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Alternative Energy Sources for Non-Highway Transportation

Executive Summary

June 1980

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

Contract No. DE-AC05-77CS05438

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June 1980

Prepared for
U.S. Department of Energy
Assistant Secretary for Conservation
and Solar Energy
Office of Transportation Programs
Washington, D.C. 20585

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FOREWORD

For convenience, the material covered in this study is divided into several reports. Volume I is an executive summary covering the highlights of the study. Volume II is the technical section that covers a summary of the data used in the preliminary screening of the alternate fuels and prime movers as well as the detailed evaluation of each of the four modes from the standpoint of the user, fuel supplier and the engine designer. The detailed discussion and documentation of the data base is in Volume III, which has been subdivided into four areas due to the size of the report. Volume III contains all of the references for the data used in the preliminary screening. The information in the four volumes is as follows.

Volume IIIA contains Sections 1 through 5, and covers the background information on the various prime movers used in the non-highway transportation area, the physical property data, the fuel-prime mover interaction and a review of some alternate energy forms. The five sections are as follows:

Section 1--Prime Movers and Fuels Used in Non-Highway Transportation

Section 2--Criteria to be Used in Evaluating and Rating of Fuels and Prime Movers

Section 3--Physical Property Data

Section 4--Prime Mover-Fuel Interaction

Section 5--Review of Potential for Alternate Energy Forms for Non-Highway Transportation--Fuel Cells, Nuclear and Direct Solar

Volume IIIB covers the economics of producing, transporting, and distributing the various fuels. There are two sections in this volume.

Section 6--Economics of Production

Section 7--Economics of Transportation, Distribution and Storage

Volume IIIC is concerned with the environment issues in production and use of the fuels, the energy efficiency in use and production, the fuel logistics considerations, and the overall ratings and selection of the fuels and prime movers for the detailed evaluation. The seven sections in this volume are as follows:

Section 8--Environmental Impact in Production

Section 9--In-Use Emissions with Alternate Fuels

Section 10--Energy Efficiency in Production

Section 11--Energy Efficiency in Use

Section 12--Fuel Logistics--Resource Availability, Compatibility with
Present Fuel and Distribution System, International/
Military Considerations

Section 13--Overall Rating of Fuels/Prime Movers

Section 14--Selection of Fuels for Detailed Evaluation

Volume IIID covers the demand-related issues. The four sections
are:

Section 15--Energy Supply/Demand Projections

Section 16--Military and International Considerations

Section 17--Institutional Issues

Section 18--Experiment in Probabilistic Forecasting

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ABSTRACT

A planning study has been made for the Department of Energy (DOE) on alternate fuels for non-highway transportation (aircraft, rail, marine, and pipeline). The purpose of the study was to provide DOE with a recommendation of what alternate fuels may be of interest to non-highway transportation users from now through 2025 and to recommend R&D needed to allow non-petroleum derived fuels to be used in non-highway transportation.

In the near term (present-1985), there is unlikely to be any major change in the fuels used in any of the four modes of transportation except that the average quality of the marine fuel is likely to get worse. In the mid-term period (1985-2000), there will be a transition to non-petroleum fuels, based primarily on shale oil derived liquids, assuming a shale oil industry is started during this time.

The future outlook for possible prime movers and potential fuel sources for the long term (2000+) is as follows: In the marine area, steam engines burning coal or diesel engines with unrefined shale oil or coal slurries are the prime candidates. With the aircraft gas turbine, either synthetic liquids from shale or coal would appear to be the most desirable fuels. Railroads will probably remain with the diesel/electric prime mover using shale oil as a source of distillate. Pipelines will probably continue to use electric motors as the major type of prime mover.

R&D suggestions for each mode have been proposed.

Some general observations from the study are that interest will increase in using engines that can run on lower quality fuels, such as coal or unrefined shale oil. Use of engines with higher thermal efficiency will increase. Users may be willing to invest more for prime movers that will operate on lower quality fuels. From a fuel substitution standpoint, the marine mode has the greatest potential for substitution and the aircraft the least potential. From an environmental standpoint, the marine area offers the most likely outlet for coal or other high sulfur fuels. Considering engine lifetime, there will be a need for a fuel similar to current products for the next 20-30 years. In view of the development/design times of new engines, the aircraft offers the best chance to use non-petroleum fuel at the earliest date in a new engine. With the long lead times, the time to start a new design is now.

The study has also developed a data base for 18 different fuels and eight prime movers in four major areas: (1) fuel manufacture (economics, overall energy efficiency, and environmental impact in production), (2) fuel performance from designer/user viewpoint (toxicity, safety, materials compatibility, storage requirements, convenience in handling and storage, and environmental impact during use), (3) compatibility of the fuels and prime movers, and (4) fuel logistics factors (availability by 1990, compatibility with present system, and international considerations). The detailed evaluation considered the overall economics of the various prime movers and fuels from the user's viewpoint as well as the basic resource requirements.

INTRODUCTION

The United States faces a serious energy problem with regard to petroleum and natural gas. The transportation sector is very dependent on these two resources for fuels. A study has been made for the Department of Energy to investigate alternate energy sources for non-highway transportation (NHT), which covers marine, railroad, aircraft and pipeline. The overall objectives of the study were: (1) to examine choices for alternate fuels in each mode for three time periods, present (now to 1985), mid-term (1985-2000), and long term (2000+); and (2) to recommend R&D ideas for each mode.

In the near term (present-1985), there is unlikely to be any major change in the fuels used in any of the four modes of transportation except that the average quality of the marine fuel is likely to get worse. In the mid-term period (1985-2000), there will be a transition to non-petroleum fuels, based primarily on shale oil derived liquids, assuming a shale oil industry is started during this time.

The outlook for possible prime movers and potential fuel source for the long term (2000+) is summarized in the following table.

TABLE 1

POSSIBLE PRIME MOVERS AND POTENTIAL FUELS FOR NHT

	<u>Possible Prime Movers</u>	<u>Potential Fuel Source</u>
Marine	<ul style="list-style-type: none">• Steam Engine• Diesels	Coal Coal/Oil Slurries Unrefined Shale Oil
Aircraft	<ul style="list-style-type: none">• Gas Turbine	Shale Oil Indirect Coal Liquids
Railroads	<ul style="list-style-type: none">• Diesel/Electric• Fuel Cell?• Stirling?	Shale Oil Coal/Shale Naphtha Coal
Pipeline	<ul style="list-style-type: none">• Electric Motors	Coal or Nuclear Power

The R&D ideas are specific for each mode and are given under the respective sections. A few of the R&D ideas are summarized on the following page.

TABLE 2
R&D SUGGESTIONS

- Investigate the potential use of fluidized bed combustion for coal fired boilers in the marine areas
- Determine the compatibility of various synthetic fuels with marine bunker fuel
- Determine the logistics of coal supply for marine bunkering
- Investigate the feasibility of using fuel cells for railroad application
- Conduct an environmental assessment of using synthetic fuels in railroad diesel engines
- Studies should be made on jet engines that can operate on more aromatic jet fuels from shale oil or coal liquids
- Determine the storage stability of jet fuels from coal liquids that have been hydrogenated to various levels
- Investigate processing alternatives to severe hydrotreating to improve storage and thermal stability of shale oil derived fuels

REASONS FOR LOOKING AT ALTERNATE
FUELS FOR NON-HIGHWAY TRANSPORTATION

One may ask -- Why study alternative energy sources for the non-highway area? It is true that the amount of energy used in the non-highway modes is relatively small. The energy demand for non-highway totaled about five quads in 1975 or about seven percent of the total U.S. energy demand of 71 quads. Aircraft and pipeline were the major users. Even though most of the projections show the absolute level of demand increasing in the future, the non-highway sector will still remain at around six to eight percent of the total U.S. demand.

The major source of the energy used in the non-highway area is petroleum. About 80 percent of the energy used was liquid petroleum and the total petroleum usage was greater than 93 percent. Only the railroads used any non-petroleum fuel, amounting to much less than 1 percent of the total non-highway demand.

One reason why it is important to study alternate energy sources for non-highway applications is because the non-highway sector is critical in moving freight. The highway sector accounts for 88 percent of the passenger-miles, but non-highway accounts for about 80 percent of the freight ton-miles. Thus, any disruption in the movement of freight due to the non-availability of fuel would have a devastating effect on the economy.

Figure 1

Another reason why it is important to study alternate energy sources for non-highway transportation is because the lead times for any change are long. As shown in Figure 1, the lifetimes of the various engines are generally around 20 years or more. In addition, the development/design time for a new prime mover is on the order of ten years. Allowing for another five to ten years to introduce a new prime mover into the system means that if a new prime mover for an alternate fuel is desired by the year 2000, it is important to start working on the development now.

This summary will cover three major areas. The first area will cover a preliminary screening step where 18 different fuels and eight prime movers were evaluated. The second major area will cover the detailed evaluation for each mode of transportation. The third major area will cover some general conclusions.

PRELIMINARY SCREENING AND DATA BASE

There were three main objectives for the preliminary screening step. The first objective was to develop a methodology to evaluate alternate fuels in a sound, logical, and technical manner, based on four major areas that will be described shortly. The second objective was to establish the basic data on fuels and prime movers that could be used in the remainder of the study. The third objective was to narrow down the list of prime movers and fuels for a more detailed evaluation.

● Fuels Considered

The alternative fuels considered are represented by three different resource bases as shown in Table 3. Coal could provide 13 of the alternative fuels. The fuels considered were coal directly, coal/oil and coal/methanol slurries, synthetic liquids from coal and oil shale, alcohols from coal as well as biomass, and some of the more exotic fuels such as ammonia, hydrazine, and acetylene. Methane and hydrogen in both gaseous and liquified form were considered as well as electricity as an energy carrier. Nuclear power and direct solar radiation were also considered.

TABLE 3

MANY ALTERNATIVE FUELS CONSIDERED

	RESOURCE BASE		
	COAL	OIL SHALE	BIOMASS
SLURRIES	✓		
SYN. LIQUIDS	✓	✓	
ALCOHOLS	✓		✓
NH ₃ , AMINES, ETC.	✓		
METHANE	✓		✓
HYDROGEN	✓		
ELECTRICITY	✓		✓

Nuclear power is being used in the marine area today to generate steam to drive a turbine. Therefore, the technology exists and is being used primarily by the military today in over 200 different vessels. However, it is uncertain as to when nuclear power will become economical. In addition, there are substantial non-economic problems to be overcome, such as insurance liability protection, port entry, and international clearance issues. In the aircraft area, nuclear energy has been considered since the 1950's by the military. A nuclear reactor would be used to heat air to high temperature to drive a gas turbine. A major problem in this case is the weight penalty due to shielding to protect the crew and passengers. As a result of this, the economics are not favorable due to the cost of the airframe to carry the heavy powerplant. Also, there would be environmental and safety concerns.

Direct solar radiation was also considered using photovoltaic cells to convert sunlight directly to electric power. In this case, the collector area necessary to provide a certain horsepower was calculated. This area was then compared with the area that may be available. For example, in the case of the marine mode, the area required was around ten times greater than the actual deck area of even a large ship. Generally it was found that it was not practical to consider photovoltaic cells for application in non-highway transportation.

● Prime Movers Evaluated

The eight prime movers that were considered in the preliminary screening are shown in Table 4. Most of these prime movers are used to some extent today in one or more of the modes, except for the last three prime movers. One area that was investigated in detail, was the use of fuel cells, since their potentially high thermal efficiency could make them an attractive prime mover.

Most of the prime movers in the non-highway transportation area are large in size. In the marine area, the size of the prime movers are in the 5000 to 45,000 horsepower range; in the railroad area 1500 to 3000 horsepower; pipeline 500 to 5000 horsepower or even greater in the case of some gas pipeline stations, and in the aircraft mode, 5 to 40,000 lbs. thrust, which is equivalent to around 60,000 horsepower at 550 miles per hour for the 40,000 lbs. thrust case.

Four major factors were considered -- the first one being the fuel manufacture, which includes the economics of production and transportation to the point of use, the overall energy efficiency, and the environmental impact in production. The second factor considered was fuel performance from the designer/user viewpoint using such factors as toxicity, safety, materials compatibility, storage requirements, convenience in handling and storage and the environmental impact during use. Third, the compatibility of the fuels

TABLE 4

PRIME MOVERS CONSIDERED IN PRELIMINARY SCREENING

-
1. BOILER/STEAM TURBINE
 2. GAS TURBINE--OPEN CYCLE
--CLOSED CYCLE
 3. DIESEL--LOW SPEED
--MEDIUM SPEED
 4. OTTO CYCLE--SPARK IGNITED
--STRATIFIED CHARGE
 5. ELECTRIC MOTOR
 6. STIRLING ENGINE
 7. FREE PISTON
 8. FUEL CELL/ELECTRIC

and the various prime movers was considered, including the efficiencies of the various prime movers with each fuel. And, fourth, logistics factors were evaluated, including availability of the fuels by a given time, compatibility with the present system, and international considerations. Only a few of the data bases that were used in the study will be discussed below. Additional details are in the Technical Section and the Appendix Volumes.

● Fuel Cost

One major consideration is fuel cost. The cost to manufacture the fuel was developed using data in the literature. The literature data were adjusted to a common basis as to a rate of return, plant size, cost of raw material, contingency, etc. Figures 2 and 3 illustrate the manufacturing cost on a \$/million BTU basis in terms of 1980 dollars for the various fuels considered. The shaded area represents the range of the cost in the literature. With some fuels the variability is quite broad. The absolute cost of any of these fuels will be highly uncertain until the plants are actually built and operational experience obtained.

Figure 2

Figure 3

Figure 4

Delivered Cost of Fuels
\$/MBTU (1980)

In addition to the manufacturing cost, it is necessary to consider the upgrading cost and the cost to move the fuel to the consumer. As shown in Figure 4, the delivered cost of the fuels ranges from \$0.9-1.60/million BTU's for coal to a high of around \$18-24/million BTU's for ethanol. This figure shows the breakdown as to the manufacturing cost, the upgrading cost (to meet current hydrogen levels for the syn-fuels or liquefaction cost for methane or hydrogen), and the distribution cost.

• Resource Requirements

Another factor considered was the basic resource requirement (Figure 5). By combining the process thermal efficiency with the energy required to transport the fuels, it is possible to calculate the amount of basic resources needed to supply a given amount of transportation energy. This figure shows that coal distillates, for example, would take around 1.8 BTU of basic resource to provide a BTU of energy at the point of use. In the detailed evaluation phase, this analysis was carried one step farther in that the efficiencies of the various prime movers were considered. Thus, an overall energy efficiency was calculated which takes into account all the energy lost in conversion to engine fuel, lost in transportation to the engine, and lost as reject heat at the engine itself.

• Fuel Availability

One of the logistics factors considered was fuel availability. The general consensus of when various alternate fuels may be available is summarized in Figure 6. The dashed line indicates possible dates, the solid line the more probable date. Most of the alternate fuels probably will not be available until around the year 2000.

Figure 5

Figure 6

ALTERNATE FUEL AVAILABILITY

		AVAILABLE BY		
		1980	1990	2000
COAL	- COAL			
	- OIL SLURRY			
	- SYN FUELS			
	- METHANOL			
	- HYDROGEN			
OIL SHALE	- LIQUIDS			
	- METHANOL			
BIOMASS	- METHANOL			
	- ETHANOL			
---		POSSIBLE		
---		PROBABLE		

● Methodology of Selecting Fuels for Detailed Study

A methodology was developed to select the fuels and prime movers for a more detailed study in a sound, logical, and technical manner. The four factors that were described earlier (fuel manufacture, performance, logistics, and engine/fuel compatibility) were used in combination with a Likert scale to rate the various fuels and prime movers. The ratings from each one of the four areas were then combined into an overall rating to allow the fuels to be placed into four groups.

● Fuels and Prime Movers Selected for Detailed Study

The fuels were grouped into four categories. The prime candidates were shale liquids, coal/oil slurry, coal, unrefined shale oil, coal liquids, and liquid methane. The second group contained fuels that may be of interest such as ethanol and methanol from coal. A third category were those that were considered borderline, realizing that there may be some special reasons why some of these would look attractive, for example, electricity for pipeline use and liquid hydrogen for aircraft. The last group are those which appeared to be clearly not attractive for non-highway transportation, which included ammonia, hydrazine, methylamine and acetylene. The prime movers that were selected for detailed evaluation are shown in Figure 7. All of the eight different types of prime movers were considered in one or more of the four modes. Fuel cells were considered in three different modes.

Figure 7

DETAILED EVALUATION

The second major area covered in this summary is a detailed evaluation by each mode. Each of the modes -- pipeline, marine, railroad, and aircraft will be described separately. For each of the modes, some background information will be presented, then the economics of the fuel/prime mover interaction will be described. A summary and the conclusions for each mode will be presented and what fuel choices are seen for each time frame along with some R&D ideas.

PRIME MOVERS CONSIDERED
IN DETAILED EVALUATION

	<u>RAILROADS</u>	<u>PIPELINES</u>	<u>AIRCRAFT</u>	<u>MARINE</u>
DIESEL	✓	✓		✓
STEAM ENGINE	✓			✓
STIRLING ENGINE	✓			✓
GAS TURBINES	✓	✓	✓	✓
FUEL CELLS	✓	✓		✓
OTTO CYCLE				
- STRATIFIED CHARGE		✓		
- SPARK IGNITED		✓		
FREE PISTON				✓
ELECTRIC MOTOR	✓	✓		

PIPELINES

Pipelines are basically divided into petroleum (with sub-divisions into crude and products); water and natural gas. In the petroleum area, the electric motor provides about 80 percent of the horsepower, while with water, the diesel supplies about 80 percent of the horsepower (this is primarily for agricultural wells). For the compression and transport of natural gas, the reciprocating gas engine supplies the majority of the horsepower. Most of the energy used by pipelines is attributable to compression and transmission of natural gas. (77%)

● Summary and Conclusions

LIQUID PIPELINES

Alternates considered included using a gas turbine or diesel with the fuel that was being pumped as well as an electric motor. If the fuel in the pipeline cost more than about \$4/million BTU's then an electric motor is expected to remain the most economical. If the fuel cost is less than \$4/million BTU, the choice between diesel or gas turbine depends upon the size of the prime mover. At 500 horsepower, the two types of prime mover are about equal; above this size, the gas turbine becomes more economical.

Figure 8

GAS PIPELINES

The conclusions on which fuels and prime mover may be attractive for are based on the data shown in Figure 8. In Figure 8, the annual operating cost of different types of prime movers is shown as a function of fuel cost. The annual operating cost includes the capital recovery for the equipment, operating and maintenance cost, and fuel cost. For a reciprocating gas engine and for a regenerative gas turbine, if the gas cost more than about \$4/million BTU's an electric motor is more economical. In comparing the overall energy efficiency, the electric motor is also the most attractive. This would mean that the electric motor would be better than a gas turbine for either SNG or hydrogen. Geographical location also has an impact on the choice of the prime mover. In the smaller size range, of around 500 horsepower, all three types of prime movers are about equal. Molten carbonate fuel cells (a second generation fuel cell) showed a small advantage over the gas turbine or the gas engine, but they do not appear to be as attractive as an electric motor/central power source.

Pipeline Economics Gases

● Future Outlook on Fuels and Prime Movers

The future outlook for liquid pipelines is that the major prime mover will remain the electric motor wherever electric power can be brought to the site. If this is not the case, then there may be limited use of advanced gas turbines with whatever liquid fuel is in the pipeline, be it unrefined shale liquid, coal liquids, or alcohols. For gas pipelines, the major prime movers in the future are likely to be electric motors, which is a switch from current practice where gas engines are more attractive due to the cost of gas being less expensive. There may be a limited use of advanced gas turbines, primarily with medium BTU gas.

● Possible R&D Ideas

The R&D ideas for alternative fuels for pipelines are limited since the most likely prime mover is forecasted to be an electric motor. Improvements in existing gas turbine drivers to increase their efficiencies is one possible R&D area. It may be worthwhile to follow R&D on the molten carbonate fuel cells and, if a major cost reduction (in the range of 25 percent for the fuel cells) takes place relative to electric motors, they may look attractive.

MARINE

The energy consumption in the marine transportation industry is highest for the foreign trade area which represents about 80 percent of the total energy used. Most of this energy is purchased outside the U.S. There are six other areas (pleasure craft, coastal, inland waterways, Great Lakes, fishing, and offshore) that consume about 0.5 quad total. Most of the effort of this study was concentrated on the foreign trade sector, but the other areas are also addressed.

The world trade fleet by type of prime mover and fuel used is summarized in Table 5. The diesel engine supplies the majority (72 percent) of the total horsepower with over half of the total horsepower being supplied by the slow speed diesel. Steam turbines supply about 28 percent of the total. About 45 percent of the fuel is supplied as blends of bunker and distillate.

TABLE 5

1977 WORLD FLEET INSTALLED HORSEPOWER

MILLIONS OF HORSEPOWER		HORSEPOWER SUPPLIED BY FUEL TYPE		
		BUNKER F.O.	BLENDS	DISTILLATE
STEAM	60	60	--	--
DIESEL				
LOW SPEED	115	35	80	--
MED. SPEED	33	--	14	19
AUXILIARY	10	--	--	10
GAS TURBINE	NEGLECTIBLE	--	--	--
TOTAL	218	95	94	29
ENERGY PER YEAR - %		45	43	12

● Summary and Conclusions

The conclusions and summary for ocean vessels are based on the economics shown in Figure 9. The annual operating cost for marine vessels in the 9,000 to 15,000 horsepower range are shown for four types of prime movers as a function of fuel cost. The annual operating cost is composed of a capital recovery factor (assumed as approximately a 10% DCF return), maintenance cost, and fuel cost (function of the prime mover efficiency and the fuel used). For new vessels at high load factors, steam engines using coal would be the most economical and the most energy efficient. Diesel and regenerative gas turbine would be

Figure 9

Marine Prime Mover Economics
9,000-15,000 HP

Figure 10

Marine Prime Mover Economics
9,000-15,000 HP

attractive if a liquid fuel could be obtained in the \$3/million BTU range. Perhaps this might be unrefined shale oil or perhaps coal/oil slurries, if they would work in a slow speed diesel. Free piston and simple gas turbines are not shown on this figure because they fall above the boiler curve. From a fuels quality standpoint, the current slow speed diesels should be able to operate on an unrefined shale oil. Vessels requiring less horsepower or vessels with lower utilization rates would probably stay with diesel power up to a fuel cost of \$6-7/million BTU. Some of the other types of engines, such as the Stirling engine, and use of fuel cells are covered in Figure 10. It appears that there is very little incentive for R&D on burning coal in gas turbines or diesel engines. The difference between the annual cost for the low-speed diesel with coal and the boiler with coal is not sufficient to justify a major R&D program. This also appears to be true for the case of the Stirling engine in this size range. The use of fuel cells also does not appear to be attractive for this application unless the cost of the fuel for any application would exceed \$6-7/million BTU's.

The basic resource requirement from the mine to propeller energy for using coal in the marine sector is summarized in Table 6. The most efficient would be to use coal/oil slurry in a diesel engine. Coal in a Stirling engine would be next, but the technology isn't available for a Stirling engine in this size range. The use of coal in a steam engine would be third, with the other prime movers as shown. Similar data are available for the other three modes in the technical report.

TABLE 6

RESOURCE UTILIZATION ON USING COAL
MARINE SECTOR

FUEL	PRIME MOVER	MINE-TO-PROPELLER ENERGY - KBTU/HP
COAL/OIL SLURRY	DIESEL	7.2
COAL	STIRLING	7.6
COAL	STEAM	8.3
COAL LIQUIDS	FUEL CELL (CO ₃)	9.8
	DIESEL	11.6
	REG. GAS TURBINE	14.0
	STEAM	15.3
	FREE PISTON	17.5

● Future Outlook on Fuels and Prime Movers

The future outlook for marine in the international trade is that for the present period, it is likely that vessels will continue on petroleum with the average fuel quality likely to get worse. In the mid term, the use of coal in steam power plants, particularly for colliers, and in large vessels, should be attractive. Coal/oil slurries may also be attractive in steam turbines and maybe in slow speed diesels, if the technology is

successfully developed. For smaller size ships, unrefined shale liquids would be attractive in the slow speed diesel engine. Longer range, most new construction, from an economic standpoint, will probably go to coal-steam boilers in large size vessels and diesels in small size vessels. The choice for medium size vessels will depend on the load factor. The fuel for the diesels could be unrefined shale oil distillate.

The outlook for other marine transportation is as follows. Great Lakes vessels are unique in that their lifetime is on the order of 50 years. For these vessels, it would seem that steam engines burning coal could be attractive, or diesels using either shale or tar sand oil would be likely candidates. For the vessels carrying Alaskan crude, they may remain on some type of petroleum product in a diesel or a combined gas turbine/steam turbine engine. Other coastal vessels may find coal attractive. Inland waterway vessels will probably remain with the medium speed diesel using shale oil distillate as fuel. Pleasure craft will likely go in parallel fashion to highway vehicles, using either IC engines or diesel engines. The fuel for pleasure craft would be gasoline or diesel fuels from shale or coal or perhaps the use of alcohols in an Otto cycle engine.

● Possible R&D Ideas

Some R&D ideas in the marine sector are as follows. A study on coal fired boilers for ocean vessels would be worthwhile. For example, fluidized bed combustion may be attractive for this area since it would offer flexibility to handle different types of coal. A study on the logistics of coal supply for vessels would be another area of interest. A study on using coal/oil slurry in slow speed diesels in existing vessels would be another area of interest. A study on the compatibility of shale and coal liquids with petroleum fuel would be of interest. Also, a study on the degree of upgrading of synfuels required to be usable in the various types of marine engines would be worthwhile.

RAILROADS

The third area considered was the railroads. Ninety percent of the energy is used in moving freight by the diesel/electric locomotives with distillate as the fuel source.

Figure 11

● Summary and Conclusions

The conclusions on future fuels and prime movers for the railroads are shown in Figure 11 where the annual operating cost for the various railroad prime movers is shown as a function of fuel cost. The diesel/electric is the most economical and energy efficient, and will be hard to beat. Coal in a Stirling engine

may be slightly cheaper, but overcoming the environmental problems may be difficult. The gas turbine would not appear to be competitive. Electrification, especially in densely populated areas, must be considered if the diesel fuel cost rises to around \$8/million BTU's.

The potential for using fuel cells/electric motors as prime movers on the railroads is shown in Figure 12. The fuel cells have a higher thermal efficiency than the diesel/electric and they may be more attractive in that they would not require any idling. The molten carbonate fuel cell would appear to be competitive if and when diesel fuel exceeds about \$5/million BTU's.

Figure 12
Railroad Operating Cost Freight

• Future Outlook on Fuels and Prime Movers

The outlook for fuels and prime movers on the railroads is that in the near term, it is unlikely that there will be any major changes with the major effort being in conservation. For the mid term, the use of shale distillates in the diesel/electric engine may be possible. Longer term, it is likely that shale oil distillate would continue to be used with the diesel/electric motor, with low probabilities for three long shots: (1) fuel cells, with either coal or shale naphtha; (2) Stirling engine with coal; (3) greater electrification, primarily in densely populated areas.

• Possible R&D Ideas

Some possible R&D ideas in the railroad area are as follows. A study could be made on using coal in the Stirling engine to see if it is even feasible from an environmental standpoint. A study should be made on using fuel cells in railroads to see if the volume of the equipment can be accommodated, would the fuel cells be affected by vibration? - would there be any safety problems to be overcome? An environmental assessment on using synthetic fuels in railroad diesels would also be an area worth studying. A trade-off study between maintenance cost and fuel costs for a medium speed diesel operating with synthetic distillate would also be worthwhile.

AIRCRAFT

The fourth area of non-highway transportation covered was aircraft fuels. Since about 95 percent of the aircraft fuel is jet type, the study concentrated on using this type of fuel in an aircraft gas turbine. Future aircraft fuels fall into two basic types: synthetics (shale oil distillate, coal liquids from direct and indirect processes, and tar sands), and cryogenic (liquid hydrogen and liquid methane).

Some properties of the future aircraft fuels are shown in Table 7. Liquid hydrogen has the highest heat of combustion on a weight basis. It also has the highest specific heat, which is a measure of its ability to be used as a coolant, primarily in supersonic flight. But liquid hydrogen has two disadvantages -- the density is low compared to synthetic liquids and the boiling point is very low (it is a cryogenic liquid).

● Summary and Conclusions

Each type of fuel has been considered for both subsonic and supersonic aircraft. The subsonic aircraft data shown in Table 8 are based on data from a recent study by Lockheed. The aircraft using liquid hydrogen would have the lowest weight which means that it would also require the lowest thrust per engine. Lockheed has estimated that the cost of all three of the aircraft would be essentially the same. With the lower weight, the liquid hydrogen fueled aircraft would require the least amount of fuel on a weight basis.

Using this data, the relative cost per flight of the various fuels is summarized in Table 9. Shale oil liquids have the lowest relative cost rating with coal derived liquids second, and liquid hydrogen being the most expensive. From a resource conservation standpoint, shale liquids would also be rated first, liquid methane second, coal liquids third, and liquid hydrogen fourth. For this reason, it is felt that liquid hydrogen would not be attractive for subsonic aircraft, unless major reductions are made in the cost of liquid hydrogen.

The supersonic aircraft data are given in Table 10. The supersonic data are not as complete as for subsonic aircraft, and two different sources have been used to develop

TABLE 7

	<u>SYNTHETICS</u>		<u>LCH₄</u>	<u>LH₂</u>
	<u>SHALE</u>	<u>COAL</u>		
HEAT OF COMB-KBTU/LB	18.5	18.5	21.5	51.6
LIQUID DENSITY-LB/FT ³	51	51	28	4.4
BOILING RANGE-°F	400-550		-259	-423
SPECIFIC HEAT-BTU/LB-°F	0.48		0.82	2.3

TABLE 8

SUBSONIC AIRCRAFT

5500 N. MILES, 0.85 MACH NO., 400 PASSENGERS

	<u>SYN. JET A</u>	<u>LCH₄</u>	<u>LH₂</u>
GROSS WT - K LBS	512	494	372
THRUST/ENGINE - K LBS	42	37	30
PRICE - \$ MILLIONS	44.5	47.4	43.4
BLOCK FUEL - K - LBS	160	129	48

TABLE 9

SUBSONIC AIRCRAFT

	<u>SHALE</u>	<u>SYN JET A</u>		<u>LCH₄</u>	<u>LH₂</u>
		<u>DIRECT</u>	<u>INDIRECT</u>		
FUEL COST/FLIGHT-k\$	14-15	17-28	19-37	25-35	41-47
RELATIVE COST	1	1.3-1.9	1.4-3.5	1.8-2.3	3-3.2
RELATIVE FUEL RESOURCE REQUIREMENTS	1	1.13	1.43	1.02	1.96

TABLE 10

SUPERSONIC AIRCRAFT

4000 N. MILES, 2.7 MACH NO., 250 PASSENGERS

	<u>SYN. JET A</u>	<u>LCH₄</u>	<u>LH₂</u>
GROSS WT., KLBS	842	765	504
RELATIVE THRUST/ENG	1	-	0.6
RELATIVE COST	1	-	0.74
BLOCK FUEL, KLBS	331	252	100

the information shown in Table 10. For the supersonic case, it is estimated that the LH₂ aircraft would cost only 74 percent as much as a synthetic fuel aircraft. Data are not available for a LCH₄ fueled aircraft.

The relative comparison for the various fuels is shown in Table 11. Considering only the fuel cost, the various fuels are ranked in the same order as for the subsonic aircraft. However, since the aircraft investment is different for the different types of fuels, it is necessary to consider this fact. Assuming 400 flights per year and a capital recovery factor of 0.2 for the aircraft, the relative cost for fuel and investment was obtained. On this basis, liquid hydrogen is about 1.5 times more costly than shale oil distillate.

The cost reduction needed to make liquid hydrogen attractive is about a 45 percent reduction in the cost of hydrogen in the supersonic case compared to shale oil distillate and only about a 17 percent reduction in liquid hydrogen compared to coal liquids. A larger reduction (71% for shale liquids and 47% for direct coal liquids) would be required for the subsonic case.

Therefore, for supersonic flights, synthetic Jet A is preferred; liquid methane may be attractive, and liquid hydrogen would only be attractive for supersonic aircraft for long-range flights.

Since it appears that jet fuels similar to those in current use are the most desirable, the technology for producing jet fuels from both shale and coal liquids has been reviewed. Lab tests have shown that acceptable jet fuels can be made from coal or shale oil liquids. Producing jet engine fuels from shale oil is more straightforward than producing the fuels from coal. Shale liquids would also be preferred over coal liquids from a compositional standpoint in the combustion process.

If coal liquids were used as jet engine fuels, the incentive to develop an engine to accept a fuel with a lower hydrogen content has been investigated with the results shown in Figure 13. The cost to upgrade coal liquids is compared to the cost to modify an engine to burn a more hydrogen deficient fuel. There would be an incentive of about \$400,000/year/engine to modify the engine compared to upgrading the fuel to the 13.5 percent H₂ level.

TABLE 11

	SUPERSONIC AIRCRAFT				
	SHALE	SYN. JET A		LCH ₄	LH ₂
		DIRECT	INDIRECT		
RELATIVE COST OF FUEL/FLIGHT	1	1.2-1.9	1.4-2.5	1.7-2.2	3-3.2
RELATIVE COST - FUEL + INVESTMENT OF AIRCRAFT	1	1.1-1.3	1.1-1.6	?	1.4-1.5
RELATIVE FUEL RESOURCE REQUIREMENTS	1	1.13	1.4	1.08	2.07

Figure 13

● Future Outlook on Fuels

The future outlook for aircraft fuels is that for the near term, there probably will be no major changes, but minor specification changes may be possible if supplies are tight. In the mid term a broadcut fuel may be used if NASA efforts are successful. There may be some shale distillates used near the year 2000. Longer range, the major replacement would be synthetic liquids with liquid hydrogen unlikely unless there is a need for long range supersonic flights.

● Possible R&D Ideas

Some possible R&D ideas for aircraft are as follows. It would appear to be worthwhile to firm up the potential for liquid methane, primarily for supersonic aircraft. It might also be worthwhile to look at ways to improve the yields of indirect coal liquids, particularly if shale oil development is postponed. It would also be worthwhile to obtain data on the storage stability of coal liquids at varying pretreatment levels. Engine studies on hydrogen deficient jet fuels would appear to be worthwhile as shown by the economic comparison. Trade-off studies between upgrading the fuel for thermal stability compared to modifying the fuel systems would be worthwhile. Consideration should be given to a study on processing alternates for shale liquids to improve storage and thermal stability.

GENERAL OBSERVATIONS

● Fuel/Prime Mover Interaction

The third major area covers some general conclusions.

There will be a renewed interest in engines that can accept lower quality fuel. For example as shown in Figure 14, a boiler/turbine and a Stirling engine are able to handle solid fuels. The diesel engine, with a fairly high thermal efficiency, can operate generally on poorer quality liquid fuels. The gas turbine, the Otto cycle, and the fuel cells require higher quality fuels. In general, the higher the quality, the higher the cost.

The comparison between engines from a fuel compositional standpoint is shown in Figure 15. The boiler, the Stirling, and the free piston engines are not sensitive to chemical composition. The gas turbine and the diesel generally require a more paraffinic fuel. The Otto cycle prefers an aromatic fuel. Fuel cells essentially require a chemically simple molecule such as hydrogen or CO.

Figure 14

Figure 15

As the fuel cost increases, engine efficiency will become more critical and the user will be willing to spend more on engines that can operate on a lower quality fuel. Fuel cost is important now but it is going to be even more important in the future. Fuel cost currently represents greater than 50% of the annual operating cost for all four of the modes.

- Fuel Substitution

In the fuel substitution area, the marine area appears to offer the most promise, since they are used to handling poor quality fuels. There would appear to be limited flexibility for the railroad mode. For aircraft, there is practically no flexibility with the present aircraft. Limited specification changes may be possible with some engine modifications. The pipeline mode is a special case, with no substitution possible in this area.

- Environmental Considerations

From an environmental consideration, aircraft currently have standards which require them to use some type of clean fuel. Pipelines also have current standards for stationary drivers that will require clean fuel. The railroads should not use a fuel that would give emissions that are worse than the current fuel in a diesel engine. For the marine area, it is necessary to use a clean fuel in port or for inland shipping, but on the open seas, it should be possible to use a poor quality fuel.

- Institutional Issue

In addition to the technical factors considered, the potential institutional issues were briefly addressed. The introduction of a new engine and a new fuel at the same time could create major problems.

- Military and International Considerations

From a fueling standpoint, it is necessary to have a fuel that would be available worldwide for the marine and aircraft modes. Also it is very important from an equipment standpoint to consider the international aspects for aircraft and railroad use. From the military viewpoint, a worldwide supply is important. They are interested in liquid fuels meeting current specifications with the synthetics coming primarily from shale oil.

- Use of Alcohol Fuels In Non-Highway Transportation

The use of alcohols in non-highway transportation would appear to be limited. In the case of aircraft, the energy density is too low to be attractive. In the marine area, cheaper boiler fuels are available. Miscibility with water would also be a problem. The use of alcohols in pleasure craft is a possible outlet. For pipeline, the electric motor would be more economical than burning the alcohol in a turbine. Railroads may offer a possible outlet. However, the lower energy density would require carrying additional fuel or limiting the range between fueling stops, plus it would mean some modifications to the diesel engine.

GENERAL CONCLUSIONS

The use of synthetic fuels in their pure form, unmixed with petroleum, will probably be after the year 2000 in the non-highway transportation sector. Initially, synthetics are likely to be commingled with petroleum products since they may be refined in existing facilities.

As was shown earlier, the time for change is long. This means that fuels similar to the current product will be needed for the next 20-30 years.

Aircraft, which represent the largest user of fuels in the non-highway area, would appear to offer the best potential to change to a new fuel.

The possible prime mover and fuels for each of the four modes in the long term is as follows. In the marine area, steam engines burning coal, or diesel engines with unrefined shale oil, or coal slurries are the prime candidates. With the aircraft gas turbine, synthetic liquids from either shale or coal would appear to be the most desirable fuels. Railroads will probably remain with the diesel/electric prime mover using shale oil as a source of distillate. Pipelines will probably use electric motors with the electricity being generated from coal or nuclear power.

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16. Abstracts <p>A planning study has been made for DOE on alternate fuels for non-highway transportation (aircraft, rail, marine, and pipeline). The purpose of the study was to provide DOE with a recommendation of what alternate fuels may be of interest to non-highway transportation users from now through 2025 and to recommend R&D needed to allow non-petroleum derived fuels to be used in non-highway transportation.</p> <p>In the near term (present-1985), there is unlikely to be any major change in the fuels used in any of the four modes of transportation except that the average quality of the marine fuel is likely to get worse. In the mid-term period (1985-2000), there will be a transition to non-petroleum fuels, based primarily on shale oil derived liquids assuming a shale oil industry is started during this time.</p> <p>(over)</p>																												
17. Key Words and Document Analysis. 17a. Descriptors <table border="0"> <tr> <td>Alternate Fuels</td> <td>Free Piston Engine</td> <td>Direct Solar Radiation</td> </tr> <tr> <td>Marine</td> <td>Stirling Engine</td> <td>Energy Supply/Demand</td> </tr> <tr> <td>Aircraft</td> <td>Closed Cycle Gas Turbine</td> <td>Institutional Issues</td> </tr> <tr> <td>Pipeline</td> <td>Physical Properties of Alternate Fuels</td> <td>Environmental Impact</td> </tr> <tr> <td>Railroad</td> <td></td> <td>Resource Requirements</td> </tr> <tr> <td>Prime Movers</td> <td>Otto Cycle Engines</td> <td>Energy Efficiency in Use</td> </tr> <tr> <td>Diesel Engines</td> <td>Nuclear Power</td> <td>Economics of Production</td> </tr> <tr> <td>Gas Turbines</td> <td>Fuel Cells</td> <td>Transportation Cost</td> </tr> </table>					Alternate Fuels	Free Piston Engine	Direct Solar Radiation	Marine	Stirling Engine	Energy Supply/Demand	Aircraft	Closed Cycle Gas Turbine	Institutional Issues	Pipeline	Physical Properties of Alternate Fuels	Environmental Impact	Railroad		Resource Requirements	Prime Movers	Otto Cycle Engines	Energy Efficiency in Use	Diesel Engines	Nuclear Power	Economics of Production	Gas Turbines	Fuel Cells	Transportation Cost
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16. ABSTRACTS (cont.)

The future outlook for possible prime movers and potential fuel sources for the long term (2000+) is as follows. In the marine area, steam engines burning coal or diesel engines with unrefined shale oil or coal slurries are the prime candidates. With the aircraft gas turbine, either synthetic liquids from shale or coal would appear to be the most desirable fuels. Railroads will probably remain with the diesel/electric prime mover using shale oil as a source of distillate. Pipelines will probably use electric motors as the major type of prime mover.

The Appendices cover the highlights of the study.

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