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Technical Memorandum
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FEASIBILITY OF USING DIESEL FUEL IN GASOLINE-POWERED ENGINES

by

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EXECUTIVE SUMMARY

Internal combustion engines burn a fuel-air mixture and develop shaft horsepower in direct proportion to the heating value and mass of the fuel burned. In a reciprocating engine, the power produced in the cylinder is transmitted from the piston, through the connecting rod and crankshaft, to the output shaft. The two most common types of reciprocating piston engines are based on either the spark-ignition (Otto) cycle or compression-ignition (diesel) cycle. Due to variations in introducing fuel (before compression for spark-ignition engines - typically gasoline powered, and toward the end of compression for compression-ignition engines - typically diesel powered), each engine requires specific fuel characteristics to operate properly. Spark-ignition engines require a volatile fuel which will vaporize and mix uniformly with the combustion air, with its associated additives to reduce preignition and detonation. Compression-ignition engines require fuel with low volatility and short ignition lag. Additives that change the volatility and molecular properties of diesel fuel for operation in gasoline engines are not currently available. Although an experimental commercial product, A-21 (a mixture of water, naphtha, and emulsifier), is advertised as a single fuel for both gasoline and diesel engines, data and long term tests to support these claims are not yet available. Also, since A-21 contains up to 55 percent water by volume, the fuel cannot be used at extreme subfreezing temperatures.

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INTRODUCTION

The Marine Expeditionary Force requires two types of fuel: (a) gasoline for gasoline-powered engines, and (b) diesel, JP-5 or JP-8, for diesel-powered engines. Transporting two different types of fuel presents a logistical challenge. If diesel fuel, commonly used in the fleet, can be readily modified to have the same properties as gasoline for use in the few remaining gasoline-powered items, the logistics problem of carrying both gasoline and diesel can be avoided. In addition, the hazards associated with transporting and storing the more volatile gasoline can be prevented.

This paper outlines the basic refining process necessary to obtain the different types of fuel such as gasoline, naphtha, kerosene, and diesel. Also, the difference between the spark-ignition (Otto) cycle and compression-ignition (diesel) cycle and the fuel requirements of each cycle are discussed.

DISCUSSION

Fuel

The liquid fuels commonly used in internal combustion engines are processed from crude oil. The discovery that the boiling point of hydrocarbons increases with their molecular weight led to the development of the fractional distillation refining process (Ref 1). In the basic distillation process, the lighter fractions of crude oil are vaporized at lower temperatures and the heavier components at higher temperatures. As shown in Figure 1, the lighter vapors such as gasoline migrate to the upper part of the tower and the progressively heavier vapors settle at the bottom. The fractional distillation tower contains numerous trays. The lighter hydrocarbons are condensed at the upper trays and the heavier hydrocarbons are condensed at the lower trays. The fuel refined ranges from the lightest straight run gasoline to naphtha, kerosene, fuel oils (diesel fuel), and lubricating oils. After the distillation process, a residue (asphalt) is left which is commonly used in building roads (Ref 2).

The high demand for gasoline is greater than what can be economically produced from the fractional distillation process. This high demand resulted in the development of the cracking process. The cracking process breaks down the molecules of heavier fuels into more desirable lighter fuels such as gasoline. Thus, a portion of diesel fuel can be converted into gasoline by the cracking process. It should be noted that the products of cracking not only include lighter hydrocarbons, but also hydrocarbons that are heavier than the original stock. Other processes such as hydrogenation, reforming, and alkylation are also employed to produce lighter fuels from heavier fuels.

Figure 2 shows a typical distillation curve for the different kinds of fuel. The distillation temperatures are indicative of the volatility of the fuels. Gasoline, for instance, with a lower distillation temperature than other fuels, is highly volatile. On the other hand, diesel, with its high distillation temperature, is considered a low volatility fuel.

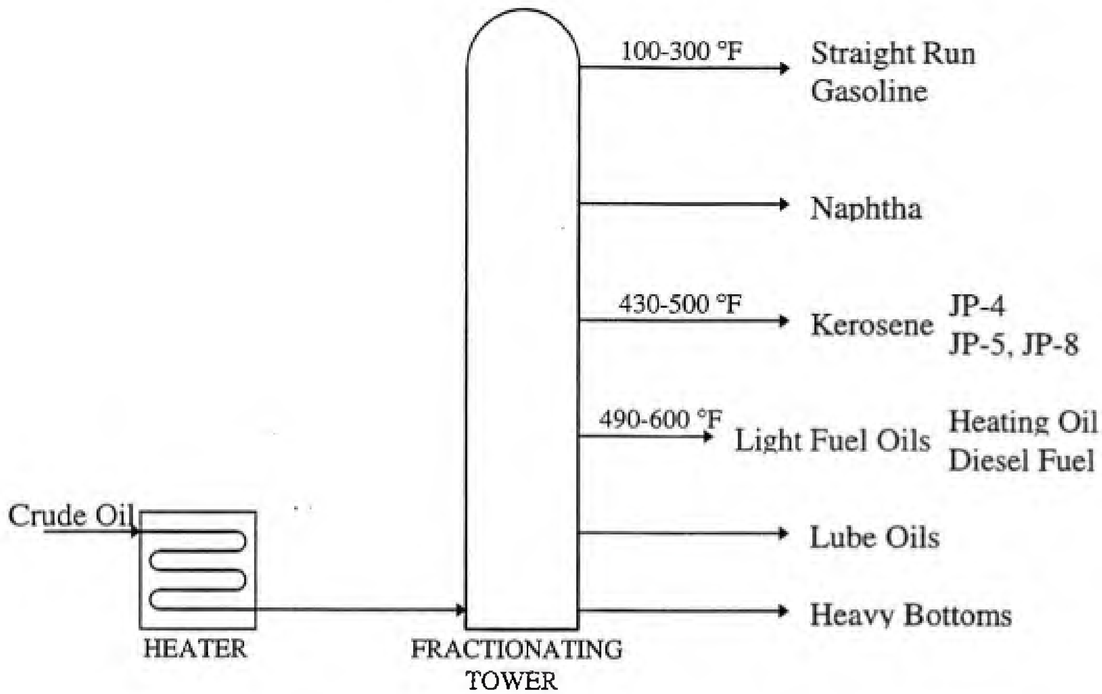

Figure 1. Basic fractional distillation process.

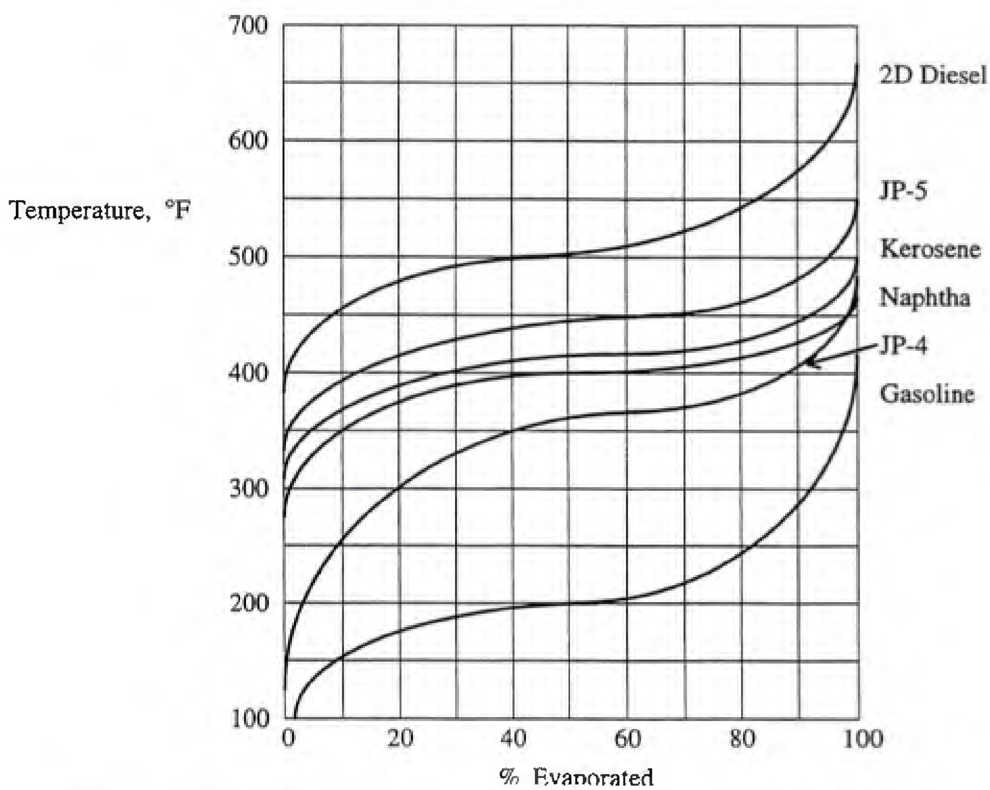

Figure 2. Typical distillation curves (for illustration only, adapted from Ref 2).

Within each class of liquid fuel are different grades to meet the needs of various engine designs. Different grades of gasoline are rated based on their octane numbers. A higher octane number indicates better antiknock (antidetonation) properties. Gasoline differs from diesel fuel as shown in Table 1. Gasoline has a flash point of -45°F vice 125°F for diesel. The higher flash point renders diesel fuel more stable. The high flash point means lower fire hazards. As long as air temperature is below 125°F (which is true for most geographic areas), diesel fuel will not vaporize at atmospheric pressure.

The characteristics of diesel for a smooth running engine are based on its cetane number. The cetane number is an indication of the ignition delay. Higher cetane numbers provide better starting characteristics in cold weather and better antiknock properties (Ref 3). Compared to the octane number, the high cetane number translates to a low octane number and vice versa (Ref 4). Thus, a high quality diesel fuel has a very low octane number.

Table 1. Autoignition Temperature

Fuel	Flash Point (°F)	Autoignition Temperature (°F)
Gasoline (92 Octane)	-45	734
Naphtha	20 to 45	450
Kerosene	115	410
JP-4	below 0	475
JP-5	140	475
JP-8	100	466
Diesel Oil (Paraffin Type)	125	477

During the early usage of diesel fuel, wide variation in properties was prevalent based on the regions where crude oil was refined. With the advent of jet-powered aircraft, the military implemented specifications to obtain more uniform and better quality aviation fuels. As a result, specifications for JP-4, JP-5, and more recently JP-8 fuels were implemented. JP-4, JP-5, and JP-8 have properties similar to diesel fuel as shown in Table 2. JP-4 (a mixture of gasoline and kerosene) is more dangerous to handle than JP-5 or JP-8 because of its low flash point. The single fuel, JP-8, which can be used for all military vehicles, aircraft, and other equipment, has properties similar to JP-5. Commercial Jet A-1 (without additives) is a kerosene type fuel, the same as JP-8. The primary difference between Jet A-1 and JP-8 is that JP-8 contains several additives: a corrosion inhibitor, a lubricity improver, and a fuel system icing inhibitor.

Naphtha, a low grade or low octane gasoline, is commonly used as an industrial solvent. The boiling range and volatility of naphtha falls between gasoline and kerosene. Diesel and the kerosene based JP fuels (except JP-4) have higher boiling ranges than naphtha.

Table 2. Properties of Fuel Oils

Requirement	JP-4	JP-5	JP-8	Diesel (2D)
Cetane Rating				40
Flash Point, °F, min.	below 0°F	140	100	125
Freezing Point, °F	-72	-51	-53	
Heating Value (Btu/lb)	18,400	18,300	18,400	18,400
Sulfur, % Mass	0.4	0.4	0.3	0.5

Basic Engine Operation

The two most commonly used internal combustion engines are based on either the spark-ignition (Otto) cycle or the compression-ignition (diesel) cycle.

Spark-Ignition Engine. The basic four-stroke spark-ignition (SI) engine operates as follows: (1) piston travels down during the intake stroke to draw a combustible fuel-air mixture into the cylinder; (2) the piston travels up in the compression stroke that raises the temperature of the mixture; (3) there is ignition by the spark plug and combustion of the mixture, raising the temperature and pressure inside the cylinder; the high pressure in the cylinder forces the piston downward in the expansion or power stroke; and (4) the piston travels up in the exhaust stroke to remove the products of combustion (Ref 2). SI engines have compression ratios between 6:1 to 12:1 and cylinder pressures from 150 to 300 psi (Ref 5). It should be noted that in the SI engine, air and fuel are mixed before the start of the compression stroke and are external to the combustion chamber.

Compression-Ignition Engine. Compression-ignition (CI) or diesel engines may operate in a similar four-stroke cycle or in a two-stroke cycle. The major difference between SI and CI engines is that in the diesel engine, air alone (no fuel) is compressed and the fuel is injected directly into the combustion chamber toward the end of the compression stroke. The heat produced by rapid compression of the air raises the air temperature 1,000°F or higher, which is sufficient to ignite the fuel when injected in the cylinder near the top of the compression stroke. The spark plug ignition source in the SI engine is essentially replaced with the heat of compression in the CI engine. CI engines have compression ratios ranging from 12:1 to 23:1 and cylinder pressures from 400 to 700 psi (Refs 2, 5).

Two-Stroke Cycle. The two-stroke cycle can be used for both the SI and CI engines. Although two-stroke SI engines are typically quite small, large two-stroke CI engines are quite common. The four-stroke cycle requires two crankshaft rotations for each power stroke while the two-stroke requires only one.

Engine Knock and Ignition Delay. Because fuel is already mixed with air at the beginning of the compression stroke, the compression ratios and pressures of SI engines are limited to prevent premature ignition and detonation or "knock." As the fuel-air mixture is compressed, the temperature in the combustion chamber rises. The higher the compression ratio, the greater the rise. The high temperatures resulting from the high pressures may exceed the autoignition point resulting in preignition (ignition before the piston reaches the optimum position). Detonation ("knock," an explosion of the fuel-air mixture as opposed to a controlled burn) may also be caused by high temperatures and pressures. Both of these conditions result in power loss, overheating, and ultimately engine failure.

Even if the autoignition temperature is reached as a result of the high pressure, an ignition lag or time delay can be present before the mixture becomes explosive (Ref 1). Thus, for SI engines, fuel with long ignition lag is desirable to allow the flame front to travel from the ignition source through the fuel-air mixture and across the combustion chamber to obtain a uniform burn.

In CI engines, ignition lag is characterized as the time delay from fuel injection until combustion. Engine knock occurs in CI engines when the ignition lag of the fuel is too long. With long ignition lag a greater portion of the fuel is allowed to vaporize and form an explosive mixture. As the piston continues to move toward the top of the cylinder and compression heat rises, the vaporized fuel will detonate producing the characteristic engine knock. The vaporized fuel will predetonate producing the characteristic engine knock. Thus, CI engines require fuel with short ignition lag.

Diesel Fuel in Gasoline Engines

Gasoline-powered engines operate on the spark-ignition (Otto) cycle. The ignition source (spark) is applied at the optimum point in the compression stroke to maximize power. The spark is introduced at a single source which ignites the fuel-air mix across a flame front, burning the fuel-air mixture in a controlled manner as the flame front propagates across the combustion chamber. It requires volatile fuels with long ignition lag to minimize engine knock in the SI engine. Engine knock occurs when the fuel-air mixture is raised above its autoignition temperature due to high compression ratios. Engine knock also occurs when the last fraction of unburned fuel-air mixture is compressed by the fraction that has burned. The increased pressure increases the temperature of the unburned mixture above its autoignition temperature resulting in spontaneous, explosive ignition.

Gasoline is commonly used for SI engines because of its high volatility which allows it to mix readily and uniformly with air. Since gasoline flashes at temperatures as low as -45°F, it is readily vaporized when mixed with air and introduced into the engine cylinder. The presence of liquid in the fuel-air mixture is not desirable for SI engines and will result in poor starting characteristics and poor performance. As a minimum, using diesel fuel in a gasoline engine would require preheating the diesel fuel to allow it to vaporize prior to combustion.

Gasoline is ideal for SI engines since it is highly volatile, has a long ignition lag, and a high autoignition temperature. Diesel fuel on the other hand is not volatile (without adding heat), has a short ignition lag, and a low autoignition temperature (see Table 1). To use diesel in gasoline engines will result in poor performance, ignition system fouling, and premature engine failure.

Gasoline in Diesel Engines

Diesel engines were originally developed to burn coal dust (Ref 2). Because of their rugged design, diesel engines can burn almost any type of fuel. Dual-fuel engines, which are modified diesel engines modified with lower compression ratios, can burn both diesel fuel and compressed or liquefied natural gas. Natural gas as an alternative fuel is predominantly used because it is plentiful and cheap. Gasoline can be used in diesel engines if the engine is modified to accept the characteristics of gasoline. Attempts to run unmodified diesel engines with gasoline will result in engine knock since gasoline has a long ignition lag, and diesel engines require fuels with short ignition lag. Also, to obtain suitable fuel injection pressures (3,000 psi or higher), the fuel pump needs to be adjusted because the density of gasoline is lower than that of diesel fuel. Unmodified diesel engines using gasoline will also result in shorter engine life since the natural lubricating properties of diesel fuel are not present in gasoline. It should be noted that diesel fuel is sometimes referred to as diesel oil.

Naphtha in Lieu of Gasoline

Naphtha cannot be used in place of gasoline in SI engines because of its low octane number. Hydroforming is a refining process in reforming naphtha (sometimes called low octane gasoline) to increase its octane number. In this process naphtha reacts with hydrogen in the presence of a catalyst (Ref 6).

Fuel Additives

Gasoline, a mixture of many hydrocarbons, is principally derived from crude oil. Aside from straight run fractional distillation, cracking and other processes to break down heavier hydrocarbons into lighter hydrocarbons are employed to increase the availability of gasoline from crude oil. Also, additives are blended with gasoline to meet a variety of engine requirements and increase the octane number. The additives include: antiknock, to minimize undesirable engine knock; deposit modifiers, to minimize combustion chamber deposits which promote surface and preignition; antioxidants, to reduce gum formation; lubricants, to lubricate the upper cylinder; anticorrosion, anti-icing agents, etc. Similarly, additives are blended with diesel fuel to obtain desirable characteristics. They include: cetane improvers, to increase the cetane number; stability improvers, to reduce gum deposits; and microbiological growth inhibitors, corrosion inhibitors, and lubricity improvers, to improve fuel pump and injector lubrication etc. (Ref 2).

Diesel fuel has characteristics different than those of gasoline. To use diesel in an SI engine, the flash point needs to be lowered to allow it to vaporize readily when introduced into the engine. Liquid fuel must be vaporized and mixed with air in order for the spark to ignite the mixture. In addition, the ignition lag of diesel needs to be increased to prevent premature ignition.

A literature search of technical databases and a survey of engine manufacturers and refineries was conducted seeking methods that would allow the use of diesel fuel in gasoline engines. No additive(s) and no current research in additive(s) were found that would modify diesel fuel to operate in a gasoline engine. Although gasoline and diesel fuel (see Figure 3) are mixtures of many hydrocarbons, gasoline is considered to be octane (C_8H_{18}), and diesel is considered to be dodecane ($C_{12}H_{26}$) (Ref 7). Thus, to modify diesel fuel into gasoline, the molecular structure of diesel fuel needs to be changed. In other words, carbon-carbon bonds of diesel fuel need to be broken and reformed resulting in lighter hydrocarbons such as gasoline.

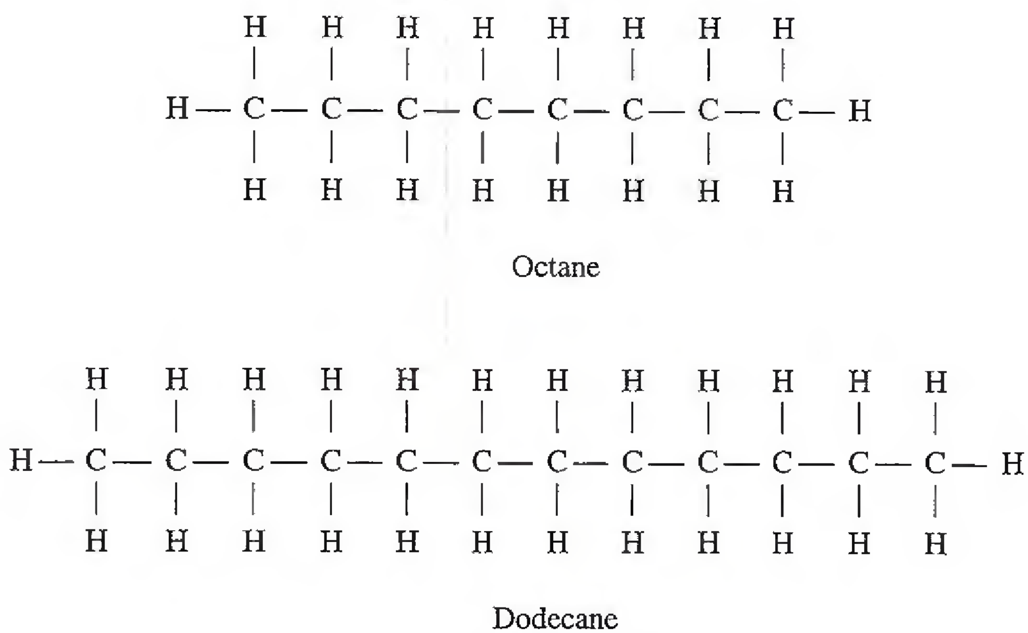

Figure 3. Schematic of open-chain structure of octane and dodecane.

Similarly, gasoline cannot be converted into diesel by merely combining with an additive, since it will require changing its molecular structure from a light fuel to a heavy fuel.

In summary, additives are commonly used in both gasoline and diesel fuel to obtain specific characteristics to meet the requirements of SI and CI engines. However, additives are not yet available to convert diesel fuel into gasoline and vice versa. Converting fractions of diesel fuel are done at the refineries by using refining processes such as cracking to break down the molecular structure of heavier fuels into lighter fuels. If developed, however, any additive or combination of several additives to change the specific characteristics of diesel fuel will likely present logistics problems similar to those presented by gasoline. Because diesel fuel is less volatile than gasoline, any potential additive may need to be more volatile (and therefore hazardous) than gasoline. Additional notes are provided in the Appendix.

Alternative Fuel

In 1992 Rodulph Gunnerman, an inventor from Reno, Nevada, was issued U.S. Patent No. 5,156,114, "Aqueous Fuel for Internal Combustion Engine and Method of Combustion." Although the patent covers all the combinations of water and hydrocarbons, the current development is geared toward a water-naphtha-emulsifier mixture. The fuel mixture is dubbed

A-21 (alternative fuel for the 21st Century), which is a fuel mixture of up to 55 percent water by volume. The emulsifier is used to blend water and naphtha which normally don't mix. The blend results in a milky liquid that is claimed to run both diesel and gasoline engines.

In order to use the A-21 fuel, existing engines need to be modified. Because of different properties of A-21 fuel, larger fuel injectors and higher output fuel pumps are needed. Block heaters are also needed when operating in cold regions. The water contained in the fuel lowers the engine operating temperature resulting in lower emissions and reduced nitrous-oxides.

Only fresh water can be used with the fuel blend. It can be water, distilled water, or deionized water. Because of its lower heating value per gallon, A-21 is not a diesel fuel extender. The energy content of 1 gallon of diesel fuel is approximately equivalent to 1-1/2 gallons of the A-21 mixture. The lower energy content per gallon of A-21 will reduce the range of vehicles operating on A-21 by 33 percent.

In 1994, Gunnerman and Caterpillar (a large heavy equipment manufacturer) formed a partnership company (Advanced Fuels) to commercialize the A-21 fuel. Caterpillar is currently conducting research on the new fuel to evaluate its viability when used in heavy duty diesel engines. Results of the tests are currently not available due to the proprietary nature of the tests.

Although A-21 is advertised as a single fuel for both gasoline engines and diesel engines, data to support these claims are not yet available. Also, since the fuel contains water, up to 55 percent, the fuel cannot be used at extreme subfreezing temperatures. The development of A-21 is primarily intended to reduce harmful emissions in both gasoline and diesel engines and may ultimately be a good candidate fuel for stationary engines.

CONCLUSION

Due to variations in introducing fuel, before compression for gasoline-powered engines (spark-ignition) and toward the end of compression for diesel-powered engines (compression-ignition), each engine requires a specific fuel to operate properly. Spark-ignition engines require a volatile fuel with its associated additives to reduce knock. Compression-ignition engines require fuel with low volatility and short ignition lag. Additives which change the volatility and molecular properties of diesel fuel to convert it into gasoline are not currently available.

RECOMMENDATION

To solve the logistical difficulty of carrying two types of fuel, the fleet should be encouraged to use a single type of engine, preferably the diesel engine. Diesel engines operate at higher efficiency compared to gasoline engines and require a lower volatility fuel, thus minimizing fire hazards and logistics problems.

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Appendix

NOTES ON FUEL CHEMISTRY*

CRACKING

Pyrolysis or cracking is the process when a molecule is broken up by heat. When alkanes or paraffins are pyrolyzed, the C-C bond cleave to produce smaller alkyl radicals.

$$CH_3\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}CH_3 \rightarrow CH_3\cdot + CH_2\text{-}CH_2\text{-}CH_2\text{-}CH_3\cdot$$

pentane	methyl radical	butyl radical

or

$$CH_3\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}CH_3 \rightarrow CH_3\text{-}CH_2\cdot + CH_3\text{-}CH_2\text{-}CH_2\cdot$$

pentane	ethyl radical	propyl radical

The free radicals which are highly reactive will recombine to form alkanes such as ethane (C_2H_6), propane (C_3H_8), and hexane (C_6H_{14}). Another possible reaction is disproportionation, where one radical transfers a hydrogen atom to another radical and produces an alkane and an alkene (i.e., ethane, C_2H_6 + propylene, C_3H_6). The net result of cracking is the breaking up of large alkanes to a mixture of smaller alkanes and alkenes.

With higher alkanes such as fuels, the cleavage occur randomly along the chain. The bond dissociation energy required for cleavage of the C-C bond is 88 kcal/mole. To increase the supply of lighter hydrocarbons such as gasoline, refineries commonly crack the crude oil by pyrolysis (derived from the Greek word pyros, fire; and lysis, loosening).

ENERGY CONTENT AND EFFICIENCY

For a specific engine design, the power that can be obtained from a fuel is dependent on the heating value of the fuel. The heating value of diesel and JP fuels is usually expressed in mass basis (Btu/lb). The heating value in volume basis was obtained by taking the product of the minimum heating value and the average density of the fuel. The density is usually expressed in kg/l. The values shown in Table A-1 are converted into English units (lb/gal). Since the fuel usage is usually expressed in terms of volume (i.e., gallons/mile), comparing the heat values expressed in Btu/gallon is considered more relevant.

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*Reference: C.H. Heathcock and A. Streitser, Jr. Introduction to organic chemistry. New York, NY, Macmillan Publishing Co., Inc., 1976; Notes of Theresa Hoffard, Research Chemist, NFESC Code 63, Jun 1996.

Table A-1. Heating Values

Fuel	Heating Value (Btu/gal)	HV Fuel/ HV Diesel
JP-4	118,973*	0.91
JP-5	124,422*	0.95
JP-8	123,723*	0.95
Diesel	130,627**	1

* Obtained by multiplying the heating value and average of the minimum and maximum density listed in MIL-T-5624R & MIL-T-83133D.
** Reference 5.

As shown in Table A-1, the heating value of diesel is higher than the JP fuels. The heating value of JP-8 is only 95 percent compared to that of diesel fuel. The fuel consumption of vehicles using JP-8 should be expected to be higher than that of diesel. Consequently, the range of vehicles using JP-8 will be reduced.