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Emergency Fuels Utilization Guidebook

Alternative Fuels Utilization Program

August 1980

MASTER

Prepared For:
U.S. Department of Energy
Assistant Secretary for Conservation and
Solar Energy
Division of Automotive Technology Development

Under Contract No. AC01-78CS54269

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Dr. 1592

DOE/CS/54269-01
Dist. Category UC-96

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U.S. Department of Energy
Assistant Secretary for Conservation and
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Division of Automotive Technology Development
Washington, D.C. 20585

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ACKNOWLEDGEMENTS

This guidebook is the culmination of a two-year program of experimental and analytical research. Individuals and organizations who made invaluable direct and indirect contributions would be too numerous to list here. It is appropriate, however, to identify certain of the Southwest Research Institute staff who worked diligently to develop the *quantitative* aspects of the material: Todd Ford, George Mathis and Randy Hollon for conducting the engine tests; George Lee and Ed Lyons for supervising the emergency fuels blending operations; Norm Sefer for expert guidance on fuels specs and properties; Jim Pryor for editorial coordination.

With regard to the more *qualitative* "textbook" aspects, Kenneth Boldt, Union Oil Company of California, and B.R. Hall, American Petroleum Institute, will recognize much of the descriptive material as having been derived from their excellent ASTM Special Technical Publication 7C, "Significance of Tests for Petroleum Products." Our deepest thanks are due to Editors Boldt and Hall as well as the forty or so authors and to T.W. Legalski, the original publication project coordinator.

The use of facilities and technical support from the U.S. Army Fuels and Lubricants Research Laboratory at Southwest Research Institute is gratefully acknowledged for testing and analytical work done with the concurrence of the U.S. Army Mobility Equipment Research and Development Command (MERADCOM), Fort Belvoir, Virginia.

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August 1980

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CAUTION

Emergency fuels should be used as a last resort. The charts, text, and general format of this document may give the reader the impression that this is a manual to formulate fuels for long-term ROUTINE FLEET OPERATIONS. (Indeed, an ambitious fleet operator might initiate a program to reduce fuel costs by using emergency blends in nonemergency situations.) Certain points must be made clear:

- Emergency blends are aimed at base fuel stretch-out for weeks or months; fleet-operating economics will not be a governing consideration under these circumstances. Engines may have to be intentionally sacrificed simply to continue essential services.
- There are elements of risk in the use of emergency fuels: risk to the engine (high wear, malcombustion damage, corrosion and deposits) and to personnel (flammability hazards, toxicity). These can be *minimized* by good operating procedures but never eliminated.
- Use of such blends in engines still under warranty will very likely void these warranties (commercial gasohol being an exception at this time).
- Engine adjustments or modifications* to accommodate such fuels may correspondingly void warranties.
- It is mandatory that all cognizant Federal, State and local environmental authorities approve use of emergency blends and engine changes prior to use. Whereas, in a severe emergency, it is very likely that such waivers will be granted, this must not be overlooked.

These blends are insurance. Someday they may have to be used. Until that time, the *most economic* policy is to continue to burn specification grade fuels which provide both good performance and long engine life.

*For specific guidance regarding tampering with emissions equipment, see Federal Register 40 CFR, Part 85, Volume 45, No. 43, pp 13732-13734, March 3, 1980.

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INTRODUCTION

In a domestic fuels supply emergency, it is essential that certain critical civilian services be maintained and desirable that others be continued. These include the operation of transportation services involving medical, fire, police, and mass transit vehicles. Although a wide variety of scenarios can be constructed for projected domestic emergencies, each would include the following fundamental premises regarding fuel supplies:

- Specification-quality gasoline and diesel fuel would be closely controlled and distributed at federal, state, and municipal levels.
- These fuels would be allocated to key transportation functions on some priority basis.
- Liquid hydrocarbon materials which *could be effectively* mixed with these specification quality fuels would be made available to fleet operators for emergency fuels blending.
- Any resulting sacrifice in environmental quality would be minimized simply because of the drastic reduction in total vehicle utilization.

Given these assumptions, an emergency fuel is: *a specification quality automotive gasoline or diesel fuel to which a supplement has been added which permits (a) effective extended utilization of the base fuel, (b) acceptable (but perhaps decreased) vehicle performance, and (c) minimum sacrifice in environmental quality.*

Whereas some sacrifices in vehicle performance and driveability as well as exhaust emissions may be permitted by cognizant authorities in such circumstances, emergency blends should actually *increase the miles per gallon of gasoline or diesel fuel* as compared to the use of neat gasoline or diesel fuel. Certainly, there must be *no compro-*

mise in safety, blending, storing, fueling, or vehicle operation.

Thus, the basic concept of an emergency fuel is to safely and effectively use blends of specification fuels and hydrocarbon liquids which are "free" in the sense that they have been *commandeered* or *volunteered* from lower priority uses to provide critical transportation services for short-duration emergencies on the order of weeks, or perhaps months.

This document has been devised to serve as textbook, cookbook, and planning guide. A wide variety of liquid hydrocarbons not normally used as fuels for internal combustion engines have been categorized *generically*, including limited information on physical characteristics and chemical composition which might prove useful and instructive to fleet operators. The cookbook aspect entails "Tradeoff Charts" (described below) which are intended to serve as *general guidelines*, permitting individual fleet operators a certain discretionary range in selecting "recipes" which represent a balance between performance sacrifice and base fuel stretch-out.

It should be emphasized that all data in this guidebook have been generalized, based upon an intensive 2-year program of experimental laboratory research using a limited but representative collection of diesel and spark ignition engines. Data from bench tests, single and multicylinder engine dynamometer testing, and highly limited vehicle chassis dynamometer and road tests have been weighted and combined to provide *representative* curves which illustrate individual characteristics of fuel blends. Certainly, actual vehicle performance and economy will vary from these guideline charts. At this point, there has been no comprehensive road or fleet evaluations of these blends, and therefore all data and curves must be used as indicators of relative performance in comparing one blend to another.

TRADEOFF AND EMISSIONS INDEX CHARTS

Each section of this guidebook contains material for a specific class of emergency extender liquid which might conceivably be (a) available for fleet operations in practicable quantities and (b) compatible with gasoline, diesel fuel, or both.

The first portion of each section contains general material on each extender class including information on physical and chemical properties. The balance of each section then contains graphical material on engine performance, fuel conservation, and exhaust emissions.

Two types of charts have been devised to guide fleet operators in determining best extender/base fuel proportions to effect a balance between sacrifice in engine performance and gasoline or diesel fuel stretch-out. These are designated "Tradeoff Chart" and "Emissions Index," respectively. For the purposes of extreme emergency fleet operations, it is assumed that environmental impact due to increased exhaust emissions will be minimized due to a drastic reduction in numbers of vehicles operating in any given locale. Consequently, emissions have been relegated to lowest priority as compared to fuel stretch-out and engine performance. Accordingly, emissions data are shown on separate charts throughout the guidebook.

1. Tradeoff Charts

Figure 1 presents a typical Tradeoff Chart which exemplifies how such curves can be used by the fleet operator. The three curves shown (Conservation Index, Power Index, and Tradeoff Index)* reflect (a) how much baseline fuel is conserved, (b) how much power sacrifice can be expected, and (c) the total of these two factors (Tradeoff Index) for each concentration (volume percent) of *ethanol* blended with gasoline and operated in a *spark ignition* engine.

The Conservation Index curve increases with increasing concentration of ethanol, reaching a maximum of about 0.42 at a 50/50 blend of ethanol and gasoline. This means that from zero to 50 percent concentration of ethanol in gasoline, more and more gasoline is conserved up to a maxi-

mum of about 40 percent.

The power index curve remains essentially constant at 1.0 to about 40 percent volume ethanol. This means that the power developed with ethanol/gasoline blends (over a reasonably wide range of operating conditions for *unmodified* spark ignition engines) is comparable to that developed by "neat" gasoline up to about a 40/60 proportion of ethanol/gasoline. Above this value, power drops off dramatically (with stock carburation) decreasing to about 0.35 (35 percent of power developed by neat gasoline) at 75 percent ethanol/25 percent gasoline.

Tradeoff Index is simply the sum of the two curves for Power Index and Conservation Index. When the vertical values (ordinates) for Conservation and Power Index at a given ethanol concentration level are added, the result is the ordinate for Tradeoff Index. This particular Tradeoff Index curve peaks at 40 percent volume ethanol which reflects the *optimum balance between gasoline stretch-out and engine performance degradation* for typical spark ignition engines with unmodified carburetion using ethanol as emergency extender.

Figure 2 shows a similar Tradeoff Chart using a South Texas sour crude blended with diesel fuel. Note that the Power Index curve reflects very little engine performance degradation (only about 10 percent when operating the diesel engine with neat crude oil). The Conservation Index curve then correspondingly increases from zero (operation with neat diesel fuel) to 1.0 (operation with neat crude oil and consequent 100-percent conservation of diesel fuel). The sum of these two curves—Tradeoff Index—consequently varies from 1.0 at neat diesel fuel to 1.9 at neat crude.

Obviously, there is no peaking of the Tradeoff Index curve so an optimum value cannot be clearly identified except to say that this particular crude oil was operated satisfactorily as a neat fuel in several two-stroke and four-stroke diesel engines under controlled laboratory conditions. Thus, it *might* be used as a 100-percent replacement for diesel fuel for brief periods of operation. *Long-term operating effects are unknown.*

It must be emphasized that engine endurance using emergency blends may be severely

*Mathematical definitions of these Indexes are given in Appendix A.

FIGURE 1
TRADEOFF CHART
GASOLINE EMERGENCY BLEND
EXTENDER: ETHANOL

FIGURE 2
TRADEOFF CHART
DIESEL EMERGENCY BLEND
EXTENDER: SOUTH TEXAS SOUR CRUDE

limited by increased engine deposits, plug fouling, injector and fuel pump wear, and a wide variety of other problems. Practical maximum operating time for any given emergency fuel blend will doubtless vary tremendously, depending on engine type, climatic condition, vehicle utilization, etc. These cannot be defined without extensive and costly fleet testing, an activity which is economically prohibitive and which will likely not take place except in the event of an actual emergency situation.

2. Emissions Index

Figures 3 and 4 present typical Emissions Index curves for the principal exhaust emissions now regulated in the United States. These data have been "normalized" (referenced) to corresponding data for either neat gasoline or neat diesel fuel throughout this guidebook, as appropriate.

Figure 3 indicates that the emissions indices are for "road" operation, corresponding to about 30 to 55 miles per hour in an actual vehicle. For the ethanol data in Figure 3, Carbon Monoxide index remains constant, i.e., values for CO for spark ignition engines run with neat gasoline were the same as for ethanol/gasoline blends up to 40 percent ethanol. Oxides of Nitrogen actually decreased to only a small fraction of those for neat

gasoline (about 0.1, or 10 percent), while Hydrocarbon Index increase indicates that as more and more ethanol is added, HC emissions increase until they are between 2.5 to 3 times as high as those for neat gasoline.

A similar chart for diesel fuel blended with No. 5 burner oil is shown in Figure 4. In this instance, unburned hydrocarbons for blends decreased to values slightly below those of neat diesel fuel. Oxides of Nitrogen remained constant at values equal to those for neat diesel fuel, and smoke and carbon monoxide gradually increased reaching values from 1.5 to 2 times those for neat diesel fuel.

The above format for Tradeoff and Emissions Index charts has been adhered to consistently throughout this guidebook. The reader should be cautioned that (a) the "Volume Percent Extender" (X-axis value) does not always go all the way to 100 percent since there were many cases where engine operation was not possible with neat extender, and (b) all values of the several indices are intended to be *guidelines* to assist the fleet operator in selecting an emergency blend for a specific application which seems to be a *proper compromise* between engine performance, emissions degradation, and gasoline or diesel fuel stretch-out.

FIGURE 3
EMISSIONS INDEX-ROAD
EMERGENCY GASOLINE BLEND
EXTENDER:ETHANOL

FIGURE 4
EMISSIONS INDEX
EMERGENCY DIESEL BLEND
EXTENDER:NO.5 BURNER OIL

EMERGENCY FUEL HANDLING AND SAFETY

1. Fuel Handling and Engine Modifications

Fuel handling must be dealt with from the time of initial resource recovery to the point of ultimate utilization; in transportation fuels, this point is a combustion chamber. Fortunately for the emergency fuel user, most of these handling problems have been resolved, and emergency fuels operations can be safely accomplished with minor but important modifications to existing systems and procedures. Existing storage facilities will meet the requirements of the available fuel as received. However, subsequent formulation, blending, storage, and final utilization emergency fuels is of concern.

a. Storage and Blending

Emergency blends such as those suggested in this guidebook will likely have poor storage stability. Upon blending, fuels may be incompatible and react in a relatively short time to form solid oxidation products which can cause problems in the fuel delivery system by plugging filters, increasing combustion chamber deposits and, of course, decreasing vehicle performance. This problem is especially significant when blending products from different crude sources and refinery backgrounds. Therefore, it is highly recommended that *emergency fuels be blended only as needed*. Utilization of the fuel should occur in most cases within a matter of days or even hours if possible. This is particularly true in blends of diesel fuel. Other fuel blends such as those containing alcohol should also be used as quickly as practical because of the increasing possibility of water contamination and subsequent phase separation. Other reasons for blending on a *need basis* include the fact that vehicle performance problems associated with blends may not be identified for some time and, if fuels are blended in large quantity, considerable waste might occur. This, of course, would defeat the whole purpose of emergency fuels. All of these factors point to *blending only on an immediate need basis*, avoiding all but limited storage of emergency fuel blends.

Most fleet operations do not have separate blending facilities which could be used for

blending and formulation of emergency fuel. Alternatives might include blending in existing storage units, such as underground tanks, by simply adding a desired extender to a large supply of a base fuel. This could introduce a problem in being able to observe and agitate the mixture to maintain a homogeneous blend. Smaller, above-ground tanks would assure homogeneous mixtures and appropriate quantities for short-term utilization. Drum quantities may ultimately prove to be best for emergency mixing and fleet use.

Another alternative for blending would be to simply use vehicle tanks, thus avoiding intermediate storage. It also would provide adequate mixing which would be achieved through motion of the vehicle. This may be the most practical method of blending except in the case of very large fleets where repeated fuel blend measurements for each vehicle would be undesirable. In the case of a *neat extender*, direct use of vehicle tanks is obvious.

Phase separation is a major area of concern in blending operations. The vast majority of liquid hydrocarbon refinery products and crude oils are completely miscible in all concentrations. *Anhydrous* ethanol (pure ethanol without water) is also miscible in most liquid hydrocarbons. Anhydrous methanol is miscible in gasoline but not in diesel fuel. Hydrated alcohols (alcohol with water) are not miscible in liquid petroleum products and when blended, phase separation occurs. The alcohol/water phase settles to the bottom of the tank and is then the first feed pumped to the engine. This phase will simply not combust in most unmodified engines.

In order to ensure homogeneous mixtures, some agitation of hydrocarbon components may be necessary. Addition of light fuel to heavy fuel will also aid the mixing process in blends of widely different densities. Care must be exercised to avoid water contamination in alcohol/hydrocarbon blends. Atmospheric humidity is often sufficient to cause a separation of phases in such blends.

b. Fuel Delivery Systems

Materials compatibility (both chemical and physical) is of primary concern in vehicle

fuel delivery systems. *Even as the engine itself is designed to run on a specification fuel, so the fuel delivery system is designed to handle a narrow range of fluids.* Nonstandard fuels can introduce problems in fuel tanks, fuel lines, filters, pumps, and injection or induction equipment.

In diesel fuel systems, the fuel itself provides lubrication for the pumps and injectors. When utilizing a light fuel of low viscosity such as gasoline or alcohol, abnormal friction and wear in these moving parts can lead to failure of the system. On the other hand, fuels of excessively high viscosity may be too thick to pump properly and may also cause injector failure because of the large pressure build-up that may occur. Excessively viscous fuels may also cause filter plugging as may other low-refined or unrefined petroleum products. Less refined fuels may also be corrosive to fuel tanks and fuel lines and may contain particulate contaminants. Alcohols are also known to have corrosive properties which affect some fuel systems.

In spark ignition systems, efficient carburation of certain emergency blends is a critical problem. Unusually heavy extenders such as diesel fuel will not vaporize sufficiently in existing carburetors to allow complete combustion. This can lead to crankcase dilution as the fuel condenses in the cylinder and drains past piston rings. Alcohols may dissolve or loosen some fuel tank coatings and may also cause swelling or deterioration of carburetor seals and gaskets. Denaturants in ethanol may also cause many of these same problems. Some alcohol blends, particularly methanol in low concentrations, may cause volatility problems or vapor lock in the fuel lines or fuel pump. Conversely, neat alcohol may not have adequate volatility for starting at low temperatures. Also, fuel metering systems may not be adequate for delivery of neat alcohol or blends of high-alcohol concentration to meet required air-fuel ratios.

Many of these difficulties in fuel delivery may be overcome by appropriate modifications to existing systems. Following are some suggested modifications that can be easily performed.

(1) Diesel

- I. No mechanical options are presently available to avoid excessive wear in pumps and injectors

due to use of light fuels. Fuel blending may be a partial solution: base diesel fuel often provides increased lubricity in a blend, or if available, addition of small amounts of lubricant additives or motor oil to the fuel will greatly enhance lubricity. *Relatively small amounts of additives or motor oil will go a long way in improving lubricity.*

- II. Excessively viscous or heavy fuels which cannot be pumped or injected may be utilized through use of commercially available fuel heaters. Relocation of fuel lines out of the windstream and nearer to the engine block will also aid the flow properties. Insulation and/or use of electric tape heaters on both fuel tank and fuel lines is helpful during shut-down and operation.

Fuel blending will reduce the *cloud* point somewhat but does not affect pour point appreciably, except in high concentrations. Blending with alcohol or gasoline can improve the flow properties of a heavier fuel but the risk of explosion in the fuel tank is also introduced because of the flammable vapor mixture formed in the fuel tank air space. This is especially true at low concentrations of volatile blend components.

- III. Filter plugging may be avoided to some extent by the above (II) suggestions in the case of heavy or viscous fuels. Use of larger or multiple filters in parallel will increase filter surface area and delay or eliminate plugging. Utilization of unrefined or contaminated fuels may be possible by prefiltering. In many cases, this will also reduce viscosity.

- IV. Rerouting the fuel return line to the filter inlet will help supply heated fuel directly to the fuel intake to avoid filter plugging and other flow problems. Under some operating conditions, this method could cause damage to the fuel pump or reduce engine performance if the fuel becomes too hot. Another method following the same idea would be to simply operate on less than a full tank. The lower the fuel level, the higher will be the recirculated fuel temperature which will in turn improve flow properties.

- V. Fuel tank and fuel line corrosion is normally of concern only in the long term (fuel tanks usually outlive the engine). Sometimes coatings may be immediately affected with a residue collecting on filters. A simple filter change will remedy this situation. If the corrosion is due to acid concentration in the fuel, addition of an appropriate organic base may neutralize the problem. If more serious problems are expected, use of an auxiliary tank of compatible material may be advisable.

2. Gasoline

- I. In carburetted spark ignition engines, vaporization of unusually heavy fuels can be enhanced by manifold heating. This will help to avoid inlet mixture condensation and subsequent crankcase dilution. Heating the inlet mixture can cause preignition and decrease volumetric efficiency. This is therefore undesirable, unless closely controlled.
- II. Incompatibility of fuel tank materials, fuel lines, and carburetor parts with unusual fuel blends can be avoided by substituting alternate materials. This would include using an auxiliary fuel tank, replacing fuel lines and carburetor parts, or even entire carburetors. These incompatibilities are usually quite selective and it may be easier to simply substitute vehicles with compatible materials where fleet size will allow.
- III. Vapor lock tendencies may be reduced by re-routing fuel lines away from heat sources and exposing them to cool air from fan action or windstreams. Insulation of lines near heat sources may also be effective.
- IV. Operation on alcohol requires a much richer fuel mixture than with gasoline. Existing carburetors may be easily modified by increasing jet size to match the appropriate air-to-fuel ratio. Obert gives a method for estimating jet sizes.

2. Safety

A critical factor in exercising safe fuel handling procedures is understanding that fuels can be extremely dangerous when improperly handled. This simple realization alone can significantly reduce the risk of a serious accident. Fuels, by def-

inition, are combustible materials. When used in a controlled manner, they can produce useful heat or power. When a fuel is accidentally ignited in an uncontrolled environment, the effects can be devastating. Also, many fuels have toxic properties. The hazards associated with fuel handling are extremely serious. An understanding of this can lead to their safe and proper utilization.

Because of the unusual procedures which may be required for emergency fuel utilization, it is strongly suggested that safety awareness be re-emphasized. Review of standard safety procedures, emergency phone numbers, alarm locations and safety equipment location and operation is highly advisable. The use of emergency fuels introduces new hazards which may demand appropriate new safety precautions. Personnel should be advised of these precautions and observed to see that actions are carried out correctly. Supervision and such follow-through practices will contribute to smooth operation and also help reinforce safety awareness.

a. Fire Hazards

Fire consists of three elements: fuel, oxygen and heat. Fire or combustion is a thermal reaction in which oxygen and fuel are combined in an oxidation process. The reaction must be initiated by an external heat source, but once initiated, the reaction self-propagates from the overabundance of heat generated. In order for combustion to continue, all three elements must be present. Effective fire prevention involves careful separation of these three elements. Fires are extinguished by removal of either heat, fuel, or oxygen.

Emergency fuel blending and utilization introduces some unique fire hazards which do not exist in the normal transportation fuel setting. Whenever there is extra blending and handling of fuel, fire hazards increase. A major problem in emergency fuel use deals with *vapor concentration in fuel tanks*. In vehicles fueled with gasoline, the vapor in the air space above the fuel in the tank is very concentrated. The vapor, in fact, displaces most of the air in the tank so that even with an ignition source there is little danger of fire because of the lack of air. In diesel fuel tanks, the vapor above the fuel is of very low concentration. If an ignition

source is introduced under these conditions, a fire would not occur because of the lack of fuel in the air. *Blends such as gasoline in diesel fuel may produce a vapor-air mixture which is highly susceptible to explosion. Blends of alcohol in diesel fuel and also high concentrations of alcohol in gasoline including pure alcohol fuels also fall into this hazardous category. Especially dangerous concentrations of gasoline in diesel fuel are present between 0 to 10 percent. Slightly higher concentrations of alcohol in diesel produce similar dangerous conditions. The vapor over either pure methanol or pure ethanol is flammable at ambient temperatures.*

Extreme caution must be exercised to avoid any source of ignition around the fuel, especially when refueling. Open flames, electrical equipment, hot surfaces, sparks, static electricity and mechanical friction are all potential ignition sources. To reduce the potential of static charge ignition, all equipment should be appropriately bonded or grounded. (It is, of course, wise to always observe these precautions when dealing with any fuel or flammable material.)

When refueling vehicles to be operated on emergency blends, it is essential to ground the fuel tanks because of the static charge which can build up when fuel is transferred from one tank to another. Electrical connections should be made between the tank being refueled and the supply source with the final connection made well away from any fuel vapor. If exact fuel composition is unknown, the fuel odor may indicate presence of gasoline or another volatile component. It is a wise practice to ground or bond the tanks if any uncertainty exists.

Engine fire is another source of hazards in the utilization of emergency fuel blends. Unusual fuel blends may cause an engine to misfire as in the case of a carburetor that has been jetted too lean. A backfire may spread or splash fuel and cause a fire to ignite. In diesel engines, use of fuels with low viscosity may produce leaks in the fuel line where fuel will be exposed to the atmosphere, causing a potential fire. Many other possibilities for fires in and around the engine are apparent when modifications to both the fuel and fuel system are made. Steps should be taken to prevent such hazardous conditions whenever possible.

Included as a part of fire-protection, along with prevention, is loss limitation. An adequate supply of fire extinguishing equipment should always be on hand. Flammable liquids such as oils, gasolines, solvents, etc. are Class B Fires. A blanketing or smothering method that will remove oxygen from the fire is essential to extinguish this class of fire. Carbon dioxide, dry chemical, foam or vaporizing-liquid type extinguishers are effective. Water from a hose will sometimes only aggravate the fire danger by spreading the flammable liquid. Water is most effective when used as a spray. A water-soaked fire blanket may also be effective in smothering a small fire. Water-based foams may collapse in contact with alcohol fires if foam quantity is limited so that overall blanketing cannot be accomplished.

b. Blending

When using large tanks for blending, the normal safety precautions should be observed. Isolation and diking may prevent small accidents from becoming disasters. Any spillage or leaking should be avoided. If dikes are not present, blending should take place on ground which slopes away from equipment and buildings. Proper connections and fittings including shut-off valves should be ensured. If use of electrical equipment is necessary, proper grounding and insulation practices should be followed. Normal safety precautions for tank gauging, including grounding personnel and equipment before and after contact with the tank, should be followed. When refueling tanks, the supply tank and the tank being refueled should be bonded together by electrical connection to avoid any static discharge. This is particularly important in cold dry climates. Slow fueling rates also help to avoid static charges that can be created in high-velocity streams, during splash filling or from fuel passing through a filter. There are also antistatic fuel additives commercially available. These improve the conductivity of the fuel, but may not be available under emergency conditions.

If blending is performed in drum quantities, proper drum handling procedures should be observed. Cool storage areas should be provided. Drums should be opened with caution under ventilated conditions. The *bung side* should

be tilted up and any residual pressure or vacuum should be released slowly. Valves should be snugly secured to avoid leaks. *Any blend should always be labeled properly.* Memory alone is an insufficient record, even for short periods of time.

Old tanks may have to be reconditioned for emergency fuel blending. Failure to observe proper safety precautions while cleaning or repairing old tanks could result in a serious accident. Tanks which have contained flammable liquids should be purged of any residual vapors that may be present. This may be accomplished with an inert gas such as carbon dioxide or nitrogen or with steam or water. Nonmetal scrapers should be used to avoid sparks. Cleaning agents, especially caustics, must be used with caution because of explosive reactions that can occur.

c. Toxicity

Although alcohols and petroleum products (or other emergency fuel constituents in general) are not classified as *highly toxic*, their toxicity is still a matter of concern. A toxic substance is one which can produce injury to a body or site through *chemical action*. The human body may be exposed to a toxic substance by contact with the skin or eyes, ingestion or inhalation. All of these modes of contact are of concern when dealing with emergency fuels. It must be emphasized that not all people react with the same intensity or symptoms when exposed to a toxic material. Since there is no way to predict susceptibility, avoidance of contact is the best method to avoid harmful reactions. All materials should be handled with *respect for their unknown properties*.

After prolonged contact with the skin, petroleum products may cause a mild irritation. More serious effects can also result. Benzene, for instance, which is contained in many petroleum products, is a known carcinogen*. Other aromatic compounds found in petroleum are also suspected of having carcinogenic properties. Die-

sel fuel vapors can cause headache and stupor. Ingestion of diesel or gasoline fuel can cause stomach irritation and vomiting. Gasoline is also a strong eye irritant. The toxicity of gasoline increases with increasing aromatic content. Crude petroleum, like diesel fuel and gasoline, has the following toxic hazard ratings in the following areas:

- (1) slight to moderate irritant
- (2) slight allergen
- (3) moderate ingestion
- (4) slight inhalant.

Because methanol and ethanol are often simply labeled as *alcohols*, ingestion of methanol sometimes occurs by mistake. It can also enter the body through inhalation or absorption through the skin. Methanol has narcotic properties and disturbs the central nervous system. Of particular danger is the effect methanol has on the optic nerve which can lead to permanent vision damage and even blindness. Methanol is a *cumulative* poison which is only slowly released from the body. Repeated exposure to vapors may result in illness. Methanol also has a low odor intensity, increasing its danger.

Ethanol is not as toxic as methanol. It is rapidly oxidized in the body to carbon dioxide and water and does not have the cumulative effect of methanol. Exposure to ethanol vapors in large concentrations will cause eye and upper respiratory irritation. The danger in ingesting ethanol (prescribed for fuel use) is in the *denaturant* required by the Bureau of Alcohol, Tobacco, and Firearms (BATF). Many different denaturants are used but, in general, ingestion of denatured ethanol will cause vomiting and severe stomach cramps.

NOTE:

For more information on toxicology of individual compounds, Armistead (see bibliography) provides a comprehensive list of dangerous substances and their properties.

*Cancer-forming.

ENGINE ADJUSTMENTS AND MODIFICATIONS

All data in this guidebook have been generalized from results obtained in an experimental program involving a modest but representative variety of spark ignition and diesel engines operated in so-called "stock" configuration. This has been done to provide estimates of the relative degradation in stock engine performance, fuel consumption, and emissions when using emergency blends. In this laboratory program, the engines were tuned properly to provide best performance on appropriate specification-quality fuel. Each engine was then "mapped" over a variety of combinations of engine speed and load, measuring horsepower, fuel consumption and (in most cases) emissions. This was done first with the neat specification-quality fuel and then with each emergency blend. All data in this guidebook have been expressed in relation to engine operation with specification-quality fuel.

While major engine modifications and redesign were far beyond the scope of this program, there are some adjustments and minor modifications within the capabilities of most fleet operations which could permit improved engine performance with emergency blends. *These should be considered as "possibilities" and not general truths applying to any and all combinations of engines and emergency fuels.* For spark-ignition engines, retarding the spark advance to accommodate low octane fuel blends may be necessary to avoid knock in the high load operating conditions. This is done only at the expense of a decrease in fuel economy. It was found in the laboratory program that gasoline blends with octane ratings as low as 75 still operated satisfactorily (without knock) throughout EPA city and highway driving cycles in a single late model vehicle set at factory-prescribed spark advance. Correspondingly, rejetting of the carburetor also was found to be unproductive in using hydrocarbon extenders because the stoichiometric AFR was relatively unaffected in these blends. In contrast, blends of alcohol with gasoline do require a larger jet size for adequate operation at higher concentrations of alcohol (greater than 10% methanol or 30-40% ethanol). This is especially true in late model cars which are tuned for lean operation on specification grade gasoline. By using larger jets (size depending upon

altitude, engine type, etc.), it is possible to use neat alcohol fuels as adequate replacements for gasoline in spark ignition engines. A starting aid may be necessary for operation at low temperatures. Other fuel system modifications such as replacement of standard fuel tanks with larger tanks to accommodate the lower energy content of alcohols may prove reasonable and practicable in a specific fleet operation which has access to large quantities of alcohol in the extreme emergency involving a virtual total absence of gasoline.

For diesel engines, replacement of standard fuel injectors with larger sizes may increase the power output of the engine when operated with low density fuels. In addition, advancing injection timing to compensate for ignition delay in low cetane fuels may prove helpful. Experience with engine dynamometer operation of numerous emergency blends in both two-stroke and four-stroke diesel engines in this program indicated that these modifications offered little significant benefit in engine performance improvement and, in some cases, even proved to be detrimental relative to operating under standard conditions.

While it may be possible to improve engine performance for both spark ignition and diesels by such adjustments, the prudent path will always be to experiment with a single vehicle to define the outer bounds of an emergency blend which meets minimum emission performance criteria for the fleet in question. Premature commitment to operation on a specific emergency formulation may very likely result in actual waste of gasoline and diesel fuel (as opposed to *conservation* which is the primary objective of this guidebook).

No engine endurance, wear, deposition or other maintenance impact information are presented herein. Operation with emergency blends should be considered for days, perhaps even weeks. The tradeoff between acceptable maintenance increase and extended fleet operation in a period of specification fuel shortfall must be considered on an individual basis. Decisions in such situations will always be arbitrary; it is hoped that the general guidelines presented in the following sections will be helpful to those having the responsibility to make such decisions.

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II. GASOLINE AND DIESEL FUEL

It is possible to envision a situation where emergency services of the gasoline-powered fraction of a mixed fleet would take precedence over those of the diesel-powered fraction; it is equally possible to envision the reverse. Such a fleet would logically have both types of fuel available. Consequently, the *two most obvious emergency blends* would be either:

- high-priority gasoline with *diesel fuel* as extender
- high-priority diesel fuel with *gasoline* as extender

Such situations are hardly theoretical; there have been many precedents, particularly in times of war.

The material in this section has consequently been broken into two parts: Section A contains general information and Tradeoff Charts for *gasoline as the base fuel* using diesel fuel as the extender in *spark ignition engines*; and Section B contains corresponding information and charts for *diesel fuel* using gasoline as extender for operation in diesel engines.

A. Gasoline (Diesel as extender)

Automotive gasolines are used to fuel internal combustion spark-ignition engines. While gasolines are used primarily in passenger car and highway truck service, they also are used extensively in off highway utility vehicles, farm machinery, two and four-stroke cycle marine engines, and other spark-ignition engines employed in a variety of different service applications.

Automotive gasolines are blends of hydrocarbons derived from petroleum.* In addition, they may contain selected additives that impart specific features to the finished gasoline. The hydrocarbons are derived from fractional distillation of crude oil as well as from complex processes that increase either the amount or quality of the gasoline obtained.** These components vary from indi-

vidual compounds such as normal butane to wide-boiling range products that contain hundreds of different hydrocarbons. The properties of commercial gasolines are influenced by the refinery practices employed and the nature of the crude oils from which they are produced. Finished gasolines encompass a boiling range of about 85° to 437° F (30° to 225° C).

Gasolines are blended to satisfy diverse automobile requirements. Antiknock quality, distillation characteristics, vapor pressure, sulfur content, oxidation and anticorrosion behavior are balanced to provide satisfactory vehicle performance. Additives may be used to provide or enhance specific performance features.

1. Grades of Gasoline

Historically, automotive gasolines have been classified into two grades—"premium" and "regular"—on the basis of octane number. In recent years, the *Research Octane Number* (RON) of premium gasoline has been about 100 while that of regular gasoline has been about 94. (The significance of octane numbers will be discussed in the following section.) In high-altitude areas of the country, both premium and regular octane levels have been somewhat lower than at sea level because car octane requirements decrease with altitude. "Super premium," "Intermediate," and "Sub regular" grades of gasoline also have been marketed as well as blends of high- and low-octane grades.

With the exception of one premium gasoline marketed on the east coast of the United States, all automotive gasolines until 1970 contained lead alkyl antiknock compounds to increase octane quality. Because lead antiknock compounds are detrimental to the performance of catalytic emission control systems, United States passenger car manufacturers in 1971 began to build engines designed to operate satisfactorily on gasolines of nominal 91 Research Octane Number. Some of these engines were designed to operate on unleaded fuel while others required low-lead fuel. The 91 RON level was chosen in the belief that low-lead and unleaded gasolines could be made available in the quantities required using cur-

*This document does not consider synthetic fuels derived from coal, oil shale, etc., as *Emergency Fuels*.

**For more details on petroleum chemistry, see Appendix B.

rent refinery processing equipment. Accordingly, during 1970 unleaded and low-lead gasolines were introduced to supplement the conventional gasolines already available.

Unleaded fuels are generally defined as those to which no lead antiknock compound has been added *deliberately*. However, a small amount of lead pickup can occur in gasoline distribution. Since most vehicles in the United States were equipped with catalytic converters beginning with the 1975 model year, the United States government (Environmental Protection Agency) required most service stations, beginning in July 1974, to offer for sale at least one grade of unleaded gasoline. This gasoline must have a Research Octane Number of at least 91 and contain no more than 0.05 g lead/gal. and no more than 0.005 g phosphorus/gal. Low-lead fuels (no longer in widespread use), as opposed to unleaded fuels, are those to which lead antiknock compound has been added with a maximum concentration of 0.5 g lead/gal. "Conventionally leaded" gasolines are those having lead contents above 0.5 but no more than 4.23 g lead/gal.*

2. Antiknock Quality

The antiknock quality of gasoline is of prime importance; if antiknock quality is too low, knock occurs. Knock is a high pitched, metallic rapping noise. In addition to being audibly annoying, in severe cases knock may lead to uncontrolled preignition which can cause burning of piston crowns and other engine damage. There is also evidence that knock increases the rate of engine wear. The potential durability, power, and fuel economy of a given engine is realized only when the gasoline antiknock quality is adequate. However, there is no advantage in using a gasoline having antiknock quality higher than the engine requires.

Knock depends on complex physical and chemical phenomena highly interrelated with engine design and operating conditions. It has not been possible to completely characterize the antiknock performance of gasoline with any single measurement. The anti knock performance of a gasoline is related intimately to the engine in which it is

used and the engine operating conditions. Furthermore, this relationship varies from one engine design to another and may even be different among engines of the same design due to normal production variations.

For most automotive engines and operating conditions, the road octane number of a gasoline will be between its *Research* and *Motor* Octane Numbers (RON and MON). The relationship between Research and Motor Octane Numbers used to predict the road antiknock quality of gasolines is dependent upon the vehicles and operating conditions. Antiknock Index is a currently accepted method of relating Research Octane Number (RON) and Motor Octane Number (MON) to actual road antiknock performance of cars. It is obtained by merely averaging the RON and MON of a gasoline; that is $(RON + MON)/2$.

Octane curves for gasoline blended with No. 2 grade diesel fuel and with marine diesel fuel (DFM) are shown in Figures 5 and 6.

3. Volatility

The volatility characteristics of a gasoline are also of prime importance. Gasoline is used in a great variety of engines with large variations in operating conditions and under a wide range of atmospheric temperatures. These variations impose many limitations on the volatility of gasoline if it is to give satisfactory performance. Gasoline that vaporizes too readily in pumps, fuel lines, and carburetors will cause decreased fuel flow to the engine, resulting in rough engine operation or stoppage (vapor lock). Conversely, gasolines that do not vaporize readily enough may cause hard starting and poor warm-up and acceleration, as well as unequal distribution of fuel to the individual cylinders, which may cause knock. Fuels that vaporize too readily also may cause, if certain atmospheric conditions exist, ice formation in the carburetor throat, resulting in rough idle and stalling.

The volatility of automotive gasoline must be carefully "balanced" to provide the optimum compromise among performance features that depend upon the vaporization behavior. Superior performance in one respect may give serious trouble in another. Therefore, volatility characteristics of automotive gasolines must be adjusted for seasonal variations in atmospheric temperatures and geographical variations in altitude.

*EPA lead reduction timetables will eventually reduce this value to 0.5 g/gallon for refinery *pooled* production.

FIGURE 5
OCTANE NUMBER VS BLEND CONCENTRATION

GASOLINE EMERGENCY BLEND
 EXTENDER:NO.2 DIESEL FUEL

FIGURE 6
OCTANE NUMBER VS BLEND CONCENTRATION

GASOLINE EMERGENCY BLEND
 EXTENDER:MARINE DIESEL FUEL

Since gasoline is a mixture of many hydrocarbons, it does not have a single boiling point. Its tendency to vaporize is characterized by determining a series of temperatures at which various percentages of the gasoline have evaporated. The temperatures at which 10-, 50-, and 90-percent evaporation occurs are used to characterize the volatility of automotive gasolines.

Vapor pressure is the force per unit area exerted on the walls of a closed container by the vaporized portion of the liquid contained therein. For hydrocarbon mixtures such as gasoline, the vapor pressure depends on the ratio of vapor to liquid in the container and the temperature. Vapor pressure of gasoline, when measured at 100°F (38°C) in a bomb having a 4:1 ratio of air to liquid, is known as Reid Vapor Pressure (RVP).

Gasoline vaporization tendency may also be expressed in terms of vapor/liquid ratio (V/L) at temperatures and pressures approximating those found in critical parts of the fuel system.

In general terms, the following relationships between volatility and performance apply:

- (a) High-vapor pressures and low temperatures for 10 percent evaporated are both conducive to ease of cold starting. However, under hot-operating conditions, they are also conducive to vapor lock and increased vapor formation in fuel tanks and carburetors. The amount of vapors formed in fuel tanks and carburetors which must be contained by the evaporative loss control system are related to the RVP and distillation temperatures, respectively. Thus, a proper balance must be maintained and seasonally adjusted for good overall performance.
- (b) Although vapor pressure is a factor in the amount of vapor formation under vapor-locking conditions, vapor pressure alone is not a good index. A better index for measuring the reactive vapor-locking performance of gasolines in current model cars is the temperature for

20 vapor/liquid ratio. The lower the temperature at $V/L = 20$, the greater the tendency to cause vapor lock.

- (c) The temperature for 50-percent evaporated is a broad indicator of warm-up and acceleration performance under cold-starting conditions. The lower the 50-percent evaporated temperature, the better the performance. However, carburetor icing tendency and consequent engine stalling are increased by low 50-percent evaporated temperatures.
- (d) The temperature for 90-percent evaporated and the "end point" (EP) indicate the amount of relatively high-boiling components in gasoline. A high 90-percent evaporated temperature, because it usually is associated with higher density and high-octane number components, may contribute to improved fuel economy and resistance to knock. If the 90-percent evaporated temperature and the EP are too high, they can cause poor mixture distribution in the intake manifold and combustion chambers, excessive combustion chamber deposits, and excessive varnish and sludge deposits in the engine.

Distillation and volatility curves (RVP) for gasoline/diesel blends are given in Figures 7, 8, 9, and 10.

4. Other Properties

In addition to providing acceptable antiknock quality and volatility characteristics, automotive gasolines must also provide for satisfactory engine cleanliness, both physical and chemical. The following properties have a direct bearing on the overall performance of a gasoline.

FIGURE 7
DF2-GASOLINE BLEND DISTILLATION

FIGURE 8
DFM-GASOLINE BLEND DISTILLATION

FIGURE 9
RVP VS BLEND CONCENTRATION

FIGURE 10
RVP VS BLEND CONCENTRATION

a. *Workmanship and Contamination*

A finished gasoline is essentially a blend of petroleum fractions visually free of undissolved water, sediment, and suspended matter. It is clear and bright when observed at 70°F (21°C). Physical contamination may occur during distribution of the fuel. Control of such contamination is a matter requiring constant vigilance. Solid and liquid contamination can lead to restriction of fuel metering points, improper seating of inlet valves, corrosion, fuel line freezing, gel formation, and filter plugging.

b. *Sulfur Content*

Crude petroleum contains sulfur compounds, most of which are removed during refining. Currently, the average sulfur content of gasolines distributed in the United States is about 0.03 percent by weight with the maximum reported values generally being less than 0.15 percent by weight.

Sulfur oxides formed during combustion may be converted to acids that promote rusting and corrosion of engine parts and piston ring and cylinder wall wear. Sulfur oxides formed in the exhaust are undesirable atmospheric pollutants; however, the contribution of automotive exhaust to total sulfur oxide emissions is negligible for specification quality fuels.

c. *Existent Gum and Stability*

During storage, gasolines may oxidize slowly in the presence of air and form undesirable oxidation products called *gum*. The gum is usually soluble in the gasoline but may appear as a sticky residue on evaporation. These residues may deposit on carburetor surfaces, intake valves, stems, and guides. ASTM Specification for Automotive Gasoline (D439) limits gasoline to a maximum of 5 mg of gum/100 ml of gasoline.

Automotive gasolines have a negligible gum content when manufactured but may form gum during extended storage.

Most automotive gasolines contain special chemicals (antioxidants) to prevent oxidation and gum formation. Some gasolines also contain metal deactivators for this purpose. Commer-

cial gasoline is not designed for abnormally severe conditions of storage. Gasoline purchased for severe bulk storage conditions or for prolonged storage in vehicle fuel systems generally has additional amounts of antioxidant and metal deactivator added.

d. *Gravity*

"Gravity" is a term used to denote the density of gasolines and is useful as a means of identification. Two methods of expressing gravity commonly are used. *Specific gravity* is the ratio of the mass of a given volume of gasoline at a temperature of 60°F (15.6°C) to the mass of an equal volume of water at the same temperature. Typically, automotive gasolines have specific gravities between 0.72 and 0.75 and American Petroleum Institute (API) gravities between 65 and 57. *API gravity* is based on an arbitrary hydrometer scale and related to specific gravity as follows

$$\text{API gravity, deg} = \frac{141.5}{\text{sp gr at } 60/60^{\circ}\text{F}} - 131.5$$

API gravity data for gasoline/diesel blends are given in Figures 11 and 12.

e. *Additives*

Gasoline additives are used to enhance or provide various performance features related to the satisfactory operation of engines as well as to minimize gasoline handling and storage problems. These compounds complement refinery processing in attaining the desired level of product quality.

The amount and variety of additives used in gasolines have grown rapidly. For many years, antiknocks were almost the only additives used; however, now the list also includes combustion chamber deposit modifiers, antioxidants, metal deactivators, corrosion or rust inhibitors, carburetor anti-icing additives, fuel line anti-freeze agents, gasoline detergents, gasoline dispersants, and identifying dyes. Gasoline additives currently available are shown by class and function in Table 1.

FIGURE 11
API GRAVITY VS BLEND CONCENTRATION

FIGURE 12
API GRAVITY VS BLEND CONCENTRATION

TABLE 1. COMMERCIAL GASOLINE ADDITIVES

<u>Class or Function</u>	<u>Common Additive Type</u>
1. Antiknock compounds—to improve research, motor, and road octane quality.	Lead alkyls such as tetraethyl lead, tetramethyl lead, and physical or reacted mixtures: organo-manganese compounds such as methyl cyclopentadienyl manganese tricarbonyl
2. Combustion deposit modifiers—to minimize surface ignition, rumble, preignition, and spark plug fouling.	Organic or organo-metallic compounds usually containing phosphorus
3. Antioxidants—to minimize oxidation and gum formation in gasoline and improve handling and storage characteristics.	Phenylene diamine, pheno, and aminophenol compounds
4. Metal deactivators—to deactivate small traces of copper and other metal ions that are powerful oxidation catalysts.	Diamine and aminophenol compounds
5. Corrosion or rust inhibitors—to minimize corrosion and rusting of fuel system and storage and handling facilities.	Derivatives of carboxylic, sulfonic, or phosphoric acids, many of which have surface-active properties
6. Carburetor anti-icing additives—to minimize engine stalling due to ice accumulation on the throttle.	Derivatives of carboxylic, sulfonic, or phosphoric acid that have surface-active properties: freeze point depressants such as alcohols, glycols
7. Gasoline detergents—to remove or minimize or both the accumulation of deposits in the throttle section of the carburetor, which adversely affect the metering characteristics.	Amines and derivatives of carboxylic, sulfonic, or phosphoric acid having surface-active properties, some of which are polymeric
8. Gasoline dispersants—to extend PCV valve life, reduce engine sludge, and remove or minimize or both the accumulation of deposits in the carburetor, intake manifold, intake parts, and underside of the intake valves.	Amines and low-molecular-weight synthetic polymers: specific fractions of special oils
9. Deposit control additives—to combine the functions of classes 7 and 8 with the additional effect of minimizing the accumulation of varnish and sludge deposits on piston rings and skirts, rocker arms, and covers as well as removing and minimizing gumming deposits in the PCV system.	Derivatives, usually amino- or aminoimido of polymeric hydrocarbons of molecular weight in the 500 to 2000 range: used in combination with special oils
10. Dyes—to identify gasoline blends.	Oil soluble and liquid dyes

NOTE: Some materials may also be marketed as multifunctional or multipurpose additives performing more than one of the functions described in items 5, 6, 7, 8, and 9.

B. Diesel Fuel

The diesel engine is a high-compression, self-ignition engine. Fuel is ignited by the heat of the high compression, and no spark plug is used. The diesel cycle consists of charging the combustion chamber with air, compressing the air, injecting the fuel which ignites spontaneously, expanding the burned gases, and expelling the products of combustion.

Diesel engines may be designed to operate on a four- or a two-stroke cycle. Each type has advantages and disadvantages, so the choice depends upon the application. The four-stroke cycle has better volumetric efficiency, good combustion characteristics, and positive exhaust gas scavenging. The principal advantage of the two-stroke cycle is compactness in relation to power output.

Diesel engines vary greatly in size, power output, and operating speeds. While some small units develop only a few brake horsepower, at the other extreme there are engines having cylinder diameters as large as 1050 mm (41.34 in.), developing several thousand horsepower per cylinder. Design sizes and horsepower output continue to increase. Operating speeds are almost as diverse as size and power output. They range from below 100 rpm for some larger engines to 4000 rpm and above for those used in automotive and other vehicle prime-mover service. Diesel engines now are established fully in all forms of surface transportation and construction as well as for a wide range of power generation and pumping applications. The entire range of diesel engines can be divided into three broad classification groups indicated in Table 2.

It should not be surprising that diesel engines also vary extensively in their requirements for fuel. Selection of the proper fuel is not a simple procedure but depends upon many variables. Among the most important considerations are:

1. Engine size and design
2. Operating speed and load ranges
3. Frequency of speed and load changes
4. Maintenance considerations
5. Atmospheric conditions
6. Fuel price and availability

Each of the foregoing factors plays a part in dictating the fuel to be chosen for a diesel engine. The relative influence of each factor is determined by the specific application and installation involved.

Grades No. 1-D and 2-D (sometimes called DF-1 and DF-2) are distillate fuels which are the types most commonly used in high-speed engines of the mobile type medium-speed stationary engines, and railroad engines. Grade 4-D covers the class of more viscous distillates which are blended frequently with residual fuel oils. No. 4-D fuels are applicable to low- and medium-speed engines employed in services involving sustained load and predominantly constant speed.

1. Cetane Number

In the majority of diesel engines, the ignition delay period is shorter than the duration of injection. Under such circumstances, the total

TABLE 2. RANGE OF DIESEL ENGINES

<u>Classification</u>	<u>Speed Range</u>	<u>Conditions</u>	<u>Typical Applications</u>
Low Speed	Below 300 rpm	Sustained heavy load, constant speed	Marine main propulsion; electrical power generation
Medium Speed	300-1000 rpm	Fairly high load and relatively constant speed	Marine auxiliaries; stationary power generators; pumping units
High Speed	1000 rpm or above	Frequent and wide variation in load and speed	Road transport vehicles; diesel locomotives, construction equipment

combustion period can be divided into the following four stages:

- (1) Ignition delay
- (2) Rapid pressure rise
- (3) Constant pressure or controlled pressure rise
- (4) Burning on the expansion stroke

The rapid pressure rise results from the large number of ignition points and the accumulation of fuel during the ignition delay period. Following this stage, the rate of combustion can be controlled to a much greater degree by controlling the injection rate, since the fuel is being injected into flame. Because the rapid pressure rise represents uncontrolled and inefficient combustion, it is desirable to limit ignition delay to a minimum. This limitation can be accomplished mechanically by the selection of a spray pattern configuration properly tailored to the combustion chamber. Ignition delay also can be reduced by the use of high-fuel injection pressures and high-fuel/air turbulence to promote rapid fuel jet breakup and thorough fuel distribution.

The nature of the fuel is also an important factor in reducing the ignition delay. Physical characteristics such as viscosity, gravity, and mid-boiling point are influential. Hydrocarbon composition also is important as it affects both the physical and combustion characteristics of the fuel. Straight-chain paraffins ignite readily under compression, but branched-chain paraffins and aromatics react poorly. Since the ignition delay characteristics of diesel fuels directly influence the interval of uncontrolled combustion during injection and, as a result, the overall engine performance, this property is of primary importance. Thus, it becomes desirable to have a numerical basis for evaluating the fuel ignition delay and measuring or predicting this property.

The cetane number of a diesel fuel is the numerical result of an engine test designed to evaluate fuel ignition delay. To establish the cetane number scale, two reference fuels were selected. One, normal cetane, has excellent ignition qualities and, consequently, a very short ignition delay. A cetane number of 100 was arbitrarily assigned to this fuel. The second fuel, alphas-methylnaphthalene, has poor ignition qualities and was assigned a

cetane number of zero. In 1962 alphas-methylnaphthalene was replaced as a primary reference fuel by heptamethylnonane which has a cetane number of 15 as determined by use of the two original primary reference fuels.

To determine the cetane number of any fuel, its ignition delay is compared in a standard test engine with a blend of reference fuels.

The cetane number of a diesel fuel is defined as "the whole number nearest to the value determined by calculation from the percentage by volume of normal cetane (Cetane number = 100) in a blend with heptamethylnonane (Cetane number = 15) which matches the ignition quality of the test fuel when compared by this method." The matching blend percentages to the first decimal are inserted in the following equation to obtain the cetane number:

$$CN = \% \text{ n-cetane} + 0.15 (\% \text{ heptamethylnonane})$$

The shorter the ignition delay period, the higher the cetane number of the fuel and the smaller the amount of fuel in the combustion chamber when the fuel ignites. Consequently, high-cetane number fuels generally cause lower rates of pressure rise and lower peak pressures. Both of these tend to lessen combustion noise and to permit improved control of combustion, resulting in increased engine efficiency and power output.

In addition to these advantages, higher cetane number fuels tend to result in easier starting, particularly in cold weather, and faster warmup. Reduced exhaust smoke and odor are associated also with higher cetane numbers.

High-speed diesel engines normally are supplied with fuels in the range of 45 to 55 cetane number (their requirements may be as low as 35). Table 3 summarizes the typical inspections of various marketed diesel fuels characterized primarily on the basis of use. As can be seen, the cetane number ranges from 50 for kerosene to 38 for marine distillate fuel (DFM).

Since gasoline properties and requirements are virtually the opposite of diesel fuels, the effect of using gasoline as a diesel extender in reducing cetane number is shown in Figure 13.

FIGURE 13
CETANE NUMBER VS BLEND CONCENTRATION
DIESEL EMERGENCY BLEND
EXTENDER: GASOLINE

TABLE 3. TYPICAL INSPECTIONS OF DIESEL FUELS

Fuel Property	Fuel Type			
	Kerosene	Premium Diesel	Railroad Diesel	Marine Distillate Diesel (DFM)
Cetane number	50	47	40	38
Boiling range, °F (°C)	325 to 550 (163 to 288)	360 to 675 (182 to 357)	350 to 675 (176 to 357)	350 to 500 (176 to 250) (90 percent)
Viscosity, SUS at 100°F (38°C)	33	35	36	47
Gravity, API	42	37	34	26
Sulfur, Wt %	0.12	0.30	0.50	1.2
Uses	high-speed city buses	high-speed buses, trucks, tractors, light marine engines	medium speed buses, railroad, marine, and stationary engines	low-speed buses, heavy marine and large stationary engines

2. Cetane Index

Since the determination of cetane number by engine testing requires special equipment as well as being time consuming and costly, alternate methods have been developed for calculating estimates of cetane number. The calculations are based upon equations involving values of other known characteristics of the fuel.

One of the most widely used methods is based on the Calculated Cetane Index formula. This formula represents a method for estimating the cetane number of distillate fuels from American Petroleum Institute (API) gravity and midboiling point. The index value as computed from the formula is designated as ASTM Calculated Cetane Index of Distillate Fuels (D976/IP 218). Since the formula is complicated in its manipulation, a nomograph based on the equation has been developed. This nomograph, together with the equation, is shown in Figure 14. An example illustrating the use of the chart is also presented. It must be recognized that the calculation of cetane index is not an optional method for expressing cetane number. Rather, it is a supplemental tool for predicting cetane number with considerable accuracy when used with due regard for its limitations. The following are among the limitations of calculated cetane index:

- It is not applicable to fuels containing additives for raising cetane number.

- It is not applicable to pure hydrocarbons, synthetic fuels, alkylates, or coal tar products.
- Correlation is fair for a given type of fuel but breaks down if fuels of widely different composition are compared.
- Appreciable inaccuracy in correlation may occur when used for crude oils, residuals, or products having end points below 260°C (500°F).

3. Gravity

Gravity is an indication of the density or weight per unit volume of the diesel fuel. ASTM Test for Density, Specific Gravity, or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method (D 1298/IP 160) shows that the principal use of specific gravity is to convert weights of oil to volumes or volumes to weights. Specific gravity also is required when calculating the volume of oil at a temperature different from that at which the original volume was measured.

Although specific gravity by itself is not a significant measure of quality, when considered with other tests, it may give useful information. For a given volatility range, high-specific gravity is associated with aromatic or naphthenic hydrocarbons and low-specific gravity with paraffinic hydrocarbons. The specific heat energy, British ther-

FIGURE 14. NOMOGRAPH FOR CALCULATED CETANE INDEX
(ESC-1 METER BASIS—METHOD D 613)

NOTE—The Calculated Cetane Index equation represents a useful tool for *estimating* cetane number. Due to inherent limitations in its application, Index values may not be a valid substitute for ASTM Cetane Numbers as determined in a test engine.

mal unit per pound, potentially available from the fuel decreases with an increase in density or specific gravity. However, the pounds per gallon increase with density as does the potential total British thermal unit per gallon.

API gravity (ASTM D 1298/IP 160) is an arbitrary figure which permits calculations to be made in whole numbers. It is related to the specific gravity in accordance with the following formula,

$$\text{API gravity, deg} = \frac{141.5}{\text{sp gr at } 60/60^{\circ}\text{F}} - 131.5$$

API gravity for diesel/gasoline blends is shown in Figure 15.

4. Distillation

Particularly in medium- and high-speed engines, distillation (or volatility) characteristics of a diesel fuel exert a great influence on its performance. Distillation characteristics are measured with a procedure in which a sample of the fuel is distilled and the vapor temperatures recorded for the percentages of evaporation or distillation throughout the range.

The average volatility requirements of diesel fuels vary with engine speed, size, and design. However, fuels having too low volatility tend to reduce power output and fuel economy through poor atomization, while those having too high volatility may reduce power output and fuel economy through vapor lock in the fuel system or inadequate droplet penetration from the nozzle. In general, the distillation range should be as low as possible without adversely affecting the flash point, burning quality, heat content, or viscosity of the fuel. If the 10-percent point is too high, poor starting may result. An excessive boiling range from 10 to 50 percent evaporated may increase warmup time. A low 50 percent is desirable to minimize smoke and odor. Low 90 percent and end points tend to ensure low carbon residuals and minimum crankcase dilution.

The temperature for 50 percent evaporated, known as the mid boiling point, usually is taken as an overall indication of the fuel distillation characteristics when a single numerical value is used alone. For example, in high-speed engines a

50-percent point above 302°C (575°F) might cause smoke formation, give rise to objectionable odor, cause lubricating oil contamination, and promote engine deposits. At the other extreme, a fuel with excessively low 50-percent point would have too low a viscosity and heat content per unit volume. Therefore, a 50-percent point in the range of 232° to 280°C (450° to 535°F) is desirable for the majority of higher speed type diesel engines. This temperature range usually is broadened for larger, slower speed engines. Distillation characteristics of diesel/gasoline blends are shown in Figure 16.

5. Viscosity

Viscosity may be described as a measure of a liquid's resistance to flow. It usually is measured by recording the time required for a given volume of fuel at a constant temperature to flow through a small orifice of standard dimensions. The viscosity of diesel fuel is important primarily because of its effect on the handling of the fuel by the pump and injector system.

Fuel viscosity exerts a strong influence on the shape of the fuel spray. High viscosities can cause poor atomization, large droplets, and high-spray jet penetration. With high viscosities, the jet tends to be a solid stream instead of a spray of small droplets. As a result, the fuel is not distributed in, or mixed with, the air required for burning. This results in poor combustion, accompanied by loss of power and economy. In small engines, the fuel spray may impinge upon the cylinder walls, washing away the lubricating oil film and causing dilution of the crankcase oil. Such a condition contributes to excessive wear.

Low-fuel viscosities result in a spray which is too soft and does not penetrate far enough in the combustion chamber for good mixing. Combustion is impaired and power output and economy are decreased. Low viscosity can lead to excessive leakage past the injection pump plunger. Fuel metering becomes inaccurate and engine efficiency is reduced. Wear of the fuel system components may increase because lubricating properties of fuels tend to decrease with viscosity.

Fuel viscosities for high-speed engines range from 1.8 to 5.8 cSt (32 to 45 SUS) at 37.8°C (100°F). Usually the lower viscosity limit is established to prevent leakage in worn fuel injection

FIGURE 15
API GRAVITY VS BLEND CONCENTRATION

FIGURE 16
GASOLINE-DIESEL BLEND DISTILLATION

equipment as well as to supply lubrication for injection system components in certain types of engines. During operation at low-atmospheric temperatures, the viscosity limit sometimes is reduced to 1.4 cSt (30 SUS) at 37.8°C (100°F) to obtain increased volatility and sufficiently low-pour point. Fuels having viscosities greater than 5.8 cSt (45 SUS) usually are limited in application to the slower-speed engines. The very viscous fuels commonly used in large stationary and marine engines normally require preheating for proper pumping, injection, and atomization. Viscosity characteristics of diesel/gasoline blends are shown in Figure 17.

6. Heat of Combustion

The heat of combustion of a fuel is the amount of heat produced when the fuel is burned completely. There are two heats of combustion, or calorific values, for every petroleum fuel—gross and net. When hydrocarbons are burned, one of the products of combustion is water vapor. The difference between the two calorific values is that the gross includes the heat given by the water vapor in condensing, while the net value does not include this heat.

The power available from an engine under constant, part-throttle, running conditions and with a constant rate of fuel supply is governed by the calorific value of the fuel. A fuel of low-calorific value yields less heat on combustion and, therefore, less power than the same amount of a fuel with high-calorific value. To maintain power output with the low-calorific value fuel, more of it would have to be used. The importance of this quality depends on whether the user purchases fuel on a weight or a volume basis.

Heat of combustion for diesel/gasoline blends is shown in Figure 18.

7. Cloud Point

Under low-temperature conditions, paraffinic constituents of a fuel may be precipitated as a wax. The wax settles out and blocks the fuel system lines and filters causing malfunctioning or stalling of the engine. The temperature at which the precipitation occurs depends upon the origin, type, and boiling range of the fuel. The more par-

affinic the fuel, the higher precipitation temperature and the less suitable the fuel for low-temperature operation.

The temperature at which wax is first precipitated from solution can be measured by ASTM Test for Cloud Point of Petroleum Oils (D 2500/IP 219) or by ASTM Test for Wax Appearance Point of Distillate Fuels (D 3117). The cloud point of a fuel is a guide to the temperature at which it may clog filter systems and restrict flow. Cloud point is becoming increasingly important for fuels used in high-speed diesel engines because of the trend toward finer filters. The finer the filter, the more readily it will become clogged by small quantities of precipitated wax. Larger fuel lines, filters of greater capacity, and filters located to receive engine heat reduce the problem and therefore widen the cloud point range of fuels which can be used.

8. Pour Point

The diesel pour point is the lowest temperature at which fluid movement can be detected. The cloud point temperature is usually several degrees higher than the pour point. Both these measurements are highly significant when operating at low temperatures. It is recommended that there be a certain margin between lowest operating temperature and the pour point.

Figure 19 shows pour points for diesel/gasoline blends.

9. Sulfur Content

Sulfur content has been related to engine wear and corrosion. This wear or corrosion varies with engine type and operating conditions. Unless oil additives are used to combat these effects, crankcase contamination will require shortened drain intervals. Harmful exhaust emissions are also a drawback of high-sulfur fuels. These may pollute the atmosphere or, if condensed in the exhaust system, form corrosive acids which shorten the life of an exhaust system.

Sulfur content for diesel/gasoline blends is shown in Figure 20.

10. Carbon Residue

Carbon residue is a measure of the car-

FIGURE 17
 VISCOSITY VS BLEND CONCENTRATION
 EMERGENCY DIESEL BLEND
 EXTENDER: GASOLINE

FIGURE 18
 GROSS HEAT OF COMBUSTION VS BLEND CONCEN
 DIESEL EMERGENCY BLEND
 EXTENDER: GASOLINE

FIGURE 19
POUR POINT VS BLEND CONCENTRATION

FIGURE 20
SULFUR CONTENT VS BLEND CONCENTRATION

bonaceous material left in a fuel after all the volatile components are vaporized in the absence of air. At one time there was believed to be a definite correlation between Conradson carbon results (ASTM D 189/IP 13) in diesel fuels and deposit formation on injector nozzles, but this view now is thought to be an over simplification.

The type of carbon formed is as important as the amount. Small quantities of hard, abrasive deposits can do more harm than larger amounts of soft, fluffy deposits. The latter can be eliminated largely through the exhaust system.

Carbon residue tests are used primarily on residual fuels since distillate fuels which are satisfactory in other respects do not have high Conradson carbon residue. Because of the considerable difference in Conradson carbon residue results between distillate and residual fuels, the test can be used as an indication of contamination of distillate fuel by residual fuel.

The significance of the Conradson carbon test results also depends on the type of engine in which the fuel is being used. Fuels with up to 12 percent weight Conradson carbon residue have been used successfully in slow-speed engines.

11. Ash

Small amounts of nonburnable material are found in fuels in two forms: (1) solid particles and (2) oil or water-soluble metallic compounds. These materials are designated as ash. The solid particles are for the most part the same material that is designated as sediment in the water and sediment test.

Since diesel fuel injection components are made with great precision to extremely close fits and tolerances, they are very sensitive to any abrasive material in the fuel. Depending on their size, solid particles can contribute to wear in the fuel system and plugging of the fuel filter and fuel nozzle. In addition, abrasive ash materials can cause wear within the engine by increasing the overall deposit level and adversely affecting the nature of the deposits. The soluble metallic compounds have little or no effect on wear or plugging, but they can contain elements that produce corrosion and deposits.

12. Stability

On leaving the refinery, the fuel will inevitably come into contact with air and water. If the fuel includes unstable components, which may be the case with fuels containing cracked products, storage in the presence of air can lead to the formation of gums and sediments. These gums and sediments can cause filter plugging, combustion chamber deposit formation, and gumming or lacquering of injection system components with resultant sticking and wear.

An accelerated stability test, ASTM Test for Stability of Distillate Fuel Oil (Accelerated Method) (D 2774), often is applied to fuels to measure their stability. A sample of fuel is heated for a fixed period at a given temperature, sometimes in the presence of a catalyst metal, and the amount of sediment and gum formed is taken as a measure of the stability.

Stability characteristics for diesel/gasoline blends are shown in Figure 21. Note the indication of poorest stability (higher mg/100 ml) in the range of 25 percent gasoline.

13. Water and Sediment

One of the most important characteristics of a fuel is the water and sediment content. High-water and sediment content is the result of poor handling and storage practices from the time the fuel leaves the refinery until the time it is delivered to the engine injection system.

Water can easily find its way into fuels as a result of breathing in moisture laden air in storage facilities. When sudden drops in atmospheric temperature take place, condensation of moisture occurs. Also, leakage of rain into fuel transportation and storage facilities, leakage of water during shipment by tanker, and the presence of water accumulated in tanks used for storage and handling can cause water contamination.

Sediment generally consists of carbonaceous material, metals, or other inorganic matter. There are several causes of this type of contamination:

- (1) Rust or dirt present in tanks and lines
- (2) Dirt introduced through careless

FIGURE 21
ACCEL STABILITY VS BLEND CONCENTRATION

- handling practices
- (3) Dirt present in the air breathed into the storage facilities with fluctuating atmospheric temperature.

Particularly during storage and handling at elevated temperatures, instability and resultant degradation of the fuel in contact with air contribute to the formation of organic sediment.

Water can contribute to filter blocking and cause corrosion of the injection system components. In addition to clogging of the filters, sediment can cause wear and create deposits both in the injection system and in the engine.

C. Tradeoff Charts

1. Spark Ignition Engines

Figures 22 and 23 are tradeoff charts for unleaded regular grade gasoline baseline fuel blended with either No. 2 diesel fuel or marine diesel fuel (DFM). These two charts are virtually identical and are differentiated here only to emphasize that marine diesel fuel can likely be used interchangeably with No. 2 diesel fuel as *emergency extender in gasoline for spark ignition engine applications* in a wide variety of emergency fleet operations situations. Both diesel fuels indicate a gradually increasing Conservation Index to about 20 percent volume. The Power Index decreases as concentration of either type of diesel fuel is increased. This results in an overall Tradeoff Index which is essentially constant to about 30 percent diesel fuel concentration, dropping off to about 0.7 at 50 percent concentration. This is the maximum concentration at which a variety of stock spark ignition engines was able to operate to derive these curves under laboratory conditions. It is highly unlikely that economical and adequate operation of spark ignition engines using fuels having more than about 25 percent diesel fuel as emergency extender can be achieved. This is not suggested as an absolute limit; engine tolerance will vary enormously from situation to situation.

Figures 24 through 27 present Emissions Index curves for the three principal exhaust emis-

sions currently regulated: unburned hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x). Note that data for Figures 24 and 26 are for engine operation at *idle* while data for Figures 25 and 27 are emissions characteristics for *road* operation (roughly 30 to 50 miles per hour). There is little variation in exhaust emissions for either idle or road-running conditions as compared to neat gasoline emissions up to 20 percent volume diesel fuel (either No. 2 or marine) in gasoline. Above this level, exhaust emissions can be expected to be quite aberrant and data are not shown beyond 20 percent.

2. Diesel Engines*

Figure 28 is a Tradeoff Chart for typical diesel engine performance using No. 2 diesel fuel as baseline with regular grade unleaded gasoline as emergency extender. Conservation Index increases, reaching a maximum at about 60 percent volume gasoline, whereas Power Index gradually decreases to this point and drops off even more sharply thereafter. This results in an overall Tradeoff Index curve which increases to about 1.2 at 40 percent volume gasoline and remains constant until 60 percent, dropping off precipitously thereafter. It would appear that adequate engine performance could be sustained up to something on the order of 30 to 40 percent gasoline-in-diesel fuel in operating a wide variety of *diesel* engines.

Figure 29 presents Emissions Index curves for the four principal diesel exhaust emissions: unburned hydrocarbons, carbon monoxide, oxides of nitrogen, and smoke. CO decreases to about 50 percent of neat diesel values at 50/50 blend level, smoke decreases to about 75 percent of neat diesel fuel, and NO_x increases about 25 percent above neat diesel fuel. The HC Index curve increases until, at the 50/50 point, it is over three times that of neat diesel fuel. This may be because of the increasing concentration of aromatic hydrocarbons which are characteristic of gasoline; the significance of such an increase *in an emergency situation* must be considered in each individual case.

*Note: Extreme fire and or explosion hazard on blends of the type.

FIGURE 22
TRADEOFF CHART
GASOLINE EMERGENCY BLEND
EXTENDER:NO.2 DIESEL FUEL

FIGURE 23
TRADEOFF CHART
GASOLINE EMERGENCY BLEND
EXTENDER:MARINE DIESEL FUEL

FIGURE 24
EMISSIONS INDEX-IDLE

EMERGENCY GASOLINE BLEND
EXTENDER: NO.2 DIESEL FUEL

FIGURE 25
EMISSIONS INDEX-ROAD

EMERGENCY GASOLINE BLEND
EXTENDER: NO.2 DIESEL FUEL

FIGURE 26
EMISSIONS INDEX-IDLE
EMERGENCY GASOLINE BLEND
EXTENDER: MARINE DIESEL FUEL

FIGURE 27
EMISSIONS INDEX-ROAD
EMERGENCY GASOLINE BLEND
EXTENDER: MARINE DIESEL FUEL

FIGURE 28
TRADEOFF CHART
DIESEL EMERGENCY BLEND
EXTENDER: GASOLINE

FIGURE 29
EMISSIONS INDEX
EMERGENCY DIESEL BLEND
EXTENDER: GASOLINE

III. ALCOHOLS

Chemically, the alcohols such as methanol, ethanol, isopropanol, tertiary butanol, etc., differ from hydrocarbon fuels due to the presence of oxygen in the molecule. This is illustrated in Table 4. This results in different fuel combustion characteristics such as amount of oxygen required and volumes of resulting combustion products. These differences become important when consideration is given to alcohols for replacement or extenders of gasoline or diesel fuel in motor vehicles.

The use of *straight alcohols* to power internal combustion engines offers some potential advantages that could outweigh disadvantages when compared to gasoline or diesel fuel. However, this practice will require modification of carburetor systems in the current production of spark-ignited engines and considerable diesel fuel system changes. Areas where differences between use of neat alcohol and gasoline are particularly evident are:

- *Thermal Efficiency/Fuel Economy*—Thermal efficiency is potentially better with alcohols because they have more

favorable thermochemical properties, can be burned leaner, and can operate at higher useful compression ratios. However, as a result of the lower energy content (heat of combustion) of alcohols, fewer miles per gallon will be obtained. Methanol has about half the energy content per volume of gasoline, ethanol about two-thirds, and higher alcohols (much more energy intensive to produce) have from three-fourths to seven-eighths.

- *Exhaust emissions* of neat ethanol and methanol are close to those for gasoline when compared to the same relative mixture strength. Aldehyde emissions are peculiar to alcohol exhaust and, of course, are much higher while nitrogen oxides are lower than with gasoline.
- *Driveability* remains argumentative and has not been investigated comprehensively at this time. Such effects as cold-

TABLE 4. SOME PROPERTIES OF ALCOHOLS AND GASOLINE

Property	Methanol	Ethanol	Isopropanol	Tertiary Butanol	Gasoline
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 100-105 avg
Molecular Weight	32.04	46.07	60.09	74.12	
Composition, wt %					
Carbon	37.5	52.2	59.9	64.8	85-88
Hydrogen	12.6	13.1	13.4	13.6	12-15
Oxygen	49.9	34.7	26.6	21.6	0
Specific Gravity, 60°F/60°F	0.796	0.794	0.789	0.791	0.72-0.78
Density, lb/gal	6.63	6.61	6.57	6.59	5.8-6.5
Boiling					
Temperature, °F	149	172	180	181	≈80-437
Flash Point, °F	52	55	53	52	-45
Autoignition					
Temperature, °F	867	793	750	892	495
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	64,640	84,610	93,620	100,830	124,850

starting difficulties and vapor-lock at higher operating temperatures, etc., can be troublesome but can be overcome through good design practice in the automotive industry.

- **Materials Compatibility**—Automobile fuel tank lining materials, fuel system plumbing, and elastomer seals in some specific instances show increased softening or swelling when exposed to alcohols. This too is very system-specific and can be eliminated through choice of elastomer and coating materials.

When alcohols and gasoline are blended in concentrations *up to about 20 percent*, no extensive engine modifications or materials replacement are normally necessary. The performance characteristics of blends in unmodified cars are predictable from the relatively leaner air-fuel mixtures they produce:

- **Thermal Efficiency/Fuel Economy**—The thermal efficiency increases especially in those cars with rich mixture calibrations (mainly pre-1968 models); however, fuel economy (miles per gallon) decreases proportionately to the amount of alcohol in the blend because of the lower energy content.
- Exhaust emissions change to the same extent they would have changed using gasoline if the carburetor had been adjusted to an equivalent leaner mixture strength. Therefore, unburned hydrocarbons and carbon monoxide are reduced somewhat (particularly in older cars originally set rich). Aldehyde emissions are higher for alcohol blends as compared with neat gasoline; NO_x emissions are not significantly affected.
- Driveability and vapor-lock problems may occur with some frequency when using gasoline blends, but to date no significant nationwide problems have been reported.

A. Physical and Chemical Properties

1. Octane Number

The chief advantage of operating vehicles on gasoline-alcohol blends is the im-

proved antiknock property of the blend. Alcohols have much higher octane numbers than most current unleaded gasolines (which are nominally about $88 (R + M)/2$). Most investigators point out that neat alcohols can and should be metered much leaner than gasoline if the properties of these fuels are to be exploited to the fullest extent. Operating a so-called "stock" carburetion system (for which all of the data in this section is illustrative), an octane-improving characteristic for ethyl alcohol (ethanol) is dramatically apparent (see Figure 30) while characteristics of methyl alcohol (methanol) blended with gasoline result in similar (although reduced) improvements in octane number (see Figure 31).

2. Vapor Pressure

The addition of alcohols to gasoline in small concentrations increases the vapor pressure somewhat up to about 5 or 10 percent by volume and decreases Reid Vapor Pressure (RVP) thereafter, much more so for ethanol than for methanol (see Figures 32 and 33, respectively).

Distillation characteristics of ethanol blended with gasoline are shown in Figure 34. Characteristically, gasoline-alcohol blends produce flat spots (horizontal sections) on such distillation curves because the *alcohols are pure compounds and as such have single boiling points* as opposed to gasoline which is a blend of thousands of different hydrocarbon types and consequently has a typical *boiling range* from 80° to 347°F .

3. API Gravity

Typical API gravity characteristics for ethanol and methanol with gasoline are shown in Figures 35 and 36, respectively.

4. Water Sensitivity

The solubility of alcohols in gasoline and diesel fuel when water is present even in minute quantities is limited at room temperature. When small amounts of water are added to methanol or ethanol blends with hydrocarbon fuels, hydrogen bonds form between the water and alcohol molecules and the blends separate into two phases. Paraffinic hydrocarbons predominate in the upper phase, while the lower phase consists primarily of

FIGURE 30
OCTANE NUMBER VS BLEND CONCENTRATION

GASOLINE EMERGENCY BLEND
 EXTENDER: ETHANOL

FIGURE 31
OCTANE NUMBER VS BLEND CONCENTRATION

GASOLINE EMERGENCY BLEND
 EXTENDER: METHANOL

FIGURE 32
RVP VS BLEND CONCENTRATION

FIGURE 33
RVP VS BLEND CONCENTRATION

FIGURE 34
ETHANOL-GASOLINE BLEND DISTILLATION

FIGURE 35
API GRAVITY VS BLEND CONCENTRATION

FIGURE 36
API GRAVITY VS BLEND CONCENTRATION
GASOLINE EMERGENCY BLEND
EXTENDER: METHANOL

alcohol, water, and small amounts of aromatic hydrocarbons. Ethanol is more miscible in gasoline and diesel fuels than methanol (in fact, methanol is simply not miscible in diesel fuel); experience indicates that, at room temperature, water in concentrations of about 0.5 percent or higher will cause *phase separation*. Water tolerance is also significantly decreased at lower temperatures.

Often, inclusion of higher molecular weight alcohols (e.g., tertiary butyl alcohol, isopropyl alcohol, *n*-hexanol) with either ethanol or methanol will significantly increase water tolerance at reduced temperatures. In some alcohol-producing processes, small quantities of these higher alcohols are (fortuitously) present.

B. Tradeoff Charts—Gasoline Base Fuel

1. Ethyl Alcohol

Figure 37 presents a Tradeoff Chart for ethyl alcohol as an emergency extender with gasoline.* Note that performance as evaluated by Power Index is essentially constant to 40 percent volume ethanol with a relatively sharp dropoff thereafter. Conservation Index increases to slightly beyond this at the 50/50 point and remains constant thereafter. This results in a peaking effect for the Tradeoff Index curve at about 40 percent volume ethanol. Essentially, it would seem that any concentration up to about 50 or 60 percent would result in no performance penalties *if the engine is appropriately modified for concentrations this high*.

Figures 38 and 39 present Idle and Road* Emissions Index data, respectively. At idle, emissions are somewhat comparable to those of neat gasoline up to 40 percent volume ethanol. Under road conditions (30 to 50 miles per hour), carbon monoxide emissions remain constant while oxides of nitrogen decrease dramatically. Unburned hydrocarbons increase to almost three times those of neat gasoline at 40 percent ethanol concentration. It should be emphasized that the emissions characteristics of fuels containing significant concentrations of alcohols will differ in character radically from those of conventional hydrocarbon fuels. Techniques to measure these emis-

sions and their possible environmental impact are currently under evaluation.

2. Methyl Alcohol

Figure 40 presents tradeoff charts for methanol as a gasoline emergency extender. Power Index is essentially constant to 40 percent volume methanol and Conservation Index increases mildly, resulting in an overall Tradeoff Index curve only slightly peaked at about 20 percent volume methanol. As with ethanol, it will, of course, be necessary to modify most spark ignition engines for concentrations above about 20 percent volume methanol.

Figures 41 and 42 present Idle and Road Emissions Index data for methanol to 40 percent concentration in gasoline. Essentially, oxides of nitrogen decrease, carbon monoxide remains constant, and unburned hydrocarbons increase radically with increasing methanol concentration.

3. Methyl Tert Butyl Ether (MTBE)

Although MTBE is not an alcohol but an ether, it does fit into the same fuel category as an oxygenated compound. Ethers are quite similar to alcohols in their properties. Ethers are effective octane improvers while still maintaining high solubility in hydrocarbon blends. This indicates promising performance in gasoline emergency blends as illustrated in the MTBE Tradeoff Chart in Figure 43. MTBE can be used as a neat fuel with some modification to carburetion and tuning.

Power Index for all concentrations is constant while Conservation Index increases linearly from 1.0 to 2.0.

4. Complex Alcohol Emergency Blends

A limited number of combinations of emergency extenders in gasoline was evaluated, and Tradeoff and Emissions Charts were developed. These emergency extenders were naphtha, kerosene, No. 2 diesel fuel, and marine diesel fuel, each blended in equal parts with ethanol using gasoline as the base fuel.

(a) Spark Ignition Engines

Figures 44 through 51 present Tradeoff

* Figures 37 and 38 are the same as used in the Introduction Section for Chart format explanation.

FIGURE 37
TRADEOFF CHART
GASOLINE EMERGENCY BLEND
EXTENDER: ETHANOL

FIGURE 38
EMISSIONS INDEX-IDLE
EMERGENCY GASOLINE BLEND
EXTENDER: ETHANOL

FIGURE 39
EMISSIONS INDEX-ROAD
EMERGENCY GASOLINE BLEND
EXTENDER: ETHANOL

FIGURE 40
TRADEOFF CHART
GASOLINE EMERGENCY BLEND
EXTENDER: METHANOL

FIGURE 41
EMISSIONS INDEX-IDLE
EMERGENCY GASOLINE BLEND
EXTENDER:METHANOL

FIGURE 42
EMISSIONS INDEX-ROAD
EMERGENCY CRUISE BLEND
EXTENDER:METHANOL

FIGURE 43
TRADEOFF CHART
GASOLINE EMERGENCY BLEND
EXTENDER:MTBE

FIGURE 44
TRADEOFF CHART
GASOLINE EMERGENCY BLEND
EXTENDER: NAPHTHA-ETHANOL

FIGURE 45
EMISSIONS INDEX-IDLE
EMERGENCY GASOLINE BLEND
EXTENDER: NAPHTHA-ETHANOL

FIGURE 46
EMISSIONS INDEX-ROAD
EMERGENCY GASOLINE BLEND
EXTENDER:NAPHTHA-ETHANOL

FIGURE 47
TRADEOFF CHART
GASOLINE EMERGENCY BLEND
EXTENDER:DFM-ETHANOL

FIGURE 48 EMISSIONS INDEX-IDLE

EMERGENCY GASOLINE BLEND
EXTENDER:DFM-ETHANOL

FIGURE 49 EMISSIONS INDEX-ROAD

EMERGENCY GASOLINE BLEND
EXTENDER:DFM-ETHANOL

FIGURE 50
TRADEOFF CHART
GASOLINE EMERGENCY BLEND
EXTENDER:NO.2 DIESEL FUEL-ETHANOL

FIGURE 51
TRADEOFF CHART
GASOLINE EMERGENCY BLEND
EXTENDER:KEROSENE-ETHANOL

Charts and Emissions Index data for these complex blends. In each case, the volume percent of the complex combination should be interpreted as the *total* volume concentration. That is, a 20-percent concentration of naphtha with ethanol in gasoline would mean 10-percent naphtha, 10-percent ethanol, and the remaining 80-percent gasoline. This is true for all complex blends included. Generally, all such complex blends look promising, and further work may reveal optimum proportions of two or even three extenders.

C. Tradeoff Charts—Diesel Base Fuel

Figures 52 and 53 present Tradeoff and Emissions data for ethyl alcohol used as emergency extender in No. 2 diesel fuel. This combination has recently been nicknamed (among other terms) "dieselhol" and may well have great potential in agricultural applications, although it must be emphasized that *typical agriculturally-derived ethanol may be of much lower proof than the 200-proof ethanol used to develop these curves* (see next subsection). Performance in diesel engines is decreased only slightly, up to 40 percent ethanol concentration. This results in a Tradeoff Index curve which peaks at about 30 percent volume (which may well be the practicable limit for alcohols in diesel engines). As with gasoline, increasing concentration of ethanol in diesel fuel serves to reduce considerably both smoke and carbon monoxide, with oxides of nitrogen increasing slightly. Also as with gasoline, increasing ethanol concentration

serves to drastically increase unburned hydrocarbons to over double that of neat diesel fuel.

D. Tradeoff Charts—Neat Lower Proof Ethanol in Spark Ignition Engines

As mentioned previously, 200-proof (anhydrous) ethanol has been used to develop all the preceding data. Such high-proof ethanol will likely not be typical of small-scale agriculturally-derived ethanol production in the next few years. A limited amount of data for *lower-proof ethanol operated "neat" in a modified spark ignition engine** has been developed. A Tradeoff Chart for these data is shown in Figure 54. Note that *water has been taken as the "extender"* in this instance and ethanol as the base fuel to be stretched out. In this chart, 200-alcohol performance is then indicated at the "0-percent water" (Y-axis) point. Lower-proof alcohols then generally show reduced performance as water concentration is increased, although a dramatic break is not observed until 15-percent water (170-proof) ethanol was used. Although spark ignition engines can be operated at relatively high water concentrations (lower proofs), the Conservation Index curve indicates that alcohol is *not extended* but simply *wasted* as compared to operation with 200 proof ethanol. *Further research and development with engine system modifications may well negate this tentative conclusion, but such modifications will likely be sophisticated and expensive—or highly innovative.*

*In order to accommodate the high fuel flow demand of low-proof alcohol blends, the main metering jets of the carburetor must be replaced or enlarged. Discharge tubes may also have to be drilled.

FIGURE 52
TRADEOFF CHART
DIESEL EMERGENCY BLEND
EXTENDER: ETHANOL

FIGURE 53
EMISSIONS INDEX
EMERGENCY DIESEL BLEND
EXTENDER: ETHANOL

FIGURE 54
TRADEOFF CHART
GASOLINE EMERGENCY BLEND
ETHANOL EXTENDER WITH WATER

IV. SOLVENTS

A. General Information

The term "petroleum solvents" describes the special liquid hydrocarbon fractions obtained from petroleum for use in industrial processes and commercial formulations to dissolve, suspend, or transport the other ingredients of the process or formulation. In recent years, the variety of petroleum solvents has increased considerably due to the development of refinery processes designed primarily for the transformation of low-octane feedstocks to high-octane fuels. These new developments led to the production of certain important solvents and intermediates which were obtained previously only from the coal-carbonizing industry. By definition, the solvents obtained from the petrochemical industry (the alcohols, ethers, etc.) are outside the scope of this section.

Petroleum solvents are available for a variety of applications. Modern refining techniques produce solvents with a high degree of purity and stability in a wide range of grades and boiling points. Petroleum solvents are particularly attractive, because they are readily available in large volumes at low costs compared to solvents from other sources.

Solvents are used extensively by industry in manufacturing processes for such diverse products as paint, printing ink, polish, adhesives, perfumes, glues, fats, etc. Further uses are found in the dry cleaning, leather, and fur industries and the pesticide field. Solvents, in highly purified condition, also are becoming increasingly important for use as reaction media in certain catalytic processes.

The variety of applications emphasizes the versatility of petroleum solvents. The main characteristics which determine the suitability of a petroleum fraction for a particular use are its solvent properties, volatility, purity, gravity, odor, toxicity, and air pollution control/limitations.

1. General Solvent Types

Of necessity selection and use of solvents are based solely on the properties of com-

mercial products as determined by tests. Solvent users are guided mainly by the following commercial classification of hydrocarbon solvents:

- (1) Narrow cut aliphatics
- (2) Special boiling range solvents
- (3) Mineral spirit types
- (4) Aromatics
- (5) Kerosene*

The approximate properties of these typical hydrocarbon solvents are shown in Table 5.

2. Specific Types of Solvents

Although industrial users of solvents are guided by the commercial classification just outlined, there are specific types of commercial solvents that merit a thumbnail description.

Hexane and Heptane: These are used frequently in multistage processes in which the solvent must be present in one step but gone completely prior to a subsequent step. They are also used as solvents and suspending agents in the petrochemical industry in which they are recovered and reused. Heptane is used in place of hexane when a higher flash point or higher boiling range solvent is needed.

Petroleum Ether: Petroleum ether is the fastest evaporating of the commonly used solvents and therefore has obvious advantages, but its flash point is correspondingly low. It is used as a solvent for oils, fats, waxes, in paints and varnishes, and as a fuel.

"Textile" Spirits: This close cut solvent is predominantly hexane. It is used only when very fast setting is desired, but since it has a broader boiling range than hexane, evaporation occurs over a longer time interval.

Lacquer Diluent: Lacquer diluent is designed primarily for use in nitrocellulose lacquer as a replacement, or partial replacement, for toluene. Lacquer diluent is used in place of toluene because it is cheaper. The quality of lacquer diluent is proportional directly to aromatic content. The more aromatics, the better the quality. Lacquer diluents are used also as solvents in gravure inks for printing.

*Covered separately in a subsequent section.

TABLE 5. APPROXIMATE PROPERTIES OF TYPICAL HYDROCARBON SOLVENTS

	Distillation Range, °F		Evaporation Rate N = BuAc = 100	Flash Point, Tag Closed Cup, °F	Kauri- Butanol Value	Aniline Point, °F	Aromatics, Vol %	Sp Gr 60/60
	Initial	Dry Point						
<i>Narrow-Cut Aliphatics</i>								
Hexane	151	157	>1000	>0	31	146	>1	0.680
Heptane	201	209	600	23	38	127	3	0.728
<i>Special Boiling Point Solvents</i>								
Petroleum ether	95	140	>1000	-60	26	150	0	0.645
Textile spirits	145	175	850	-20	34	134	5	0.690
Rubber solvent	144	248	700	>0	36	131	5	0.712
Lacquer diluent	200	220	400	20	40	120	15	0.728
VM&P naphtha	210	300	150	45	38	130	10	0.752
Ink oil	495	560	>1	240	26	176	>5	0.820
<i>Mineral Spirits</i>								
Regular (Stoddard)	320	380	10	108	39	130	15	0.789
140-Flash point	360	400	5	140	35	143	15	0.792
Odorless	350	380	7	125	27	184	>1	0.759
High solvency	320	380	8	110	44	105	30	0.808
<i>Aromatics</i>								
Benzene	175	177	500	>10	115	57*	99 +	0.885
Toluene	230	232	200	40	105	46*	99 +	0.870
Xylene	282	285	60	83	98	52*	99 +	0.869
High-flash aromatic naphtha	310	350	19	107	92	56*	98 +	0.874
High-flash aromatic naphtha	360	410	4	151	90	64*	97 +	0.891
Heavy aromatic naphtha	360	540	1	152	105	76*	86 +	0.933
<i>Kerosene</i>								
Regular	350	515	1	140	30	160	>25	0.804
Odorless	400	480	1	170	27	190	1	0.782

*Mixed aniline point, °F.

VM&P* Naphtha: Large quantities of VM&P naphtha are used. It resembles regular mineral spirits in hydrocarbon type composition and has about the same solvency. However, it is lower boiling, has a lower flash point, and evaporates much faster. The fast evaporation and low-flash point make it generally unsuitable for interior architectural finishes, but it is well adapted for application by spraying and, in some cases, by dipping. The grades with an initial boiling point of about 235°F or higher are differentiated frequently as high-flash VM&P naphtha.

Ink Oils: Ink oils are used in place of kerosenes where narrow-cut ink solvents are desired. The narrow cut provides better drying control of the ink.

Mineral Spirits: Mineral spirits constitute about three-fourths of all hydrocarbon solvents used in the paint industry and 90 percent of the solvents in architectural finishes. It comprises four general types: (1) regular, (2) odorless, (3) high flash, and (4) high solvency. Within each of these types, there are products that offer a choice in boiling range and volatility, and thus permit some control of "setting" rate, brushability, and wet-edge time.

Benzene (Benzol): The use of benzene in coatings is considered bad practice because the vapors are toxic. Its only common use by the paint industry is in solvent type paint and varnish removers where it is more effective than the higher-boiling aromatics.

Toluene (Toluol): Toluene is used widely when maximum solvency and rather fast evaporation are desired. It is the best fast diluent for nitrocellulose lacquers and also is used in synthetic enamels of several types. The industrial pure grades with distillation ranges of a few degrees centigrade give the same results as the 1°C nitration grade.

Xylene (Xylol): Xylene is essentially a mixture of the ortho, meta, and para isomers of xylene with ethylbenzene. It is used instead of toluene where slower evaporation is sought. In both lacquers and synthetic enamels, xylene is used frequently in admixture with toluene. It is the sole or main hydrocarbon solvent in many synthetic industrial enamels that are applied by spraying. Unlike toluene, xylene does not require a red label for

interstate shipments.

Hi-Flash Solvent Naphtha: Formerly this term referred only to a high-boiling fraction obtained from coal tar. Today it also covers an equivalent product that is derived from petroleum. Many industrial paints require at least a portion of a strong hydrocarbon solvent that evaporates slower than xylene. Hi-flash solvent naphtha fills this need.

Kerosene: Kerosene is the only hydrocarbon solvent that is rated as having a wide distillation range. It is used when extremely slow setting and rather low solvency are desired, and the kerosene odor is permissible. Two such purposes are wood fillers and putties. In most applications, kerosene is combined with a larger amount of mineral spirits.

3. Key Properties of Solvents

a. Specific Gravity

The determination of specific gravity serves two purposes: it provides a check on the uniformity of shipments, and it permits calculation of the weight per gallon.

Specific gravity is defined as the ratio of a weight of a given volume of material to the weight of an equal volume of water under specified conditions. Specific gravity for petroleum solvents is usually determined by ASTM Tests for Specific Gravity of Industrial Aromatic Hydrocarbons and Related Materials (D 891). A gravity balance or a glass hydrometer is used with this procedure. Producers of petroleum solvents frequently use American Petroleum Institute (API) gravity instead of specific gravity. API gravity was developed to permit the use of whole numbers.

To avoid dealing with two kinds of gravity, paint laboratories usually convert the API values to specific gravity by use of conversion tables or by the formula,

$$\text{API gravity, deg} = \frac{141.5}{\text{sp gr at } 60/60^{\circ}\text{F}} - 131.5$$

For figuring formula yields and important composition relationships, paint laboratories must have a list of raw materials that includes the weight per

*Varnish Makers and Painters.

gallon of all liquid materials at normal operating temperature. When the specific gravity of solvents is determined at the customary 60/60°F, a temperature conversion factor must be used to obtain the specific gravity at 70°F, and this factor differs with the solvent. This corrected specific gravity must then be converted to pounds per gallon. API gravity curves for typical naphtha solvents blended with gasoline and diesel are shown in Figures 55 and 56, respectively.

b. Distillation

The significance of distillation results is based on the close relationship to volatility which, in turn, largely governs evaporation rate. ASTM Test for Distillation of Petroleum Products (D 86/IP123) is used for solvents with a wide distillation range (this includes the common aliphatic and aromatic naphtha solvents). ASTM Test for Distillation Range of Volatile Organic Liquids (D 1078) is the procedure used for solvents with a narrow range of distillation (aromatic hydrocarbons, alcohols, esters, and ketones). Regardless of solvent type, a very narrow distillation range has no direct advantage in coatings. However, it may have significance as an indication of the degree of purity of oxygenated solvents. Distillation curves for naphtha gasoline blends are given in Figure 57, and for naphtha-diesel blends in Figure 58.

c. Flash Point

The flash point of a liquid is the lowest temperature at which application of a flame causes the vapor above the sample to ignite. Flash point is indicative of potential fire hazard. The most common method of determining flash point is with the ASTM Flash Point by Tag Closed-Cup Tester (D 56) which confines the vapor until the instant the flame is applied. However, Interstate Commerce Commission regulations on the shipping of flammable solvents are based on the ASTM Flash Point of Liquids by Tag Open-Cup Apparatus (D 1310) which gives slightly higher values.

In mixtures of solvents and in coatings, the flash point is substantially that of the lowest flash portion that is present in an appreciable amount. Flash point characteristics of naphtha blended with diesel fuel are shown in Figure 59.

d. Sulfur

Sulfur compounds are objectionable because they impart odor and may cause darkening of cooked varnishes and resins. Typical sulfur content for naphtha-diesel fuel blends is shown in Figure 60.

e. Other Key Properties

Since the constituency and characteristics of solvents vary widely, it is virtually impossible to generalize regarding blends of solvents with gasoline and diesel fuel. The preceding figures in this section are illustrative of neat and blend characteristics of typical naphtha solvents since these are considered to be one of the more prevalent classes. Figures 61 through 67 present a supplementary collection of blend properties of such naphthas with either gasoline or diesel fuel as seems most appropriate to illustrate how these emergency extenders might affect base fuel characteristics. These include volatility (RVP), API gravity, viscosity, pour point, gross heat of combustion, storage stability, and (most important) octane and cetane number in gasoline and diesel fuels, respectively.

B. Tradeoff Charts

As mentioned previously, *naphthas* are considered to be typical and prevalent among solvents and thus all the material following has been generated for typical naphtha solvents blended with either gasoline or diesel fuel. *Kerosene* which is considered a prevalent solvent is handled separately in Section VI of this guidebook.

1. Spark Ignition Engines

Figures 68, 69, and 70 present Tradeoff Charts and Emissions Index data for typical naphtha blended with gasoline. Note that Power Index drops off gradually with increasing naphtha concentration. Conservation Index rises slowly to about 20 vol % naphtha and remains essentially constant thereafter, resulting in an overall Tradeoff Index curve which peaks at about 20 vol % naphtha and drops off to a value of about 0.9 at 50 vol %. It would thus appear that concentrations between 15 and 30 vol % naphtha in gasoline would

FIGURE 55
API GRAVITY VS BLEND CONCENTRATION

FIGURE 56
API GRAVITY VS BLEND CONCENTRATION

FIGURE 57
NAPHTHA-GASOLINE BLEND DISTILLATION
 GASOLINE EMERGENCY BLEND
 EXTENDER: NAPHTHA

FIGURE 58
NAPHTHA-DIESEL BLEND DISTILLATION
 DIESEL EMERGENCY BLEND
 EXTENDER: NAPHTHA

FIGURE 59
FLASH POINT VS BLEND CONCENTRATION

FIGURE 60
SULFUR CONTENT VS BLEND CONCENTRATION

FIGURE 61
RVP VS BLEND CONCENTRATION

FIGURE 62
VISCOSITY VS BLEND CONCENTRATION

FIGURE 63
POUR POINT VS BLEND CONCENTRATION

FIGURE 64
GROSS HEAT OF COMBUSTION VS BLEND CONCEN

FIGURE 65
ACCEL STABILITY VS BLEND CONCENTRATION

FIGURE 66
OCTANE NUMBER VS BLEND CONCENTRATION

FIGURE 67
CETANE NUMBER VS BLEND CONCENTRATION

FIGURE 68
TRADEOFF CHART

GASOLINE EMERGENCY BLEND
EXTENDER: NAPHTHA

FIGURE 69
EMISSIONS INDEX-IDLE
EMERGENCY GASOLINE BLEND
EXTENDER: NAPHTHA

FIGURE 70
EMISSIONS INDEX-ROAD
EMERGENCY GASOLINE BLEND
EXTENDER: NAPHTHA

be the most required for optimum conservation with minimum loss in power. Emissions data for both idle and road operation indicate some possibility of increase in oxides of nitrogen as naphtha concentration approaches 20 vol %, but otherwise virtually no change from emissions characteristics of neat gasoline.

2. Diesel Engines

Tradeoff Charts for typical road operation of diesel engines with two types of naphthas are shown in Figures 71 and 72, for medium and heavy naphthas, respectively. While the heavy naphtha has a somewhat higher boiling range than the medium naphtha, note that tradeoff characteristics are virtually identical for the two naphtha extenders. Power index dropped off to a value of

about 0.7 when diesel engines were operated with 100 percent medium naphtha. Conservation Index rose linearly, causing a resulting Tradeoff Index curve which is essentially linear, implying that diesel engines may well be operated for short periods of time on extremely high concentrations of naphtha material.

Emissions data are shown in Figures 73 and 74 for these two extender candidates and (with the exception of unburned hydrocarbons), emissions were virtually the same or somewhat less than those for neat No. 2 diesel fuel. Unburned hydrocarbons increased to about twice that for neat diesel fuel using neat heavy naphtha and to something over four times that of neat diesel fuel for the neat medium naphtha. Minor engine adjustments for specific diesel operation can likely attenuate some of this drastic increase.

FIGURE 71
TRADEOFF CHART
DIESEL EMERGENCY BLEND
EXTENDER: MEDIUM NAPHTHA

FIGURE 72
TRADEOFF CHART
DIESEL EMERGENCY BLEND
EXTENDER: HEAVY NAPHTHA

FIGURE 73
EMISSIONS INDEX

EMERGENCY DIESEL BLEND
EXTENDER: MEDIUM NAPHTHA

FIGURE 74
EMISSIONS INDEX

EMERGENCY DIESEL BLEND
EXTENDER: HEAVY NAPHTHA

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V. JET FUELS

Aircraft gas-turbine engines require a fuel with quite different properties from those for aviation gasoline. Probably the greatest difference is that antiknock value is of no importance and is replaced by the need for a heating fuel with good combustion characteristics and high-energy content. Illuminating kerosene was chosen as the fuel for the first generation of engines largely because of its ready availability, low-fire hazard, good combustion properties, and, not least, the war-time (WW II) need to conserve gasoline supplies. As engine and fuel system designs have become more complicated, so have fuel specifications become more varied and restrictive. Jet fuel quality worldwide is dictated on the commercial side largely by the British Ministry of Defense (D Eng RD) specifications and those specifications of the airlines, engine manufacturers, and industry groups such as ASTM and the International Air Transport Association (IATA). Military jet fuel is dictated largely by the U.S. Department of Defense (U.S. MIL) specifications and corresponding D Eng RD specifications. Grades of commercial and military fuels are virtually identical in basic properties and differ mainly in the types of additives permitted. The only significant exception is the fuel type used in the USSR and most East European countries. These grades are based on USSR state standards (GOST specifications) and differ in several major respects from their nearest "Western" equivalents.

Only two basic types of jet fuel are in general use worldwide: kerosene type and wide-cut gasoline type. The former is a modified development of the illuminating kerosene originally used in gas-turbine engines. The latter is a wider boiling-range material which includes some gasoline fractions developed primarily in the United States to improve on availability from crude oil. In addition, a number of specialized fuel grades are required for limited military use and as referee fuels.

Since turbine fuels have excellent potential for use as emergency diesel extenders, all material in this section refers to diesel/turbine fuel/blends.

American Military Jet Fuels: In the United States, jet fuel development followed a different pattern. The early United States specification for

JP-1 called for a paraffinic kerosene with a freeze point of -60°C (-76°F). These restrictive requirements limited the availability of the fuel, and the grade soon became obsolete. JP-1 has been superseded by a series of military wide-cut fuels.

The wide-range distillate type of turbine fuel originated in the United States where it was realized that, in times of military emergency the fuel supply could be increased considerably if more of the readily available gasoline fractions were incorporated into jet fuel to supplement the basic kerosene component. This philosophy is the converse of the World War II choice of kerosene for the early jet engines. Kerosene was chosen in order to conserve gasoline stocks for the then predominant piston-type aircraft engines.

The first wide-cut grade (JP-2) allowed a Reid Vapor Pressure of 2 lb max to increase availability through the inclusion of heavy gasoline fractions. Experience suggested that a further increase in volatility might be tolerated to give an advantage in engine starting, and the specification of JP-3, therefore, was introduced with vapor pressure limits of 5.0 to 7.0 lb. However, operational problems due to high-venting losses at altitude led finally to the formulation of the JP-4 specification in 1950. With slight modifications to the specific gravity and distillation requirements, plus the inclusion of certain additives, JP-4 remains the main fuel for military jet aircraft in the United States and many other countries. Kerosene-type jet fuels have not achieved any significant military use in the United States with the exception of JP-5, a low-volatility kerosene fuel used by naval aircraft during ship-board operations. JP-6 was a light kerosene-type fuel of improved thermal stability intended for a supersonic bomber but has been declared obsolete. JP-7 is another low-volatility, high-flash point kerosene with enhanced combustion and thermal stability properties that was developed as a fuel for very high-performance (Mach 3) aircraft.

Concern over combat hazards when using wide-cut fuels has led the Department of Defense to reconsider the use of standard kerosene-type fuel. Service trials on a proposed new JP-8 grade fuel have been completed. Although the trials were successful, the advantages to be gained from

switching from JP-4 to JP-8 may be outweighed by the undesirable impact on world jet fuel supplies that might occur if a major international user should change from a wide-cut fuel to a kerosene-type.

American Civil Jet Fuels: The basic civil jet fuel specification used in the United States is ASTM Specification for Aviation Turbine Fuels (D 1655) which outlines requirements for three types of fuel: *Jet A*, a nominal -40°C freeze-point kerosene; *Jet A-1*, a nominal -50°C freeze-point kerosene; and *Jet B*, a wide-cut gasoline grade (similar to JP-4 but without certain additives).

Jet A is used internally within the United States by all domestic operators, while Jet A-1 is the standard grade used for international flights. To differentiate from the military fuel grades (which often contain special additives not used commonly in civil fuels), the terms Jet A-1 and Jet B are now used worldwide to describe the basic kerosene and wide-cut gasoline types of civil jet fuel although the latter is only in fairly limited civil usage at present.

A number of jet fuel specifications also are issued by the major United States aircraft engine manufacturers and certain airlines. These are either similar to the equivalent ASTM grades or are less restrictive versions of one or more ASTM grades.

A. Chemical Properties and Composition

The requirements for jet fuels stress a different combination of properties and tests than those required for aviation gasoline. The same basic controls are needed for such properties as storage stability and corrosivity, but the gasoline antiknock tests are replaced by tests directly and indirectly controlling energy content and combustion characteristics. Therefore, it is convenient to deal with the chemical properties and composition separately from the physical properties of jet fuel.

1. Hydrocarbon Makeup

Jet fuels consist entirely of hydrocarbons except for trace quantities of sulfur compounds and approved additives. Since jet fuels are produced normally by blending straight-run distillate components, they contain virtually no olefins.

The amounts of aromatics also are

limited directly because they do not burn as clean as other hydrocarbon types. High aromatics can cause smokiness and carbon deposition in the engines. They also degrade elastomers in the fuel system and increase the luminosity of the combustion flame, which can adversely affect the life of certain designs of combustion chamber.

2. Sulfur

The principal nonhydrocarbon components permitted in jet fuels are sulfur compounds. The amount and type of sulfur compound vary with crude source, but normally there is no difficulty in meeting the specified total sulfur content which ranges in level between 0.2 and 0.4 percent by weight maximum.

Experimental evidence indicates high-sulfur levels may adversely affect the carbon-forming tendency in combustion chambers, and the presence of large amounts of sulfur oxides in the combustion gases may lead to corrosion problems.

Mercaptan sulfur content of jet fuels is limited to a maximum in the range of 0.001 to 0.005 percent by weight because of objectionable odor, adverse effect on certain fuel system elastomers, and corrosiveness toward fuel system metals.

Figures 75 and 76 show overall sulfur levels for blends of diesel fuel with Jet A and Jet A-1 turbine fuels.

3. Additives and Storage Stability

The various approved additives for jet fuels include oxidation inhibitors to improve storage stability, copper deactivators to neutralize the adverse effect of copper on fuel stability, and corrosion inhibitors intended for the protection of storage tanks and pipelines. An anti-icing additive (fuel system icing inhibitor) is called for in many military fuels, and an electrical conductivity improver (antistatic additive) may be required to minimize fire and explosion risks due to electrostatic discharges in installations and equipment during pumping operations. Storage stability characteristics of blends of Jet A and Jet A-1 with diesel fuel are shown in Figures 77 and 78.

FIGURE 75
SULFUR CONTENT VS BLEND CONCENTRATION

FIGURE 76
SULFUR CONTENT VS BLEND CONCENTRATION

FIGURE 77
ACCEL STABILITY VS BLEND CONCENTRATION
DIESEL EMERGENCY BLEND
EXTENDER: JET A

FIGURE 78
ACCEL STABILITY VS BLEND CONCENTRATION
DIESEL EMERGENCY BLEND
EXTENDER: JET A-1

4. Contaminants

Modern fuel systems demand a fuel free from water, dirt, and other foreign contaminants. To deliver fuel in the desired condition requires stringent storage and handling procedures. Fine-particle filtration and water separation facilities generally are provided to ensure that dirt and free water contents are well below maximum levels of 1.0-mg/liter dirt and 330-ppm free water.

Another contamination problem is that of microbiological growth activity which can give rise to service troubles of various types. This problem generally can be avoided by the adoption of good housekeeping techniques, but major incidents in recent years have led to the development of several microbiological monitoring tests for aviation fuel. In one of these, fuel is filtered through a sterile membrane which is cultured subsequently for microbiological growths. Other tests employ various techniques to detect the presence of viable microbiological matter, but none of the tests has yet been standardized.

5. Density and Heat of Combustion

Density and heat of combustion are important properties of jet fuel since they control the total energy content of the fuel on a weight or volume basis or both. Specific gravity and calorific values vary somewhat according to crude source. Paraffinic fuels have a slightly lower specific gravity but higher gravimetric calorific value than those from naphthenic crudes. Naphthenic fuels have superior calorific values on a volume basis (Btu/gal). The relative importance of energy content on a weight or volume basis depends on the design and flight pattern of an aircraft which could be either weight or volume limited in its fuel load. Figures 79 through 82 present diesel/turbine fuel blend API gravity and heats of combustion for Jet A and Jet A-1 fuels.

6. Volatility

Volatility is one of the more obvious differences between kerosene and wide-cut jet fuels. The low-volatility requirements for kerosene are controlled by flash point and a small number of distillation points. Distillation and Vapor Pressure

characteristics dictate the higher volatility of wide-cut jet fuels. The overall effect of volatility control is to give a reasonable compromise between safety, combustion efficiency, and fuel availability.

Distillation points of 10, 20, 50, and 90 percent are specified in various ways to ensure that a properly balanced fuel is produced with no undue proportion of light or heavy fractions. The distillation end point excludes any heavy material which would give poor fuel vaporization and ultimately affect engine combustion performance. Figures 83 and 84 present distillation curves for diesel fuel blended with Jet A and Jet A-1.

7. Flash Point

Flash point is a guide to the fire hazard associated with the fuel. Figures 85 and 86 present flash point curves for Jet A and Jet A-1 in diesel fuel.

8. Low-Temperature Properties

Jet fuels must have acceptable freezing points and low-temperature pumpability characteristics so that adequate fuel flow to the engine is maintained during long cruise periods at high altitude.

The viscosity of fuels at low temperature is limited to ensure that adequate fuel flow and pressure are maintained under all operating conditions and that fuel injection nozzles and system controls will operate down to design temperature conditions. Viscosity can affect significantly the lubricating property of the fuel which has an influence on fuel pump service life. Figures 87 through 90 present data for pour point and viscosity for diesel blends with Jet A and Jet A-1.

9. Combustion Quality

Combustion quality is largely a function of the hydrocarbon composition of the fuel. Paraffins have excellent burning properties in contrast to those of aromatics (particularly the heavy polynuclear types): Naphthenes have intermediate combustion characteristics that are nearer to those of paraffins. Because of compositional differences, jet fuels of the same class can vary widely in burning quality as measured by smoke formation,

FIGURE 79
API GRAVITY VS BLEND CONCENTRATION
DIESEL EMERGENCY BLEND
EXTENDER: JET A

FIGURE 80
API GRAVITY VS BLEND CONCENTRATION
DIESEL EMERGENCY BLEND
EXTENDER: JET A-1

FIGURE 81
GROSS HEAT OF COMBUSTION VS BLEND CONCEN
DIESEL EMERGENCY BLEND
EXTENDER: JET A

FIGURE 82
GROSS HEAT OF COMBUSTION VS BLEND CONCEN
DIESEL EMERGENCY BLEND
EXTENDER: JET A-1

FIGURE 83
JET A-DIESEL BLEND DISTILLATION
 DIESEL EMERGENCY BLEND
 EXTENDER: JET A

FIGURE 84
JET A1 DIESEL BLEND DISTILLATION
 DIESEL EMERGENCY BLEND
 EXTENDER: JET A-1

FIGURE 85
FLASH POINT VS BLEND CONCENTRATION

FIGURE 86
FLASH POINT VS BLEND CONCENTRATION

FIGURE 87
POUR POINT VS BLEND CONCENTRATION

FIGURE 88
POUR POINT VS BLEND CONCENTRATION

FIGURE 89
VISCOSITY VS BLEND CONCENTRATION

FIGURE 90
VISCOSITY VS BLEND CONCENTRATION

carbon deposition, and flame radiation. Figures 91 and 92 show cetane number for blends of diesel fuel with Jet A and Jet A-1.

10. Smoke Point

The combustion performance of wide-cut fuels correlates well with smoke point when a fuel volatility factor is included because carbon formation tends to increase with boiling point.

11. Water Retention and Separating Properties

Because of their higher density and viscosity, jet fuels tend to retain fine particulate matter and water droplets in suspension for a much longer time than aviation gasoline.

Jet fuels also can vary considerably in their tendency to pick up and retain water droplets or to hold fine water hazes in suspension, depending on the presence of trace surface active impurities (surfactants). Some of these materials (such as sulphonic and naphthenic acids and their sodium salts) may originate from the crude source or from certain refinery treating processes. Others may be picked up by contact with other products during transportation to the airfield, particularly in multiproduct pipelines. These latter materials may be natural contaminants from other less highly refined products (for example, heating oils) or may consist of additives from motor gasolines (such as glycol-type anti-icing agents). In addition, some of the additives specified for jet fuels also have surface active properties. Examples of these are corrosion inhibitors and electrical conductivity improvers.

The presence of surfactants can also impair the performance of the water-separating equipment (filter/separators) used in fuel-handling systems to remove traces of free (undissolved) water. Very small traces of free water can affect adversely jet engine and aircraft operations in several ways. The water retention and separating properties of jet fuels have become a critical quality consideration in recent years.

12. Thermal Stability

Although the conventional (storage) stability of aviation fuel has long been defined and controlled by the existent and actual gum tests, another test is required to measure the stability of a fuel to the thermal stresses which can arise during sustained supersonic flight and in some high-subsonic applications. In high-speed flight, the fuel is subjected to considerable heat input due to kinetic heating of the airframe and also to the use of the bulk fuel as a coolant for engine oil, hydraulic and air conditioning equipment, etc. Consequently, fuel for supersonic flight must perform satisfactorily at temperatures up to about 250°C (480°F) without formation of lacquer and deposits which can adversely affect the efficiency of heat exchangers, metering devices, fuel filters, and injector nozzles. The Jet Fuel Thermal Oxidation Test (JFTOT) is a measure of these high-temperature properties. JFTOT data for Jet A and Jet A-1 blends in diesel fuel are given in Figures 93 and 94, respectively, wherein a higher number (Spun TDR) indicates greater deposition.

B. Tradeoff Charts

As mentioned previously, the chemical composition and physical properties of jet fuels make them particularly applicable as emergency extenders for diesel fuel. Figures 95 and 96 present Tradeoff Chart curves for Jet A and Jet A-1, respectively, blended with diesel fuel. As can be seen, Power Index drops off only slightly more for Jet A-1 than for Jet A, and Conservation Index increases as either jet fuel concentration is increased to 100 percent. For both fuels, this results in a Tradeoff Index curve increasing to roughly 1.8.

Figures 97 and 98 present Emissions Index data for these two jet fuels blended with diesel fuel. All gaseous emissions and smoke are less than or equal to those for neat diesel fuel except for unburned hydrocarbons, which increased to values of two to three times that of neat diesel fuel at 100 percent jet fuel concentration.

All of the above discussion and data strongly indicate that any available aviation jet fuels should be given high priority for diesel fleets when considering emergency extender applications for surface fleets.

FIGURE 91
CETANE NUMBER VS BLEND CONCENTRATION

FIGURE 92
CETANE NUMBER VS BLEND CONCENTRATION

FIGURE 93

JFTOT RATING VS BLEND CONCENTRATION

DIESEL EMERGENCY BLEND
EXTENDER: JET A

FIGURE 94

JFTOT RATING VS BLEND CONCENTRATION

DIESEL EMERGENCY BLEND
EXTENDER: JET A-1

FIGURE 95
TRADEOFF CHART
DIESEL EMERGENCY BLEND
EXTENDER: JET A

FIGURE 96
TRADEOFF CHART
DIESEL EMERGENCY BLEND
EXTENDER: JET A-1

FIGURE 97 EMISSIONS INDEX

EMERGENCY DIESEL BLEND
EXTENDER: JET A

FIGURE 98 EMISSIONS INDEX

EMERGENCY DIESEL BLEND
EXTENDER: JET A-1

VI. KEROSENE

Following the discovery of oil in 1859, kerosene became the major petroleum product and was used, initially, for illumination and, subsequently, for heating. While modern technology has diminished the importance of kerosene, it is still utilized as a primary source of light in some lesser developed countries and for standby or emergency lighting in the more advanced areas of the world. Because it is inexpensive, portable, and flexible, kerosene also is used for domestic space and water heating, refrigeration, heating of garages and greenhouses, incubation of chicken brooders, and cooking. The discussion of kerosene in this section will focus on its two primary uses—illumination and heating.

Kerosene is obtained by fractional distillation of crude oil between approximately 149°C (300°F) and 302°C (575°F) and constitutes a potential 5 to 20 percent volume yield, depending on the crude source. (In the United States, less than 2 percent of the crude oil is utilized for kerosene.) To decrease smoking, paraffinic stocks are used normally in the manufacture of kerosene for lighting and heating. For the same reason, aromatic stocks and cracked components are avoided.

When low-sulfur paraffinic crudes are fractionated to yield the proper boiling range cut for kerosene, only a drying operation may be required before shipment. Usually, however, some objectionable odors (mercaptans) are present, and these are removed by caustic washing or converted to odorless compounds by sweetening processes.

Kerosene from naphthenic or high-sulfur crudes requires hydrotreating, acid treatment and water wash, or extraction with a solvent and caustic wash and clay brightening to remove undesirable aromatics or sulfur compounds. Following treatment, the kerosene streams are blended to meet specifications, and the finished product is ready for marketing.

A. Physical and Chemical Properties

Much of all of the discursive material included in **Section IV. Solvents** applies to kerosene. Figures 99 through 108 illustrate the same gamut of properties as for the naphtha solvents in that section, except for kerosene blended with gasoline or diesel fuel.

Figures 109 and 110 present Cetane and Octane curves for gasoline/kerosene and diesel/kerosene blends, respectively.

B. Tradeoff Charts

Figures 111 and 112 present Tradeoff Charts for kerosene blended with gasoline and diesel fuel, respectively. When used as a gasoline emergency extender, Power Index drops off gradually to about 60 percent of that of neat gasoline at 50 percent kerosene concentration. The gradual increase in Conservation Index results in an overall Tradeoff Index curve which remains essentially constant at that equivalent to neat gasoline up to almost 40 percent kerosene concentration.

When kerosene is used as a diesel extender, corresponding power dropoff is not quite as sharp with a Power Index of about 0.85 at 100 percent volume kerosene. Linear increase of Conservation Index results in a corresponding increase in the Tradeoff Index curve to about 1.8 at 100 percent kerosene concentration.

Figure 113 presents Emissions Index data for kerosene used as a diesel extender. All gaseous emissions and smoke remain essentially constant or drop off slightly (for CO), again excepting unburned hydrocarbons which increase to about double that of neat diesel fuel at 100 percent volume kerosene concentration.

It would thus appear that kerosene can effectively be used as an emergency extender for either gasoline (in concentrations up to about 40 percent) or diesel fuel (to much higher concentrations, perhaps even 100 percent).

FIGURE 99
API GRAVITY VS BLEND CONCENTRATION

FIGURE 100
VISCOSITY VS BLEND CONCENTRATION

FIGURE 101
FLASH POINT VS BLEND CONCENTRATION
 DIESEL EMERGENCY BLEND
 EXTENDER: KEROSENE

FIGURE 102
POUR POINT VS BLEND CONCENTRATION
 DIESEL EMERGENCY BLEND
 EXTENDER: KEROSENE

FIGURE 103
GROSS HEAT OF COMBUSTION VS BLEND CONCEN
 DIESEL EMERGENCY BLEND
 EXTENDER: KEROSENE

FIGURE 104
ACCEL STABILITY VS BLEND CONCENTRATION
 DIESEL EMERGENCY BLEND
 EXTENDER: KEROSENE

FIGURE 105
SULFUR CONTENT VS BLEND CONCENTRATION
 DIESEL EMERGENCY BLEND
 EXTENDER: KEROSENE

FIGURE 106
API GRAVITY VS BLEND CONCENTRATION
 GASOLINE EMERGENCY BLEND
 EXTENDER: KEROSENE

FIGURE 107
RVP VS BLEND CONCENTRATION

FIGURE 108
KEROSENE-GASOLINE BLEND DISTILLATION

FIGURE 109
CETANE NUMBER VS BLEND CONCENTRATION

FIGURE 110
OCTANE NUMBER VS BLEND CONCENTRATION

FIGURE 111
TRADEOFF CHART
GASOLINE EMERGENCY BLEND
EXTENDER: KEROSENE

FIGURE 112
TRADEOFF CHART
DIESEL EMERGENCY BLEND
EXTENDER: KEROSENE

FIGURE 113
EMISSIONS INDEX

EMERGENCY DIESEL BLEND
EXTENDER: KEROSENE

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VII. HEATING OILS

Although most petroleum product can be utilized as fuels, the term "fuel oil," if used without qualification, may be interpreted differently in various countries. For example, in Europe fuel oil generally is associated with the black, viscous, residual material (see Section VIII following) which remains as the result of refinery distillation of crude oil either alone or in a blend with lighter components. This fuel is used for steam generation, for large, slow-speed diesel engine operation and industrial heating and processing. In the United States, the term "fuel oil" is applied to both the residual-type material and the distillate-type products such as domestic heating oil, kerosene, and burner fuel oils.

Because of the wide variety of petroleum fuel oils, the arbitrary divisions or classifications which have become widely accepted in industry are based more on their application than on their chemical or physical properties. Thus, it is not uncommon to find large variations in properties among petroleum products sold on the market for the same purpose. However, two broad classifications are generally recognized: (1) "distillate" fuel oils and (2) "residual" fuel oils. The latter are often referred to as heavy fuel oils and may contain cutter stock or distillates. These are covered in a subsequent section.

Distillate fuel oils are petroleum fractions that have been vaporized and condensed. They are produced in the refinery by a distillation process in which petroleum is separated into its fractions according to their boiling range. Distillate fuel oils may be produced not only directly from crude oil, that is, "straight-run," but also from subsequent refinery processes such as thermal or catalytic cracking. Domestic heating oils and kerosene are examples of distillate fuel oils.

Domestic heating oils are distillate products. Their approximate boiling range generally is from 160°C (320°F) to 343°C (650°F). They can include components from three sources: (1) virgin stocks cut directly from crude, (2) oils manufactured by catalytic cracking of heavier stocks, and (3) thermally cracked streams. The percentages of these components blended into the heating oil pool will vary considerably among individual refineries and

between various countries. For example, domestic heating oil in most areas outside North America normally consists of straight-run gas oil from the distillation of the crude; in the United States, the straight-run gas oil fraction is usually blended with the appropriate boiling-range material from catalytic cracking processing.

With few exceptions, the components cut to the proper boiling range for domestic heating oil require some chemical treatment (for example, additional treatment may be required to remove or convert mercaptans to nonodorous disulfides). Following the chemical treatment, the oils usually are washed with water to remove all traces of the treating residues. As a finishing step, the oil is dried by clay filtration or coalescing.

Domestic heating oils derived from heavier catalytic and thermal stocks may require more severe treatment to remove olefins and other unstable compounds. This is accomplished commonly by catalytic hydrogen treating.

A. Physical and Chemical Properties

1. API Gravity and Heating Value

API gravity of a fuel oil is based on an arbitrary hydrometer scale which is related to specific gravity in accordance with the formula,

$$\text{API gravity, deg} = \frac{141.5}{\text{sp gr at } 60/60^{\circ}\text{F}} - 131.5$$

This scale generally is used for most transactions in the United States as well as in refinery practice. API gravity for a typical heater oil blended with diesel fuel is shown in Figure 114.

On a weight basis, the heating value of petroleum fuels decreases with increasing specific gravity (decreasing API gravity), since the weight ratio of carbon (low-heating value) to hydrogen (high-heating value) increases as the specific gravity increases. On a volume basis, the increasing specific gravity more than compensates for the decreasing heating value per unit weight, with the net result that fuels having high-specific gravity yield more heat energy per unit volume than those of low-specific gravity. Typical heating values

FIGURE 114

API GRAVITY VS BLEND CONCENTRATION

DIESEL EMERGENCY BLEND
EXTENDER: NO. 4 FUEL OIL

(gross heat of combustion) for heater oil/diesel blends are given in Figure 115.

2. Flash Point

The flash point of a fuel is a measure of the temperature to which the fuel must be heated to produce an ignitable vapor-air mixture above the liquid fuel when exposed to an open flame. (The "fire point" of a fuel is defined as the temperature at which an oil in an open container gives off vapor at a sufficient rate to continue to burn after a flame is applied.) Flash point is normally included in industry specifications for fuel oil.

Flash point is used primarily as an index of fire hazards. As an example, the U. S. Department of Transportation shipping regulations use flash point as the criterion to establish labeling requirements. Consequently, most industry specifications or classifications place limits on the flash point to ensure compliance with fire regulations, insurance, and legal requirements.

A reduction in the normal flash point of an oil may indicate contamination by more volatile products such as gasoline. Therefore, determination of flash point can be useful in detecting such contamination and thereby avoiding serious safety hazards.

Depending upon the apparatus and method of test used, the determined flash point of a fuel may vary. In all cases, however, it is an empirical value because the conditions of the test do not match all possible conditions of commercial handling of the product. Flash point characteristics of diesel/heater oil blends are shown in Figure 116.

3. Viscosity

The viscosity of a fluid is a measure of its resistance to flow and is expressed in various units depending upon the equipment and method used for determination. These units include Saybolt Universal seconds, Saybolt Furol seconds, and kinematic viscosity in centistokes.

Viscosity is one of the more important heating oil characteristics. It is indicative of the rate at which the oil will flow in fuel systems and the ease with which it can be atomized in a given type of engine. Since the viscosities of heavier fuel oils are high, this property tends to be particularly

relevant to its handling and utilization characteristics. The viscosity of a heavy fuel decreases rapidly with increasing temperature. For this reason, heavy fuels can be handled easily and atomized properly by the application of preheat. If no preheating facilities are available, lighter or less viscous oils must be used, and, if the preheating equipment is inadequate, it may be necessary to use a lighter oil during cold weather.

Viscosity also affects the output or delivery of a spray nozzle and the angle of spray. With improper viscosity, poor atomization can result in carbonization of the tip, carbon deposition, or other conditions leading to poor combustion.

Viscosity of heater oil/diesel fuel blends is shown in Figure 117. As can be seen, there is little change since the lighter heating oils often have viscosity characteristics almost identical to diesel fuels.

4. Pour Point

Pour point is defined as the lowest temperature at which the oil will just flow under standard test conditions. Anticipated storage conditions and fuel application are usually the primary considerations in the establishment of pour-point limits. (Storage of the higher viscosity fuel oils in heated tanks will permit higher pour points than would otherwise be possible.)

While the failure to flow at the pour point normally is attributed to the separation of wax from the fuel, it also can be due to the effect of viscosity in the case of very viscous oils. In addition, pour points, particularly in the case of residual fuels, may be influenced by the previous thermal history of the oils. As an example, any loosely knit wax structure built up on cooling of the oil can be normally broken by the application of relatively little pressure. Thus, the usefulness of the pour-point test in relation to residual fuel oils is open to question, and the tendency to regard pour point as the limiting temperature at which a fuel will flow can be misleading unless correlation is made with low-temperature viscosity. Typical pour point characteristics for heating oil/diesel fuel blends are shown in Figure 118.

FIGURE 115
GROSS HEAT OF COMBUSTION VS BLEND CONCEN
 DIESEL EMERGENCY BLEND
 EXTENDER:NO.4 FUEL OIL

FIGURE 116
FLASH POINT VS BLEND CONCENTRATION
 DIESEL EMERGENCY BLEND
 EXTENDER:NO.4 FUEL OIL

FIGURE 117
VISCOSITY VS BLEND CONCENTRATION

FIGURE 118
FOUR POINT VS BLEND CONCENTRATION

5. Cloud Point

Distillate fuels, especially, begin to form wax crystals and become cloudy in appearance as they are cooled towards the pour point. The temperature at which this begins to occur is called the cloud point. Cloud points often occur at 4° to 5°C (7° to 9°F) above the pour point, and temperature differentials of 8°C (15°F) are not uncommon. Basically, the temperature differential between cloud and pour point depends upon the nature of the fuel components, but the use of wax crystal modifiers or pour depressants tends to accentuate these differences.

As the temperature continues to decrease below the cloud point, the formation of wax crystals is accelerated. These crystals clog fuel filters and lines and thus reduce the supply of fuel to the burner. Since the cloud point is at a higher temperature than the pour point, it can be considered even more important than the pour point in establishing distillate fuel oil specifications for cold weather usage.

6. Sulfur Content

Fuel oils contain varying amounts of sulfur depending on the crude source, refining processes, and fuel grade. The high-boiling range fractions and the residual fuels usually contain higher amounts of sulfur which is generally regarded as an undesirable constituent because of its potential to create corrosion and pollution problems.

Combustion of sulfur-containing fuel oils produces sulfur oxides which have been identified as atmospheric pollutants. Figure 119 shows sulfur content for diesel/heating oil blends.

7. Distillation

Distillation characteristics reflect the amount of liquid vaporized and subsequently condensed as the temperature of the fuel in the distillation flask is raised at a prescribed rate. A record is made of the volume of distillate collected at specified temperatures or, conversely, the temperature at each increment of volume distilled (usually 10-percent increments). The temperature at which the first drop of condensate is collected is called

the "initial boiling point." The "end point" usually is the highest temperature recorded as the bottom of the flask becomes dry. If oils are heated above 370°C (700°F), they tend to crack and give unreliable results. The test usually is stopped when this point is reached. Some distillations may be run under a high (10-mm) vacuum in order to avoid cracking, ASTM Test for Distillation of Petroleum Products at Reduced Pressure (D 1160). Under these conditions, heavy fuel oils may be distilled up to temperatures equivalent to 510°C (950°F) at atmospheric pressure. However, distillation tests generally are not applied to the heavy fuel oils.

The distillation test is significant for the distillate fuels. When engines are operated with distillate fuel oils, it is essential that the fuels contain sufficient volatile components to ensure that ignition can be accomplished easily. Figure 120 shows distillation curves for diesel/heating oil blends.

8. Stability

In essence, stability can be defined as the capability of a fuel to resist change in composition. Instability is manifested by a change in color, the formation of gummy materials or insoluble elements, waxy sludge or asphaltic deposition on the bottom of storage tanks, etc.

The storage stability of fuel oils may be influenced by many factors. Among these are crude oil origin, hydrocarbon composition, and refinery treatment. Fuels containing unsaturated hydrocarbons and catalytically cracked components are inherently less stable chemically and have a greater tendency to form sediment on aging than the straight-run fuels. The presence of reactive compounds of sulfur, nitrogen, and oxygen may also contribute to a fuel oil instability.

Much speculation exists regarding the mechanism of sludge deposition. It may be a consequence of such factors as oxidation, polymerization, and the method of production of the fuel which can result in the formation of insoluble compounds that eventually settle to the tank bottoms and form sludge. The instance of such deposition in light residual fuel oils used in large heating installations may be reflected by clogging of external cold filters, blockage or restriction of pipelines, and combustion difficulties.

FIGURE 119
SULFUR CONTENT VS BLEND CONCENTRATION

FIGURE 120
NO. 4 FUEL OIL-DIESEL BLEND DISTILLATION

Asphaltic deposition may result from the mixing of fuels of different origin and treatment, each of which may be perfectly satisfactory when used alone. Such fuels are said to be incompatible. Straight-run fuels from the same crude oil normally are stable and mutually compatible. Fuels produced from the thermal cracking and visbreaking operations may be stable by themselves but can be unstable or incompatible if blended with straight-run fuels and vice versa.

Instability can be a serious problem that ranges in severity from simple customer dissatisfaction with an off-color fuel to a cause of serious equipment malfunctions. Therefore, test procedures are necessary to predict fuel stability and ensure a satisfactory level of performance by the fuel oil. Accelerated oxidation stability of a No. 4 fuel oil blended in diesel fuel is illustrated in Figure 121.

9. Cetane Number

Figure 122 presents cetane number versus blend concentration for a typical No. 4 fuel oil blended with diesel fuel. Since this fuel oil or heater oil is so close in character to diesel fuel in many respects, its cetane number is accordingly virtually identical to neat diesel fuel.

B. Tradeoff Charts

Figure 123 presents Tradeoff curves for diesel/No. 4 fuel oil blends. Because of the above-mentioned flat cetane characteristic throughout the range, Power Index curve is essentially constant at neat diesel fuel values. This results in Conservation Index curve going linearly from zero to 1.0 at 100 percent No. 4 fuel oil concentration and the overall Tradeoff Index correspondingly increasing in a parallel manner. The implication is that many such light fuel oils would make excellent candidates as emergency fuels for *diesel* application. It should again be cautioned that fuel oil composition and character will vary and that *operation with higher concentrations of fuel oil in diesel fuel may not necessarily result in such excellent performance.*

Not surprisingly, emissions characteristics as shown in Figure 124 are virtually identical for all blends of diesel and No. 4 fuel oil. Unburned hydrocarbons do increase to values nearly double those of neat diesel fuel for 100 percent No. 4 concentration. This is quite likely due to some of the higher molecular weight constituents of the fuel oil which do not completely combust in relatively high-speed transportation diesel engine.

FIGURE 121
ACCEL STABILITY VS BLEND CONCENTRATION

FIGURE 122
CETANE NUMBER VS BLEND CONCENTRATION

FIGURE 123 TRADEOFF CHART

DIESEL EMERGENCY BLEND
EXTENDER:NO.4 FUEL OIL

FIGURE 124 EMISSIONS INDEX

EMERGENCY DIESEL BLEND
EXTENDER:NO.4 FUEL OIL

VIII. RESIDUAL FUELS

Residual fuel oils have a flash point of 60°C (140°F) and viscosities that generally vary between 30 and 300 SFS at 50°C (122°F). The oil viscosity required to obtain satisfactory atomization varies according to the type of burner used and is approximately 40 SFS or 80 cSt for steam atomizing burners and 180 and 200 SUS or 39 to 43 cSt min for mechanical atomizing burners. Therefore, it is necessary to heat the oil in order to achieve the required viscosity reduction. This is done in a heat exchanger, consisting of a tube assembly through which the oil flows, placed inside a shell containing the heating medium. Usually the medium, at a pressure of 20 psig (1.406 kg/cm²) or less, is steam. Generally, the heating is done in two steps. The first step heats the oil as it is withdrawn from the storage tank, or, in some cases, the whole tank of oil is heated to about 37.8°C (100°F) so that its viscosity is within the pumping range of 400 to 500 SFS or 850 to 1000 cSt. In the second step, transfer pumps deliver the oil from storage to the burner heating and pumping equipment at which point it is raised to the required temperature and pressure for atomization.

Residual or heavy fuel oils are composed wholly or in part of undistilled petroleum fractions from crude distillation (atmospheric or vacuum), visbreaking, or other refinery operations. The various grades of heavy fuel oils generally are produced to meet definite specifications in order to assure suitability for their intended purpose. Residual fuel oils are classified usually by viscosity in contrast with distillate oils which are normally defined by boiling range.

A. Physical and Chemical Properties

1. API Gravity and Heating Value

These properties have been discussed and defined in previous sections. It is important to contrast the gravity and heating value characteristics of diesel fuel/residual fuel blends as compared to blends of diesel fuel with heating oil discussed in Section VII. Figures 125 and 126 present API gravity and gross heat of combustion characteristics for diesel/residual fuel blends. Note that both

quantities decrease with increasing residual fuel concentration as contrasted with mild increases for these characteristics when diesel fuel was blended with the No. 4 heating fuel oil in Section VII.

2. Viscosity

Figure 127 presents viscosity versus blend concentration for diesel/residual fuel blends and must again be contrasted with the corresponding data in Section VII for heating oils. Note the flat characteristic in Figure 117 for heater oils while Figure 127 reflects a dramatic increase in viscosity above about 50 percent heating oil in diesel fuel. At lower temperatures, this can likely present an insurmountable problem as regards pumpability, spray patterns, etc., and blends beyond this concentration are not recommended.

3. Pour Point

Figure 128 presents pour point versus blend concentration for blends of No. 6 fuel oil with diesel fuel. There is an abrupt increase in pour point at the 50 percent concentration point indicative of the much heavier and higher melting characteristics of residual fuels.

4. Sulfur Content

Figure 129 presents sulfur content for diesel/residual fuel blends. In contrast to the corresponding curve for heating oils in the previous section, sulfur content goes up with increasing residual fuel concentration since such fuels characteristically have higher concentrations than diesel fuel.

5. Ash Content

The total ash content in different residual fuels is normally similar and less than 0.2 percent by weight. In composition, the ash will vary among residual fuels, largely as a function of their crude oil antecedents, but metallic compounds such as sodium, vanadium, nickel, iron, and silica generally are present.

FIGURE 125
API GRAVITY VS BLEND CONCENTRATION

FIGURE 126
GROSS HEAT OF COMBUSTION VS BLEND CONCEN

FIGURE 127
VISCOSITY VS BLEND CONCENTRATION

FIGURE 128
POUR POINT VS BLEND CONCENTRATION

FIGURE 129
SULFUR CONTENT VS BLEND CONCENTRATION

Depending on the use of the fuel, ash composition has a considerable bearing on whether or not detrimental effects will occur. Ash in heavy fuel oils can cause slagging or deposits and high-temperature corrosion. Since most of the ash in heavy fuels occurs naturally, it is usually difficult for the refiner to remove it economically. Therefore, methods have been developed for counteracting the affects of ash. These include the use of additives, modification in equipment design, and the application of fuel-processing methods such as water washing.

6. Carbon Residue

The carbon residue of burner fuels serves as a rough approximation of the tendency of the fuel to form deposits. Little is known concerning the relationship of carbon residue to residual fuel oil performance. This is particularly true in the application of residual fuels as emergency diesel extenders. *Laboratory experiments have indicated strongly that this can contribute to spark plug fouling in gasoline engines; for this reason, application of heavier residual heater fuels as spark ignition emergency extenders is not recommended,* rather that diesel application alone be considered. Even here, fuel injector fouling and combustion chamber deposits should be monitored closely by fleet operators using diesel/residual fuel blends.

7. Cetane Number

Figure 130 presents cetane number of residual fuel/diesel fuel blends. Note that there is

immediate tendency to decrease cetane number as concentration of the residual fuel varies from zero to 25 percent at which point there is an even more abrupt decrease in the rate of cetane number drop-off. This is in contrast to the heating oil characteristics for diesel blends shown in the previous section wherein there was virtually no effect upon cetane number as heating oil concentration was increased. For this reason residual fuel concentrations in diesel fuel should be initially restricted to conservative values.

B. Tradeoff Charts

Figures 131 and 132 present Tradeoff Charts for typical residual fuel oils (No. 5 burner oil and No. 6 fuel oil respectively). Power Index is essentially unaffected over the entire range of concentrations up to about 60 percent where a mild dropoff can be observed. Correspondingly, Conservation Index increases linearly for both residual fuel types with overall Tradeoff Index characteristics being virtually identical for both. The implication here would be that concentrations of these classes of burner fuels in diesel fuel could be tolerated up to as much as 60 percent.

Figures 133 and 134 present Emissions Index characteristics for these same two residual fuels with smoke and oxides of nitrogen essentially unaffected up to 80 percent concentration. Carbon monoxide and unburned hydrocarbons increased considerably as concentration is increased for both residual fuels reaching values as high as two or three times that of neat diesel fuel at 80 percent concentration.

FIGURE 130
CETANE NUMBER VS BLEND CONCENTRATION

FIGURE 131
TRADEOFF CHART

FIGURE 132
TRADEOFF CHART
DIESEL EMERGENCY BLEND
EXTENDER:NO.6 FUEL OIL

FIGURE 133
EMISSIONS INDEX
EMERGENCY DIESEL BLEND
EXTENDER:NO.5 BURNER OIL

FIGURE 134
EMISSIONS INDEX

EMERGENCY DIESEL BLEND
EXTENDER: NO. 6 FUEL OIL

IX. CRUDE OILS

While crude oil is not typically classified as a fuel oil, attention has begun to focus on its potential as a power generation fuel. Stimulated by the energy shortage, utilities have burned crude oil under power station boilers and as fuel for gas turbines that drive standby generators. In addition, considerable laboratory work has been accomplished burning neat crude oils in automotive diesel engines. The results of much of this work have reflected the high degree of fuel-tolerance of the diesel engine. Specifications for crude oil as power generation fuels have not been established; there are known critical factors that must be considered. *Since crude oils normally have relatively low flash points, their use has associated fire hazards and explosive aspects.* This fact necessitates the use of proper storage and handling facilities. These facilities must be explosion-proof, vapor-proof, and vapor-retaining. Furthermore, the crude oil must be fluid or pumpable, and it must have low ash and sulfur contents to meet emissions standards that satisfy environmental regulations.

A. Physical and Chemical Properties

There is no overall or generally accepted method of classifying crude oils. What is termed an *ultimate analysis* gives the composition as a percentage of the principal elements—carbon, hydrogen, nitrogen, oxygen, and sulfur. A *chemical analysis* gives the composition in percentages of paraffinic, naphthenic, and aromatic-type compounds. These types of analyses are valuable in formulating a general idea of the usefulness of the crude in producing various refinery products, but the analyses give little indication of the quantity of the various products that can be produced.

Since many of the properties of crude oils change with change of temperature and pressure or length of exposure to atmospheric environment, proper sampling is very important. If the dissolved light hydrocarbons, such as methane, ethane, propane, and butane, are permitted to escape by exposure to the atmosphere, qualities such as gravity, vapor pressure, octane number, and distillation tests will change.

In general, crude oil properties can be divided into two groups:

- (1) Those properties such as pour point, viscosity, fuel cleanliness, and volatility which are important for short-term operational effects, and
- (2) Those properties such as sulfur, residuum content, asphalt, and ash whose effects manifest during longer-term operation.

Short-term crude oil properties are those properties which either allow or prevent the direct use of crude oil regardless of time and are mainly related to fuel handling and delivery characteristics. Assuming that a crude oil has satisfactory short-term properties, the long-term properties will determine the length of trouble-free operation that can be expected.

Because crudes inherently contain the heavy residual materials as discussed in the preceding section, they make *most likely candidates for diesel emergency extenders and highly unlikely candidates for gasoline extenders.* They are thus presented as possible diesel supplements.

The following discussion of physical and chemical properties for crude oils is restricted to only a few domestic crudes which illustrate the wide variety of properties possible. Table 6 presents properties of a number of such crudes.

1. Gravity

API gravity has been previously described and defined. Figure 135 presents gravity versus blend concentration for typical crude oils blended with specification quality diesel fuel. Obviously, it is possible to tailor a blend depending upon the characteristics of the crude oil used to a wide variety of desired gravities or densities.

2. Sulfur

The sulfur content of crude oil is an important quality because the complexity and expense of the refining operation increases tremendously as the sulfur content of the crude increases.

TABLE 6. PHYSICAL AND CHEMICAL PROPERTIES FOR SELECTED CRUDES

Oilfield State	Conroe TX	N. Alazan TX	KMA TX	TXL TX	Eugene Is. LA	Califou Is. LA	Venice LA	Greeley CA	Wilmington CA	Inglewood CA	Red Wash UT	ASTM Method	Reference Diesel DF-2
<i>Physical Properties</i>													
Specific gravity	0.84	0.82	0.82	0.84	0.82	0.84	0.85	0.90	0.96	0.93	0.91	D 1298	0.86
(° API)	(37.2)	(41.3)	(41.2)	(37.2)	(40.8)	(36.5)	(35.9)	(26.4)	(15.4)	(21.4)	(24.1)	D 287	(33.2)
Sulfur, wt %	0.05	0.06	0.20	0.43	0.07	0.13	0.17	0.67	1.73	1.95	0.12	D 129	0.42
Viscosity, cSt, 37.8°C	2.2	2.0	2.6	4.6	3.1	4.6	4.6	24.5	397	41.2	89.2	D 445	3.2
Pour point, °C	-12	-25	-34	-18	-4	2	-12	-1	-15	-37	32	D 97	-8
Flash point, °C	-3	-6	-8	2	-4	0	-9	28	99	43	32	D 92	85
Copper corrosion	1A	1A	3-a	1-A	1-A	1-A	1-A	1-A	—	—	—	D 130	1A
<i>GC BP Distribution</i>													
10% Recovery to °C	122	112	97	97	150	127	131	174	242	177	222	242	363
30% Recovery to °C	202	189	195	207	228	223	232	293	291	386		259	463
50% Recovery to °C	266	244	301	319	283	303	312	410	400	496		271	568
70% Recovery to °C	324	293	236	456	356	380	420	603	510	610		286	—
90% Recovery to °C	454	443	—	—	535	496	604	—	—	—		317	—
Estimated asphalt, wt %	2	2	7	8	1	8	6	26	41	31	14	—	—
Residuum, % (BP > 427°C)	13	11	31	34	19	21	29	48	58	45	64	—	—
Heat of combustion (gross), MJ/kg	48.4	46.2 ^c	46.2 ^b	45.9 ^b	45.6 ^b	45.8 ^b	46.1 ^b	45.0 ^b	—	43.2	—	D 240	45.5 ^b
Cetane number	45	44	42 ^c	46 ^c	51	47	46	39	21	28	27	D 613	47 ^b
Water, ppm	500	300	300	500	500	5800	1800	1100	—	2700	—	D 1744	—
Solids on 5X10 ⁻⁴ cm filter before filtered, mg/100 ml	104	15	42	20	7	210	26	—	114	88	115	—	—
Ash, wt %	0.003	0.002	0.004	0.005	0.002	0.001	0.009	0.035	—	—	—	D 482	0.006
<i>Elemental Analysis</i>													
Ni, ppm	<5	<5	<5	5	<5	<5	<5	40	65	43	20	D 2788	—
V, ppm	<5	<5	<5	7	<5	<5	<5	30	40	52	<40		

^aDark tarnish.^bCalculated value.^cVapor problems encountered.

FIGURE 135
API GRAVITY VS BLEND CONCENTRATION

Sulfur content varies from practically zero to as high as several percent in some crudes. This is illustrated in Figure 136 wherein the same representative crudes having a wide variety of sulfur content have been blended with specification quality diesel fuel.

3. Salt Content

The salt content of crudes also varies over a rather wide range which results principally from two factors: production practices in the oil fields and the handling of the crude in the tankers bringing it to the refinery. Salt content can be of great importance in utilization in a transportation diesel engine since certain metallic salts will break down and liberate corrosive acids in the combustion chamber.

4. Water and Sediment

Sediment normally exists in crude oil as extremely fine, well dispersed solids. Solids that originate in the reservoir from which the crudes came or in drilling fluids used to drill the wells may take the form of sand, clay, shale, or rock particles. Other sediments such as scale can be picked up from tubing, pipe, tanks, and other production and transportation equipment. Water may appear in the crude as droplets or as emulsion and contain chemical salts and other harmful substances. Prior to use of crudes as emergency extender fuels, filtration and other means to remove water should be considered.

5. Viscosity and Pour Point

Figure 137 presents typical viscosity variation for several representative crudes blended with specification diesel fuel. Obviously, blending of select crudes can have little or no effect on viscosity or can have radical effect, rendering them inapplicable as emergency extender, particularly in low temperature environments.

Figure 138 presents corresponding pour point curves, indicating much the same phenomena with pour point increasing for certain of the crudes beyond 25 percent concentration.

6. Metallic Contaminants

Metallic trace components such as iron, sodium, nickel, vanadium, lead, and arsenic have an adverse affect on refining or processing operations. These materials are catalyst poisons and some of them do additional harm through corrosive reaction and abrasion.

7. Flash Point

Figure 139 illustrates the wide variety of flash point characteristics for the several domestic crudes blended with specification diesel fuel. As mentioned previously in this section, *this is probably the single most critical safety hazard aspect of the use of crudes as emergency extenders*, and fleet operators employing crude oils should proceed accordingly.

8. Cetane Number

Figure 140 presents cetane number as a function of blend concentration in specification diesel fuel for the four domestic crudes used for illustration throughout this section. If cetane history of a specific crude is not already known, it would be virtually imperative that such information be obtained prior to using the crude as a diesel emergency extender in any sizable concentration. Such determinations can be made relatively inexpensively at any of a number of established engine test laboratories in the United States.

B. Tradeoff Charts

Figure 141 presents an illustrative Tradeoff Chart for one of the four crudes used for illustration in this section (South Texas Sour Crude).^{*} Power Index is virtually constant throughout the entire range of neat diesel fuel to neat sour crude. Note from the preceding curve on cetane number that this crude has a reasonably high cetane number as compared to neat diesel fuel. Obviously, this crude would make an excellent emergency candidate if it does not possess other adverse properties. *Generalization is impossible for crudes and each must be considered individually for emergency fuel extender application.* Nevertheless, crude oils used as diesel extenders show excellent promise if employed properly with a previous knowledge of their physical and chemical characteristics.

^{*}Used in Section I for explaining chart interpretation.

FIGURE 136
SULFUR CONTENT VS BLEND CONCENTRATION
 DIESEL EMERGENCY BLEND
 EXTENDER: CRUDE OIL

FIGURE 137
VISCOSITY VS BLEND CONCENTRATION
 DIESEL EMERGENCY BLEND
 EXTENDER: CRUDE OIL

FIGURE 138
POUR POINT VS BLEND CONCENTRATION

FIGURE 139
FLASH POINT VS BLEND CONCENTRATION

FIGURE 140
CETANE NUMBER VS BLEND CONCENTRATION

DIESEL EMERGENCY BLEND
EXTENDER: CRUDE OIL

FIGURE 141
TRADEOFF CHART

DIESEL EMERGENCY BLEND
EXTENDER: SOUTH TEXAS SOUR CRUDE

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X. VEGETABLE OILS

Vegetable oils as automotive fuels lend themselves particularly to applications in diesel engines. Research and engine testing in this area dates from about 1930 and has principally been limited to nations having little or no domestic petroleum reserves while having extensive agricultural industries. An excellent illustration of application of vegetable oils during periods of extreme fuel shortage occurred in World War II in India when, in 1942, the Department of Scientific and Industrial Research Bureau of India issued a report on the use of vegetable oils as fuels.*

Typical vegetable oils can be derived from such materials as the following:

- Castor
- Grape Seed
- Maize
- Pumpkin Seed
- Beechnut
- Sunflower
- Soybean
- Peanut
- Corn

Availability of such materials in quantities to satisfy even emergency fleet appetites is questionable, but limited data have been included in this section since vegetable oils may in fact be available on a highly localized basis. Some selected properties of vegetable oils are given in Tables 7 and 8.

Typical cetane number versus blend concentration for four such vegetable oils blended with

diesel fuel are given in Figures 142 through 145. Note that, for peanut oil and soybean oil, cetane numbers of 40 or above are sustained either to 100 percent or at least to very high concentrations. Sunflower and corn oil showed decreasing cetane number with increasing vegetable oil concentration down to values in the low to mid-thirties. Even at these lower values, satisfactory operation of diesel engines in emergency situations can be anticipated.

Since vegetable oils are derived from seed materials, there will be several properties which contrast such liquids from the relatively pure petroleum derived fuels. Particulate matter resulting from the seed processing will be one of these as will potential corrosion problems resulting from relatively high acidity of some vegetable oils. Such corrosion is expected to be restricted to combustion chamber areas.

Since vegetable oils typically have lower calorific values as compared to petroleum diesel fuels, poorer specific fuel consumption can be anticipated; this fuel penalty, if any, is not anticipated to be very large. Experimental data and conclusions on the operation of diesel engines with a wide variety of vegetable oils vary tremendously. *Nevertheless, most data reflect that vegetable oils are practical fuels for use in high-speed diesel engines without any important alterations in engine running conditions being required.* At this time, considerable interest is being expressed by the railroad industry in application to larger lower-speed diesel engines.

*Chowhury, D.H., "Indian Vegetable Oils as Fuels for Diesel Engines," Bulletin No. 19, 1942.

TABLE 7. VEGETABLE OIL COMPOSITION AND PROPERTIES*

	Corn Oil	Cottonseed Oil	Olive Oil	Peanut Oil	Safflower Oil	Sesame Oil	Soybean Oil	Sunflower Oil
Fatty-acid Components	10	25	11	18	8	14	15	
Saturated, g/100g	28	21	76	47	15	38	20	
Olefin (oleic), g/100g	53	50	7	29	72	42	52	
Myristic (C ₁₄), %	0.1-1.7							
Palmitic (C ₁₆), %	8-12		9.4	8.3	6.4		14	6.4
Stearic (C ₁₈), %	2.5-4.5		2.0	3.1	3.1			1.3
C ₁₆ Olefin, %	0.2-1.6							
Oleic (C ₁₈), %	19-49		83.5	56	13.4		26	21.3
Linoleic (C ₁₈), %	34-62		4.0	26	76.6-79		49	66.2
Linolenic (C ₁₈), %							11	
Arachidic (C ₂₀), %			0.9	2.4	0.2			4.0
Behenic (C ₂₂), %								0.8
Specific Gravity	0.916-0.912	0.915-0.921	0.909-0.915	0.921-0.922	0.916-0.920	0.916-0.922	0.915-0.919	
Melting Point, °C	-18-10	-5-0	3-5	-5	—	-5	-10-16	-18
Flash Point, °C	321	—	225	283	—	—	282	—
Saponification No.	187-193	190-198	187-196	188-195	188-194	188-193	189-195	188-194
Iodine No.	109-133	105-114	79-90	84-102	140-150	103-122	127-138	125-136
Index of Refraction								
n _D ²⁵	1.470-1.474	—	1.466-1.468	1.466-1.470	1.472-1.475	—	1.471-1.475	1.472-1.474
n _D ⁴⁰	1.464-1.468	1.465	1.460-1.464	1.461-1.465	1.469	1.465-1.467	—	1.466-1.468

TABLE 8. VEGETABLE OIL/DIESEL FUEL BLEND PROPERTIES

	Viscosity at 100°F, cSt	API Gravity, at 60°F	Flash Point* °F (°C)	Pour Point °F (°C)	Cetane Number	Gross Heat of Combustion, Btu/lb	Carbon, wt %	Hydrogen, wt %
Reference Diesel Fuel (rail- road diesel)	3.46	32.0	159(71)	-58(+ 50)	44.3	19215	86.34	12.81
Peanut Oil								
25%	6.60	29.5		5(-15)	41.8			
50%	12.60	27.1	183(84)	16(-9)	40.5			
100%	39.51	22.7	622(328)	28(-2)	39.0	17045	77.13	11.67
Corn Oil								
25%	6.85	28.8		-6(-21)	42.0			
50%	11.37	26.5	181(83)	-6(-21)	40.0			
100%	33.46	21.8	608(320)	-2(-19)	34.4	16965	77.33	11.45
Sunflower Oil								
25%	6.40	29.3		-4(-20)	42.1			
50%	10.75	26.7	177(81)	-2(-19)	40.8			
100%	33.46	21.9	608(320)	16(-9)	33.4	17010	77.36	11.40
Soy Oil								
25%	6.25	29.3		-13(-25)	43.6			
50%	11.28	26.7	179(82)	-2(-19)	41.9			
100%	32.31	21.9	597(314)	16(-9)	41.5	16770	77.39	11.44

*100% Vegetable Oil—D-92 Cleveland Open Cup Method.

Reference Fuel — Oil Blends—D-93 Pensky-Martin Closed Cup Method.

FIGURE 142
CETANE NUMBER VS BLEND CONCENTRATION

FIGURE 143
CETANE NUMBER VS BLEND CONCENTRATION

FIGURE 144
CETANE NUMBER VS BLEND CONCENTRATION

FIGURE 145
CETANE NUMBER VS BLEND CONCENTRATION

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XI. GASEOUS FUELS

Gaseous fuels are defined as natural gas [compressed natural gas (CNG) or liquefied natural gas (LNG) and liquefied petroleum gas (LP gas or LPG).] Natural gas is primarily composed of methane (CH_4), and LPG is mainly composed of propane (C_3H_8) with small concentrations of ethane (C_2H_6) and butane (C_4H_{10}). LPG also contains some olefins of the same carbon numbers: propylene (C_3H_6), ethylene (C_2H_4) and butylene (C_4H_8). There are four grades of LPG which are:

- (1) Commercial propane which is predominantly propane and/or propylene;
- (2) Commercial butane which is predominantly butanes and/or butylenes;
- (3) Commercial B-P mixtures which are predominantly mixtures of butanes and/or butylenes with propane and/or propylene; and
- (4) HD-5 propane which has not less than 90 liquid volume percent propane and not more than 5 liquid volume percent propylene. HD-5 propane is the only grade of LP-gas suitable for use in automotive engines.

Gaseous fuels may be used as alternative fuels for spark ignition engines. Blending gaseous fuels with specification gasoline is highly impractical. This type of fuel therefore does not fit the "pour in a drum and stir with a stick" definition of an emergency fuel. However, gaseous fuels can be used as highly qualified substitutes for spark ignition engines with the appropriate modifications and thereby stretch standard grade gasoline supplies in the event of a fuel shortage.

A. Operation of Gaseous Fuels in Automotive Engines

There are many fleets which use gaseous fuels on a routine basis with no decrease in performance or engine life. On an energy basis, gaseous fuels have efficiencies equivalent to that for gasoline. In the case of duty cycles with frequent stops and starts and/or frequent cold starts and warm-ups, gaseous fuels may even have greater energy

efficiencies. Due to lower energy density, gaseous fuels may have as little as half the range of gasoline on equivalent volumes of fuel. However, range can improve depending on the driving cycle, and may even approach a figure equal to that of gasoline in a frequency top-and-go duty cycle.

A number of factors make natural gas or LP gas attractive as spark ignition fuels. Both have research octane numbers near 120. Since the fuels are introduced in gaseous form, little or no fuel dilution occurs in cold weather due to condensation on cold cylinder walls. This allows extended oil drain intervals as compared to gasoline. Spark plugs also tend to last longer. Gaseous fuels offer improved cylinder-to-cylinder distribution which results in a smoother running engine. Cold startability is also improved. Exhaust emissions are not increased when using gaseous fuels. There is, in fact, some evidence of decreased emissions.

B. Fuel System Modification

The cost of converting present spark ignition engines is estimated to fall between \$1000 to \$2000. This amount includes a separate fuel storage unit, pressure regulator, and a mixing and metering device to prepare the air-fuel mixture for introduction into the manifold. With this modification, the vehicle has dual fuel capability and may run on either gasoline or gaseous fuels. Conversion is available commercially in most areas or parts may be ordered from any one of several national manufacturers. Besides cost, one disadvantage to conversion is increased vehicle weight due to the extra fuel tank. Tank weights can vary up to 1400 pounds for 20-gallon capacity. This added weight will have a detrimental effect on fuel economy, which may result in a 5- to 25-percent decrease in energy economy depending on weight of the storage unit. *It is recommended that only qualified organizations perform such retrofit.*

C. Safety

Extreme caution should be exercised when utilizing gaseous fuels. Although commercial storage tanks are designed with many safety features,

release of fuel vapors into the atmosphere can be dangerous due to hazards of asphyxiation and/or explosion. Fuel systems should be periodically checked for leaks with a soap-based leak tester. Refueling is probably the greatest source of accidents involved with gaseous fuel utilization. The following are guidelines for safe refueling of LPG.

LPG Fueling Rules

1. Stop motor, set brakes, block wheels before connecting LPG hose.
2. Check for open flames and other ignition sources in the immediate vicinity before connecting LPG hose.
3. Do not smoke while transferring LPG.
4. Check the working pressure of the LPG cylinder being filled. This cylinder working pressure should be at least equal to the vapor pressure of the LPG to be transferred.
5. Stand by the filling valve during the LPG transfer. Fill ONLY to "10% valve capacity." After filling LPG cylinder, stop pump motor before disconnecting hose.
6. Walk completely around the vehicle before leaving fueling site, making sure all

hoses are disconnected and properly secured.

7. Purge all tanks before making any repairs or alterations.
8. Keep fire extinguishers in good condition and handy. Refill immediately after use.
9. Do not use an open flame to locate LPG leak.
10. Do not fill any cylinder within ten feet of any building or recreational vehicle.

Overfilling tanks can be very dangerous. Normal expansion can cause release of the emergency pressure relief valve. If this occurs near an ignition source, the results could be disastrous.

Explosion hazard due to vehicle collision is also increased when using gaseous fuels. Commercial storage tanks are quite sturdy and if tanks are shielded from the possibility of direct collision, this hazard can be greatly reduced.

Another source of possible danger is in the fuel regulators. These should be periodically inspected to ensure proper working condition. Pressure gauges should be closely monitored. Any abnormal pressures should be quickly analyzed or reconciled after first shutting off the main valve at the tank.

BIBLIOGRAPHY

- Application Engineering Bulletin**, Number 70.11, Cumming Engine Co., October 1979.
- Armistead, Jr., G., **Safety in Petroleum Refining and Related Industries**, John G. Simmonds & Co., Inc. New York, 1950.
- ASTM Manual for Rating Motor, Diesel, and Aviation Fuels**, American Society for Testing and Materials, 1974-1975.
- ASTM Specifications for Petroleum Products**, American Society for Testing and Materials, 1978.
- Bailey, B. K. and Russell, J. A., "Emergency Fuels Composition and Impact—Phase II: Formulation & Screening" MED Report No. 101, Southwest Research Institute, June 1979.
- Bailey, B. K. and Russell, J. A., "Emergency Fuels Composition and Impact—Phase III: Formulation and Screening—Gasoline Emergency Fuels," MED Report No. 111, Southwest Research Institute, February 1980.
- Benson, J. D., Bigley, H. A., Jr., and Keller, J. L., "Passenger Car Driveability in Cool Weather," SAE Paper No. 710138, Society of Automotive Engineers, 1971.
- Bettoney, W. E., Burt, J. G., and Scheule, H. J., "Factors Affecting the Performance of Additives in Gasoline," Sixth World Petroleum Conference Proceedings, Section VI, Paper 22, June 1963, pp. 111-130.
- Brewster, B. and Kerley, R. V., "Automotive Fuels and Combustion Problems," SAE Paper No. 725C, Society of Automotive Engineers, August 1963.
- "Comparative Automotive Engine Operation When Fueled With Ethanol and Methanol," DOE HCP/W1737-01, U.S. Department of Energy, May 1978.
- "CRC Revised Road Rating Techniques," Report No. 436, Coordinating Research Council, Inc., July 1970.
- Crowley, A. W., et al., "Methanol-Gasoline Blends Performance in Laboratory Tests and In Vehicles," SAE Paper No. 750419, Society of Automotive Engineers, 1975.
- Daly, P. J. and Watson, W. W., "Emergency Fuel Substitutes for Spark-Ignition Engines," Technical Report R 589, Naval Civil Engineering Laboratory, June 1968.
- "Danger! Use Only as Directed. The Care and Handling of LPG", **Transport Times of the West**, April 1973.
- Dimitriadis, B., Eccleston, B. H., and Hurn, R.W., "An Evaluation of the Fuel Through Direct Measurement of Photochemical Reactivity of Emissions," Paper presented at the 62nd Annual Air Pollution Control Association Meeting, New York, June 1969.
- Durrans, T. H., **Solvents**, Chapman & Hall, London, 1957.
- Engelman, H.W., Guenther, D. A. and Silvis, T. W., "Vegetable Oil As a Diesel Fuel," ASME 78-DGP-19, The American Society of Mechanical Engineers, November 1978.
- Everett, R. L., "Measuring Vehicle Driveability," SAE Paper No. 710137, Society of Automotive Engineers, 1971.
- Felt, A. E. and Kerley, R. V., "Engines and Effects of Lead-Free Gasoline," SAE Paper No. 710367, Society of Automotive Engineers, 1971.
- Fuchs, E. J., "Unleaded Versus Leaded Fuel Results in Laboratory Engine Tests," SAE Paper No. 710676, Society of Automotive Engineers, 1971.
- Gary, J. H., and Handwerk, G. E., **Petroleum Refining Technology and Economics**, Marcel Dekker, Inc., New York 1975.
- "Gaseous Fuels for Automotive Engines," U.S. Department of Energy, Office of Transportation Programs, April 1980.
- "Identification of Probable Automotive Fuels Composition: 1985-2000," DOE HCP/W3684-01/1, U.S. Department of Energy, May 1978.
- Ingamells, J. C. and Lindquist, R. H., "Methanol as a Motor Fuel or Gasoline Blending Component," SAE Paper No. 750123, Society of Automotive Engineers, February 1975.
- Keller, J. L., "Alcohols As Motor Fuel?" **Hydrocarbon Processing**, Vol. 58, May 1979.
- Kerley, R. V. and Thurston, K. W., "Knocking Behavior of Fuels and Engines," SAE Transactions, Vol. 64, p. 554, 1956.
- Manual on Hydrocarbon Analysis**, ASTM STP 332, American Society for Testing and

- Materials, 1st Edition, 1933.
- Manual on Hydrocarbon Analysis*, ASTM STP 332A, American Society for Testing and Materials, 1968.
- Marsden, L., *Solvents Guide*, Cleaver-Hume, London, 2nd Edition, 1963.
- Mellan, I., *Industrial Solvents*, Reinhold, New York, 2nd Edition, 1950.
- Mellan, I., *Handbook of Solvents*, Vol. 1, Reinhold, New York, 1957.
- Mellan, I., *Industrial Solvents Handbook*, Noyes Data Corporation, Newark, New Jersey, 1970.
- Modern Petroleum Technology**, Institute of Petroleum, London, 3rd Edition, 1962.
- Moffitt, J. V. and Lestz, G. J., "Performance of Diesel and Turbine Fuels in a Military Spark Ignition Engine," Interim Report AFLRL No. 60, U.S. Army Fuels and Lubricants Research Laboratory, Southwest Research Institute, March 1975.
- Moody, G. B., "Origin, Migration, and Occurrence of Petroleum," **Petroleum Exploration Handbook**, McGraw-Hill, New York, Chapter 5.
- Nelson, W. L., **Petroleum Refinery Engineering**, 4th Edition, McGraw-Hill, New York, 1958.
- Owens, E. C. and Frame, E. A., "Direct Utilization of Crude Oil as a Fuel for High-Speed Diesel Engines," SAE Paper No. 750762, Society of Automotive Engineers, September 1975.
- Pahnke, A. J. and Bettoney, W. E., "Role of Lead Antiknocks in Modern Gasolines," SAE Paper No. 710842, Society of Automotive Engineers, 1971.
- Petroleum Products Handbook**, V. B. Guthrie, Ed., McGraw-Hill, New York, 1960.
- "Properties of Crude Oils and Liquid Condensate," **Petroleum Production Handbook**, T. C. Frick, Ed., Vol. II, McGraw-Hill, New York, Chapter 18.
- "Recommended Practice for Protection Against Ignitions Arising Out of Static, Lightning and Stray Currents," API RP2003, 2nd Edition, American Petroleum Institute, New York, 1967.
- Reynolds, W. W., **Physical Chemistry of Petroleum Solvents**, Reinhold, New York, 1963.
- Sax, N. I., **Dangerous Properties of Industrial Materials**, 3rd Edition, Reinhold Publishing Corp., New York, 1968.
- Scott, W. M., "Alternative Fuels for Automotive Diesel Engines," Ricardo Consulting Engineers.
- Service/Parts Topics Bulletin*, Number 70.11, Cumming Engine Co., October 1979.
- Shehan, T. J., Dorer, C. J., Jr., and Miller, C. O., "Detergent-Dispersant Fuel Performance and Handling," SAE 890516, Society of Automotive Engineers Mid-Year Meeting, Chicago, May 1969.
- "Status of Alcohol Fuels Utilization Technology for Highway Transportation" DOE HCP/M2923-01, U.S. Department of Energy, June 1978.
- Symposium on Hydrocarbon Analysis, ASTM STP 389, American Society for Testing and Materials, 1965.
- Teasley, R. E., "Open Letter to Our Friends in the Fuels and Lubricants Industry," Mail Code 50183, Cummins Engine Co., January 1980.
- The Bureau of Mines Routine Method for the Analysis of Petroleum, U.S. Bureau of Mines Bulletin 490.
- The Merck Index**, M. Windholz, Ed., Merck & Co., Inc., Rathway, New Jersey, 1976.
- Wigg, E. E. and Lunt, R. S., "Methanol as a Gasoline Extender-Fuel Economy, Emissions, and High-Temperature Driveability," SAE Paper No. 741008, Society of Automotive Engineers, October 1974.
- Wimer, W. W. and Russell, J. A., "Emergency Fuels Composition and Impact, Phase I: Emergency Fuels Constituents Identification," MED Report No. 109, Southwest Research Institute, December 1978.

APPENDIX A. TRADEOFF CHARTS AND EMISSIONS INDEX DEFINITIONS

The several special parameters and the graphical formats used in this guidebook have been developed through laboratory engine tests for a limited but representative collection of spark ignition and diesel engines to provide blend performance comparisons to evaluate the effectiveness of each extender. All of these have been presented as a function of volume percent extender in tradeoff charts and emissions index plots. These plots represent composite data correlated from engine dynamometer, chassis dynamometer, and highly limited road vehicle testing and provide general, relative estimates of vehicle performance as compared to neat gasoline or neat diesel fuel.

In engine dynamometer evaluations, one of the basic measurements is "Brake Specific Fuel Consumption" which is the pounds of fuel consumed per hour for each horsepower developed at a particular engine running condition. Units for BSFC are pounds per brake horsepower hour (lb/BHP-hr). In blending either gasoline or diesel fuel with a particular emergency extender, the extender itself is considered to be "free." That is, in an emergency situation its commercial value has no meaning, and it is in fact "priceless" in context to such a situation (such liquids would likely be allocated—perhaps even commandeered.)

A fair measure of gasoline or diesel fuel stretch-out is to compare the BSFC of the blend with that of neat gasoline or neat diesel fuel, subtracting out the fuel consumption fraction of the emergency extender. The resulting net BSFC for the gasoline or diesel fuel to be stretched out has been called "Brake Specific Gasoline Consumption (BSGC)" or "Brake Specific Diesel Consumption (BSDC)" respectively. BSGC and BSDC are calculated by:

$$\text{BSGC} = \text{BSFC} \times \frac{\text{lb gasoline}}{\text{lb total blend}}$$

$$\text{BSDC} = \text{BSFC} \times \frac{\text{lb diesel fuel}}{\text{lb total fuel}}$$

BSGC and BSDC are then measures of *base fuel* consumption in a given blend.

The "Conservation Index" normalizes BSGC

and BSDC to neat base fuel consumption. Expressed in words, "Conservation Index" is the fraction of base fuel replacement or conservation that occurs as a result of using a given emergency blend at a particular concentration. Mathematically, it is defined by the following:

$$\text{Conservation Index} = 1 - \frac{\text{BSGC}_{(\text{blend})}}{\text{BSGC}_{(\text{base})}}$$

or

$$1 - \frac{\text{BSDC}_{(\text{blend})}}{\text{BSDC}_{(\text{base})}}$$

Blend horsepower performance is normalized to that of the neat base fuel by means of the "Power Index." It is the fraction of base power associated with a given blend and indicates degree of power penalty over a reasonably wide range of engine speeds. The "Power Index" is defined by:

$$\text{Power Index} = \frac{\text{BHP}_{(\text{blend})}}{\text{BHP}_{(\text{base})}}$$

A tradeoff decision often exists between a base fuel *conservation bonus* and a *power penalty* when utilizing such nonspecification fuel blends as in this Guidebook. The "Tradeoff Index" is a measure of this compromise and is defined by:

$$\text{Tradeoff Index} = \text{Conservation Index} + \text{Power Index}$$

This concept is arithmetically permissible since both Conservation Index and Power Index are "pure numbers" (no units), each having been normalized to base fuel characteristics. Tradeoff Index reflects the balance between increase in base fuel *conservation* and drop in power (if any) with increasing extender concentration. Tradeoff Index is, in effect, the vector sum of the ordinates of the Conservation Index and Power Index curves at a specific concentration. A change in slope of the Tradeoff Index curve from positive to negative (i.e., a peaking) reflects a maximum advisable extender concentration. Beyond this peak, there is reason to believe base fuel may be wasted. This occurred for a considerable number of gasoline

blends, but for a wide variety of diesel extenders it was found that both two- and four-stroke diesel engines could be operated (in the laboratory) with concentrations approaching or reaching 100-percent extender. In such a case, no *optimum* or *peaking* characteristic of the Tradeoff Index curve occurs, and the curve simply increases toward a maximum value of 2.0 (Conservation Index = 1 plus Power Index = 1).

Significant changes in emissions quality can be expected when utilizing nonspecification emergency blends. The "Emissions Index" plots are presented in terms of HC Index, CO Index, NO_x Index, and Smoke Index. Each of these is defined by the following generalized formula:

$$\text{Emissions Index} = \frac{\text{Emissions}_{(\text{blend})}}{\text{Emissions}_{(\text{base})}}$$

Emissions Index is simply a fraction (expressed decimally and sometimes greater than unity) of the base fuel emissions value for a given concentration of extender. Whereas it might be

used as a factor to multiply base fuel emissions to estimate increase in emergency fuel emissions, this is not recommended because of the inherent aberrant nature of both gasoline and diesel engine emissions from operating condition to operating condition. Rather, the general functionality of each index curve should be considered (i.e., whether the curve increases drastically or gradually, or decreases).

Each of the indices described above relates emergency blend performance to that observed when using a standard specification quality gasoline or diesel fuel. These are guidelines which can be used when mixing an emergency blend for use by a specific fleet. *It must again be emphasized that all such data were derived in laboratory environments and are only rough guidelines; individual vehicle performance will doubtless vary considerably from that indicated in the plots.* Nevertheless, in the absence of actual fleet test data, they will serve as usable values in projecting fleet performance and overall fuel consumption.

APPENDIX B. PETROLEUM CHEMISTRY

I. BACKGROUND

The most important source of hydrocarbons today is crude oil, more commonly known as petroleum. Although the various crude oils differ in their physical characteristics, depending upon their geographic location, the amount of carbon usually is in the range of 84 to 88 percent and that of hydrogen from 12 to 14 percent. The variations in the crude are probably related to the nature of the original material from which it is derived and to geological history.

The large oil reserves in the United States are mainly in Texas, Oklahoma, California, and Alaska. There is no rigorous classification of crudes but instead, each oil company usually develops its own system to meet its specific needs.

For example, crudes could be classified:

- (a) Foreign vs Domestic
- (b) High sulfur (>1% ; sour crudes) vs low sulfur (sweet crudes)
- (c) Paraffinic; Naphthenic; Aromatic
- (d) Wax-Free vs Waxy
- (e) According to its suitability in making special products.

A chemical analysis of the crude is helpful in the processing of the various crude oils in the modern refinery. This refining process is complex and is discussed later. But first, some chemistry related to petroleum is discussed.

II. HYDROCARBON CHEMISTRY

The two elements in hydrocarbons, *carbon* and *hydrogen*, can be combined in different proportions forming hundreds of different hydrocarbon compounds, each with its own set of properties. Because of the large number of known different hydrocarbon compounds, and a still greater number that is theoretically possible, it is necessary to classify them in some appropriate way. The most convenient classification is by structure, since some hydrocarbons have structures like chains, others like rings, etc. The properties of the hydrocarbons depend on the number of carbon and hydrogen atoms in the molecule and the manner in which they are arranged. When compounds have similar structures, they usually have similar chemical and physical properties.

A. Carbon Atoms In Chains (Aliphatic Hydrocarbons)

1. Paraffins

If the carbon atoms are arranged in chains, they are called *aliphatic*. There are two general classes of aliphatic hydrocarbons: saturated and unsaturated. If the hydrocarbon is un-

able to combine with additional hydrogen atoms, they are called "saturated", and are sometimes referred to as *alkanes* or more often as *paraffins*. The simplest member of the paraffin series of hydrocarbons is methane, CH_4 . Methane constitutes the largest proportion of "natural gas" that is associated with oil fuels and petroleum. In hydrocarbons, each carbon requires four covalent bonds with each hydrogen atom being held to the carbon by sharing a pair of electrons (covalent bond) between the atoms as in Figure B-1.

FIGURE B-1

The covalent bond is more often drawn as a "dash" as in Figure B 2.

FIGURE B-2

The next hydrocarbon in this series is ethane, C_2H_6 . Table B-1 lists some of the members of this homologous series, i.e., the formulas for any one of these hydrocarbons differ by only one carbon and two hydrogens (CH_2) from the one below it or the one above it in the series. The general formula for this series is C_nH_{2n+2} . Therefore, propane, the next member of the series, has three carbons and would have the formula, C_3H_8 . The boiling points of the paraffins in Table B-1 are included for reference.

TABLE B-1. HYDROCARBON SERIES

Number of Carbon Atoms	Formula	Name of the Hydrocarbon	Approximate Boiling Point, °C
1	CH_4	Methane	-161
2	C_2H_6	Ethane	-88
3	C_3H_8	Propane	-45
4	C_4H_{10}	Butane	-0.6
5	C_5H_{12}	Pentane	36
6	C_6H_{14}	Hexane	69
7	C_7H_{16}	Heptane	98
8	C_8H_{18}	Octane	124
9	C_9H_{20}	Nonane	151
10	$C_{10}H_{22}$	Decane	174
11	$C_{11}H_{24}$	Undecane	197
12	$C_{12}H_{26}$	Dodecane	216
13	$C_{13}H_{28}$	Tridecane	234
14	$C_{14}H_{30}$	Tetradecane	253
15	$C_{15}H_{32}$	Pentadecane	271
16	$C_{16}H_{34}$	Hexadecane	288
17	$C_{17}H_{36}$	Heptadecane	303
18	$C_{18}H_{38}$	Octadecane	317
19	$C_{19}H_{40}$	Nonadecane	330
20	$C_{20}H_{42}$	Eicosane	205 ¹⁵ *
25	$C_{25}H_{52}$	Pentacosane	259 ¹⁵
30	$C_{30}H_{62}$	Triacontane	304 ¹⁵
70	$C_{70}H_{142}$	Heptacontane	300 ^{0.00001}

*The superscript number refers to pressure in millimeters of mercury at which the boiling point was determined. If there is no superscript, then atmospheric pressure (760 mm of Hg) is implied.

If the paraffin has more than three carbons, there is the possibility of having more than one arrangement of the carbon and hydrogen atoms in the molecule. Molecules which contain the same number and the same kind of atoms, but differ in structure, are called *isomers*. For example,

three structural isomers of pentane (C_5H_{12}) are possible.

Because these isomers have different structural configurations, their physical properties are different. For example, neopentane is a gas at room temperature while n-pentane is a liquid. Three of their properties are compared in Table B-2.

TABLE B-2

	n-pentane	isopentane	neopentane
Boiling Pt., °C	36.1	27.9	9.5
Melting Pt., °C	-129.7	-159.9	-16.5
Density (at 20°C compared to water at 4°C)	0.6262	0.6201	0.6135

The number of possible isomers increases with increasing carbon number. For example, there are 75 isomeric forms of decane possible, and over four billion (4,111,846,763) possible forms of tricontane ($C_{30}H_{62}$).

Because of the large number of organic compounds, a system of nomenclature was adopted by the International Union of Chemistry (IUC) that was based on naming a compound as the derivative of that hydrocarbon having the longest continuous chain of carbon atoms. The carbon atoms in the chain are numbered in such a way that the position of any substituent chain (radical) will be at the lowest possible numbered carbon. The word "radical" refers to a chain that might be substituted minus one hydrogen atom. For example, methane (CH_4) minus one hydrogen gives the methyl radical CH_3^- .

ethyl $C_2H_5^-$
propyl $C_3H_7^-$
butyl $C_4H_9^-$

pentyl (or amyl) $C_5H_{11}^-$
hexyl $C_6H_{13}^-$
etc.

Under the IUC system of naming compounds, *iso-pentane* would be 2-methyl butane. When identical groups are substituted in the compound, the prefix "di" is used for two groups, "tri" for three, and "tetra" for four. The IUC name of neopentane would be 2,2 dimethyl propane, indicating there are two methyl groups, each attached to the second carbon in the chain. There are some pitfalls in the IUC system of nomenclature. For example,

This is not 4-methyl pentane, but 2-methyl pentane. It does not matter at which end of the chain we start numbering the carbon atoms, as long as the numbering places the substituted radical at the lowest possible numbered carbon. Another example is

This is not 1 methyl 4-propyl pentane, nor is it 2 propyl 4 methyl pentane. But, it is 2,4 dimethyl hexane. The longest chain has six carbon atoms (hexane) with methyl groups located at the second and fourth carbons.

2. Olefins

The other class of aliphatic hydrocarbons also has several names: alkenes, unsaturates, or olefins. They are characterized by a double bond between two carbon atoms and have a general formula C_nH_{2n} . As with the *alkanes*, where the name of the member hydrocarbon ended with *-ane*, the alkenes members end with *-ene*.

In the IUC system, the positions of the double bonds between the carbon atoms in the alkenes (olefins) are numbered. For example,

The *di* in butadiene indicates two double bonds.

As with the paraffin (alkane) series, the first several members are gases at ambient conditions and the boiling points increase as the carbon number is increased.

	Boiling Point, °C
ethene (ethylene)	-104
propene (propylene)	-47
1-butene	-6
2-butene	1.4
1-pentene	30
2-pentene	36
1-hexene	64
1-heptene	93
1-octene	123
1-nonene	145
1-decene	172

Alkenes are usually referred to as olefins in oil refining. Olefins do not naturally occur in crude oils, but form during the processing. They are generally undesirable in the finished products because double bonds are reactive and these compounds are more easily oxidized and polymerized. Some diolefins (two double bonds) react very rapidly.

3. Alkynes

The other type of unsaturated hydrocarbons is the *alkynes*, characterized by a triple bond between two carbon atoms and having the general formula C_nH_{2n-2} , and their name ending in *-yne*. Some examples are:

When there is only one possible structure for the compound, the number indicating the double bond or triple bond location, or the radical attachment is usually omitted.

B. Carbon Atoms in Rings

1. Aromatic Hydrocarbons

Another class of hydrocarbons is the cyclic compounds. Of these hydrocarbons having ring structures, the aromatics are the best known. The name was given to these compounds because they were originally obtained from aromatic gums and oils. The main compound of this group is benzene.

The aromatics are characterized by six carbon atoms forming a closed ring with double bonds between each second pair of carbon atoms. Benzene, the simplest member of the series, is shown below.

A more common representation is the abbreviated structure, where the carbon and hydrogen atoms are omitted, and just assumed to be there.

There are thousands of possible "benzene derivatives" that can be obtained by replacing one or more hydrogen atoms with other groups, such as paraffinic types.

METHYL BENZENE
(TOLUENE)

1, 3 DIMETHYL BENZENE
(META - XYLENE)

1, 4 DIMETHYL BENZENE
(PARA - XYLENE)

1, 2 DIMETHYL BENZENE
(ORTHO - XYLENE)

When the groups are on adjacent carbons, they are said to be "ortho" to each other; when at the 1,3 position, they are in the "meta" configuration, and when they are at the 1,4 carbon positions, they are said to be "para."

Substitutions are not limited to the paraffinic hydrocarbons.

For example, an unsaturated group, such as ethene (ethylene), can be attached to the ring. This compound is commonly known as styrene.

2. Polynuclear Hydrocarbons

Other hydrocarbons that have atoms in rings are the polynuclear hydrocarbons. These hydrocarbons contain two or more rings. They

be divided into two groups. One group of these polynuclear hydrocarbons has individual nuclei. Some examples of this group are biphenyl, triphenylmethane, fluorene, cyclopentadiene, and indene.

BIPHENYL

FLUORENE

INDENE

TRIPHENYLMETHANE

CYCLOPENTADIENE

CYCLOPENTADIENE

CYCLOBUTENE

CYCLOPROPANE

CYCLOBUTANE

CYCLOHEXANE

The other group is called "condensed rings systems" since some of the carbon atoms in the polynuclear hydrocarbons are common to two, or even three rings. Some examples are shown below.

NAPHTHALENE

ANTHRACENE

PHENANTHRENE

PYRENE

	Boiling Point, °C	Density, g/ml
cyclopropane	-33	0.6769 (at -30°C)
cyclobutane	12	0.720 (at 5°C)
cyclopentane	49	0.7457 (at 20°C)
cyclohexane	81	0.7786 (at 20°C)
cycloheptane	118	0.8098 (at 20°C)
cyclooctane	149	0.8349 (at 20°C)
cyclobutene	2	0.733 (at 0°C)
cyclopentadiene	40	0.8021 (at 20°C)

3. Alicyclic Hydrocarbons

Other ring hydrocarbons are the alicyclics. These compounds have aliphatic character, may be saturated or unsaturated, and the rings or the side chains attached to the ring may contain

any of the common substituent groups. Because they contain other substituent groups, they can be compounds other than just hydrocarbons, such as alcohols, ketones, acids, etc. Some of the representative hydrocarbons of this type are shown below:

Alicyclic hydrocarbons are present in petroleum, in terpenes from plants and from coal tar. These alicyclic compounds are sometimes called cycloparaffins, but in the petroleum industry they are usually referred to as "naphthenes."

III. PETROLEUM REFINING

Petroleum refining is the separation of the different hydrocarbons in the crude oil into groups, and then the conversion of the groups into marketable products. This is illustrated in the simplified refinery flow diagram shown in Figure B.3. Refining involves increasing the yield of the desired hydrocarbons, methods of processing them to the desired hydrocarbons, and purifying them to the marketable product. The principal method of separating the various hydrocarbon fractions in the refinery is by distillation.

The molecules in a liquid are in constant haphazard motion. The bonds of molecules in the liquid are relatively weak compared to those in a solid object. Those molecules that have a high enough velocity can escape from the liquid and enter into the gaseous phase. This process is called evapora-

tion. If a given liquid, e.g., hexane, is placed in a closed container, some of the faster moving molecules will have enough energy to escape into the gas (or vapor) phase. While this is occurring, some of the molecules from the gas phase will be re-entering the liquid phase. This is called condensation. When the rate of evaporation equals the rate of condensation, there is a balance established between these fast moving (dynamic) molecules, and this state is known as a dynamic equilibrium. There is a pressure that results from the vapor in equilibrium with its liquid and is called the vapor pressure of the liquid. As the temperature is increased, the molecules in the liquid move at a greater velocity and thus more are able to escape to the vapor state and therefore a higher vapor pressure results. When the vapor pressure is the same as the exter-

FIGURE B-3

Source: Petroleum Refining, James H. Gary, Glenn E. Handwerk

nal pressure on its surface, the boiling point has been reached. Boiling points are usually expressed in reference to atmospheric pressure (760 mm). At pressure less than atmospheric, the liquid will boil at a corresponding lower temperature. A crude oil can be separated into fractions (cuts) by using the range of boiling points of the various hydrocarbons in the crude and a process called distillation. Distillation separates the fractions by differences in volatility (the tendency of a liquid to enter into the vapor state at ordinary temperature). In the refinery, the distillation process is conducted on a continuous basis in a column referred to as a fraction-

ating tower. In this column, repeated vaporizations and condensations take place, and with each one, the percentage of the more volatile components will be greater in the condensed vapor than in the original crude oil. If the tower is operated under reduced pressure (less than atmospheric) in the presence of steam, the boiling points are decreased, and the possibility of thermal decomposition that might occur during the distillation process is greatly reduced. Let us examine in more detail what takes place in a fractionating tower. Figure B-4 illustrates a typical modern fractionating tower. The crude oil is heated to about 370°-400° C

FIGURE B-4

by pumping it rapidly under pressure through pipe coils located in a furnace and followed by releasing it into a "flash" chamber that is at a much lower pressure. Most of the hot crude oil vaporizes because of this differential in pressure. The vapors then pass through the column containing many fractionating plates of special design that enable the gases and vapors to flow upward through narrow passages and special pipes for liquid returning downward. As the vapor travels upward, it condenses at each plate and the resulting liquid is then partially revaporized. The portion that remains a liquid returns down to the next lower plate. The vapors that are newly formed rise to the next higher plate and the process is repeated. This process results in the ascending vapors becoming progressively richer in those hydrocarbons having low-boiling points, and the liquids descending (reflux) becoming progressively richer in those hydrocarbons having high-boiling points. Table B-3 shows the common petroleum fractions and their boiling ranges.

TABLE B-3. PETROLEUM FRACTIONS AND THEIR BOILING RANGES

Fraction	Boiling Range	
Gas	<50°C	C ₁ to C ₅
Gasoline	40°C - 180°C	C ₆ - C ₁₀
Kerosene	180°C - 230°C	C ₁₁ - C ₁₈
Light Gas Oil	230°C - 305°C	C ₁₃ - C ₁₇
Heavy Gas Oil	305°C - 405°C	C ₁₈ - C ₂₅
Residium (Lube Fraction)	405°C - 515°C	C ₂₆ - C ₆₀

Figure B-5 shows the boiling ranges of the various components of crude oil.

A. Gas Fraction

This fraction contains the low-boiling paraffins (methane, ethane, propane, and butane), and the corresponding olefins, which are all gases at ambient temperature and pressure. Methane (CH₄) is usually used as a refinery fuel, although it does have other minor uses. Ethane (C₂H₆) has value as

FIGURE B-5

Source: Courtesy M. E. Peterkin, Sun Oil Co.

a feedstock to produce either ethylene or hydrogen and can be used to fuel the refinery. Propane (C_3H_8) has a value as a liquified petroleum gas (LPG) or a refinery fuel. Its olefin counterpart, propene (propylene, C_3H_6) is sometimes sold to manufacturers of polypropylene. Butanes (C_4H_{10}) that are recovered from crude oil or produced by various refinery processes are used either as components of gasoline or sold as liquified petroleum gases.

B. Gasoline Fractions

Only a limited amount of suitable hydrocarbons can be obtained from the crude oil which can be used in gasoline without modification. In the production of gasoline, the components are blended to promote (a) high anti-knock performance, (b) easy starting, (c) fast warm-up, (d) low engine deposits, and (e) low tendency to encounter vapor lock.

1. Anti-Knock Performance

The anti-knock characteristics of gasolines are expressed in terms of "octane numbers." The octane number is based on standard mixture of two chemically pure substances, 2,2,4-trimethylpentane and normal heptane. The former is referred to as "iso-octane" but is in fact misnamed. (In actuality, iso-octane is 2-methyl heptane and is not used as the reference.)

On the scale-measuring octane number, n-heptane ($CH_3-CH_2-CH_2-CH_2-CH_2-CH_2-CH_3$) was arbitrarily given an octane number of zero (0) because it detonates very easily.

So called "iso-octane" (2,2,4-trimethylpentane) was given a rating of 100 because it had exceptionally good antiknock characteristics.

A mixture of n-heptane and "iso-octane", in all proportions, gives a series of mixtures covering the complete rating scale. Thus, a mixture containing 5 volume percent "iso-octane" and 15 volume

percent n-heptane would have an octane rating of 85.

It should be noted that normal octane, being a long straight chain hydrocarbon, with no branching, has an octane rating of less than zero.

N-OCTANE

In paraffinic hydrocarbons, there is less tendency to knock when the molecule is compact and as the number of methyl groups attached to the carbon chain is increased. Aromatics as a rule knock less than any other type of hydrocarbon. The general order of decreasing knocking tendency would be:

Straight-chain paraffins
Naphthenes
Straight-chain olefins
Naphthenes with unsaturated side-chains
Paraffins with branched chains
Olefins with branched chains
Aromatics

Branching of aliphatic chains and double bonds are good anti-knock features in hydrocarbons.

2. Easy Starting

This subject is related to the volatility of the gasoline. Many oil companies adjust the volatility of the gasoline according to the climate of the geographic location where it will be used. For an engine to start readily, a certain fraction of the gasoline must be low boiling hydrocarbons. This volatile portion allows a combustible mixture to be formed at the surrounding air temperature. The ease of starting is therefore related to the delivery of the fuel, having the correct air-vapor mixture, to the cylinders. A mixture of 12 parts air, 1 part vapor, is considered satisfactory for starting.

Many of the properties of gasoline are measured by or related to the ASTM (American Society for Testing Material) gasoline distillation

curve. The most common is the ASTM Distillation Test (D86). A typical ASTM gasoline distillation curve is shown in Figure B-6 with the significance attached to various portions of the curve defined.

FIGURE B-6

Source: Chemical Technology of Petroleum, Gruse & Stevens

In the D86 distillation, the 10% point is used as a measurement related to ease of starting. It is the temperature recorded when 10 volume percent of the sample has been distilled. In general, the lower the temperature at the 10% point, the easier an engine can be started.

3. Fast Warm-Up

From Figure B-6, it can be seen that the engine warm-up is related to the mid-range in the curve. Just as the 10% point in the distillation curve can indicate ease of starting, the 50% point can indicate the ability of the gasoline to contain the proper mixture during the warmup of the vehicle. It is especially important if there is acceleration during this time. Better acceleration performance is achieved as the temperature at the 50% point is lowered, but tendencies for carburetor icing and engine stalling are increased.

4. Low Engine Deposits

For most gasolines, the 90% evaporated temperature is in the range of 149° to 177°C (300°-350°F). If the temperature is too high, excessive combustion chamber deposits can result, and excessive varnish and sludge deposits are more likely to occur in the engine. Gasolines may undergo slow oxidation in the presence of air with the resultant product being a gum. This gum formation usually is the result of prolonged storage of the fuel in the presence of air. The gum is usually soluble in the gasoline, but upon evaporation a sticky residue is obtained that can often result in deleterious effects. Some refiners treat their gasolines with antioxidants to prevent gum formation from occurring. Most commercial gasoline, however, would not be subjected to conditions that would result in gum formation. Crude petroleum, as received, can contain sulfur compounds. Most of these compounds are removed during the refining processes. If not removed, the sulfur oxides formed during the combustion in the engine may be converted to acids. These acids can promote corrosion of various parts of the engine.

5. Vapor Lock

Vapor lock in an engine occurs when the liquid fuel flow is either partially or completely interrupted because of the vaporization of the fuel. The normal fuel flow is reduced because the vapor occupies a greater volume than the liquid. Bubbles of vapor are formed in fuel lines, carburetor passages or in the pump. This condition causes a loss in power or complete stoppage of the engine and is directly related to the volatility of the low boiling "front end" hydrocarbons. Vapor lock is more likely to occur when the fuel is exposed to either high temperatures or low pressure in the fuel system.

6. Other Gasoline Requirements

There are other requirements for a good gasoline. It should have a low gum content to prevent the valves from sticking, carburetor problems and the development of deposits in the engine and intake manifolds. It should be low in sulfur to prevent corrosion and unpleasant odors. A good gasoline should have good stability against oxidation.

that might cause deterioration and gum formation during storage. In order to insure good fuel distribution and to prevent crankcase dilution and deposit, it should contain very few excessively high-boiling hydrocarbons.

C. Refinery Processes for Gasoline Components

As there is only a limited fraction of suitable hydrocarbons in crude oil that can be removed and used directly in gasoline, other refinery processes are necessary to alter the other fractions obtained from the crude oil to gasoline-range fractions. Some of these processes are described below.

1. Cracking

Refinery cracking is simply the breaking down of large hydrocarbon molecules, having high boiling points, to smaller molecules having lower boiling ranges and different physical properties. While the larger molecules are decomposing to smaller molecules, some of the latter are reactive and are combining with each other to give even larger molecules than those in the original stock. The more stable molecules can be removed as cracked gasoline, while the reactive ones polymerize to tar and under certain conditions, go to form coke. Figure B-7 summarizes gas-oil cracking.

Source: Petroleum Processing, Hengstebeck

Cracking is a very complicated process as there are many secondary reactions taking

place, with other products being formed continuously. These products can be liquids, solids, or gases. Those liquids in the gasoline boiling range would be the desirable products, while coke and gas are the unavoidable and unwanted by-products. Cracking can be either a thermal or a catalytic process. In the modern refinery, catalytic cracking has almost completely replaced the older thermal process. The thermal cracking process can be either liquid-phase or vapor-phase. In thermal cracking, time, temperature, and pressure are the major variables.

For approximately every 10°C (18°F) rise in cracking temperature, the yield of gasoline will double, provided the cracking time stays constant. However, as the higher cracking temperatures are approached, a large increase in temperature is needed to double the yield.

The liquid-phase cracking process usually operates at temperatures of 450°-510°C and in the pressure range of 68 to 102 atmospheres (1000-1500 psi). The gas-oil fraction is usually heated in a special furnace to the predetermined temperature and for a sufficient length of time to obtain the degree of cracking desired. Recycling is used in thermal cracking because if the hydrocarbon fraction is cracked too severely in one pass through the cracking unit, excess coke will be formed.

Vapor-phase cracking is a high-temperature, low-pressure conversion process. Feed stock can vary from gaseous hydrocarbons to gas oil, with the latter being the one most used. The dehydrogenation reaction is favored under the given conditions and results in higher yields of olefins and aromatics.

In catalytic cracking, the feed stock may vary anywhere from reduced crude oils to naphtha fractions. When naphtha is used, the process is called reforming. The purpose of reforming this fraction is to convert the naphtha into more volatile components of higher octane number for improving the anti-knocking quality of the gasoline.

Catalytic cracking has almost entirely replaced thermal cracking because it can convert heavy oils into higher yields of higher octane gasoline and with less unsaturated gases and other heavy oils being produced. There are two types of catalytic-cracking processes in operation today with many variations of each. They are the moving bed and the fluidized-bed processes.

2. Moving Bed Cracking

A good representative of the moving bed type is the Thermoform catalytic-cracking process (TCC). The catalyst hopper is located directly above the reactor and approximately 80 to 95 percent of the catalyst used in the process enter into the top of the reactor. As the catalyst free falls, it is sprayed with the hydrocarbon feed and the hydrocarbon spray thereby mixes with the catalyst particles. The remaining 5 to 20 percent of the circulating catalyst is used to maintain the level of the catalyst bed so as to meet the space velocity requirement needed at the desired throughput. The catalyst and hydrocarbons both move downward through the reactor. At the bottom the catalyst is removed from the cracked product by stripping off the hydrocarbons with a current of steam. The hydrocarbon vapors in the reactor are also separated from the fuel gases in the regenerator by using steam as a sealing medium. In the kiln, the downflowing catalyst is heated in the presence of injected air in order to burn off the coke. The TCC process is illustrated in Figure B-8.

Source: Refining Fundamentals, Petro/Chem Engineer

3. Fluidized-Bed Catalytic Cracking (FCC Process)

In the fluidized bed operation, the fluidized catalyst (finely divided powder) is circulated

continuously between the reaction zone and the regeneration zone. The petroleum vapors are mixed with the hot catalyst (heated in a kiln) at the desired cracking temperature. When the cracking reaction is completed, the catalyst particles are allowed to settle. The vapors go to a distillation unit and the catalyst is picked up and transported by a stream of hot air to the catalyst regenerating unit. The coking that has occurred on the catalyst is burnt off by a stream of hot-gas mixture. After the catalyst is separated from the gas by reducing the stream velocity in the regenerator, the catalyst particles flow down into the catalyst section and are mixed with more hydrocarbon vapors to start another cycle. Any fine catalyst that remains in the hydrocarbon vapors or air leaving the reactor or regenerator is removed with electric precipitators or cyclone separators. Cyclone separators work on the same principle as centrifuges. However, in cyclone separators, the gases are given the rotating motion rather than having the container revolve as with the centrifuge. Figure B-9 shows the Model IV design of Esso Research and Engineering Company.

Source: Refining Fundamentals, Petro/Chem Engineer

4. Reforming

The purpose of reforming is to convert the gasoline fractions having higher octane numbers and suitable for blending into finished gaso-

line. The process is usually limited to using straight run stocks in the 93°-205°C range (200°-400°F). Thermal reforming has now been almost completely replaced by catalytic reforming. The reac-

tions that take place in the reforming process depend on the catalyst and the conditions under which it is used. Examples of some reactions are shown below:

- isomerization of alkylcyclopentanes (methylcyclopentane isomerization to cyclohexane)
- Naphthenes lose hydrogen to give corresponding aromatic, having a higher octane value. (cyclohexane undergoes dehydrogenation and yields benzene). Reactions (a) + (b) Dehydroisomerization
- Paraffins having low octane, loses hydrogen to yield an aromatic (dehydrogenation of normal hexane to give benzene)

- Straight-chain paraffins rearrange to yield branched-chain isomers. The examples given here are only two of the many isomerization reactions that can take place (n-hexane is isomerized to give branched hydrocarbons having higher octane numbers)
- Hydrocracking heavy paraffins having a low octane number to lighter paraffins with improved octane values. Normal decane is hydrocracked to yield butane (a gas) and iso-hexane (a liquid).

sure is maintained at a level that prevents olefins from being formed from the paraffinic hydrocarbons.

Hydrocracking is simply the cracking of hydrocarbons in the presence of added hydrogen and is used to convert much higher molecular weight hydrocarbons to lighter gasoline type fractions. Hydrocracking involves relatively slow reactions that are exothermic and the products are lighter liquids and gases.

5. Alkylation

- Exceptionally good anti-knock gasoline components can be made by a process called alkylation. The process produces hydrocarbon liquids in the gasoline range from refinery gases. Alkylation requires an acid catalyst, either sulfuric or hydrofluoric. In the alkylation process, an olefinic gas is reacted with a paraffinic gas to produce a liquid branched-chain paraffinic hydrocarbon.

$$\begin{array}{c}
 \begin{array}{c} \text{H} \quad \text{CH}_3 \\ | \quad | \\ \text{H}-\text{C}-\text{C}=\text{CH} \\ | \\ \text{H} \end{array} + \begin{array}{c} \text{CH}_3 \\ | \\ \text{CH}_3-\text{CH}-\text{CH}_3 \end{array} \longrightarrow \begin{array}{c} \text{CH}_3 \quad \text{CH}_3 \\ | \quad | \\ \text{CH}_3-\text{C}-\text{CH}_2-\text{CH}-\text{CH}_3 \\ | \\ \text{CH}_3 \end{array} \\
 \text{ISOBUTYLENE} \qquad \qquad \text{ISOBUTANE} \qquad \qquad \text{2, 2, 4 TRIMETHYLPENTANE} \\
 \text{(GAS)} \qquad \qquad \qquad \text{(GAS)} \qquad \qquad \text{(ISOOCTANE)} \\
 \\
 \text{OR} \\
 \\
 \begin{array}{c} \text{H} \quad \text{H} \quad \text{H} \\ | \quad | \quad | \\ \text{H}-\text{C}-\text{C}=\text{CH} \\ | \\ \text{H} \end{array} + \begin{array}{c} \text{CH}_3 \\ | \\ \text{CH}_3-\text{CH}-\text{CH}_3 \end{array} \longrightarrow \begin{array}{c} \text{CH}_3 \\ | \\ \text{CH}_3-\text{CH}-\text{CH}_2-\text{CH}_2-\text{CH}_3 \\ | \\ \text{CH}_3 \end{array} \\
 \text{PROPYLENE} \qquad \qquad \qquad \text{2, 2 DIMETHYLPENTANE} \\
 \qquad \qquad \qquad \text{(ISOEPTANE)}
 \end{array}$$

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6. Polymerization

Polymerization can be defined as a reaction in which two or more molecules are combined to form a single molecule having the same elements and in the same proportions as in the original molecules. In the refining of petroleum, poly-

merization is used to combine two light olefins to form heavier hydrocarbons. It is used in the production of both aviation and motor fuel components from cracked gases. The term polymer gasoline therefore refers to products from polymerization of gaseous hydrocarbons to liquid hydrocarbons boiling in the gasoline range.

Example:

The polymerization can continue

There are many other reactions that are also taking place at the same time in polymerization. These result in producing numerous isomers of liquid hydrocarbons of different boiling points. The same type of reactions can occur with butylene or other unsaturated hydrocarbons. When there is a mixture of unsaturated hydrocarbons and polymerization occurs, the products are called "cross-polymers". Since a wide range of hydrocarbons can be produced from just a few gaseous hydrocarbons, the mixture must be distilled to separate the gasoline fraction from the others. Catalysts are employed in these polymerization reactions. There are many commercial catalysts such as phosphoric acid on a fine, powdered diatomaceous earth (kieselguhr), phosphoric acid on quartz chips, liquid phosphoric acid, copper pyrophosphate on charcoal, etc. The conversion of olefins is dependent not only on the type of catalyst

and its activity, but on temperature, pressure, reaction time and the types of olefins being used.

7. Aviation Gasoline

This is a fuel especially suited for aircraft use, as it has high volatility, high octane rating and good stability. Aviation gasoline is a blend of catalytically cracked naphthas, straight run naphthas, alkylate, and isopentane. Grades 80-87 are designed for small civilian aircraft. Grades 100-130 are used in larger civilian aircraft and transport military planes with supercharged engines. Grades 108-135 are fuels for aircraft that require a slightly higher octane rating than grades 100-130. Grades 115-145 are for combat aircraft and those with supercharged engines for long-range high altitude flights. The specifications of these aviation gasolines can be found in ASTM D 910. See Table B-4.

TABLE B-4. DETAILED REQUIREMENTS FOR AVIATION GASOLINES

	Grade 80	Grade 100	Grade 100LL	ASTM Test Method ^b
Knock value, min. octane number, lean rating	80	100	100	D 2700 ^c
Knock value, min. octane number, rich rating	87	isooctane plus 1.28 ml of tetraethyllead per gallon	isooctane plus 1.28 ml of tetraethyllead	D 909
Color	red ^a	green	blue	per gallon D 2392
Dye content:				
Permissible blue dye, ^f max, mg/gal	0.5	4.7	5.7	
Permissible yellow dye, ^g mg/gal	none	5.9	none	
Permissible red dye, ^h max, mg/gal	8.65	none	none	
Tetraethyllead, ⁱ max, ml/gal	0.5	4.0	2.0	D 2547, D 2599, or D 3241
Net heat of combustion, ^j min. Btu/lb	18 720	18 720	18 720	D 1405 or D 3338

Requirements for all Grades

Distillation temperature, deg °F (deg °C):			
10 percent evaporated, max temp		167 (75)	D 86
40 percent evaporated, min temp		167 (75)	
50 percent evaporated, max temp		221 (105)	
90 percent evaporated, max temp		275 (135)	
Final boiling point, max, deg °F (deg °C)		338 (170)	
Sum [*] of 10 and 50 percent evaporated temperatures, min, deg °F (deg °C)		307 (135) [*]	
Distillation recover, min, percent		97	
Distillation residue, max, percent		1.5	
Distillation loss, max, percent		1.5	
Acidity of distillation residue		shall not be acid	D 1093
Vapor pressure, max, lb		7.0	D 323 or D 2551
Copper strip corrosion, max		No. 1	D 130
Potential gum (5h aging gum), ^k max, mg/100 ml		6	D 873
Visible lead precipitate, ^l max, mg/100 ml		3	D 873
Sulfur, wt max, percent		0.05	D 1266 or D 2622
Freezing point, max, deg °F (deg °C)		-72 (-58)	D 2386
Water reaction		volume change not to exceed 2 ml	D 1094
Permissible antioxidants, ^m max, lb/1000 bbl (42 gal)		4.2	

^aRequirements contained herein are absolute and are not subject to correction for tolerance of the test methods. If multiple determinations are made, average results shall be used.

^bThe test methods indicated in this table are referred to in Section 9.

^cThe values shown in Table 1 represent Aviation Method ratings. Motor octane ratings obtained by ASTM Method D 2700 should be converted to aviation ratings by Conversion Table 2. If mutually agreed between purchaser and seller, Method D614 may be used to obtain aviation ratings directly.

^dThese colors have been approved by the Medical Director Chief, Division of Occupational Health, U. S. Department of Health, Education and Welfare.

^eIf mutually agreed upon between the purchaser and the supplier, Grade 80 may be required to be free from tetraethyllead. In such a case, the fuel shall not contain any dye and the color as determined in accordance with ASTM Method D 156. Test for Saybolt Color of Petroleum Products (Saybolt Chromometer Method) shall not be darker than +20.

^fThe only blue dye which shall be present in the finished gasoline shall be essentially 1,4-dialkylamino-anthraquinone.

^gThe only yellow dye which shall be present in the finished gasoline shall be essentially p-diethylaminoazobenzene (Color Index No. 11020).

^hThe only red dye which shall be present in the finished gasoline shall be essentially methyl derivatives of azobenzene-4-azo-2-naphthol (methyl derivatives of Color Index No. 26105).

ⁱThe tetraethyllead shall be added in the form of an antiknock mixture containing not less than 61 weight percent of tetraethyllead and sufficient ethylene dibromide to provide two bromine atoms per atom of lead. The balance shall contain no added ingredients other than kerosine, and an approved inhibitor, and blue dye, as specified, herein.

^jUse the value calculated from Table 1 in ASTM Method D 1405, Test for Estimation of Net Heat of Combustion of Aviation Fuels,⁵ ASTM Method D 2382, Test for Heat of Combustion of Hydrocarbon Fuels by Bomb Calorimeter (High-Precision Method)⁴ may be used as an alternative method. In case of dispute, Method D 2382 must be used. In this latter case, the minimum values for the net heat of combustion in Btu's per pound shall be 18,700 for Grades 80, 100, and 100LL.

^{*}Note that the temperature conversion for the sum is $C_1 + C_2 = 5/n (F_1 - 32 + F_2 - 32)$.

D. Aviation Turbine Fuels

These fuels are for use in jet-propulsion aircraft. They are classified as Jet A, Jet A-1, and Jet B. Jet A is a high flash point distillate, similar to kerosene. Jet A-1 is similar to Jet A but differs in aromatic content, freezing point and smoke point. A high smoke point indicates a fuel of low smoke-producing tendency. In general, the higher the aromatic content, the more smoky the flame. Jet B is a fuel of relatively wide boiling range volatile distillate. The specifications of these aviation turbine fuels can be found in Table B-5. The military designations for jet fuels are:

JP-1 This is the earliest jet fuel. It is a petroleum product very similar to kerosene.

JP-4 This fuel contains approximately 35 percent light petroleum distillate and 65 percent gasoline. The fuel has rigid specifications and is used as a fuel in military jet aircraft.

JP-5 This fuel is a specially refined kerosene used by the military as a jet fuel. It has a flash point of 60°C (140°F) and a freezing point of -40°C (-40°F).

E. Naphtha

Naphtha is a confusing term because it means different things to different people. Naphtha sometimes refers to a narrow-boiling fraction of petroleum with a boiling range between that of gasoline and kerosene. In the refinery, the term is usually reserved for straight-run materials, although it has been used in referring to cracked distillates. Naphtha also refers to a dry cleaning fluid derived from petroleum and similar to Stoddard solvent but not necessarily meeting all its specifications. Painter's naphtha, used as a thinner in paints and varnish, refers to any one of a number of narrow boiling-range petroleum fractions between 93° -149°C (200°-300°F). Heavy naphtha is a mixture of xylenes and higher homologs, whose flash point is less than 38°C (100°F) with a boiling range of 160°-220°C. This naphtha is usually obtained from coal-tar fractions or recovered from illuminating gas by scrubbing. The terms "naphtha" and "solvent" are often used interchangeably as naphtha is often used as a solvent. "Solvent naphtha" is also derived from coal-tar or recovered from illuminating gas and is comprised of a mixture

of small quantities of benzene and toluene with xylene and higher homologs, with 80-90% boiling about 160°C and a flash point of about 26°C. When used in reference to petroleum, naphtha is a generic term applied to petroleum products and liquid products of natural gas, of which not less than 10% distill below 175°C and not less than 95% distill below 240°C by ASTM D 86. These products can be unrefined, refined, or partly refined.

F. Solvents

There are many different types of solvents that can be made from petroleum.

a) *Stoddard solvent* is made from a petroleum distillate conforming to certain requirements, some of which are listed below.

Distillation range: Not less than 50% shall be recovered in the receiver at 177°C (350°F).

Flash Point: Not lower than 37.8°C (100°F) using the tag closed cup apparatus.

Color: Water-White or not darker than 21 by the Saybolt chromometer.

Appearance: Clear and free from suspended matter and undissolved water.

Stoddard solvent is used for dry cleaning clothes and degreasing metal parts. It is usually composed of straight-run naphtha that has been chemically treated, and from paraffin-base or mixed-base crudes.

b) *Painter's naphtha* (V.M. and P. naphthas) This could be any number of narrow-boiling range fractions of petroleum in the boiling range of 93° to 149°C (200°-300°F), the exact fraction depending on its use. It is sometimes called petroleum spirits or mineral spirits. This solvent is a general purpose solvent and thinner for paint, varnish and similar uses and is about the same as Stoddard solvent.

c) *Aromatic solvents*. These include benzene, toluene, xylene, etc. These solvents are high solvent-power thinners for use with synthetic resins and for use in the rubber and plastic industry. They are derived from the various aromatization processes in the refining of petroleum.

d) *Petroleum extender oils*. Although these should not be classified as a solvent, they are used in the processing of styrene-butadiene rubbers and butadiene rubbers. They are derived from straight-run naphthas from a paraffinic base crude.

TABLE B-5. DETAILED REQUIREMENTS OF AVIATION TURBINE FUELS^A

Property	Jet A or Jet A-1	Jet B	ASTM Test Method ^B
Acidity, total max, mg KOH/g	0.1	---	D 974 or D 3242
Aromatics, vol, max, %	20 ^C	20 ^C	D 1319
Sulfur, Mercaptan, ^D wt, max, %	0.003	0.003	D 1323
Sulfur, total wt, max, %	0.3	0.3	D 1266 or D 1552 or D 2622
Distillation temperature, °F (°C)			
10% recovered, max, temp	400(204.4)	---	D 86
20% recovered, max, temp	---	290(143.3)	
50% recovered, max, temp	report	370(187.8)	
90% recovered, max, temp	report	470(243.3)	
Final boiling point, max, °F (°C)	572(300)	---	
Distillation residue, max, %	1.5	1.5	
Distillation loss, max, %	1.5	1.5	
Flash point, min, °F (°C)	100(37.8)		D 56 or D 3243
Gravity, max, °API (min sp gr) at 60 °F	51(0.7753)	57(0.7507)	D 1298
Gravity, min API (min sp gr) at 60 °F	37(0.8398)	45(0.8017)	D 1298
Vapor pressure, max, lb	---	3	D 323
Freezing point, max, °C	-40 ^E Jet A -50 ^E Jet A-1	-50 ^E	D 2386
Viscosity -4° F (-20° C) max, cSt	8	---	D 445
Net heat of combustion, min, Btu/lb	18.400 ^F	18.400 ^F	D 1405 or D 2382
Combustion properties: one of the following requirements shall be met:			
(1) Luminometer number, min or	45	15	D 1740
(2) Smoke point, min or	25	25	D 1322
(3) Smoke point, min and	20 ^G	20 ^G	D 1322
Naphthalenes, vol, max, %	3	3	D 1840
Corrosion, Copper strip 2 h at 212 °F(100° C) max	No. 1	No. 1	D 130
Thermal stability: one of the following requirements shall be met:			
(1) Filter pressure drop, max, in. Hg	3	3	D 1600 ^H
Preheater deposit less than	Code 3	Code 3	
(2) Filter pressure drop, max, mm Hg	25	25	D 3241 ^I
Tube deposit less than	Code 3	Code 3	
Existent gum, mg/100ml, max	7	7	D 381
Water reaction:			
Separation rating, max	2	2	D 1094
Interface rating, max	lb	lb	D 1094
Additives		See 4.2	
Electrical conductivity, pS/m			D 2624 or D 3114

^AThe requirements herein are absolute and are not subject to correction for tolerance of the test methods. If multiple determinations are made, average results shall be used.

^BThe test methods indicated in this table are referred to in Section 9. ^CJet A with an aromatics content over 20 volume % but not exceeding 25 volume % and Jet A-1 or Jet B with an aromatics content over 20 volume % but not exceeding 22 volume % is permitted provided the supplier (seller) notifies the purchaser of the volume, distribution and aromatic content at date of such shipments. This footnote is subject to reapproval in 1979.

^DThe mercaptan sulfur determination may be waived if the fuel is considered sweet by the doctor test described in 4.2 of Specification D 484, for Hydrocarbon Drycleaning Solvents.³

^EOther freezing points may be agreed upon between supplier and purchaser.

^FUse for Jets A and A-1 the value calculated from Table 8 or Eqs 5, and 9 in Method D 1405. Method D 2382 may be used as an alternative. In case of dispute, Method D 2382 must be used.

^GJet A having a smoke point less than 20 but not less than 18 and a maximum of 3 volume % of naphthalenes and Jet A-1 or Jet B having a smoke point less than 20 but not less than 19 and a maximum of 3 volume % of naphthalenes is permitted provided the supplier (seller) notifies the purchaser of the volume, distribution, smoke point and naphthalene content at date of such shipments. This footnote is subject to reapproval in 1979.

^HThermal stability test shall be conducted for 5 h at 300°F(148.9°C) preheater temperature 400°F(204.4°C) filter temperature, and at a flow rate of 6 lb/h.

^IThermal stability test (JFTOT) shall be conducted for 2.5 h at a control temperature of 260°C but if the requirements of Table 1 are not met, the test may be conducted for 2.5 h at a control temperature of 245°C. Results at both test temperatures shall be reported in this case. Tube deposits shall always be reported by the Visual Method; a rating by the Tube Deposit Rating (TDR) optical density method is desirable but not mandatory.

e) Solvent Naphthas. The ASTM designations are shown below:

Refined Naphtha D-838
Crude Light Naphtha D-839
Crude Heavy Naphtha D-840

G. Kerosene Fraction

The kerosene fraction is that material that distills after the gasoline fraction. For purposes of this discussion, the boiling range is taken to be 180° to 230°C, although it is sometimes considered to be broader. The exact cut is usually determined by the specification of the finished kerosene. Number 1 fuel oil (204°-330°C), because of its similar properties, is sometimes sold as kerosene. In Europe, Africa and Asia, kerosene is often sold as jet fuel. To be of value as a fuel for lamps and stoves, the kerosene must burn satisfactorily. The viscosity of the fuel is an important factor in lighting as the flame size will diminish if the oil is too viscous to climb the wick as rapidly as the flame burns the fuel. A good kerosene, especially one that is to be used as fuels for lamps and cooking stoves, should

not contain aromatic, unsaturated, or sulfur compounds. The aromatic compounds cause the fuel to smoke upon burning, sulfur causes the formation of a translucent white deposit, "bloom" on the lamp chimney, and the unsaturated compounds are apt to form coke deposits on the wick.

The ASTM Standard specification for kerosene is described in Table B-6. The chemical and physical requirements are listed in Table 1 of that Standard and are reproduced as Table B-6..

1. Solvent Extraction

Solvent extraction can be employed as a means of removing compounds having a low hydrogen content, from materials having a higher hydrogen concentration. Solvent extraction (solvent refining) was first used for the upgrading of kerosene but it is now used for improving lubricating oils, upgrading the charge stocks to catalytic cracking units, separating light aromatics from gasoline, separating iso-butene from butane-butene mixtures, and for removing mercaptans from gasoline. Mercaptans are a group of organic com-

TABLE B-6. CHEMICAL AND PHYSICAL REQUIREMENTS

Property	ASTM Test Method ^a	Limit
Appearance:		
Color	D 156	+ 16 min.
Composition:		
Mercaptan sulfur, ppm	D 1323	30 max ^b
Sulfur, wt % —	D 1266, D 2622	
No. 1-K		0.04 max
No. 2-K		0.30 max
Volatility:		
Distillation, °C (°F)	D 86	
10% recovered		205 (401) max
Final boiling point		300 (572) max
Flash point, °C (°F)	D 56, D 3242	38 (100) min
Fluidity:		
Freezing point, °C (°F)	D 2386	-30 (-22) max
Viscosity at 40°C (104°F), cSt	D 445	1.0 min/1.9 max
Combustion:		
Burning quality	D 187	pass (see 4.2)
Corrosion:		
Corrosion, 3h at 100°C (212°F)	D 130	No. 3 max

pounds, resembling alcohols, but having the oxygen replaced by sulfur.

Example:

METHYL ALCOHOL
(METHANOL)

METHYL MERCAPTAN

Table B-7 lists some of the solvents used in the refining of petroleum and their applications. This is by no means a complete list, but rather, a representative sampling.

TABLE B-7

Solvents	Application
a) Furtural, nitrobenzene, phenol, liquid propane, 2,2'-dichloroethylether (clorex)	Séparation of paraffinic compounds from naphthenic-aromatic compounds, especially for improving lubricating oils.
b) Liquid propane, ketones	Dewaxing of lubricating oils
c) SO ₂	Removal of aromatics from petroleum stocks of all boiling ranges, especially kerosene
d) Glycols	Light aromatics from gasoline
e) Caustic soda + organic solvents	Treatment of naphthas for purification and removal of mercaptans.
f) Light paraffins	Preparation of residual crude oil prior to catalytic cracking
g) Anilino, liquid SO ₂ , concentrated acetic acid	Séparation of high and low antiknock fractions in petroleum naphthas and diesel fuels.

H. Diesel Fuel

Although diesel fuels and distillates have about the same boiling range, the latter will tolerate naphthenic and aromatic hydrocarbons while diesel fuels will not. There are many grades of diesel fuels, covering a wide boiling range and other specifications. Some of these may be straight-run products while others may contain cracked material.

The cetane rating for diesel fuels was established in the same manner as the octane ratings for gasoline. On the cetane scale, n-hexadecane (cetane) was given a rating of 100 as it was readily ignited in a compression-ignition (CI) engine.

1-methyl naphthalene (alpha methyl naphthalene) was arbitrarily assigned a value of zero cetane. A cetane rating of 40 assigned to a fuel oil means that the fuel, in a standard engine and operating under standard conditions will have autoignition properties equal to those of a mixture of 40 parts (by volume) of normal hexadecane and 60 parts of 1-methyl naphthalene.

Paraffinic hydrocarbons with a high cetane number may also have a high pour point. The pour point thus may limit the yield of diesel fuel in refining. The lighter portions of catalytic cycle oils, boiling between 200°-315°C are widely used as components of heating oils and diesel fuels. Table B-8 from ASTM D975 lists the requirements for the various grades of diesel fuel.

Grade No. 1-D is usually composed of straight-run fractions including kerosene. It can have intermediate cuts from the distillation of paraffinic crudes or cuts that have been solvent refined from mixed base crudes. This grade of diesel fuel is designed for high-speed engines that would vary with speeds and loads. It can be used where low-temperature service might be required.

Grade No. 2-D is used in high-speed engines that are subjected to high loads at uniform speed. This grade is very similar to No. 1-D except it has a lower volatility.

Grade No. 4-D is a blend of viscous distillates and residual fuel oils and is for use in engines that have sustained loads and constant speeds. It is also for use at large stationary installations.

I. Gas Turbine Fuel Oils

There are several grades of gas-turbine fuel oils. No. O-GT is a naphtha or other low-flash hydrocarbon liquid. This grade includes naphtha, Jet B fuel and other volatile hydrocarbon liquids. No. 1-GT is suitable for almost all gas turbines but not primarily for use in aircraft. It is composed of light distillates including some gas oil fractions and it is required to burn cleaner than No. 2-GT. No. 2-GT is a distillate of low ash and suitable for gas turbine where the clean burning requirement is not needed. It is composed of heavier distillates than in the above mentioned grades. Grade No. 3-GT are made from residual fuel that meets the low ash requirements and are for use in gas turbine operating at gas inlet temperatures below 650°C. Grade 4-

GT is a fuel composed of residual component and a high vanadium content. Table B-9 summarizes the detailed requirements for these gas turbine fuel oils.

J. Fuel Oils

Fuel oils can be defined as any liquid or liquifiable petroleum product used for generation of heat or power, not including oils with flash points below 37.8°C (100°F) and oils such as kerosene that are burned in wool or cotton wick burners. The basic requirement is that they must burn with a reasonable degree of completeness. The specifications contain the amount of water and incombustible solid matter that they can contain. No. 1 fuel oil (range oil, kerosene) is used in vaporizing pot-type burners and is made from the straight-run distillate that is treated for stability. No. 2 fuel oil is from the straight-run or catalytically cracked distillates and can be used in atomizing-type burners. No. 4 fuel oil comes from the much heavier straight-run and catalytically cracked distillates and/or light residual. Thus fuel can be used for light industrial installations. No. 5 is termed residual fuel and contains some lighter distillates. This fuel may require preheating before it can be burned. No. 6 (bunker C) requires preheating and has a relatively high viscosity. It is obtained from straight-run or cracked residuums. The specifications for these fuels are listed in ASTM D 396 and are summarized in Table B-10 from that specification.

K. Lubricating Oils

The composition of the heavy fractions used in making the lubricating oils is very complex. The lubricating oil fractions have a wide variety of components, such as waxes, asphalts, low-viscosity index hydrocarbons and high-viscosity index hydrocarbons. The viscosity index is an empirical scale based upon two extreme types of lubricating oils. The index was established before the development of solvent refining, and oils that are manufactured now sometimes have better characteristics than original standards and thus the viscosity index can exceed 100.

Pour point can be described as the lowest temperature at which an oil will pour or flow when it is chilled undisturbed under definite conditions

as prescribed by ASTM method D 97. Waxes are solids at room temperature. If there are solutions of waxes in oil, the waxes will solidify upon cooling and hinder the flow of the oil. The higher the concentration of wax, the higher will be the pour point of the oil. Those fractions of crude oil that contain high-viscosity index materials are valuable components for lubricating oil manufacturing. The viscosity changes relatively little with increasing or decreasing temperature and are stable in use. Asphalts cannot be distilled but they will crack if heated to high temperature to yield carbon (coke). If oils contain asphalt they tend to be unstable and carbonize the engine in which they are used.

The hydrocarbons intermediate between an oil and the wax are sometimes referred to as pseudo-waxes while the hydrocarbons between the oil and asphalt are called resins. Both these intermediates may be desirable components while the waxes and asphalts are not usually desirable. The progression from waxes to asphalts can be thought of as:

Waxes
Pseudo Waxes
High Viscosity Index Constituents
Low Viscosity Index Constituents
Resins
Asphalts

The type of crude is important in the manufacturing of lubricating oil since crudes vary widely depending on the source. The older methods of refining lubricating oils still exist to some degree. The new refining methods use solvent extraction for separating asphalt, wax and low-viscosity index constituents from the oil. Old methods used sulfuric acid, whereby a sludge was produced. The asphalt can be removed by precipitation with liquid propane or similar solvents or removed as "still bottoms" from distillation of the oil using high distillation temperature, vacuum and steam. Using propane to extract the oil, the separation can be made according to the size of the molecule. Thus by varying the conditions of the extraction, the charge stock can be separated into oil, resin, and asphalt fractions.

There are two general types of waxes known. The waxes associated with the high distillates are termed paraffinic waxes. Paraffinic wax has a crystalline structure. Petrolatum is a type of wax asso-

TABLE B.8. DETAILED REQUIREMENTS FOR DIESEL FUEL OILS^{A,H}

Grade of Diesel Fuel Oil	Flash Point, °C	Cloud Point, °C (°F)	Water and Sediment vol %	Carbon Residue on, 10% Residue, %	Ash weight %	Distillation temperatures, °C (°F)		Kinematic, cSt ^G at 40°C		Saybolt, SUS at 100°F		Sulfur, ^D weight %	Copper Strip Corrosion	Cetane Number ^E
	Min	Max	Max	Max	Max	Min	Max	Min	Max	Min	Max	Max	Max	Min
No. 1-D														
A volatile distillate fuel oil for engines in service requiring frequent speed and load changes														
	38 (100)	B	0.05	0.15	0.01	---	288 (550)	1.3	2.4	---	34.4	0.50	No. 3	40 ^F
No. 2-D														
A distillate fuel oil of lower volatility for engines in industrial and heavy mobile service														
	52 (152)	B	0.05	0.35	0.01	232C	338 (540)	1.9 (640)	4.1	32.6	40.1	0.50	No. 3	40 ^F
No. 4-D														
A fuel oil for low and medium speed engines														
	55	B	0.50	---	0.10	---	---	5.5	24.0	45.0	125.0	2.0	---	30 ^F

^ATo meet special operating condition, modifications of individual limiting requirements may be agreed upon between purchaser, seller, and manufacturer.

^BIt is unrealistic to specify low-temperature properties that will ensure satisfactory operation on a broad basis. Satisfactory operation should be achieved in most cases if the cloud point (or wax appearance point) is specified at 6°C above the tenth percentile minimum ambient temperature for the area in which the fuel will be used. The tenth percentile minimum ambient temperatures for the U.S. are shown in Appendix X2. This guidance is of a general nature; some equipment designs, use of improver additives, fuel properties, and/or operations may allow higher or require lower cloud point fuels. Appropriate low temperature operability properties should be agreed on between the fuel supplier and purchaser for the intended use and expected ambient temperatures.

^CWhen cloud point less than -12°C (10°F) is specified the minimum viscosity shall be 1.7 cSt (or mm²/s) and the 90% point shall be waived.

^DIn countries outside the U.S.A., other sulfur limits may apply.

^EWhere cetane number by Method D613 is not available, ASTM Method D 976, Calculated Cetane Index of Distillate Fuels may be used as an approximation. Where there is disagreement, method D613 shall be the referee method.

^FLow-atmospheric temperatures as well as engine operation at high altitudes may require use of fuels with higher cetane ratings.

^G1 cSt = 1 mm²/s.

^HThe values stated in SI units are to be regarded as the standard. The values in U.S. customary units are for information only.

**TABLE B-9. DETAILED REQUIREMENTS FOR GAS TURBINE FUEL OILS AT TIME
AND PLACE OF CUSTODY TRANSFER TO USER**

Designation	Grade of Gas Turbine Fuel Oil	Flash Point, °C (°F) ^a	Pour Point, °C (°F) ^b	Water and Sediment vol % Max	Carbon Residue on 10% Residuum, wt % Max	Ash wt % Max	Distillation Temperature, 90% Point		at 40°C Min	Kinematic Viscosity cSt ^c		Saybolt Viscosity, s ^d		Specific Gravity 60/60°F (API) ^e
		Min	Max				°C (°F)	°C (°F)		at 40°C Max	at 50°C (122°F) Max	Universal at 35°C (100°F) Min	Max	
							Min	Max						Max
No. 0-GT	A naphtha or other low-flash hydrocarbon liquid	D	---	0.05	0.15	0.01	---	---	D	---	---	---	---	---
No. 1-GT	A distillate for gas turbines requiring a fuel that burns cleaner than No. 2-GT	38 (100)	-18 ^f (0)	0.05	0.15	0.01	---	285 (550)	1.3	2.4	---	---	(34.4)	0.850 (35 min)
No. 2-GT	A distillate fuel of low ash suitable for gas turbines not requiring No. 1-GT	38 (100)	-6 (20)	0.05	0.35	0.01	282 (540)	338 (640)	1.9	4.1	---	(32.6)	(40.2)	0.876 (30 min)
No. 3-GT	A low-ash fuel that may contain residual components	55	---	1.0	---	0.03	---	---	5.5	---	638	(45)	---	(300)
No. 4-GT	A fuel containing residual components and having higher vanadium content than No. 3-GT	66 (150)	---	1.0	---	---	---	---	5.5	---	638	(45)	---	(300)

^aNo. 0-GT includes naphtha, Jet B fuel, and other volatile hydrocarbon liquids. No. 1-GT corresponds in general to Specification D396 Grade No. 1 fuel and Classification D975 Grade No. 1-D diesel fuel in physical properties. No. 2-GT corresponds in general to Specification D 396 Grade No. 2 fuel and Classification D 975 Grade No. 2-D diesel fuel in physical properties. No. 3-GT and No. 4-GT viscosity ranges brackets Specification D 396 Grade No. 4, No. 5 (light), No. 5 (heavy) and No. 6 and Classification D 975 Grade No. 4-D diesel fuel in physical properties.

^bValues in parentheses are for information only and may be approximate.

^c1cSt = 1mm²/s.

^dWhen flash point is below 38°C, or when kinematic viscosity is below 7.3 cSt at 40°C, or when both conditions exist, the turbine manufacturer should be consulted with respect to safe handling and fuel system design.

^eFor cold weather operation, the pour point should be specified 6°C below the ambient temperature at which the turbine is to be operated except where fuel heating facilities are provided. When a pour point less than -18°C is specified for Grade No. 2-GT, the minimum viscosity shall be 1.7 cSt, and the minimum 90% point shall be waived.

^fGas turbines with waste heat recovery equipment may require sulfur limits in the fuel to prevent cold-end corrosion (see Appendix X2.4.1.11).

TABLE B-10. DETAILED REQUIREMENTS FOR FUEL OILS^A

Grade of Fuel Oil	Flash Point, °C	Pour Point, °C	Water and Sediment vol %	Carbon Residue on 10% Bottoms, %	Ash Weight %	Distillation Temperature °C (°F)			Saybolt Viscosity, s ^B				Kinematic Viscosity, cSt ^C				Specific Gravity 60/60°F (deg API)		Copper Strip Corrosion	Sulfur %	
	°C Min	°C Max	Max	Max	Max	10% Point	90% Point	Max	Universal 38°C (100°F)		Fuel at 50°C (122°F)		at 38°C (130°F)		at 40°C (104°F)		at 50°C (122°F)		Max	Max	
						Max	Min		Max	Min	Max	Min	Max	Min	Max	Min	Max				
No. 1 A distillate oil intended for vaporizing pot-type burners and other burners requiring this grade of fuel	38 (100)	-18°C (0)	0.05	0.5	---	215 (420)	---	288 (550)	---	---	---	---	1.4	2.2	1.3	2.1	---	---	0.8499 (35 min)	No. 3	0.5
No. 2 A distillate oil for general purpose heating for use in burners not requiring No. 1 fuel oil	38 (100)	-6°C (20)	0.05	0.35	---	---	282°C (540)	338 (640)	(32.6)	(37.5)	---	---	2.0 ^D	3.6	1.9 ^C	3.4	---	---	0.8762 (30 min)	No. 3	0.5 ^E
No. 4 Preheating not usually required for handling or burning	55	-6°C	0.50	---	0.10	---	---	---	(45)	(125)	---	---	5.8	>25.4 ^F	5.5	>24.0 ^F	---	---	---	---	---
No. 5 (Light) Preheating may be required depending on climate and equipment	55 (130)	---	0.0	---	0.10	---	---	---	(>125)	(300)	---	---	26.4	>35 ^F	24.0	58 ^F	---	---	---	---	---
No. 5 (Heavy) Preheating may be required for burning and in cold climates, may be required for handling	55 (130)	---	1.00	---	0.10 ^G	---	---	---	(>300)	(900)	(23)	(40)	>35	134 ^F	>58	168 ^F	(42)	(81)	---	---	---
No. 6 Preheating required for burning and handling	60 (140)	G	5.00 ^H	---	---	---	---	---	(900)	(>45)	(300)	---	---	---	>92	638 ^F	---	---	---	---	(>900)

^AIt is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.

^BIn countries outside the United States other sulfur limits may apply.

^CLower or higher pour points may be specified whenever required by conditions of storage or use. When pour point less than -18°C (0°F) is specified, the minimum viscosity for grade No. 2 shall be 1.7 cSt (3.15 SUS) and the minimum 90% point shall be waived.

^DViscosity values in parentheses are for information only and not necessarily limiting.

^EThe amount of water by distillation plus the sediment by extraction shall not exceed 2.00%. The amount of sediment by extraction shall not exceed 0.50%. A deduction in quantity shall be made for all water and sediment in excess of 1.0%.

^FWhere low sulfur fuel oil is required, fuel oil falling in the viscosity range of a lower numbered grade range of the initial shipment shall be identified and advance notice shall be required when changing from one viscosity range to another. This notice shall be in sufficient time to permit the user to make the necessary adjustments.

^GWhere low sulfur fuel oil is required Grade 6 fuel oil will be classified as low pour + 15°C (60°F) max or high pour (no max). Low pour fuel oil should be used unless all tanks and lines are heated.

ciated with the residium (residual oils) and is termed as an amorphous wax as it has a microcrystalline structure. Since the structures are different, methods for their removal from the lubricating oil fraction require different approaches. Unfortunately for the refiners, the waxes extend throughout the entire boiling range of the lubricating-oil stocks and cannot be separated by fractionation. The paraffin wax can, however, be removed by filtering and the microcrystalline wax can be removed by centrifugation.

Bright stock is the term used for refined, high-viscosity lubricating oils, usually made from residual stocks by appropriate treatment. In the past, the centrifuge process was used to remove the wax (dewax) but it is now being replaced with various solvent processes. These newer solvent processes employ such special solvents as propane, methyl ethyl ketone, methyl ethyl ketone (MEK)-benzol mixtures, (MEK)-benzol mixtures, acetone-benzene, trichloroethylene, etc. Examples of dewaxing processes using filters are the Propane process, the Methyl-Butyl-Ketone Process and the Benzol-Ketone Process. Examples of those using centrifuges are the Bari-Sol Process and the Separator-Nobel Dewaxing Process.

The Dewaxing process is often conducted in two steps. First, the oil containing the wax is diluted with the selected solvent, chilled, and the wax separated. Next, the newly separated wax is mixed with additional solvent and reprocessed for obtaining the oil still remaining in the wax. The solvent from this operation contains very little oil and can be used in diluting a fresh oil change thus reducing the distillation cost. Solvent refining is used to extract the low-viscosity index constituents. The term "solvent refining" is usually used for liquid-liquid type extractions, rather than in the dewaxing or deasphalting processes that separate wax or asphalt from the oil. No one solvent has been found that can make good sharp separations between the high viscosity index constituents and the low viscosity index constituents. In the refining of lubricating oil, the minimum number of stages used is three, but usually eight or more are needed for best results as a variety of stocks and solvents are used. In recent years, additives have been finding extensive use in the manufacturing of lubricating oil. These additives have many functions, such as viscosity index improvers, oxidation inhibitors, pour-point depressants, anti-corrosion agents, de-

tergents, dyes, oilness carriers, etc.

The viscosity of an oil increases with decreasing temperature. The viscosity index of an oil is a measure of this change of viscosity with temperature. The viscosity of the oil is adjusted so that good lubrication is provided for the engine at its normal operating temperature. The "oiliness" of the lubricating oil is its ability to form a tenacious film on and around metal surfaces from which it may be squeezed out by excessive pressures. This is especially important during the break-in period of automobile and certain types of machinery. Another important property of an oil is its pour point. An oil must remain a liquid at low temperature to be effective. If it contains wax, it might congeal and not be able to circulate freely. The pour point is the temperature, usually reported in Fahrenheit degrees, at which the oil stops flowing under the experimental conditions that are specified in the test method. The viscosity of motor oil is usually reported as an SAE (Society of Automotive Engineers) number. The lightest grade of oil (for winter use) is SAE-10W. The heaviest grade of oil (for winter use) is SAE-30W. If the "W" is omitted, the oils have the same properties as the oils mentioned above except that they have a higher pour point. This would make them not suitable for winter use. SAE-30 and SAE-40 are summer grade oils, SAE-50 and higher are for vehicles that have had exceptionally heavy wear.

Some of the material and information in this section was derived from the publications listed below. We wish to acknowledge and thank the many authors, editors and contributors for their efforts:

- Boldt, K. and Hall, B.R., editors, *Significance of Tests for Petroleum Products*, prepared by ASTM Committee D-2 on Petroleum Products and Lubricants, American Society for Testing and Materials, Philadelphia, PA (1977).
- Brewster, R.Q., *Organic Chemistry*, Prentice-Hall, Inc., New York, N.Y. (1949)
- Dushman, S., *Chemistry and Petroleum*, American Petroleum Institute, New York, N.Y.
- Ehert, W.F., *Smith's College Chemistry*, D. Appleton-Century Company, Inc., New York, N.Y., (1946)
- Fieser, L.F. and Fieser, M., *Advanced Organic Chemistry*, Reinhold Publishing Corporation, New York, N.Y. (1962)

- Gary, J.H. and Handwerk, G.E., *Petroleum Refining, Technology & Economics*, Marcel Dekker, Inc., New York, N.Y. (1975)
- Gibbs, G.B. and Hoffman, H.L., "Petroleum (Products)", *Kirk-Othmer Encyclopedia of Chemical Technology*, Vol. 15, John Wiley and Sons, Inc., New York, N.Y., 1966.
- Grant, J., editor, *Hackh's Chemical Dictionary*, Third Edition, McGraw-Hill Book Company, Inc., New York, N.Y. (1944)
- Griswold, J., *Fuels, Combustion and Furnaces*, First Edition, McGraw-Hill Book Company, Inc., New York, N.Y. (1946)
- Gruse, W.A. and Stevens, D.R., *Chemical Technology of Petroleum*, Third Edition, McGraw-Hill Book Company, Inc., New York, N.Y. (1960)
- Guthrie, J.A., "Introduction to the Refinery", Sun Valley School, Aston, Pa., 22 September 1969.
- Hengstebeck, R.J., *Petroleum Processing. Principles and Applications*. McGraw-Hill Book Company, Inc., New York, N.Y. (1959)
- Kalichevsky, V.A., *Refining Fundamentals Petro-/Chem Engineer*, The Petroleum Engineer Publishing Co., Dallas, Texas
- Lane, J.C., "Gasoline and Other Motor Fuels," *Kirk-Othmer Encyclopedia of Chemical Technology*, Vol. 10, John Wiley and Sons, Inc., New York, N.Y., 1966.
- Lukens, R.P., Managing Standards Editor, *Annual Book of ASTM Standards, Part 23, Petroleum Products and Lubricants (I)*, American Society for Testing and Materials, Philadelphia, Pa (1979)
- Lukens, R.P., Managing Standards Editor, *Annual Book of ASTM Standards, Part 24, Petroleum Products and Lubricants (II)*, American Society for Testing and Materials, Philadelphia, Pa. (1979)
- Nelson, W.L., *Petroleum Refinery Engineering*, Fourth Edition, McGraw-Hill Book Company, Inc., New York, N.Y. (1969)
- Obert, E.F., *Internal Combustion Engines. Analysis and Practice.*, Second Edition, International Textbook Company, Scranton, Pa. (1950)
- Perry, R.H. and Chilton, C.H., Editors, *Chemical Engineer's Handbook*, Fifth Edition, McGraw-Hill Book Company, Inc., New York, N.Y. (1973)
- Popovich, M. and Hering, C., *Fuels and Lubricants*, John Wiley and Sons, Inc., (1957)
- Rose, A. and Rose, E., Editors, *The Condensed Chemical Dictionary*, Fifth Edition, Reinhold Publishing, Corp., New York, N.Y. (1956)
- Shreve, R.N., *The Chemical Process Industries*, First Edition, McGraw-Hill Book Company, Inc., New York, N.Y. (1945)
- The Story of Gasoline*, Ethyl Corporation, New York, N.Y. (1964)
- Weast, R.C., Editor, *CRC Handbook of Chemistry and Physics*, 59th Edition, CRC Press, Inc., West Palm Beach, Florida, (1978)

APPENDIX C. GENERAL FUELS INFORMATION

The material in this Appendix is intended to provide overall information on key fuels properties, including data and graphical relationships useful in blending operations typical of those expected for a fleet operating under emergency conditions. Major topics covered are:

- Fuel specifications excerpts
- Typical spec fuels inspections

- Fuel property correlations
- Fuel blending tables/ charts
- Conversion tables/ charts

As with all other data in this guidebook, the information is general and illustrative. *Fleet operators are strongly encouraged to consult with fuels technologists prior to initiating emergency fuels operations.*

TABLE C-1. DETAILED REQUIREMENTS FOR GASOLINE

Gasoline Volatility, Class	Distillation Temperatures, °F (°C), at Percent Evaporated ^A					Dist. Residue, % max	Vapor/Liquid Ratio ^A	
	10 max	50		90 max	End Point, max		Test Temperature, °F (°C)	V/L, max
		min	max					
A	158(70)	170(77)	250(121)	374(190)	437(225)	2	140(60)	20
B	149(65)	170(77)	245(118)	374(190)	437(225)	2	133(56)	20
C	140(60)	170(77)	240(116)	365(185)	437(225)	2	124(51)	20
D	131(55)	170(77)	235(113)	365(185)	437(225)	2	116(47)	20
E	122(50)	170(77)	230(110)	365(185)	437(225)	2	105(41)	20

Gasoline Volatility, Class	Reid Vapor Pressure, psi(kPa), max	Lead Content, g/gal (g/ litre), max		Copper Strip Corrosion, max	Existent Gum, mg/ 100 ml, max	Sulfur, wt %, max		Oxidation Stability, min	Anti-knock Index
		Lead Level				Leaded	Un-leaded		
		Unleaded ^B	Conventional						
A	9.0(62)	0.05(0.013)	4.2(1.1)	No. 1	5	0.15	0.10	240	"
B	10.0(69)	0.05(0.013)	4.2(1.1)	No. 1	5	0.15	0.10	240	"
C	11.5(79)	0.05(0.013)	4.2(1.1)	No. 1	5	0.15	0.10	240	"
D	13.5(93)	0.05(0.013)	4.2(1.1)	No. 1	5	0.15	0.10	240	"
E	15.0(103)	0.05(0.013)	4.2(1.1)	No. 1	5	0.15	0.10	240	"

^A At 760 mm Hg pressure (101.3 kPa).

^B The intentional addition of lead compounds is not permitted. Current EPA promulgations call for 0.05 g of lead per gallon (0.013 g/litre) maximum and 0.005 g of phosphorus per gallon (0.0013 g/litre) maximum, effective July 1, 1974.

^C See Table 3.

Source: ASTM D439-79, 1979

TABLE C-2. GASOLINE ANTIKNOCK INDEXES AND THEIR APPLICATION

Leaded Gasoline (for Vehicles Which can or Must use Leaded Gasoline)	
Antiknock Index (RON + MON)/2, min ^A	Application
87	For vehicles with low antiknock requirements.
89	Meets antiknock requirements of most 1970 and prior model vehicles that were designed to operate on leaded gasoline and most 1971 and later model vehicles that can use leaded gasoline.
93	For 1970 and most prior model vehicles with high antiknock requirements and for later model vehicles with high antiknock requirements that can use leaded gasoline.
Unleaded Gasoline (for Vehicles Which can or Must use Unleaded Gasoline)	
Antiknock Index (RON + MON)/2, min ^A	Application
85	For vehicles with low antiknock requirements.
87 ^B	Meets antiknock requirements of most 1971 and later model vehicles.
90	For most 1971 and later model vehicles with high antiknock requirements.

^A Reductions for altitude are allowed in accordance with Fig. 1 of Specification D 439.

^B In addition, motor octane number must not be less than 82.0.

Source: ASTM, D439-79, 1979

TABLE C-3. SCHEDULE OF SEASONAL AND GEOGRAPHICAL VOLATILITY CLASSES

This schedule, subject to agreement between purchaser and seller, represents the time and place of use of the gasoline. Shipments intended for future use may anticipate this schedule. Where alternative classes are permitted, the option shall be exercised by the seller.

State	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Alabama	D	D	D/C	C	C/B	B	B	B	B/C	C	C/D	D
Alaska	E	E	E	E/D	D	D	D	D	D/E	E	E	E
Arizona	D/C	C	C/B	B	B/A	A	A	A	A/B	B/C	B/C	C/D
Arkansas	D	D	D/C	C	C/B	B	B	B	B/C	C	C/D	D
California:												
North Coast	D	D	D	D/C	C	C	C	C	C	C	C/D	D
South Coast	D	D	D/C	C	C	C/B	B	B	B	B/C	C	C/D
Southeast	D/C	C	C/B	B	B/A	A	A	A	A/B	B/C	B/C	C/D
Interior	D	D	D/C	C	C/B	B	B	B	B	B/C	C/D	D
Colorado	D	D	D/C	C/B	B	B/A	A	A	A/B	B/C	C/D	D
Connecticut	E	E	E/D	D	D/C	C	C	C	C	C/D	D/E	E
Delaware	E	E/D	D	D/C	C	C	C	C	C	C/D	D	D/E
District of Columbia	E	E/D	D	D/C	C	C	B/C	B/C	C	C/D	D	D/E
Florida	D/C	C	C	C	C	C	C	C	C	C	C	C/D
Georgia	D	D	D/C	C	C/B	B	B	B	B/C	C	C/D	D
Hawaii	C	C	C	C	C	C	C	C	C	C	C	C
Idaho	E	E/D	D	D/C	C/B	B	B	B	B	B/C	C/D	D/E
Illinois:												
N 40° Latitude	E	E	E/D	D/C	C	C	C	C	C	C/D	D	D/E
S 40° Latitude	E	E/D	D	D/C	C/B	B	B	B	B/C	C	C/D	D/E
Indiana	E	E	E/D	D/C	C	C	C	C	C	C/D	D	D/E
Iowa	E	E	E/D	D/C	C	C/B	B	B	B/C	C/D	D	D/E
Kansas	E/D	D	D/C	C	C/B	B	B	B	B	B/C	C/D	D
Kentucky	E	E/D	D/C	C	C	C/B	B	B	B/C	C	C/D	D/E
Louisiana	D	D	D/C	C	C/B	B	B	B	B/C	C	C/D	D
Maine	E	E	E/D	D	D/C	C	C	C	C	C/D	D/E	E
Maryland	E	E/D	D	D/C	C	C	B/C	B/C	C	C/D	D	D/E
Massachusetts	E	E	E/D	D	D/C	C	C	C	C	C/D	D/E	E
Michigan	E	E	E/D	D	D/C	C	C	C	C	C/D	D/E	E
Minnesota	E	E	E/D	D/C	C	C	C	C	C	C/D	D/E	E
Mississippi	D	D	D/C	C	C/B	B	B	B	B/C	C	C/D	D
Missouri	E	E/D	D/C	C	C/B	B	B	B	B/C	C	C/D	D/E
Montana	E	E/D	D	D/C	C	C/B	B	B	B/C	C	C/D	D/E
Nebraska	E	E/D	D/C	C	C/B	B	B	B	B/C	C	C/D	D/E
Nevada:												
N 38° Latitude	E/D	D	D/C	C	C/B	B/A	A	A	A/B	B/C	C/D	D/E
S 38° Latitude	D	D/C	C/B	B	B/A	A	A	A	A/B	B/C	C/D	D/E
New Hampshire	E	E	E/D	D	D/C	C	C	C	C	C/D	D/E	E
New Jersey	E	E	E/D	D/C	C	C	C	C	C	C/D	D/E	E
New Mexico:												
N 34° Latitude	D	D/C	C	C/B	B/A	A	A	A/B	B	B/C	C/D	D
S 34° Latitude	D/C	C	C/B	B	B/A	A	A	A	A/B	B/C	C	C/D
New York	E	E	E/D	D/C	C	C	C	C	C	C/D	D/E	E
North Carolina	E/D	D	D/C	C	C/B	B	B	B	B/C	C	C/D	D/E
North Dakota	E	E	E/D	D/C	C	C/B	B	B	B/C	C/D	D/E	E
Ohio	E	E	E/D	D/C	C	C	C	C	C	C/D	D	D/E
Oklahoma	D	D	D/C	C	C/B	B	B	B	B	B/C	C/D	D
Oregon:												
E 122° Longitude	E	E/D	D	D/C	C/B	B	B	B	B	B/C	C/D	D/E
W 122° Longitude	E	E	E/D	D	D/C	C	C	C	C	C/D	D/E	E
Pennsylvania	E	E	E/D	D/C	C	C	C	C	C	C/D	D	D/E
Rhode Island	E	E	E/D	D	D/C	C	C	C	C	C/D	D/E	E
South Carolina	D	D	D/C	C	C/B	B	B	B	B/C	C	C/D	D
South Dakota	E	E/D	D	D/C	C	C/B	B	B	B	B/C	C/D	D/E
Tennessee	E/D	D	D/C	C	C	C/B	B	B	B/C	C	C/D	D/E
Texas:												
E 99° Longitude	D/C	C	C	C/B	B	B	B	B	B	B/C	C	C/D
W 99° Longitude	D/C	C	C/B	B	B/A	A	A	A	A/B	B/C	C	C/D
Utah	E	E/D	D/C	C/B	B/A	A	A	A	A/B	B/C	C/D	D/E
Vermont	E	E	E/D	D	D/C	C	C	C	C	C/D	D/E	E
Virginia	E	E/D	D/C	C	C	C	B/C	B/C	C	C	C/D	D/E
Washington:												
E 122° Longitude	E	E	E/D	D/C	C	C/B	B	B	B/C	C/D	D/E	E
W 122° Longitude	E	E	E/D	D	D/C	C	C	C	C	C/D	D/E	E
West Virginia	E	E/D	D	D/C	C	C	C	C	C	C/D	D/E	E
Wisconsin	E	E	E/D	D	D/C	C	C	C	C	C/D	D/E	E
Wyoming	E	E/D	D/C	C	C/B	B/A	A	A/B	B	B/C	C/D	D/E

^a Details of State Climatological Division by county as indicated:

California, North Coast—Alameda, Contra Costa, Del Norte, Humboldt, Lake, Marin, Mendocino, Monterey, Napa, San Benito, San Francisco, San Mateo, Santa Clara, Santa Cruz, Solano, Sonoma, Trinity
 California, Interior—Lassen, Modoc, Plumas, Sierra, Siskiyou, Alpine, Amador, Butte, Calaveras, Colusa, El Dorado, Fresno, Glenn, Kern (except that portion lying east of the Los Angeles County Aqueduct), Kings, Madera, Mariposa, Merced, Placer, Sacramento, San Joaquin, Shasta, Stanislaus, Sutter, Tehama, Tulare, Tuolumne, Yolo, Yuba, Nevada
 California, South Coast—Orange, San Diego, San Luis Obispo, Santa Barbara, Ventura, Los Angeles (except that portion north of the San Gabriel Mountain range and east of the Los Angeles County Aqueduct)
 California, Southeast—Imperial, Riverside, San Bernardino, Los Angeles (that portion north of the San Gabriel Mountain range and east of the Los Angeles County Aqueduct), Mono, Inyo, Kern (that portion lying east of the Los Angeles County Aqueduct)

Source: ASTM, D439-79, 1979

TABLE C-4. DETAILED REQUIREMENTS FOR DIESEL FUEL OILS^{A,H}

Grade of Diesel Fuel Oil	Flash Point, °C	Cloud Point °C	Water and Sediment, vol %	Carbon Residue on, 10 % Residue, %	Ash, weight %	Distillation Temperatures, °C (°F)		Viscosity				Sulfur, ^g weight %	Copper Strip Corrosion	Cetane Number ^k
	Min	Max	Max	Max	Max	90 % Point		Kinematic, cSt ^c at 40°C		Saybolt, SUS at 100°F		Max	Max	Min
						Min	Max	Min	Max	Min	Max			
No. 1-D A volatile distillate fuel oil for engines in service requiring frequent speed and load changes	38 (100)	^a	0.05	0.15	0.01	...	288 (550)	1.3	2.4	...	34.4	0.50	No. 3	40 ^e
No. 2-D A distillate fuel oil of lower volatility for engines in industrial and heavy mobile service.	52 (125)	^a	0.05	0.35	0.01	282 ^c (540)	338 (640)	1.9	4.1	32.6	40.1	0.50	No. 3	40 ^e
No. 4-D A fuel oil for low and medium speed engines.	55 (130)	^a	0.50	...	0.10	...	...	5.5	24.0	45.0	125.0	2.0	...	30 ^e

^A To meet special operating conditions, modifications of individual limiting requirements may be agreed upon between purchaser, seller, and manufacturer.

^B It is unrealistic to specify low-temperature properties that will ensure satisfactory operation on a broad basis. Satisfactory operation should be achieved in most cases if the cloud point (or wax appearance point) is specified at 6°C above the tenth percentile minimum ambient temperature for the area in which the fuel will be used. The tenth percentile minimum ambient temperatures for the U.S. are shown in Appendix X2. This guidance is of a general nature; some equipment designs, use flow improver additives, fuel properties, and/or operations may allow higher or require lower cloud point fuels. Appropriate low temperature operability properties should be agreed on between the fuel supplier and purchaser for the intended use and expected ambient temperatures.

^C When cloud point less than -12°C (10°F) is specified, the minimum viscosity shall be 1.7 cSt (or mm²/s) and the 90 % point shall be waived.

^D In countries outside the U.S.A., other sulfur limits may apply.

^E Where cetane number by Method D 613 is not available, ASTM Method D 976, Calculated Cetane Index of Distillate Fuels⁴ may be used as an approximation. Where there is disagreement, method D 613 shall be the reference method.

^F Low-atmospheric temperatures as well as engine operation at high altitudes may require use of fuels with higher cetane ratings.

^G 1 cSt = 1 mm²/s.

^H The values stated in SI units are to be regarded as the standard. The values in U.S. customary units are for information only.

Source: ASTM D975-78, 1979

TABLE C-5. DETAILED REQUIREMENTS OF AVIATION TURBINE FUELS^A

Property	Jet A or Jet A-1	Jet B	ASTM Test Method ^B
Acidity, total max, mg KOH/g	0.1	...	D 974 or D 3242
Aromatics, vol, max, %	20 ^C	20 ^C	D 1319
Sulfur, mercaptan, ^D wt, max, %	0.003	0.003	D 1323
Sulfur, total wt, max, %	0.3	0.3	D 1266 or D 1552 or D 2622
Distillation temperature, °F (°C):			
10% recovered, max, temp	400 (204.4)	...	D 86
20% recovered, max, temp	...	290 (143.3)	
50% recovered, max, temp	report	370 (187.8)	
90% recovered, max, temp	report	470 (243.3)	
Final boiling point, max, °F (°C)	572 (300)	...	
Distillation residue, max, %	1.5	1.5	
Distillation loss, max, %	1.5	1.5	
Flash point, min, °F (°C)	100 (37.8)	...	D 56 or D 3243 ^E
Gravity, max, °API (min, sp gr) at 60°F	51 (0.7753)	57 (0.7507)	D 1298
Gravity, min, °API (max, sp gr) at 60°F	37 (0.8398)	45 (0.8017)	D 1298
Vapor pressure, max, lb	...	3	D 323
Freezing point, max, °C	-40 ^F Jet A -50 ^F Jet A-1	-50 ^F	D 2386
Viscosity -4°F (-20°C) max, cSt	8	...	D 445
Net heat of combustion, min, Btu/lb	18,400 ^F	18,400 ^F	D 1405 or D 2382
Combustion properties: one of the following requirements shall be met:			
(1) Luminometer number, min or	45	45	D 1740
(2) Smoke point, min or	25	25	D 1322
(3) Smoke point, min and	20 ^G	20 ^G	D 1322
Naphthalenes, vol, max, %	3	3	D 1840
Corrosion, copper strip 2 h at 212°F (100°C) max	No. 1	No. 1	D 130
Thermal stability: one of the following requirements shall be met:			
(1) Filter pressure drop, max, in. Hg	3	3	D 1660 ^H
Preheater deposit less than	Code 3	Code 3	
(2) Filter pressure drop, max, mm Hg	25	25	D 3241 ^I
Tube deposit less than	Code 3	Code 3	
Existent gum, mg/100 ml, max	7	7	D 381
Water reaction:			
Separation rating, max	2	2	D 1094
Interface rating, max	1b	1b	D 1094
Additives	See 4.2		
Electrical conductivity, pS/m	...	...	D 2624 or D 3114

^A The requirements herein are absolute and are not subject to correction for tolerance of the test methods. If multiple determinations are made, average results shall be used.

^B The test methods indicated in this table are referred to in Section 9.

^C Jet A with an aromatics content over 20 volume % but not exceeding 25 volume % and Jet A-1 or Jet B with an aromatics content over 20 volume % but not exceeding 22 volume % is permitted provided the supplier (seller) notifies the purchaser of the volume, distribution and aromatic content within 90 days of date shipment unless other reporting conditions as agreed to by both parties. This footnote is subject to reapproval in 1981.

^D The mercaptan sulfur determination may be waived if the fuel is considered sweet by the doctor test described in 4.2 of Specification D 484, for Hydrocarbon Drycleaning Solvents.

^E Other freezing points may be agreed upon between supplier and purchaser.

^F Use for Jets A and A-1 the value calculated from Table 8 or Eqs 5, and 9 in Method D 1405. Use for Jet B the value calculated from Table 6 or Eqs 5, and 7 in Method D 1405. Method D 2382 may be used as an alternative. In case of dispute, Method D 2382 must be used.

^G Jet A having a smoke point less than 20 but not less than 18 and a maximum of 3 volume % of naphthalenes and Jet A-1 or Jet B having a smoke point less than 20 but not less than 19 and a maximum of 3 volume % of naphthalenes is permitted provided the supplier (seller) notifies the purchaser of the volume, distribution, smoke point and naphthalene content within 90 days of date shipment unless other reporting conditions as agreed to by both parties. This footnote is subject to reapproval in 1981.

^H Thermal stability test shall be conducted for 5 h at 300°F (148.9°C) preheater temperature 400°F (204.4°C) filter temperature, and at a flow rate of 6 lb/h.

^I Thermal stability test (JFTOT) shall be conducted for 2.5 h at a control temperature of 260°C but if the requirements of Table 1 are not met, the test may be conducted for 2.5 h at a control temperature of 245°C. Results at both test temperatures shall be reported in this case. Tube deposits shall always be reported by the Visual Method; a rating by the Tube Deposit Rating (TDR) optical density method is desirable but not mandatory.

^J A limit of 50 to 300 conductivity units (pS/m) applies only when an electrical conductivity additive is used and under the

^K Results obtained by Method D 3243 may be up to 3°F (1.7°C) below those obtained by Method D 56 which is the preferred method. In case of dispute, Method D 56 will apply.

$$1 \text{ pS/m} = 1 \times 10^{-12} \Omega^{-1} \text{ m}^{-1}$$

Source: ASTM D1655-79, 1979

TABLE C-6. DETAILED REQUIREMENTS FOR FUEL OILS^A

Grade of Fuel Oil	Flash Point, °C (°F)	Pour Point, °C (°F)	Water and Sediment, vol %	Carbon Residue on 10 % Bottoms, %	Ash, weight %	Distillation Temperatures, °C (°F)			Saybolt Viscosity, s ^B				Kinematic Viscosity, cSt ^C						Specific Gravity 60/60°F (deg API)	Copper Strip Corrosion	Sulfur, %
						10 % Point	90 % Point		Universal at 38°C (100°F)		Furol at 50°C (122°F)		At 38°C (100°F)		At 40°C (104°F)		At 50°C (122°F)				
	Min	Max	Max	Max	Max	Max	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Max	Max
No. 1 A distillate oil intended for vaporizing pot-type burners and other burners requiring this grade of fuel	38 (100)	-18° (0)	0.05	0.15	...	215 (420)	...	288 (550)	...	...	...	...	1.4	2.2	1.3	2.1	...	...	0.8499 (35 min)	No. 3	0.5
No. 2 A distillate oil for general purpose heating for use in burners not requiring No. 1 fuel oil	38 (100)	-6° (20)	0.05	0.35	...	...	282° (540)	338 (640)	(32.6)	(37.9)	...	...	2.0°	3.6	1.9°	3.4	...	...	0.8762 (30 min)	No. 3	0.5 ^H
No. 4 Preheating not usually required for handling or burning	55 (130)	-6° (20)	0.50	...	0.10	...	...	...	(45)	(125)	...	...	5.8	26.4°	5.5	24.0°	...	...	...	...	...
No. 5 (Light) Preheating may be required depending on climate and equipment	55 (130)	...	1.00	...	0.10	...	...	...	(>125)	(300)	...	...	>26.4	65°	>24.0	58°	...	...	...	...	...
No. 5 (Heavy) Preheating may be required for burning and, in cold climates, may be required for handling	55 (130)	...	1.00	...	0.10	...	...	...	(>300)	(900)	(23)	(40)	>65	194°	>58	168°	(42)	(81)	...	...	...
No. 6 Preheating required for burning and handling	60 (140)	"	2.00 ^E	...	...	...	...	...	(>900)	(9000)	(>45)	(300)	...	...	...	...	>92	638°	...	...	...

^A It is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.

^B In countries outside the United States other sulfur limits may apply.

^C Lower or higher pour points may be specified whenever required by conditions of storage or use. When pour point less than -18°C (0°F) is specified, the minimum viscosity for grade No. 2 shall be 1.7 cSt (31.5 SUS) and the minimum 90 % point shall be waived.

^D Viscosity values in parentheses are for information only and not necessarily limiting.

^E The amount of water by distillation plus the sediment by extraction shall not exceed 2.00 %. The amount of sediment by extraction shall not exceed 0.50 %. A deduction in quantity shall be made for all water and sediment in excess of 1.0 %.

^F Where low sulfur fuel oil is required, fuel oil falling in the viscosity range of a lower numbered grade down to and including No. 4 may be supplied by agreement between purchaser and supplier. The viscosity range of the initial shipment shall be identified and advance notice shall be required when changing from one viscosity range to another. This notice shall be in sufficient time to permit the user to make the necessary adjustments.

^G Where low sulfur fuel oil is required, Grade 6 fuel oil will be classified as low pour +15°C (60°F) max or high pour (no max). Low pour fuel oil should be used unless all tanks and lines are heated.

Source: ASTM D396-79, 1979

TABLE C-7. SUMMARY OF VALUES, SUMMER MOTOR GASOLINE

Test	ASTM method	Grades of motor gasolines		
		Unleaded Average	Regular Average	Premium Average
Gravity, °API	D287	59.3	60.5	61.0
Corrosion, No.	D130	1	1	1
Sulfur content, wt %	D1266	0.029	0.043	0.028
Gum, mg/100 ml	D381	1	1	1
Manganese, g/gal		0.03	-	-
Lead, g/gal	D526	-	2.00	2.50
Octane number, Research	D2699	92.9	93.2	98.7
Octane number, Motor	D2700	83.9	85.9	91.2
Antiknock index [(R+M)/2]		88.5	89.6	95.0
Reid vapor pressure, lb	D323	9.8	9.7	10.0
Vapor-liquid ratio of 20, °F	D439	136	135	135
Distillation	D86			
Temp, °F				
IBP		89	91	89
5% evaporated		107	108	106
10% Do.		121	121	120
20% Do.		146	142	144
30% Do.		171	164	170
50% Do.		221	211	217
70% Do.		266	267	261
90% Do.		333	343	331
95% Do.		367	378	366
End point		410	417	410
Residue, vol %		1.0	1.0	1.0
Loss, vol %		1.7	1.5	1.7

Source: BETC, 1978

TABLE C-8. SUMMARY OF VALUES, WINTER MOTOR GASOLINE

Test	ASTM method	Grades of motor gasolines		
		Unleaded Average	Regular Average	Premium Average
Gravity, °API	D287	60.9	62.2	62.6
Corrosion, No.	D130	1	1	1
Sulfur content, wt %	D1266	0.028	0.038	0.028
Gum, mg/100 ml	D381	1	1	1
Benzene	D3606	1.19	1.28	1.11
Manganese, AA, g/gal		0.03	-	-
Lead, g/gal	D526	-	1.56	2.15
Octane number, Research	D2699	92.9	93.2	98.8
Octane number, Motor	D2700	83.9	85.7	91.0
Antiknock index [(R+M)/2]		88.4	89.5	94.9
Reid vapor pressure, lb	D323	12.5	12.4	12.3
Vapor-liquid ratio of 20, °F	D439	122	120	122
Distillation	D86			
Temp, °F				
IBP		83	83	83
5% evaporated		95	95	95
10% Do.		107	107	108
20% Do.		130	127	131
30% Do.		157	150	158
50% Do.		212	201	210
70% Do.		259	258	256
90% Do.		329	334	328
95% Do.		363	370	363
End point		405	410	406
Residue, vol %		0.9	0.9	0.9
Loss, vol %		2.4	2.2	2.4

Source: BETC, 1978

TABLE C-9. SUMMARY OF CITY-BUS TYPE DIESEL FUELS

Geographic distribution of diesel fuels Districts within region Additional districts Number of fuels		Eastern region A,B,C D,E,F,G 29			Southern region D A,B,C,E,F,G,I,J 16			Central region E,F,G A,B,C,D,I,J,K 27			Rocky Mountain region H,I,J,K D,E,F,G,L,M,N,P 15			Western region L,M,N,O,P H,I,K 16		
Test	ASTM	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum
Gravity, °API	D287	35.1	42.3	46.1	34.6	41.8	45.2	34.6	41.4	44.6	35.0	41.3	44.9	32.8	41.3	48.3
Flash point, °F	D93	124	-	200	126	-	172	122	-	172	120	-	170	110	-	172
Color:																
ASTM	D1500	10.5	-	10.5	10.5	-	1.0	10.5	-	1.5	0.5	-	0.5	10.5	-	3.0
Saybolt chromometer	D156	+30	-	+18	+30	-	+17	+30	-	+17	+30	-	+20	+30	-	+16
Viscosity at 100° F:																
Kinematic, cs	D445	1.44	1.76	2.56	1.5	1.92	2.98	1.49	1.91	2.98	1.4	1.87	2.98	1.4	1.72	2.98
Saybolt Universal, sec.	D68	-	-	34.5	-	-	32.3	-	-	32.3	-	-	32.2	-	-	35.2
Cloud point, °F	D2500	-50	-	10	<-60	-	6	-50	-	8	-68	-	8	-68	-	12
Pour point, °F	D97	-60	-	0	<-60	-	0	-55	-	0	-80	-	0	-80	-	5
Sulfur content, wt %	D129	0.00	0.068	0.30	0.005	0.086	0.39	0.00	0.127	0.39	0.001	0.127	0.39	0.001	0.169	1.10
Aniline point, °F	D611	138.0	146.6	166	135.0	148.1	175.2	135.0	146.8	158.0	136.2	144.8	158.0	131.2	140.9	164.5
Carbon residue on 10%, wt %	D524	0.00	0.057	0.15	0.00	0.059	0.16	0.00	0.071	0.17	0.00	0.064	0.103	0.02	0.080	0.16
Ash, wt %	D482	0.000	0.001	0.01	0.000	0.0003	0.001	0.000	0.0008	0.01	0.000	0.0003	0.001	0.000	0.0005	0.002
Cetane number	D613	44.9	49.2	52.0	45.2	50.6	61.5	44.0	49.1	52.0	40.6	45.4	51	40.6	46.0	51
Cetane index	D975	48.0	52.4	61.9	46.8	50.1	54.7	43.7	50.3	54.7	43.7	50.3	54.7	42.8	48.7	57.6
Distillation temp, °F, volume recovered:	D86															
IBP		303	353	401	326	361	392	303	352	396	326	355	396	299	350	388
10%		351	391	437	320	396	434	355	393	434	367	399	434	323	392	432
50%		401	436	500	406	439	513	406	442	513	408	437	513	395	429	509
90%		460	497	598	456	499	603	460	506	596	458	500	586	441	487	612
End point		498	538	650	501	540	650	501	550	642	495	540	630	490	531	677

Source: BETC, 1978

TABLE C-10. SUMMARY OF TRACTOR-TRAILER TYPE DIESEL FUELS

Geographic distribution of diesel fuels Districts within region Additional districts Number of fuels		Eastern region A,B,C D,E,F,G,J 56			Southern region D A,B,C,E,F,G,I,J 31			Central region E,F,G A,B,C,D,I,J,K,M,N,O 60			Rocky Mountain region H,I,J,K C,D,E,F,G,L,M,N,O 29			Western region L,M,N,O,P G,H,I,J,K 27		
Test	ASTM	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum
Gravity, °API	D287	31.3	36.3	45.3	31.3	35.8	45.2	31.4	36.5	44.6	32.5	36.7	44.6	30.7	35.5	42.5
Flash point, °F	D93	140	-	200	140	-	186	122	-	210	122	-	194	120	-	212
Color, ASTM	D1500	10.5	-	2.0	10.5	-	2.0	0.0	-	12.0	0.0	-	12.0	10.5	-	3.0
Viscosity at 100° F:																
Kinematic, cs	D445	1.55	2.49	3.05	1.55	2.68	3.21	1.56	2.53	3.42	1.6	2.57	3.42	1.53	2.88	4.1
Saybolt Universal, sec.	D68	-	34.3	36.1	33.2	34.9	36.6	-	34.4	37.3	-	34.5	37.3	-	35.6	39.5
Cloud point, °F	D2500	-48	-	26	<-24	-	14	-48	-	14	-52	-	28	-57	-	50
Pour point, °F	D97	-50	-	5	<-30	-	12	-50	-	5	-50	-	25	-55	-	25
Sulfur content, wt %	D129	0.01	0.184	0.46	0.012	0.236	0.97	0.03	0.225	0.46	0.05	0.279	0.47	0.02	0.308	1.10
Aniline point, °F	D611	118.5	142.9	166	128	145.8	175.2	118.5	145.9	176	136.5	146.4	158.7	129.2	145.8	158.0
Carbon residue on 10%, wt %	D524	0.004	0.102	0.32	0.004	0.100	0.32	0.00	0.101	0.24	0.00	0.082	0.18	0.03	0.094	0.22
Ash, wt %	D482	0.000	0.0019	0.01	0.000	0.0022	0.01	0.000	0.0014	0.01	0.000	0.0006	0.005	0.000	0.0006	0.002
Cetane number	D613	39	46.5	57	40	46.3	61.5	39	46.3	57	44	46.6	53.0	43.8	45.9	49
Cetane index	D975	40.3	49.4	61.9	42.4	50.0	55.8	42.4	49.6	56.2	43.7	49.3	55.0	42.7	50.2	65.7
Distillation temp, °F, volume recovered:	D86															
IBP		303	372	426	323	380	420	303	374	451	332	373	426	336	379	469
10%		371	424	459	386	430	460	360	424	478	353	421	462	370	438	508
50%		415	494	536	415	502	533	408	492	528	408	491	538	416	506	544
90%		466	576	618	466	585	626	470	573	618	466	574	645	473	587	645
End point		508	624	688	518	632	688	508	621	682	512	619	693	512	633	693

Source: BETC, 1978

TABLE C-11. SUMMARY OF RAILROAD TYPE DIESEL FUELS

Geographic distribution of diesel fuels Districts within region Additional districts Number of fuels		Eastern region A,B,C D,E,F,G,J 25			Southern region D A,B,C,E,G,I,J 20			Central region E,F,G A,B,C,D,I,J,M,N,O 32			Rocky Mountain region H,I,J,K C,D,E,F,G,L,M,N,O,P 20			Western region L,M,N,O,P G,H,I,J,K 11		
Test	ASTM	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum
Gravity, °API	D287	30.2	35.5	43.3	30.2	34.7	39.4	30.2	34.5	41.3	30.0	34.8	41.3	32.5	35.1	36.5
Flash point, °F	D93	138	-	200	138	-	182	134	-	194	150	-	194	156	-	210
Color, ASTM	D1500	10.5	-	12.0	0.0	-	12.0	0.0	-	3.0	0.0	-	12.0	10.5	-	3.0
Viscosity at 100° F:																
Kinematic, cs	D445	2.1	2.65	4.99	2.06	2.70	3.21	1.82	2.55	3.01	1.82	2.69	3.42	2.3	2.89	3.76
Saybolt Universal, sec.	D88	32.9	34.8	42.4	32.8	35.0	36.6	32.0	34.5	36.0	32.0	34.9	37.3	33.6	35.6	38.4
Cloud point, °F	D2500	-6	-	28	-6	-	20	-6	-	12	-16	-	28	-20	-	28
Pour point, °F	D97	-30	-	15	-30	-	0	-30	-	0	-30	-	25	-30	-	25
Sulfur content, wt%	D129	0.02	0.195	0.46	0.09	0.239	0.46	0.06	0.281	0.74	0.06	0.343	0.74	0.06	0.290	0.45
Aniline point, °F	D611	118.0	141.4	180	110	139.5	156	118.0	140.6	156	131.6	141.3	155.0	112.6	144.5	158.0
Carbon residue on 10%, wt%	D524	0.02	0.105	0.19	0.01	0.093	0.20	0.0	0.109	0.20	0.04	0.105	0.18	0.056	0.112	0.22
Ash, wt %	D482	0.000	0.0009	0.005	0.000	0.0007	0.005	0.000	0.0010	0.007	0.000	0.0008	0.007	0.000	0.0005	0.002
Cetane number	D613	35.8	45.5	55.1	35.8	43.8	49.6	35.8	42.5	49.6	39.3	44.2	50	34.0	44.8	48
Cetane index	D975	44.2	54.3	68.9	34.8	48.7	54.9	42.4	48.2	54.9	43.0	48.9	55.0	45.8	50.4	55.0
Distillation temp, °F, volume recovered:	D86															
IBP		332	377	512	346	375	402	332	373	426	338	379	426	343	380	426
10 %		404	432	540	409	427	444	398	427	459	405	435	462	405	437	474
50 %		474	505	572	469	499	533	442	497	527	442	503	538	436	506	544
90 %		544	585	631	544	583	609	494	583	619	494	588	645	540	595	645
End point		597	632	665	606	633	661	520	633	670	520	634	693	615	644	693

Source: BETC, 1978

TABLE C-12. SUMMARY OF STATIONARY/MARINE TYPE DIESEL FUELS

Geographic distribution of diesel fuels Districts within region Additional districts Number of fuels		Eastern region A,B,C E,F,G 4			Southern region D 3			Central region E,F,G C 3			Rocky Mountain region H,I,J,K L 2			Western region L,M,N,O,P K 2		
Test	ASTM	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	(2 fuels)			(2 fuels)		
Gravity, °API	D287	15.2	26.7	39.6	24.7	29.5	34.2	33.4	34.8	37.4	-	-	-	-	-	-
Flash point, °F	D93	144	-	>230	160	-	250	134	-	148	-	-	-	-	-	-
Color, ASTM	D1500	11.0	-	1.5	0.5	-	1.0	0.5	-	2.0	-	-	-	-	-	-
Viscosity at 100° F:																
Kinematic, cs	D445	2.28	2.38	2.47	2.44	8.10	19.2	2.12	2.40	2.70	-	-	-	-	-	-
Saybolt Universal, sec.	D88	33.6	33.9	34.2	34.1	52.4	94.5	33.0	34.0	35.0	-	-	-	-	-	-
Cloud point, °F	D2500	-2	-	8	-4	-	0	-2	-	0	-	-	-	-	-	-
Pour point, °F	D97	-25	-	75	-15	-	65	-25	-	-15	-	-	-	-	-	-
Sulfur content, wt %	D129	0.21	0.33	0.52	0.09	1.02	2.84	0.15	0.30	0.42	-	-	-	-	-	-
Aniline point, °F	D611	-	-	157.0	-	-	-	-	-	136.0	-	-	-	-	-	-
Carbon residue:																
on 10%, wt%	D524	-	-	0.12	0.01	0.03	0.05	0.12	0.14	0.18	-	-	-	-	-	-
on 100%, wt%		-	-	-	-	-	0.40	-	-	-	-	-	-	-	-	-
Ash, wt%	D482	0.0	-	<0.001	0.000	0.007	0.01	0.0	0.001	0.001	-	-	-	-	-	-
Cetane number	D613	-	-	-	38	40	41	-	-	-	-	-	-	-	-	-
Cetane index	D975	44.2	49.1	53.9	-	-	-	42.4	44.2	47.1	-	-	-	-	-	-
Distillation temp, °F, volume recovered:	D86															
IBP		332	334	336	368	376	383	332	349	358	-	-	-	-	-	-
10 %		400	404	408	422	433	443	398	412	425	-	-	-	-	-	-
50 %		484	489	493	502	516	530	470	485	493	-	-	-	-	-	-
90 %		530	556	582	598	625	652	562	584	597	-	-	-	-	-	-
End point		631	643	654	642	661	679	622	630	637	-	-	-	-	-	-

Source: BETC, 1978

TABLE C-13. SUMMARY OF JET FUELS

	JP-4	JP-5	Jet A	Jet A-1	Jet B
Number of fuels	28	7	65	1	2
Gravity, °API	53.9	41.4	43.2	47.2	55.2
Distillation					
Temperature:					
10% recovered, °F	211	385	370	369	230
50% recovered, °F	299	420	414	401	332
90% recovered, °F	395	470	472	426	414
Recovered at 400°F, %	85.7	24.1	37.6	45.5	85.4
Reid Vapor pressure, lb	2.6	---	0.2	---	2.5
Freezing point, °F	-79	-56	-50	-68	-78
Viscosity, kinematic, -30°F, cSt	2.4	9.7	9.4	6.17	---
Aniline point, °F	130.8	143.0	143.6	153.5	135.6
Aniline-gravity constant, No.	7,061	5,920	6,204	7,245	7,485
Water tolerance, ml	0.3	0.0	0.3	0.0	0.0
Sulfur:					
Total, wt %	0.044	0.068	0.061	0.05	0.042
Mercaptan, wt %	0.0004	0.0006	0.0008	<0.0001	0.0004
Naphthalenes, wt %	0.2	1.0	1.70	0.1	---
Aromatic content, vol %	12.2	18.0	17.2	9.5	10.5
Olefin content, vol %	0.8	0.9	1.2	<0.5	0.9
Smoke point, mm	27.7	22.6	23.1	28.0	28.1
Smoke volatility index	63.5	32.7	38.8	47.1	64.0
Gum, mg/100 ml:					
Existent, at 450°F	0.7	1.1	0.9	1.0	0.8
Potential, at 212°F	1.0	1.0	1.5	---	---
Heat of combustion, net, Btu/lb	18,715	18,533	18,589	18,703	18,761
Luminometer number	61	48	50	---	---
Thermal stability:					
Pressure drop, in. Hg	0.5	0.4	0.3	0.0	1.0
Water separator index, No.	90	96	94	96	91

Source: BETC, 1978

TABLE C-14. SUMMARY OF GRADE 1 FUELS

Geographic distribution of heating oils		Eastern region			Southern region			Central region			Rocky Mountain region			Western region		
Districts within region		A,B,C			D			E,F,G			H,I,J,K			L,M,N,O,P		
Additional districts		D,E,F,G,H			A,B,C,E,F,G,I,J,N			A,B,C,D,E,H,I,J			E,F,G,L,M,N,O,P			A,B,D,H,I,K		
Number of fuels		30			16			30			17			18		
Test	ASTM	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum
Gravity, °API	D287	40.3	42.9	47.9	40.7	42.2	43.3	40.3	42.5	45.3	40.2	42.2	45.3	38.0	42.4	47.8
Flash point, °F	D56	120	-	156	120	-	154	112	-	154	112	-	134	114	-	154
Viscosity at 100° F, cSt	D445	1.0	1.02	1.99	1.49	1.66	1.94	1.5	1.68	1.99	1.5	1.65	1.94	1.40	1.58	1.82
Cloud point, °F	D2500	-68	-	-10	-68	-	-24	-54	-	-20	-60	-	-24	-66	-	-30
Pour point, °F	D97	-70	-	-10	-70	-	-25	-65	-	-25	-80	-	-30	-80	-	-30
Sulfur content, wt%	D129	0.004	0.064	0.29	0.005	0.056	0.17	0.005	0.082	0.29	0.004	0.087	0.2	0.001	0.066	0.15
Aniline point, °F	D611	138	146.2	162	126	143.7	153.6	126	145.7	155	136.4	145.4	152	129.2	143.1	159.0
Carbon residue on 10%, wt%	D524	0.00	0.049	0.14	0.00	0.04	0.08	0.00	0.055	0.19	0.01	0.064	0.19	0.01	0.060	0.12
Water and sediment, vol%	D1796	0.00	0.001	0.01	0.00	0.00	0.00	0.00	0.0004	0.01	0.000	0.000	0.001	0.00	0.0001	0.001
Distillation temp, °F																
volume recovered:	D86															
10%		321	348	377	321	355	379	314	347	380	314	344	380	294	342	377
50%		359	383	400	362	387	413	354	385	413	354	381	413	344	377	400
90%		396	424	448	410	429	448	404	428	455	408	428	447	386	423	448
End point		439	477	506	460	482	506	460	484	530	459	488	520	436	478	516
		476	519	564	490	520	539	490	527	564	492	532	578	490	522	578

Source: BETC, 1978

TABLE C-15. SUMMARY OF GRADE 2 FUELS

Geographic distribution of heating oils Districts within region Additional districts Number of fuels		Eastern region A,B,C D,E,F,G,J 51			Southern region D A,B,C,E,F,G,I,J 25			Central region E,F,G A,B,C,D,I,J 39			Rocky Mountain region H,I,J,K A,B,D,E,F,G,L,M,N,O,P 22			Western region L,M,N,O,P H,I,J,K 20		
Test	ASTM	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum
Gravity, °API	D887	21.6	34.8	45.5	30.7	35.1	45.2	21.6	35.1	40.0	31.9	35.1	39.4	31.9	35.4	41.6
Flash point, °F	D93	130	-	196	144	-	184	126	-	196	126	-	218	136	-	218
Viscosity at 100° F, cs	D445	1.93	2.68	4.71	2.19	2.78	3.65	2.0	2.55	3.65	1.86	2.77	3.76	2.10	2.94	3.63
Cloud point, °F	D2500	<-20	-	40	-16	-	20	<-20	-	20	-10	-	20	-12	-	46
Pour point, °F	D97	<-30	-	35	-35	-	5	-40	-	5	-40	-	0	-40	-	15
Sulfur content, wt%	D129	0.041	0.219	0.48	0.06	0.198	0.48	0.095	0.230	0.46	0.07	0.29	0.47	0.01	0.245	0.47
Aniline point, °F	D611	69	141.0	180	130	146.6	176.0	69	139.4	180	126	144.4	159	126	146.4	158
Carbon residue on 10%, wt%	D524	0.00	0.105	0.30	0.015	0.107	0.20	0.00	0.111	0.20	0.04	0.109	0.20	0.02	0.103	0.19
Water and sediment, vol%	D1796	0.000	0.004	0.05	0.0	0.0001	0.002	0.0	0.002	0.05	0.000	0.004	0.05	0.00	0.005	0.05
Distillation temp, °F volume recovered:	D86															
IBP		310	369	425	322	373	420	338	375	425	332	375	432	327	389	444
10%		374	422	468	406	430	455	378	425	468	376	431	484	378	445	484
50%		460	496	572	465	504	541	460	496	541	464	506	541	476	516	541
90%		542	588	674	542	593	614	542	580	612	548	586	619	557	590	619
End point		581	640	740	612	640	664	581	631	674	586	630	674	586	634	674

Source: BETC, 1978

TABLE C-16. SUMMARY OF GRADE 4 FUELS

Geographic distribution of heating oils Districts within region Additional districts Number of fuels		Eastern region A,B,C E,F,G 4			Southern region D -			Central region E,F,G C,I,J 3			Rocky Mountain region H,I,J,K O 5			Western region L,M,N,O,P -		
Test	ASTM	Minimum	Average	Maximum	No analyses			Minimum	Average	Maximum	Minimum	Average	Maximum	No analyses		
Gravity, °API	D887	23.0	25.2	28.3	-			20.0	22.1	23.2	14.4	21.1	30.1	-		
Flash point, °F	D93	146	-	200	-			166	-	230	154	-	230	-		
Viscosity at 100° F, cs	D445	13.0	65.1	140	-			13.0	55.7	140	10.3	14.1	20.3	-		
Pour point, °F	D97	-5	-	88	-			-5	-	65	-35	-	65	-		
Sulfur content, wt%	D129	0.33	0.69	1.10	-			0.53	0.81	1.10	0.53	0.85	1.26	-		
Carbon residue on 100%, wt%	D524	-	-	-	-			-	-	-	0.24	3.14	7.3	-		
Ash, wt%	D482	0.02	0.04	0.05	-			0.02	0.04	0.05	0.0	0.009	0.02	-		
Water and sediment, vol%	D1796	0.05	0.12	0.20	-			0.05	0.08	0.1	0.0	0.05	0.1	-		

Source: BETC, 1978

TABLE C-17. SUMMARY OF GRADE 5 (LIGHT) FUELS

Geographic distribution of heating oils Districts within region Additional districts Number of fuels		Eastern region A,B,C E,F,G 1			Southern region D -			Central region E,F,G C,I,J 5			Rocky Mountain region H,I,J,K E,G 4			Western region L,M,N,O,P -		
Test	ASTM	(1 fuel)			No analyses			Minimum	Average	Maximum	Minimum	Average	Maximum	No analyses		
Gravity, °API	D287	20.2			-			17.5	19.6	23.4	4.9	13.3	23.4	-		
Flash point, °F	D93	180			-			150	-	195	135	-	195	-		
Viscosity:																
at 100° F, cs	D445	48.0			-			23.1	43.1	63	28.6	61.0	147	-		
at 122° F, Furol sec	D68	-			-			-	-	-	-	-	-	-		
Pour point, °F	D97	5			-			-15	-	80	5	-	80	-		
Sulfur content, wt%	D129	0.75			-			0.72	1.10	1.49	0.72	1.66	2.82	-		
Carbon residue on 100%, wt%	D524	-			-			-	-	-	-	-	-	-		
Ash, wt%	D482	-			-			0.007	0.014	0.02	0.015	0.018	0.02	-		
Water and sediment, vol%	D1796	0.20			-			0.0	0.10	0.20	0.05	0.08	0.1	-		

Source: BETC, 1978

TABLE C-18. SUMMARY OF GRADE 5 (HEAVY) FUELS

Geographic distribution of heating oils		Eastern region	Southern region	Central region	Rocky Mountain region	Western region		
Districts within region		A,B,C	D	E,F,G	H,I,J,K	L,M,N,O,P		
Additional districts		E			L,N	H,K		
Number of fuels		1	1	1	2	5		
Test	ASTM	(1 fuel)	(1 fuel)	(1 fuel)	Minimum - Maximum	Minimum	Average	Maximum
Gravity, °API	D287	15.0	18.0	15.0	12.5 22.1	12.5	14.3	15.8
Flash point, °F	D93	200	202	200	212 220	182	-	212
Viscosity:								
at 100° F, cs	D445	340	183.5	340	114.0 162.8	77.6	116.2	150
at 122° F, Furol sec	D56	-	-	-	-	-	-	-
Four point, °F	D97	80	-	80	80 90	-15	-	80
Sulfur content, wt%	D129	1.50	1.92	1.50	.88 1.26	0.90	1.26	1.57
Carbon residue on 100%, wt%	D524	-	-	-	-	6.6	7.34	8.22
Ash, wt%	D482	0.05	0.0035	0.05	2.85 .0	0.01	0.023	0.030
Water and sediment, vol%	D1796	0.1	0.1	0.1	0.20	0.0	0.18	0.5

Source: BETC, 1978

TABLE C-19. SUMMARY OF GRADE 6 FUELS

Geographic distribution of heating oils		Eastern region			Southern region			Central region			Rocky Mountain region			Western region		
Districts within region		A,B,C			D			E,F,G			H,I,J,K			L,M,N,O,P		
Additional districts		H,E,F,G			A,B,C,E,G,J			S,C,D,I,J			D,E,F,G,L,H			14		
Number of fuels		26			23			20			12					
Test	ASTM	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum
Gravity, °API	D287	11.0	16.1	24.5	10.2	13.9	23.4	5.5	14.0	20.6	1.7	11.5	20.6	7.1	12.3	19.2
Flash point, °F	D93	164	-	346	164	-	250	160	-	356	152	-	312	168	-	276
Viscosity at 122° F, Furol sec	D56	86	162.1	232	22.8	187.2	285	86	194.8	297	68	183.0	297	36	170	223
Four point, °F	D97	15	-	105	15	-	65	0	-	90	0	-	85	0	-	70
Sulfur content, wt%	D129	0.16	1.22	3.11	0.57	1.70	3.11	0.51	1.45	2.99	0.74	1.57	2.45	0.24	1.46	3.09
Carbon residue on 100%, wt%	D524	0.88	6.81	11.0	3.6	8.16	12.3	0.88	8.43	16	5.1	10.9	16.2	5.4	10.8	16.2
Ash, wt%	D482	0.0	0.038	0.26	0.0025	0.020	0.05	0.003	0.03	0.097	0.003	0.053	0.199	0.001	0.027	0.06
Water by distillation, vol%	D95	0.0	0.08	0.2	0.0	0.09	0.40	0.0	0.08	0.3	0.00	0.08	0.2	0.0	0.06	0.2
Sediment by extraction, wt%	D473	0.0	0.06	0.2	0.00	0.04	0.11	0.00	0.06	0.16	0.00	0.04	0.12	0.02	0.08	0.2

Source: BETC, 1978

TABLE C-20. DENSITY CONVERSION

API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR			API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR		
		LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F			LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F
0.0	1.0760	8.962	67.05	376.4	5.0	1.0366	8.634	64.59	362.6
0.1	1.0752	8.956	67.00	376.1	5.1	1.0359	8.627	64.54	362.3
0.2	1.0744	8.949	66.95	375.8	5.2	1.0351	8.621	64.49	362.1
0.3	1.0736	8.942	66.89	375.6	5.3	1.0344	8.615	64.45	361.8
0.4	1.0728	8.935	66.84	375.3	5.4	1.0336	8.608	64.40	361.6
0.5	1.0720	8.928	66.79	375.0	5.5	1.0328	8.602	64.35	361.3
0.6	1.0712	8.922	66.74	374.7	5.6	1.0321	8.596	64.31	361.0
0.7	1.0703	8.915	66.69	374.4	5.7	1.0313	8.590	64.26	360.8
0.8	1.0695	8.908	66.64	374.1	5.8	1.0306	8.583	64.21	360.5
0.9	1.0687	8.901	66.59	373.9	5.9	1.0298	8.577	64.17	360.2
1.0	1.0679	8.895	66.54	373.6	6.0	1.0291	8.571	64.12	360.0
1.1	1.0671	8.888	66.49	373.3	6.1	1.0283	8.565	64.07	359.7
1.2	1.0663	8.881	66.44	373.0	6.2	1.0276	8.558	64.03	359.5
1.3	1.0655	8.875	66.39	372.7	6.3	1.0269	8.552	63.98	359.2
1.4	1.0647	8.868	66.34	372.4	6.4	1.0261	8.546	63.93	358.9
1.5	1.0639	8.861	66.29	372.2	6.5	1.0254	8.540	63.89	358.7
1.6	1.0631	8.855	66.24	371.9	6.6	1.0246	8.534	63.84	358.4
1.7	1.0623	8.848	66.19	371.6	6.7	1.0239	8.527	63.79	358.1
1.8	1.0615	8.841	66.14	371.3	6.8	1.0231	8.521	63.75	357.9
1.9	1.0607	8.835	66.09	371.1	6.9	1.0224	8.515	63.70	357.6
2.0	1.0599	8.828	66.04	370.8	7.0	1.0217	8.509	63.65	357.4
2.1	1.0591	8.821	65.99	370.5	7.1	1.0209	8.503	63.61	357.1
2.2	1.0583	8.815	65.94	370.2	7.2	1.0202	8.497	63.56	356.9
2.3	1.0575	8.808	65.89	369.9	7.3	1.0195	8.490	63.52	356.6
2.4	1.0568	8.802	65.84	369.7	7.4	1.0187	8.484	63.47	356.3
2.5	1.0560	8.795	65.80	369.4	7.5	1.0180	8.478	63.43	356.1
2.6	1.0552	8.788	65.75	369.1	7.6	1.0173	8.472	63.38	355.8
2.7	1.0544	8.782	65.70	368.8	7.7	1.0165	8.466	63.33	355.6
2.8	1.0536	8.775	65.65	368.6	7.8	1.0158	8.460	63.29	355.3
2.9	1.0528	8.769	65.60	368.3	7.9	1.0151	8.454	63.24	355.1
3.0	1.0520	8.762	65.55	368.0	8.0	1.0143	8.448	63.20	354.8
3.1	1.0513	8.756	65.50	367.7	8.1	1.0136	8.442	63.15	354.6
3.2	1.0505	8.749	65.45	367.5	8.2	1.0129	8.436	63.11	354.3
3.3	1.0497	8.743	65.40	367.2	8.3	1.0122	8.430	63.06	354.0
3.4	1.0489	8.736	65.36	366.9	8.4	1.0114	8.424	63.02	353.8
3.5	1.0481	8.730	65.31	366.6	8.5	1.0107	8.418	62.97	353.5
3.6	1.0474	8.723	65.26	366.4	8.6	1.0100	8.412	62.93	353.3
3.7	1.0466	8.717	65.21	366.1	8.7	1.0093	8.406	62.88	353.0
3.8	1.0458	8.710	65.16	365.8	8.8	1.0086	8.400	62.84	352.8
3.9	1.0451	8.704	65.11	365.6	8.9	1.0078	8.394	62.79	352.5
4.0	1.0443	8.697	65.07	365.3	9.0	1.0071	8.388	62.75	352.3
4.1	1.0435	8.691	65.02	365.0	9.1	1.0064	8.382	62.70	352.0
4.2	1.0427	8.685	64.97	364.8	9.2	1.0057	8.376	62.66	351.8
4.3	1.0420	8.678	64.92	364.5	9.3	1.0050	8.370	62.61	351.5
4.4	1.0412	8.672	64.87	364.2	9.4	1.0043	8.364	62.57	351.3
4.5	1.0404	8.665	64.83	364.0	9.5	1.0035	8.358	62.52	351.0
4.6	1.0397	8.659	64.78	363.7	9.6	1.0028	8.352	62.48	350.8
4.7	1.0389	8.653	64.73	363.4	9.7	1.0021	8.346	62.44	350.5
4.8	1.0382	8.646	64.68	363.1	9.8	1.0014	8.340	62.39	350.3
4.9	1.0374	8.640	64.64	362.9	9.9	1.0007	8.334	62.35	350.0

NOTE -- GAL = U. S. GALLON, BBL = 42 U. S. GALLONS.

Source: API, 1972

TABLE C-20. DENSITY CONVERSION (Cont'd)

API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR			API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR		
		LB/GAL AT 60F	LB/CU FT AT 60F	LB/8BL AT 60F			LB/GAL AT 60F	LB/CU FT AT 60F	LB/8BL AT 60F
10.0	1.0000	8.328	62.30	349.8	15.0	0.9659	8.044	60.17	337.8
10.1	0.9993	8.322	62.26	349.5	15.1	0.9652	8.038	60.13	337.6
10.2	0.9986	8.316	62.22	349.3	15.2	0.9646	8.033	60.09	337.4
10.3	0.9979	8.311	62.17	349.0	15.3	0.9639	8.027	60.05	337.1
10.4	0.9972	8.305	62.13	348.8	15.4	0.9632	8.022	60.01	336.9
10.5	0.9965	8.299	62.08	348.6	15.5	0.9626	8.016	59.97	336.7
10.6	0.9958	8.293	62.04	348.3	15.6	0.9619	8.011	59.93	336.5
10.7	0.9951	8.287	62.00	348.1	15.7	0.9613	8.005	59.89	336.2
10.8	0.9944	8.281	61.95	347.8	15.8	0.9606	8.000	59.85	336.0
10.9	0.9937	8.276	61.91	347.6	15.9	0.9600	7.995	59.81	335.8
11.0	0.9930	8.270	61.87	347.3	16.0	0.9593	7.989	59.77	335.5
11.1	0.9923	8.264	61.82	347.1	16.1	0.9587	7.984	59.73	335.3
11.2	0.9916	8.258	61.78	346.8	16.2	0.9580	7.978	59.69	335.1
11.3	0.9909	8.252	61.74	346.6	16.3	0.9574	7.973	59.64	334.9
11.4	0.9902	8.247	61.69	346.4	16.4	0.9567	7.967	59.60	334.6
11.5	0.9895	8.241	61.65	346.1	16.5	0.9561	7.962	59.56	334.4
11.6	0.9888	8.235	61.61	345.9	16.6	0.9554	7.957	59.52	334.2
11.7	0.9881	8.229	61.56	345.6	16.7	0.9548	7.951	59.48	334.0
11.8	0.9874	8.224	61.52	345.4	16.8	0.9541	7.946	59.44	333.7
11.9	0.9868	8.218	61.48	345.1	16.9	0.9535	7.941	59.40	333.5
12.0	0.9861	8.212	61.43	344.9	17.0	0.9529	7.935	59.36	333.3
12.1	0.9854	8.206	61.39	344.7	17.1	0.9522	7.930	59.32	333.1
12.2	0.9847	8.201	61.35	344.4	17.2	0.9516	7.925	59.28	332.8
12.3	0.9840	8.195	61.31	344.2	17.3	0.9509	7.919	59.24	332.6
12.4	0.9833	8.189	61.26	343.9	17.4	0.9503	7.914	59.20	332.4
12.5	0.9826	8.184	61.22	343.7	17.5	0.9497	7.909	59.16	332.2
12.6	0.9820	8.178	61.18	343.5	17.6	0.9490	7.903	59.12	331.9
12.7	0.9813	8.172	61.14	343.2	17.7	0.9484	7.898	59.08	331.7
12.8	0.9806	8.166	61.09	343.0	17.8	0.9478	7.893	59.04	331.5
12.9	0.9799	8.161	61.05	342.8	17.9	0.9471	7.887	59.01	331.3
13.0	0.9792	8.155	61.01	342.5	18.0	0.9465	7.882	58.97	331.0
13.1	0.9786	8.150	60.97	342.3	18.1	0.9459	7.877	58.93	330.8
13.2	0.9779	8.144	60.92	342.0	18.2	0.9452	7.872	58.89	330.6
13.3	0.9772	8.138	60.88	341.8	18.3	0.9446	7.866	58.85	330.4
13.4	0.9765	8.133	60.84	341.6	18.4	0.9440	7.861	58.81	330.2
13.5	0.9759	8.127	60.80	341.3	18.5	0.9433	7.856	58.77	329.9
13.6	0.9752	8.121	60.76	341.1	18.6	0.9427	7.851	58.73	329.7
13.7	0.9745	8.116	60.71	340.9	18.7	0.9421	7.845	58.69	329.5
13.8	0.9738	8.110	60.67	340.6	18.8	0.9415	7.840	58.65	329.3
13.9	0.9732	8.105	60.63	340.4	18.9	0.9408	7.835	58.61	329.1
14.0	0.9725	8.099	60.59	340.2	19.0	0.9402	7.830	58.57	328.8
14.1	0.9718	8.093	60.55	339.9	19.1	0.9396	7.824	58.53	328.6
14.2	0.9712	8.088	60.51	339.7	19.2	0.9390	7.819	58.50	328.4
14.3	0.9705	8.082	60.46	339.5	19.3	0.9383	7.814	58.46	328.2
14.4	0.9698	8.077	60.42	339.2	19.4	0.9377	7.809	58.42	328.0
14.5	0.9692	8.071	60.38	339.0	19.5	0.9371	7.804	58.38	327.8
14.6	0.9685	8.066	60.34	338.8	19.6	0.9365	7.798	58.34	327.5
14.7	0.9679	8.060	60.30	338.5	19.7	0.9358	7.793	58.30	327.3
14.8	0.9672	8.055	60.26	338.3	19.8	0.9352	7.788	58.26	327.1
14.9	0.9665	8.049	60.22	338.1	19.9	0.9346	7.783	58.22	326.9

NOTE -- GAL = U. S. GALLON, BBL = 42 U. S. GALLONS.

Source: API, 1972

TABLE C-20. DENSITY CONVERSION (Cont'd)

API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR			API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR		
		LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F			LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F
20.0	0.9340	7.778	58.19	326.7	25.0	0.9042	7.529	56.32	316.2
20.1	0.9334	7.773	58.15	326.5	25.1	0.9036	7.524	56.29	316.0
20.2	0.9328	7.768	58.11	326.2	25.2	0.9030	7.519	56.25	315.8
20.3	0.9321	7.762	58.07	326.0	25.3	0.9024	7.515	56.22	315.6
20.4	0.9315	7.757	58.03	325.8	25.4	0.9018	7.510	56.18	315.4
20.5	0.9309	7.752	57.99	325.6	25.5	0.9013	7.505	56.15	315.2
20.6	0.9303	7.747	57.96	325.4	25.6	0.9007	7.500	56.11	315.0
20.7	0.9297	7.742	57.92	325.2	25.7	0.9001	7.495	56.07	314.8
20.8	0.9291	7.737	57.88	325.0	25.8	0.8996	7.491	56.04	314.6
20.9	0.9285	7.732	57.84	324.7	25.9	0.8990	7.486	56.00	314.4
21.0	0.9279	7.727	57.80	324.5	26.0	0.8984	7.481	55.97	314.2
21.1	0.9273	7.722	57.77	324.3	26.1	0.8978	7.476	55.93	314.0
21.2	0.9267	7.717	57.73	324.1	26.2	0.8973	7.472	55.90	313.8
21.3	0.9260	7.712	57.69	323.9	26.3	0.8967	7.467	55.86	313.6
21.4	0.9254	7.707	57.65	323.7	26.4	0.8961	7.462	55.82	313.4
21.5	0.9248	7.702	57.62	323.5	26.5	0.8956	7.457	55.79	313.2
21.6	0.9242	7.696	57.58	323.3	26.6	0.8950	7.453	55.75	313.0
21.7	0.9236	7.691	57.54	323.0	26.7	0.8944	7.448	55.72	312.8
21.8	0.9230	7.686	57.50	322.8	26.8	0.8939	7.443	55.68	312.6
21.9	0.9224	7.681	57.46	322.6	26.9	0.8933	7.439	55.65	312.4
22.0	0.9218	7.676	57.43	322.4	27.0	0.8927	7.434	55.61	312.2
22.1	0.9212	7.671	57.39	322.2	27.1	0.8922	7.429	55.58	312.0
22.2	0.9206	7.666	57.35	322.0	27.2	0.8916	7.425	55.54	311.8
22.3	0.9200	7.661	57.32	321.8	27.3	0.8911	7.420	55.51	311.6
22.4	0.9194	7.656	57.28	321.6	27.4	0.8905	7.415	55.47	311.4
22.5	0.9188	7.651	57.24	321.4	27.5	0.8899	7.411	55.44	311.2
22.6	0.9182	7.646	57.20	321.2	27.6	0.8894	7.406	55.40	311.0
22.7	0.9176	7.642	57.17	320.9	27.7	0.8888	7.401	55.37	310.9
22.8	0.9170	7.637	57.13	320.7	27.8	0.8883	7.397	55.33	310.7
22.9	0.9165	7.632	57.09	320.5	27.9	0.8877	7.392	55.30	310.5
23.0	0.9159	7.627	57.05	320.3	28.0	0.8871	7.387	55.26	310.3
23.1	0.9153	7.622	57.02	320.1	28.1	0.8866	7.383	55.23	310.1
23.2	0.9147	7.617	56.98	319.9	28.2	0.8860	7.378	55.19	309.9
23.3	0.9141	7.612	56.94	319.7	28.3	0.8855	7.373	55.16	309.7
23.4	0.9135	7.607	56.91	319.5	28.4	0.8849	7.369	55.13	309.5
23.5	0.9129	7.602	56.87	319.3	28.5	0.8844	7.364	55.09	309.3
23.6	0.9123	7.597	56.83	319.1	28.6	0.8838	7.360	55.06	309.1
23.7	0.9117	7.592	56.80	318.9	28.7	0.8833	7.355	55.02	308.9
23.8	0.9111	7.587	56.76	318.7	28.8	0.8827	7.350	54.99	308.7
23.9	0.9106	7.582	56.72	318.5	28.9	0.8822	7.346	54.95	308.5
24.0	0.9100	7.578	56.69	318.3	29.0	0.8816	7.341	54.92	308.3
24.1	0.9094	7.573	56.65	318.1	29.1	0.8811	7.337	54.89	308.1
24.2	0.9088	7.568	56.61	317.8	29.2	0.8805	7.332	54.85	307.9
24.3	0.9082	7.563	56.58	317.6	29.3	0.8800	7.327	54.82	307.8
24.4	0.9076	7.558	56.54	317.4	29.4	0.8794	7.323	54.78	307.6
24.5	0.9071	7.553	56.51	317.2	29.5	0.8789	7.318	54.75	307.4
24.6	0.9065	7.548	56.47	317.0	29.6	0.8783	7.314	54.71	307.2
24.7	0.9059	7.544	56.43	316.8	29.7	0.8778	7.309	54.68	307.0
24.8	0.9053	7.539	56.40	316.6	29.8	0.8772	7.305	54.65	306.8
24.9	0.9047	7.534	56.36	316.4	29.9	0.8767	7.300	54.61	306.6

NOTE -- GAL = U. S. GALLON, BBL = 42 U. S. GALLONS.

Source: API, 1972

TABLE C-20. DENSITY CONVERSION (Cont'd)

API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR			API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR		
		LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F			LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F
30.0	0.8762	7.295	54.58	306.4	35.0	0.8498	7.076	52.94	297.2
30.1	0.8756	7.291	54.54	306.2	35.1	0.8493	7.072	52.91	297.0
30.2	0.8751	7.287	54.51	306.0	35.2	0.8488	7.068	52.87	296.8
30.3	0.8745	7.282	54.48	305.8	35.3	0.8483	7.064	52.84	296.7
30.4	0.8740	7.278	54.44	305.7	35.4	0.8478	7.059	52.81	296.5
30.5	0.8735	7.273	54.41	305.5	35.5	0.8473	7.055	52.78	296.3
30.6	0.8729	7.269	54.38	305.3	35.6	0.8468	7.051	52.75	296.1
30.7	0.8724	7.264	54.34	305.1	35.7	0.8463	7.047	52.72	296.0
30.8	0.8718	7.260	54.31	304.9	35.8	0.8458	7.042	52.68	295.8
30.9	0.8713	7.255	54.28	304.7	35.9	0.8453	7.038	52.65	295.6
31.0	0.8708	7.251	54.24	304.5	36.0	0.8448	7.034	52.62	295.4
31.1	0.8702	7.246	54.21	304.3	36.1	0.8443	7.030	52.59	295.2
31.2	0.8697	7.242	54.18	304.2	36.2	0.8438	7.026	52.56	295.1
31.3	0.8692	7.237	54.14	304.0	36.3	0.8433	7.021	52.53	294.9
31.4	0.8686	7.233	54.11	303.8	36.4	0.8428	7.017	52.50	294.7
31.5	0.8681	7.228	54.08	303.6	36.5	0.8423	7.013	52.46	294.5
31.6	0.8676	7.224	54.04	303.4	36.6	0.8418	7.009	52.43	294.4
31.7	0.8670	7.220	54.01	303.2	36.7	0.8413	7.005	52.40	294.2
31.8	0.8665	7.215	53.98	303.0	36.8	0.8408	7.000	52.37	294.0
31.9	0.8660	7.211	53.94	302.8	36.9	0.8403	6.996	52.34	293.8
32.0	0.8654	7.206	53.91	302.7	37.0	0.8398	6.992	52.31	293.7
32.1	0.8649	7.202	53.88	302.5	37.1	0.8393	6.988	52.28	293.5
32.2	0.8644	7.197	53.84	302.3	37.2	0.8388	6.984	52.25	293.3
32.3	0.8639	7.193	53.81	302.1	37.3	0.8383	6.980	52.22	293.1
32.4	0.8633	7.189	53.78	301.9	37.4	0.8378	6.976	52.18	293.0
32.5	0.8628	7.184	53.75	301.7	37.5	0.8373	6.971	52.15	292.8
32.6	0.8623	7.180	53.71	301.6	37.6	0.8368	6.967	52.12	292.6
32.7	0.8618	7.176	53.68	301.4	37.7	0.8363	6.963	52.09	292.5
32.8	0.8612	7.171	53.65	301.2	37.8	0.8358	6.959	52.06	292.3
32.9	0.8607	7.167	53.61	301.0	37.9	0.8353	6.955	52.03	292.1
33.0	0.8602	7.162	53.58	300.8	38.0	0.8348	6.951	52.00	291.9
33.1	0.8597	7.158	53.55	300.6	38.1	0.8343	6.947	51.97	291.8
33.2	0.8591	7.154	53.52	300.5	38.2	0.8338	6.943	51.94	291.6
33.3	0.8586	7.149	53.48	300.3	38.3	0.8333	6.939	51.91	291.4
33.4	0.8581	7.145	53.45	300.1	38.4	0.8328	6.934	51.88	291.2
33.5	0.8576	7.141	53.42	299.9	38.5	0.8324	6.930	51.85	291.1
33.6	0.8571	7.136	53.39	299.7	38.6	0.8319	6.926	51.82	290.9
33.7	0.8565	7.132	53.35	299.5	38.7	0.8314	6.922	51.78	290.7
33.8	0.8560	7.128	53.32	299.4	38.8	0.8309	6.918	51.75	290.6
33.9	0.8555	7.123	53.29	299.2	38.9	0.8304	6.914	51.72	290.4
34.0	0.8550	7.119	53.26	299.0	39.0	0.8299	6.910	51.69	290.2
34.1	0.8545	7.115	53.23	298.8	39.1	0.8294	6.906	51.66	290.0
34.2	0.8540	7.110	53.19	298.6	39.2	0.8289	6.902	51.63	289.9
34.3	0.8534	7.106	53.16	298.5	39.3	0.8285	6.898	51.60	289.7
34.4	0.8529	7.102	53.13	298.3	39.4	0.8280	6.894	51.57	289.5
34.5	0.8524	7.098	53.10	298.1	39.5	0.8275	6.890	51.54	289.4
34.6	0.8519	7.093	53.07	297.9	39.6	0.8270	6.886	51.51	289.2
34.7	0.8514	7.089	53.03	297.7	39.7	0.8265	6.882	51.48	289.0
34.8	0.8509	7.085	53.00	297.6	39.8	0.8260	6.878	51.45	288.9
34.9	0.8504	7.081	52.97	297.4	39.9	0.8256	6.874	51.42	288.7

NOTE -- GAL = U. S. GALLON, BBL = 42 U. S. GALLONS.

Source: API, 1972

TABLE C-20. DENSITY CONVERSION (Cont'd)

API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR			API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR		
		LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F			LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F
40.0	0.8251	6.870	51.39	288.5	45.0	0.8017	6.675	49.93	280.3
40.1	0.8246	6.865	51.36	288.4	45.1	0.8012	6.671	49.91	280.2
40.2	0.8241	6.862	51.33	288.2	45.2	0.8008	6.667	49.88	280.0
40.3	0.8236	6.858	51.30	288.0	45.3	0.8003	6.663	49.85	279.9
40.4	0.8232	6.854	51.27	287.9	45.4	0.7999	6.660	49.82	279.7
40.5	0.8227	6.850	51.24	287.7	45.5	0.7994	6.656	49.79	279.5
40.6	0.8222	6.846	51.21	287.5	45.6	0.7990	6.652	49.76	279.4
40.7	0.8217	6.842	51.19	287.4	45.7	0.7985	6.648	49.74	279.2
40.8	0.8212	6.838	51.15	287.2	45.8	0.7981	6.645	49.71	279.1
40.9	0.8208	6.834	51.12	287.0	45.9	0.7976	6.641	49.68	278.9
41.0	0.8203	6.830	51.09	286.9	46.0	0.7972	6.637	49.65	278.8
41.1	0.8198	6.826	51.06	286.7	46.1	0.7967	6.633	49.62	278.6
41.2	0.8193	6.822	51.03	286.5	46.2	0.7963	6.630	49.60	278.4
41.3	0.8189	6.818	51.00	286.4	46.3	0.7958	6.626	49.57	278.3
41.4	0.8184	6.814	50.98	286.2	46.4	0.7954	6.622	49.54	278.1
41.5	0.8179	6.810	50.95	286.0	46.5	0.7949	6.618	49.51	278.0
41.6	0.8174	6.806	50.92	285.9	46.6	0.7945	6.615	49.48	277.8
41.7	0.8170	6.802	50.89	285.7	46.7	0.7941	6.611	49.46	277.7
41.8	0.8165	6.798	50.86	285.5	46.8	0.7936	6.607	49.43	277.5
41.9	0.8160	6.794	50.83	285.4	46.9	0.7932	6.604	49.40	277.3
42.0	0.8156	6.790	50.80	285.2	47.0	0.7927	6.600	49.37	277.2
42.1	0.8151	6.786	50.77	285.0	47.1	0.7923	6.596	49.35	277.0
42.2	0.8146	6.783	50.74	284.9	47.2	0.7918	6.592	49.32	276.9
42.3	0.8142	6.779	50.71	284.7	47.3	0.7914	6.589	49.29	276.7
42.4	0.8137	6.775	50.68	284.5	47.4	0.7909	6.585	49.26	276.6
42.5	0.8132	6.771	50.65	284.4	47.5	0.7905	6.581	49.24	276.4
42.6	0.8128	6.767	50.62	284.2	47.6	0.7901	6.578	49.21	276.3
42.7	0.8123	6.763	50.59	284.0	47.7	0.7896	6.574	49.18	276.1
42.8	0.8118	6.759	50.57	283.9	47.8	0.7892	6.570	49.15	276.0
42.9	0.8114	6.755	50.54	283.7	47.9	0.7887	6.567	49.13	275.8
43.0	0.8109	6.751	50.51	283.6	48.0	0.7883	6.563	49.10	275.6
43.1	0.8104	6.748	50.48	283.4	48.1	0.7879	6.559	49.07	275.5
43.2	0.8100	6.744	50.45	283.2	48.2	0.7874	6.556	49.04	275.3
43.3	0.8095	6.740	50.42	283.1	48.3	0.7870	6.552	49.02	275.2
43.4	0.8090	6.736	50.39	282.9	48.4	0.7865	6.548	48.99	275.0
43.5	0.8086	6.732	50.36	282.7	48.5	0.7861	6.545	48.96	274.9
43.6	0.8081	6.728	50.33	282.6	48.6	0.7857	6.541	48.93	274.7
43.7	0.8076	6.724	50.30	282.4	48.7	0.7852	6.537	48.91	274.6
43.8	0.8072	6.721	50.28	282.3	48.8	0.7848	6.534	48.88	274.4
43.9	0.8067	6.717	50.25	282.1	48.9	0.7844	6.530	48.85	274.3
44.0	0.8063	6.713	50.22	281.9	49.0	0.7839	6.527	48.83	274.1
44.1	0.8058	6.709	50.19	281.8	49.1	0.7835	6.523	48.80	274.0
44.2	0.8054	6.705	50.16	281.6	49.2	0.7831	6.519	48.77	273.8
44.3	0.8049	6.701	50.13	281.5	49.3	0.7826	6.516	48.74	273.7
44.4	0.8044	6.698	50.10	281.3	49.4	0.7822	6.512	48.72	273.5
44.5	0.8040	6.694	50.08	281.1	49.5	0.7818	6.509	48.69	273.4
44.6	0.8035	6.690	50.05	281.0	49.6	0.7813	6.505	48.66	273.2
44.7	0.8031	6.686	50.02	280.8	49.7	0.7809	6.501	48.64	273.1
44.8	0.8026	6.682	49.99	280.7	49.8	0.7805	6.498	48.61	272.9
44.9	0.8022	6.679	49.96	280.5	49.9	0.7800	6.494	48.58	272.8

NOTE -- GAL = U. S. GALLON, BBL = 42 U. S. GALLONS.

Source: API, 1972

TABLE C-20. DENSITY CONVERSION (Cont'd)

API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR			API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR		
		LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F			LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F
60.0	0.7389	6.151	46.02	258.3	65.0	0.7201	5.994	44.84	251.8
60.1	0.7385	6.148	45.99	258.2	65.1	0.7197	5.991	44.82	251.6
60.2	0.7381	6.145	45.97	258.1	65.2	0.7194	5.988	44.80	251.5
60.3	0.7377	6.141	45.94	257.9	65.3	0.7190	5.985	44.78	251.4
60.4	0.7374	6.138	45.92	257.8	65.4	0.7186	5.982	44.75	251.3
60.5	0.7370	6.135	45.90	257.7	65.5	0.7183	5.979	44.73	251.1
60.6	0.7366	6.132	45.87	257.5	65.6	0.7179	5.976	44.71	251.0
60.7	0.7362	6.129	45.85	257.4	65.7	0.7175	5.973	44.68	250.9
60.8	0.7358	6.126	45.82	257.3	65.8	0.7172	5.970	44.66	250.7
60.9	0.7354	6.122	45.80	257.1	65.9	0.7168	5.967	44.64	250.6
61.0	0.7351	6.119	45.78	257.0	66.0	0.7165	5.964	44.62	250.5
61.1	0.7347	6.116	45.75	256.9	66.1	0.7161	5.961	44.59	250.4
61.2	0.7343	6.113	45.73	256.7	66.2	0.7157	5.958	44.57	250.2
61.3	0.7339	6.110	45.71	256.6	66.3	0.7154	5.955	44.55	250.1
61.4	0.7335	6.106	45.68	256.5	66.4	0.7150	5.952	44.53	250.0
61.5	0.7332	6.103	45.66	256.3	66.5	0.7146	5.949	44.50	249.9
61.6	0.7328	6.100	45.63	256.2	66.6	0.7143	5.946	44.48	249.7
61.7	0.7324	6.097	45.61	256.1	66.7	0.7139	5.943	44.46	249.6
61.8	0.7320	6.094	45.59	255.9	66.8	0.7136	5.940	44.44	249.5
61.9	0.7316	6.091	45.56	255.8	66.9	0.7132	5.937	44.41	249.3
62.0	0.7313	6.087	45.54	255.7	67.0	0.7128	5.934	44.39	249.2
62.1	0.7309	6.084	45.52	255.5	67.1	0.7125	5.931	44.37	249.1
62.2	0.7305	6.081	45.49	255.4	67.2	0.7121	5.928	44.35	249.0
62.3	0.7301	6.078	45.47	255.3	67.3	0.7118	5.925	44.32	248.8
62.4	0.7298	6.075	45.45	255.1	67.4	0.7114	5.922	44.30	248.7
62.5	0.7294	6.072	45.42	255.0	67.5	0.7111	5.919	44.28	248.6
62.6	0.7290	6.069	45.40	254.9	67.6	0.7107	5.916	44.26	248.5
62.7	0.7286	6.065	45.38	254.7	67.7	0.7103	5.913	44.23	248.3
62.8	0.7283	6.062	45.35	254.6	67.8	0.7100	5.910	44.21	248.2
62.9	0.7279	6.059	45.33	254.5	67.9	0.7096	5.907	44.19	248.1
63.0	0.7275	6.056	45.31	254.4	68.0	0.7093	5.904	44.17	248.0
63.1	0.7271	6.053	45.28	254.2	68.1	0.7089	5.901	44.15	247.8
63.2	0.7268	6.050	45.26	254.1	68.2	0.7086	5.898	44.12	247.7
63.3	0.7264	6.047	45.24	254.0	68.3	0.7082	5.895	44.10	247.6
63.4	0.7260	6.044	45.21	253.8	68.4	0.7079	5.892	44.08	247.5
63.5	0.7256	6.041	45.19	253.7	68.5	0.7075	5.889	44.06	247.3
63.6	0.7253	6.037	45.17	253.6	68.6	0.7071	5.886	44.04	247.2
63.7	0.7249	6.034	45.14	253.4	68.7	0.7068	5.883	44.01	247.1
63.8	0.7245	6.031	45.12	253.3	68.8	0.7064	5.880	43.99	247.0
63.9	0.7242	6.028	45.10	253.2	68.9	0.7061	5.878	43.97	246.9
64.0	0.7238	6.025	45.07	253.1	69.0	0.7057	5.875	43.95	246.7
64.1	0.7234	6.022	45.05	252.9	69.1	0.7054	5.872	43.93	246.6
64.2	0.7230	6.019	45.03	252.8	69.2	0.7050	5.869	43.90	246.5
64.3	0.7227	6.016	45.00	252.7	69.3	0.7047	5.866	43.88	246.4
64.4	0.7223	6.013	44.98	252.5	69.4	0.7043	5.863	43.86	246.2
64.5	0.7219	6.010	44.96	252.4	69.5	0.7040	5.860	43.84	246.1
64.6	0.7216	6.007	44.94	252.3	69.6	0.7036	5.857	43.82	246.0
64.7	0.7212	6.004	44.91	252.1	69.7	0.7033	5.854	43.79	245.9
64.8	0.7208	6.000	44.89	252.0	69.8	0.7029	5.851	43.77	245.7
64.9	0.7205	5.997	44.87	251.9	69.9	0.7026	5.848	43.75	245.6

NOTE -- GAL = U. S. GALLON, BBL = 42 U. S. GALLONS.

Source: API, 1972

TABLE C-20. DENSITY CONVERSION (Cont'd)

API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR			API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR		
		LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F			LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F
50.0	0.7796	6.491	48.56	272.6	55.0	0.7587	6.316	47.25	265.3
50.1	0.7792	6.487	48.53	272.5	55.1	0.7583	6.313	47.23	265.1
50.2	0.7788	6.483	48.50	272.3	55.2	0.7579	6.310	47.20	265.0
50.3	0.7783	6.480	48.48	272.2	55.3	0.7575	6.306	47.18	264.9
50.4	0.7779	6.476	48.45	272.0	55.4	0.7571	6.303	47.15	264.7
50.5	0.7775	6.473	48.42	271.9	55.5	0.7567	6.299	47.13	264.6
50.6	0.7770	6.469	48.40	271.7	55.6	0.7563	6.296	47.10	264.4
50.7	0.7766	6.466	48.37	271.6	55.7	0.7559	6.293	47.08	264.3
50.8	0.7762	6.462	48.34	271.4	55.8	0.7555	6.289	47.05	264.2
50.9	0.7758	6.459	48.32	271.3	55.9	0.7551	6.286	47.03	264.0
51.0	0.7753	6.455	48.29	271.1	56.0	0.7547	6.283	47.00	263.9
51.1	0.7749	6.451	48.26	271.0	56.1	0.7543	6.279	46.97	263.7
51.2	0.7745	6.448	48.24	270.8	56.2	0.7539	6.276	46.95	263.6
51.3	0.7741	6.444	48.21	270.7	56.3	0.7535	6.273	46.92	263.4
51.4	0.7736	6.441	48.18	270.5	56.4	0.7531	6.269	46.90	263.3
51.5	0.7732	6.437	48.16	270.4	56.5	0.7527	6.266	46.87	263.2
51.6	0.7728	6.434	48.13	270.2	56.6	0.7523	6.263	46.85	263.0
51.7	0.7724	6.430	48.10	270.1	56.7	0.7519	6.259	46.82	262.9
51.8	0.7720	6.427	48.08	269.9	56.8	0.7515	6.256	46.80	262.7
51.9	0.7715	6.423	48.05	269.8	56.9	0.7511	6.253	46.78	262.6
52.0	0.7711	6.420	48.03	269.6	57.0	0.7507	6.249	46.75	262.5
52.1	0.7707	6.416	48.00	269.5	57.1	0.7503	6.246	46.73	262.3
52.2	0.7703	6.413	47.97	269.3	57.2	0.7499	6.243	46.70	262.2
52.3	0.7699	6.409	47.95	269.2	57.3	0.7495	6.239	46.68	262.0
52.4	0.7694	6.406	47.92	269.0	57.4	0.7491	6.236	46.65	261.9
52.5	0.7690	6.402	47.90	268.9	57.5	0.7487	6.233	46.63	261.8
52.6	0.7686	6.399	47.87	268.7	57.6	0.7483	6.229	46.60	261.6
52.7	0.7682	6.395	47.84	268.6	57.7	0.7479	6.226	46.58	261.5
52.8	0.7678	6.392	47.82	268.5	57.8	0.7475	6.223	46.55	261.4
52.9	0.7674	6.388	47.79	268.3	57.9	0.7471	6.219	46.53	261.2
53.0	0.7669	6.385	47.77	268.2	58.0	0.7467	6.216	46.50	261.1
53.1	0.7665	6.381	47.74	268.0	58.1	0.7463	6.213	46.48	260.9
53.2	0.7661	6.378	47.71	267.9	58.2	0.7459	6.210	46.45	260.8
53.3	0.7657	6.375	47.69	267.7	58.3	0.7455	6.206	46.43	260.7
53.4	0.7653	6.371	47.66	267.6	58.4	0.7451	6.203	46.40	260.5
53.5	0.7649	6.368	47.64	267.4	58.5	0.7447	6.200	46.38	260.4
53.6	0.7645	6.364	47.61	267.3	58.6	0.7443	6.197	46.36	260.3
53.7	0.7640	6.361	47.58	267.2	58.7	0.7440	6.193	46.33	260.1
53.8	0.7636	6.357	47.56	267.0	58.8	0.7436	6.190	46.31	260.0
53.9	0.7632	6.354	47.53	266.9	58.9	0.7432	6.187	46.28	259.8
54.0	0.7628	6.350	47.51	266.7	59.0	0.7428	6.183	46.26	259.7
54.1	0.7624	6.347	47.48	266.6	59.1	0.7424	6.180	46.23	259.6
54.2	0.7620	6.344	47.46	266.4	59.2	0.7420	6.177	46.21	259.4
54.3	0.7616	6.340	47.43	266.3	59.3	0.7416	6.174	46.19	259.3
54.4	0.7612	6.337	47.41	266.1	59.4	0.7412	6.170	46.16	259.2
54.5	0.7608	6.333	47.39	266.0	59.5	0.7408	6.167	46.14	259.0
54.6	0.7603	6.330	47.35	265.9	59.6	0.7405	6.164	46.11	258.9
54.7	0.7599	6.327	47.33	265.7	59.7	0.7401	6.161	46.09	258.8
54.8	0.7595	6.323	47.30	265.6	59.8	0.7397	6.158	46.06	258.6
54.9	0.7591	6.320	47.28	265.4	59.9	0.7393	6.154	46.04	258.5

NOTE -- GAL = U. S. GALLON, BBL = 42 U. S. GALLONS.

Source: API, 1972

TABLE C-20. DENSITY CONVERSION (Cont'd)

API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F	API GRAVITY AT 60F	SPECIFIC GRAVITY 60F/60F	WEIGHT IN AIR LB/GAL AT 60F	LB/CU FT AT 60F	LB/BBL AT 60F
70.0	0.7022	5.845	43.73	245.5	75.0	0.6852	5.704	42.67	239.6
70.1	0.7019	5.842	43.71	245.4	75.1	0.6849	5.701	42.65	239.4
70.2	0.7015	5.840	43.69	245.3	75.2	0.6846	5.698	42.63	239.3
70.3	0.7012	5.837	43.66	245.1	75.3	0.6842	5.695	42.61	239.2
70.4	0.7008	5.834	43.64	245.0	75.4	0.6839	5.693	42.59	239.1
70.5	0.7005	5.831	43.62	244.9	75.5	0.6836	5.690	42.57	239.0
70.6	0.7001	5.828	43.60	244.8	75.6	0.6832	5.687	42.54	238.9
70.7	0.6998	5.825	43.58	244.7	75.7	0.6829	5.684	42.52	238.7
70.8	0.6995	5.822	43.56	244.5	75.8	0.6826	5.682	42.50	238.6
70.9	0.6991	5.819	43.53	244.4	75.9	0.6823	5.679	42.48	238.5
71.0	0.6988	5.816	43.51	244.3	76.0	0.6819	5.676	42.46	238.4
71.1	0.6984	5.814	43.49	244.2	76.1	0.6816	5.673	42.44	238.3
71.2	0.6981	5.811	43.47	244.0	76.2	0.6813	5.671	42.42	238.2
71.3	0.6977	5.808	43.45	243.9	76.3	0.6809	5.668	42.40	238.0
71.4	0.6974	5.805	43.43	243.8	76.4	0.6806	5.665	42.38	237.9
71.5	0.6970	5.802	43.41	243.7	76.5	0.6803	5.662	42.36	237.8
71.6	0.6967	5.799	43.38	243.6	76.6	0.6800	5.660	42.34	237.7
71.7	0.6964	5.796	43.36	243.4	76.7	0.6796	5.657	42.32	237.6
71.8	0.6960	5.794	43.34	243.3	76.8	0.6793	5.654	42.30	237.5
71.9	0.6957	5.791	43.32	243.2	76.9	0.6790	5.651	42.28	237.4
72.0	0.6953	5.788	43.30	243.1	77.0	0.6787	5.649	42.26	237.2
72.1	0.6950	5.785	43.28	243.0	77.1	0.6783	5.646	42.24	237.1
72.2	0.6946	5.782	43.26	242.8	77.2	0.6780	5.643	42.22	237.0
72.3	0.6943	5.779	43.23	242.7	77.3	0.6777	5.641	42.20	236.9
72.4	0.6940	5.776	43.21	242.6	77.4	0.6774	5.638	42.18	236.8
72.5	0.6936	5.774	43.19	242.5	77.5	0.6770	5.635	42.16	236.7
72.6	0.6933	5.771	43.17	242.4	77.6	0.6767	5.633	42.14	236.6
72.7	0.6929	5.768	43.15	242.3	77.7	0.6764	5.630	42.12	236.5
72.8	0.6926	5.765	43.13	242.1	77.8	0.6761	5.627	42.10	236.3
72.9	0.6923	5.762	43.11	242.0	77.9	0.6757	5.624	42.08	236.2
73.0	0.6919	5.759	43.09	241.9	78.0	0.6754	5.622	42.06	236.1
73.1	0.6916	5.757	43.07	241.8	78.1	0.6751	5.619	42.04	236.0
73.2	0.6913	5.754	43.04	241.7	78.2	0.6748	5.616	42.02	235.9
73.3	0.6909	5.751	43.02	241.5	78.3	0.6745	5.614	42.00	235.8
73.4	0.6906	5.748	43.00	241.4	78.4	0.6741	5.611	41.98	235.7
73.5	0.6902	5.745	42.98	241.3	78.5	0.6738	5.608	41.96	235.6
73.6	0.6899	5.743	42.96	241.2	78.6	0.6735	5.606	41.94	235.4
73.7	0.6896	5.740	42.94	241.1	78.7	0.6732	5.603	41.92	235.3
73.8	0.6892	5.737	42.92	241.0	78.8	0.6728	5.600	41.90	235.2
73.9	0.6889	5.734	42.90	240.8	78.9	0.6725	5.598	41.88	235.1
74.0	0.6886	5.731	42.88	240.7	79.0	0.6722	5.595	41.86	235.0
74.1	0.6882	5.729	42.86	240.6	79.1	0.6719	5.592	41.84	234.9
74.2	0.6879	5.726	42.83	240.5	79.2	0.6716	5.590	41.82	234.8
74.3	0.6876	5.723	42.81	240.4	79.3	0.6713	5.587	41.80	234.7
74.4	0.6872	5.720	42.79	240.2	79.4	0.6709	5.584	41.78	234.5
74.5	0.6869	5.717	42.77	240.1	79.5	0.6706	5.582	41.76	234.4
74.6	0.6866	5.715	42.75	240.0	79.6	0.6703	5.579	41.74	234.3
74.7	0.6862	5.712	42.73	239.9	79.7	0.6700	5.576	41.72	234.2
74.8	0.6859	5.709	42.71	239.8	79.8	0.6697	5.574	41.70	234.1
74.9	0.6856	5.706	42.69	239.7	79.9	0.6693	5.571	41.68	234.0

NOTE -- GAL = U. S. GALLON; BBL = 42 U. S. GALLONS.

Source: API, 1972

TABLE C-21. TEMPERATURE CONVERSION CHART

NOTE: The numbers in boldface refer to the temperature in degrees, either Centigrade or Fahrenheit, which it is desired to convert into the other scale. If converting from Fahrenheit to Centigrade degrees, the equivalent temperature will be found in the left column; while if converting from degrees Centigrade to degrees Fahrenheit, the answer will be found in the column on the right.

Centigrade	Fahrenheit	Centigrade	Fahrenheit	Centigrade	Fahrenheit	Centigrade	Fahrenheit	Centigrade	Fahrenheit
-223.3	-370	-70.6	-95	2.2	36	32.8	91	288	550
-220.6	-365	-67.8	-90	2.8	37	33.3	92	293	560
-217.8	-360	-65.0	-85	3.3	38	33.9	93	299	570
-215.0	-355	-62.2	-80	3.9	39	34.4	94	304	580
-212.2	-350	-59.4	-75	4.4	40	35.0	95	310	590
-209.4	-345	-56.7	-70	5.0	41	35.6	96	316	600
-206.7	-340	-53.9	-65	5.6	42	36.1	97	321	610
-203.9	-335	-51.1	-60	6.1	43	36.7	98	327	620
-201.1	-330	-48.3	-55	6.7	44	37.2	99	332	630
-198.3	-325	-45.6	-50	7.2	45	37.8	100	338	640
-195.6	-320	-42.8	-45	7.8	46	43	110	343	650
-192.8	-315	-40.0	-40	8.3	47	49	120	349	660
-190.0	-310	-37.2	-35	8.9	48	54	130	354	670
-187.2	-305	-34.4	-30	9.4	49	60	140	360	680
-184.4	-300	-31.7	-25	10.0	50	66	150	366	690
-181.7	-295	-28.9	-20	10.6	51	71	160	371	700
-178.9	-290	-26.1	-15	11.1	52	77	170	377	710
-176.1	-285	-23.3	-10	11.7	53	82	180	382	720
-173.3	-280	-20.6	-5	12.2	54	88	190	388	730
-170.6	-275	-17.8	0	12.8	55	93	200	393	740
-167.8	-270	-17.2	1	13.3	56	99	210	399	750
-165.0	-265	-16.7	2	13.9	57	100	212	404	760
-162.2	-260	-16.1	3	14.4	58	104	220	410	770
-159.4	-255	-15.6	4	15.0	59	110	230	416	780
-156.7	-250	-15.0	5	15.6	60	116	240	421	790
-153.9	-245	-14.4	6	16.1	61	121	250	427	800
-151.1	-240	-13.9	7	16.7	62	127	260	432	810
-148.3	-235	-13.3	8	17.2	63	132	270	438	820
-145.6	-230	-12.8	9	17.8	64	138	280	443	830
-142.8	-225	-12.2	10	18.3	65	143	290	449	840
-140.0	-220	-11.7	11	18.9	66	149	300	454	850
-137.2	-215	-11.1	12	19.4	67	154	310	460	860
-134.4	-210	-10.6	13	20.0	68	160	320	466	870
-131.7	-205	-10.0	14	20.6	69	166	330	471	880
-128.9	-200	-9.4	15	21.1	70	171	340	477	890
-126.1	-195	-8.9	16	21.7	71	177	350	482	900
-123.3	-190	-8.3	17	22.2	72	182	360	488	910
-120.6	-185	-7.8	18	22.8	73	188	370	493	920
-117.8	-180	-7.2	19	23.3	74	193	380	499	930
-115.0	-175	-6.7	20	23.9	75	199	390	504	940
-112.2	-170	-6.1	21	24.4	76	204	400	510	950
-109.4	-165	-5.6	22	25.0	77	210	410	516	960
-106.7	-160	-5.0	23	25.6	78	216	420	521	970
-103.9	-155	-4.4	24	26.1	79	221	430	527	980
-101.1	-150	-3.9	25	26.7	80	227	440	532	990
-98.3	-145	-3.3	26	27.2	81	232	450	538	1000
-95.6	-140	-2.8	27	27.8	82	238	460	566	1050
-92.8	-135	-2.2	28	28.3	83	243	470	593	1100
-90.0	-130	-1.7	29	28.9	84	249	480	621	1150
-87.2	-125	-1.1	30	29.4	85	254	490	649	1200
-84.4	-120	-0.6	31	30.0	86	260	500	677	1250
-81.7	-115	0.0	32	30.6	87	266	510	704	1300
-78.9	-110	0.6	33	31.1	88	271	520	732	1350
-76.1	-105	1.1	34	31.7	89	277	530	760	1400
-73.3	-100	1.7	35	32.2	90	282	540	788	1450
								816	1500

The formulas at the right may also be used for converting Centigrade or Fahrenheit degrees into the other scales.

$$\text{Degrees Cent., } C^{\circ} = \frac{5}{9} (F^{\circ} + 40) - 40$$

$$\text{Degrees Kelvin, } K^{\circ} = C^{\circ} + 273.18$$

$$\text{Degrees Fahr., } F^{\circ} = \frac{9}{5} (C^{\circ} + 40) - 40$$

$$\text{Degrees Rankine, } R^{\circ} = F^{\circ} + 459.72$$

Source: Chicago Bridge & Iron Co., 1960

C-22. CONVERSION FACTORS

TEMPERATURE

To Convert

From	To	°C	°F	°R	°K
°C.....	—	—	$1.8(^{\circ}\text{C}) + 32$	$1.8(^{\circ}\text{C}) + 459.7$	$^{\circ}\text{C} + 273.2$
°F.....	$(^{\circ}\text{F} - 32)/1.8$	—	—	$^{\circ}\text{F} + 459.7$	$(^{\circ}\text{F} + 459.7)/1.8$
°R.....	$(^{\circ}\text{R} - 491.7)/1.8$	—	$^{\circ}\text{R} - 459.7$	—	$^{\circ}\text{R}/1.8$
°K.....	$^{\circ}\text{K} - 273.2$	—	$1.8(^{\circ}\text{K}) - 459.7$	$1.8(^{\circ}\text{K})$	—

LENGTH

To Convert

From	To	Cm	Meters	Inches	Feet
<i>Multiply By</i>					
Centimeters.....	1.000	0.0100	0.3937	0.03281	
Meters.....	100.0	1.000	39.37	3.281	
Inches.....	2.540	0.0254	1.000	0.08333	
Feet.....	30.48	0.3048	12.00	1.000	

AREA

To Convert

From	To	Sq cm	Sq m	Sq in.	Sq ft
<i>Multiply by</i>					
Sq cm.....	1.000	1.000×10^{-4}	0.1550	1.076×10^{-3}	
Sq m.....	10,000	1.000	1.550	10.76	
Sq in.....	6.451	6.451×10^{-4}	1.000	6.944×10^{-3}	
Sq ft.....	929.0	0.09290	144.0	1.000	

VOLUME

To Convert

From	To	Cu in.	Cu ft	US gal	Imp gal	Cu cm	Liters	Bbl (42's)
<i>Multiply by</i>								
Cu in.	1.000	5.787×10^{-4}	4.329×10^{-3}	3.007×10^{-3}	16.39	0.01639	1.031×10^{-4}	
Cu ft.....	1,728	1.000	7.481	6.232	2.832×10^4	28.32	0.1781	
US gal ...	231.0	0.1337	1.000	0.8326	3,785	3.785	0.02381	
Imp gal ...	277.3	0.1605	1.200	1.000	4,543	4.543	0.02857	
Cu cm....	0.06102	3.531×10^{-5}	2.642×10^{-4}	2.201×10^{-4}	1.000	1.000×10^{-3}	6.290×10^{-6}	
Liters.....	61.02	0.03531	0.2642	0.2201	1,000	1.000	6.290×10^{-3}	
Bbl (42's).	9,700	5.614	42.00	34.97	1.590×10^5	159.0	1.000	

FORCE

To Convert

From	To	Poundals	Pounds	Dynes	Grams
<i>Multiply by</i>					
Poundals.....	1.000	0.03108	13,830	14.10	
Pounds.....	32.17	1.000	4.448×10^5	453.6	
Dynes.....	7.233×10^{-8}	2.248×10^{-6}	1.000	1.020×10^{-3}	
Grams.....	0.07093	2.205×10^{-3}	980.7	1.000	

Source: Maxwell, 1962

C-22. CONVERSION FACTORS (Cont'd)

DENSITY
 To Convert
 From

To	Sp gr	Lb/gal	Lb/cu ft
		<i>Multiply by</i>	
Sp gr.....	1.000	8.347	62.43
Lb/gal.....	0.1198	1.000	7.481
Lb/cu ft.....	0.01602	0.1337	1.000

RATE OF FLOW
 To Convert

From	To	Liters per sec	Gal per min	Gal per hr	Cu ft per sec	Cu ft per min	Cu ft per hr	Bbl per hr	Bbl per day
					<i>Multiply by</i>				
Liters/sec 1.000			15.85	951.2	0.03532	2.119	127.1	22.66	543.8
Gal/min. 0.06308			1.000	60.00	2.228×10^{-3}	0.1337	8.019	1.429	34.30
Gal/hr .. 1.052×10^{-3}			0.01667	1.000	3.713×10^{-5}	2.228×10^{-3}	0.1337	0.02382	0.5716
Cuft/sec 28.30			448.9	2.693×10^4	1.000	60.00	3,600	641.1	1.538×10^4
Cuft/min 0.4717			7.481	448.9	0.01667	1.000	60.00	10.69	256.5
Cu ft/hr. 7.862×10^{-3}			0.1246	7.481	2.778×10^{-4}	0.01667	1.000	0.1781	4.272
Bbl/hr .. 0.04415			0.6997	42.00	1.560×10^{-3}	0.09359	5.615	1.000	24.00
Bbl/day . 1.840×10^{-3}			0.02917	1.750	6.498×10^{-5}	3.899×10^{-3}	0.2340	0.04167	1.000

ENERGY, HEAT, AND WORK
 To Convert

From	To	BTU	Gm-cal	Ft-lb	Hp-hr	Kw-hr
				<i>Multiply by</i>		
BTU.....	1.000		252.0	777.5	3.928×10^{-4}	2.928×10^{-4}
Gm-cal.....	3.968×10^{-3}		1.000	3.086	1.558×10^{-6}	1.162×10^{-6}
Ft-lb.....	1.286×10^{-3}		0.3241	1.000	5.050×10^{-7}	3.767×10^{-7}
Hp-hr.....	2,547		6.417×10^5	1.980×10^6	1.000	0.7457
Kw-hr.....	3,415		8.605×10^5	2.655×10^6	1.341	1.000

POWER
 To Convert

From	To	BTU per hr	Ft-lb per min	Ft-lb per sec	Hp	Kw	Kg-cal per sec	G-cal per sec	Tons of refrig
						<i>Multiply by</i>			
BTU/hr.. 1.000			12.96	0.2160	3.928×10^{-4}	2.928×10^{-4}	6.999×10^{-5}	0.06999	8.333×10^{-5}
Ft-lb/min 0.07715			1.000	0.01667	3.033×10^{-5}	2.260×10^{-5}	5.402×10^{-6}	5.402×10^{-3}	6.431×10^{-6}
Ft-lb/sec 4.630			60.00	1.000	1.820×10^{-3}	1.356×10^{-3}	3.241×10^{-4}	0.3241	3.858×10^{-4}
Hp..... 2,547			33,000	550.0	1.000	0.7457	0.1782	178.2	0.2122
Kw..... 3,415			44,250	737.6	1.341	1.000	0.2390	239.0	0.2845
Kg-cal/sec 1.428×10^4			1.851×10^5	3,086	5.610	4.183	1.000	1,000	1.191
G-cal/sec 14.28			185.1	3.086	5.610×10^{-3}	4.183×10^{-3}	0.0010	1.000	1.191×10^{-3}
Tons of refrig 1.200×10^4			1.555×10^5	2,592	4.712	3.514	0.8400	840.0	1.000

Source: Maxwell, 1962

C-23. HEATS OF COMBUSTION OF LIQUID PETROLEUM FRACTIONS

C-24. NOMOGRAPH FOR CALCULATED CETANE INDEX (ESC-1 METER BASIS—METHOD D 613)

CALCULATED CETANE INDEX

NOTE—The Calculated Cetane Index equation represents a useful tool for *estimating* cetane number. Due to inherent limitations in its application, Index values may not be a valid substitute for ASTM Cetane Numbers as determined in a test engine.

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Source: ASTM D 976-66, 1977

C-25. ALIGNMENT CHART FOR COMPARING VISCOSITY SCALES Use a straight-edge to read horizontally across all scales—far left and far right scales are identical. See Example 2-5 and Table 2.6.

Source: No. American Mfg Co., 1978

C-26. RELATION BETWEEN HEAT OF COMBUSTION AND ANILINE POINT AND GRAVITY OF DISTILLATE PETROLEUM FUELS

Source: Esso Research and Engineering Co., Linden, New Jersey

C-27. GROSS HEATING VALUE FOR DIESEL FUELS

Source: "Diesel Engine Fuel Specifications," compiled by Ethyl Corporation, Detroit, Michigan, August, 1967.

C-28. RELATED PROPERTIES OF DISTILLATE DIESEL FUELS

Source: A. J. Blackwood and G. H. Cloud, "Characteristics of Diesel Fuels, Influencing Power and Economy," SAE Transactions, Vol. 35, (1940), pp. 49-53.

C-29. VOL. PERCENT LINEAR BLENDING CHART

C-30. GRAVITY OF BLENDED FLUIDS

How to Use: Lay straight edge joining gravity of light fluid at the left edge and of heavy fluid at right edge. Read gravity of blended fluid along this line at desired percentage compositions. All gravities must be at same temperature. **Example:** A light fluid with an API

gravity of 30 deg and a heavy fluid with a specific gravity of 1.12 are blended by volume, 60% light and 40% heavy. Employing the above chart, the specific gravity of the blended fluid is 0.973 or 13.8 deg API. API gravity = $141.5 / \text{sp gr} = 131.5$.

TABLE C-31. POUR POINT BLENDING INDICES FOR DISTILLATE STOCKS

ASTM 50% Temp	300	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700
Pour Point																
70	133	131	129	128	127	125	123	120	118	115	113	110	108	105	103	100
65	114	111	109	107	105	103	101	98	96	94	91	88	85	82	79	76
60	99	94	92	90	87	85	82	80	77	74	72	69	67	64	62	60
55	88	79	77	75	73	71	68	66	63	61	58	56	53	50	48	46
50	72	68	66	63	61	59	56	54	52	49	47	44	42	39	37	35
45	60	56	54	52	50	48	46	44	42	40	38	35	33	31	29	27
40	52	48	46	44	42	40	38	36	34	32	30	28	26	24	22	21
35	44	41	39	37	35	33	32	30	28	26	24	23	21	19	18	16
30	37	34	32	31	29	27	26	24	23	21	19	18	16	15	14	13
25	32	29	27	26	24	23	21	20	18	17	15	14	13	12	11	10
20	27	24	23	21	20	19	17	16	15	14	12	11	10	9.1	8.3	7.5
15	23	20	19	18	17	16	14	13	12	11	10	9.0	8.1	7.2	6.4	5.8
10	20	17	16	15	14	13	12	11	9.8	8.8	8.0	7.1	6.3	5.6	5.0	4.5
5	17	15	14	13	12	11	9.7	8.8	7.9	7.1	6.3	5.6	5.0	4.4	3.8	3.3
0	14	12	11	10	9.6	8.7	7.9	7.1	6.3	5.6	5.0	4.4	3.8	3.4	3.0	2.7
-5	12	10	9.5	8.7	8.0	7.2	6.5	5.8	5.1	4.5	3.9	3.4	3.0	2.7	2.4	2.1
-10	10	8.8	8.0	7.3	6.6	5.9	5.3	4.7	4.1	3.6	3.2	2.8	2.5	2.2	1.9	1.6
-15	8.8	7.4	6.8	6.1	5.5	4.9	4.4	3.9	3.4	3.0	2.6	2.2	1.9	1.7	1.4	1.2
-20	7.5	6.3	5.7	5.1	4.6	4.1	3.6	3.2	2.8	2.4	2.1	1.8	1.5	1.3	1.1	0.94
-25	6.4	5.3	4.7	4.2	3.7	3.3	2.9	2.5	2.2	1.9	1.7	1.4	1.2	1.0	0.90	0.72
-30	5.5	4.5	4.0	3.6	3.2	2.8	2.4	2.1	1.8	1.5	1.3	1.1	0.96	0.80	0.67	0.56
-35	4.6	3.7	3.3	2.9	2.6	2.3	2.0	1.7	1.4	1.2	1.0	0.90	0.75	0.62	0.51	0.43
-40	4.0	3.2	2.8	2.5	2.3	1.9	1.6	1.4	1.2	1.0	0.86	0.73	0.62	0.51	0.41	0.33
-45	3.3	2.7	2.4	2.1	1.8	1.5	1.3	1.1	0.98	0.82	0.68	0.58	0.48	0.38	0.31	0.25
-50	2.8	2.3	2.0	1.7	1.5	1.3	1.1	0.93	0.78	0.66	0.56	0.47	0.38	0.31	0.25	0.20
-55	2.5	1.9	1.7	1.4	1.2	1.1	0.90	0.77	0.65	0.55	0.46	0.37	0.30	0.24	0.19	0.15
-60	2.1	1.6	1.4	1.2	1.0	0.87	0.74	0.62	0.52	0.43	0.36	0.30	0.24	0.19	0.14	0.10
-65	1.8	1.4	1.2	1.0	0.85	0.72	0.60	0.50	0.41	0.34	0.28	0.23	0.18	0.14	0.10	0.07
-70	1.5	1.1	0.99	0.84	0.71	0.60	0.50	0.42	0.36	0.30	0.25	0.20	0.15	0.11	0.08	0.05

Source: Chevron Research Company, 1971

TABLE C-32. VISCOSITY BLENDING INDEX NUMBERS

FACTORS FOR VOLUME BLENDING OF VISCOSITIES AT
CONSTANT TEMPERATURE CORRESPONDING TO VALUES
OF KINEMATIC VISCOSITY

Centistokes	0.06	0.21	0.07	0.23	0.08	0.25	0.09	0.26	0.10	0.27	0.11	0.28	0.12	0.29	0.13	0.30	0.14	0.31	0.15	0.32	0.16	0.33	0.17	0.34	0.18	0.35	0.19	0.36	0.20	0.37	0.21	0.38	0.22	0.39	0.23	0.40	0.24	0.41	0.25	0.42	0.26	0.43	0.27	0.44	0.28	0.45	0.29	0.46	0.30	0.47	0.31	0.48	0.32	0.49	0.33	0.50	0.34	0.51	0.35	0.52	0.36	0.53	0.37	0.54	0.38	0.55	0.39	0.56	0.40	0.57	0.41	0.58	0.42	0.59	0.43	0.60	0.44	0.61	0.45	0.62	0.46	0.63	0.47	0.64	0.48	0.65	0.49	0.66	0.50	0.67	0.51	0.68	0.52	0.69	0.53	0.70	0.54	0.71	0.55	0.72	0.56	0.73	0.57	0.74	0.58	0.75	0.59	0.76	0.60	0.77	0.61	0.78	0.62	0.79	0.63	0.80	0.64	0.81	0.65	0.82	0.66	0.83	0.67	0.84	0.68	0.85	0.69	0.86	0.70	0.87	0.71	0.88	0.72	0.89	0.73	0.90	0.74	0.91	0.75	0.92	0.76	0.93	0.77	0.94	0.78	0.95	0.79	0.96	0.80	0.97	0.81	0.98	0.82	0.99	0.83	1.00	0.84	1.01	0.85	1.02	0.86	1.03	0.87	1.04	0.88	1.05	0.89	1.06	0.90	1.07	0.91	1.08	0.92	1.09	0.93	1.10	0.94	1.11	0.95	1.12	0.96	1.13	0.97	1.14	0.98	1.15	0.99	1.16	1.00	1.17	1.01	1.18	1.02	1.19	1.03	1.20	1.04	1.21	1.05	1.22	1.06	1.23	1.07	1.24	1.08	1.25	1.09	1.26	1.10	1.27	1.11	1.28	1.12	1.29	1.13	1.30	1.14	1.31	1.15	1.32	1.16	1.33	1.17	1.34	1.18	1.35	1.19	1.36	1.20	1.37	1.21	1.38	1.22	1.39	1.23	1.40	1.24	1.41	1.25	1.42	1.26	1.43	1.27	1.44	1.28	1.45	1.29	1.46	1.30	1.47	1.31	1.48	1.32	1.49	1.33	1.50	1.34	1.51	1.35	1.52	1.36	1.53	1.37	1.54	1.38	1.55	1.39	1.56	1.40	1.57	1.41	1.58	1.42	1.59	1.43	1.60	1.44	1.61	1.45	1.62	1.46	1.63	1.47	1.64	1.48	1.65	1.49	1.66	1.50	1.67	1.51	1.68	1.52	1.69	1.53	1.70	1.54	1.71	1.55	1.72	1.56	1.73	1.57	1.74	1.58	1.75	1.59	1.76	1.60	1.77	1.61	1.78	1.62	1.79	1.63	1.80	1.64	1.81	1.65	1.82	1.66	1.83	1.67	1.84	1.68	1.85	1.69	1.86	1.70	1.87	1.71	1.88	1.72	1.89	1.73	1.90	1.74	1.91	1.75	1.92	1.76	1.93	1.77	1.94	1.78	1.95	1.79	1.96	1.80	1.97	1.81	1.98	1.82	1.99	1.83	2.00	1.84	2.01	1.85	2.02	1.86	2.03	1.87	2.04	1.88	2.05	1.89	2.06	1.90	2.07	1.91	2.08	1.92	2.09	1.93	2.10	1.94	2.11	1.95	2.12	1.96	2.13	1.97	2.14	1.98	2.15	1.99	2.16	2.00	2.17	2.01	2.18	2.02	2.19	2.03	2.20	2.04	2.21	2.05	2.22	2.06	2.23	2.07	2.24	2.08	2.25	2.09	2.26	2.10	2.27	2.11	2.28	2.12	2.29	2.13	2.30	2.14	2.31	2.15	2.32	2.16	2.33	2.17	2.34	2.18	2.35	2.19	2.36	2.20	2.37	2.21	2.38	2.22	2.39	2.23	2.40	2.24	2.41	2.25	2.42	2.26	2.43	2.27	2.44	2.28	2.45	2.29	2.46	2.30	2.47	2.31	2.48	2.32	2.49	2.33	2.50	2.34	2.51	2.35	2.52	2.36	2.53	2.37	2.54	2.38	2.55	2.39	2.56	2.40	2.57	2.41	2.58	2.42	2.59	2.43	2.60	2.44	2.61	2.45	2.62	2.46	2.63	2.47	2.64	2.48	2.65	2.49	2.66	2.50	2.67	2.51	2.68	2.52	2.69	2.53	2.70	2.54	2.71	2.55	2.72	2.56	2.73	2.57	2.74	2.58	2.75	2.59	2.76	2.60	2.77	2.61	2.78	2.62	2.79	2.63	2.80	2.64	2.81	2.65	2.82	2.66	2.83	2.67	2.84	2.68	2.85	2.69	2.86	2.70	2.87	2.71	2.88	2.72	2.89	2.73	2.90	2.74	2.91	2.75	2.92	2.76	2.93	2.77	2.94	2.78	2.95	2.79	2.96	2.80	2.97	2.81	2.98	2.82	2.99	2.83	3.00	2.84	3.01	2.85	3.02	2.86	3.03	2.87	3.04	2.88	3.05	2.89	3.06	2.90	3.07	2.91	3.08	2.92	3.09	2.93	3.10	2.94	3.11	2.95	3.12	2.96	3.13	2.97	3.14	2.98	3.15	2.99	3.16	3.00	3.17	3.01	3.18	3.02	3.19	3.03	3.20	3.04	3.21	3.05	3.22	3.06	3.23	3.07	3.24	3.08	3.25	3.09	3.26	3.10	3.27	3.11	3.28	3.12	3.29	3.13	3.30	3.14	3.31	3.15	3.32	3.16	3.33	3.17	3.34	3.18	3.35	3.19	3.36	3.20	3.37	3.21	3.38	3.22	3.39	3.23	3.40	3.24	3.41	3.25	3.42	3.26	3.43	3.27	3.44	3.28	3.45	3.29	3.46	3.30	3.47	3.31	3.48	3.32	3.49	3.33	3.50	3.34	3.51	3.35	3.52	3.36	3.53	3.37	3.54	3.38	3.55	3.39	3.56	3.40	3.57	3.41	3.58	3.42	3.59	3.43	3.60	3.44	3.61	3.45	3.62	3.46	3.63	3.47	3.64	3.48	3.65	3.49	3.66	3.50	3.67	3.51	3.68	3.52	3.69	3.53	3.70	3.54	3.71	3.55	3.72	3.56	3.73	3.57	3.74	3.58	3.75	3.59	3.76	3.60	3.77	3.61	3.78	3.62	3.79	3.63	3.80	3.64	3.81	3.65	3.82	3.66	3.83	3.67	3.84	3.68	3.85	3.69	3.86	3.70	3.87	3.71	3.88	3.72	3.89	3.73	3.90	3.74	3.91	3.75	3.92	3.76	3.93	3.77	3.94	3.78	3.95	3.79	3.96	3.80	3.97	3.81	3.98	3.82	3.99	3.83	4.00	3.84	4.01	3.85	4.02	3.86	4.03	3.87	4.04	3.88	4.05	3.89	4.06	3.90	4.07	3.91	4.08	3.92	4.09	3.93	4.10	3.94	4.11	3.95	4.12	3.96	4.13	3.97	4.14	3.98	4.15	3.99	4.16	4.00	4.17	4.01	4.18	4.02	4.19	4.03	4.20	4.04	4.21	4.05	4.22	4.06	4.23	4.07	4.24	4.08	4.25	4.09	4.26	4.10	4.27	4.11	4.28	4.12	4.29	4.13	4.30	4.14	4.31	4.15	4.32	4.16	4.33	4.17	4.34	4.18	4.35	4.19	4.36	4.20	4.37	4.21	4.38	4.22	4.39	4.23	4.40	4.24	4.41	4.25	4.42	4.26	4.43	4.27	4.44	4.28	4.45	4.29	4.46	4.30	4.47	4.31	4.48	4.32	4.49	4.33	4.50	4.34	4.51	4.35	4.52	4.36	4.53	4.37	4.54	4.38	4.55	4.39	4.56	4.40	4.57	4.41	4.58	4.42	4.59	4.43	4.60	4.44	4.61	4.45	4.62	4.46	4.63	4.47	4.64	4.48	4.65	4.49	4.66	4.50	4.67	4.51	4.68	4.52	4.69	4.53	4.70	4.54	4.71	4.55	4.72	4.56	4.73	4.57	4.74	4.58	4.75	4.59	4.76	4.60	4.77	4.61	4.78	4.62	4.79	4.63	4.80	4.64	4.81	4.65	4.82	4.66	4.83	4.67	4.84	4.68	4.85	4.69	4.86	4.70	4.87	4.71	4.88	4.72	4.89	4.73	4.90	4.74	4.91	4.75	4.92	4.76	4.93	4.77	4.94	4.78	4.95	4.79	4.96	4.80	4.97	4.81	4.98	4.82	4.99	4.83	5.00	4.84	5.01	4.85	5.02	4.86	5.03	4.87	5.04	4.88	5.05	4.89	5.06	4.90	5.07	4.91	5.08	4.92	5.09	4.93	5.10	4.94	5.11	4.95	5.12	4.96	5.13	4.97	5.14	4.98	5.15	4.99	5.16	5.00	5.17	5.01	5.18	5.02	5.19	5.03	5.20	5.04	5.21	5.05	5.22	5.06	5.23	5.07	5.24	5.08	5.25	5.09	5.26	5.10	5.27	5.11	5.28	5.12	5.29	5.13	5.30	5.14	5.31	5.15	5.32	5.16	5.33	5.17	5.34	5.18	5.35	5.19	5.36	5.20	5.37	5.21	5.38	5.22	5.39	5.23	5.40	5.24	5.41	5.25	5.42	5.26	5.43	5.27	5.44	5.28	5.45	5.29	5.46	5.30	5.47	5.31	5.48	5.32	5.49	5.33	5.50	5.34	5.51	5.35	5.52	5.36	5.53	5.37	5.54	5.38	5.55	5.39	5.56	5.40	5.57	5.41	5.58	5.42	5.59	5.43	5.60	5.44	5.61	5.45	5.62	5.46	5.63	5.47	5.64	5.48	5.65	5.49	5.66	5.50	5.67	5.51	5.68	5.52	5.69	5.53	5.70	5.54	5.71	5.55	5.72	5.56	5.73	5.57	5.74	5.58	5.75	5.59	5.76	5.60	5.77	5.61	5.78	5.62	5.79	5.63	5.80	5.64	5.81	5.65	5.82	5.66	5.83	5.67	5.84	5.68	5.85	5.69	5.86	5.70	5.87	5.71	5.88	5.72	5.89	5.73	5.90	5.74	5.91	5.75	5.92	5.76	5.93	5.77	5.94	5.78	5.95	5.79	5.96	5.80	5.97	5.81	5.98	5.82	5.99	5.83	6.00	5.84	6.01	5.85	6.02	5.86	6.03	5.87	6.04	5.88	6.05	5.89	6.06	5.90	6.07	5.91	6.08	5.92	6.09	5.93	6.10	5.94	6.11	5.95	6.12	5.96	6.13	5.97	6.14	5.98	6.15	5.99	6.16	6.00	6.17	6.01	6.18	6.02	6.19	6.03	6.20	6.04	6.21	6.05	6.22	6.06	6.23	6.07	6.24	6.08	6.25	6.09	6.26	6.10	6.27	6.11	6.28	6.12	6.29	6.13	6.30	6.14	6.31	6.15	6.32	6.16	6.33	6.17	6.34	6.18	6.35	6.19	6.36	6.20	6.37	6.21	6.38	6.22	6.39	6.23	6.40	6.24	6.41	6.25	6.42	6.26	6.43	6.27	6.44	6.28	6.45	6.29	6.46	6.30	6.47	6.31	6.48	6.32	6.49	6.33	6.50	6.34	6.51	6.35	6.52	6.36	6.53	6.37	6.54	6.38	6.55	6.39	6.56	6.40	6.57	6.41	6.58	6.42	6.59	6.43	6.60	6.44	6.61	6.45	6.62	6.46	6.63	6.47	6.64	6.48	6.65	6.49	6.66	6.50	6.67	6.51	6.68	6.52	6.69	6.53	6.70	6.54	6.71	6.55	6.72	6.56	6.73	6.57	6.74	6.58	6.75	6.59	6.76	6.60	6.77	6.61	6.78	6.62	6.79	6.63	6.80	6.64	6.81	6.65	6.82	6.66	6.83	6.67	6.84	6.68	6.85	6.69	6.86	6.70	6.87	6.71	6.88	6.72	6.89	6.73	6.90	6.74	6.91	6.75	6.92	6.76	6.93	6.77	6.94	6.78	6.95	6.79	6.96	6.80	6.97	6.81	6.98	6.82	6.99	6.83	7.00	6.84	7
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TABLE C-33. FLASH POINT BLENDING INDEX NUMBERS

May be used to blend flash temperatures determined in any apparatus but, preferably, not to blend closed cup with open cup determinations.

Flash Point, °F	0	1	2	3	4	5	6	7	8	9
0	168,000	157,000	147,000	137,000	128,000	120,000	112,000	105,000	98,600	92,400
10	86,600	81,200	76,100	71,400	67,000	62,900	59,000	55,400	52,100	49,000
20	46,000	43,300	40,700	38,300	36,100	34,000	32,000	30,100	28,400	26,800
30	25,200	23,800	22,400	21,200	20,000	18,900	17,800	16,800	15,900	15,000
40	14,200	13,500	12,700	12,000	11,400	10,800	10,200	9,680	9,170	8,690
50	8,240	7,810	7,410	7,030	6,670	6,330	6,010	5,700	5,420	5,150
60	4,890	4,650	4,420	4,200	4,000	3,800	3,620	3,441	3,280	3,120
70	2,970	2,830	2,700	2,570	2,450	2,330	2,230	2,120	2,020	1,930
80	1,840	1,760	1,680	1,600	1,530	1,460	1,400	1,340	1,280	1,220
90	1,170	1,120	1,070	1,020	978	935	896	857	821	786
100	753	722	692	662	635	609	584	560	537	515
110	495	475	456	438	420	404	388	372	358	344
120	331	318	305	294	283	272	261	252	242	233
130	224	216	208	200	193	186	179	172	166	160
140	154	149	144	138	134	129	124	120	116	112
150	108	104	101	97.1	93.8	90.6	87.5	84.6	81.7	79.0
160	76.3	73.8	71.4	69.0	66.7	64.5	62.4	60.4	58.4	56.5
170	54.7	52.9	51.3	49.6	48.0	46.5	45.1	43.6	42.3	40.9
180	39.7	38.4	37.3	36.1	35.0	33.9	32.9	31.9	30.9	30.0
190	29.1	28.2	27.4	26.6	25.8	25.0	24.3	23.6	22.9	22.2
200	21.6	20.9	20.3	19.7	19.2	18.6	18.1	17.6	17.1	16.6
210	16.1	15.7	15.2	14.8	14.4	14.0	13.6	13.3	12.9	12.5
220	12.2	11.9	11.6	11.2	10.9	10.6	10.4	10.1	9.82	9.56
230	9.31	9.07	8.83	8.60	8.37	8.16	7.95	7.74	7.55	7.35
240	7.16	6.98	6.80	6.63	6.47	6.30	6.15	5.99	5.84	5.70
250	5.56	5.42	5.29	5.16	5.03	4.91	4.79	4.68	4.56	4.45
260	4.35	4.24	4.14	4.04	3.95	3.86	3.76	3.68	3.59	3.51
270	3.43	3.35	3.27	3.19	3.12	3.05	2.98	2.91	2.85	2.78
280	2.72	2.66	2.60	2.54	2.48	2.43	2.37	2.32	2.27	2.22
290	2.17	2.12	2.08	2.03	1.99	1.95	1.90	1.86	1.82	1.79

Flash Point, °F	0	10	20	30	40	50	60	70	80	90
300	1.75	1.41	1.15	0.943	0.777	0.643	0.535	0.448	0.376	0.317
400	0.269	0.229	0.196	0.168	0.145	0.125	0.108	0.094	0.082	0.072
500	0.063	0.056	0.049	0.044	0.039	0.035	0.031	0.028	0.025	0.022

Example:	Component	Volume	Flash Point, °F	Blending Index	Volume X Blending Index
	A	0.30	100	753	226
	B	0.10	90	1,170	117
	C	0.60	130	224	134
	Total	1.00	111	477	477

Source: Chevron Research Company, 1971

**TABLE C-34. REID VAPOR PRESSURE BLENDING INDEX NUMBERS FOR
GASOLINES AND TURBINE FUELS**

Vapor Pressure, psi	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.00	0.05	0.13	0.22	0.31	0.42	0.52	0.64	0.75	0.87
1	1.00	1.12	1.25	1.38	1.52	1.66	1.79	1.94	2.08	2.23
2	2.37	2.52	2.67	2.83	2.98	3.14	3.30	3.46	3.62	3.78
3	3.94	4.11	4.28	4.44	4.61	4.78	4.95	5.13	5.30	5.48
4	5.65	5.83	6.01	6.19	6.37	6.55	6.73	6.92	7.10	7.29
5	7.47	7.66	7.85	8.04	8.23	8.42	8.61	8.80	9.00	9.19
6	9.39	9.58	9.78	9.98	10.2	10.4	10.6	10.8	11.0	11.2
7	11.4	11.6	11.8	12.0	12.2	12.4	12.6	12.8	13.0	13.2
8	13.4	13.7	13.9	14.1	14.3	14.5	14.7	14.9	15.2	15.4
9	15.6	15.8	16.0	16.2	16.4	16.7	16.9	17.1	17.3	17.6
10	17.8	18.0	18.2	18.4	18.7	18.9	19.1	19.4	19.6	19.8
11	20.0	20.3	20.5	20.7	20.9	21.2	21.4	21.6	21.9	22.1
12	22.3	22.6	22.8	23.0	23.3	23.5	23.7	24.0	24.2	24.4
13	24.7	24.9	25.2	25.4	25.6	25.9	26.1	26.4	26.6	26.8
14	27.1	27.3	27.6	27.8	28.0	28.3	28.5	28.8	29.0	29.3
15	29.5	29.8	30.0	30.2	30.5	30.8	31.0	31.2	31.5	31.8
16	32.0	32.2	32.5	32.8	33.0	33.2	33.5	33.8	34.0	34.3
17	34.5	34.8	35.0	35.3	35.5	35.8	36.0	36.3	36.6	36.8
18	37.1	37.3	37.6	37.8	38.1	38.4	38.6	38.9	39.1	39.4
19	39.7	39.9	40.2	40.4	40.7	41.0	41.2	41.5	41.8	42.0
20	42.3	42.6	42.8	43.1	43.4	43.6	43.9	44.2	44.4	44.7
21	45.0	45.2	45.5	45.8	46.0	46.3	46.6	46.8	47.1	47.4
22	47.6	47.9	48.2	48.4	48.7	49.0	49.3	49.5	49.8	50.1
23	50.4	50.6	50.9	51.2	51.5	51.7	52.0	52.3	52.6	52.8
24	53.1	53.4	53.7	54.0	54.2	54.5	54.8	55.1	55.3	55.6
25	55.9	56.2	56.5	56.7	57.0	57.3	57.5	57.9	58.1	58.4
26	58.7	59.0	59.3	59.6	59.8	60.1	60.4	60.7	61.0	61.3
27	61.5	61.8	62.1	62.4	62.7	63.0	63.3	63.5	63.8	64.1
28	64.4	64.7	65.0	65.3	65.6	65.8	66.1	66.4	66.7	67.0
29	67.3	67.6	67.9	68.2	68.4	68.8	69.0	69.3	69.6	69.9
30	70.2									
40	101									
(nC ₄) 51.6	138									
(iC ₄) 72.2	210									
(C ₃) 190	705									

Example: Calculate the vapor pressure of a gasoline blend as follows:				
Component	Volume Fraction	Vapor Pressure, psi	Vapor Pressure Blending Index No.	Volume Fraction x VPBI
n-Butane	0.050	51.6	138	6.90
Light Straight Run	0.450	6.75	10.9	4.90
Heavy Refined	0.500	1.00	1.00	0.50
Total	1.000	7.4	12.3	12.30

Equation: VPBI = $\sum v_i P_i^{1.25}$

Source: Chevron Research Company, 1971

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