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MODIFICATION TECHNIQUES AND PERFORMANCE CHARACTERISTICS OF HYDROGEN—POWERED IC ENGINES—STATE OF THE ART, 1975

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PREPARED BY AEROJET NUCLEAR COMPANY FOR
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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ABSTRACT

Over the past quarter of a century there has been a significant amount of work on modification of internal combustion (IC) engines to operate on hydrogen. However, comparisons are difficult because of large variation in designs, engine parameters, and test conditions. This paper presents, under a unifying format, a comparative summary of the recent work on hydrogen-powered engines. This includes material extracted from published reports and obtained by private communication. It is intended that this survey be of value to those beginning work in the field, and will provide some guidance in determining the direction of future research. Included are the following: engine parameters, modifications, operating conditions, running characteristics, performance, and related comments. More detailed discussion is included on the manpower and material costs associated with the modification of one of the engines listed.

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I. INTRODUCTION

Although the concept of using hydrogen to fuel an engine is credited to the Reverend W. Cecil in 1820, the first real development work began with the work of Ricardo [1] and Burstall [2] in England; and Erren and Campbell [3] in Germany and England starting in the 1920's. This interest in using hydrogen to fuel an internal combustion engine was spurred by the advantage to be gained in propelling dirigibles with the hydrogen which was normally released to the atmosphere to maintain proper altitude in flight [4]. Larger payloads could be delivered if hydrogen could be used to replace some of the petroleum fuel normally stored on board. Erren also expanded into the field of hydrogen-fueled IC engines for submarines, trucks, and buses. His work resulted in many patents in both England and Germany. The only complete files on Erren's work were destroyed by Allied bombs in Berlin during World War II [4]. For this reason, much of the recent work to convert engines to run on hydrogen fuel is done with very little benefit of Erren's experience.

All of the early researchers experienced difficulty with preignition and backflashing into the carburetor. Ricardo misinterpreted the primary causes of backflashing and discontinued his efforts. Erren tried several methods to overcome this problem, including direct injection of hydrogen into the combustion chamber at the proper point in the cycle.

Since he had only compressed hydrogen gas, his work also included attempts at "hydrogen supercharging". Reference [1, 3] is also made to the use of stratified charge techniques by both Ricardo and Erren even at this early stage of IC engine development. The subject of some of Erren's patents deal with successful control of what he termed "detonation" which was actually backflashing.

It is worth noting that these early researchers made thermal efficiency measurements and noted that, "remarkable thermal efficiencies were attained" with hydrogen [1]. Ricardo measured not only thermal efficiency of hydrogen but made comparisons between hydrogen and "petrol" fuel in the same engine. He observed a 17% increase in thermal efficiency for hydrogen over that for the "petrol" fuel in the E-35 Cooperative Fuels Research (CFR - a standard, variable compression engine used for testing purposes only) engine used for the experiments.

During World War II and shortly thereafter, both Australia [5] and Canada [6, 7] gave some attention to converting IC engines to operate on hydrogen fuel and mixtures of hydrogen and "town gas" in an attempt to relieve some of the pressures of the petroleum fuel shortage. R. O. King and his associates [6, 7] in Canada made substantial progress in understanding the enhanced tendency for IC engines to develop preignition and backflashing problems when operating on hydrogen fuel rather than on gasoline. Their work laid the foundation for the work of the researchers listed in this report.

King noted from the work of Ricardo and others the increased tendency in the Otto cycle engine for hydrogen to "detonate" or explode prematurely. This phenomenon was usually attributed to the ignition of the hydrogen-air mixture by hot surfaces or ignition being the final result of a reaction proceeding at the temperature attained by sudden compression. King offered an alternate explanation. He theorized that finely divided particles of carbon provided by pyrolysis of the lubricating oil formed nuclear centers of ignition. He consequently performed experiments with a CFR engine which confirmed this theory. By carefully pre-cleaning the engine before operating it on hydrogen and by careful fitting of the rings to keep the oil consumption low he determined that operation was possible over a wide range of fuel-air mixture with no preignition or backflashing. He further demonstrated that preignition and backflashing could be induced by introducing finely divided particles of carbon and other dusts into the fuel-air mixture.

The past decade has seen renewed interest in hydrogen as a fuel for IC engines for two reasons: (1) reduction of automotive pollution in urban areas and (2) fuel shortages and the dramatic increase in petroleum fuel costs.

A result of this renewed interest has been the conversion of a variety of sizes and kinds of IC engines to operate on hydrogen fuel by a number of different researchers and experimenters. This paper catalogs the engine modification techniques and performance characteristics of these engines so that the "state of the art" can be more readily visualized. It is hoped that this survey will be of value to those beginning to work in this field, and will provide some guidance in determining the direction of future experimental work.

Escher [8] has surveyed contemporary U.S. hydrogen-fueled IC engine projects and lists 42 engine conversions. Of these, 26 are conventional automotive engines, 8 are small utility engines, 5 are single-cylinder laboratory research engines and 3 are rotary engines. In all, 15 research activities were recently surveyed. Recent engine conversions have also been made in Canada, Germany, and Japan.

Table I lists a number of engine parameters before and after conversion for various types of engines by different investigators. The data are obtained from the open literature and from contacts with experimenters. The IC engines and automobiles listed in the table have been converted to operate on hydrogen in the past decade. Most of them are conventional "off the shelf" stock engines. However, special research engines which have been converted are also listed. Primarily, only air-breathing hydrogen engines are included. References, where available, are listed in the table.

II. ENGINE TYPES

One is immediately impressed with the variety and kinds of engines which have been successfully converted and operated on hydrogen fuel. The list ranges from simple single-cylinder utility engines to the most up-to-date automotive power plants. It includes multi-cylinder four-cycle piston engines, rotary engines, diesel engines, and at least one small two-cycle engine.

Many of the engines have been operated only in bench tests; however, a representative number of engines have been operated in automobiles on actual road tests and demonstrations.

The conversions were made with various objectives and purposes in mind. This has resulted in wide disparity in the format and content in reporting results. Table I contains several headings which list those measurable characteristics of a converted engine which would be of interest to a researcher today in light of the current interest in hydrogen as a non-polluting substitute for petroleum fuels. These are: (1) decrease in maximum power, (2) oxides of nitrogen emission, (3) thermal efficiency, and (4) fuel storage method. A useful base for making comparisons is operation of the same engine or automobile using gasoline fuel.

Only a few direct comparisons have been made. These comparisons show in general that a marked decrease in maximum power will occur unless some method of pressure injecting the hydrogen is used. This is the direct result of a less dense fuel-air mixture in the combustion chamber. Internal combustion engines will operate on much leaner mixtures with hydrogen than with gasoline. The flammability limits for gasoline are $0.72 < \phi < 2.4$ while for hydrogen they are $0.1 < \phi < 7.1$. The equivalence ratio ϕ is defined as the ratio of the fuel-air to the stoichiometric fuel-air ratio. Operation at ϕ much greater than 1.0 is to no advantage for either hydrogen or gasoline. However, operation at a smaller ϕ shows a gain in efficiency at a given power level as long as complete combustion is achieved. Since the lower flammability limit for hydrogen is much lower than for gasoline, it is possible to operate hydrogen engines at idle or part load by throttling only the hydrogen. Thus, ϕ and power output are reduced and efficiency is increased. Thermal efficiency shows a marked increase with hydrogen fuel (from 50% to 100% increases reported).

Very low emission of pollutants can be achieved by reducing peak temperatures further using water induction. This allows lower peak temperature--lower NO_x --and higher thermal efficiency. The throttle losses are also reduced or eliminated.

III. METHODS OF POWER REGULATING AND OTHER MODIFICATIONS

Several methods of power regulation of hydrogen fueled engines have been developed. Billings Energy Research Corporation (BERC) and the University of California, Los Angeles (UCLA) group have favored direct throttling through a carburetor system for their operational vehicles. Some test engines have used a variable fuel-air mixture. Variable mixture is achieved by allowing unrestricted air entry and controlling the hydrogen flow only. This mode of lean operation results in reduced power for low loads with substantial increases in efficiency due to less pumping loss.

The Miami University, Oklahoma State University and Cornell University groups have favored techniques for introducing the hydrogen directly into the cylinder. Miami has pioneered the "hydrogen induction technique" which utilizes an induction tube with a throttle valve. The air is unthrottled. Induction of hydrogen into the cylinder is actuated by opening the intake valve which also opens the induction tube. Jet Propulsion Laboratory working with Cornell University has recently converted a diesel engine using a similar technique. The method of direct induction of the fuel into the cylinder requires more intricate engine modifications, but does apparently produce the advantage of less complicated backflash control. Direct throttling and variable fuel mixture are relatively simple techniques to achieve mechanically. However, it generally requires some method to control NO_x emission, preignition, and backflashing such as water induction or exhaust gas recirculation to slow the flame front and reduce the peak combustion temperature.

Many of the researchers report modifications to the spark plug, usually narrowing the spark gap and using colder plugs. Hot spots in the combustion chamber are a possible cause of preignition which may be followed by backflashing. Other modifications reported are the addition of multiple rings to reduce oil leakage into the combustion chamber. Oil leakage leaves pyrolytic carbon deposits on piston and cylinder walls which can act as nuclear centers for ignition and preignite the charge.

High-quality, shielded spark plug leads are used by some experimenters to prevent spurious induced electrical discharge across the spark plug. Careful routing of the leads is an alternative to shielded cables.

Some experimenters have lowered the compression ratio to reduce the backflashing problem. This results in a reduction of power and efficiency. On the other hand BERC, in general, favors increasing the compression ratio to give better engine efficiency and then controlling backflashing and NO_x emission by water induction at an appropriate water-to-hydrogen mass ratio.

The UCLA group has pioneered the use of exhaust gas recirculation (EGR). This relatively simple technique usually consists of routing the exhaust gases from selected cylinders back into the intake manifold to dilute the intake charge. The result is slowing of the flame front and control of preignition and backflashing, but, at the expense of lower engine efficiency because of charge dilution.

Thomas at the University of Illinois has experimented with "internal exhaust gas recirculation" by increasing the amount of residual gases in the cylinders. This technique requires changes in valve timing to assure that sufficient residual combustion gases remain in the chamber to dilute the incoming fresh charge.

IV. FUEL STORAGE SYSTEMS

Since many of the hydrogen engine experiments performed to date were of a bench test nature to explore engine parametric effects, the source of hydrogen fuel was of little consequence. These experiments, for the most part, utilized a simple "bottle gas" storage system using pressurized gas cylinders. However, some experimenters wishing to demonstrate automotive systems adequate for transportation vehicles have pushed the state of the art and demonstrated the use of liquid hydrogen and metal hydride on-board storage systems. This is possible because of progress made in the space program on highly efficient cryogenic storage tanks [9] and recent progress made by Brookhaven National Laboratory and others on metal-hydride storage tanks.

Los Alamos Scientific Laboratory, UCLA, and BERC have demonstrated use of cryogenic liquid hydrogen in vehicle road tests. The main objections to this storage method are cost and safety.

Vehicle road test demonstrations using metal-hydride storage tanks have been conducted by BERC and stationary engine tests with a metal-hydride tank have been demonstrated at Brookhaven with a small rotary engine. The UCLA group has also investigated metal-hydride storage systems. At the present time Fe-Ti hydride is a principal choice because its dissociation temperature is compatible with the exhaust temperature available from IC engines. A major drawback to Fe-Ti hydride is weight. Lighter metal hydrides are available, but require substantially higher dissociation temperatures and energies. Needless to say, the kinetics of formation and decomposition of any hydride considered for a hydrogen storage medium is of prime concern. The main area for development is a relatively light-weight metal-hydride with thermodynamic properties compatible with the exhaust temperature from an IC engine.

V. SOME REASONS FOR NOTED ENGINE EFFICIENCY INCREASE WHEN USING HYDROGEN FUEL

If hydrogen is to become a serious contender as a substitute for gasoline in our transportation systems, the fuel cost per mile for hydrogen must be competitive with other synthetic fuels. Cost of production is certainly one factor in the fuel cost per mile, but the potential thermal efficiency which may be achieved with a given fuel should also be considered.

Hydrogen has certain properties, which if exploited, can result in a higher thermal efficiency for a given engine over that for gasoline. Listed below are some of the reasons hydrogen engines can be operated more efficiently than gasoline engines. Obviously, trade-offs must be considered in any design.

- (1) Higher compression ratios can be tolerated provided proper techniques are employed to control preignition and backflashing.

- (2) Charge dilution occurs because the density of the fuel-air charge is decreased by hydrogen displacing air. This reduces the power output of the engine. At reduced power settings, the engine need not be throttled as strongly (less pumping work loss). If the engine displacement is increased to achieve the same maximum power, then this efficiency advantage is not observed.
- (3) Lean burning is more efficient. A throttled engine typically has an equivalence ratio between 0.6 and 0.8.
- (4) The equivalence ratio ϕ can be adjusted over a very wide range ($0.4 < \phi < 1.0$). This characteristic of hydrogen fuel makes it possible to use unthrottled air (unrestricted air flow means low pumping work losses). Only the hydrogen need be throttled.
- (5) The thermodynamic cycle of hydrogen fueled engines is closer to the theoretical Otto cycle than that of gasoline fueled engines. The reason for this is the higher flame speed, which makes spark timing much closer to "top dead center" (TDC) possible. Therefore, burning takes place near TDC.
- (6) Hydrogen is a gas which diffuses rapidly to produce a uniform mixture in the combustion chamber. A uniform premixed charge also has a lower peak temperature.
- (7) There is no efficiency drop due to inadequate vaporization as with gasoline.
- (8) There is no cold wall quenching. Complete combustion occurs, even very near the cylinder walls. The quench distance is of the order of 0.05 centimeter with hydrogen. There is no condensation of fuel on cold metal parts as with gasoline. Much of the inefficiency with short-range cold-start driving with gasoline is eliminated.

VI. AN EXAMPLE OF MANPOWER AND MATERIALS ASSOCIATED WITH AN ENGINE CONVERSION

A 1975 400-in³ Pontiac engine was converted to operate on hydrogen by Idaho Engineering Laboratory (INEL) personnel. This work was directed by BERC. The primary purpose was for the participants to gain experience in the field. To this end, more effort was expended on this practically new engine than was really necessary. For example, the engine was completely disassembled, and all clearances and components checked and found to be within specifications. As is well known, hydrogen engines are often run at lean equivalence ratios to prevent backflashing. This, in combination with a low volumetric efficiency, results in a considerable loss in power. It was decided to see if this power could be partially regained by raising the compression ratio. The engine was measured and found to have a standard compression ratio of 7.7:1. An investigation showed that older model (1969) heads and pistons would give 10.5:1 compression ratio, and that "aftermarket" pistons were available to raise it further to 12.0:1. However, the '69 heads had smaller valves than the '75 heads and thus, the engine would

have a lower volumetric efficiency already a problem. Therefore, it was decided to have special pistons made for the '75 heads, and try for a compression ratio of about 14:1.

After the new pistons had been installed, it was determined that the deck height was different on the two banks, so the higher deck was shaved 0.010", and 0.012" was taken off each head. With the new pistons and these modifications the compression ratio was found to be 12.7:1. The following additional changes were also made:

- (1) The heat riser port to the intake manifold was blocked off.
- (2) The EGR valve was disconnected.
- (3) Shielded ignition wires were installed.
- (4) A 165°F thermostat was installed.

The engine was broken in on the dynamometer using gasoline as the fuel. The gasoline carburetor was then replaced with a propane carburetor, the spark plugs regapped to 0.015", the centrifugal advance on the distributor blocked out, and the timing set at 7° BTDC. Power tests were made with the engine operating on the dynamometer and using hydrogen as the fuel.

The total costs expended for teardown, measuring, assembly, break-in final conversion and testing is estimated to be 150 manhours with a materials cost of approximately \$400.

VII. CONCLUSIONS AND RECOMMENDATIONS

- (1) Several good demonstrations involving conversion of modern automobiles to operate on hydrogen engines and actual vehicle road tests have been accomplished. These demonstrations show, in general, that hydrogen-air systems can be designed which easily meet government pollution emission standards. Safety can be readily designed into automobile systems, especially with use of metal-hydride storage tanks. There is a substantial increase in thermal efficiency with hydrogen fuel. Some designs have about one-third less power.
- (2) The amount of blank space in Table 1 illustrates the need for improved documentation and publication of test results as well as illustrating a lack of some important measurements. Future researchers are encouraged to establish test programs which will include all categories as a minimum. Whenever possible the data should include curves of power and torque as a function of engine RPM for different fuels. This would enable engineers to make choices for specific applications.

- (3) Specialty carburetors using "computer" control would be advantageous for variable mixture designs.
- (4) Very little long-term endurance testing has been done on hydrogen engines. Hydrogen is so clean burning that conversion of new engines is usually preceded by a break-in period on gasoline which produces enough abrasive action to "seat" piston rings and close tolerance engine parts. However, questions arise about hydriding of engine parts under normal and extreme operating conditions over the lifetime of the engine. If hydriding effects are small, engine life may be extended considerably, resulting in large national resource savings in steel and lubrication oil. This should be a high priority effort.
- (5) The authors feel that the state of the art is advanced to the point where fleet demonstrations should be initiated. This demonstration should include an efficient production system, refueling, handling, bulk storage system, and a sufficiently large fleet operation within a limited area to produce comparative overall system efficiency. The existence of government fleets at national laboratories presents a good opportunity for the federal government to fund such a demonstration with participation by industrial research organizations.
- (6) High quality system modeling using computer simulation is warranted to study parametric tradeoffs and establish the relative importance of various reasons for efficiency improvement and peak temperature (NO_x) reduction.
- (7) The metal-hydride form of fuel storage in conjunction with an internal combustion engine shows definite advantages in performance (acceleration and range), weight, total cost, and refueling time when compared to electric vehicles with battery storage [10, 11, 12]. Furthermore, if the production and distribution of hydrogen or electricity is taken into consideration, as it should be, the advantage electric vehicles may have in emissions and overall efficiency may be significantly reduced. An operational comparison between two urban vehicles with identical payload is warranted.

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TABLE I-1A CATALOG OF IC ENGINE CONVERSIONS TO HYDROGEN FUEL

ITEM NO.	RESEARCHERS	REF. NO.	APPROX. TEST DATE	ENGINE OR VEHICLE	UNMODIFIED ENGINE DATA						
					NO. CYL'S	BORE & STROKE IN. (mm)	ENGINE CID (LITER)	C. R.	MAX. HORSE POWER@ RPM	PEAK TORQUE FT-LBS@RPM	IGNITION SYSTEM
1	UCLA Lynch, Finegold et.al.	29	1970-72	Briggs & Stratton, Air Cooled	1		7.75 (.127L)	6.1:1			
2	UCLA Lynch, Finegold et.al.	30	1970-72	Ford	8		351 (5.75L)	7.8:1			
3	UCLA Lynch, Finegold et.al.	30	1970-72	Ford	8		289 (4.73L)	9.3:1			
4	UCLA Lynch, Finegold et.al.	30	1970-72	Chevrolet Engine	4		140 (2.3L)	8:1			
5	UCLA Lynch, Finegold et.al.	30	1970-72	Chevrolet Engine	8		235 (3.85L)	8.75:1			
6	UCLA Lynch, Finegold et.al.	29,30	1972-73	Ford "Boss" Engine	8		351 (5.75L)	11.7:1			
7	UCLA Van Vorst et.al.	29,31,13	1973-74	1973 Chev. V8 Engine	8	Stock	350 (5.74L)	8.5:1			S.I.
8	UCLA Van Vorst	14	1975	AMC Jeep	6	232 (3.8L)	232 (3.8L)				
9	R. Billings		1963-65	Briggs & Stratton (1961)	1	2.35x1.50	6.0 (.0983L)	6.0:1	2.5@3600	3.3@3200	S.I. Magneto
10	R. Billings	14	1965-66	1931 Ford Model "A"	4	3.88x4.25 (98.6x108)	200 (3.28L)	4.2:1	40@2200	128@1000	S.I. Kettering

TABLE I-1B CATALOG OF RECENT IC ENGINE CONVERSIONS TO HYDROGEN FUEL

ITEM NO.	TEST CONDITIONS - HYDROGEN FUEL							
	C. R.	EQUIV. RATIO	POWER REGULATION	DECREASE IN MAX. POWER	NOX CONCEN.	THERMAL EFF. (%)	HYDROGEN STORAGE METH.	PURPOSE OF EXPERIMENT AND GENERAL COMMENTS
1								-Develop methods for controlling oil leakage past rings. Used elaborate multiple ring configuration.
2								-Study the effects of various engine operating parameters.
3								-Study the effects of various engine operating parameters.
4								-Study the effects of various engine operating parameters.
5								-Study the effects of various engine operating parameters.
6	8.9:1				205gm/mi		Press. Cyl's.	-Urban vehicle design competition. Extensive engine modifications made. Used exhaust gas recirculation to control flashback.
7	8.5:1	Variable .2 to 1	Variable Mixture		0 to 28 ppm over oper. range	Up to 100% better than gasoline	Cryogenic liquid	-Get direct comparison of engine performance and NOX emission for gasoline and hydrogen. Operated with and without water induction on hydrogen fuel. Very good data reported.
8		Variable	Throttle				Cryogenic liquid	-Show that liquid hydrogen can be used to fuel a vehicle efficiently and safely. Used water induction method.
9	6.0:1	Variable	Variable Mixture				Press. Cyl.	-Determine if pure H ₂ and air are capable of powering an IC engine.
10	4.2:1	Variable	Variable Mixture				Compressed Gas	-Determine NOX formation. Power a vehicle on hydrogen and air. Believed to be first hydrogen powered automobile.

TABLE I-2A

ITEM NO.	RESEARCHERS	REF. NO.	APPROX. TEST DATE	ENGINE OR VEHICLE	UNMODIFIED ENGINE DATA						
					NO. CYL'S	BORE & STROKE IN. (mm)	ENGINE CID (LITER)	C. R.	MAX. HORSE POWER@ RPM	PEAK TORQUE FT-LBS@RPM	IGNITION SYSTEM
11	Billings Energy Research Corp.	14	1970-71	1971 Ford-6 Engine	6	3.68x3.13 (93.5x79.5)	200 (3.28L)	8.7:1	115@4000	180@2200	S.I. Kettering
12	Billings Energy Research Corp.	14	1970-71	1968 Ford-V8 Engine	8	4.05x3.78 (103x96)	390 (6.39L)	9.5:1	270@4400	390@2600	S.I. Kettering
13	Billings Energy Research Corp.	14	1972	1972 Volkswagon	4	3.36x2.72 (85.3x69.1)	96.6 (1.58L)	7.3:1	46@4000	72@2800	S.I. Kettering
14	Billings Energy Research Corp.	14	1972	1972 Mazda RX-2 Wankel	2R		70 (1.15L)	9.4:1	130@7000	115@4000	S.I. Kettering
15	Billings Energy Research Corp.	14	1972	1970 Sachs Wankel Engine	1R		18.5 (.303L)	8:1	20@5000		S.I. Kettering
16	Billings Energy Research Corp.	14	1972	1931 Ford Model "A"	4	3.88x4.25 (98.6x108)	200 (3.28L)	4.2:1	40@1200	128@1000	S.I. Kettering
17	Billings Energy Research Corp.	15, 16	1972-73	Briggs & Stratton(1970) L-Head, 4 Cyc. Air Cooled	1	2.38x1.50 (60.3x38.1)	6.65 (.109L)	5.5:1	225@3600	3.4@3150	S.I. Magneto
18	Billings Energy Research Corp.	14	1973	1970 Ford Falcon	6	4.0x3.18 (102x80.8)	240 (3.93L)	9.2:1	150@4000	234@2200	S.I. Kettering
19	Billings Energy Research Corp.	14	1973-74	1972 Winnebago Motor Home	8	4.32x3.75 (110x95.3)	440 (7.21L)	8.2:1	225@4400	345@3200	S.I. Electronic
20	Billings Energy Research Corp.	14	1970-75	Two Cycle Engine (1956)	1	1.25x1.07 (31.8x27.2)	1.31 (.0215L)	11.7:1			S.I. Magneto

TABLE 1-2B

TEST CONDITIONS - HYDROGEN FUEL								
ITEM NO.	C. R.	EQUIV. RATIO	POWER REGULATION	DECREASE IN MAX. POWER	NOX CONCEN.	THERMAL EFF. (%)	HYDROGEN STORAGE METH.	PURPOSE OF EXPERIMENT AND GENERAL COMMENTS
11	8.7:1	Variable	Variable Mixture				Compressed Gas	-Compare exhaust gas recirculation and water induction to control flashback and preignition.
12	9.5:1	Variable	Variable Mixture				Compressed Gas	-Test water induction technique to control flashback.
13	13:1	.8-1.5	Variable Mixture		.2gm/mi		Press. Cyl.	-Entry in Urban Vehicle Design Competition. Used water injection to control flashback and NOX emissions.
14	9.4:1	Variable	Variable Mixture				Compressed Gas	-Urban Vehicle Design Competition. Used exhaust gas recirculation to control flashback and NOX emissions.
15	8:1	Variable	Variable Mixture				Compressed Gas	-Test a Wankel engine conversion to hydrogen fuel.
16	4.2:1	Variable	Throttle				Compressed Gas	-Test surface area technique to control flashback.
17	5.5 to 10.5:1	Variable	Variable Mixture	34-45%	less than 1 ppm	22.5% @ 2900 RPM $\phi = .73$	Press. Cyl. or Hydride	-Demonstrate wide range of operating ϕ ($.4 < \phi < 1.$). Water induction used to control preignition and NOX.
18	11:1		Throttle				Press. Cyl.	-Demonstration of increased efficiency with hydrogen fuel. Used water induction to control flashback and NOX emissions.
19	10.5:1	Variable	Throttle				Cryogenic Liquid	-Demonstrate a vehicle completely powered by hydrogen including the stove, refrigerator, and auxiliary electrical power generator.
20	11.7:1	Variable	Variable Mixture					-Evaluate two-cycle capabilities with hydrogen fuel.

TABLE I-3A

ITEM NO.	RESEARCHERS	REF. NO.	APPRGX. TEST DATE	ENGINE OR VEHICLE	NO. CYCL'S	UNMODIFIED ENGINE DATA					
						BORE & STROKE IN. (mm)	ENGINE CID (LITER)	C.R.	MAX. HORSE POWER@ RPM	PEAK TORQUE FT-LBS@RPM	IGNITION SYSTEM
21	Billings Energy Research Corp.	14	1973-74	1972 Onan Generator	2	3.25x3.0 (82.6x76.2)	49.6 (.816L)	5.5:1			S.I. Coil-battery
22	Billings Energy Research Corp.	14	1974	1974 Monte Carlo V8	8	4.0x3.48 (102x88.4)	350 (5.74L)	8.5:1	175@4400	270@2400	S.I. 7° BTC Kettering
23	Billings Energy Research Corp.	14	1975	1975 Winnebago Passenger Bus	8	4.32x3.75 (110x95.3)	440 (7.21L)	8.2:1	220@3600	350@2400	S.I. Electronics
24	Billings Energy Research Corp.	14	1975	Pontiac Grande Ville 1975, 400 CID Engine	8	4.12x3.75 (105x95.3)	400 (6.56L)	8:1	200@4000	320@2400	S.I. Energy Ignit. Coil
25	Billings Energy Research Corp.		1974-75	1949 CFR Diesel	1	3.25x4.5 (82.6x114.3)	37.4 (.612L)	Variable			Compression
26	Mercedes-Benz H. Buchner	14	1975	Mercedes-Benz M115 KV23	4		140.4 (2.3L)	9:1	59 (44 KW)		Stock
27	Oklahoma State Univ. Murry & Schoepfel	17,18,19	1970	Clinton Model 494-0301 L-Head, 4 Cyl. Aircooled	1	2.38x1.88 (60.3x47.6)	8.3 (.136L)	6.5:1	4@2500 to 3500	5.5@3500	S.I.
28	Univ. of Calgary Karim & Klat	20	1974-75	Gardner Duel-Fuel Diesel	1	4.21x5.98 (107x152)		14.5:1			Compression
29	Univ. of Miami Swain & Adt.	21,22	1972	1971 Toyota, sta. wgn. 2 I-C engine, 4 spd. trans.	4		97.6 (1.6L)	9:1			S.I.
30	Univ. of Miami Adt., Swain et. al.	21,23	1973	Pontiac Engine, 4 Cyl., Overhead Valve	4		195 (3.20L)	10:1			S.I. Stock

TABLE I-3B

TEST CONDITIONS - HYDROGEN FUEL								
ITEM NO.	C. R.	EQUIV. RATIO	POWER REGULATION	DECREASE IN MAX. POWER	NOX CONCEN.	THERMAL EFF. (%)	HYDROGEN STORAGE METH.	PURPOSE OF EXPERIMENT AND GENERAL COMMENTS
21	9:1	Variable	Variable Mixture				Cryogenic Liquid	-Converted to generate electric power for a hydrogen powered Winnebago motor home.
22	11.5:1	.55-.7	Throttle Air and H ₂		.02 gm/mi	80% over gasoline (urban driving)	1) Press. Cyl. 2) Cryogenic 3) Hydride	-Demonstrate advantage of improved part load efficiency. Tested under urban driving conditions. Used water induction to control flashback and NOX emissions
23	12:1	.65-.75	Throttle Air and H ₂	14%			Metal Hydrides	-Evaluate feasibility of implementing an H ₂ fueled bus fleet. Used water induction to control flashback and NOX emissions.
24	10:1	.65-.75	Throttle Air and H ₂	30% for $\phi = .7$			Metal Hydrides	-Demonstrate a metal hydride fuel storage system on an operating hydrogen fueled vehicle. Used water induction to control flashback and NOX emissions.
25	10-15:1	Variable	Variable Mixture					-Evaluate diesel capability of hydrogen. Used water induction to control flashback and NOX emissions.
26	8:1						Fe Ti Hydride	-Demonstrate Mercedes-Benz operations on hydrogen fuel. Fuel tank, 200 kg Fe Ti (~ 4 kg H), about same volume as gasoline tanks.
27	6.5:1	Variable .3 to 1.3	H ₂ Inject. @ High Press.	None	365 ppm @ peak pwr.		Press. Cyl.	-Investigate emissions for EPA, no loss in power because injection pressure adjusted.
28	11.6:1	Variable						-Investigate performance of a compression ignition engine with hydrogen fuel. Ignited by injection of pilot fuel charge near end of compression stroke.
29	9:1	Variable	Hydrogen Induction Technique		Meets 1975 Standards	Indicate 50% Increase Over gasoline	Press. Cyl.	-Demonstrate hydrogen induction technique. Some major engine modifications. Road tested.
30	Less Than Stock	Variable	Hydrogen Induction Technique		< 1500 ppm	25 to 23		-Compare hydrogen and methanol characteristics in the same engine. Good data obtained.

TABLE I-4A

ITEM NO.	RESEARCHERS	REF. NO.	APPROX. TEST DATE	ENGINE OR VEHICLE	UNMODIFIED ENGINE DATA						
					NO. CYCL'S	BORE & STROKE IN. (mm)	ENGINE CID (LITER)	C. R.	MAX. HORSE POWER @RPM	PEAK TORQUE FT-LBS@RPM	IGNITION SYSTEM
31	Gen. Mot. Research Lab R. F. Stebar and F. B. Parks	24	1973-74	ASTM-CFR Split-head Variable Compression Ratio	1	3.25x4.50 (82.6x114.3)	37.4 (.612L)	Variable			S.I. Waukesha C.D.
32	Cornell Univ. P.C.T deBoer et. al.	25	1973-74	CFR with Diesel Head Modified for S.I.	1		37.4 (.612L)	8:1			S.I.
33	JPL & Cornell Univ. R. K. Reynolds, H. F. Homan		1975	Ceteane CFR Waukesha Diesel	1	3.25x4.50 (82.6x114)		15 to 29:1			
34	Jet Propulsior Lab J. Rupe	14	1973	CFR Engine, Otto-cycle head	1						S.I.
35	Univ. of Illinois S. R. Thomas	14	1974	1971 Vega	4						
36	International Ecological Systems Corp.	14	1973	Stock Cadillac	8		472 (7.74L)	8.5:1	220@4000		
37	Musashi Insititute of Technology-Japan	26	1972	Katsura K6A	1	3.35x3.35 (85x85)	29.4 (.482L)	4.8:1			
38	Martin-Marietta Corp. Denver, Colo.	14	1970	Waukesha Mod. 180			155 (2.54L)	7.5:1	400@1800		Magneto 25° BTDC
39	Perris Smogless Auto. Association	28, 14	1970	1930 Ford, Model "A"							
40	Perris Smogless Auto. Association	28, 14	1971	Ford F250	8						Stock

TABLE I-4B

TEST CONDITIONS - HYDROGEN FUEL								
ITEM NO.	C. R.	EQUIV. RATIO	POWER REGULATION	DECREASE IN MAX. POWER	NOX CONCEN.	THERMAL EFF. (%)	HYDROGEN STORAGE METH.	PURPOSE OF EXPERIMENT AND GENERAL COMMENTS
31	8:1	Variable .18 to 1.04	Variable Mixture		< 33 gm/ihp - hr		Press. Cyl.	-Explore emission control with hydrogen supplemented fuel. Some direct comparisons between hydrogen and isobutane operation.
32	8:1 to 12:1	Variable	H ₂ Injection into Cyl.			20 to 25 @ 1200 ppm		-Measure fuel economy and NOX emissions and compare with an analytical model. Open throttle, direct H ₂ injection to cyl.
33	15 to 29:1	.1 to .3			NOX Decrease as C.R. Increased	Reported Poor		-Feasibility demonstrations on direct injection hydrogen. Could not pressure ignite even at CR = 29:1. Used glow-plug ignition.
34		.1 to .6			.4 gm/ihp-hr @ $\phi = .5$	35 to 40% Ind.	Bottled	-Derive base data for studying hydrogen-gasoline mixtures as a fuel.
35		.4 to .6	Throttle		Not Meas.			-Evaluate modified valve timing to provide a measure of "internal exhaust gas recirculation" to control flashback by slowing flame speed.
36								-Reported no loss of power at high loads. Factor of 2.18 gain in energy efficiency over gasoline. Used various methods for flashback control.
37	6:1 & 7.9:1	Variable	Variable Mixture		< 5000 ppm		Compressed Gas	-Study NOX emission in hydrogen fueled engine.
38			Variable Mixture					-Feasibility test of hydrogen fuel.
39							Compressed Gas Bottles	-Demonstrate hydrogen-oxygen automotive system. System is essentially sealed, no air is inducted.
40							Cryogenic	-Demonstrate hydrogen-oxygen fueled vehicle using cryogenic storage of hydrogen and oxygen.

TABLE I-5A

ITEM NO.	RESEARCHERS	REF. NO.	APPRX. TEST DATE	ENGINE OR VEHICLE	UNMODIFIED ENGINE DATA						
					NO. CYCL'S	BORE & STROKE IN. (mm)	ENGINE CID (LITER)	C. R.	MAX. HORSE POWER @ RPM	PEAK TORQUE FT-LBS @ RPM	IGNITION SYSTEM
41	International Materials Corp.	27	1972	1971 Ford Torino	8		305 (5.0L)	9.5:1			
42	Brookhaven	14	1972	Air Cooled Fitted & Sachs AG NSU-Wankel KM 48					8		
43	Los Alamos Sci. Lab.	14	1973	1972 Dodge 1/2 Ton Pick-Up Truck 4 Speed Trans.							
44	University of Florida J. E. Lenerz	14	1973	Fairbanks-Morse Diesel (Mod. 45BD-1/8) Converted to S.I.	1	3.125x4.0 (76.4x102)	30.8 (.505L)	8.2:1			
45	Idaho Engineering Lab (INEL)		1975	1975 Pontiac Engine	8	4.12x3.75 (105x95.3)	400 (6.56L)	7.7:1	2000@4000	3200@2400	S.I. High Energy Coil

TAB.E I-5B

TEST CONDITIONS - HYDROGEN FUEL								
ITEM NO.	C. R.	EQUIV. RATIO	POWER REGULATION	DECREASE IN MAX. POWER	NOX CONCEN.	THERMAL EFF. (%)	HYDROGEN STORAGE METH.	PURPOSE OF EXPERIMENT AND GENERAL COMMENTS
41	10.5:1							-Demonstrate a system using hydrogen fuel entirely reformed from gasoline.
42			Variable Mixture	67%		~ 20%	Fe Ti Hydride	-Demonstrate hydride fuel storage system with an IC engine.
43				~ 50% noted			Cryogenic	-Test cryogenic storage of hydrogen for vehicle use. Used exhaust gas recirculation to suppress backflashing.
44	8.2 to 10.9:1	.9 to 1.6	Variable Mixture	~ 30%		36 ind.		-Study combustion chamber phenomena. Used water injection to control flame speed on some tests.
45	12.7:1	.25 to .85	Throttle				Press. Cyl.	-Training program for INEL personnel by BERC.

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