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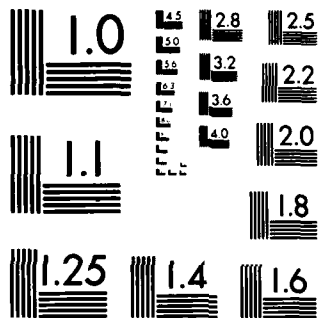
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SURVEY OF ALTERNATIVE FUELS FOR CORPS OF ENGINEERS DIESEL ENGINE POWERED DREDGES

**INTERIM REPORT
AFLRL No. 177**

By

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San Antonio, Texas

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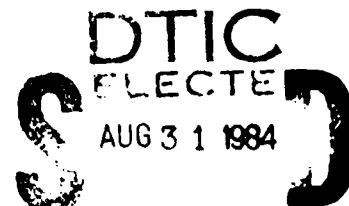
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The program described in this report was a brief survey of existing informa- tion on alternative fuels for the medium-speed class of diesel engines that is used on Corps of Engineer dredges. The alternative fuels of main interest were alcohols, vegetable oils, and liquid coal fuels. Available literature were reviewed and, where information was lacking, predictions were made of the effects of the candidate fuels on engine		

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20. ABSTRACT (Cont'd)

>performance, wear and durability. The fuels were then ranked according to potential for diesel fuel replacement, extent of required dredge retrofit, impact on engine wear and durability, and fuel cost and availability. The highest ranking nonpetroleum fuels, which were shale oil, vegetable oils and methanol, were recommended for a dredge field demonstration.

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FOREWORD

The work reported herein was conducted at Southwest Research Institute for the U.S. Army Fuels and Lubricants Research Laboratory (AFLRL), Southwest Research Institute, San Antonio, Texas under Contract No. DAAK70-82-C-0001 and covers the period January 1984 through April 1984. The work was funded by the U. S. Army Construction Engineering Research Laboratory (CERL), Champaign, Illinois through the U.S. Army Belvoir Research and Development Center, Fort Belvoir, Virginia. Contracting Officer's Representative was Mr. F. W. Schaekel, Fuels and Lubricants Division/STRBE-VF. The CERL Technical Monitor was Mr. Ben J. Sliwinski.

This study was performed jointly by the Departments of Engine and Vehicle Research and Energy Conversion and Combustion Technology at Southwest Research Institute. The SwRI Project Manager was Q. A. Baker, and the Principal Investigators were J. A. Russell and T. W. Ryan, III. The authors wish to thank SwRI engineers who provided comments and/or references in support of this study.



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I. INTRODUCTION

This report describes alternative fuels that can be used by dredges operated by the Corps of Engineers to reduce petroleum consumption. Energy conservation methods are another approach to reduce petroleum consumption, such as waste heat recovery or improved duty cycle operation, but far greater gains can be made by substituting a non-petroleum fuel for presently used diesel fuel.

There are a number of factors that must be considered when converting from diesel fuel to a non-petroleum fuel. Among these are safety in handling, material compatibility, and corrosion. The alternative fuel may not be suitable for direct replacement of diesel fuel due to its physical and chemical properties; as a result, the extent of engine and fuel system modifications must be considered. Engine performance, emissions, and wear are, of course, of concern as well as the cost and availability of the alternatives. Each of the above factors was addressed to the degree possible during this brief study.

The objectives of the study were:

- 1) Review and summarize the findings of research programs that dealt with the use of alternative fuels in medium-speed diesel engines. Alcohols, vegetable oils, and liquid coal fuels were of primary concern.
- 2) Determine the best alternative fuels for the Corps of Engineers dredges considering the retrofit requirements, operations and maintenance impacts, and fuel availability.

The program can best be described as a brief survey of existing information on alternative fuels for the medium-speed class of diesel engines. The intent of the project was to gather sufficient data to select the alternatives that are best suited for use in dredges. The approach taken to meet the objectives was:

- Review literature on hand, either SwRI generated or previously obtained from other sources. A literature search was not conducted although a few additional documents were secured.
- Predict the effects of candidate alternative fuels where data is not available based on experience with medium-speed diesels or small engines using similar fuels.
- Select the fuel that best meets CERL's needs.
- Define areas that require study before the selected fuels can be field tested.

Alcohols, coal liquids, synthetic fuels, vegetable oils, and petroleum alternative fuels are discussed individually in the following report sections. The fuels are then compared and ranked in Section VIII. The reader who desires a summary of the report findings should refer to Section VIII.

II. ALCOHOLS

There are four principal alcohols which are currently considered as candidates for fuels components in internal combustion engines. In order of increasing molecular weight these are:

- Methyl alcohol (methanol)
- Ethyl alcohol (ethanol)
- Propyl alcohol (isopropanol)
- Tertiary butyl alcohol (tertiary butanol)

These four basic alcohols are sometimes abbreviated as MeOH, EtOH, IPA, and TBA, respectively. Methanol and ethanol appear to be (at this time) the only viable candidates as supplements or alternatives to liquid hydrocarbon fuels such as gasoline and diesel fuel. Some of the higher alcohols are often blended with methanol and/or ethanol as "cosolvents" to inhibit phase separation. This is simply the separation of alcohol from the hydrocarbon fuel caused by the presence of excess water.

A. Process Descriptions

As mentioned above, the only two alcohols which show potential for large-quantity displacement of liquid hydrocarbon fuels are methanol and ethanol.⁽¹⁾ For this reason only the principal means of producing these two alcohols will be summarized here.

Methanol - Prior to 1926, when a synthetic process for producing methanol was introduced, the destructive distillation of wood was the only commercial source of methanol. This is why, even today, it is commonly referred to as "wood alcohol." At the present time, virtually all of the methanol produced commercially is made from natural gas (methane, CH₄). Prior to its emerging popularity as a liquid transportation fuel, this methane-derived methanol was mostly utilized by the petrochemical industry.^(2,3)

Another means of manufacturing commercial methanol uses synthesis gas as the starting material. Synthesis gas, by definition, is a mixture of hydrogen and carbon monoxide in any proportion. This definition is often extended to include carbon dioxide. There are many different sources of synthesis gas, such as coke oven gas, off-gas from catalytic reformers, and from the gasification of coal (as described under indirect liquefaction). The synthesis gas must be purified of all sulfur compounds to avoid catalyst poisoning during its conversion to methanol. It must also be "shift-converted" to the proper carbon-to-hydrogen ratio. The catalysts used for this conversion are chromium and zinc or copper oxides. The reaction takes place under conditions of elevated temperatures (400°C) and pressures (50-350 atmospheres). A diagram for the typical production of methanol from natural gas is shown in Figure 1.⁽⁴⁾ Correspondingly, processing of routes for coal conversion to methanol and other desired products are summarized in Figure 2.

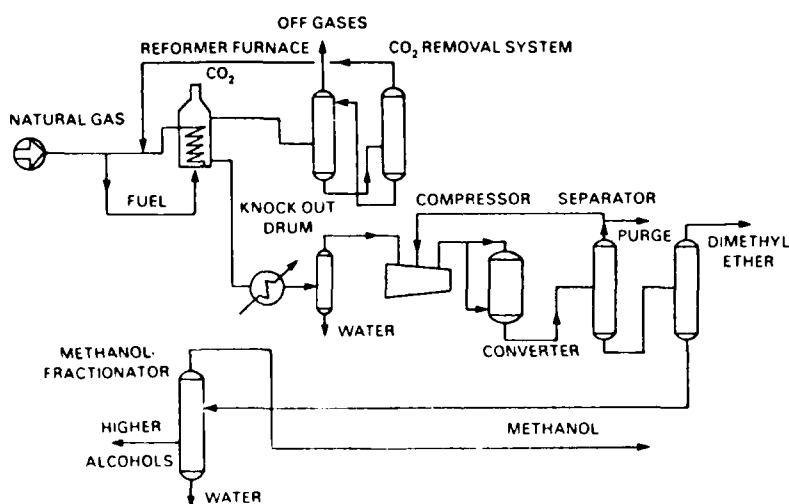


FIGURE 1 METHANOL PLANT

Another source of methanol is biomass. As a feed stock for making fuel, biomass has the advantages of being a renewable energy source and having a very low sulfur

content. Current research is directed toward gasification of various biomass materials to synthesis gas, and much of the technology is already available, but economics and circumstances have not yet favored its full use. Cellulosic materials can be gasified to produce synthesis gas for methanol production. Figure 3 shows possible biomass-to-fuel conversion routes.

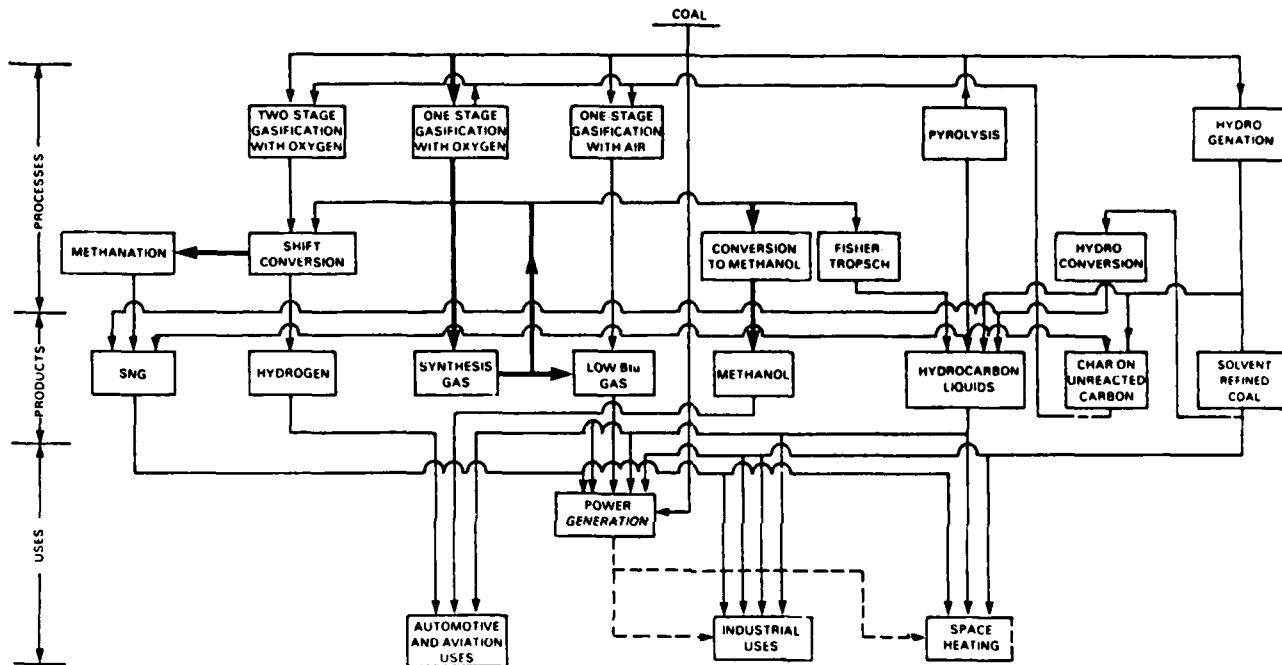


FIGURE 2 PROCESSING ROUTES FOR COAL CONVERSION

Ethanol - Popularly, ethanol is produced via the well-known fermentation, but most of the industrial ethanol is produced in the United States from ethylene during petroleum refining operations.

Alcohol fermentation is based upon the conversion of sugars to ethanol by the action of yeast. Black strap molasses has traditionally been the main source of sugar used in the production of ethanol via fermentation. It usually is obtained as a by-product from sugar mill operations, and has a sugar content of between 50-60 percent.

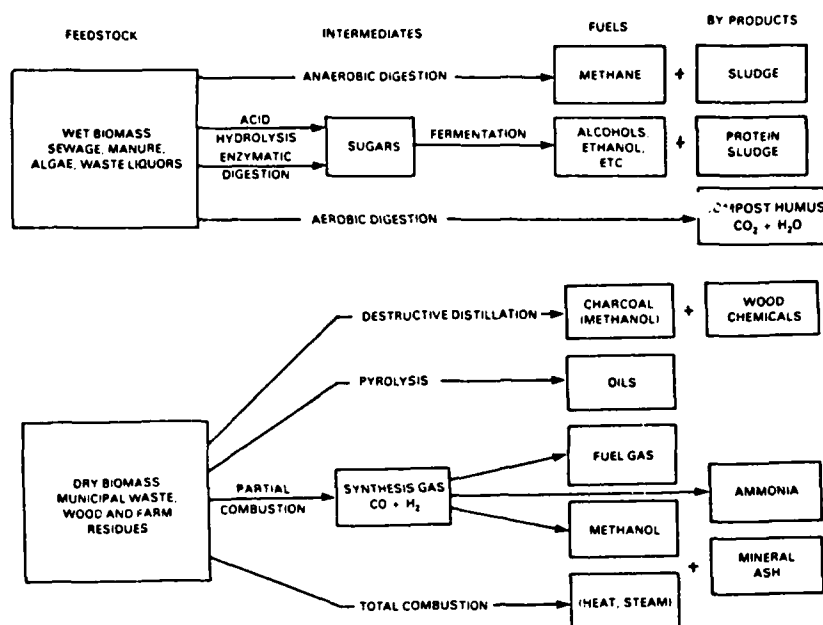


FIGURE 3 BIOMASS TO FUEL CONVERSION ROUTES

B. Alcohol Properties Comparison

Chemically, the alcohols differ from hydrocarbon fuels due to the presence of oxygen in the molecule. This is illustrated in Table 1.⁽⁵⁾ Since combustion in an engine is a process of rapid oxidation, the alcohol molecule can be considered to be already partially oxidized. This results in different fuel combustion characteristics, such as amount of oxygen required and volumes of resulting combustion products. The use of straight alcohols or alcohol blends to power internal combustion engines offers some potential advantages that could outweigh disadvantages when compared to gasoline or diesel fuel. Because of methanol's and ethanol's inherently high octane number (about 110)⁽¹¹⁾, these two liquids obviously offer great potential for spark ignition engines. Because of the inverse relationship between octane and cetane numbers, they show far less potential for diesel engines - without diesel fuel system modifications such as dual injection. Again, since dredge engines are diesel, information on product properties and product handling will be restricted to alcohol/diesel blends. Use of

Table 1 Some Properties of Alcohols, Gasoline and Diesel Fuel

Property	Methanol	Ethanol	Isopropanol	Tertiary Butanol	Gasoline	DF-2
Formula	CH ₃ OH	CH ₃ CH ₂ OH	(CH ₃) ₂ CHOH	(CH ₃) ₃ COH	Mixture of C ₄ to C ₁₂ Hydrocarbons	Mixture of C ₁₀ plus Hydrocarbons
Molecular Weight	32.04	46.07	60.09	74.12	100 - 115 average	180 - 200 average
Composition, wt%						
Carbon	37.5	52.2	59.9	64.8	85 - 88	87 - 88
Hydrogen	12.6	13.1	13.4	13.6	12 - 15	12 - 13
Oxygen	49.9	34.7	26.6	21.6	0	0
Specific Gravity, 60°F/60°F	0.796	0.794	0.789	0.791	0.72 - 0.78	0.83 - 0.86
Density, lb/gal	6.63	6.61	6.57	6.59	5.8 - 6.5	7.0 - 7.2
Boiling Temperature, °F	149	172	180	181	80 - 437	350 - 675
Flash Point, °F	52	55	53	52	-45	125 - 200
Autoignition Temperature, °F	867	793	750	892	495	550
Flammability Limits, vol %						
Lower	6.7	4.3	2.0	2.4	1.4	*
Higher	36	19.0	12.0	8.0	7.6	*
Energy Content, BTU/gal	64,600	84,610	93,620	100,830	124,850	134,550

* Not applicable to diesel injection.

alcohols in spark ignition engines is well-documented and will not be repeated here, save to state that, generally, methanol and ethanol can be used neat or blended with gasoline up to about 20 percent alcohol with no engine modifications. Above this level, fuel pump, carburetor jet, timing, and some fuel-wetted materials modifications may be required. Again, this is very engine-specific.

Methanol and other low-carbon-number alcohols in general have relatively high autoignition temperatures, and therefore do not satisfy cetane requirements of compression ignition engines. Numerous approaches have been explored to meet the cetane requirement. One approach has been to fumigate the engine with methanol, and supply diesel fuel through the injection systems for only ignition and additional power. This method proved unsuccessful. The incoming mixture of methanol and air produced unburned methanol emissions and poor combustion efficiency, especially at low load conditions, since the lean mixtures necessary at low load conditions cannot sustain flame propagation across the combustion chamber. Another method is by use of distillate fuel pilot injection to initiate combustion and methanol injection for the majority of the fuel heat input.

Methanol has a very limited solubility in diesel fuel unless the aromatic content is abnormally high. Dry ethanol, however, is completely soluble in diesel fuel as long as the water content of the fuel is less than 0.5 percent. Attempts to use co-solvents (TBA) have not been undertaken with diesel blends to any great extent. The formation of stable emulsions, rather than use of co-solvents to form alcohol/diesel fuel blends appears to be the trend of current research efforts. This approach solves the miscibility problem, but creates others, such as poor long-term storage stability and compatibility with other diesel formulations. Surfactants which permit emulsion stability are quite expensive, may poison filter/water separators, and can produce unwanted exhaust emission species.

The investigation into the applicability of methanol to compression ignition engines is being presently supported by the Departments of Energy (DOE), Transportation (DOT), and Defense (DOD), and the California Energy Commission. Field programs are mainly centered around municipal bus systems while laboratory work has been carried out on

commercial engines by a number of contractors. The primary emphasis is on capability to retrofit vehicles for methanol use.

The Alternative Fuels for Medium-Speed Diesel Engines Program, sponsored by the Association of American Railroads, Department of Energy and Department of Transportation, tested methanol and ethanol use in the form of emulsions and solutions with DF-2, and in a dual-fuel mode of operation.^(7,8,9) The results of these tests are discussed later in this section.

C. Special Characteristics

Toxicology - Of the four basic alcohols (methanol, ethanol, isopropanol and tertiary butanol), methanol is generally the most dangerous and ethanol the least. Methanol when ingested, even in small quantities, can be lethal. When inhaled, methanol vapors can cause headache, vertigo, nausea, convulsions, and even loss of vision. It is of interest that, while cutaneous exposure of neat methanol is reasonably tolerable, methanol/petroleum mixtures can be highly irritating to the skin. It has been suggested that this is because of the de-fatting effect from the petroleum constituent which enhances permeability of the skin to methanol.

Ethanol is medically classified as a depressant, acting primarily on the central nervous system. Its popularity as a beverage (in dilute form) is well-documented. Because of a somewhat euphoric intermediate stage on the road to total inebriation, many people think (incorrectly) that ethanol is a stimulant. It is interesting to note that, if an individual is alone, this apparent stimulant effect may not occur, but rather drowsiness and sleep. There are, of course, terminal blood alcohol concentrations from ingestion, but these are quite high when compared to the other basic alcohols. This is equally true of cutaneous absorption, but inhalation of ethanol vapors can be just as intolerable and suffocating as methanol vapors when concentrations of either alcohol go above roughly 40-60 mg/L of air.

Isopropanol, or "rubbing alcohol", is widely used in minor medical applications, even in the household. Obviously, cutaneous absorption, unless carried to extremes, is not a

significant problem. Intolerable inhalation levels are roughly the same as those for methanol and ethanol.

Interestingly, because of specific physiological reactions within the human system, isopropanol can be ingested at moderate levels, especially if undiluted, without serious permanent effect. The fatal dose of isopropanol for humans has been estimated to be approximately 166 ml.

Tertiary butanol (TBA) can be a skin irritant, and, if inhaled, may cause headache, dizziness, and dry skin. It has a toxic effect somewhere between ethanol and the propanols.

Safety in Handling - For those experienced in handling volatile and flammable liquids, alcohols and alcohol-hydrocarbon mixtures present no new problems. Handling toxic materials is also not a new procedure to refining operations or to powerplant operators. There are, however, a well-established set of recommended (and required) handling procedures associated with alcohol storage, transfer, loading and unloading. The procedures for ethanol differ from those of methanol mainly because of the greater toxicity of the latter.

The principal difference in dealing with alcohols is their wider range of flammable limits, compared to hydrocarbons. Like all hydrocarbon vapors (except methane vapor), alcohol vapors are heavier than air and will, therefore, collect in pockets in lower elevation. As shown in Table 2, alcohol vapors will produce explosive mixtures over a much wider range of concentrations than is the case for hydrocarbons. It must be assumed that alcohol-hydrocarbon liquid mixtures will exhibit this wider range of explosive limits in the vapor space above the liquid level (sometimes called "ullage space") in any container. Extra precautions are therefore indicated in handling such mixtures in refining, downstream operations, transporting, and utilization as fuels for internal combustion engines.

The data in Table 2 indicate that, unlike gasoline, the equilibrium vapor space above ethanol and methanol contains an explosive mixture with air.

**Table 2 Criteria for Evaluating Hazards
of Alcohol Fuels and Gasoline**

<u>Fuel</u>	<u>Flashpoint (°F)</u>	<u>Ignition Temperature (°F)</u>	<u>Flammability Limits In Air % Vol.</u>	<u>Saturation Volume (at 100°F)</u>
Ethanol	55	793	3.3 - 19	15%
Methanol	52	725	6.0 - 36	31%
Gasoline	45	700	1.4 - 7.6	68%

Source: U.S. National Alcohol Fuels Commission (1981), and National Fire Code Book.

In the interest of brevity, suffice to say that there are a well-defined sequence of criteria/regulations which govern alcohol operations from first aid to fire hazards (e.g., methanol fires are relatively invisible, witness Indianapolis 500 fires) to storage and handling and waste disposal.

D. Production/Market Penetration

Table 3(6) presents essential statistics on North American fuel alcohols. Although not shown in this table, total methanol production in 1983 was 1.2 billion gallons. Since the total production capacity is shown as 2.465 billion gallons, methanol production can be presumed to be operating at about 50 percent of total capacity. Ethanol-containing gasoline blends are rising steeply, probably because of the change in sales philosophy involving "super unleaded" as opposed to the old term of "gasohol." Methanol is just beginning to be introduced significantly within the past year and yet has already reached 3.65 percent market penetration.

E. Medium-Speed Diesel Engine Alcohol Conversions

The principle problem encountered in adapting a diesel engine to alcohol use is one of overcoming an inadequate fuel cetane number. Methanol and ethanol, the two principle alcohol candidates, have essentially nil cetane numbers. They cannot be used in an unmodified diesel engine.

**Table 3 United States Alcohol Fuels Industry
Year End, 1983**

FUEL ETHANOL PRODUCTION

# of Fermentation Ethanol Facilities	140	
Operating	73	
Non-Operating	67	
Total Anhydrous Production Capacity	700,010,000	(GPY)
Total Fermentation Production Capacity	772,510,000	(GPY)
Operable Anhydrous Capacity	493,060,000	(GPY)
Anhydrous Capacity Under Construction	216,740,000	(GPY)

NORTH AMERICAN METHANOL PRODUCTION (Gallons)

# of Methanol Production Facilities	17	
Total Production Capacity	2,465,000,000	
Methanol Fuel Sales	(N) 172,285,000	* (1983)
(1983) Methanol Fuel Sales	(N) 89,678,680	* (1982)

ETHANOL/GASOLINE BLEND SALES (Gallons)

Total U.S. "Gasohol" Sales (Projected)	4,435,445,000	* (1983)
Total U.S. "Gasohol" Sales	2,306,100,000	(1982)
Total U.S. "Gasohol" Sales	829,068,000	(1981)
% Change in 1983 vs. 1982	+92.34%	
% Change in 1982 vs. 1981	+178.16	

GASOLINE MARKET (Gallons)

Total U.S. Gasoline Sales	99,829,124,000	* (1983)
Total U.S. Gasoline Sales	98,548,000,000	(1982)
Total U.S. Gasoline Sales	101,960,000,000	(1981)
% Change in 1983 vs. 1982	1.30%	
% Change in 1982 vs. 1981	-3.35%	

MARKET PENETRATION LEVELS

Ethanol/Gasoline Blends (%)	4.44%	* (1983)
Ethanol/Gasoline Blends (%)	2.34%	(1982)
Ethanol/Gasoline Blends (%)	0.81%	(1981)
Methanol/Gasoline Blends (%)	(N) 3.65%	* (1983)
Methanol/Gasoline Blends (%)	N	(1982)

MAJOR ETHANOL FEEDSTOCKS

Corn, Corn Starch

MAJOR METHANOL FEEDSTOCKS

Natural Gas, Coal

ETHANOL GRAIN UTILIZATION CAPACITY

(Fermentation Capacity divided by
Average Feedstock Yields)

287,522,448 (Bu.)

* Projected by Information Resources

N Definitive Information Not Available at This Time

Numerous methods have been explored to overcome the cetane deficiency. Engine compression ratio can be increased to the point where methanol or ethanol will compression ignite. Unfortunately, the mechanical stresses associated with the high compression ratios are usually too high for standard production engines. Alternatively, the engine can be converted to spark or glow plug ignition. Detroit Diesel Allison recently converted a bus engine to 100 percent methanol operation using glow plugs, reducing scavenging air flow with only a modest increase in compression ratio.⁽¹⁰⁾ A similar conversion has not been attempted on a medium-speed diesel engine. Spark ignition is not attractive because of poor part load efficiency. Another approach is to fumigate the engine with methanol, and supply diesel fuel through an injection system for ignition. This method is undesirable in comparison with other conversion methods. The incoming mixture of methanol and air produce unburned methanol emissions and poor combustion efficiency, especially at low load condition, since the lean mixtures necessary at low load conditions cannot sustain propagation across the combustion chamber. A second dual-fuel method uses pilot diesel fuel injection to initiate combustion, which is followed by methanol injection, methanol providing a majority of the fuel heat input. This method has been tested successfully on medium-speed diesel engines and shown to produce high efficiencies along with good combustion characteristics.

The final conversion method is to mix alcohols and diesel fuel and inject the blend using conventional injection systems. Unfortunately, methanol and ethanol have very limited solubility in diesel fuel. Dry ethanol is completely soluble in diesel fuel as long as the water content of the fuel is less than 0.5 percent, but dry ethanol is not a good candidate because of its high cost and limited availability. Mixtures of alcohol and diesel fuel must be consumed in the form of emulsions, which may be either stabilized or unstabilized. Stabilized emulsions contain surfactants which prevent separation of the alcohol and diesel fuel. Unstabilized emulsions will separate quickly after blending.

The low volumetric heat content (BTU/gallon) and the poor lubricity of methanol and ethanol require modifications to the fuel system. The volumetric output of the injection system must be approximately twice that of a conventional diesel fuel system if the engine is to maintain full power output. This can present problems if limited space is available for the injection equipment, such as with the EMD unit injectors.

Lubrication can be provided to the injection equipment by mixing a small percentage, usually less than 5 percent volume, of a lubricant with the alcohol. Researchers have used castor oil, light petroleum lubricating oils and diesel fuel successfully as the lubricant. Another approach is to modify the injectors to provide forced lubrication of running fits.

Alcohol Emulsions/Solutions - The use of alcohols in emulsions or solutions with diesel fuel involves the least amount of engine and fuel system retrofit of the methods mentioned above. Stabilized emulsions and anhydrous ethanol/diesel fuel solutions are particularly attractive for this reason. These fuels can be handled like single component fuels. Modifications may be necessary to the fuel storage tank to comply with alcohol storage requirements and to prevent water contamination. Unstabilized emulsions require more extensive retrofit. The alcohol and diesel fuel are stored separately. An emulsifier is added to the fuel system, preferably as close to the engine as possible, to produce an emulsion on-line. Since the emulsion is unstable, return fuel from the injectors cannot be pumped back to the fuel storage tanks as is common practice. Instead, return fuel is led back to the emulsifier where it is remixed and consumed. Special precautions must be taken to purge the engine's fuel system of emulsions before the engine is stopped to prevent separation in the injection system.

It may be necessary to increase the volume output of the injection system in order to maintain full engine power output when consuming an emulsion. This modification is necessary because the volumetric heat content (BTU/gallon) of an emulsion decreases as alcohol content increases. The standard injection equipment on EMD and GE engines restricted alcohol consumption to 15 and 25 percent at rated speed and load, respectively.⁽⁹⁾ Emulsion tests using the above engines revealed that the amount of methanol or ethanol that can be consumed is limited by engine knocking. The cetane number of the emulsion is proportional to the volume content of alcohol and diesel fuel, and decreases as the proportion of the alcohol increases. A maximum of 30 and 25 percent volume of the alcohols was tested in the EMD and GE, respectively. Loud audible knocking was present at these alcohol inputs. Mild knocking was first detected at alcohol percentages of approximately one-half these levels. Thus, approximately 15 percent volume would be a practical limit. Thermal efficiency of the EMD is comparable to neat diesel fuel when operating on the alcohol emulsions at all tested

conditions, and on the GE at the higher speed and load conditions. However, the GE did not perform well on the alcohol emulsions at low speed and load conditions, generating high smoke levels and low thermal efficiencies.

Stabilized emulsions were tested in a two-cylinder EMD 567B engine⁽⁸⁾. The stabilized emulsions were found to be undesirable for two reasons. First, large quantities of a chemical stabilizer were required to produce the stabilized emulsions. This volume was very nearly equal the volume of alcohol. Second, performance of the stabilized emulsion was poor in comparison to unstabilized emulsions containing an equivalent volume of alcohol. Thermal efficiency of the stabilized emulsions were consistently below the unstabilized emulsions containing the same volume of alcohol. However, it should be pointed out that the stabilized emulsions may be attractive in an emergency situation because they can be handled like a single component fuel. If necessary, a stabilized emulsion could be used without any engine or fuel system modification.

Engine performance when using an anhydrous ethanol/diesel fuel solution was found to be very much like that of the 190 proof ethanol/diesel fuel emulsion. The advantage to using the anhydrous ethanol solution is that it can be handled like a single component fuel and it does not require a chemical stabilizer. The disadvantages are that anhydrous ethanol is more expensive than 190 proof ethanol, is not as commonly available, and separation will occur if the solution is contaminated with more than .5 percent volume water.

Dual-Fuel - A dual-fuel conversion is quite a bit more extensive than the conversion described above for alcohol emulsions, but offers the potential for high alcohol utilization. Tests conducted on an EMD two-cylinder engine^(2,8) indicated that from 85 to 95 percent of the fuel heat input requirement could be provided by methanol, the remainder being the pilot diesel fuel heat contribution.

Two separate fuel injection systems are required for dual-fuel operation, one for pilot diesel fuel injection and the second for alcohol. The addition of a second injection system usually requires cylinder head modification to permit installation of the second injection nozzle. An extra cam lobe may be needed for each cylinder to actuate the second injection pump.

Independent storage of the alcohol and diesel fuel is required. Finally, a lubricant must be added to the methanol to achieve adequate alcohol injection equipment life. Since diesel fuel will be stored on board the dredge, it is most convenient to emulsify 2 to 3 percent volume diesel fuel into the alcohol to act as the lubricant.

Reasonably good engine performance has been achieved using a laboratory medium-speed diesel. Alcohol utilization was high as mentioned above. Thermal efficiencies were approximately equal to levels recorded when the engine was operated in its normal diesel fuel configuration. The engine could be operated without knocking at its standard compression ratio.

The majority of the research to date in the area of alcohol's use in diesel engines have not addressed the long-term impact of alcohol fueling. Of particular interest are engine durability, suitability of existing lube oils, and lube oil degradation. The study currently underway for DOE using methanol in Detroit Diesel powered buses may provide some insight into the areas.

III. COAL LIQUIDS

There are a variety of categories of coal ranging from low grade (lignite) through medium grades (subbituminous and bituminous), to high-quality (anthracite). Because of variation in water and ash content, energy content for these categories range from about 5000 BTU per pound for lignite up to about 15,000 BTU per pound for anthracite (which is used almost exclusively in the steel industry). Lignite and bituminous comprise by far the majority of domestic coal.

A. Process Description

It is technically possible to make diesel fuels of varying qualities from these several grades of coal. These processes can be divided into two main groups:

- Direct liquefaction (COED, H-Coal, SRC-II and EDS)
- Indirect liquefaction, or gasification (Sasol)

Individual processes, properties and problems are discussed below. Technology has been developed to produce coal liquids (not necessarily finished diesel fuels) and demonstrated at various levels of output. To date, no plans have been announced for any commercial coal liquefaction operations in the U.S. This will only happen when the economics of coal liquefaction compare favorably with those of other resources (petroleum, shale). Current projections do not show this occurring until 1990 at the earliest and more likely at sometime past the year 2000. It must be emphasized that it takes from 5 to 7 years to design and build a coal liquefaction plant. Even when this occurs it is also important to note that products from the first plants built may not be available all over the United States but just in localized marketing areas.

It is further possible (and even necessary for this discussion) to subcategorize direct liquefaction into the following as shown in Figure 4:

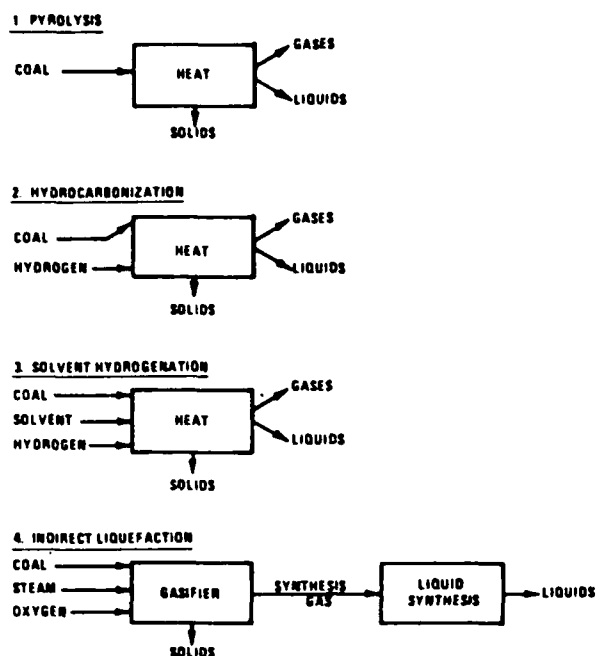


FIGURE 4 CLASSIFICATION OF COAL LIQUEFACTION PROCESSES

- Pyrolysis - coal is simply heated to produce solids, liquids, and gases (COED)
- Hydrocarbonization - coal and hydrogen together are heated (no candidate processes)
- Solvent hydrogenation - coal, hydrogen and appropriate solvent are heated at temperatures to 850°F and pressures to 3000 psi (H-Coal, SRC, and EDS)
- Indirect liquefaction - coal is reacted with steam and oxygen in a gasifier to produce synthesis gas (mainly hydrogen and carbon monoxide) which is then passed through a catalyst bed for which catalyst, temperatures, pressures, and flow rates are adjusted to produce the desired product slate (Sasol)

COED (Char-Oil Energy Development)(12)

The COED project was conducted by the FMC Corporation at Princeton, New Jersey in the early 1970's. The COED process converts coal to gas, oil, and char through heating in multi-stage fluidized beds. In this process, coal is first crushed and dried, then pyrolyzed in a series of four fluidized-bed reactors with successively higher temperatures. Heat for pyrolysis is provided primarily by burning a portion of the char with oxygen in the presence of steam in the fourth stage of pyrolysis. (Nitrogen is used for startup to fluidize the first stage until enough flue gas is available.) Hot gases from the fourth stage flow counter-current to the char. These gases, which provide the fluidizing medium for the third and second stages of pyrolysis, are then passed to a product recovery system where the gas and oil are produced. Product distribution based on Illinois No. 6 coal is approximately 60 percent char, 20 percent liquid and 15 percent gas, with the remainder solid matter.

By June 1974, the COED pilot plant had processed 18,000 tons of coal. Six different coal types were tested (lignite to bituminous); liquid yields ranged from 0.4 to 1.5 barrels/ton of coal, depending on the feed coal type. COED syncrude was successfully used as a bunkering fuel for a U.S. Navy destroyer in 1974 in tests conducted as a part of the U.S. Department of Navy "Project Seacoal."

Tabular comparison of COED liquids and liquids from other coal processes will be given below.

H-Coal Process (12)

H-Coal was developed by Hydrocarbon Research Incorporated as an extension of their H-Oil process which desulfurizes heavy residues and converts them to lighter oils. In 1962, DOE (then ERDA), Electric Power Research Institute, Ashland Synthetic Fuels, Conoco Coal Development, Mobil Oil, Standard Oil of Indiana, and the Commonwealth of Kentucky began with a bench-scale unit which evolved to a 3.0 ton/day unit. These same sponsors continued to back a 200-600 tons/day plant at Catlettsburg, Kentucky operated by Ashland Oil. Ashland projected feasibility of a 50,000 bbl/day plant on the basis of the Kentucky pilot plant.

Five major steps are involved in H-Coal process are:

- Coal pulverization
- Slurry preparation
- Hydrogenation
- Separation
- Slurry oxidation/recycle and product collection

In a reactor, coal reacts with recycled oil and hydrogen in the presence of a catalyst. Reaction temperatures and pressures are varied to determine the net product yield and product slate requirements. High severity (high degree of hydrogenation) yields only a distillate material while low severity yields a distillate and heavy fuel oil. Also, upward liquid flow causes the catalyst bed to expand and fluidize, called ebullating (or boiling). Since the catalyst is in constant motion, a portion can be withdrawn and replaced with regenerated catalyst at any time during reaction so that high catalyst activity can be maintained.

SRC (Solvent Refined Coal)(12)

Intense efforts on SRC-II were begun in about 1978-79 by Gulf Oil Company who foresaw some competition for a liquid product with high-sulfur coal wherever small boilers operate at low-load factor such as in manufacturing plants. The major market would be for fuel oil, the largest SRC-II product. In the SRC-II process, the coal-solvent slurry is recycled as the feed stream rather than using fresh distillate material. A large proportion of coal is converted to liquids and gas which can be distilled, thereby eliminating the problem of separating solids by filtration (which had been a major problem in SRC-I). The solvent is a high aromatic fraction provided from the coal and recovered in the distillation steps. Five major steps are involved in the conversion of raw coal to finished products by SRC-II:

- Coal pulverization
- Slurry preparation
- Hydrogenation
- Distillation
- Slurry recycle and product collection

SRC-II fuel oil has a lower viscosity and contains less sediment and sulfur than either petroleum No. 4 or No. 6 burner fuels. However, it has a slightly higher nitrogen content and density. Because of its low hydrogen content, it has a lower heat of combustion per unit weight than do petroleum fuels. SRC-II middle distillate has properties similar to petroleum No. 2 burner fuel, the main difference being higher specific gravity and viscosity. It contains a high proportion of aromatic (cyclic) compounds which have poor ignition performance (cetane number) in diesel engines.

Exxon Donor Solvent (EDS)(12,13)

The EDS process was the result of 10 years of coal liquefaction research by Exxon Corporation and was entirely self-funded. The work culminated with a one ton/day pilot plant. In 1976, Electric Power Research Institute and DOE, through a cooperative agreement with Exxon, helped to construct a 250 ton/day pilot plant which was completed in 1980 with Exxon as chief operator.

The EDS process is similar in some respects to the SRC-II process, except that the recycle solvent is treated catalytically to restore its hydrogen content. The solvent then acts as a hydrogen donor after being mixed with the coal. The major steps in the EDS process are:

- Coal pulverization
- Slurry preparation with hydrogenated recycle (donor) solvent
- Hydrogenation
- Distillation
- Recycle (donor) solvent hydrogenation
- Bottoms recycle

The heavy bottoms stream is fed to a Flexicoking unit which, by thermal cracking, produces high yields of liquids and gases from organic material in the unconverted portion of the coal.

Middle and heavy distillate EDS products are mostly aromatics, (about 85 percent), some asphaltenes and a few saturates, whereas comparable petroleum fractions are better than 50 percent saturates. The coal-derived distillates are suitable for use as burner oils, but low cetane number (caused by higher aromatics content)

make them unsuitable for diesel fuels. High severity hydrogenation processing is required to saturate the aromatics and increase the cetane number. The hydrogenation also reduces nitrogen and sulfur contents, and improves stability.

Sasol (Indirect Liquefaction)

"Sasol" is an acronym stemming from the South African Coal, Oil, and Gas Corporation. It is the only indirect liquefaction process which currently produces liquid hydrocarbon fuels from coal in commercial quantities. It is based upon technology known as "Fischer-Tropsch synthesis" which South Africa developed in the 1950's based upon German technology in the 1930's and 1940's which, in turn, was based upon technology developed in the United States circa 1925.

Fischer-Tropsch liquefaction is complex when compared to other processes. The major steps in conversion are:

- Coal pulverization
- Delivery to ash removal and gasifier
- Steam and oxygen addition
- Gas production
- Gas to heat exchanger and shift converter
- Separation of tar, sulfur, carbon dioxide, and acid gas
- Liquefaction
- Heavy-light hydrocarbons separation
- Tail gas reforming
- Light oil, gas, and hydrogen separation
- Hydrogen recycle
- Light hydrocarbon isomerization and cracking

Liquefaction occurs in circulating catalytic fluidized bed reactors, and product composition is dependent on operating conditions.

Coal Liquid Technology Problems

COED - The char product from the COED process contains too much sulfur to be advantageous to consumer power companies in the United States, although the product oil and gas may be marketable.

H-Coal - When producing heavy oil, separation of solids (such as ash) from heavy liquids presents difficulties. A de-ashing unit may be a necessary solution.

SRC-II - The aromatics content of SRC-II middle distillate is high (about 75 percent as compared to 30 percent for petroleum distillates), rendering it unsatisfactory for diesel engine applications and for use as home heating oils without severe hydrotreating which drastically increases cost. SRC-II middle distillate has been used as a blend stock with conventional No. 2 petroleum diesel fuel, but blends containing more than 35 volume percent coal-derived material are too low in cetane number for use in conventional, unmodified engines.

EDS - EDS fuel oil may be incompatible with petroleum fuels. Separate storage and handling facilities would be necessary for a plant using both EDS and petroleum products. Additional upgrading by hydrogenation will be necessary; it is technically feasible to do so but may not be economically attractive.

B. Product Properties Comparison

Of the four direct liquefaction processes described above, COED is essentially obsolescent while the other three (H-coal, SRC-II, EDS) have been developed through demonstration plants. None of these processes generate what might be called a "specification-quality" finished distillate fuel comparable to finished petroleum diesel fuels. The products from these four processes would best be thought of as intermediate feed streams, each requiring further processing (typically hydrotreating) for upgrading to a finished product. Nevertheless, most properties are available for each of the four processes and are compared to a high grade petroleum diesel fuel in Table 4.(12, 13,14,16)

COED

Note that the fuel has a 24 cetane number (typical of intermediate coal liquid feed streams) as compared to typical petroleum diesel fuel minimum requirements of about 40 cetane number. Also, gravity was 18.4° API - quite dense, as confirmed by 9.78 cSt viscosity and 55°F pour point.

**Table 4 Comparison of Coal Liquids Properties
with Typical Petroleum Diesel Fuel**

	<u>Petroleum No. 2 Diesel</u>	<u>COED</u>	<u>H-Coal</u>	<u>SRC II</u>	<u>EDS</u>	<u>Sasol</u>
Gravity, °API	35.9	18.4	24.8	12.3	16.5	44.5
Specific Gravity	0.8453	0.9440	0.9053	0.9840	0.9560	0.8040
Distillation, D86, °F						
IBP	410	300	410	368	376	374
10%	458	300	423	412	427	392
50%	508	460	457	473	500	434
90%	589	760	541	553	675	643
EP	648	875	587	613	695	760
Recovery %	98.5	*	98.5	99.0	*	99.0
Residue	1.5	*	1.0	1.0	*	1.0
Loss	0.0	*	0.5	0.0	*	0.0
Viscosity, cSt @ 100°F	2.74	9.78	2.25	3.68	3.89	2.09
Flash Point, °F	175	145	*	176	190	160
Pour Point, °F	-10	55	*	-54	-11	5
Hydrocarbon Type (FIA) vol %						
Aromatics	28.3	47.0	*	91.2	*	24.0
Olefins	1.3	*	*	0.7	*	0.0
Saturates	70.4	*	*	8.1	*	76.0
Elemental Analysis, wt%						
Carbon	86.39	82.48	87.20	86.15	88.50	85.70
Hydrogen	13.15	12.97	11.44	8.64	10.30	14.00
Oxygen	0	0	0.02	3.90	0.99	0.01
Nitrogen	0	0.403	0	0.82	0.12	0
Sulfur	0.31	0.02	0.006	0.26	0.09	0
Hydrogen/Carbon Atom Ratio	1.81	1.83	1.57	1.19	1.40	1.96
Net Heat of Combustion BTU/lb	18,210	17,782	*	17,200	17,629	18,884
Cetane Number	54	24	*	16	21	50

* Not available

H-Coal

The physical properties shown in Table 4 would strongly indicate that while stability would probably be very good because of the relatively high hydrogen content, cetane number (not reported) would likely be quite poor (on the order of 20-25).

SRC-II

The SRC-II liquid had only a 16 cetane number. Aromatics content (a precursor of engine deposits and high particulate emissions) was 91.2 as compared to 28.3 for the neat petroleum diesel fuel.

On a more optimistic note, this coal liquid has been shown to be miscible with petroleum diesel fuels and, given that most medium-speed diesel engines have a minimum cetane requirement of about 35 (this is a generality and is highly engine-dependent), it would appear that about 30 percent SRC-II could be blended with a typical No. 2 diesel fuel as a maximum combination.

EDS

The EDS liquid was of considerably higher density (specific gravity of 0.956 as compared to about 0.8453 for diesel fuel), but viscosity at 100°F was 3.89 cSt, which meets the No. 2 diesel specification. Low temperature testing (0°C) of the EDS liquid resulted in formation of crystals in the fuel, obstructing flow through the viscosity meter and obscuring the results. These were attributed to a component of the fuel (naphthalenes). It must again be re-emphasized that this coal liquid was an intermediate feed stream, not a finished fuel, but was typical of EDS product.

As with the SRC-II fluid (above), cetane number was 21.0, quite low and probably unacceptable in most diesel engines.

Sasol (Indirect Liquefaction)

As mentioned previously, Sasol is the only commercial-scale activity in the world producing finished fuels from coal. Sasol diesel fuel compares favorably (even excellently) with petroleum products: cetane number was 50. Aromatics content (an indicator of engine deposits and potential emissions and cetane number problems) was quite low. Further, olefins (an indicator of potential storage stability problems) was 0.0 for the diesel fuel.

C. Coal Liquid Use in Medium-Speed Diesel Engines

The primary obstacle for use of present coal liquids is the cetane number. COED, H-Coal, SRC, and EDS have cetane numbers in the mid- to low 20's range. Sasol is the only product which is suitable for direct replacement of diesel fuel. This product is already in use in medium-speed diesel engines in South African railways.

Medium-speed diesel engine tests have been conducted using EDS and SRC-II. The methods used to overcome the poor ignition characteristics were blending of the coal liquid with diesel fuel to achieve reasonable cetane quality, and dual-fuel operation using pilot diesel fuel direct injection to initiate combustion.^(8,13)

Fuel odor, materials compatibility, and safety in handling are also of concern when considering a coal liquid conversion. With the exception of Sasol diesel fuel, the coal liquids have a very pungent and displeasing odor. Fuel tank venting must be so arranged that fumes are carried away from the dredge. Fuel leaks and fuel spills must be tightly controlled, not only to control the odor problem but to minimize direct contact with the liquid fuel. EDS and SRC-II were found to attack common sealing materials such as Viton, Neoprene, and Buna-N. Common rubber fuel hose cannot be used with these products.

Blends of Coal Liquid with Distillate Fuel

The results of test programs conducted on a General Electric 7FDL and a Cooper-Bessemer LSV-16-GDT engine demonstrated that it is feasible to consume EDS

middle distillate in medium-speed diesel engines.⁽²³⁾ The amount of EDS that can be blended is limited by the cetane tolerance level of the engine. The General Electric 7FDL consumed a blend of 30 percent EDS and 70 percent No. 2 diesel fuel by volume, with a resulting cetane number of 39, without causing diesel knock. The Cooper-Bessemer, which is of larger displacement and slower operating speed than the GE, operated on up to 66.7 percent EDS and 33.3 percent No. 2 diesel fuel, with a cetane number of 30, without excessive knocking. Fuel filter plugging problems were encountered during both the GE and Cooper-Bessemer programs. The cause of the filtration problems was not determined; a solution is essential for practical use of EDS/No. 2 diesel fuel blends for dredge operation.

Exhaust gas emission levels can be expected to increase when consuming coal liquid/diesel fuel blends. NO_x and CO increased slightly as the concentration of EDS in the blend increased in the case of the Cooper-Bessemer engine, and NO_x and unburned hydrocarbon levels increased with the General Electric. Of greater interest may be the odor of the exhaust. Engine operators reported that the exhaust odor was similar to that of the coal liquid fuel and was quite noticeable.

Neither of the above programs ran for sufficient time to determine the effects of the blend on engine wear. A program to investigate long-term effects on engine and fuel system components is recommended prior to field application of EDS or any of the direct liquefaction coal products.

Dual-Fuel Coal Liquid Conversion

Dual-fuel medium-speed diesel engine conversions have successfully demonstrated that high coal liquid utilization is possible. The drawback to this approach is that the dual-fuel engine conversion is quite extensive. A second injection system must be added to inject a small amount of pilot diesel fuel before injection of the coal liquid occurs using the normal engine injection system. Separate diesel fuel and coal liquid storage and handling systems are necessary.

The General Electric 7FDL engine mentioned above operated at efficiency and power levels within 3 percent of normal diesel fuel operation when consuming 85

percent heat input EDS, the remainder being pilot diesel fuel. This level of pilot fueling was considered to be high. Coal liquid utilization between 90 and 95 percent heat input can be expected from a finely tuned dual-fuel engine. Engine wear and emissions data were not gathered during these experiments. Again, investigation of long-term effects is recommended prior to field evaluation.

D. General Summary of Coal Liquids

With the exception of the Sasol indirect liquefaction process, no commercial-scale activities (or even pilot plant level activities) have carried completely through to providing a product slate of finished fuels from coal. For this reason, the above descriptions of product properties and their comparisons with petroleum finished fuels, plus their blending characteristics with these petroleum fuels must be considered tentative, since at present there are no well-defined plans or programs to raise coal liquefaction technology to commercial production levels. Technically, this can be done but process economics (particularly the need for severe hydrotreating of intermediate coal liquids) results in coal processing technology comparing most unfavorably with petroleum refining technology and economics, and also with technology and economics as extrapolated for domestic oil shale (discussed below). Further, the toxicological properties of coal fluids examined to date (again with the exception of Sasol) strongly indicate that extreme caution in handling must be taken. Inhalation of coal liquid vapors and cutaneous absorption (through the skin) in pilot plant operations in the United States and in laboratory studies have resulted in a number of cases where technicians have incurred headaches, rashes, etc. Experiments with laboratory animals indicate that intermediate feed stream products are potentially carcinogenic, although absolute evidence of this is still lacking and conclusions are somewhat tentative.

Coal products available from today's direct liquefaction processes are undesirable for dredge application because of poor cetane quality and poor handling characteristics. None of the four products discussed are in production. Nonetheless, tests have demonstrated that it is feasible to consume direct liquefaction products in blends with DF-2 or in a dual-fuel mode. Little is known about long-term engine effects or exhaust emissions. Fuel filtration is a documented problem.

Sasol diesel fuel is a high quality product suitable for direct DF-2 replacement.
Unfortunately, this product is not available in the U.S.

IV. SYNTHETIC ALTERNATIVE FUELS

The term "synthetic fuel" has been much-abused in recent years. For the purpose of this report, synthetics will be limited to shale oil and tar sands bitumens. (It also usually includes coal liquids, but these have been covered above.)

A. Shale Oil

To date, the only specification-quality finished diesel fuel derived exclusively from shale has been for the Paraho II operation in 1977-78 which produced some 80,000 barrels of JP-5 jet fuel and marine diesel fuel (DFM) which, since the shale crude was so extensively hydrotreated, also qualified to DF-2 specification criteria. Properties of the finished products for both the Paraho II JP-5, and DFM are given in Table 5.

These two distillate fuels were, because of their high visibility, refined at the SOHIO Toledo facility to such high quality that they have been variously described as "vanilla ice cream" and "too good to burn in an engine." These comments, offered partially in jest, do serve one most important purpose: pilot runs of shale fuels for the next few years will be somewhat misleading and production runs may be aberrant. Again, because of their high visibility, they will very likely be refined to such high quality that they will exceed any and all specification criteria (and will be correspondingly expensive). As the shale fuel industry matures, it can be anticipated that product slate quality will deteriorate as sacrifices in refining process operations are made in the name of "process economics" (more simply, net profit). This will likely not begin to occur for the next four or five years but it is a rather obvious prediction, since shale fuels can never be competitive with petroleum counterparts until either (a) processing costs are reduced, or (b) worldwide petroleum crude is depleted to the point where the point supply/demand forces petroleum prices drastically upwards. A third scenario might be one in which a Middle East war interdicts the supply line for petroleum crudes for a significant period of time (say, two or three years). This would certainly serve to accelerate maturation of the shale fuel industry, since some 85 percent of the world's shale fuel reserves (several billions of barrels of oil equivalent) are located in the U.S.

Table 5 Shale Oil Properties

Description	Base DFM PARAHO-II	PARAHO JP-5
Gravity, °API @ 60°F (16°C)	38.7	43.5
Flash Point, °F (°C)	175 (79)	144 (62)
Cloud Point, °F (°C)	32 (0)	
Pour Point, °F (°C)	-10 (-23)	
Freeze Point, °F (°C)		-60 (-51)
Viscosity, @ 104°F (40°C), cSt	2.60	1.38
Distillation, °F (°C)		
IBP	400 (204)	
10%	448 (231)	373 (189)
20%	468 (242)	378 (192)
50%	508 (264)	396 (202)
70%	530 (277)	
90%	560 (293)	442 (228)
End Point	584 (307)	478 (248)
Residue, vol%		1.5
Loss, vol%		0
Carbon Residue, wt%	0.09	
Sulfur, wt%	0.00	0.005
Copper Strip Corrosion		
3 hrs, 122°F, (50°C)	2b	
2 hrs, 212°F, (100°C)		2c
Ash, wt%	0	
Water and Sediment, %	0	
Accelerated Stability, mg/100 cm ³	0.09	
Thermal Stability, (JFTOT)		
P, mm Hg		0
Deposit Code		1
TAN, mg KOH/g	0.01	0.00
Particulate Contamination, mg/l	0.4	0.1
Cetane Number	48.6	
Hydrocarbon Types, FIA, vol%		
Saturates	67.8	
Olefins	1.6	2
Aromatics	30.6	22
Nitrogen Content, wt%	0.004	
Hydrogen Content, wt%		12.65
Peroxide Number, ppm	0	
Aniline Point, °F (°C)		140.7 (60.4)
Net Heat of Combustion		
MJ/kg		42.89
Existent Gum, mg/100 cm ³		0.0

Of further interest to Corps of Engineers is a recently initiated large-scale shale distillate production program wherein the Defense Fuel Supply Center (DFSC) has contracted with Union Oil Company and Gary Refining Corporation to produce 10,000 bbls/month of shale-derived JP-4 and DF-2 for use by the USAF and the Army at Hill AFB, Utah, Mountain AFB, Idaho, and Dugway Proving Ground, Utah. This will be for field validation checkout of shale fuel in USAF aircraft, Army rotary- and fixed-wing aircraft, and USAF/Army tactical/combat and commercial ground vehicles. First delivery of these JP-4 and DF-2 materials is scheduled for June 1984 and will continue for at least one year, after which a determination of the suitability (and cost) of continued military utilization of military specification-quality shale fuels will be made.

Shale fuels do have a few idiosyncrasies (e.g., lubricity, elastomer compatibility, low aromatics content) which will be under continuous surveillance/evaluation in the field and in the laboratory at SwRI during the field validation operations. No significant problems are anticipated, but a thorough investigation of any new fuel from a radically new resource is always an intelligent approach. Department of Defense has designated this operation "RIVET SHALE"; Corps of Engineers access to progress reports, etc., can very likely be obtained by contacting either Dr. Herb Lander, Wright-Patterson AFB, Ohio, or Mr. M. E. LePera, Belvoir R&D Center, Fort Belvoir, Virginia.

B. Tar Sands Bitumens

Tar sands are a hard-to-define mixture consisting of rocky material and oil that has little or no light boiling point components. Technically, it cannot be distinguished from regular crude according to viscosity or gravity alone, nor according to any other simple concept.

Fortunately, the technology is better established than the definition. In fact, technology is well-established for most of the many forms that tar sands assumes. These forms vary from unique Alberta (Canada) tar sands, which is a water-wetted grain of sand with oil mixed in the matrix, to another unique deposit in California where oil is on the surface of diatomaceous earth deposits. Tar sands also take the form of water-oil emulsions on various rocks/sands deposits. Most of the ones in the U.S. are of

this latter type. Each form requires special testing to determine the process best suited to its needs.

Canada has the lead in the development of tar sands in Northern Alberta where the vast deposits are found along the Peace and Athabasca Rivers. Two plants are operated commercially by Suncor Oil Sands and Syncrude Canada. Suncor (originally Great Canadian Oil Sands) began operation of the first tar sands plant in the latter part of the 1960's and expanded production in 1981. Syncrude Canada has been operating since about 1978.⁽¹⁹⁾

Tar sands plants are also under consideration in the U.S. in Utah and California. The most advanced is the Getty Oil Company diatomite operation at McKittrick Field, California.

Six oil companies plan five tar sands mining/processing projects about 120 miles southeast of Salt Lake City near Sunnyside in Utah's Tar Sands Triangle.⁽²¹⁾ Recovery could reach 2.8 billion bbls of oil - about 80 percent of that estimated to be in place - if the Bureau of Land Management approves conversion of all 23 oil and gas leases to combine hydrocarbon leases and five projects emerge. The proposed projects are in very early stages, and operators' production estimates range from 5000 to 50,000 bbl/day. Estimated peak production would total 115,000 bbl/day, and may be reached sometime during 1988-98. Project life spans range from 20 to 55 years.

Since the Canadian operations are the only ones that have taken tar sands forward to a liquid approaching a finished fuel, it is not yet possible to describe domestic liquids properties. Table 6⁽²⁰⁾ presents properties of four treated distillates, presumably from the Athabasca tar sands. Note that the four columns represent four distillates which have been increasingly treated with hydrogen (see bottom line hydrogen consumption). Correspondingly, as hydrotreating severity is increased, total aromatics are reduced and cetane number is increased from 32.3 to 41.9. This obviously indicates good potential for tar sand distillates as diesel fuels (cost of hydrotreating notwithstanding). The tradeoff between hydrotreating severity (process economics) and tar sands distillate quality for diesel applications may show more promise in using tar sands in an intermediate configuration as a blendstock for combination with high-quality petroleum

or even oil shale diesel fuels. The mutual compatibility between distillates from these three resources has yet to be resolved.

Table 6 Hydrotreating of Canadian Tar Sands Coker Distillate

Property	Treated Distillates			
	S32	S35	S39	S42
Gravity, °API	28.9	30.0	32.3	33.2
ASTM Distillation, °F @				
10% Recovered	429	426	415	414
50% Recovered	532	527	505	508
90% Recovered	621	621	605	602
Final Boiling Point	647	651	642	633
Cetane Number	32.3	35.0	39.4	41.9
Composition Determined by Mass Spectrometry, mass %				
Chain Paraffins	12.8	14.8	13.4	13.3
Cycloparaffins	39.6	50.0	62.7	72.9
Total Paraffins	<u>52.4</u>	<u>64.8</u>	<u>76.1</u>	<u>86.2</u>
Monoaromatics	34.3	29.5	20.8	13.1
Diaromatics	10.5	4.6	2.3	0.7
Triaromatics	1.5	0.8	0.6	--
Aromatic Sulfur Compounds	1.3	0.3	0.2	--
Total Aromatics	<u>47.6</u>	<u>35.2</u>	<u>23.9</u>	<u>13.8</u>
Hydrogen/Carbon Ratio, Atomic	1.67	1.71	1.77	1.82
Sulfur, mass %	0.042	0.030	0.01	0.01
Nitrogen, ppm	165	60	9	4
Kinematic Viscosity, cSt @ 104F	3.28	3.29	2.98	3.02
Flash Point, °F	190	174	196	183
Cloud Point, °F	-22	-27	-22	-27
Pour Point, °F	-71	-94	-94	-94
Hydrogen Consumption, ft ³ /bbl	449	1404	1617	1684

Finished or semi-finished Canadian tar sands distillates can probably be acquired for testing purposes but only in limited quantities. At this point, it is understood that Canada is utilizing all of its tar sands distillates and is not exporting.

V. VEGETABLE OILS

The use of vegetable oils as fuels for diesel engines is not a new concept. Since the invention of the diesel engine, the development of this engine has been based on the availability of petroleum-derived diesel fuel which, in turn, has been tailored to meet the needs of the current engines. During this period, a wealth of empirical knowledge has been developed which serves as the data base for the current diesel fuel specifications. Periodically the vegetable-oil fuel concept has been reintroduced, usually during periods of petroleum shortages. In most cases the interest faltered due to renewed availability of more economical petroleum-derived fuels. As a result, vegetable oils have not been developed as potential fuels nor have the desirable physical and chemical properties been defined to make them totally acceptable as a fuel source.

The 1973 oil embargo signaled the beginning of a new period of petroleum shortages. As a result, the international interest in the use of vegetable oil as diesel fuel has been once again renewed. Much of the current work is being performed in countries which have little or no internal petroleum resources, such as South Africa⁽²²⁾ and Australia.^(23,24) Work has been progressing in the United States at Ohio State University,⁽²⁵⁾ North Dakota State University,^(26,27) Southwest Research Institute,⁽²⁸⁾ University of Idaho,⁽²⁹⁾ University of Alabama,⁽³⁰⁾ and at several engine manufacturers including International Harvester,⁽³¹⁾ John Deere,⁽³²⁾ Caterpillar,⁽³³⁾ and Perkins.⁽³⁴⁾ In examining the pre-1981 literature, several points became apparent:

- The energy balance for vegetable oil production is positive, much more so than the balance for ethanol production.
- In many parts of the United States, vegetable oils could be produced in surplus for use as fuels for diesel engines.
- The availability and cost of the vegetable oils are seasonable and dependent on the climatic conditions.

- The viscosities of the vegetable oils are an order of magnitude larger than diesel fuel.
- The results of engine durability tests have been somewhat scattered due to variation in engine design, oil composition, and engine operating conditions.
- The major engine problem areas are deposit formation, ring sticking, and lube oil dilution; direct-injection diesel engines appear to be more susceptible than do the indirect-injection engines.

A. Review of Previous Work

The following discussion of the previous engine-related work with vegetable oil fuels is limited to the most recent work. The reason for this is the fact that previous periods of vegetable oil interest occurred in the periods from 1920-1950. Although this information has some historical value, the engine designs have changed considerably, and the experimental hardware has become much more advanced.

Assuming no drastic changes in the market for vegetable oils, the market economics are not favorable for the use of vegetable oils as fuels for diesel engines; most cost estimates indicate the current costs of vegetable oil are approximately two times the cost of diesel fuels,⁽³⁵⁻³⁷⁾ based on equivalent amounts of energy. The cost factor can be somewhat misleading in that the vegetable oil prices would not be a factor if there were a disruption in the world petroleum supplies. A better indicator of the value of vegetable oils as diesel fuels is given by the energy balance for the production of vegetable oil fuels. Stecher⁽³⁸⁾ has estimated that the energy ratio (fuel energy output/energy input) for sunflower oil can range from 1.55 to 12.6. Other estimates made for sunflower oils are 6.5 (Quick⁽²⁴⁾) and Kaufman⁽³⁹⁾) and 10 (Bruwer et al.⁽⁴⁰⁾). Erickson and Dickson⁽³⁵⁾ have shown the energy ratio for soybean oil to be about 3:1. Chancellor⁽³⁶⁾ reported a net negative energy balance for vegetable oil production, but his results appear to be biased by an extremely large estimate of the energy requirements for irrigation. As can be seen, the numbers in general represent fairly large net positive energy balances, especially when compared to most estimates of the

energy balance for ethanol production which range from slightly less than one to slightly more than one.

Although the estimates vary somewhat, the results presented by Pryde⁽³⁷⁾ indicate that the on-farm fuel requirements could be met by devoting 16 percent of the available acreage to sunflower seed production, or 29 percent for soybean production. Hofman, et al.⁽⁴¹⁾ estimates that a farmer could replace all of his diesel fuel needs by devoting 10 percent of his total acreage to sunflower production. These estimates, as well as the energy balance analyses, are highly dependent upon the irrigation requirements, and thus upon the geographical location. It does appear, however, that farmers in many areas could be self-sufficient in diesel-engine fuel requirements if suitable fuel/engine systems were developed for vegetable oil fuels.

Pryde⁽⁴²⁾ has presented an extensive bibliography of the engine work (pre-1981) with vegetable oils. One of the major difficulties in interpreting the results of past work is a lack of standardization of the fuels, the engines, and the test conditions. In some cases (e.g. Ref. 25), the type of engine was not specified (direct-injection or indirect-injection, two-stroke or four-stroke cycle). In other cases (e.g. Ref. 43), the engines used for the studies were not representative of those used in farm tractors.

The shortcomings of the pre-1981 work were pointed out and discussed during the Seminar on Alcohol and Vegetable Oil as Alternative Fuels.⁽⁴⁴⁾ The major recommendations were that future work should include complete documentation of the vegetable oil properties and history, and complete descriptions of the test engines and test procedures. Much of the more recent work has included the above documentation and descriptions.

Humke and Barsic⁽³²⁾ used a naturally-aspirated (NA), direct-injection engine to test crude sunflower, crude peanut, crude soybean, degummed soybean, and 50/50 blends of each of the crude vegetable oils in Number 2 diesel fuel (DF-2). In all cases, the fuels were characterized with respect to standard ASTM diesel fuel test procedures. Typical Americal Oil Chemists Society (AOCS) characterizations of the vegetable oils were not presented.

The engine tests included performance and emissions tests on all oils and blends, and 25-hour steady-state durability tests on the crude and degummed soybean oils. The performance characteristics of all of the test fuels were similar to those of DF-2; the emissions, however, were generally higher. Both the performance and the emissions degenerated with time while running on the vegetable oils. The authors found that the degradation in performance and emissions corresponded to the build-up of deposits on the injection nozzles. They hypothesized that the durability problems reported by other investigators, including lube-oil dilution, abnormal engine wear, and engine deposits, result from degraded atomization caused by the build-up of deposits on the injection nozzle. In addition to the obvious effect of the vegetable oils on the nozzle deposits, the higher viscosities of the oils lead to reduced pump leakage and increased injection duration. Based on the results of these tests, the injection process is obviously affected by the use of the vegetable oils.

Hugo^(22,45) reported similar results for a 20/80 blend of degummed sunflower oil (properties undefined) and diesel fuel (properties not listed) in four different direct-injection engines (Massey Ferguson, Fiat, International Harvester, and John Deere - engine models not specified). Two Deutz F3L92W engines were tested on straight degummed sunflower oil. One engine was run at a single steady-state condition for 2300 hours without problem. The second engine was run over a series of speeds and loads for a total of 600 hours with no difficulty. Their major observation was that direct-injection engines are much more susceptible to durability problems than the indirect-injection engines when running on vegetable oil.

McCutchen⁽³³⁾ performed some very interesting experiments using Caterpillar 3300 series direct-injection and indirect-injection engines running on degummed soybean oil. A naturally-aspirated (NA), indirect-injection engine showed a nine percent loss in power and a three percent increase in energy consumption when operating on straight soybean oil. Performance of a turbocharged version of the same engine operating on a 30/70 blend of the oil was identical to the performance on DF-2. A turbocharged direct-injection engine (3306) operating on straight soybean oil showed a six percent increase in efficiency over operation on DF-2. Durability tests on straight soybean oil in the NA indirect-injection engine showed no durability problems. A turbocharged version of the same engine, however, showed excessive wear rates on a 30/70 blend.

The use of straight soybean oil in a turbocharged direct-injection engine (3306) resulted in nozzle coking and degraded performance after 110 hours of operation on variable speed-load test matrix. The author also reported a dramatic increase in the fuel-injection-system overpressure when using vegetable oil, most probably a result of the high viscosity of the oils. A major contribution of this work is the added verification of susceptibility of the direct-injection engines to the vegetable oil durability problems.

Bacon et al.⁽³⁴⁾ examined the nozzle coking problem. Documentation of the oil properties and the engine configuration was not provided. The authors hypothesized (as did Humke and Barsic^(31,32)) that the other durability problems are directly related to the onset of nozzle coking. The authors also presented a theory for the coking which involves polymerization due to thermal and oxidative attack of the double bonds in the vegetable oils. The authors did not, however, discuss the role of the viscosity in the overall mechanism.

Baranescu and Lusco⁽³¹⁾ studied the effects of straight sunflower oil and blends of sunflower oil and DF-2 on injection parameters, engine performance, and engine durability. Injection studies revealed increases in injection overpressure, longer injection duration, and early needle opening. The authors' conclusions based on still photographs of the spray patterns may not be valid due to variation in residence time, variation in the intensity and length of the exposures, and obvious smearing due to long exposure times. The authors did comment on drop sizes in the sprays. Droplet size should probably not be discussed in terms of observations made from the still photographs because of smearing effects of the long exposure times. As with the other direct-injection engine studies, the authors (using an IH DT-436B direct-injection engine) observed nozzle coking. Unlike the other investigators, however, the authors did not relate the nozzle deposits to degraded fuel injection and poor engine performance.

Kaufman^(26,27) examined the performance characteristics of sunflower oil (alkali refined), a 50/50 blend of this sunflower oil and DF-2, and the methyl ester of sunflower oil. The tests were performed using an Allis Chalmers 433I turbocharged (intercooled) direct-injection engine. Observation of the injection parameters (needle lift and line pressure) revealed that injection duration and system overpressure increased in going

from DF-2 to all of the other fuels. Unfortunately, the fuel supplied (sunflower oil) for the durability test was inadvertently contaminated with linseed oil which prevents any direct comparison with other sunflower oil durability tests. On the other hand, the increase in the number of double bonds resulting from the addition of linseed oil may have caused the much more severe durability problems encountered in this test as compared to other tests of blends of sunflower oil; this suggests that a high linolenic acid content (degree of unsaturation) is undesirable in vegetable oil fuels.

Quick et al.⁽⁴⁶⁾ performed some very interesting engine experiments using linseed oil as the test fuel. They theorized that nozzle coking and other durability problems are governed mainly by the degree of unsaturation of the oil and that viscosity has little or no effect. Some caution should be included in acceptance of the authors' theory. The elimination of viscosity from the nozzle coking theory was based on comparative results in which the linseed oil was heated to 85°C. At 85°C, the viscosity of most oils is still on the order of 15 cSt, approximately 10 times the viscosity of diesel fuel - sufficiently high to cause severe degradation of the injection process. (A fuel temperature of approximately 145°C would be required to reach 4 cSt, but polymerization of the fuel might result, clogging injector equipment and filters.) In addition, the authors reported severe nozzle coking which could have contributed to degradation of the injection process (injection characteristics were not included) which in turn could have created the other durability problems.

Basically three different theories can be postulated to explain the various durability problems:

1. The high viscosity of the vegetable oils result in degraded fuel atomization which, in turn, results in the observed durability problems.
2. The durability problems associated with the use of the vegetable oil fuels result directly from chemical structure of the oils and the effect of this structure on the combustion chemistry.
3. The durability problems are a result of incomplete combustion of the fuels (either spray or chemically induced) and the subsequent reaction of

the fuels and/or partial combustion products on the metal surfaces and in the lube oil.

Although there is evidence that fuel chemistry affects the durability problems, the majority of evidence indicates that the high viscosity of the oils is the major factor controlling the onset and severity of the durability problems.

The high viscosities of the vegetable oils could also be the cause of reported discrepancies between the cetane ratings and their actual knock characteristics in real engines. The cetane rating is actually a measure of the ignition quality of the fuel and is affected by the atomization and vaporization processes encountered in the cetane rating engine. With high viscosity fuels, the degree of atomization would be expected to decrease, resulting in a longer ignition delay time and thus a lower cetane rating. Real engines would not necessarily have the same sensitivities to vegetable oils as the cetane engine.

There are several possible solutions to the viscosity problems presented by the use of vegetable oils. The solutions include increasing the injection pressure, heating the fuel to reduce the viscosity, modification of the oils (transesterification), and blending. Preliminary work done at Southwest Research Institute (SwRI) with blends of DF-2 with peanut oil and with cottonseed oil (food quality) have indicated that the combustion performance of the fuels is excellent as long as the viscosity does not become excessive.⁽⁴⁷⁾ This work was done with blends ranging from neat DF-2 to neat vegetable oil in a very quiescent, direct-injection research engine (an engine extremely dependent on an effective fuel-injection process).

The most recent vegetable oil work at SwRI was performed in two different projects. In one project, a series of diesel injection studies and engine experiments were used to develop a preliminary specification for vegetable oil fuels for diesel engines.⁽⁴⁸⁾ In the second project, neat sunflower oil and blends of sunflower oil and diesel fuel (DF-2) were tested in three different medium-speed diesel engines.

In the first project, four different vegetable oils, each in at least three different stages of processing, were characterized with respect to their physical and chemical

properties, their injection and atomization characteristics, and their performance and combustion characteristics in both a direct-injection and an indirect-injection version of the Caterpillar 3304 engine.

A high-pressure, high-temperature injection and atomization facility was used to characterize the injection of the vegetable oil. The injection and atomization characteristics of the vegetable oils were significantly different than those of petroleum-derived diesel fuels, mainly as the result of their high viscosities. Heating the oils, however, results in spray characteristics more like those observed with diesel fuel.

The two engine types demonstrated different sensitivities to the composition of the various oils. The combustion characteristics and the durability of the direct-injection engine were affected by the oil composition. In the DI engine, highly unsaturated oils (high iodine values in conjunction with large linolenic/linoleic ratios), demonstrated the best combustion characteristics. These same oils, however, tended to cause lube oil dilution and engine deposit problems if the injection and atomization processes were less than ideal. Lube oil dilution with vegetable oils is of concern because polymerization of the vegetable oil in the crankcase is likely. The result is thickening of the lube oil. At this time, the concentration of vegetable oil in the lube oil and the time and temperature needed to cause polymerization are unknown.

The results of this study indicated that there is a need for two different fuel specifications, one for direct-injection engines and one for indirect-injection engines. Table 7 is a listing of the recommended preliminary specifications for both engine types and a listing of the current ASTM No. 2-D specification. It should be noted that the DI engine requirements include fairly stringent limitations on the composition of the oils. The IDI requirements, on the other hand, do include a relatively mild limit on iodine number in an effort to eliminate such potentially bad fuels as linseed oil (highly unsaturated). The specifications for both engines also include a fuel temperature requirement of 140°C for acceptable viscosity. This was included for the IDI engines because the composition could become a factor with reduced atomization quality.

**Table 7 Recommended Preliminary Specifications
for Vegetable Oil Fuels for Diesel Engines
as Compared to No. 2-D Specifications**

	<u>DI Engines</u>	<u>IDI Engines</u>	<u>ASTM No. 2-D Specifications</u>
Cloud Point (C), max. (with heated tank)	22	22	--
Viscosity (cSt), max. @ 140°C	5	5	--
Particulate Matter (mg/L), max.	8	8	--
Water (vol %), max.	0.01	0.01	.05
Copper Corrosion (rating), max.	3	3	3
Flash Point (C), min.	52	52	52
Heat of Combustion, (MG/kg), min.	39	39	--
Cetane Number	35	35	40
Ash (wt %)	0.01	0.01	0.01
Linolenic/Linoleic Ratio, min.*	.07	--	--
Lineoenic Acid (wt %), max.	5	--	--
Iodine No., max.	135	135	--
Thermal/Oxidative Stability	?	?	--
Viscosity (cSt @ 37.8°C)	--	--	1.9 - 4.1

* Applies only when the linolenic acid content is greater than 1 percent.

The purposes underlying the compositional limitations are to obtain maximum performance by maximizing the linolenic/linoleic ratio while still limiting the linolenic acid content (degree of unsaturation) to obtain the desired durability characteristics. The iodine number limits the degree of unsaturation for those oils which contain little or no linolenic acid.

One important property missing from the specifications listed in Table 7 is a measure of the thermal/oxidative stability. This property is important for the DI engine, but could also have an effect in some IDI engines. A specification has not been included because of the lack of an appropriate test for diesel engine fuels.

All of the other fuel properties recommended in the specification correspond to either the ASTM No. 2-D specification or the current military diesel fuel specification (VV-F-800). The exception is the cetane number. It appears that the current cetane procedure may not be applicable to the vegetable oils, but an acceptable value, as determined in this study, was included to provide some measure of the ignition quality of the oils.

In the medium-speed diesel (DI) experiments, bleached and deodorized sunflower oil was selected for testing. The oil did meet the specifications listed in Table 7. Blends of 25, 50, and 75 percent sunflower oil in DF-2 and neat sunflower oil were tested in an EMD two-cylinder blower scavenged research engine. In addition, a 50/50 blend of the sunflower oil in DF-2 and the neat sunflower were tested in a 12-cylinder GE and in a 12-cylinder EMD diesel engine. Both engines were turbocharged. The EMD engines operate on a two-stroke cycle while the GE operates on a four-stroke cycle. The vegetable oil fuels were not heated in any of the tests. Therefore, the viscosities of the vegetable oil fuels were higher than that of the baseline diesel fuel.

The test results were very similar for the two EMD engines. In both cases, the power output of the engines at fixed rack positions decreased as the percentage of vegetable oil in the blend increased.

The power drop with the neat vegetable oil was more than could be attributed to the reduced energy content of the vegetable oil (as compared to the DF-2). Corresponding to the power drop, the engine thermal efficiency with the vegetable oil was slightly lower than with the DF-2. The thermal efficiency effects were reduced as the concentrations of vegetable oil decreased. At some test conditions, it appeared that the 50/50 blend had a slightly higher thermal efficiency than the baseline fuel at the same rack position. At equal power output levels, the vegetable oil fuels and the DF-2 exhibited very similar thermal efficiencies in the 12-cylinder engine. At equal power output levels in the two-cylinder engine, the vegetable oils exhibited lower thermal efficiencies than the DF-2. The use of vegetable-oil fuels resulted in reductions in the smoke emissions from both engines.

The performance of the vegetable-oil fuels in the GE engine was very similar to the performance in the EMD engines. At the higher power settings, the vegetable oil fuels and the DF-2 exhibited very similar thermal efficiencies. At the lighter load conditions, however, the vegetable oil fuels had consistently lower thermal efficiencies than the DF-2. This was also reflected in higher smoke levels at the lighter load conditions.

These medium-speed diesel experiments indicated that the vegetable oils performed very well in these types of engines. Engine speed and load were very stable during the tests, reflecting the excellent combustion characteristics of the vegetable oil fuels. The duration of the experiments was too short to assess the durability characteristics of the vegetable oil fuels. Light nozzle deposits were, however, observed in all engines, possibly reflecting the effects of the higher viscosities on the fuel atomization process.

B. Summary

Based on the current literature, the most important questions concerning the utilization of vegetable oils as fuels for diesel engines involve the engine durability characteristics when using the oils. Aside from the filter plugging problems associated with dirty vegetable oils, the problems include injection nozzle deposits, engine (piston and ring) deposits, and lube oil dilution. It appears that direct injection engines are more sensitive to these problems than indirect-injection engines. The durability problems, including filter plugging problems, can be minimized by using oils which meet the preliminary specification presented in Table 7.

In order to meet the viscosity requirement, the oils must be heated, or modified (transesterification), or blended with diesel fuel. At this point in time, heating appears to be the best approach because it does not involve additional processing and offers the potential for total substitution of the petroleum-derived fuels.

On a national level, the most likely candidates are soybean oil and sunflower oil. Both of the oils will, with adequate processing, generally meet the requirements of the preliminary specification. It appears that soybean oils will have to be degummed and

filtered. In addition to degumming and filtration, the sunflower oils will also require dewaxing in order to meet the cloud-point requirements.

The cost of the vegetable oils are difficult to project due to uncertainties in the supply and demand on a worldwide basis. Based upon observations over the past two years, the cost of crude soybean oil has ranged from \$1.45 per gallon during times of surplus to \$2.50 per gallon during times of high demand or low supply. It is estimated that processing would add 5 to 7 cents per gallon to the cost. The price of sunflower oil has been consistently higher than that of soybean oil. It is felt, however, that the price may be somewhat inflated due to limited production of sunflowers.

VI. PETROLEUM ALTERNATIVE FUELS

There are a number of lower grade distillate fuels and residual fuels made from petroleum as well as gaseous fuels which are petroleum by-products that can be used as substitutes for specification-quality diesel fuels. These fuels can be used either neat or blended with specification diesel fuels depending on the amount of sacrifice in key properties a specific engine type can accommodate.

The material below is a brief description of four categories of non-specification fuels which could be used in diesel applications to conserve specification quality diesel fuel. Since all of these are produced from conventional refining methods, no process descriptions will be given. Rather, the emphasis will be on key properties of these fuels and blends with diesel fuel.

A. Middle Distillates

Cracked distillate stocks in the DF-2 boiling range are mainly light cycle from catalytic cracking and hydrocracking products. These materials are typically used in DF-2 and heating oil blends, and have lower cetane number than straight run distillates. They have been shown to have potential as railroad diesel blends and would therefore correspondingly have potential for Corps of Engineers power plants. Table 8⁽⁴⁹⁾ shows a variety of typical distillate blend stocks from cracking, including seven light cycle oil samples which were products of fluid catalytic cracking and one hydrocracker distillate. These particular fuels were provided by several suppliers in a number of regions throughout the U.S. and are thus considered to be a reasonable cross section of middle distillates. Three of the light cycle oils with low, medium, and high aromatic content were blended with this baseline DF-2 in varying proportions. The three light cycle oils selected were from Eastern Region C (54 percent aromatics, 39.7 cetane number), Eastern Region B (69 percent aromatics, 26.8 cetane number) and Rocky Mountain Region K (83 percent aromatics, 18.3 cetane number). Table 9⁽⁴⁹⁾ shows the effect on cetane number of blending these three fluids with DF-2. Also shown is the effect of blending for a hydrocracker distillate from Eastern Region B (61.7 percent aromatics, 33.0 cetane number). The low aromatic blend showed the lowest effect on baseline

Table 8 Distillate Blend Stocks from Cracking

FUEL SUPPLIER/REGION	Test Method	Lt Cycle Oil 1/Eastern C	Lt Cycle Oil 4/Central G	Lt Cycle Oil 3/R.Mtn. I	Lt Cycle Oil 5/Southern D	Lt Cycle Oil 5/R. Mtn K	Lt Cycle Oil 7/Western N	Lt Cycle Oil 8/Eastern B	Hydroc Dist 6/Eastern B
Gravity, °API 60°F	D287	15.5	19.5	21.8	21.3	24.6	17.0	18.8	27.2
Specific Gravity, 60°F		0.9626	0.9371	0.9230	0.9260	0.9065	0.9529	0.9415	0.8916
Density, lb/gallon		8.016	7.804	7.686	7.711	7.549	7.935	7.841	7.424
Distillation	D86								
IBP/°S		428/457	459/490	403/443	410/435	491/508	415/460	271/437	437/451
10/20		472/491	505/521	460/483	448/466	571/528	473/492	479/512	458/467
30/40		505/517	533/546	499/514	484/504	540/553	505/518	530/544	476/489
50/60		529/544	563/582	530/550	526/550	568/584	536/556	558/572	502/520
70/80		562/589	602/624	571/596	576/606	601/620	584/616	592/618	540/564
90/95		628/660	649/666	624/642	639/660	641/657	652/678	649/673	594/618
EP		687	684	664	685	683	706	697	644
Recovery		98.5	99.0	99.0	99.0	99.0	99.0	99.0	99.0
Residue		1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Cetane Number	D613	18.3				39.7		26.8	33.0
Cetane Index	D976	23.2	30.5	30.3	29.3	37.2	25.4	29.3	34.2
Viscosity, cSt @ 104°F (40°C)	D445	2.97	4.03	2.91	2.94	4.03	3.47	3.55	2.79
Viscosity, SUS @ 104°F (40°C)	D445	35.9	39.3	35.7	35.8	39.3	37.5	37.7	35.3
Pour Point, °F	D97	0				37		16	0
Hydrocarbon Type (FIA) vol%	D1319								
Aromatics		83.3	68.9	69.3	71.8	53.8	81.7	68.8	61.7
Olefins		0.7	4.4	3.1	3.7	3.0	1.9	--	1.6
Saturates		16.0	26.7	27.6	24.5	43.2	16.4	31.2	36.7
Elemental Analysis, wt%									
Carbon	--	90.12				88.10		88.78	88.32
Hydrocarbon	--	9.40				11.22		10.03	11.81
Sulfur	D2622	0.60	0.94	0.63	0.50	0.60	0.36	0.65	0.01
Hydrogen/Carbon Atom Ratio	--	1.252	-	-	-	1.528	-	1.356	1.605
Heat of Combustion	D240								
Gross, Btu/lb		18236	-	-	-	18880	-	18430	19161
Gross, MJ/kg		42.417	-	-	-	43.915	-	42.867	44.568
Net, Btu/lb		17378	-	-	-	17856	-	17515	18084
Net, MJ/kg		40.421	-	-	-	41.533	-	40.740	42.063
Net, BTU/Gallon		139,302	-	-	-	134,995	-	137,335	134,256
Accelerated Stability, mg/100mL	D2274	0.3	-	-	-	0.6	-	0.5	0.2
Carbon Residue, 10% btms. wt%	D524	0.62	-	-	-	0.31	-	0.69	0.20
Ash, wt%	D482	0.00	-	-	-	0.00	-	0.00	0.00
Particulates, mg/L	D2276	3.2	-	-	-	1.5	-	8.7	1.1
Aniline Point, °F	D611	92.7*	-	-	-	123.1	-	81.0	89.6
Aniline Point, °C		33.7*	-	-	-	50.6	-	27.2	32.0

* Mixed Aniline Point, True Aniline below room temperature

**Table 9 Effect of Distillate Blend Stock Concentration
on Cetane Number**

	<u>Volume Percent Light Cycle Oil in Blend with Base DF-2</u>				
	<u>0</u>	<u>25</u>	<u>50</u>	<u>75</u>	<u>100</u>
High Aromatic LCO FL-03220F	47.8	39.1	33.6	24.8	18.3
Medium Aromatic LCO FL-0346-F	47.8	43.4	37.8	32.8	26.8
Low Aromatic LCO F-0334-F	47.8	46.2	44.5	41.8	39.7
Hydrocracker Distillate F-0342-F	47.8	42.9	39.2	36.5	33.0

cetane number, while the medium and high aromatic blends caused successively greater decrease in cetane number with increasing blend concentration. To meet a target 35 cetane number (a proposed lower cetane limit for locomotive engines which is discussed later), the low aromatic light cycle oil could be used as total replacement for specification DF-2. The medium and high aromatic light cycle oils could be blended in concentrations of 62 and 42 volume percent, respectively, to meet the target 35 cetane number. At these high blend concentrations, a small difference in fuel price could amount to a significant savings for operations consuming large amounts of diesel fuel. The critical property of cetane number in light cycle oil is widely variable, and therefore blends must be evaluated on a case-by-case basis.⁽⁵⁰⁾

For the hydrocracker distillate, it was possible to blend 70 percent with the baseline DF-2 to meet the target 35 cetane number. This is obviously a substantial replacement of the base fuel, and therefore a small differential in fuel cost between base fuel and hydrocracker distillate would make this an attractive option. Because of the high processing costs associated with hydrocracking, the price differential between a baseline DF-2 and hydrocracker distillate may be minimal, but it does have potential as a favorable blend stock.

Still greater quantities of light cycle oil or hydrocracker distillate can be consumed if the engine is converted to dual-fuel operation. This conversion removes the cetane

number limitation, but adds considerably to the retrofit cost. The trade-off between fuel cost reduction and increased equipment cost must be analyzed to determine whether blending or dual-fueling is most cost effective.

B. Heavy Distillates and Residuals

Progressing further to "bottom of the barrel," Table 10⁽⁴⁹⁾ shows properties for some typical heavy oil blend stocks, including a heavy gas oil from a fluid coker and a heavy catalytic gas oil from a fluid catalytic cracker. A No. 5 fuel oil and marine fuel oil are also shown. Again, these samples originated from two separate regions in the U.S.

Note that these fuels show a wide variance in key properties. For example, the marine fuel oil was high in viscosity, so distillation and cetane number determinations were not attempted. Cetane quality for the other samples ranged from 21.2 to 52.6. Blending compatibility with DF-2 shown was of paramount importance. Compatibility was rated good for all the heavy oils with the DF-2, while toluene and pentane insolubles were very high for the marine fuel oil. Only the light coker gas oil could be filtered to remove particulates.

Thus, particulate concentration would likely be a key measurement in determining blending applicability of heavy oils with diesel fuel.

In a study for General Electric Company guidelines for allowable variation in key properties were established.⁽⁵¹⁾ These guidelines are listed in the first column of Table 11 and maximum concentrations of the heavy oil blend stocks were calculated and listed in subsequent columns in the table. Note that the guideline specified limited blend concentration of the heavy oil to values considerably lower than those for the middle distillates (discussed above). Based on these calculated limitations, actual blends were made up and analyzed for critical properties for verification. These are shown in Table 12 which shows that limiting concentration will depend on specific properties of a specific heavy oil. Higher concentrations of blendstocks of this nature could be used if cetane number were the only limiting factor. Other property limits might be imposed due to fuel handling requirements such as viscosity, pour point, etc. These limits could conceivably be expanded through modifications of the fuel handling

Table 10 Residual and Heavy Distillate Blend Stocks

FUEL SUPPLIER/REGION		No. 5 Fuel Oil 2/Southern D	Lt Coker G.O. 6/Eastern B	Hvy Cat G.O. 9/Southern D	Marine F.O. 9/Southern D
	Test Method				
Gravity, °API	D287	25.6	10.5	8.0	12.0
Specific Gravity, 60°F		0.9007	0.9965	1.0143	0.9861
Density, LB/gallon		7.500	8.299	8.448	8.212
Distillation, °F					
IBP/5		511/574	506/615	345/534	--
10/20		611/646	640/667	596/638	--
30/40		669/688	686/702	659/670	--
50/60		704/720	715/726	682/692	--
70/80		739/763	734/760	704/724	--
90/95		--	--	762	--
EP		--	--	--	--
Recovery		84	85	91	--
Residue		16	15	9	--
Cetane Number	D613	52.6	28.5	21.2	NA
Cetane Index	D976	41.6	24.3	22.9	NA
Viscosity, cSt @ 104°F (40°C)	D445	22.18	72.24	16.75	710.71
cSt @ 122°F (50°C)	D445	15.01	--	--	328.88
Flash Point, °F	D93	273	224	141	199
Pour Point, °F	D97	-	9	60	-
Carbon Residue, wt%	D524	0.55			13.5
Sulfur, wt%	XRF	0.14	5.15	2.01	2.40
Corrosion, Cu. Strip, 50°C	D130	1B	2A	1B	1B
Pentane Insolubles, wt%	D893	0.20	0.07	0.03	10.10
Toluene Insolubles, wt%	D893	0.02	0.01	0.01	1.69
Compatibility	D2781				
Procedure A (warm)		1	1	1	1
Procedure B (cool)		1	1	1	1
Particulates, mg/mL filtered	*D2276	13.5/90	12.2/1000	8.2/400	NA
mg/100 mL		15.0	1.2	2.0	NA
Accelerated Stability	*D2274	NA	NA	NA	NA
Insolubles, mg/100mL					
Carbon, wt%	-	87.05	84.50	88.84	86.52
Hydrogen, wt%	-	12.73	10.02	8.95	10.40
Heat of Combustion	D240				
Gross, Btu/lb		19461	17143	17604	17966
Net, Btu/lb		18300	16229	16787	17016
Net, Btu/gallon		137,250	134,684	141,817	139,735
Vanadium, ppm wt	AA	1	1	1	119
Nickel, ppm wt	AA	1	1	1	3
Sodium ppm wt	AA	5	1	1	36
Potassium, ppm wt	AA	1	1	1	1
Aluminum, ppm wt	AA	1	1	1	1
Silicon, ppm wt	AA	10	10	10	10
Iron, ppm wt	AA	1	1	1	10

* Modified
NA Not Applicable

**Table 11 Proposed Guideline and Limiting Concentrations
for Blends of Residual and Heavy Distillate with Base DF-2**

Property	Proposed Guideline ⁽¹⁾	Residual Content Calculated by	Limiting Concentration in Blends			
			(13)	(11)	(17)	(8)
Gravity, °API	NS					
Distillation, °F						
90% Recovered	680	vol %	(13)	(11)	(17)	(8)
End Point	NS					
Recovery	NS					
Cetane Number	35 min.	vol %				
Cetane Index	35 min.	vol %	100	53	50	NE
Viscosity						
cSt @ 100°F (37.8°C)	16.5					
cSt @ 104°F (40°C)	15.0	vol %	85	63	95	45
Flash Point, °F	NS					
Pour Point, °F	NS					
Ash, wt%	0.02					
Carbon Residue						
wt% on Oil, Ramsbottom	1.5		100			11
wt% on Oil, Conradson	2.0					
Sulfur, wt%	1.5	wt %	100	23	68	55
Corrosion, Cu. Strip	3					
Total Water and Sediment, vol%	0.10					
Particulates, mg/100mL	NS					
Pentane Insolubles, wt%	1.0	wt %	100	100	100	10
Organic Chlorides	NS					
Metals, wt ppm						
Vanadium	30	wt %	100	100	100	25
Nickel	10	wt %	100	100	100	100
Sodium + Potassium	10	wt %	100	100	100	27
Aluminum	5	wt %	100	100	100	100
Silicon	NS					
Calcium	NS					
Lead	NS					
Catalyst Fines	NS					
Compatibility	2					
Accelerated Stability	NS					

NOTES:

- (1) All maximum unless noted
- (2) NS - Not specified
- (3) NE - Not estimated
- (4) () - Limiting Concentration

Table 12 Residual and Heavy Distillate Blends with Base DF-2

FUEL		No. 5 F.O. 13 vol%	Lt. Coker G.O. 11 v.1%	Hvy. Cat G.O. 17 vol%	Marine F.O. 8 vol %
VOLUME % IN BLEND					
	Test Method				
Gravity, °API	D287	34.4	32.6	30.3	33.6
Specific Gravity, 60°F		0.8529	0.8623	0.8745	0.8571
Density, LB/gallon		7.102	7.180	7.282	7.136
Distillation, °F	D86				
IBP/5		372/395	373/404	369/403	366/398
10/20		416/452	422/450	425/452	417/444
30/40		478/498	474/495	477/500	469/490
50/60		519/539	517/536	522/542	509/528
70/80		561/592	557/588	566/601	546/570
90/95		652/734	657/752	657/710	619/665
EP		748	-	-	672
Recovery		98	97.5	99.0	98.0
Residue		2.0	2.5	1.0	*
Cetane Number	D613	47.7	44.2	43.4	45.2
Cetane Index	D976	47.0	44.0	41.1	44.8
Viscosity					
cSt @ 104°F(40°C)	D445	3.05	3.15	3.16	3.15
cSt @ 122°F(50°C)	D445	-	-	-	-
Flash Point, °F	D93	-	-	-	-
Pour Point, °F	D97	27	5	0	-50
Carbon Residue, wt%	D524	0.14	0.32	0.38	1.23
Sulfur, wt.%	XRF	0.34	0.98	0.69	0.56
Corrosion, Cu Strip, 50°C	D130	1A	1A	1A	1A
Pentane Insolubles, wt%	D893	0.02	0.02	0.01	0.85
Toluene Insolubles, wt%	D893	0.01	0.01	0.01	0.04
Compatibility	D2781**				
Procedure A (warm)		2	2	2	4
Procedure B (Cool)		2	2	2	4
Particulates, mL filtered ++	M-D2276	176	-	1000	30
Accelerated Stability	M-D2274	N/A	N/A	N/A	N/A

G.O. = Gas Oil

F.O. = Fuel Oil

M = Modified procedure using 8.0 micron filter

NA = Not Applicable

* = Residue coked

** = Procedure run undiluted

++ = The modified particulates test was used to determine relative filterability of these blends, actual particulates were not determined.

systems for a given operation. The limits shown for these blends were based on distillation recovery. This factor may cause increased maintenance and would be of critical concern to any operation utilizing such heavy petroleum constituents.^(49,51)

Tests conducted for the AAR using 12-cylinder turbocharged EMD and GE engines operating on No. 6 fuel oil/DF-2 blends indicated that blends falling within the blend guideline limits (Table 11) were acceptable for rail use, which would be acceptable for dredge use as well.⁽⁴⁹⁾ Fuel heating was necessary to achieve acceptable fuel filter life, but no other engine or fuel system modifications were necessary.

Tests using No. 6/DF-2 blends exceeding the guideline limits showed increased ring and valve guide wear and increased accumulation of organic material in the lube oil. Also, combustion chamber and exhaust system deposits formed very rapidly when operating at low speed and load. Idling on such fuels will not be possible. Fuel filter life was less than 100 hours in several cases in spite of fuel heating to 160°F.

C. Gaseous Fuels

In this context, gaseous fuels are meant to be compressed natural gas (methane or CNG), liquid petroleum gas (LPG) and liquid natural gas (LNG).

Natural gas or its major component (methane), has been used commercially in modified diesel engines to drive electric generators or gas pipeline compressors. Spark plugs can be installed in each cylinder to assure ignition, or the engine may be set up for dual-fuel operation where a small amount of diesel fuel is injected to take the place of a spark plug. These engines are usually four-stroke design that are readily adapted to gaseous fuels. Gas is admitted to the engine by carburation or continuous port injection. For two-stroke engines with scavenging air flow, too much fuel would be lost with the exhaust. In these engines, fuel would be admitted by timed port injection or timed cylinder injection.

The stationary application with an assured source of natural gas fuel eliminates the need for providing fuels storage.⁽⁵²⁾ Methane has also been used for vehicles with gasoline engines, but the compressed gas at 2400 psig pressure requires heavy storage

tanks. Current research programs are aimed at fuel storage systems for CNG (compressed natural gas) or LNG (liquified natural gas at -260°F and atmospheric pressure). Both CNG and LNG are being used by several fleets of trucks and a few automobiles.

Propane has a high octane number (about 130 Research Octane Number) which encourages its use in gasoline engines. It may also be used in modified diesel engines with fuel systems similar to the natural gas systems just discussed. A moderate pressure fuel tank is required for about 200 psig at ambient temperature. The energy content of propane is about 72 percent of gasoline or 63 percent of diesel fuel on a volume basis, which makes propane economical when the price per gallon has the same or lower ratio to the other fuels.

VII. COAST GUARD REGULATIONS

The Coast Guard Regulations were studied to determine which, if any, pertain to the use of alternative fuels in dredges. The main areas of concern were regulations that restricted the type of fuel or fuel properties, or dealt with fuel tanks, tank venting, or special provisions for spark ignition or unconventional fuels. The Coast Guard was contacted for assistance^(53,54) and the Code of Federal Regulations was reviewed.⁽⁵⁵⁾

The portions of the Code dealing with dredges and fuels are Subchapter I, Cargo and Miscellaneous Vessels, and Subchapter F, Fuels for Internal Combustion Engines. Subchapter I was found to contain no relevant information and referred to Subchapter F regarding fuel. The pertinent regulations in Subchapter F are:

Part 56.50	Cargo Oil and Fuel Oil Systems
Part 58.01-10	Fuels for Internal Combustion Engines on Passenger Vessels
Part 58.10	Internal Combustion Engine Installations
Part 58.50	Design Requirements Pertaining to Specific Systems
Part 64	Marine Portable Tanks

Part 58.01 specifies that fuels for passenger vessels have a minimum flash point of 110°F. However, a classification could not be found for dredges. It was the opinion of the Coast Guard that a dredge is not a passenger vessel and that this requirement does not apply, but that the final decision would be up to the district office under which the dredge operated. It may be possible to receive a waiver for use of a low flash point fuel for the dredges if they are classified as passenger vessels. Alcohols are the only fuels studied in this program that are below the flash point limit.

The regulations are quite specific about diesel fuel and gasoline tank requirements, including vents, fill necks, materials and grounding. These regulations impose no limitations for the alternative fuels with the possible exception of alcohol fuels. Alcohols absorb water from air. It will be necessary to minimize water contamination through special venting. Whatever vent design is selected will require approval if it does not conform to the Code.



The regulations make no mention of special precautions for alcohols, which produce combustible air/fuel mixtures in storage tanks. Part 64.9, Dangerous Articles for Which Tanks May Be Approved, indicates that portable tanks may be approved for alcohols. Portable tanks may be a good method to ensure adequate safety precautions and may prove useful when separate storage is needed for two fuels for dual-fuel operation.

In short, the Coast Guard felt that the regulations did not pertain to alternative fuel usage in dredges. Also, the Coast Guard pointed out that the dredges may not be certificated, in which case the Code does not apply. However, OSHA and American Bureau of Shipping requirements may have to be satisfied.

VIII. RANKING OF ALTERNATIVE FUELS

The fuels addressed in this study are summarized in Table 13. This table contains an estimate of the amount of each alternative that can be substituted for DF-2 when the fuel is consumed in neat form, blended with DF-2 (or an equivalent fuel), or when consumed in a dual-fuel mode using pilot diesel fuel injection as an ignition source. Also, Table 13 contains a general estimate of the extent of retrofit needed to convert a dredge to use of an alternative fuel. The extent of retrofit was gauged as high, medium, low, or none using the following convention:

- High - any retrofit that requires internal engine modification
- Medium - injection and fuel systems modifications, but without cylinder head removal
- Low - fuel storage and handling systems minor modifications
- None - fuel is used in existing systems without modification

Fuel cost was approximated on a relative basis compared with DF-2 taking into account differences in heating value. For example, approximately twice as much volume of alcohol is needed to equal the heat content of diesel fuel. Relative cost of alcohol was estimated by multiplying the price per gallon by two.

Fuel availability was likewise estimated on a relative basis, high availability being that which is comparable to DF-2 at least on a general statewide geographic basis and medium availability being a commercially available commodity but in quantities significantly below DF-2 and/or on a spot market basis.

The fuel ranking, the final column in Table 13, was generated according to the following criteria. Fuels which are immediately available, do not require engine retrofit, and are miscible with DF-2 were given a rank of 1. Fuels immediately available but which required retrofit were given a rank of 2. A rank of 3 was assigned to fuels that did not require retrofit, were not immediately available in quantity, but which have the potential for high volume production in the near future. A rank 4 indicates fuels for which production technology has been developed, but which are not available in the

Table 13 Summary of Alternative Fuels Studied for Dredge Application

Fuel	Percent Substitution for DF-2			Extent of Retrofit		Relative Engine Wear, Maintenance	Fuel Cost Relative to DF-2	Relative Current Fuel Availability	Rank
	Neat	Blended w/DF-2	Dual-Fuel	Neat	Blended w/DF-2				
Methanol	0	15*(3)	90	N.A.	Medium	High	Slightly higher	High	2
Ethanol	0	15*(3)	90	N.A.	Medium	High	High	High	2
COED	0	30	90	N.A.	Low	High	U.A.	U.A.	5
H-COAL	0	30	90	N.A.	Low	High	High	U.A.	5
SRC II	0	30	90	N.A.	Low	High	Very high	U.A.	5
EDS	0	30	90	N.A.	Low	High	Very high	Small test quantities available	5
Sasol	100	A.P.	N.A.	None	None	N.A.	Higher	U.A. in USA	4
Shale Oil	100	A.P.	N.A.	None	None	N.A.	Slightly higher	Test quantities available	3
Tar Sands	100	A.P.	N.A.	Low	None	N.A.	Slightly higher	Potentially high	3
Sunflower Oil	100	A.P.	N.A.	Low	None	N.A.	Higher	Medium	1
Soybean Oil	100	A.P.	N.A.	Low	None	N.A.	Higher	Medium	1
Petroleum middle distillates	100*(1)	50 to 100*(1)	90 to 95	None	None	High	Lower	High	1
Petroleum heavy distillates	0	0 to 30*(2)	N.A.	N.A.	Low	N.A.	Much lower	High	1
Gaseous Fuels	0	N.A.	90 to 95	N.A.	N.A.	High	Same or lower	High	2

- (1) - depends on product cetane number
(2) - depends on specific fuel properties
(3) - unstabilized emulsions
N.A. - not applicable
A.P. - any proportion
U.A. - unavailable

U.S.A. Finally, a rank 5 indicates fuels that are unavailable and are not expected to be produced in the future.

The alcohols addressed in this study were methanol and ethanol. Higher order alcohols were not feasible because of both cost and availability. Methanol and ethanol cannot be used in neat form because of their extremely poor ignition quality (cetane number). These alcohols are not miscible with diesel fuel (with the exception of anhydrous ethanol) and must be emulsified into diesel fuel if a "blend" is desired. Stabilized emulsions can be produced by adding a chemical surfactant, but these are unattractive because of poor engine performance and high fuel cost. Unstabilized emulsions require an on-line emulsifying system plus separate alcohol and diesel fuel storage tanks. In either case, the emulsions are limited to a maximum of about 15 percent DF-2 replacement. A dual-fuel conversion using pilot diesel fuel injection will allow up to 90 percent DF-2 replacement, but engine and fuel system conversions are extensive. Engine wear and maintenance are expected to be high in comparison to diesel fuel, primarily stemming from high ring, liner and injection equipment wear. However, lubrication of alcohol-fueled engines is being studied by a number of researchers and should be resolved in the near future. Both methanol and ethanol were given rankings of 2. They are available in quantity at present, and methanol availability is expected to increase dramatically in the next two to five years, making it one of the top alternatives to petroleum fuels.

Five coal-derived liquid products are shown in Table 13. Four of these, COED, H-Coal, SRC II, and EDS, were produced by direct liquefaction processes. The fifth fuel, produced in South Africa by the SASOL process, uses indirect liquefaction. With the exception of the SASOL product, each of the coal products received a ranking of 5. Each product has a low cetane number which prohibited its use in neat form. Blending with diesel fuel was feasible, but diesel fuel replacement is limited to approximately 30 percent. A dual-fuel engine conversion would allow approximately 90 percent diesel fuel replacement. None of the four direct liquefaction products are in production. Small quantities of EDS are in storage and could be made available for testing.

Gasoline and diesel fuel are presently being produced in quantity in South Africa by the SASOL indirect liquefaction process. These are high quality finished products which are

suitable for direct replacement of petroleum products. Unfortunately, the SASOL product is not available in the U.S. because of political barriers.

The synthetic fuels studied (aside from the coal-derived products) were shale oil and tar sand products. Shale oil products produced to date have been high quality finished products that meet or exceed DF-2 specifications. These products could be used in neat form or could be blended with diesel fuel in any proportion. The shale oils received a ranking of 3 since they are presently unavailable, but have the potential for production in the near future. It should be mentioned that Union/Gary will produce approximately 10,000 barrels per day of JP-4 and DF-2 shale oil for the Department of Defense starting sometime within the next six months. This fuel would be an excellent candidate for a CERL dredge demonstration.

Tar sands products are widely varied in properties, with some products being suitable for direct replacement of DF-2. Other of the tar sand products have resembled heavier petroleum distillates or resids which could be blended with DF-2 for dredge engine consumption. Tar sands products are presently in production in Canada, but not in the U.S. Tar sands, like shale oil, are potentially available in large quantities in the future.

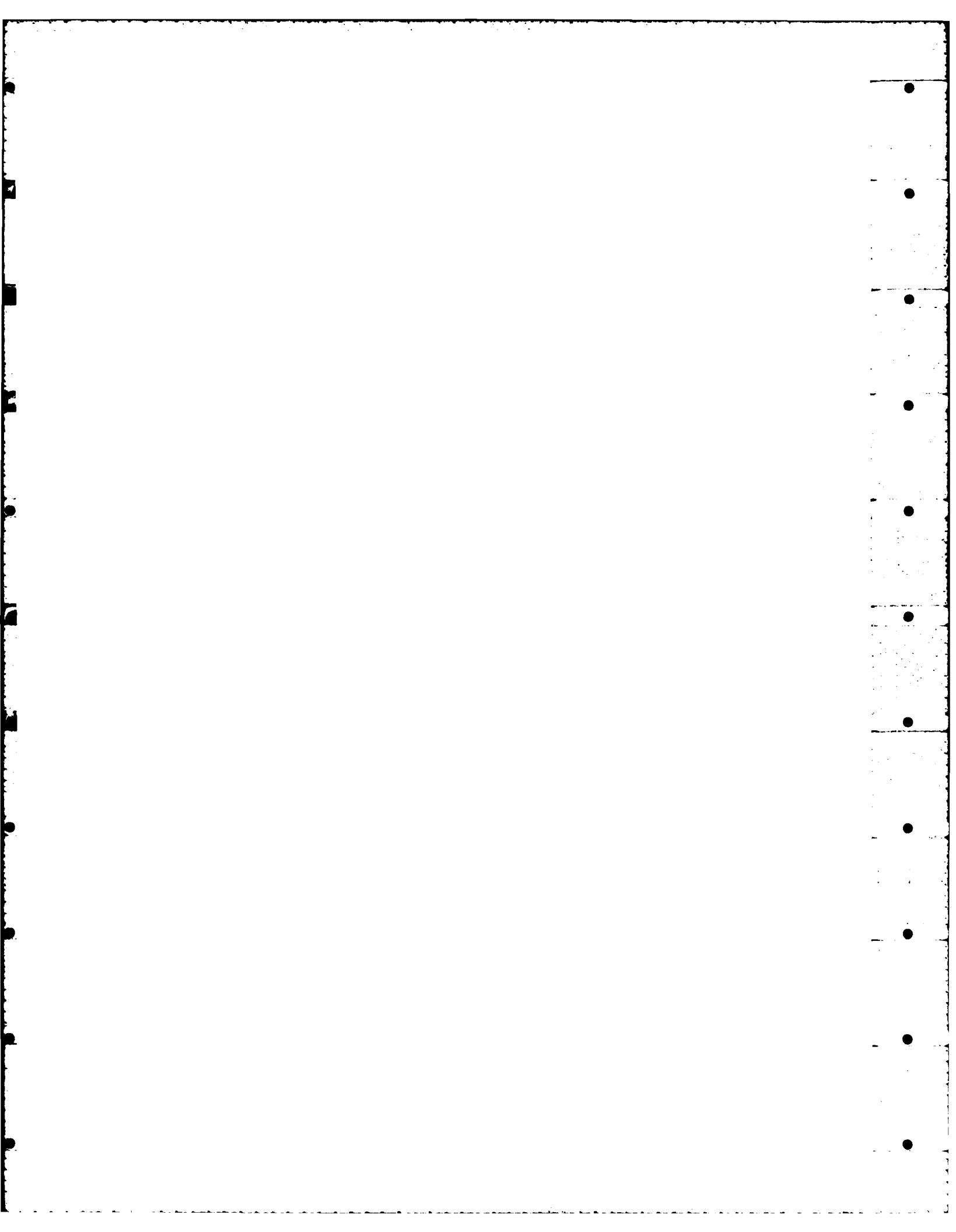
The final category of non-petroleum alternative fuels studied was the vegetable oils. Sunflower and soybean oils have the greatest production potential. In fact, either of these oils could be purchased in sufficient quantities for a brief dredge demonstration. Sunflower and soybean oil have been tested in a wide variety of diesel engines, including medium-speed diesels, and in various states of refinement. Good engine performance has been achieved in many cases, but combustion chamber deposits and engine wear have been identified as areas requiring further research. Both soybean and sunflower oil received rankings of 1. Both oils are in commercial production, but not in quantities sufficient for use as transportation fuels; however, the production potential is there if demand for either oil increases.

The final category addressed was petroleum alternatives. While CERL's mandate is to reduce dredge petroleum consumption, petroleum products are presently the best alternative to DF-2 because of both cost and availability. The petroleum alternative studies were broken into petroleum middle distillates, heavy distillate and residual fuel

oils, and gaseous fuels. The middle distillates include light cycle oils and hydrocracker products. They are typically of lower cetane quality than DF-2 which, if the cetane falls below about 35, requires that the product be blended with a higher cetane product to achieve an acceptable cetane number. The engine may be converted to dual-fuel operation to handle very low cetane middle distillates. U.S. railroads are presently exploring the use of middle distillates which can be used neat as economic replacements for DF-2. Heavy distillates and residual fuel oils cannot be used in neat form, but can be blended with DF-2 for up to 30 percent DF-2 replacement. There are fuel handling, engine wear and deposits problems associated with these heavy products, but these can be controlled by proper engine operating practices, conservative fuel quality specifications, and continual checks of fuel quality.

Use of gaseous fuels will require a rather extensive retrofit. An ignition source must be provided: spark ignition or dual-fuel using pilot injection are the most common. Ninety to 95 percent of the diesel fuel requirement can be replaced by a gaseous fuel, but dual-fueled gaseous engines are typically derated from diesel fueled versions to avoid knocking. Spark ignition gaseous fueled engines can achieve very high power ratings. Gaseous fuels are very attractive for land-based operations where the fuel is available by pipeline, but mobile conversions have proved difficult because of the large storage volume needed.

Reviewing Table 13, the petroleum middle distillates, heavy distillates and residual fuel oils are the most attractive alternatives available. Vegetable oils are the only non-petroleum alternative that are commercially available at present and will serve as a direct replacement for DF-2 without engine or fuel system modification. The alcohols, while available in far larger quantities than vegetable oils, require an extensive engine and fuel system modification for high alcohol utilization. Shale oil and tar sand products are ranked below the alcohols because they are presently unavailable; should large-scale commercial production begin, these products will be highly attractive. The coal-derived liquid products received the lowest ranking because of poor fuel ignition quality, the high degree of engine retrofit, and/or the poor availability.



IX. CONCLUSIONS

The following conclusions were reached as a result of this study.

1. The alternative fuels found to be most attractive for replacement of high quality DF-2 in the Corps of Engineers Dredge Fleet were petroleum middle distillate, heavy distillate, and residual fuel oils. Fuel costs, fuel availability, and the extent of engine and fuel system modification were the deciding factors. Vegetable oils, alcohol, shale oils, and coal-derived liquid products ranked in that sequence below petroleum alternatives.

2. Coal liquid products produced by direct liquefaction technology are poor candidates because of their low cetane number and toxicity. In all probability, if coal liquids are produced in quantity, the products will receive far more severe treatment, which will generate more acceptable fuels. Coal liquefaction technology is presently at a standstill. An estimate is not available for the time frame in which improved fuels will be available.

3. The diesel fuel produced by the Sasol indirect coal liquifaction process would be an excellent alternative, but political barriers prevent import of the product from South Africa. The Sasol fuels are presently being produced in industrial quantities in South Africa, and are in use in medium-speed diesel engines including EMDs.

4. None of the coal products are available at this time for a demonstration or experimental testing, except for a small quantity of EDS which is in storage. However, since the coal liquids are not in production and it is unlikely that future products will resemble the EDS available, tests using EDS are not recommended.

5. Alcohols are non-petroleum alternatives that are available in large quantities today. Methanol and ethanol are the two products that are feasible, methanol being the more attractive for both cost and availability reasons. The drawback to alcohol use is that engine and fuel system retrofit is required. Nonetheless, methanol should be

considered seriously since production is expected to increase dramatically in the next two to five years.

6. Shale crude can be converted into excellent distillate fuels. The technology is available and has been demonstrated. These fuels would be suitable for direct fuel replacement. Shale oils are not presently in production, but are expected to be available in the near future.

7. CERL may be able to tap the DOD Union/Gary shale oil effort during 1985 for sufficient quantities of shale diesel fuel for a demonstration or for continuous use. This product could be used in neat form as a direct diesel fuel replacement and the cost would be comparable to DF-2 because of government price guarantees. This product is the top candidate for a CERL demonstration.

8. Tar sand products that are suitable as direct diesel fuel replacements have been made and field tested. A number of these products are presently in use in Canada, but no tar sands products are in production in the U.S. Tar sands technology is presently dormant but could become active because of the tremendous potential of tar sands.

9. Vegetable oils, in particular sunflower and soybean oils, are the only non-petroleum alternatives that are presently available in commercial quantities and are suitable for direct diesel fuel replacement. Further research is needed to solve engine deposits and wear problems. The technology to produce vegetable oils has been developed, and if demand materializes, supply will increase.

10. Many questions were not answered in this study regarding a specific application of the alternative fuels to dredges because of lack of definition of the hardware currently installed in the fleet. Information will be needed regarding engines, tankage, tank heating capacity, fuel heating capacity, and fuel filtration and purification capacity before realistic retrofit estimates can be formulated.

X. RECOMMENDATIONS

1. Define the hardware currently installed in the Corps of Engineers dredge fleet. The definition should include descriptions of the main power plant, the tankage, tank heating capacity, fuel heating capacity, fuel filtration and purification capacity. In addition, auxiliary engines and fuel systems must be defined. This information should be compiled in a form which is convenient for analysis. It is envisioned that the information may be available in the construction and maintenance records of the vessels. If this is not the case, the fleet should be surveyed in order to determine the current type, status, and operating and maintenance procedures of the installed equipment. This information should then be used to assess the feasibility of using the candidate alternative on a vessel-to-vessel basis in terms of fuel handling systems (tanks, heating, and purification systems). On those vessels where it is feasible to use the candidate fuel, the engine hardware should be examined in terms of past experience with this candidate in the particular engine types. In those cases where there is no experience, appropriate experiments should be performed.

2. It is recommended that CERL consider using petroleum alternatives even though the specific objective of this task was to identify non-petroleum alternatives. As was apparent in previous sections, the petroleum alternatives rank first because of cost, availability, ease of implementation, and wide-spread distribution. Direct fuel cost savings are possible by taking advantage of the medium-speed diesel engines' fuel tolerance. A number of research programs are presently underway to study these economy fuels, the results of which would be directly applicable to the dredges.

3. Contact the Defense Supply Fuels Center (Cameron Station, Virginia) immediately to determine if the Union/Gary shale oil is available for a CERL dredge demonstration. This contact could be handled through the U.S. Army Fuels and Lubricants Research Laboratory (AFLRL) at SwRI. If this shale oil supply can be tapped, it is recommended that a demonstration using this product be considered for this year.

4. Tests of present day direct liquefaction coal-derived products are not recommended. These products are not representative of products that are likely to be available in quantity in the future.

5. A vegetable oil, either sunflower or soybean oil, is the only non-petroleum alternative that is recommended except for the shale products for a near-term demonstration. Since there has been no durability testing performed on medium-speed diesels using vegetable oils, it is recommended that 200 to 500 hour durability tests be performed in the type of engines more commonly used in the fleet. These suggested test durations are typically too short to evaluate the wear in this type of engine. It is felt, however, that the duration is long enough to point out the types of problems typically produced by the use of vegetable oils.

Since the injection and atomization characteristics of the vegetable oils have not been determined in medium-speed diesel engine equipment, it is recommended that a series of experiments be performed using the injection system most commonly used in the fleet. The experiments should be performed by injecting the oil into a high temperature, high pressure environment. The results of these experiments will indicate what oil temperatures are required for satisfactory operation in the engine. The medium-speed diesel engine durability test should be performed with vegetable oil temperatures at lowest acceptable values as determined in the injection studies.

6. The alcohols are not recommended for an immediate demonstration, but because of the potential for very large methanol production in the next two to five years, a future demonstration should be considered. Dual-fueling is the approach presently recommended for high alcohol utilization.

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LIST OF ABBREVIATIONS

AAR	-	Association of American Railroads
AFFMSDE	-	Alternative Fuels for Medium-Speed Diesel Engines program
AFLRL	-	Army Fuels and Lubricants Research Laboratory
AOCS	-	American Oil Chemists Society
A.P.	-	any proportion
API	-	American Petroleum Institute
ASTM	-	American Society for Testing and Materials
bbls	-	barrels
BTU	-	British Thermal Unit
C	-	Centigrade
calc	-	calculation
CERL	-	Construction Engineering Research Laboratory
cm ³	-	cubic centimeters
CNG	-	compressed natural gas
COED	-	Char-Oil Energy Development
cSt	-	centistokes
deg	-	degree
DF-2	-	No. 2 diesel fuel
DFSC	-	Defense Fuel Supply Center
DI	-	direct injection
DOD	-	Department of Defense
DOE	-	Department of Energy
DOT	-	Department of Transportation
EDS	-	Exxon Donor Solvent
EMD	-	Electro-Motive Division of General Motors
EP	-	End Point
EPRI	-	Electric Power Research Institute
ERDA	-	Energy Research and Development Administration
EtOH	-	Ethanol
F	-	Fahrenheit

LIST OF ABBREVIATIONS, Cont'd.

FIA	-	fluorescent indicator absorption
FMC	-	Farm Machinery Corporation
gal	-	gallon
GE	-	General Electric
IBP	-	Initial Boiling Point
IDI	-	indirect injection
IPA	-	Isopropanol
kg	-	kilogram
L	-	liter
lb	-	pound
LCO	-	Light Cycle Oil
LNG	-	Liquid natural gas
max	-	maximum
MeOH	-	Methanol
MERADCOM	-	Mobility Equipment Research and Development Command
mg	-	milligrams
MJ	-	Megajoules
ml	-	milliliter
MSDE	-	Medium-speed Diesel Engines
NA	-	naturally aspirated
N.A.	-	not applicable
ppm	-	parts per million
psig	-	gauge pressure, psi
rpm	-	revolutions per minute
Sasol	-	South African Coal, Oil and Gas Corporation
SpGr	-	Specific gravity
SRC	-	Solvent Refined Coal
SUS	-	Saybolt Universal Seconds
SwRI	-	Southwest Research Institute
TBA	-	Tertiary Butanol
U.A.	-	Unavailable

LIST OF ABBREVIATIONS, Cont'd.

U.S. - United States

vol - volume

wt - weight

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