle project. Argonne National Laboratory has had lead laboratory responsibility for this environmental process for OTP since the inception of the process in the Energy Research and Development Administration (ERDA). (An Acronyms list appears at the end of the paper to aid the reader).

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*Significant contributions to this on-going environmental work were made by numerous specialists and by the DOE project manager, Dr. Daniel P. Maxfield. Dr. Bernard is the section head of the Transportation Energy Systems Section, Energy and Environmental Systems Division, Argonne National Laboratory, U.S.A. Bevilaqua is a consultant to the section.

The DOE environmental impact evaluation process stems from the broad policies set forth in the National Environmental Policy Act of 1969 (NEPA) which states all agencies of the federal government shall:

(a) Utilize a systematic, interdisciplinary approach (natural and social sciences and environmental design arts) in planning and decision making impacting man's environment,

(b) Develop methods which will ensure environmental values are given appropriate consideration in decision making, along with economic and technical considerations, and

(c) Produce a detailed environmental impact statement (EIS) for major federal actions significantly affecting the quality of the human environment (from Sec. 102).

Specific NEPA guidance is provided by the Council on Environmental Quality (CEQ) in the form of guidelines and regulations. Table 1 summarizes the most recent CEQ rules and shows the strength of NEPA.

Table 1. Selected NEPA Rules
(CEQ, 43 CFR 55978 - 56007, Nov. 28, 1978)

A. Major Federal Action is

- Adoption of formal plans.
- Adoption of programs.
- Allocation of resources decisions.

B. Agencies shall

- Integrate the NEPA process early.
- Prepare Environmental Assessments at any time to assist in EIS decision
- Prepare EISs on major federal actions.
- Insure professional and scientific integrity of EIS.
- Request comments on EIS from federal, state, local agencies and public.
- Make diligent effort to include public.
- Adopt procedures to ensure decisions in accordance with NEPA.
- Prepare public record on decisions including environmental considerations.

C. The EIS shall

- Provide full and fair discussion of significant impacts.
- Inform decision makers and public of resonable alternatives (which should be rigorously explored and objectively evaluated).
- Be prepared on technology research, development or demonstration programs and shall be available before the program has reached a stage likely to determine subsequent development or restrict later alternatives.
- Be completed in time to be included in any recommendations or report considering one or more alternative means of accomplishing a goal.

Each federal agency has its own process for executing these rules. The DOE process is designed to incorporate environmental considerations into the day-to-day decisions on projects. For OTP, the major documents that are produced in connection with technology development projects or with alternative operating strategies or conservation policies which might require an EIS are the Environmental Development Plan (EDP), the Environmental Assessment (EA), and the Environmental Impact Statement (EIS) or, conversely, a Negative Determination (ND). Figure 1 sketches the relationship of these documents to OTP from NEPA to the commercialization or implementation of an OTP technology, strategy or policy.

ENVIRONMENTAL DEVELOPMENT PLANS*

EDPs were conceived and prepared as basic documents for planning and managing environmental requirements of energy technology development. Approximately 30 EDPs covering major developing energy technologies, including one for OTP have been prepared this year. [1]**

The OTP EDP is an annual cycle document that is developed in step with the Program Planning and Budget Review cycle of DOE. It covers all the programs and subprograms in OTP, providing concise descriptions of each technology, strategy or policy project that might require an EIS. (See Table 2). The major force of the EDP is the analysis of possible or expected environmental concerns that arise from each project and a determination of the efforts required while the project is still being developed to mitigate adverse effects.

The EDP process therefore provides a framework for:

a) Incorporating environmental considerations into OTP planning and decision processes at the earliest stages to assure they are given the same level of importance as technological, fiscal, and institutional concerns in decision-making.

b) Resolving environmental concerns concurrently with the development of energy strategies, policies and technologies, and

c) Providing a schedule of research to allow mitigation of adverse environmental effects through sound technological design or policy analysis.

Information contained in the EDP constitutes an inventory of the status of environmental problems and a plan for resolving these problems. Much of the ongoing DOE research and technology development is aimed at resolving the concerns identified in the EDP. It is, however, intended that the EDP be comprehensive so that no concerns escape notice.

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*As currently defined and required by DOE Order 5420.1, August 10, 1978, "Environmental Development Plans."

**Number in square brackets refers to reference list at the end of the paper.

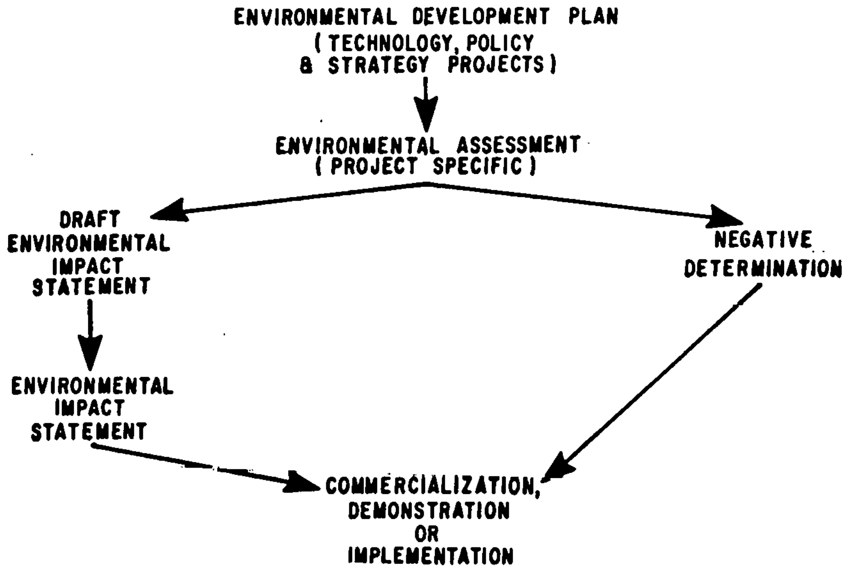

Fig. 1 The DOE NEPA Process

Table 2. OTP Technologies, Strategies and Policies Addressed in the EDP

Technology Development Program

1. Stirling Engine
2. Gas Turbine Engine
3. Turbocompound Diesel Engine
4. Gas Turbine Bus
5. Controlled Speed Accessory Drive System
6. Continuously Variable Transmission
7. Heavy Duty Diesel Truck Bottoming Cycle
8. New Hydrocarbons - Broad Cut Petroleum Fuels
9. Alcohol Fuels
10. Synthetic Fuels
11. Advanced Fuels - Hydrogen
12. Electric Vehicles
13. Hybrid Vehicles
14. Marine Diesel Bottoming Cycle
15. Coal-Oil Slurry Marine Steam Turbines
16. Pipeline Bottoming Cycle
17. Medium Speed Diesel Alternative Fuels

Strategy and Policy Program

1. Freight
2. Transport of Energy Materials
3. Intercity Passenger

Environmental Concern Identification

The first step in the EDP process is to identify and classify the environmental concerns associated with the OTP program. The classification is by environmental system and subsystem as shown in Table 3. The concern identification begins with the definition of attributes of each strategy, policy, technology or fuel that might result in an environmental impact through careful review of the technology by a multidisciplinary team. The concerns are then developed using factual information where available including the status of the understanding of the environmental effect and its control. Priorities are assigned to the concerns, primary or secondary, to identify those requiring immediate resolution.

If the concern results from issues that are characterized by lack of specific understanding to explain or estimate underlying cause/effect relationships or to adequately quantify the environmental issues, the concern is assigned primary status and exploratory research is required. If, however, the concern results from issues for which there is some understanding of the cause/effect relationship or for which the magnitude of potential impacts can be estimated, then a set of four criteria are used to determine concern status. The four criteria are: 1) the emergence of the concern impact before 1983, 2) the time required to resolve the concern via environmental assessment, research, development and demonstration, 3) the severity of the concern impact (dose-response), and 4) the size of the human population at risk. A concern is designated as primary if it meets criteria (1) or (2) and (3) or (4).

For most dose-response type impacts, the emergence date is the time of a large (several hundred vehicles) demonstration. For the others, the date is the estimated time of the implementation or commercialization. If a concern will impact a large population, or will have potentially severe effects even

Table 3. Environmental Concern Taxonomy

Environmental Systems and Subsystems

ECOSYSTEM
- Terrestrial
- Aquatic
- Human/Animal Pathways

RESOURCE
- Mineral
- Natural (Land, Water)
- Capital/Labor

PHYSICAL ENVIRONMENT
- Air Quality
- Water Quality
- Waste Disposal
- Noise Pollution
- Aesthetic Degradation

HEALTH
- Occupational
- Public

SAFETY
- Occupational
- Public

SOCIOECONOMIC
- Social
- Economic
- Institutional

on a few individuals and if the time required to resolve the concern is close to or potentially longer than the time of emergence of the concern, it is designated primary. If a concern is not exploratory and does not meet the other criteria, it is designated a secondary concern.

Before an environmental research and assessment plan can be developed, the status of the understanding of any adverse environmental concerns must be identified. The lowest level of research and assessment (level 0) is concern identification with essentially no understanding of the concern. The highest level (level IV) results in concern resolution. Depending on the results of a given level, the primary concern for which understanding and resolution is sought may 1) at some time in the future be discarded because the impact was found to be negligible or 2) require further research and assessment, usually at the next level. Before a technology or fuel is commercialized or a strategy or policy implemented, level IV (problem resolution) must be accomplished for each primary concern.

Environmental Concerns and Research Requirements

Table 4 presents a summary of the primary environmental concerns and the level of understanding for each for alcohol fuels. The table also presented the type of research that is either under way or will be initiated to address the concern. This research would be used by DOE to give direction to the development program for specific technologies and projects; to determine what further environmental research is required; to assist in setting standards or designing guidelines; and to decide if the technology or project development should be discontinued. In essence the research reports provide DOE decision-makers with the status of environmental concerns and the progress towards their resolution.

The Alcohol Fuels Plan

The EDP is a plan. That plan is presented for all of OTP's activities in a series of figures similar to Fig. 2, the research and assessment plan for alternative fuels. The figure shows relevant technology development decision points and schedules EAs, EISs, and reports called Environmental Readiness Documents (ERD), the last of which are internal to DOE and used by the Assistant Secretary for the Environment to determine the environmental status of a technology. The lower portion of the figure is the research plan.

Of interest are the alcohol (blends and neat) milestones at the top of Fig. 2, the EA and EIS for alcohols scheduled in the middle of the figure, and the individual research activities scheduled in the bottom portion of the figure. Concerning the latter, the EDP states that the DOE Office of the Assistant Secretary for the Environment (ASEV) will complete an environmental effects assessment for spillage, for UBF, aromatics and aldehydes in vehicle exhaust emissions, for control of dermal absorption and interaction effects, and for evaporative emissions by October 1, 1982. Annual progress reports may define further necessary transportation system specific health effects research which would be scheduled in subsequent EDPs. Candidate control strategies will be evaluated by October 1, 1981. Since the shipping, distribution and use of alcohol as a vehicle fuel presents many safety concerns identified in the EDP, research items are planned. A near-term report on

Table 4. Alcohol Fuels Concern/Research Relationship Map

Summary Primary Concern	Level of Understanding (see note)	Standard, Guideline or Limit: Existing or Due Date	Environmental Research Required
<u>Ecosystem</u>			
Since alcohol blends may come into widespread use in the 1980's, alcohol shipping accidents may have localized adverse aquatic impacts.	II In general, short chain alcohols are toxic to aquatic organisms.	Shipping guidelines, due 1983.	Effects study. Control and alternatives study.
<u>Physical Environment</u>			
The impact of the evaporative and exhaust emissions on air quality from any combination of alternative fuels and heat engines is of concern.	I or II depending on pollutant.	New exhaust emission goals, evaporative emissions goals for use as transport fuel, due 1983 for alcohol gasoline blends.	Engine emission tests. Effects study, possibly transport and fate studies depending on R&D results.
<u>Health</u>			
Aldehydes and unburned fuel in exhaust emissions, dermal absorption. Interaction effects.	II Quite toxic. resolution may be difficult.	As above, under physical environment.	
Aromatics in exhaust emissions.	II Known carcinogen.	Exhuast emission goals due 1983.	Effects study.
<u>Safety</u>			
Flammability and explosiveness.	III Wide flammability range relative to gasoline; invisible flame.	---	Control technology, alternative design.

Note: Level of Understanding:
0 = Concern identified but no understanding of impacts or severity.
I = Initial understanding but not relevant to transportation system or environmental systems.
II = Qualitative understanding of impacts on environmental systems but not transportation system components.
III = Full understanding of the effects on all systems/subsystems.
IV = Sufficient design, control technique, modification or alternative available.

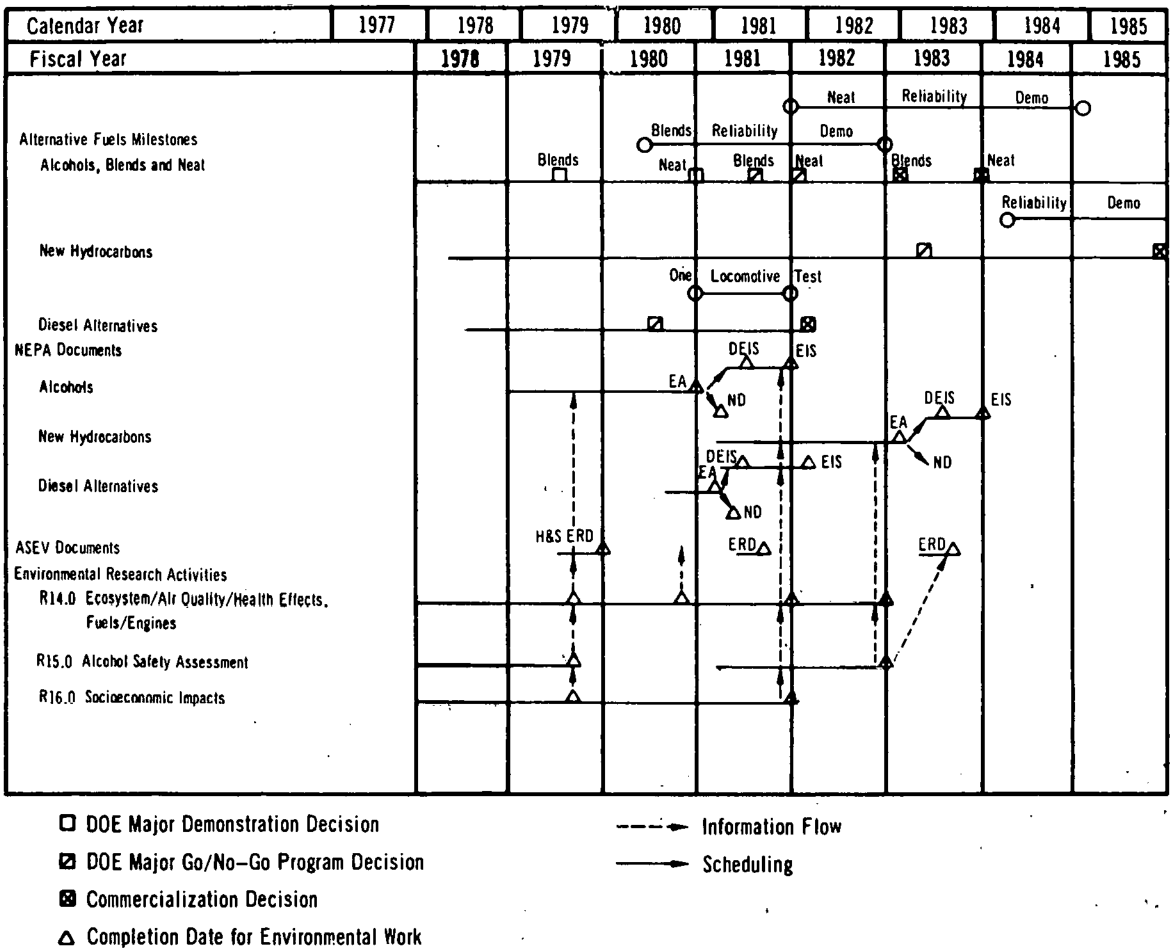

Fig. 2 Alternative Fuels Environmental Research and Assessment Plan (Source: Ref. [1], Fig. 4.5)

the state-of-the-art is scheduled to be completed by ASEV late in 1979 and a full assessment of effects and control is scheduled to assist the 1983 commercialization decision. In the area of socioeconomic impacts the EDP assigns OTP the main responsibility to assess the impacts for vehicle systems, specifically to assess the institutional and labor barriers and the economic and social impacts of commercialization. Reports are due in August 1979 and October 1981.

Environmental Assessment for DOE Alcohol Fuels Program for Small Highway Vehicles

Another product of the EDP is the scheduling of an EA for each technology before it reaches a level of usage or of development that could result in significant environmental impacts. The EA (see reference 2 for an example) is a decision document collecting all the analyses of the project or technology and the possible impacts. It is an input to the decision to write an EIS, per NEPA requirements, or to make a negative determination. If it is clear that an EIS will be required, the EA is dispensed with and the analysis is documented directly in the EIS. For the current OTP projects, EAs are scheduled first, because it is not clear what level of commercialization or implementation is most likely to occur while still at early stages of R&D. The impact of various levels can be assessed in the EA.

As Fig. 2 shows, and EA is underway for alcohol fuels for automobiles and small trucks. It is oriented toward evaluating the utilization of blends to the year 2000. The supply side for the fuels will not be investigated except at an overview level. This is not to say that the impacts of fuel production are negligable, but that the assessment of those impacts are not the topic of this EA.

Table 5 lists the tasks and subtasks of the assessment. Tasks 1 through 3 are expected to be completed this year and the remainder of the assessment by October 1, 1980.

NEPA requires the consideration of alternative federal actions. Task 1 defines those alternatives. Scenarios will be constructed for each alternative alcohol program. NEPA requires that the do nothing (no program) alternative be assessed. The scenario at the other extreme would be the total U.S. small vehicle fleet by 2000 be burning a 10% alcohol/gasoline blend. Intermediate scenarios define various methods and rates of penetration such as major rural penetrations before blends become available in large urban areas. At the time of this writing it is not clear if a scenario containing substantial neat utilization will be developed and assessed.

These scenarios are quite detailed. They combine the vehicle characteristics of task II and give vmt of each type of vehicle for each assessment year. They also define the federal government program supporting the assumed markets penetration rates while taking into account potential state, city and private alcohol fuel activities.

The assessment tasks II through VIII are based on the taxonomy of Table 3 but are defined specifically to address the expected alcohol issues as raised by the EDP. The assessment is meant to be comprehensive and the depth of the investigation for each subtask is uniform. Often sufficient information exists and a subtask is simply to put that information into a form consistent with the assessment structure. For other subtasks significant research is often necessary to increase the existing information to a level consistent with the assessment.

Environmental Impact Statements

An EIS is a NEPA-required document for major federal actions that will have a significant impact on the human environment. DOE's method of determining which actions are major and how significant the impacts may be includes the EDP/EA process described above and the judgment of the DOE Assistant Secretary for Environment. If an EIS is necessary, then the project will undergo additional public scrutiny, possibly via public hearings, and thorough examination of the draft EIS. It is possible that the project or technology or the rate of introduction of the technology could be modified as a result of the EIS. Final implementation of the project can proceed only if the EIS is acceptable.

Summary and Conclusions

This paper has reviewed the DOE environmental evaluation process designed to
ement NEPA policies and guidance. In particular it has focused on that
ess as it is being used for DOE's alcohol fuels project within the Office

Table 5. Alcohol Fuels Environmental Assessment Tasks and Subtasks

I.	ALCOHOL FUEL PROGRAM ALTERNATIVES
Task 1.1	Alternative Alcohol Fuel Utilization Scenarios
Task 1.2	Public and Private Sector Roles
II.	TECHNOLOGY CHARACTERIZATION
Task 2.1	Blend and Neat Alcohol Fuel Composition
Task 2.2	Personal and Commercial Vehicle Engine Performance Characterization
Task 2.3	Characterization of Materials Extraction, Processing and Distribution of Alcohol Fuels
III.	NATURAL RESOURCE ASSESSMENT
Task 3.1	Net Energy Analysis
Task 3.2	Raw Material Requirements and Availability
Task 3.3	Unavoidable Adverse Impacts and Offsetting Conditions
IV.	ECOSYSTEM ASSESSMENT
Task 4.1	Aquatic Systems Impact Assessment
Task 4.2	Terrestrial Systems Impact Assessment
Task 4.3	Unavoidable Adverse Impacts and Offsetting Conditions
V.	PHYSICAL ENVIRONMENT
Task 5.1	Air Quality Impact Assessment
Task 5.2	Water Quality Impact Assessment
Task 5.3	Waste Disposal Impact Assessment
Task 5.4	Noise Analysis
Task 5.5	Aesthetic Degradation
Task 5.6	Land Use
Task 5.7	Unavoidable Adverse Impacts and Offsetting Conditions
VI.	HEALTH ASSESSMENT
Task 6.1	Occupational and Public Health Impact Analysis
Task 6.2	Unavoidable Adverse Impacts and Offsetting Conditions
VII.	SAFETY ASSESSMENT
Task 7.1	Occupational and Public Safety Impact Analysis
Task 7.2	Unavoidable Adverse Impacts and Offsetting Conditions
VIII.	SOCIOECONOMIC ASSESSMENT
Task 8.1	Employment Patterns, Sills and Distribution Impact Analysis
Task 8.2	Public Institutional Impact Analysis
Task 8.3	Factor Prices Assessment
Task 8.4	User Cost Impact Analysis
Task 8.5	Capital Requirements and Return on Investment
Task 8.6	Balance of Payments Impact Analysis
Task 8.7	Mobility and Area Development Impact Analysis
Task 8.8	Transportation Sector Infrastructure Impact Analysis
Task 8.9	Unavoidable Adverse Impacts and Offsetting Conditions
IX.	RECOMMENDATIONS RELATIVE TO AN EIS
Task 9.1	Impact on the Quality of the Human Environment

of Transportation Programs. Thus far, the process is effective in addressing environmental concerns early in the development of a technology, strategy or policy and in projecting the research and assessment requirements necessary to resolve those concerns. There are, of course, some difficulties in carrying out this process; further, the real success of DOE's method for NEPA implementation will not be known until environmentally and technologically sound vehicles are available as a result of the RD&D efforts, or useful policies are implemented. Assessment efforts completed to date for the electric vehicle program have uncovered some possible impacts requiring further study to understand them and to mitigate them.

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ACRONYMS

ANL	Argonne National Laboratory
CEQ	Council on Environmental Quality
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EA	Environmental Assessment
EDP	Environmental Development Plan
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Administration
ERDA	Energy Research and Development Administration (predecessor to DOE)
ERD	Environmental Readiness Document
FY	Fiscal Year
NEPA	National Environmental Policy Act of 1969
NTIS	National Technical Information Service
OTP	Office of Transportation Programs, Assistant Secretary for Conservation and Solar Applications, DOE
RD&D	Research, Development, and Demonstration
UBF	Unburned Fuel
vmt	Vehicle Miles of Travel

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