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Sensitivities of Internal Combustion Automotive Engines to Variations in Fuel Properties

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16. Abstract

An assessment of the sensitivity of the automotive gasoline and diesel engines to variations in fuel properties has been made. The variables studied include H/C ratio, distillation range, aromatic content, ignition quality as determined by the octane number, and the auto-ignition quality as determined by the cetane number. The sensitivity of the engine is 'measured' against its power output, fuel economy, emissions, and degradation of lubricants. The sensitivity to the use of alternate fuels such as neat fuels or fuel extenders is discussed. The alternate fuels studied include shale oil derivatives, coal liquefaction derivatives, and alcohols. The impact of using emergency fuels in automotive gasoline and diesel engines is discussed.

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Sensitivity of Gasoline Engines; Sensitivity of Diesel Engines; Alternate Fuels; Fuel Characteristics.

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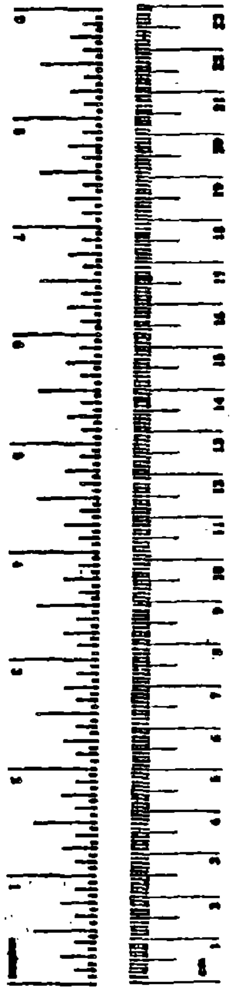
PREFACE

The purpose of this report is to assess the sensitivity of automotive gasoline and diesel engines to variations in fuel properties. Engines have different degrees of sensitivity to the different fuel properties. This report discusses the fuel properties which have major effects on engine sensitivities. Published results of past work in this area are included and analyzed. Areas which need new or additional research are also identified in this report.

METRIC CONVERSION FACTORS

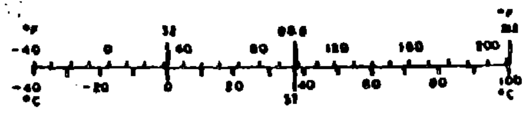
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. SUMMARY

1.1 INTRODUCTION

The properties of automotive fuels are expected to change in the future as efforts continue to extend the petroleum reserves and produce alternate fuels to replace the petroleum derived fuels. These efforts are being made to reduce imports and achieve energy self reliance. Automotive engines are sensitive to many of the fuel properties which are expected to change. This report deals with the sensitivities of the present, mass produced internal combustion, automotive gasoline and diesel engines to variations in fuel properties. Other types of automotive engines, such as stratified charge or gas turbine, are still in the research and development stage and are not included in this report.

The introduction of alternate fuels may take one of the following forms:

1. Varying the distillation range of currently produced fuels (gasoline and diesels) in order to increase the yeild of crude petroleum.
2. Mixing gasoline and diesel fuels with liquid synthetic fuels such as shale oil derivatives, coal derivatives or biomass derivatives.
3. Replacing gasoline and diesel fuels with alternate fuels.

The gradual shift from regular automotive fuels to alternate fuels in any of the above forms will result in variations in fuel properties which affect combustion, lubrication, engine performance, fuel economy, emissions and reliability. This report emphasizes the projected impact of those alternate fuels which are expected to be available in the future on automotive engines.

1.2 PROBABLE FUTURE ALTERNATE FUELS

A possible scenario for future automotive fuels is given in Table 1.1. This table is a result of studies made of reports published by DOE, oil refining companies, research institutions and automotive companies. For the immediate term (1980-1990), current types of mass produced automotive fuels will be available and are expected to be extended by alcohols or alcohol based additives. For the near term (1990-2000), in addition to alcohols, it is probable that syncrudes derived from shale oil and coal derivatives will be mixed with feedstocks of the refineries. For the midterm future (2000-2020), the production of syncrudes is expected to increase and reach about 10 percent of the U.S. petroleum demand. For the long term future (2020-2040), new engines may be mass produced to match the fuels which will then be available. The contribution of syncrudes in the production of these fuels is expected to reach 30 to 40 percent. For the far-future (2040-2060), syncrude production is expected to equal that of natural petroleum crude and gradually replace it. For post 2060, fuels (such as hydrogen) produced using inexhaustible energy sources (such as solar energy or fusion energy) are expected to be introduced. The use of hydrogen in automotive engines is contingent on the development of safe and economically competitive distribution and storage systems.

1.3 SENSITIVITY OF GASOLINE ENGINES

Gasoline engines are mainly sensitive to the following fuel properties: volatility, octane number, H/C ratio, latent heat of evaporation, volumetric energy content, and sulfur and nitrogen content.

1.3.1 Gasoline Engine Alternate Fuel Options

1.3.1.1 Synthetic Gasoline - Synthetic gasoline can be produced from oil shale or coal derivatives. Synthetic gasoline from shale oil is mainly paraffinic and is low in octane number. Synthetic

TABLE 1.1 PROBABLE FUTURE ALTERNATE FUELS

IMMEDIATE-TERM	1980 ↕ 1990	. Adequate supply of petroleum derived gasoline and diesel fuels. . Introduction of ethanol as octane improver or as a blend in gasohol (10%), and introduction of methanol. . Production of gasoline from methanol (Mobil Process) . Production of MTBE octane improver from methanol (Arco Process)
NEAR-TERM	1990 ↕ 2000	. Introduction of syncrudes from shale oil and coal derivatives in the feedstocks of the refineries. The product depends upon the amount and composition of the syncrude and the degree of refining.
MID-TERM	2000 ↕ 2020	. Production of syncrudes equivalent to about 10% of the potential U.S. petroleum demand.
LONG-TERM	2020 ↕ 2040	. Possible production of new engines to match the new fuels. . Production of syncrudes equivalent to about 30% or 40% of the potential U.S. petroleum demand.
FAR-TERM	2040 ↕ 2060	. Possible introduction of hydrogen from inexhaustable energy sources. . Production of syncrudes equivalent to more than 50% of the potential U.S. petroleum demand.
POST-2060		. Alternate non-petroleum fuels dominate.

gasoline from coal derivatives is rich in aromatic content and is high in octane number. It is expected that the alternate fuels will be introduced in the form of syncrude added to the refinery feedstock. The quality of the produced fuel will depend upon the quality of the feedstock, and energy expenditure in the refinery.

The increase in the octane number of the fuel (by using more coal derived fuels) will allow the use of higher compression ratios and improve the thermal efficiency of the gasoline engine. The control of sulfur and nitrogen content of the final product is crucial for limiting the emission of NO_x and sulfates from the gasoline engine. In addition to emissions, the nitrogen and sulfur content of the gasoline from syncrude should be reduced to avoid oil contamination, with resulting engine wear and deterioration.

1.3.1.2 <u>Alcohols</u> - Alcohols are practical extenders or substitutes for petroleum fuels. Methanol and ethanol, which are the least expensive alcohols, can be produced from many sources as indicated in Table 1.2.

TABLE 1.2 SOURCES OF ALCOHOLS

	Source
Methanol	Coal Natural gas Wood biomass Municipal waste
Ethanol	Biomass: grain sugar cane other plants

Ethanol is currently marketed as an extender to gasoline in gasohol which consists of 90 percent gasoline and 10 percent ethanol. In a recent study by T. Austin and G. Rubenstein (3.26)*,

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*References are listed in Appendix A.

the use of gasohol manufactured from U.S. grown corn was found to be uneconomical from an energy point of view, and will increase, rather than decrease the dependence of the United States on crude oil. This is an alarming finding and requires immediate action for further research.

The use of alcohols can take one of the following forms:

a. Alcohol-Gasoline Blends

Blends with a methanol content of up to 20 percent have been found by VW (4.18) to require only minor engine and vehicle modifications. The high octane number of the blend allows the use of a higher compression ratio (C.R.) resulting in a higher thermal efficiency. Using methanol without increasing the C.R. or optimizing the spark advance has no effect on the thermal efficiency.

The disadvantages are:

- Drop in fuel economy measured in miles per gallon, caused by the lower volumetric energy content of the alcohols.
- Increase in evaporative emissions, caused by the increase in the volatility of the alcohol - gasoline blends.
- Increase in NO_x exhaust emissions caused by the leaning of the charge due to blending with alcohols. (Alcohols have a lower stoichiometric air - fuel ratio.)
- Other problems related to lack of compatibility of the engine and vehicle materials with alcohol-gasoline blends, and phase separation of the methanol - gasoline blends.

b. Neat Alcohols

Neat alcohols allow the use of a high compression ratio resulting in high thermal efficiency. Also, neat alcohols with MBT (minimum advance for best torque), spark timing, and optimum C.R. can produce less NO_x, HC and CO. Problems associated with the use of neat alcohols are:

- A cold starting aid is absolutely essential for starting the engines at temperatures below 8°C (46°F).
- The fuel economy measured in miles per gallon, drops.

1.4 SENSITIVITY OF DIESEL ENGINES

Automotive diesel engines are mainly sensitive to the following fuel properties: cetane number (which affects every aspect of the diesel combustion process), distillation range, aromaticity, viscosity, sulfur content, nitrogen content, and energy density.

1.4.1 Diesel Engine Alternate Fuel Options

1.4.1.1 Broad or Wide Cut Distillates from Petroleum Crude - The increase in demand for jet fuel and heating oil is putting pressure on refineries to produce wide cut distillates or diesel fuels with more, heavier compounds. DF-3, which is heavier and has a lower cetane number than diesel fuel (DF-2), is being considered for transportation diesel engines. The anticipated main problems with DF-3 are related to increase in smoke information and the resulting limitation on power to keep smoke emissions within bounds.

The wide cut distillates contain lighter compounds than DF-2, which cause a drop in cetane number and an increase in volatility. No work has been done to study the sensitivity of automotive diesel engines to broad or wide cut distillates.

1.4.1.2 Synthetic Diesel Fuel from Oil Shale or Coal - Very limited studies have been made on blends of DF-2 and synfuels derived from shale oil and coal derivatives.

1.4.1.3 Alcohols in Diesel Engines - The use of alcohols in diesel engines may take one of the following forms:

a. Alcohol - Diesel Blends

Mixing alcohols with diesel fuel has been found to reduce the smoke emission, and increase the smoke limited power. It increases the BSFC, and the hydrocarbon, aldehyde and noise emissions.

Problem areas are related to:

- Cold starting caused by the low cetane number of alcohols,
- Lubricating oil contamination by alcohols and their combustion products, which causes engine wear, and injection system wear.

b. Alcohol - DF-2 Emulsions

The cold starting problems experienced in the DF-2 alcohol blends, may be reduced by using alcohols as emulsions. Pure DF-2 is used for cold starting. The concentration of the emulsified alcohol increases with load. This will increase the smoke-limited power.

Problem areas are related to:

- The need for an emulsifier and an extra tank.
- Complicated techniques needed to control the two fuels, particularly under transient modes.

c. Alcohol Carburetion or Manifold Injection and Autoignition of Diesel Fuel

The engine starts on diesel fuel. Alcohols are introduced into the intake manifold by carburetion or manifold injection. The fraction of alcohols increases with load.

Problem areas are related to:

- Misfiring at light loads,
- Self-ignition at high loads,

- The need for elaborate control systems to optimize the timing and metering of the two fuels,
- Excessive increase in the hydrocarbon and aldehyde emissions.

d. Two Separate Injection Systems

The engine starts on diesel fuel. The alcohol injection starts after warm up, the amount increasing with load.

Problem areas are related to:

- The need for two high pressure injection systems.
- The need for elaborate control systems.

e. Neat Alcohols

Neat alcohols have very low cetane numbers and need to be mixed with two additives: i) cetane improvers to increase their cetane number, and ii) lubricating oil to improve their lubricity.

Problem areas are related to:

- The absolute need for a starting aid. The aid can be in the form of an intake air heater, or starting on diesel fuel. The research work conducted so far on the use of alcohols in automotive diesel engines has been very limited, and definite conclusions cannot yet be reached in this area. Further work is needed.

1.5 EMERGENCY FUELS

In case of a national emergency, vehicles to conduct certain essential services would be required. Automotive gasoline and diesel engines would be required to run on emergency fuels formed from the available stock of basic fuels, extended with other liquid fuels. One program was conducted on the use of emergency fuels in automotive engines in a very limited number of vehicles. The results of this program showed the following.

a. Only alcohols can be used in automotive gasoline engines without the need to reduce the engine compression ratio in order to avoid knock. The other emergency blends studied are DF-2, marine diesel fuel, kerosene and maphtha and their blends with alcohols.

b. For diesel engines: jet fuels, kerosene, medium naphtha and No. 4 fuel oil were used without any significant differences in engine operation being observed. Blending with gasoline and alcohols decreased cetane number, and smoke. This would probably increase the engine noise, dilution of lubrication oil, and wear, particularly in the injection system.

1.6 RECOMMENDATIONS

1.6.1 Future Fuel Characterization

Develop the following:

a. Scenarios for probable future fuels based on the availability of new technologies and energy sources.

b. Data base for the variations in fuel properties caused by blending the base fuels with different extenders.

c. Data base for the effect of variations in the fuel properties on cetane number and octane number.

d. Information on the impact of alternate fuels on the lubrication of automotive engines.

1.6.2 Gasoline Engines

a. Investigate the sensitivity of gasoline engines to variations in base fuel properties.

b. Assess tradeoffs in economy, performance and emissions with variations in the fuel properties which affect cost and energy savings in the refinery.

c. Assess the impact of mass-producing gasohols on the U.S. energy situation, and the U.S. dependence on imported crude.

d. Study of the use of neat alcohols, and their blends with gasoline, in automotive gasoline engines. Engines should be optimized for the alcohols.

e. Find techniques to solve the cold starting problems of gasoline engines with alcohols.

1.6.3 Diesel Engines

a. Investigate the sensitivity of diesel engines to variations in the base DF-2 by varying the fractions of the light and heavy compounds.

b. Assess the tradeoffs in economy, performance, emissions and variations in fuel properties which have an impact on cost and energy savings in the refinery.

c. Develop a cetane scale suitable for rating the alternate fuels.

d. Study the problem of instability of the autoignition process of low-ignition-quality alternate fuels in diesel engines. Develop techniques to reduce its effect on engine reliability.

e. Determine techniques to improve the cetane number of alcohols.

f. Investigate the use of neat alcohols and their blends in automotive D.I. and I.D.I. diesel engines.

The above recommendations are made to develop basic technical information which is currently lacking. This information is essential for utilizing future alternate fuels in automotive gasoline and diesel engines.

2. INTRODUCTION AND BACKGROUND

The future supply of automotive fuels, and changes that may occur in their properties are matters of concern. While today there are ample supplies of automotive fuels derived from petroleum, the rate at which the world petroleum demand is increasing is such that adequate supplies can only reasonably be assured until approximately 1990 (2.1). Beyond 1990, it will be necessary to introduce alternative sources of liquid automotive fuels in increasing quantities. It will also be necessary for the United States to produce alternative automotive fuels from the more plentiful domestic energy sources available in order to reduce imports, and achieve greater energy independence.

Coal and oil shale are the most promising sources in the United States for the supplemental crude materials (syncrude) needed for automotive fuel production. The syncrudes may either be used separately as refinery feedstock, or fed to the refinery as part of a mixed charge of natural and synthetic crudes. The product characteristics will depend on the applicable refining technology, as well as on the material in the feedstock.

Alcohols such as methanol and ethanol represent another type of alternate fuel, which can be produced from coal or biomass. Fermentation of biomass has been used for thousands of years to produce methanol and ethanol. More recently, enzymes have been used to convert cellulose to sugar, which is then processed into ethanol.

The criteria which will affect the future automotive fuels concern the energy source, conversion technology, environmental concerns, energy efficiency, fuel distribution and storage costs, and certain properties of fuels which control their compatibility with future automotive engines.

The present types of gasoline and diesel engines are expected to power vehicles for the rest of the 20th century. The gasoline engine is the most widely used engine for passenger cars.

The diesel engine, the most efficient transportation engine, is used in heavy duty trucks and is penetrating the medium duty truck and passenger car field. Other alternative types of engines are being considered but are not currently in mass production. Alternative engines include various types of stratified charge engines, the gas turbine, the Stirling engine, and the steam engine.

This report will deal only with the sensitivity of the currently produced gasoline and diesel engines to variations in fuel properties. The sensitivity of alternative engines to variations in fuel properties is beyond the scope of this report.

3. FUEL PROPERTIES AND THEIR EFFECTS

3.1 FUTURE FUELS

3.1.1 General

There is no clear picture of what the future automotive fuels will be. Published reports by DOE, oil companies, and automotive companies indicate that the properties of future fuels might change with time according to the availability of the energy resources and refining technologies. A possible scenario of future automotive fuels, developed from the available information in the literature is as follows:

1. Immediate term (1980-1990): Alcohols represent the first alternate fuels which are expected to be introduced in limited amounts. The currently mass produced automotive fuels will be available and are expected to be extended by alcohols or alcohol-derived additives.

Alcohols have been used as fuels for internal combustion engines for many decades. Methanol and ethanol have been considered as motor fuels more so than other alcohols because they are less expensive to manufacture from a number of different raw materials. Isopropanol has been used in fuels primarily as an icing inhibitor and for water scavenging during cold seasons. Tertiary butanol is currently added to gasoline by one company as an octane booster (3.24).

Gasohol, which is a mixture of 10 percent ethanol and 90 percent gasoline, has already been considered by many workers and DOE officials as a viable alternative gasoline engine fuel which can reduce the reliance on imported foreign crude petroleum. In fact, the price of gasohol has been subsidized by the Federal Government to make it competitive with the price of gasoline (3.25). In a recent study (3.26) made by T. Austin and G. Rubenstein of California Air Resources Board, questions were raised about the validity of the use of gasohol as a more economical alternate fuel. Austin and Rubenstein indicated that the use of gasohol manufactured from U.S. grown corn has increased rather than decreased the nation's dependence on crude oil. Also, they considered that it is more economical to make synthetic fuels from coal than to use the same amount of coal to run an ethanol production facility.

It is clear that a detailed study is needed to evaluate the validity of the arguments used in the Austin/Rubenstein paper, and to evaluate the economy of the production of ethanol and its use as a gasoline extender.

2. Near-term future (1990-2000): In addition to alcohols, it is probable that syncrudes derived from shale oil and coal derivatives will be mixed with the feedstock of refineries (3.23). The quality of the final product depends on the fraction of alternate syncrude in the feedstock, the properties of the basic feedstock and the degree of refining. (3.23)

3. Mid-term future (2000-2020): The production of syncrudes is expected to increase and reach about 10 percent of the U.S. petroleum demand. (2.1)

4. Long-term future (2020-2040): New engine technologies may be developed in the future to match the fuels which will than be available. New engine candidates are the gas turbine and Stirling engine. These engines utilize continuous combustion systems which have different sensitivities to variations in fuel properties. These new engines are not covered in this report. It is expected that the syncrude contribution at the end of this time frame will reach up to 30 or 40 percent.

5. Far Future (2040-2060): The syncrude production is expected to equal that of the natural petroleum crude, and gradually replace it. Fuels such as hydrogen, produced using inexhaustible energy sources, are expected to be introduced. Currently, the use of hydrogen as an alternate automotive fuel is

contingent on the development of safe and economically competitive distribution and storage systems.

6. Post 2060: Alternate fuels from inexhaustible energy sources are expected to dominate.

3.1.2 Properties of Future Fuels

The fuel properties important to engine operation are octane quality (for gasoline engines), cetane quality (for diesel engines), volatility, viscosity, volumetric energy density, and impurity content, e.g., sulfur and/or nitrogen.

Establishing the properties of future alternate fuels is very difficult. However, general trends may be established based on the currently available data on the properties of different sources of fuels. For example, distillates derived from coal are highly aromatic in nature (3.1) (3.2) (3.3) (3.23) and are of a high octane quality. But, distillates derived from oil-shale are highly paraffinic in nature (3.4) (3.5) (3.6) (3.7) (3.23) and would likely have high cetane quality and low octane quality. The less-refined fuels from coal and oil shale are likely to have high nitrogen and/or sulfur contents (3.4) (3.6) (3.7) (3.8) (3.9) (3.10) (3.23). The presence of nitrogen compounds can lead to instability resulting in the formation of gums and particulate matter in storage, and the formation of deleterious deposits in vehicle engines (3.23). The coal-derived fuels, such as solvent-refined coal and synthetic oils, may also contain appreciable amounts of ash (3.8) (3.9) (3.11).

Table 3-1 gives the properties of automotive gasoline, diesel, and jet fuels, processed from shale oil, by Laramie Energy Research Center, Energy Research and Development Administration (3.12). Gary (3.12) indicated that technology is available to produce motor fuels meeting existing motor fuel specifications from Western oil shale, but more severe and extensive processing is required than for fuels produced from conventional crude oils. As a result, the synthetic motor fuels will be more costly and their production more energy consuming than todays petroleum based fuels.

TABLE 3.1. PROPERTIES OF SYNTHETIC MOTOR FUELS PRODUCED FROM SHALE OIL

	Gasoline	Diesel Fuel			Jet Fuel	
		1-D	2-D	4-D	JP5/ Jet A	JP4/ Jet B
Distillation, °F						
10%	130	400	422	450	376	232
20%	148	409	454	468	387	250
50%	215	422	484	507	422	292
90%	326	469	537	605	482	368
EP	385	517	554	628	518	405
Dist. Residue, %	1.0	2.0	1.0	2.0	1.0	1.0
RVP, psia (Max)	8.8					2.0
RON	82					
MON	91					
Cu Strip Corrosion	1A				1B	1B
Gum, mg/100ml	2.8					
Sulfur, ppm	30	100	200	200	27	13
Nitrogen, ppm		141	166	202		
Flash point, °F		188	212	265	140	
Pour point, °F		<0	0	20	-26	-91
Gravity, °API		41.9	39.8	39.0	44.0	57.0
Carbon Residue on 10% Resid		0.14	0.16	0.36		
Ash, Wt%		<0.001	<0.001	<0.001		
Vis. @ 100°F, cSt		1.66	2.40	2.96		
Cetane Index		48	54	56		
Net heat of combustion, Btu/lb					18,160	18,340
Aromatics, Vol %					21.0	11.7
Olefins, Vol %					4.3	0.4

Ref. 3.12

The cetane number and end-point data published by ERDA (3.13) for U.S. produced No. 2 diesel fuels are plotted in Figure 3-1 in relation to data for European-produced fuels (2.1). This figure shows that a wide variation in U.S. produced fuels has existed for some time. The trend towards fuels of increasing end-point, and decreasing cetane number is apparent in these figures.

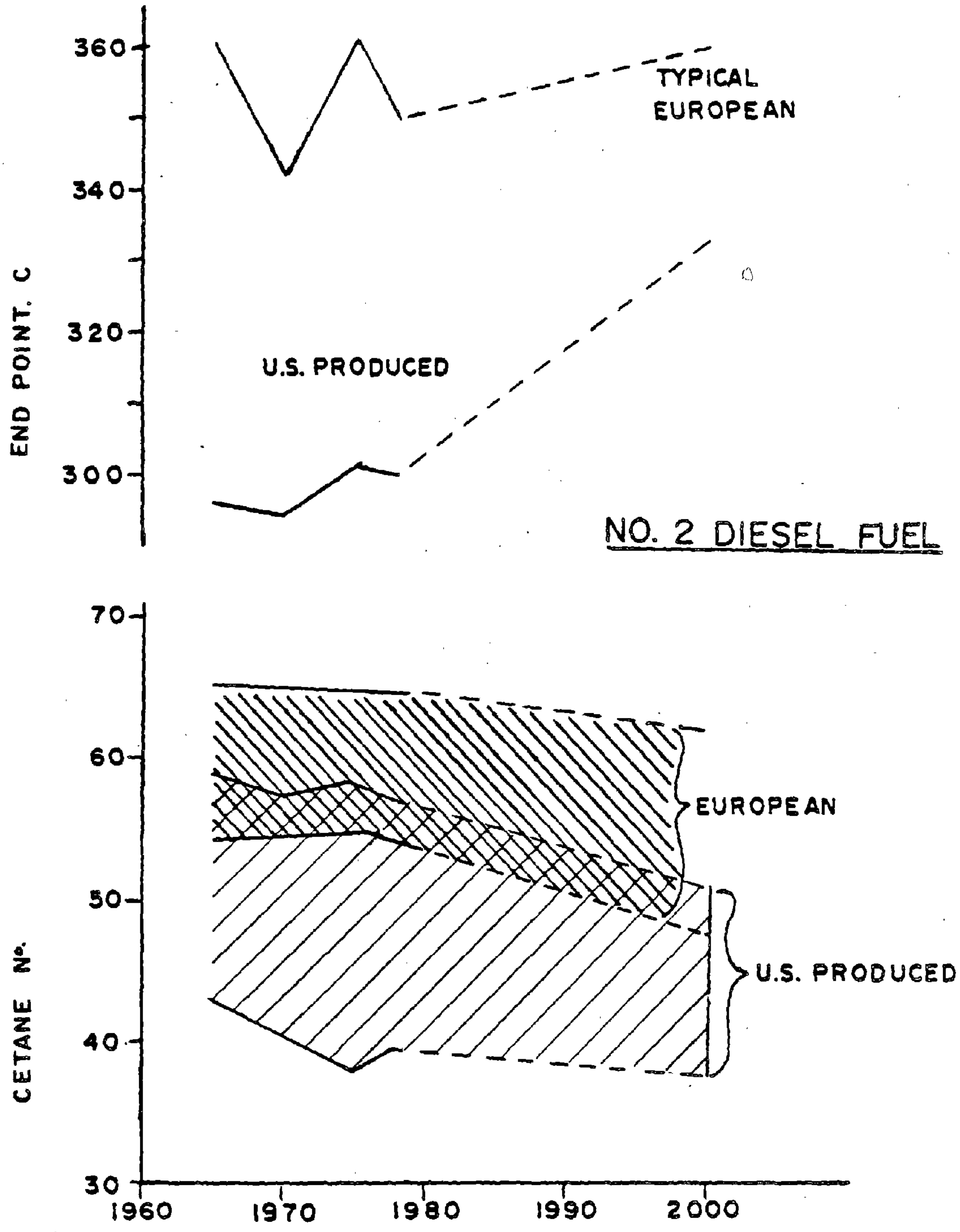
Because of the increasing demand for jet fuel and high octane gasoline, there are pressures for some degradation in cetane number, end-point, and cloud-point of diesel fuels to bring them closer to the European fuels (1). It is expected that C.N. 40 diesels fuels will be produced as 1990 nears. An end-point of 371°C (for non-US diesels) is expected for future U.S. diesel fuels (2.1).

Figure 3-2 shows that the minimum values for cloud-point for U.S. produced No. 2 diesel fuels have been consistently lower than for diesel fuels produced in Europe. The maximum values, however, are approximately the same. According to EMA (2.1), diesel No. 1 fuel or kerosene have been added to No. 2 diesel fuel to achieve the necessary filterability. The importation of No. 2 fuel produced abroad, a trend toward higher end-point for U.S. produced fuel, and diminishing availability of No. 1 fuel suggest increasing winter operational problems.

Table 3-2 from reference (2.1) summarizes the important characteristics of U.S. and non-U.S. produced diesel fuels. The information in Table 3-2 reflects, primarily, the difference in the refining procedures used. U.S. refiners crack heavy residuals to increase gasoline yield, whereas cracking is not as prevalent abroad. The difference in practice accounts for the difference in cloud-points and cetane numbers.

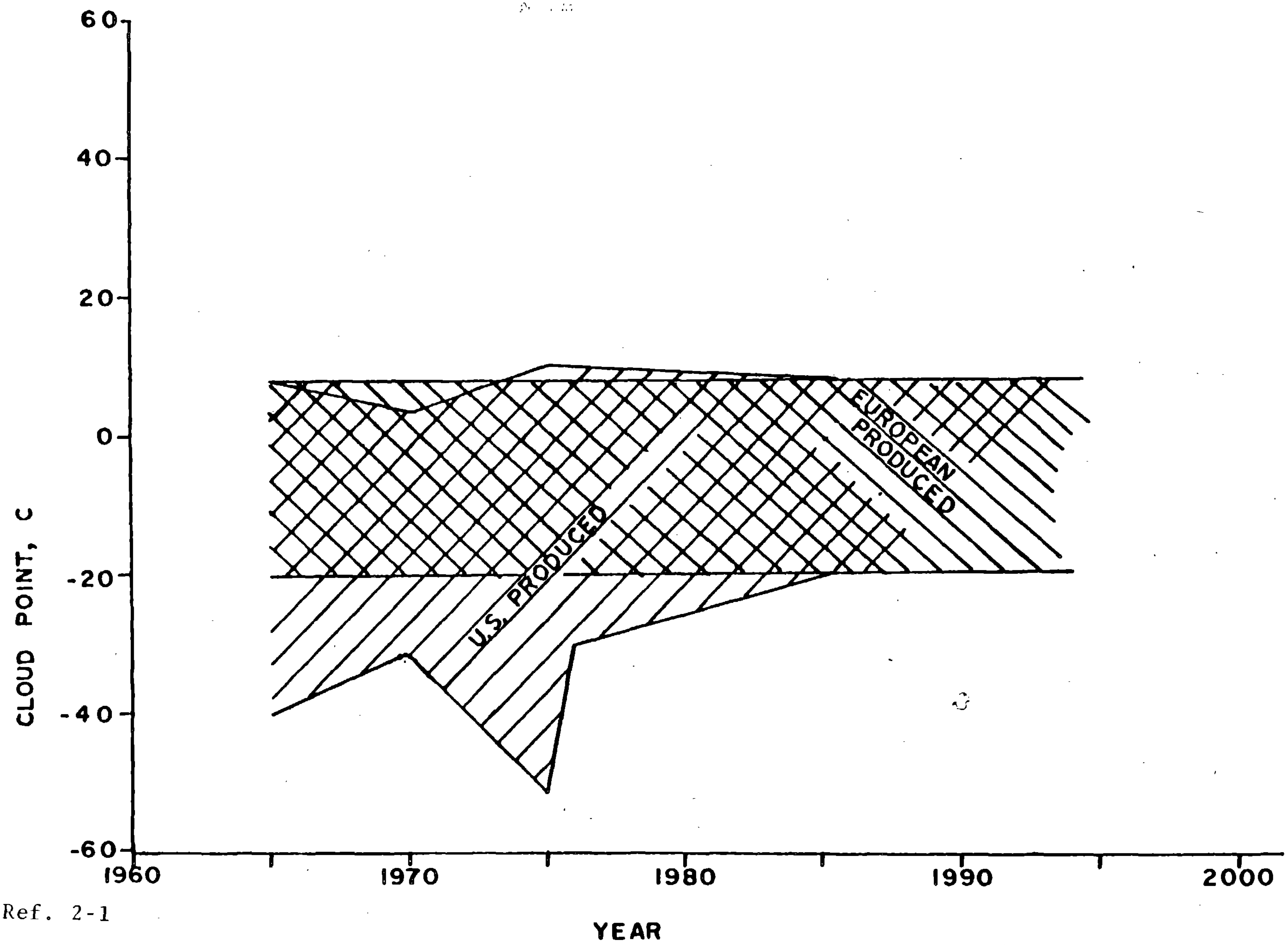
3.2 STOICHIOMETRY AND COMBUSTION

Stoichiometry and combustion are related to the H/C ratio of the fuel. For Indolene, H/C is 1.86, for diesel fuel, H/C is



Ref 2-1

FIGURE 3.1. TRENDS OF THE END-POINT AND CETANE NUMBER FOR U.S. AND EUROPEAN-PRODUCED DIESEL FUEL



Ref. 2-1

FIGURE 3.2. TRENDS OF THE CLOUD-POINT OF U.S. AND EUROPEAN PRODUCED DIESEL FUELS

TABLE 3.2. PROPERTIES OF U.S. AND NON-U.S. DIESEL FUELS

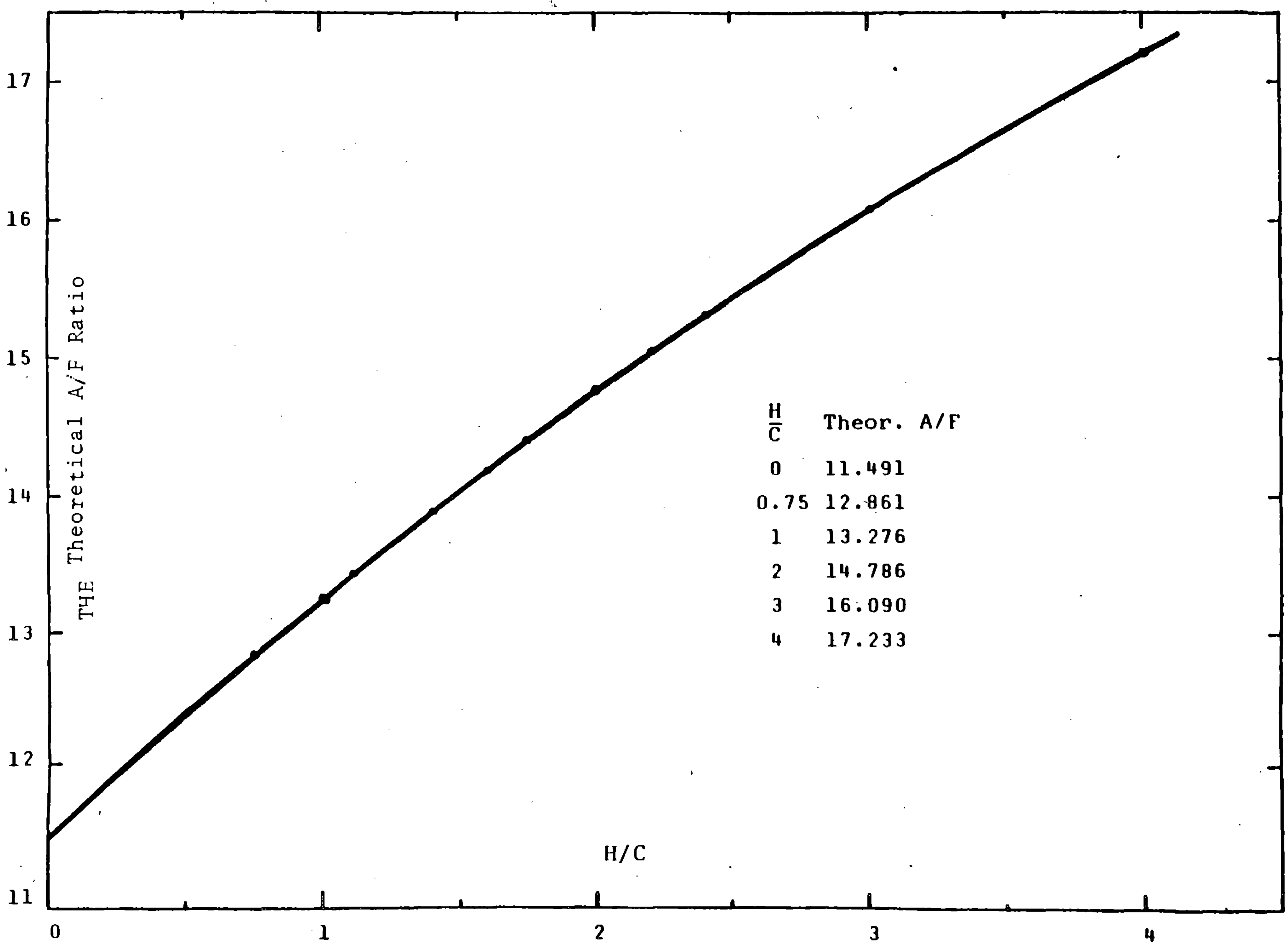
	U.S.	European
Gravity, API	30-36(31)	36-47(38)
Cetane No.	39-60(47)	55-65
Distillation Range °C	175-332	175-371
Cloud Point °C	-16 to -9(-15)	-20 to -7
Pour Point °C	-40 to -15(-23)	-20 to -9
( ) = typical value		

1.875. The H/C ratio of the fuel may change with the introduction of alternative fuels.

3.2.1 Effect of H/C Ratio on Stoichiometry

The stoichiometric air-fuel ratio depends upon the H/C ratio of the fuel. The theoretical A/F ratio varies from 11.491 for pure carbon to 17.233 for H/C = 4, as shown in Figure 3-3. Figure 3-4 is a replot of Figure 3-3 showing the stoichiometric A/F ratio plotted against the number of carbon atoms for different types of hydrocarbons. For the same number of carbon atoms, aromatics have the lowest theoretical A/F ratio. Therefore, an increase in the percentage of aromatics in a distillate fuel results in an increase in its density, and a reduction in its stoichiometric A/F ratio. The use of such a fuel in an engine designed for low aromatic fuels may affect fuel metering, the mixture strength, and the exhaust emissions (3.14).

Figure 3-4 also shows that the stoichiometric A/F ratio drops at a decreasing rate with the increase in the number of carbon atoms, n, in the paraffins C_nH_{2n+2}. For olefins, C_nH_{2n}, the stoichiometric A/F ratio is the same for all values of n. For the diolefins, C_nH_{2n-2}, and aromatics, C_nH_{2n-6}, the theoretical A/F ratio increases at a decreasing rate with the increase in n. Figure 3-4 shows that the difference between the A/F ratio for the several hydrocarbon families diminishes as n increases.



$\frac{H}{C}$	Theor. A/F
0	11.491
0.75	12.861
1	13.276
2	14.786
3	16.090
4	17.233

FIGURE 3. 3. EFFECT OF HYDROGEN-TO-CARBON RATIO ON THEORETICAL AIR-FUEL RATIO

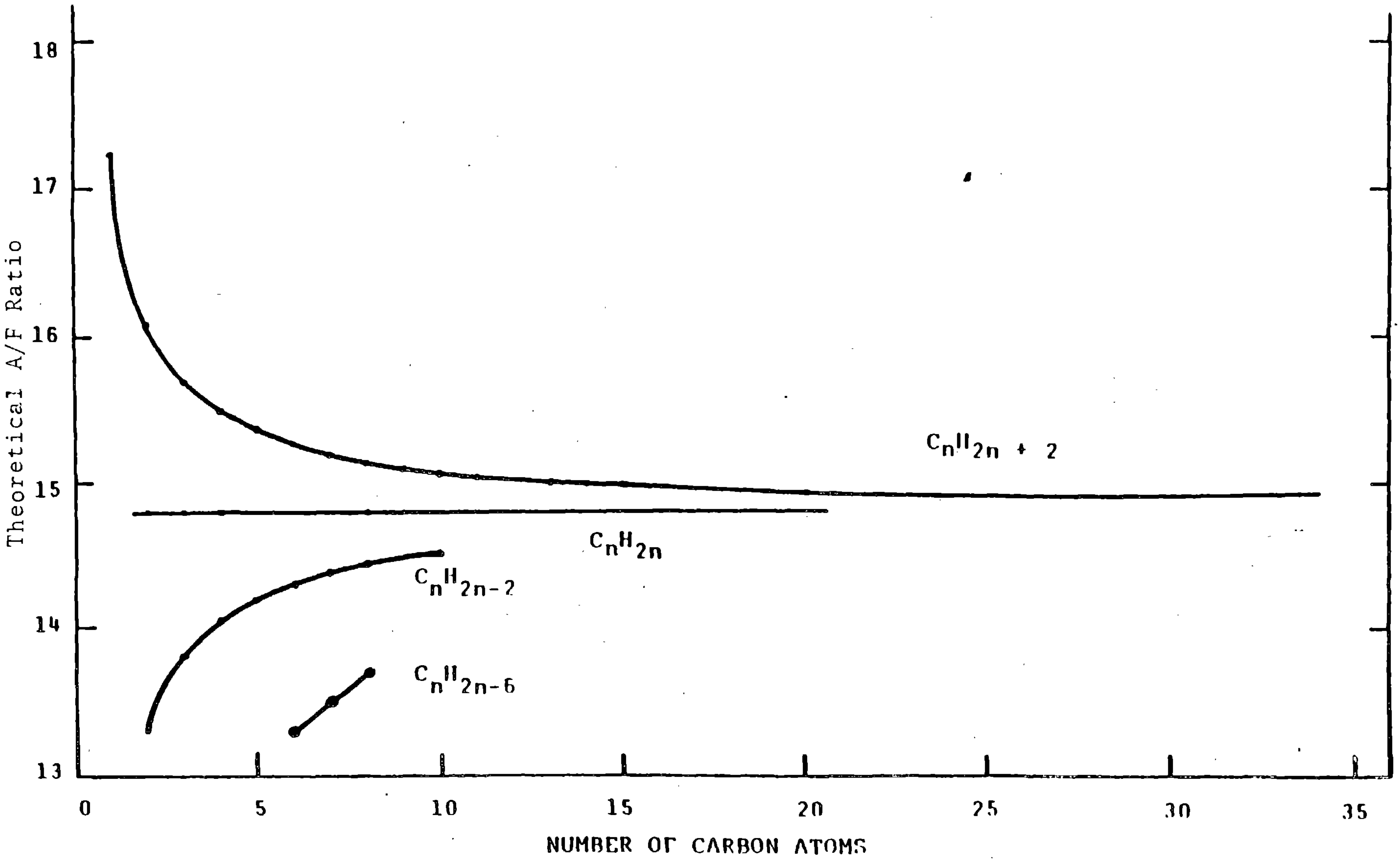


FIGURE 3.4. EFFECT OF FUEL STRUCTURE AND NUMBER OF CARBON ATOMS ON THEORETICAL AIR-FUEL RATIO

Theoretically, at n = ∞, the theoretical A/F ratio for all the hydrocarbons is that of olefins, which is 14.786.

3.2.2 Effect of H/C Ratio on the Adiabatic Flame Temperature

Figure 3-5 shows the adiabatic flame temperature calculated for the stoichiometric mixture at the end of a constant volume combustion, with chemical equilibrium (3.15). The original pressure before combustion is 10 atmospheres, and the original temperature is 77°C. It is clear that the adiabatic flame temperature increases with the decrease in H/C ratio.

3.2.3 Effect of H/C Ratio on the (F-A) Standard Cycle

The effect of H/C ratio on the (F-A) standard constant-volume cycle is shown in Figure 3-6 (3.16). The cycle conditions are as follows: compression ratio = 8.5, equivalence ratio ϕ=1, initial temperature = 294.3°K (21.3°C), initial pressure = 1 atm.

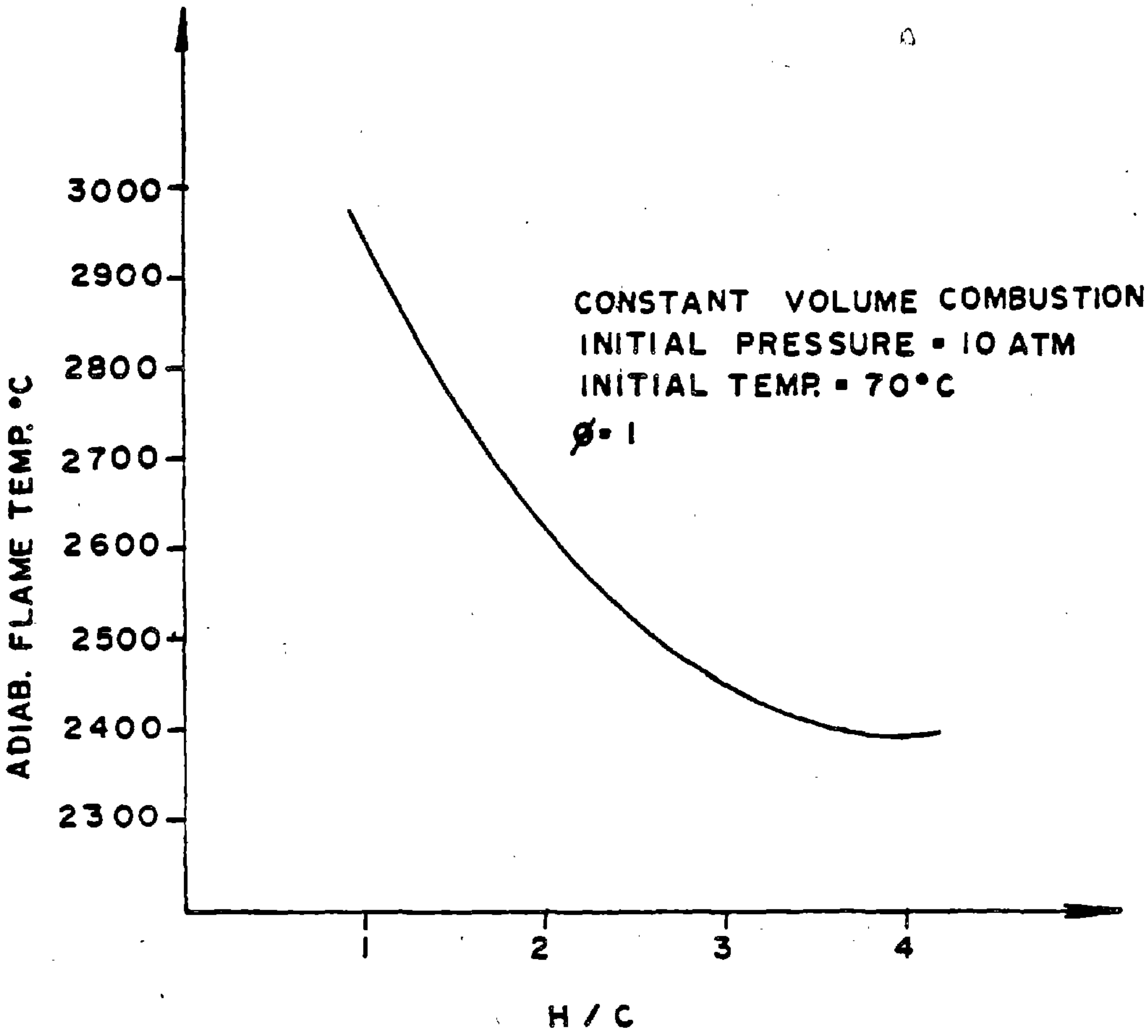
Figure 3-6 shows that, for the hydrocarbon fuels, the decrease in H/C ratio has the following general effects: increases the maximum cycle temperature, decreases the thermal efficiency, increases the maximum cycle pressure, and increases the mean effective pressure. Most of these effects are the results of the variations in the stoichiometric A/F ratio, which decreases with the drop in the H/C ratio.

For alcohols (CH_3OH and C_2H_5OH) the increase in H/C ratio has effects similar to those on the hydrocarbons, except that the stoichiometric A/F ratio increases with the decrease in H/C ratio. For example, methanol, CH_3OH, with an H/C ratio of 4, has a stoichiometric A/F ratio of 6.45, while ethanol, C_2H_5OH, with an H/C ratio of 3, has a stoichiometric A/F ratio of 9.0

3.3 GASOLINE ENGINE FUELS

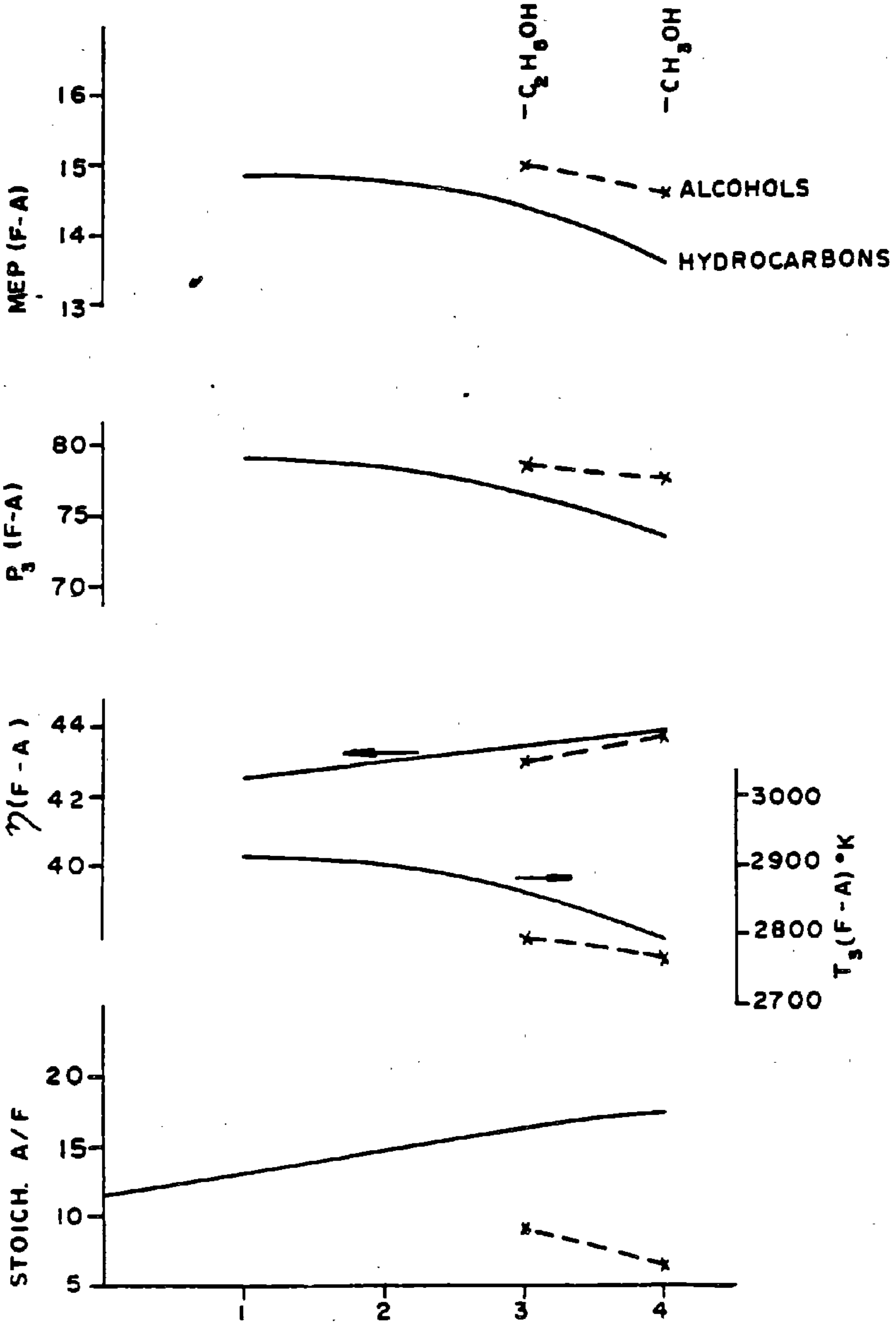
Automotive gasoline engines are sensitive to many fuel properties particularly the following:

1. Volatility and distillation range,



Ref. 3.15.

FIGURE 3.5. EFFECT OF H/C RATIO ON ADIABATIC FLAME TEMPERATURE



Ref. 3.16

FIGURE 3.6. EFFECT OF H/C RATIO ON THE (F-A) STANDARD CONSTANT VOLUME CYCLE

2. Detonation and preignition characteristics,
3. Energy Density on both a mass and volume basis,
4. Latent heat of evaporation.

Other fuel properties which affect engine performance, and which will not be discussed in this report are: chemical stability, corrosiveness, safety and cost.

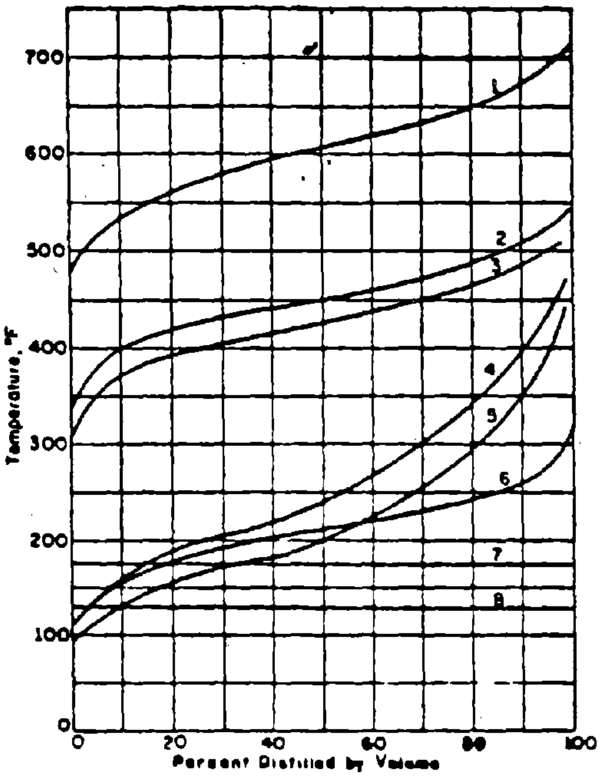
Gasoline engines are sensitive to many fuel properties particularly the following:

3.3.1 Volatility and Distillation Range

Volatility is measured by the Reid Vapor Pressure (RVP), the lighter part of the fuel on the ASTM distillation curve, or the Equilibrium Air Distillation (EAD).

Ideally, the fuel should be equally distributed among the cylinders of the engine, and completely evaporated before ignition. During cold starting, only the volatile portion of the supplied fuel will evaporate. At the same time the mass ratio of the evaporated fuel to the total supplied fuel is low. Choking is applied to increase the mass ratio of the "total fuel supplied" to the "air" (FT/A), which, in turn, will bring the ratio of evaporated fuel to air (Fv/A) above the lean ignition limit.

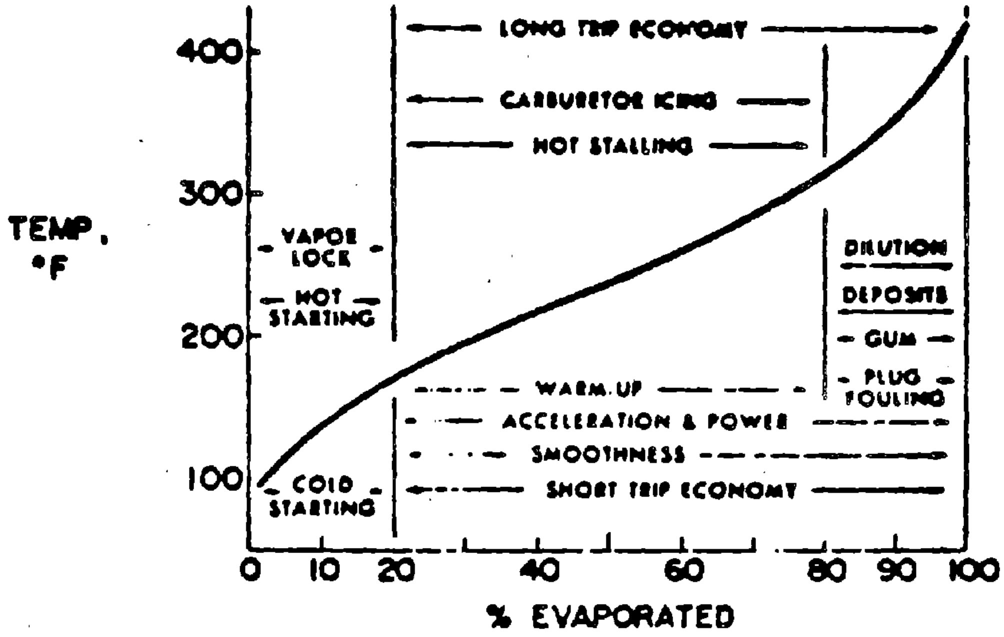
Figure 3-7 shows the distillation curves for the different fuels produced from the petroleum crude for use in automotive engines. Wide cut fuels will have a distillation range which combines that of gasoline and diesel fuels. The shape and level of the distillation curve affect gasoline engine performance. The characteristic indicating the starting quality of a fuel is generally considered to be represented by the percentage vaporized at a fixed temperature of 158°F. The warm-up characteristic is related to the temperature at which 50 percent of the fuel is vaporized. Fuel economy is related to the temperature at which 90 percent of the fuel is vaporized, because the heavy ends have higher heating values. Figure 3-8 shows the relationship between the different portions of the distillation curve and the engine



1. Heavy Diesel oil
2. Distillate
3. Kerosene
4. Summer gasoline
5. Winter gasoline
6. Aviation gasoline
7. Ethyl alcohol
8. Benzene

Ref. 3.17.

FIGURE 3.7. TYPICAL ASTM DISTILLATION CURVES



Ref. 3.18.

FIGURE 3.8. EFFECT OF DISTILLATION RANGE ON ENGINE PERFORMANCE

problems.

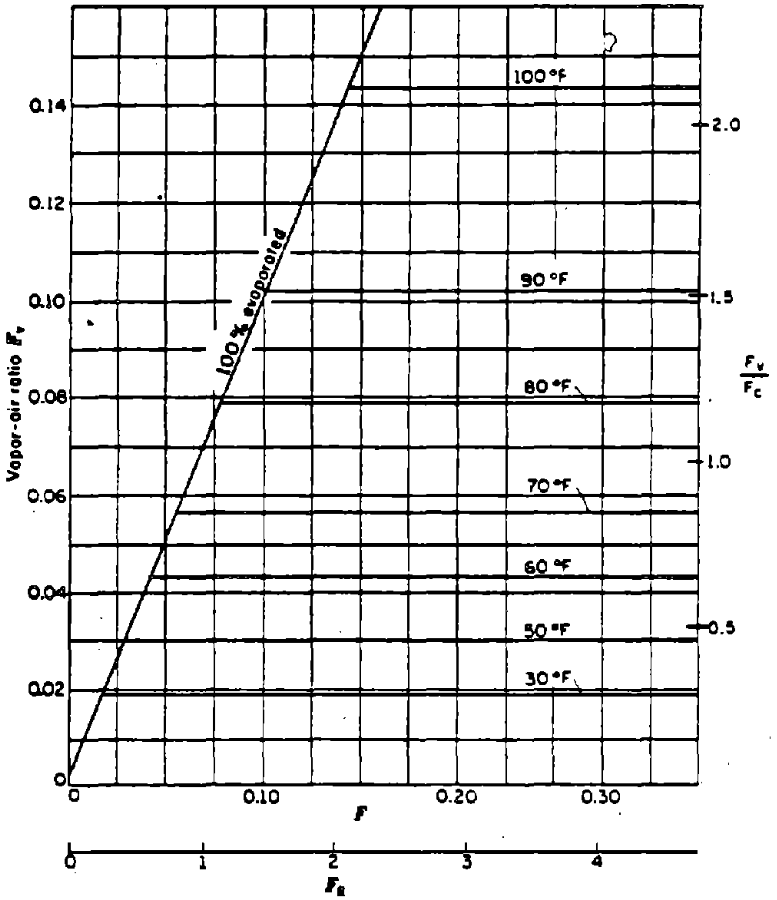
In gasoline engines, the unburned hydrocarbons and carbon monoxide emissions are reduced with more volatile fuels, because leaner mixtures can be used during warm-up. The lower the whole range of temperatures on the ASTM curve, the shorter is the warm-up period.

The heavy portions of the fuel, which are represented by temperatures above the 90 percent point on the distillation curve, may be deposited on the cylinder wall, and get mixed with the lubricating oil in the crankcase, affecting its lubricity. Wide cut fuels, which contain a larger portion of the heavy compounds, can cause more crankcase oil dilution. This will be discussed in Section 6 of this report.

For single compound fuels such as methanol and ethanol, the ratio of (F_V/F_T) depends only on the temperature, and cannot be increased by increasing (F_T/A) beyond the point of complete evaporation. This is illustrated in Figure 3-9. and explains the difficulty in cold starting with single compound fuels (such as alcohols) which have low vapor pressure at the low starting temperatures.

3.3.2 Detonation and Preignition Characteristics

3.3.2.1 Octane Rating - The tendency of any fuel to produce knock in a gasoline engine depends upon many design and operating parameters. The knock rating of a fuel is determined by measurements on a standard engine (CFR), under standard operating conditions (motoring or research conditions), using a standard knock intensity (measured by a standard knock meter) and a pair of standard reference fuels (100 for isooctane, and zero for n-heptane). The octane number of the fuel is equal to the percentage of isooctane in a mixture of isooctane and n-heptane which produces the same knock intensity as the tested fuel under the standard operating conditions. The different standard conditions for the two octane methods are given in Table 3-3.



Ref. 3.19.

FIGURE 3.9. VAPOR-AIR VERSUS FUEL-AIR RATIOS FOR OCTANE (C_8H_{18}) AT 1 ATM

TABLE 3.3. OCTANE RATING METHODS

	Motor Method (MON)	Research Method (RON)
Inlet Temperature	300°F	125°F
Speed	900 R.P.M.	600 R.P.M.

The motor method is considered more severe because of its higher inlet temperature and speed requirements.

3.3.2.2 Fuel Sensitivity - The fuel sensitivity is defined as equal to (RON-MON). The paraffins show near zero sensitivity because they are similar in structure to the two reference fuels. Therefore, the more the paraffinic content of the fuel, the lower its sensitivity. For alternate fuels, the sensitivity depends on the fuel sources. For example, fuels from coal-derived-liquids will have a higher percentage of aromatic compounds and a higher sensitivity than those derived from shale oil. At the same time, the octane number of the coal derived fuels is higher than that of the shale oil derived fuels. Sensitive fuels tend to knock sooner as the inlet temperature is increased.

The use of high octane fuels will not improve the performance and efficiency of the gasoline engine unless the compression ratio is raised, or the spark timing is advanced. It should be noted that increasing the compression ratio and/or advancing the timing may increase the NO_x and the hydrocarbon emissions.

3.3.3 Energy Density

Fuel economy is usually expressed in terms of BSFC for engines, and kilometers per liter or miles per gallon for vehicles. The BSFC is a function of the energy-mass density in addition to other thermodynamic parameters which affect the efficiency of conversion of the chemical energy of combustion to useful mechanical work. The energy-mass density of several fuels is given in

Table 3-4. Table 3-4 shows that methanol has 49 percent of the energy-volume density of gasoline, and ethanol has 65.6 percent of the energy-volume density of gasoline.

TABLE 3.4. SPECIFIC GRAVITY AND ENERGY-DENSITY FOR DIFFERENT FUELS

	Specific Gravity (Density)*	Energy-Mass Density BTU/lbm		Energy-Volume Density BTU/Gallon
		High	Low	Low
Gasoline	0.739 (6.156)	20,300	19,070	117,400
Kerosene	0.825 (6.872)	19,750	18,510	127,200
Light Diesel Fuel	0.876 (7.297)	19,240	18,250	133,200
Medium Diesel Fuel	0.920 (7.663)	19,110	18,000	138,000
Methanol	0.796 (6.630)	9,750	8,570	56,800
Ethanol	0.794 (6.614)	12,800	11,500	76,100

*Density-Pound/U.S. Gallon.

The energy-volume density is directly proportional to the product of the energy-mass density and the specific gravity. Diesel fuel has the highest energy volume density, followed by gasoline, ethanol and methanol.

The energy density of the fuel affects the storage and transportation related costs which contribute to the final market price of the fuel.

3.3.4 Latent Heat of Evaporation

Table 3-5 shows the latent heat of evaporation for several fuels, and the drop in the inlet air temperature (ΔT) with complete evaporation of the fuel in air to a stoichiometric A/F ratio.

TABLE 3.5. LATENT HEAT OF EVAPORATION OF DIFFERENT FUELS

	H_{fg} $\frac{BTU}{lbm}$	ΔT °F
Gasoline	150	40
Ethyl Alcohol	361	153
Methyl Alcohol	474	300
Light Diesel	115	30

3.4 DIESEL ENGINE FUELS

Automotive diesel engines are sensitive to many fuel properties, in particular the following:

1. Autoignition Quality
2. Volatility
3. Viscosity
4. Specific Gravity

3.4.1 Autoignition Quality

3.4.1.1 Centane Rating - The autoignition quality of the fuel is related to the rates of the preignition processes which take place in the period of time between fuel injection and combustion. These processes can be divided into two major types: physical and chemical processes. The physical processes are: (1) spray disintegration and droplet formation, (2) heating of the liquid and evaporation, and (3) diffusion of the vapor into air to form a combustible mixture. The chemical processes are: (1) the decomposition of the fuel molecule to lighter compounds, and (2) the oxidation reactions which release the chemical energy. These processes overlap, but the early processes are mainly physical and the latter processes are chemical. The fuel properties affect both the physical and chemical preignition reactions.

The autoignition quality of the fuel is measured by the period of time between the start of injection and the start of pressure rise or illumination due to combustion. In diesel engines, the start of pressure rise due to combustion is the criteria used to indicate combustion. The autoignition quality is indicated by the cetane number of the fuel which is measured in a standard engine (CFR), under standard operating conditions (RPM = 900, T_{air} = 150°F), by using a pair of standard reference fuels (100 for cetane, and 15 for hepta-methyl-nonane). In the CFR engine, the C.R. is varied to produce an ignition delay of 13°C.A., with the dynamic injection timing at 13°C.A. BTDC. The relationship between the C.R. and C.N. is given in curve 1 of Figure 3-10. The cetane number of the fuel, according to the ASTM D-613 method, is given by the following equation:

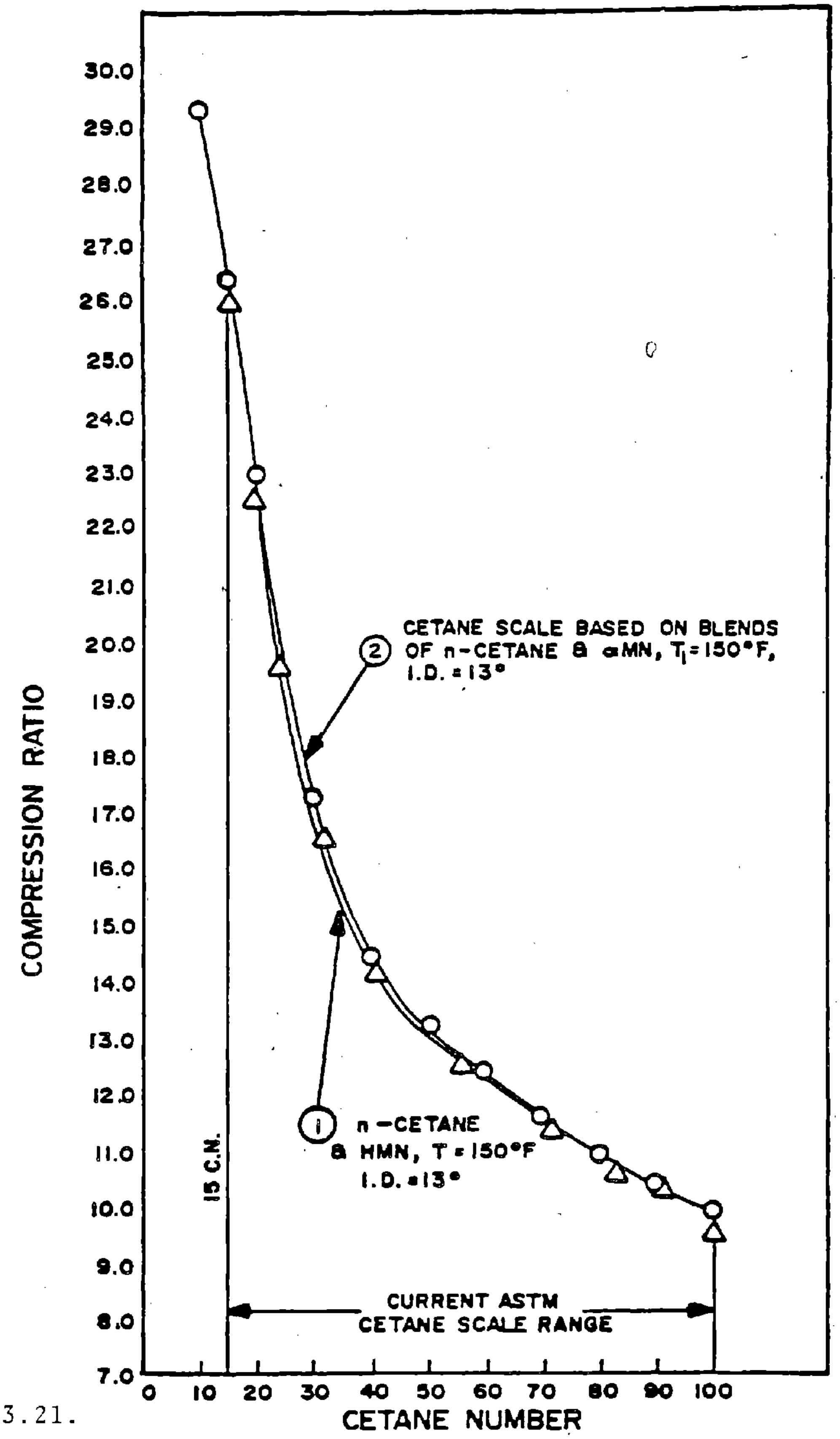
$$C.N. = \%\ n\text{-cetane} + 0.15\ (\%HMN)$$

According to the above ASTM method, fuels can be rated between C.N. 100 and C.N. 15. But below C.N. 15, fuels cannot be rated by this standard method.

3.4.1.2 Problems Related to the Autoignition of Some Alternate Fuels

a. ASTM D-613 Rating Method

Alternate fuels which have cetane numbers less than 15 cannot be rated by using the ASTM D-613 method. These fuels include gasoline, ethanol and ethanol. For such fuels, the low standard reference fuel should have a C.N. of zero rather than the C.N. of 15 used in ASTM D-613. In earlier methods, alpha-methyl-naphthalane (αMN) was used as a zero C.N. reference fuel. Curve number 2 of Figure 3-10 is a scale obtained by using n-centane and αMN as reference fuels. It is noted that a C.R. higher



Ref. 3.21.

FIGURE 3.10. RELATIONSHIP BETWEEN THE C.N. AND C.R. IN THE CFR ENGINE WITH HMN AND XMN AS REFERENCE FUELS

than 29:1 is needed for C.N. = 10. For lower cetane fuels, a C.R. exceeding the highest C.R. of the CFR engine is needed.

Many attempts have been made by the U.S. Army Fuels and Lubricants Research Laboratory to extend the scale to lower than C.N. = 15. These are summarized in a comprehensive SAE paper by Urban and Gray (3.20) and include the following:

i. Blend normal cetane with the sample, and then, calculate the sample cetane number from the cetane number of the blend.

ii. Correlate the cetane and octane numbers of the sample as shown in Figure 3-11.

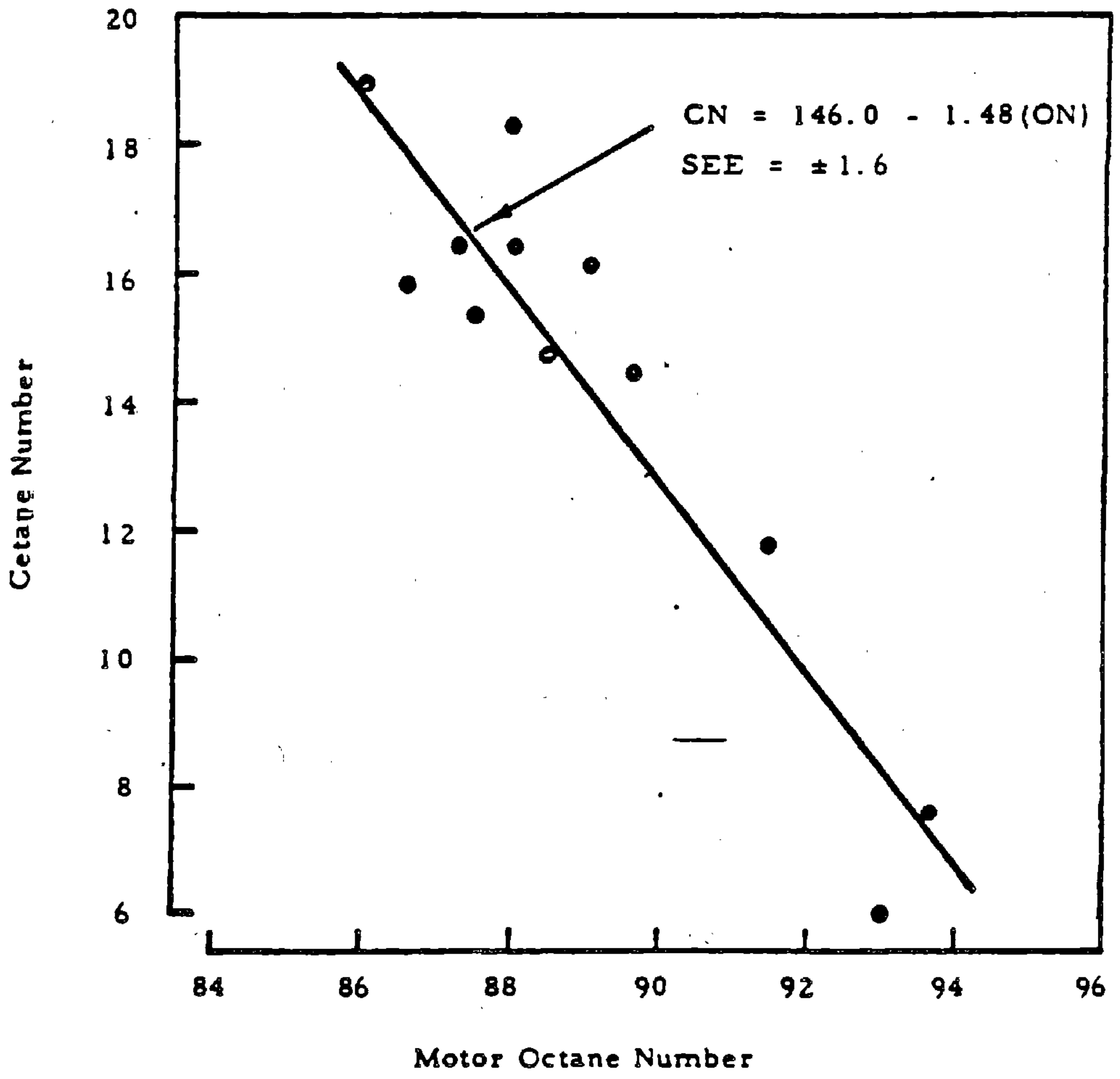
iii. Use an I.D. = 17°C.A. instead of the standard I.D. of 13°C.A.

All these methods proved to be unsatisfactory. In a more recent study (3.21), a modified cetane scale was developed by increasing the inlet air temperature from 150°F to 350°F, which allowed fuels of C.N. as low as zero to be rated at a C.R. of 19.5:1. This modified scale is shown in Figure 3-12.

There is a need for an extensive study of the modified scale by using inlet temperatures between the standard temperature of 150°F and 350°F. This study is needed to determine the most suitable inlet air temperature for the cetane rating of fuels in the CFR engine.

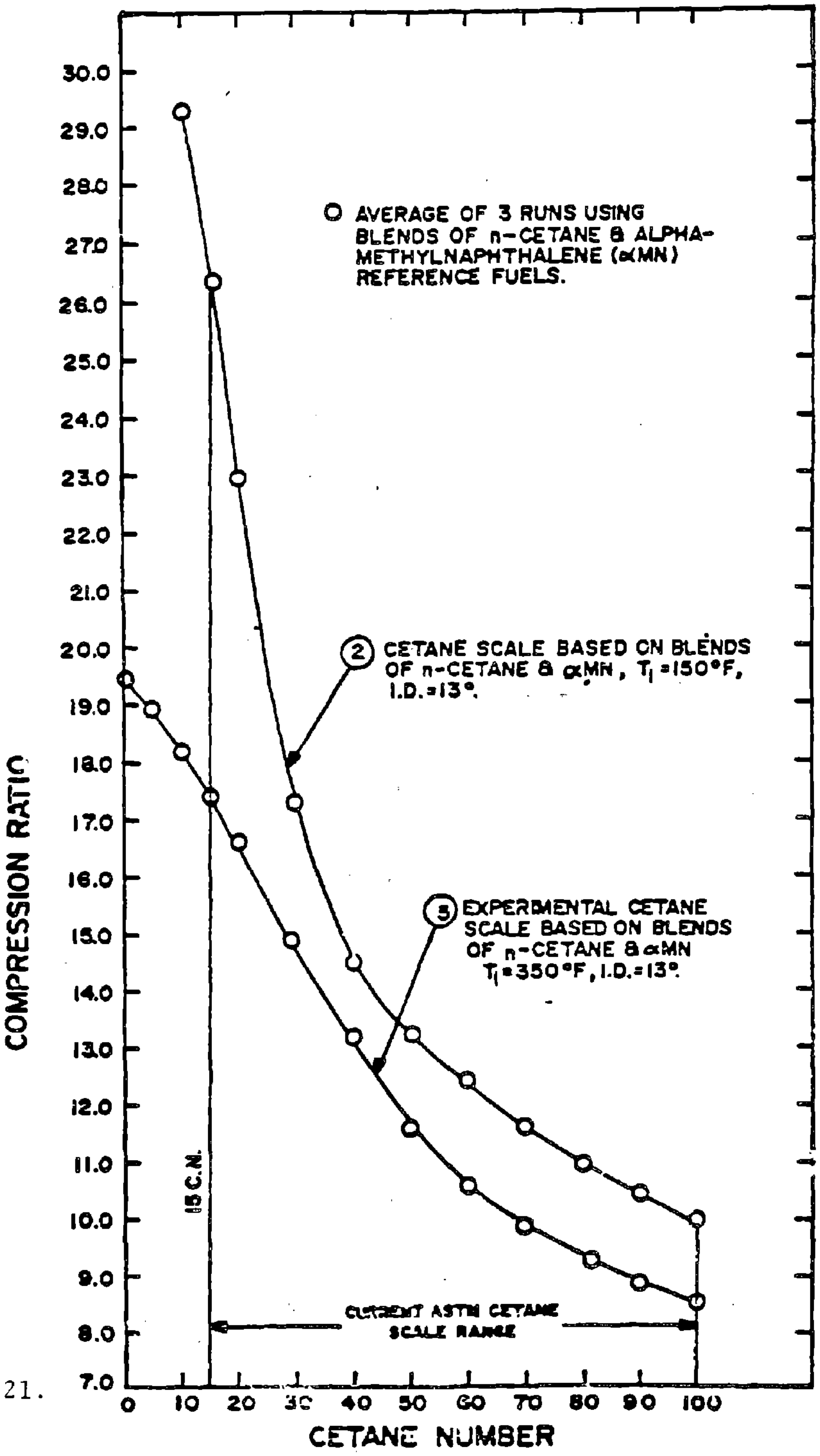
b. Cycle-to-Cycle Variation in the Ignition Delay

Low ignition quality fuels having C.N. <20 have been observed to produce cycle-to-cycle variations in the ignition delay as indicated in the pressure traces shown in Figure 3-13. It should be noted that for all the fuels shown in Figure 3-13, the start of needle lift was at 13° BTDC according to the ASTM D-613 method, and cycle-to-cycle variations in the needle lift were not observed. The cycle-to-cycle variations in the pressure trace, at the point of pressure rise due to combustion, increased with the decrease in the cetane number of the fuel from 20 to zero.



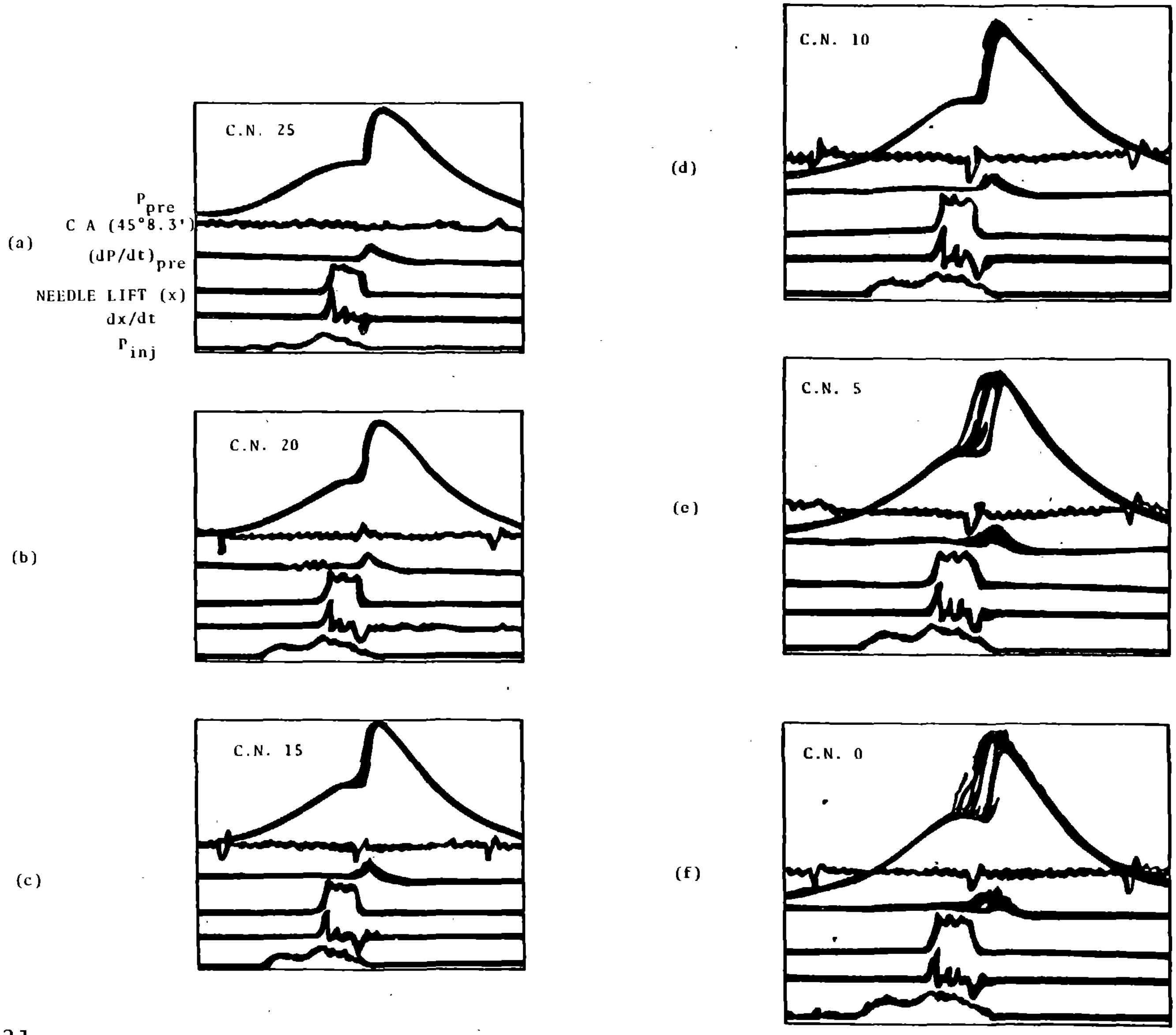
Each point represents the average of several determinations.

FIGURE 3.11. CORRELATION BETWEEN THE C.N. AND O.N. OF DIFFERENT FUELS



Ref. 3.21.

FIGURE 3.12. A MODIFIED CETANE SCALE FOR RATING LOW IGNITION QUALITY FUELS



Ref. 3.21.

FIGURE 3.13. CYCLE-TO-CYCLE VARIATION IN THE AUTOIGNITION OF FUELS OF DIFFERENT CETANE NUMBERS

This cycle-to-cycle variation in the I.D. explains the erratic operation of the I.D. meter used in the ASTM D-613 method, reported by Urban and Gray (3.20), during the rating of low C.N. fuels.

There is a need to study the source of the cycle-to-cycle variation in the autoignition of low C.N. fuels, and methods to control it.

3.4.1.3 Ignition Delay Correlations - Many correlations have been developed between the ignition delay and the air properties in diesel engines for the regular fuels. These correlations are reviewed in reference (3.22).

There correlations are of the general form

$$\text{I.D.} = \frac{Ae^{\frac{E}{\bar{R}T}}}{p^n}$$

where

I.D. is in units of time

A is a pre-exponential factor

E is the global activation energy

$\bar{R}$ is the universal gas constant

T is the absolute temperature

p is the absolute pressure

n is an exponent

There is a need to develop such correlations for the other alternate fuels which might be used in the future in diesel engines. The effects of increasing the aromaticity and the distillation range of the petroleum fuels, and blending the diesel fuel with alcohols, and coal and shale derived distillates, need to be determined. These correlations will be needed in the future to determine the sensitivity of the I.D. to fuel properties and the most effective techniques to reduce the ignition delay.

3.4.2 Volatility and Distillation Range

The sensitivity of the diesel engine to variations in fuel volatility are summarized in Figure 3-14.

3.4.3 Viscosity

The sensitivity of diesel engines to variations in the fuel viscosity are illustrated in Figure 3-15.

3.4.4 Specific Gravity

Figure 3-16 shows the relative performance versus fuel specific gravity, and BTU per gallon when operated in a particular engine at constant fuel pump setting. The increase in efficiency as the fuel becomes lighter is due to reduced F/A ratio. At a constant efficiency, the effect on power is due entirely to the changes in heat of combustion per unit volume.

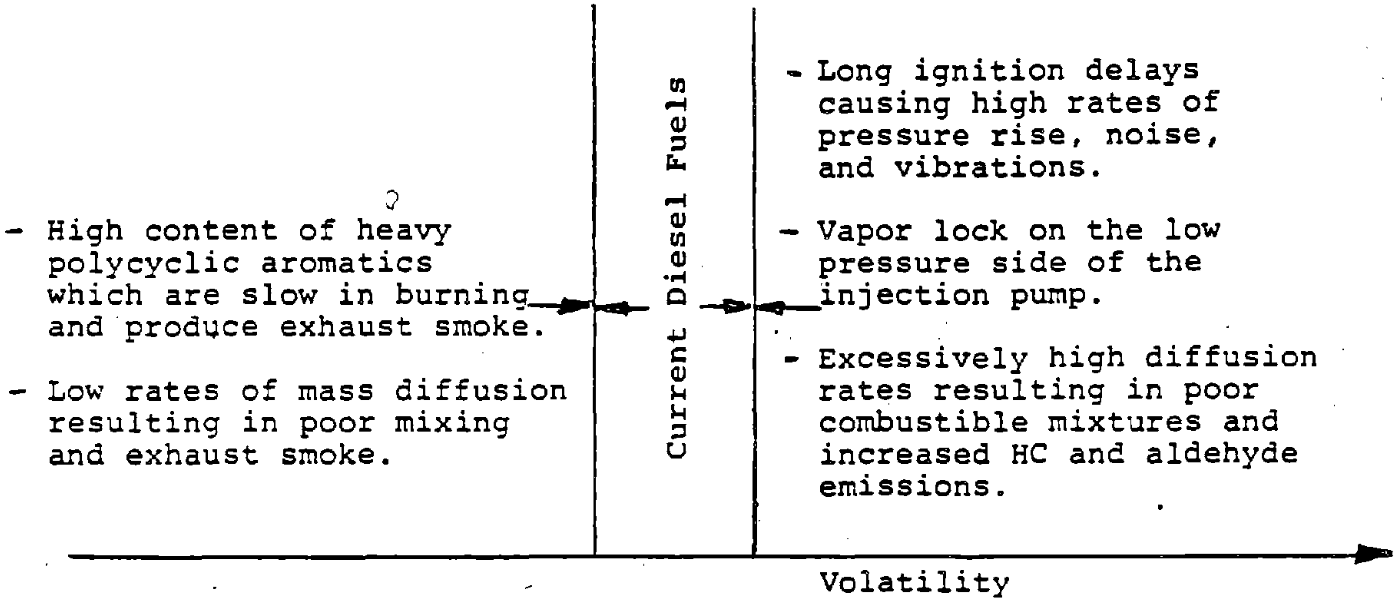


FIGURE 3.14. PROBLEMS ASSOCIATED WITH VARIATIONS IN DIESEL FUEL VOLATILITY

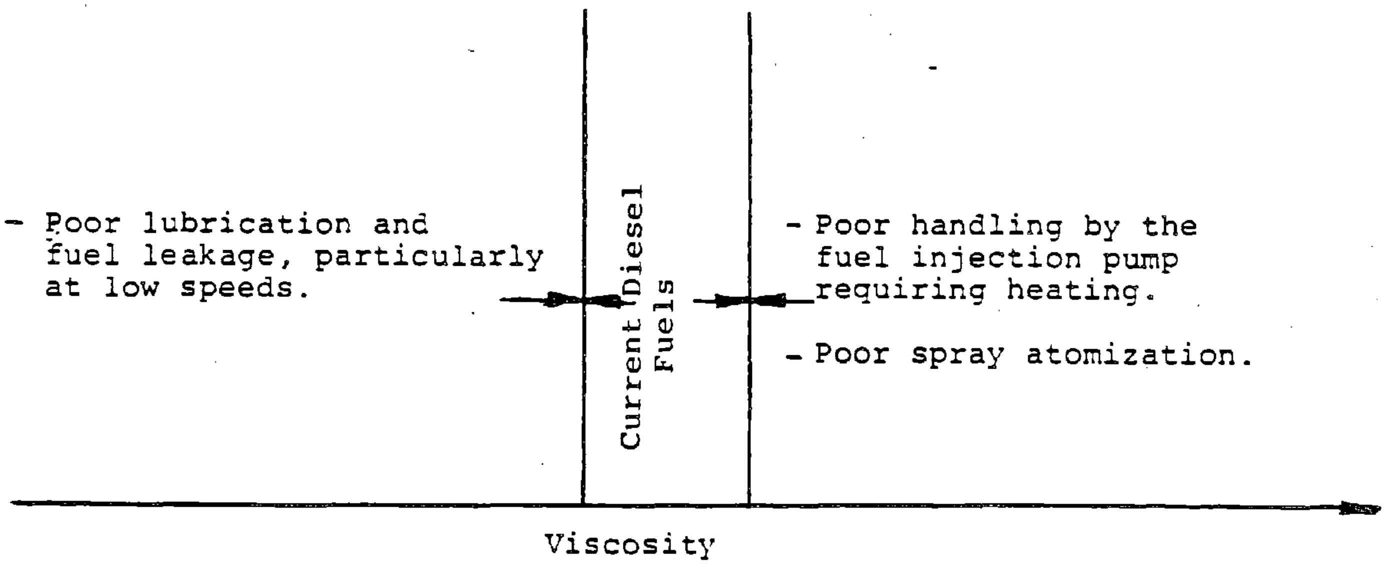
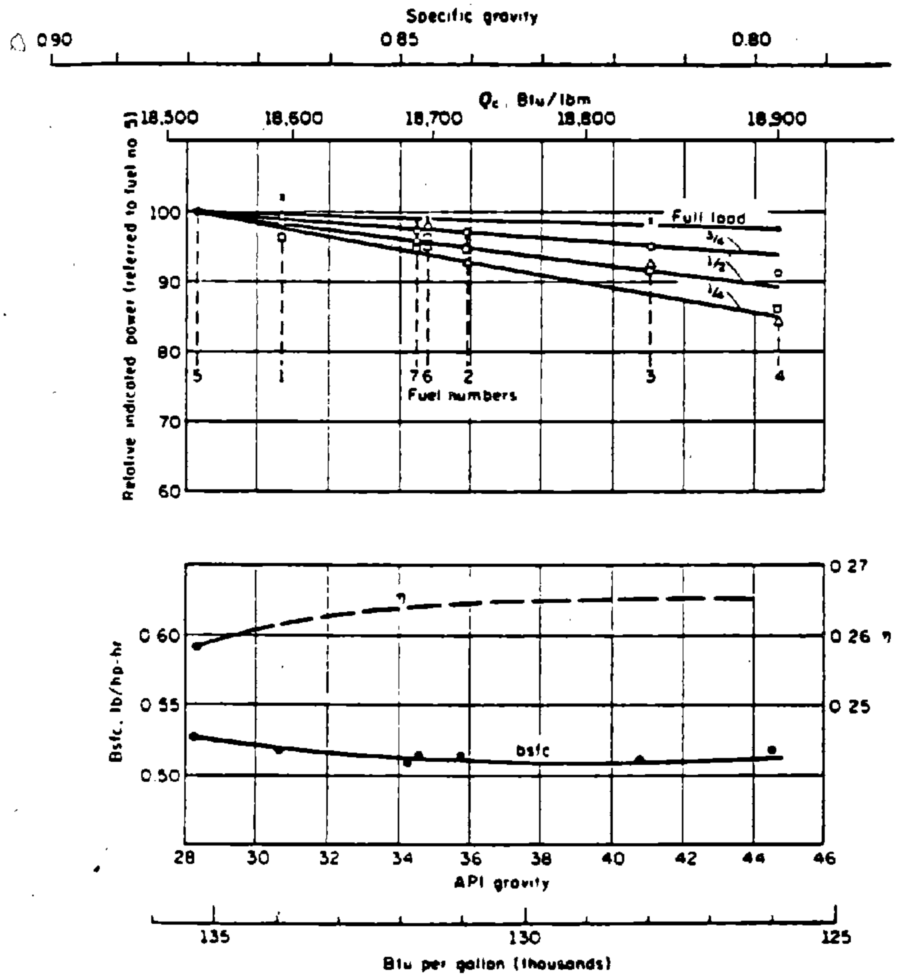


FIGURE 3.15. PROBLEMS ASSOCIATED WITH VARIATIONS IN DIESEL FUEL VISCOSITY



NOTE: BSFC Points are average for all loads

Ref. 3.19.

FIGURE 3.16. RELATIVE PERFORMANCE OF A DIESEL ENGINE AT CONSTANT FUEL-PUMP SETTINGS VERSUS SPECIFIC GRAVITY OF FUEL.

4. SENSITIVITY OF AUTOMOTIVE GASOLINE ENGINES TO VARIATIONS IN FUEL PROPERTIES

4.1 ALCOHOL-INDOLENE BLENDS

4.1.1 Effect of Blending Gasoline and Alcohols on Octane Number

Figure 4.1 shows the effect on the octane number of adding methanol to Indolene (4.1). Methanol improved RON more than MON. This observation has been made by many investigators. Johnson and Riley (4.1) developed the following correlation to describe the effect of methanol on fuel octane rating:

$$ONB = N_t + \Delta N[1-\exp(-Kx)]$$

where

ONB = octane number of blend

x = volume % methanol in blend

N_t = RON or MON of base fuel

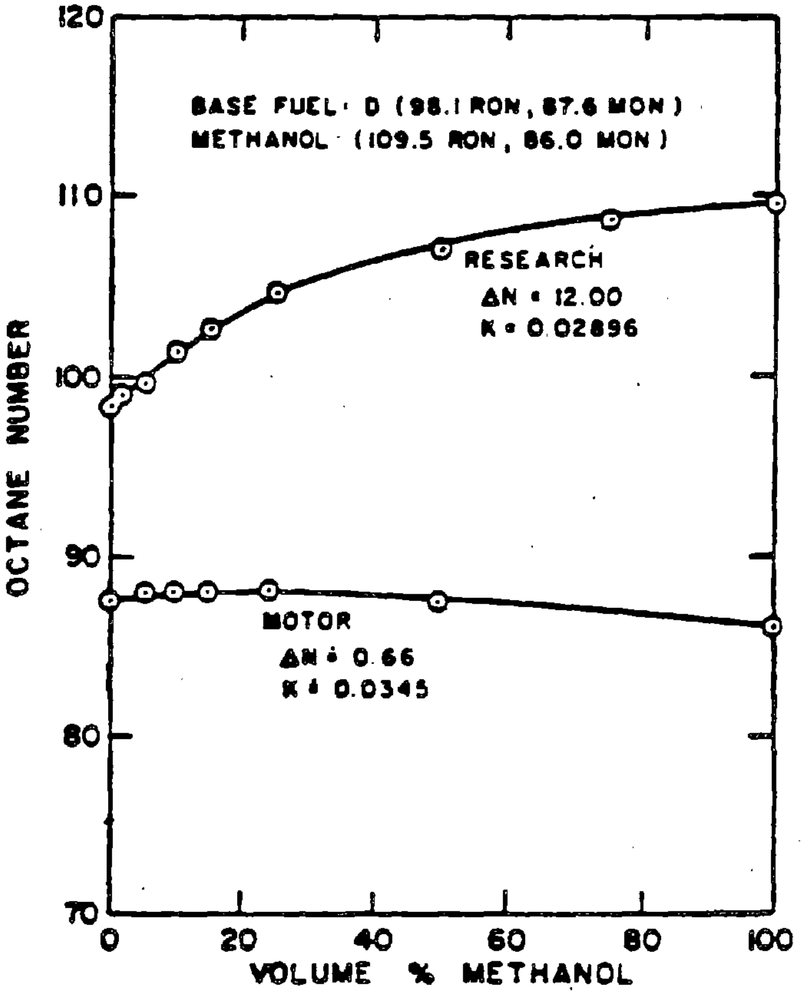
ΔN = octane increment from addition of methanol

K = base fuel response factor

ΔN is fixed for any given base fuel and indicates how effective methanol will be in raising the O.N. of the base fuel. The variation in ΔN with the base fuel O.N., obtained by Johnson (4.1), is given in Figure 4.2. This Figure shows that the higher the octane number of the base fuel, the lower the antiknock achieved by adding methanol. Also, the MON curve shows significantly smaller octane increases than those found for the RON. Base fuels with a MON greater than 83 gave virtually no change in MON when blended with methanol.

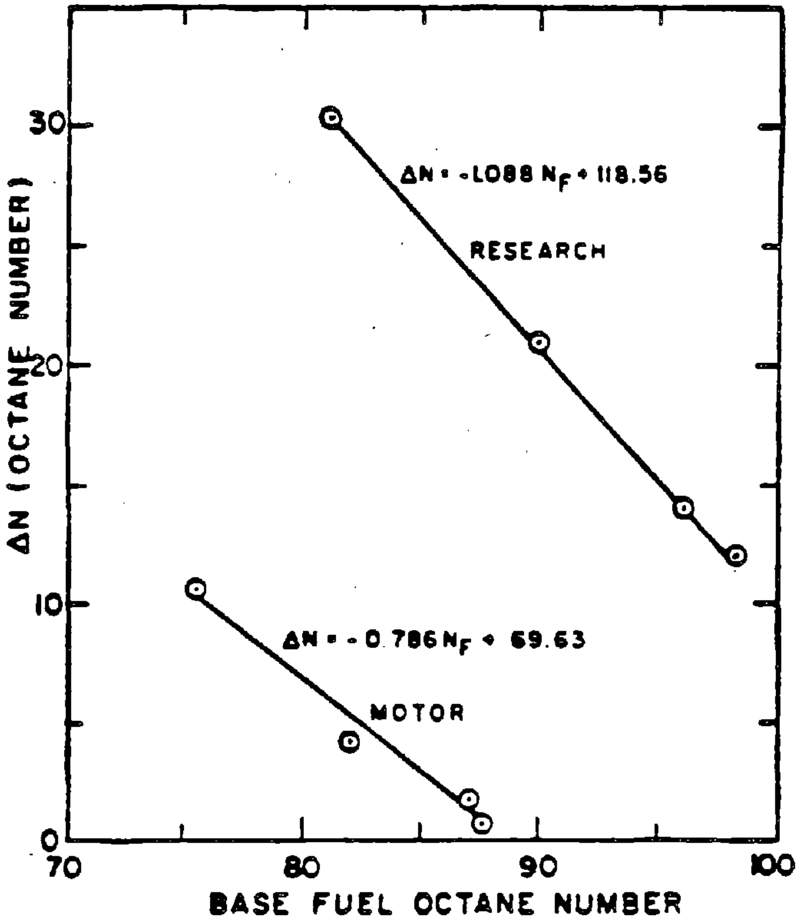
4.1.2 Effect on Flame Speed

The effect of blending Indolene and methanol on the flame speed in a CFR engine is shown in Figure 4.3. The flame speed is measured by using an ionization gap probe. This figure shows that



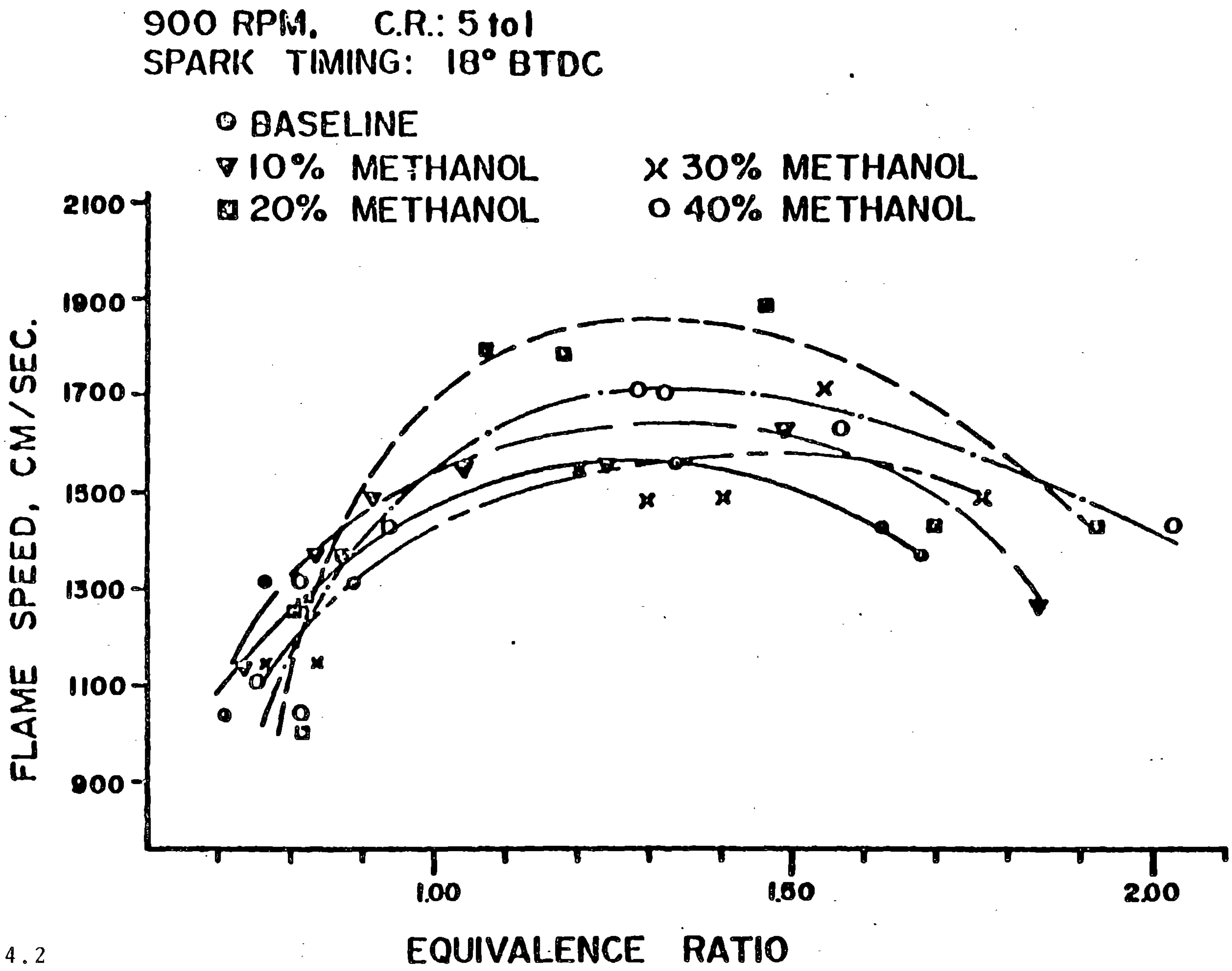
Ref. 4.1.

FIGURE 4.1. OCTANE CHARACTERISTICS OF GASOLINE METHANOL BLENDS



Ref. 4-1.

FIGURE 4.2. CORRELATION BETWEEN OCTANE INCREMENT AND BASE FUEL OCTANE NUMBER



Ref. 4.2

FIGURE 4.3 EFFECT OF BLENDING METHANOL WITH INDOLENE ON THE FLAME SPEED a blend, having 20 percent methanol, produced the highest maximum flame speed.

4.1.3 Effect on a Single Cylinder Engine's Performance, Thermal Efficiency and Emissions

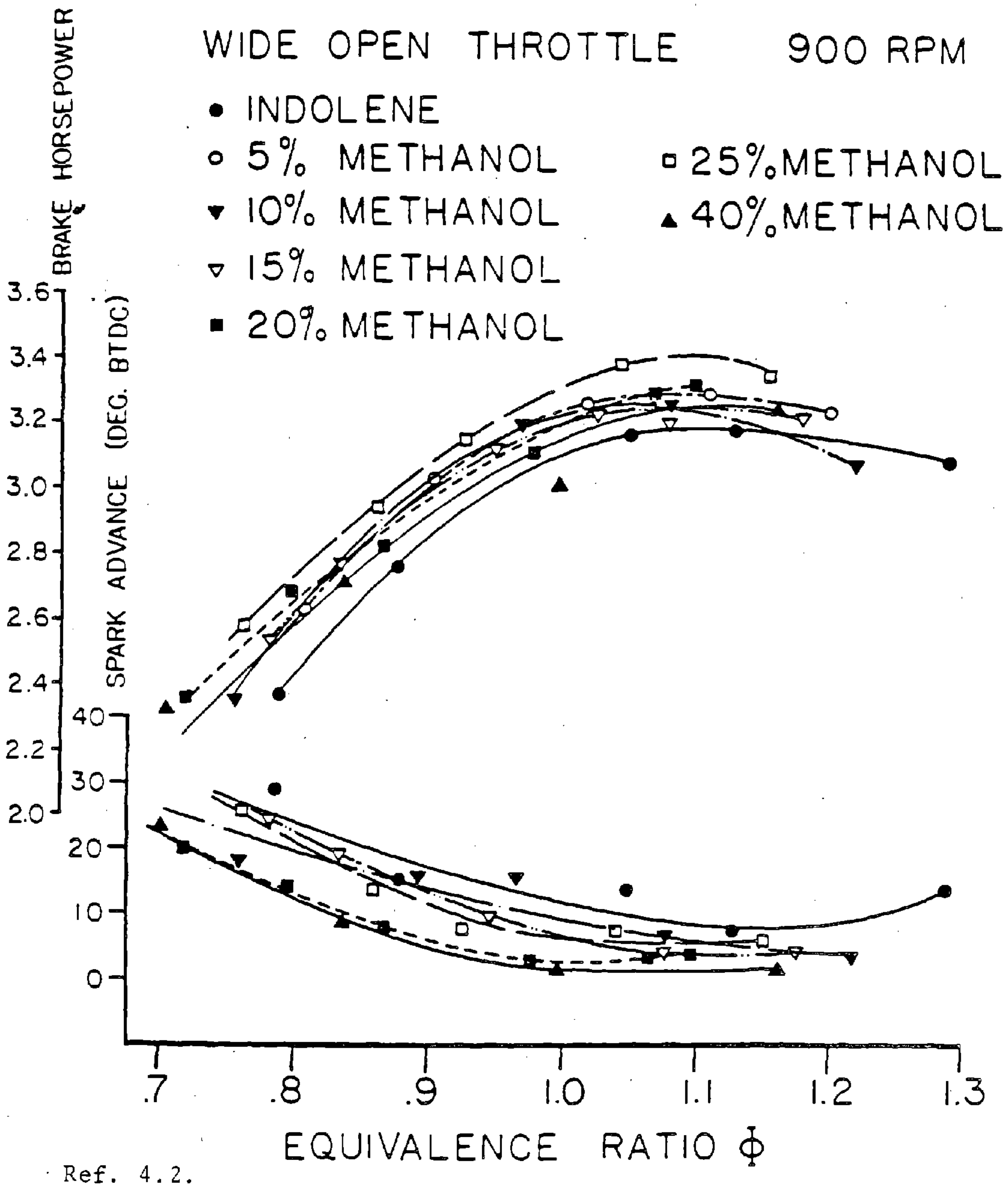
4.1.3.1 Power Output and Minimum Advance for Best Torque - Adding methanol to Indolene allowed higher compression ratios to be used without knock and resulted in a horsepower increase as shown in Figure 4.4. The maximum gain in power output is with 25 percent methanol; higher percentages of methanol do not further increase the power output. In fact, the output with 40 percent methanol is less than that with 25 percent methanol. The MBT (minimum advance for best torque) for each blend is also shown in Figure 4.4. The compression ratio that corresponds to each of the Indolene-methanol blends is given in Table 4.1.

TABLE 4.1. COMPRESSION RATIOS CORRESPONDING TO VARIOUS INDOLENE-METHANOL BLENDS

PERCENT METHANOL	0	5	10	15	20	25	40
COMP. RATIO	7.2:1	7.5:1	7.62:1	7.73:1	8.1:1	8.0:1	8.0:1

4.1.3.2 Fuel Economy - Brake specific fuel consumption results are given in Figure 4.5, and show an increase in fuel consumption with the addition of methanol. This is caused by methanol's lower heat of combustion (4800 k cal/kg) as compared to Indolene (10,600 k cal/kg).

On an energy basis, the brake specific energy consumption in K cal/BHP hr is plotted in Figure 4.6 for different blends. Adding methanol to Indolene has a definite effect on decreasing the



Ref. 4.2.

FIGURE 4.4. EFFECT OF MIXING METHANOL WITH INDOLENE FUEL ON BHP AND MBT

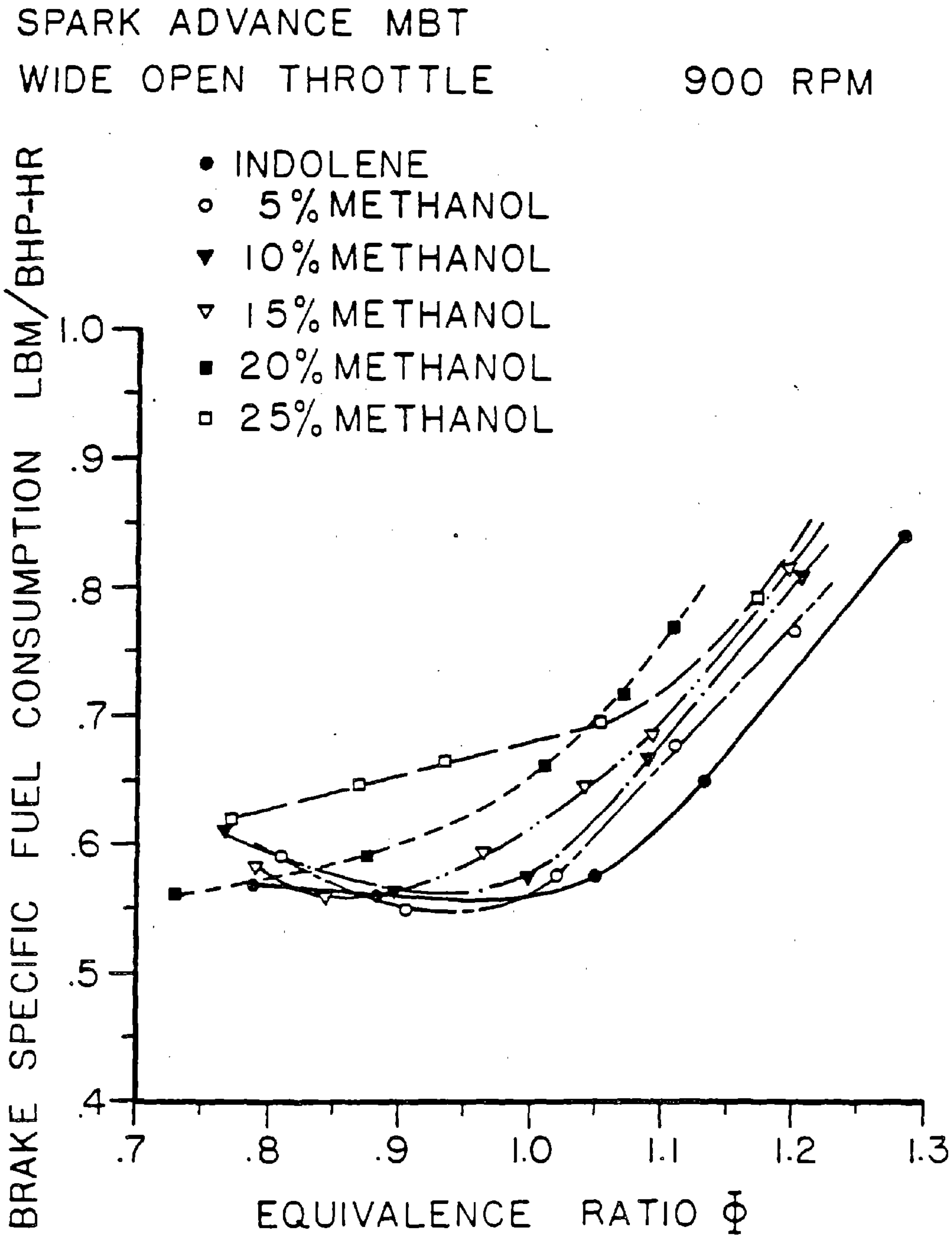


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FIGURE 4.5. EFFECT OF MIXING METHANOL WITH INDOLENE ON BRAKE SPECIFIC FUEL CONSUMPTION

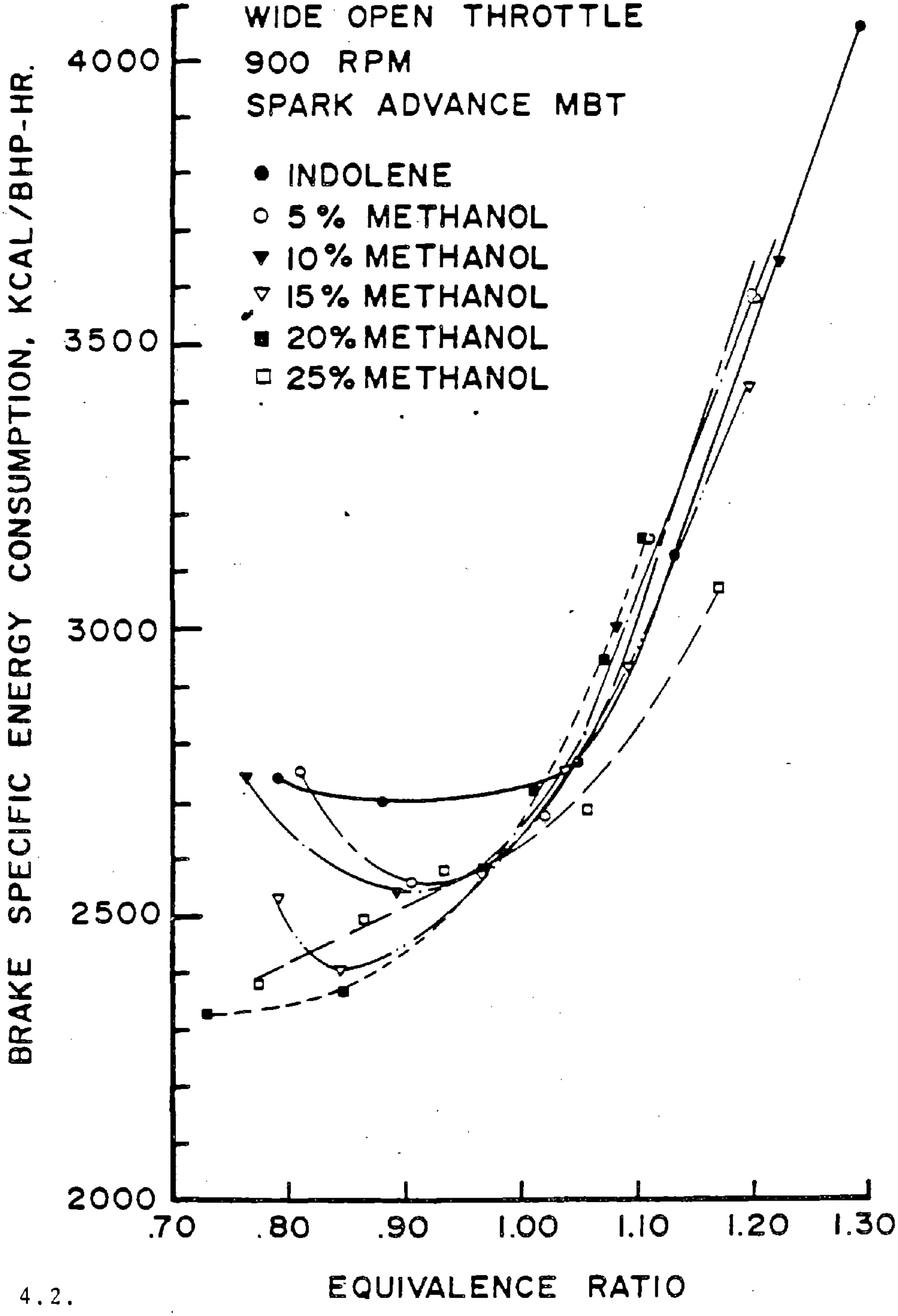

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FIGURE 4.6. EFFECT OF MIXING METHANOL WITH INDOLENE FUEL ON BRAKE SPECIFIC ENERGY CONSUMPTION

specific energy consumption or improving the brake thermal efficiency for equivalent ratios between the lean limit and the stoichiometric. This is attributed to many factors including the increase in the allowable compression ratio with methanol, the lower time losses caused by the higher flame speeds, and the lower heat losses caused by the lower combustion temperatures.

4.1.3.3 Hydrocarbons - The effect of adding methanol to Indolene on the brake specific hydrocarbons (HC) is shown in Figure 4.7 for different equivalence ratios. It is noticed that, in general, the HC emissions tend to increase with methanol, particularly in the lean mixtures. This increase is expected to be more significant if the response of the HFID (Heated Flame Ionization Detector) to methanol is into consideration.

The increase in (HC) emissions with methanol is attributed to the higher volatility of the methanol-Indolene blend (as compared to that of pure Indolene) and to the presence of more fuel per pound of air for a given blend. These factors lead to higher concentrations of HC in the quench layers and crevices.

4.1.3.4 Carbon Monoxide - Figure 4.8 shows emissions of carbon monoxide as a function of ϕ for various blends. This follows the expected trend that (with and without methanol) very little CO is emitted on the fuel-lean side down to $\phi = 0.7$, and the concentration of CO increases as ϕ increases on the fuel-rich side. At a given fuel-air equivalence ratio, the brake specific CO slightly increases with methanol.

4.1.3.5 Nitrogen Oxides - The effect of methanol on the brake specific NO_x emissions is shown in Figure 4.9 for different methanol ratios as a function of the equivalence ratio. It is noticed that the specific NO_x emissions increase with methanol for rich mixtures having ϕ more 1.1. For leaner mixtures, the specific NO_x is reduced to different degrees with methanol content. The brake specific NO_x peaks at richer mixtures with the addition of methanol.

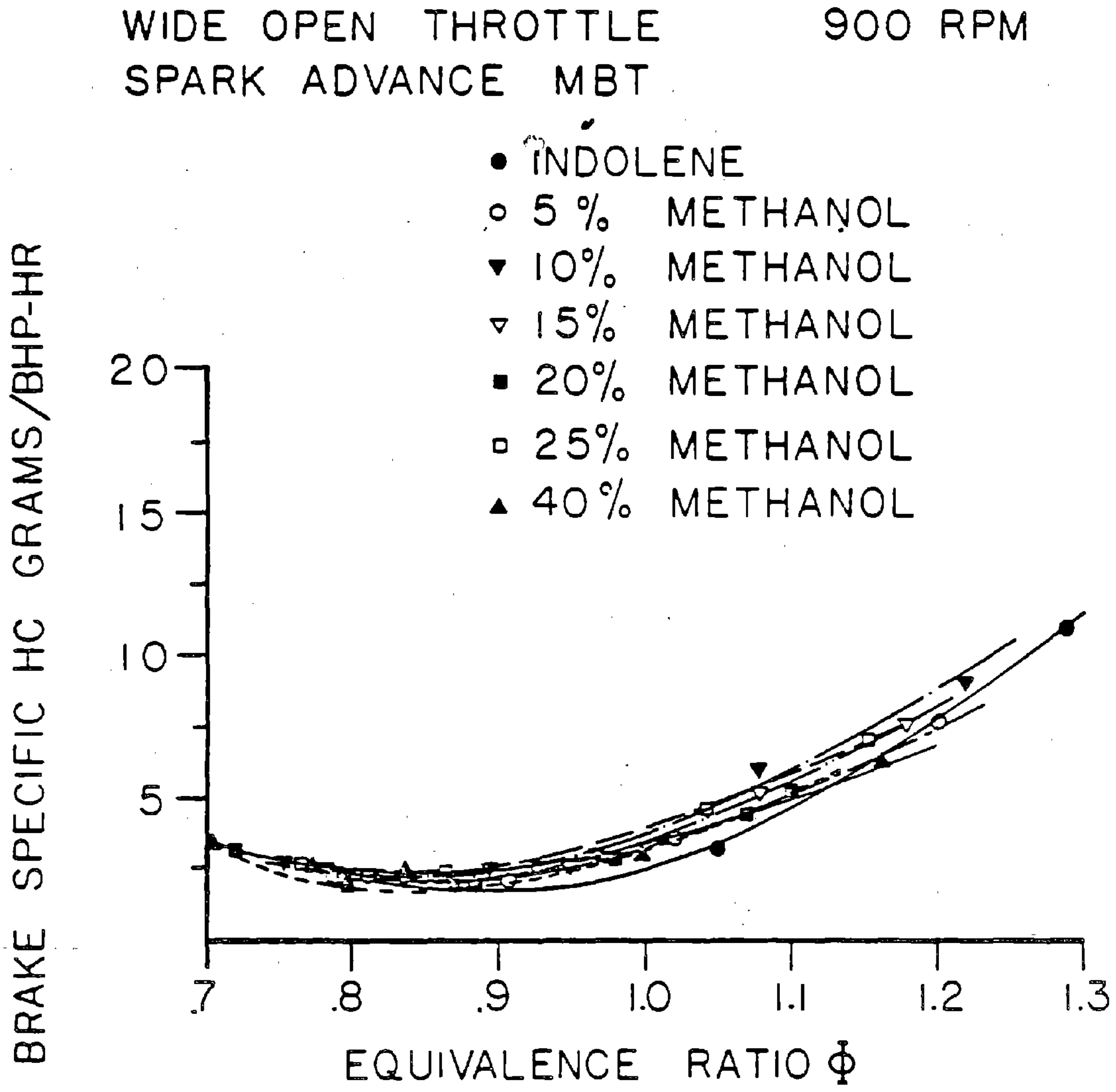

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FIGURE 4.7. EFFECT OF MIXING METHANOL WITH INDOLENE FUEL ON BRAKE SPECIFIC UNBURNED HYDROCARBONS.

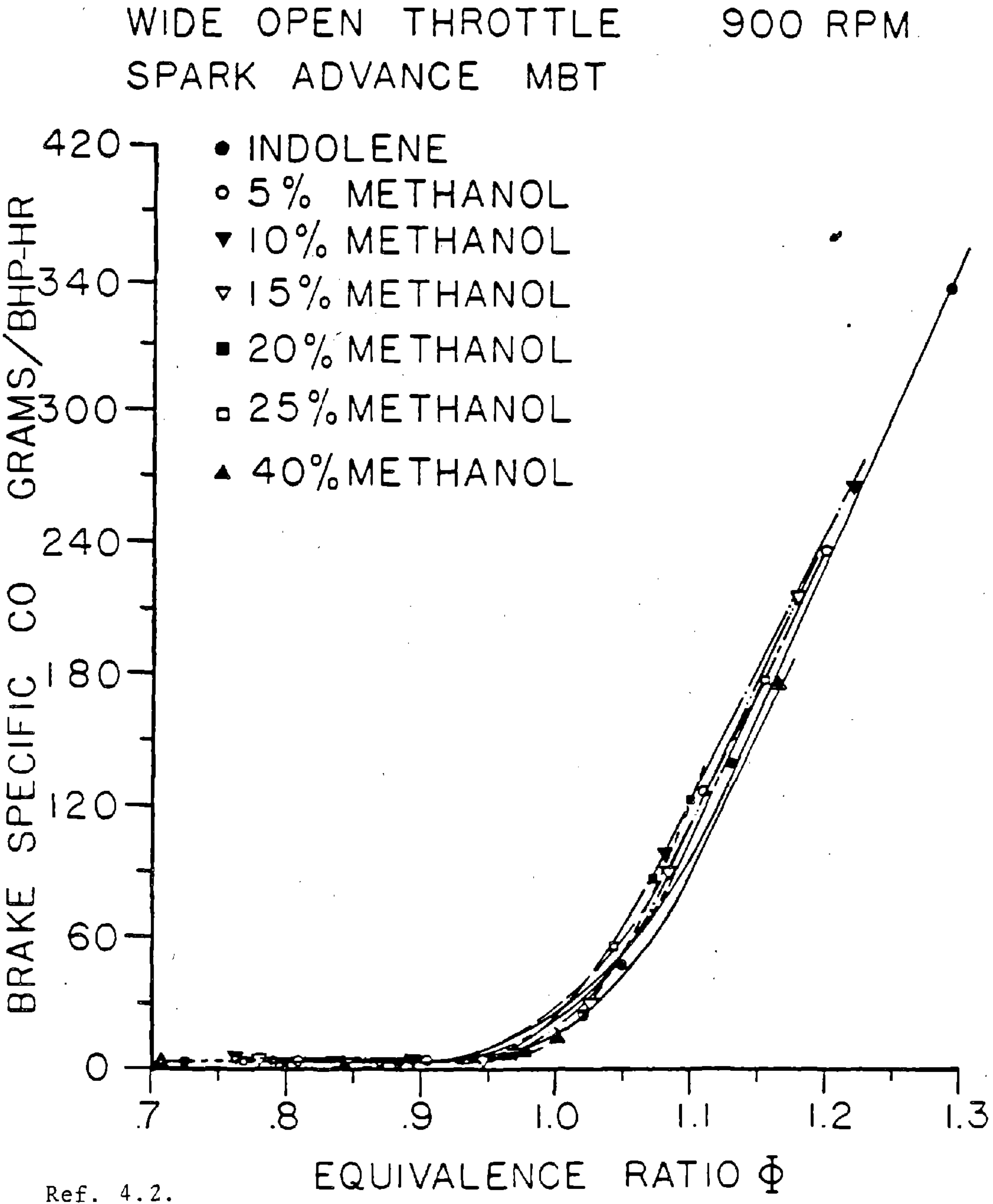

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FIGURE 4.8. EFFECT OF MIXING METHANOL WITH INDOLENE FUEL ON BRAKE SPECIFIC CARBON MONOXIDE.

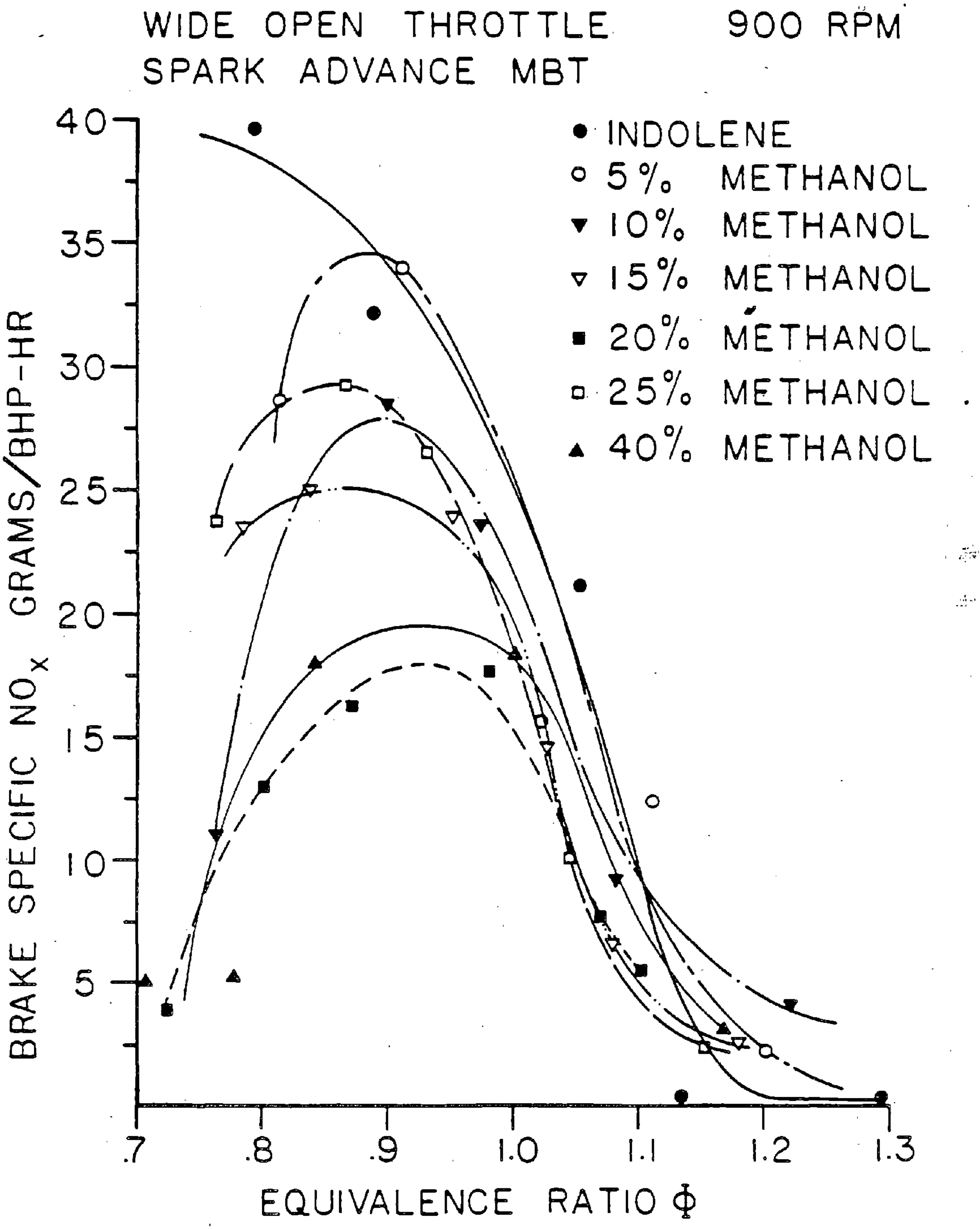

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FIGURE 4.9. EFFECT OF MIXING METHANOL WITH INDOLENE FUEL ON BRAKE SPECIFIC NITRIC OXIDES.

The peak values of the specific NO_x curves are plotted in Figure 4.10, and show a definite reduction in specific NO_x with the increase in percentage methanol up to about 30%.

4.1.4 Effect of Alcohols on a Non-Catalytic Car

The effect of using a blend of 10 percent methanol/gasoline fuel in a non-catalytic car has been reported by Johnson and Riley and is given in Figure 4.11. The baseline fuel is Indolene. Based on this figure and other results reported by Wigg and Lung (4.3) and Brinkman et al (4.4), the following conclusions are made:

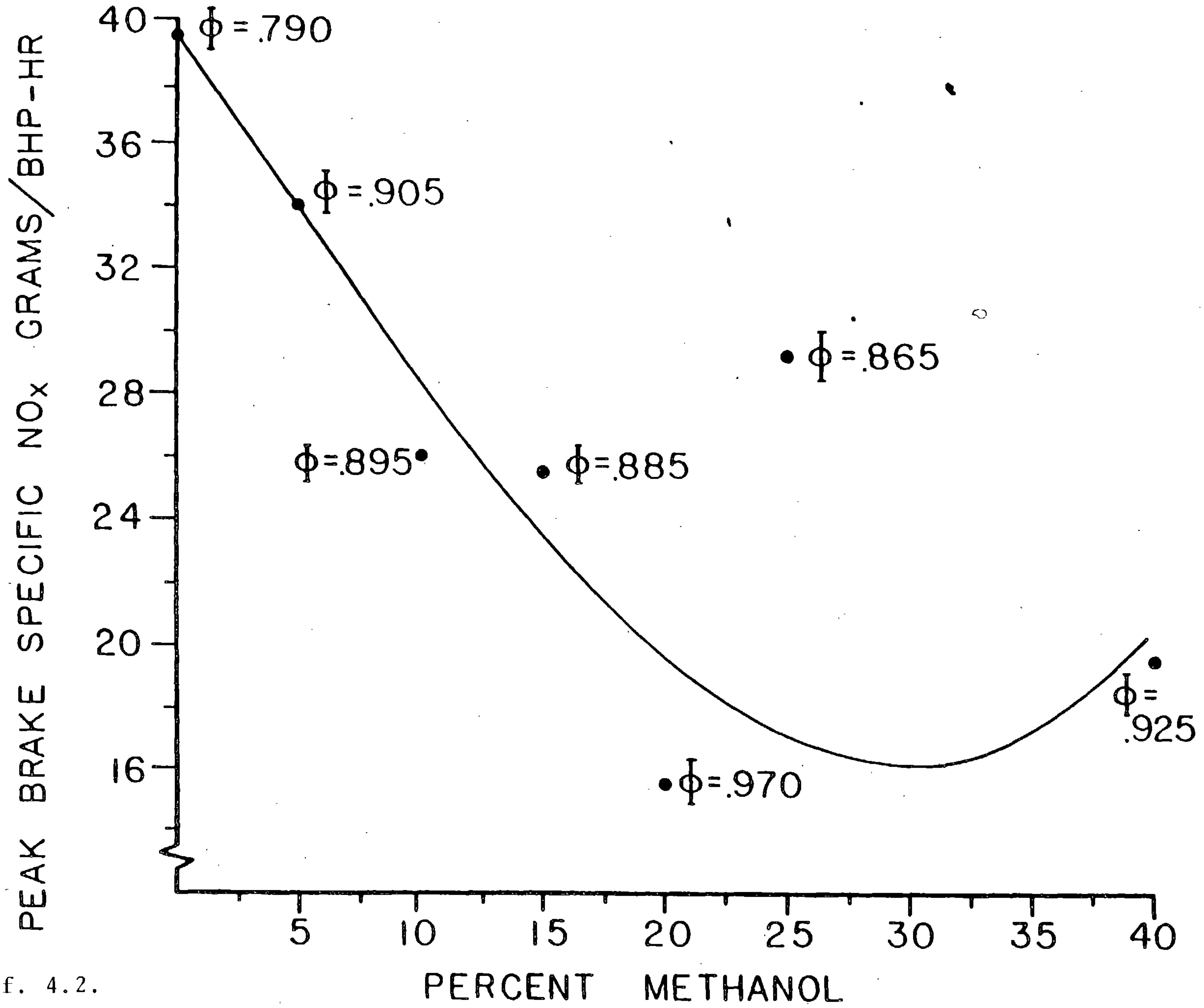
(i) Adding 10 percent methanol to unleaded gasoline will reduce the CO emissions by approcimeately 30 percent.

(ii) Adding 10 percent methanol to unleaded gasoline does not substantially change the HC or NO_x emissions.

(iii) The miles per gallon of fuel is less for the methanol blends than for the unmodified gasoline. This is caused by the low energy content per unit volume of methanol as compared with Indolene.

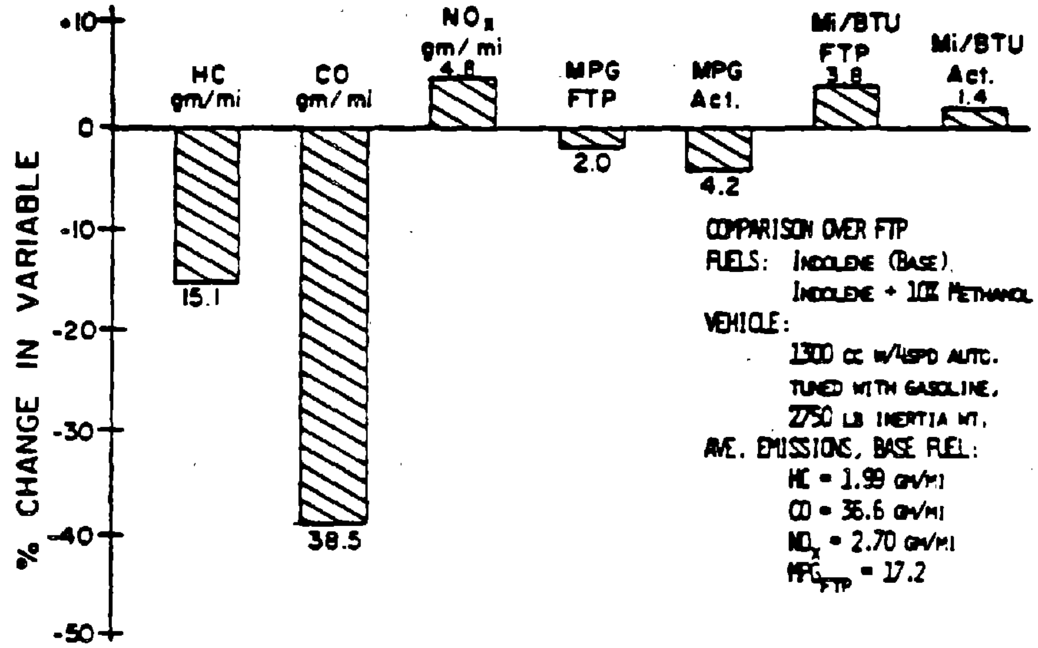
(iv) However, there was a slight increase in the miles traveled per million BTU's, indicating a slight increase in the energy efficiency.

4.1.4.1 Effect of Alcohols on 1978 Catalytic Cars - Naman and Allsup (4.15) of DOE reported the results of chassis dynamometer test on eight 1978 vehicles. Five vehicles had oxidation catalysts and 49-state emission control systems, and three vehicles were equipped with 3-way catalysts and California emission control systems. The spark timing and idle speeds were adjusted to the manufacturer's specifications (which probably were optimized for Indolene fuel). The extenders were 10 percent ethanol, 10 percent methanol, 7 percent methyl tertiary butyl ether, and 7 percent tertiary butyl alcohol. The exhaust emissions and fuel economies were measured on the 1978 Federal Test Procedure (FTP), using a chassis dynamometer. Fuel economy was measured using the carbon



Ref. 4.2.

FIGURE 4.10. EFFECT OF MIXING METHANOL WITH INDOLENE FUEL ON PEAK BRAKE SPECIFIC NITRIC OXIDES



COMPARISON OVER FTP
FUELS: INDOLENE (BASE)
INDOLENE + 10% METHANOL
VEHICLE:
1300 CC W/4SPD AUTO.
TUNED WITH GASOLINE.
2750 LB INERTIA WT.
AVE. EMISSIONS, BASE FUEL:
HC = 1.99 GM/MI
CO = 36.6 GM/MI
NO_x = 2.70 GM/MI
MPG_{FTP} = 17.2

Ref. 4.1.

FIGURE 4.11. CHANGES IN FTP RESULTS FOR 10% METHANOL ADDED TO INDOLENE IN A NON-CATALYTIC CAR

balance method. The evaporative emissions were measured using the 1978 Sealed Housing for Evaporative Determination (SHED).

The properties of the fuel and alcohols used in this investigation are given in Table 4.2. The properties of the blends are given in Table 4.3. The results reported by Naman (4.15) are given in Table 4.4). These results show the following:

1. The fuel economy, on a mpg basis, decreased from 2.7 to 7.6 percent with each blend from that of the base fuel. But from an energy point of view the miles per million BTU decreased from 0.5 to 2.02 percent from that of the base fuel. In one case, the ethanol extender increased the miles per million BTU by 0.5 percent. The results computed on an energy basis are given in Table (4.5).
2. CO emissions decreased from 8 to 46 percent depending on the emissions control system used.
3. HC emissions decreased from 5 to 32 percent.
4. NO_x emissions were either unaffected or increased.
5. Evaporative emissions increased proportional to the increase in RVP as shown in Figure 4.12. The 10 percent methanol blend has the highest evaporative emissions and RVP.

4.1.5 Effect of Blending on a 3-Way Catalyst Car with Closed Loop Emission Control System at Constant Speed

The effect of blending gasoline with methanol was determined by Lawson, et. al. (4.5) in a Volvo 244 DL car, with λ-sond emission control system. The sensor is designed to control the F/A ratio at the stoichiometric value. The effect of increasing the percentage of methanol in the gasoline/methanol blend on engine performance and emissions is shown in Figure 4.13. The oxygen sensor was found to continue to maintain stoichiometric F/A control with increasing methanol content in the blend up to

TABLE 4.2. PROPERTIES OF THE DIFFERENT FUELS

	Indolene C_8H_{15}	Ethanol C_2H_6O	Methanol CH_4O	MTBE $C_5H_{12}O$	TBA $C_4H_{10}O$
Molecular Weight	99.65	46.07	32.04	88.14	74.12
Specific Gravity	0.739	0.794	0.791	0.741	0.784
Density lb/gal.	6.15	6.62	6.60	6.18	6.54
Heat of Combustion BTU/lb	18,558	11,613	8,495	15,100	14,025
Heat of Combustion BTU/gallon	114,132	76,878	56,067	93,318	91,724
Stoichiometric $\frac{A}{F}$	14.8/1	9.0/1	6.45/1	11.7/1	11/1

Ref. 4.15.

TABLE 4.3. PROPERTIES OF BLENDS OF INDOLENE AND ALCOHOLS

	Fuel No.[1]				
	1	2	3	4	5
Specific gravity, @ 60°/60°F....	0.739	0.744	0.744	0.740	0.741
API gravity, degrees............	60.0	58.7	58.7	59.7	59.5
Sulfur, wt pct..................	.002	.002	.002	.001	.002
F.I.A., pct:					
Aromatics.....................	25	25	25	24	24
Olefins.......................	1	1	1	1	1
Saturates.....................	74	74	74	75	75
Reid vapor pressure, psi........	8.6	9.7	11.9	8.7	9.1
Hydrogen/carbon.................	1.90	1.97	2.00	1.93	1.93
Oxygen/carbon...................	-	.034	.049	.012	.014
Distillation, °F:					
IBP...........................	92	102	96	93	96
5%............................	122	120	110	120	123
10%...........................	138	130	116	133	134
20%...........................	167	143	123	157	153
30%...........................	193	152	131	178	172
40%...........................	214	182	191	200	195
50%...........................	229	222	219	228	218
60%...........................	242	238	235	238	234
70%...........................	259	250	252	252	250
80%...........................	294	284	283	282	284
90%...........................	326	320	321	322	322
95%...........................	335	334	332	330	331
End point.....................	356	346	345	348	350
Recovery, pct...................	98.0	98.0	98.0	98.5	98.0
Residue, pct....................	1.0	1.0	1.0	.5	1.0
Loss, pct.......................	1.0	1.0	1.0	1.0	1.0

[1] Fuel No. 1 = Indolene (base fuel).
Fuel No. 2 = Fuel No. 1 + 10% ethanol.
Fuel No. 3 = Fuel No. 1 + 10% methanol.
Fuel No. 4 = Fuel No. 1 + 7% MTBE.
Fuel No. 5 = Fuel No. 1 + 7% TBA.

Ref. 4.15.

TABLE 4.4. SUMMARY OF THE EXHAUST EMISSIONS, EVAPORATIVE EMISSIONS, AND FUEL ECONOMY

Fuel Description	Fuel Economy, mpg Urban	Emissions, gm/mile			Aldehydes mg/mile	Total Evaporative Emissions, gm
		HC	CO	NO_x		
OXIDATION CATALYST VEHICLES (5-CAR AVERAGE)						
Fuel No. 1 (Indolene)	18.6	0.85	8.56	1.63	18	2.8
Fuel No. 2 (Indolene + 10% ethanol)	17.9	.58	4.66	1.63	18	4.0
Fuel No. 3 (Indolene + 10% methanol	17.5	.62	4.64	1.89	27	5.4
Fuel No. 4 (Indolene + 7% MTBE)	18.0	.68	5.78	1.62	14	3.5
Fuel No. 5 (Indolene + 7% TBA)	18.0	.78	7.88	1.75	17	3.0
3-WAY CATALYST VEHICLES (3-CAR AVERAGE)						
Fuel No. 1 (Indolene)	18.5	.43	6.23	0.48	4	2.0
Fuel No. 2 (Indolene + 10% ethanol)	18.0	.39	4.55	.59	8	2.3
Fuel No. 3 (Indolene + 10% methanol)	17.1	.41	4.47	.71	4	3.8
Fuel No. 4 (Indolene + 7% MTBE)	17.9	.31	4.51	.65	7	2.2
Fuel No. 5 (Indolene + 7% TBA)	17.7	.32	4.89	.58	9	2.1

TABLE 4.5. FUEL ECONOMY WITH DIFFERENT BLENDS BASED ON THEIR ENERGY CONTENT

	Blend				
	1	2	3	4	5
Heat of Combustion BTU/gallon	114132	110407	108326	112675	112564
% Change in Heat of Combustion	0	-3.26	-5.09	-1.3	-1.4
Miles per million BTU					
(a) Oxidation catalyst cars (average of 5)	163	162.1	161.6	159.8	159.9
(b) 3-way catalyst cars (average of 3)	162.1	163	157.9	158.9	157.2
% Change in miles per million BTU					
(a) Oxidation catalyst cars	0	-0.5%	-0.9%	-1.96%	-1.9%
(b) 3-way catalyst cars	0	0.56%	-2.59%	-1.97%	-3.02%

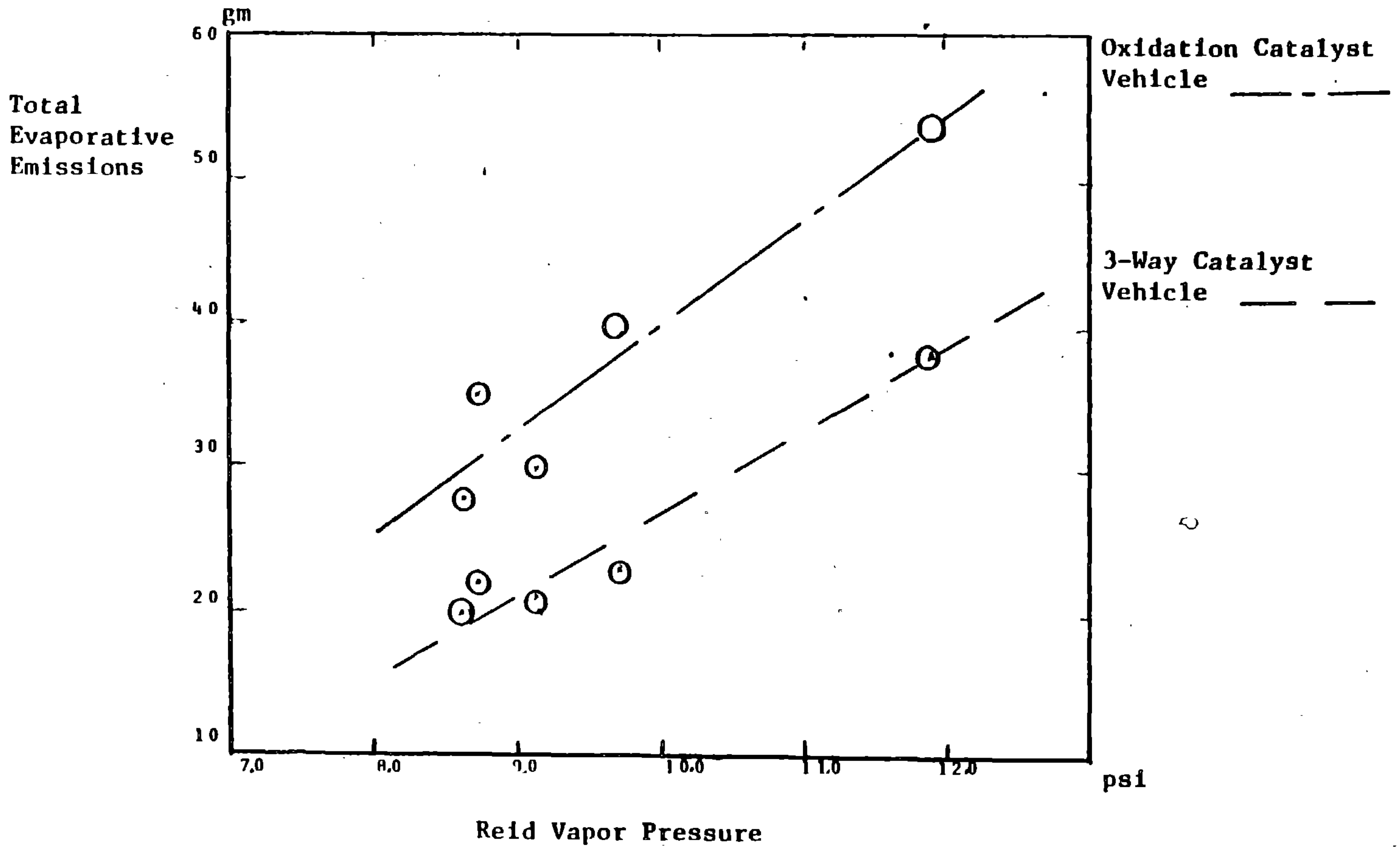


FIGURE 4.12. EFFECT OF REID VAPOR PRESSURE ON THE TOTAL EVAPORATIVE EMISSIONS.

EMISSIONS MEASURED AT 2800 RPM, 50 FT. LBS. TORQUE

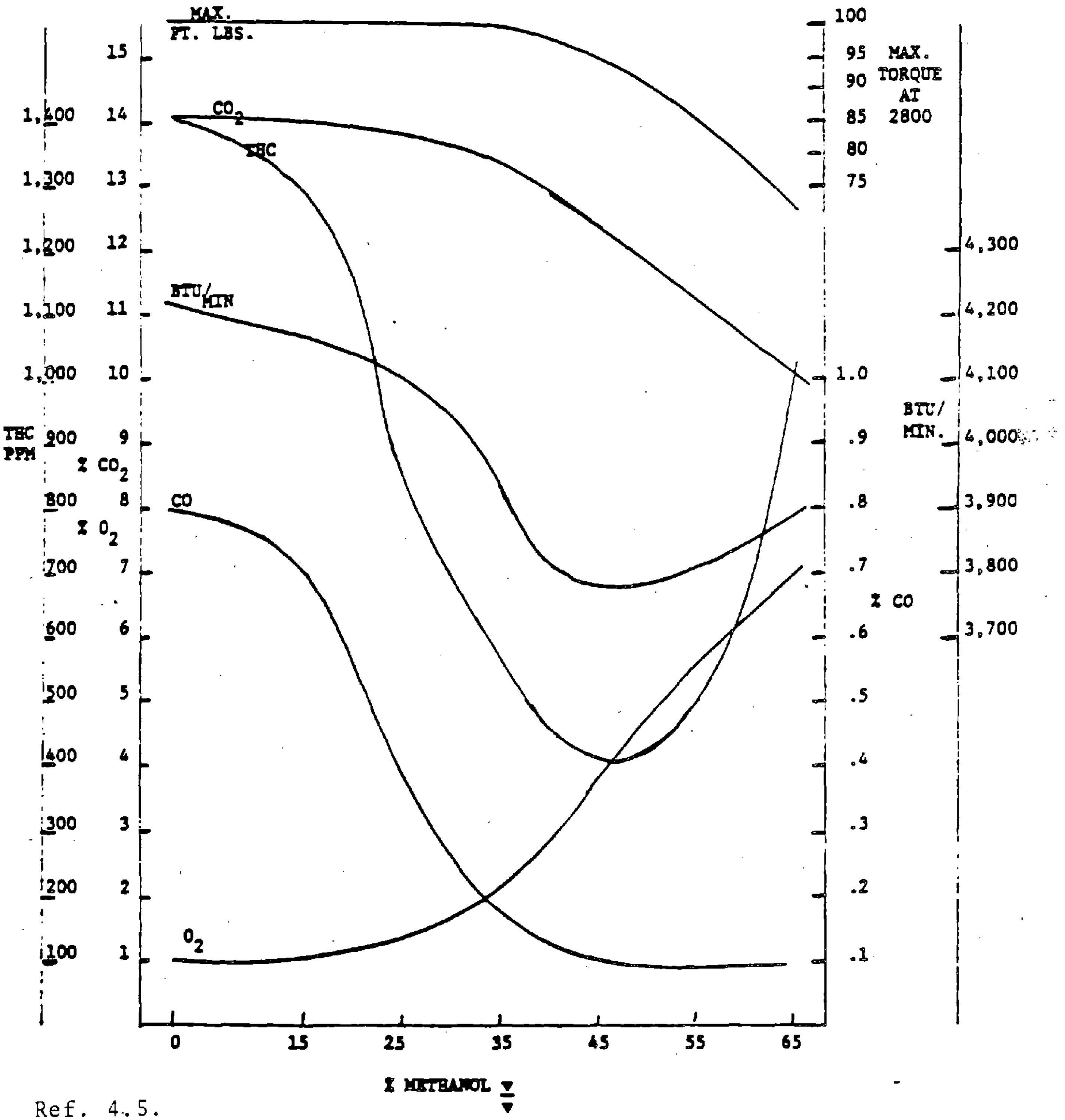


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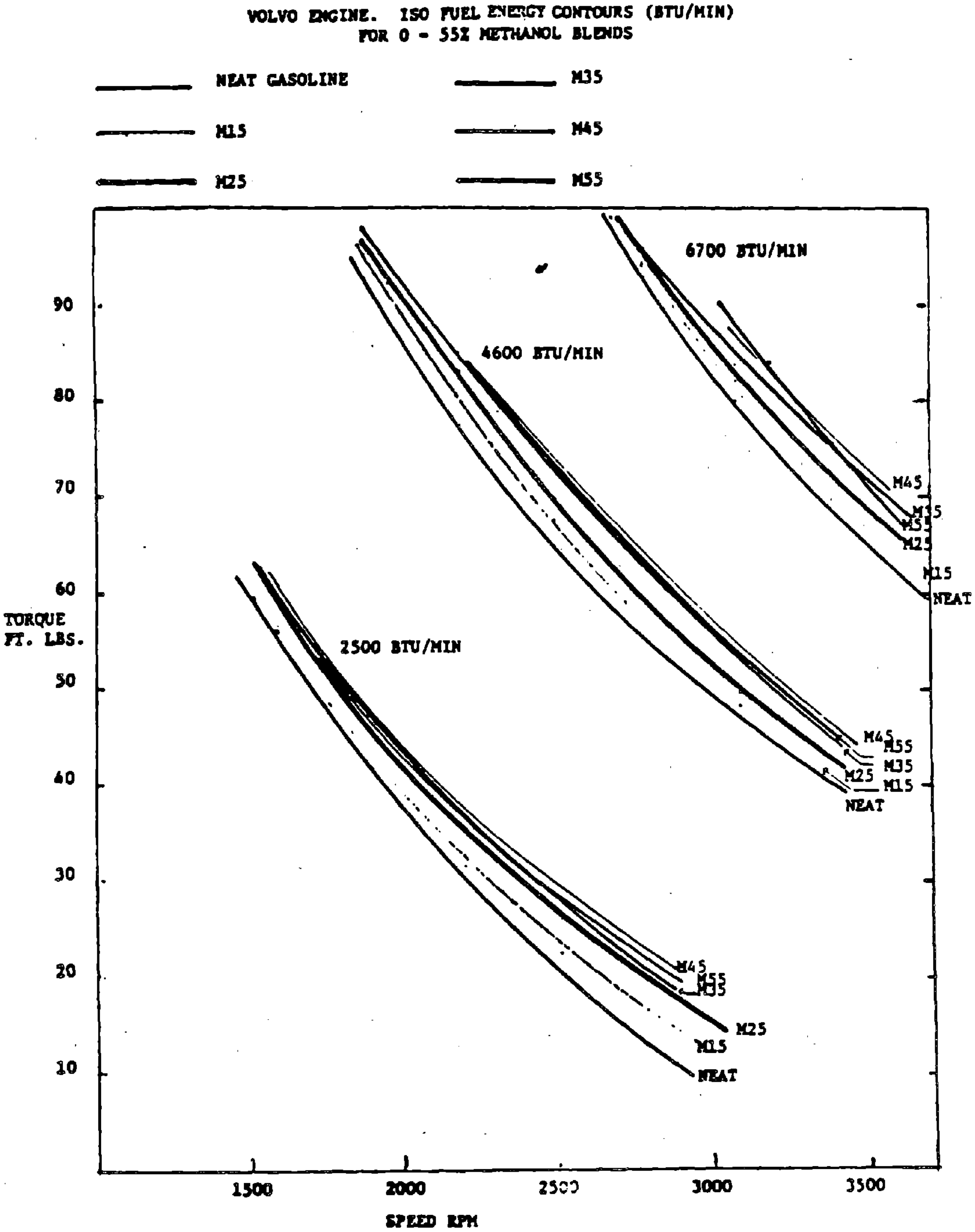
FIGURE 4.13. EFFECT OF METHANOL ON THE PERFORMANCE AND EMISSIONS OF A 3-WAY CATALYST CLOSED LOOP CAR AT CONSTANT SPEED.

about 30 percent. Up to this point, there was no change in maximum torque, but the energy required to achieve this maximum power decreased, as did the CO and hydrocarbon emissions. Between 30 and 55 percent methanol blend, the limit of the increased volumetric fuel injection was reached, and a leaning-out of the F/A ratio became evident in the form of decreased power output and increased oxygen content of the exhaust. Lawson reported that the engine continued to perform well as the efficiency continued to improve. At methanol concentrations greater than 55 percent, it was apparent from the increased hydrocarbons that the lean misfire limit had been reached. Figure 4.14 is a plot of iso-fuel energy contours obtained from operating the engine on zero to 55 percent methanol blends. This figure indicates that as the methanol content of the blend increases up to 45 percent, less BTU/min were required to achieve the same load/speed conditions.

Similar results have been obtained on VW cars fueled with 15 percent methanol and 85 percent gasoline, as reported by Bernhardt and Lee (4.13). A reduction in energy consumption of 12 percent was achieved during the ECE cold start test as compared to the gasoline operation.

4.1.6 Effect on a 3-Way Catalyst Car With Closed Loop Control System on FTP Cycle

Three-way conversion catalyst systems provide control of three types of emissions: hydrocarbons, carbon monoxide, and oxides of nitrogen. The conversion efficiency depends on the air-fuel ratio (4.6) as shown in Figure 4.15. A conversion efficiency of 80 percent or higher is possible if the A/F ratio remains, on the average, within a narrow band around the stoichiometric ratio mixture. Although the A/F ratio may vary considerably over very short periods, the average A/F within each interval of a few seconds duration must lie within a band of 1 or 2 percentage points on either side of the stoichiometric to achieve high conversion efficiency. The A/F ratio control can be achieved by a closed loop control system by which the oxygen content of the



Ref. 4.5.

FIGURE 4.14. ISO FUEL-ENERGY CONTOURS FOR METHANOL-GASOLINE BLENDS.

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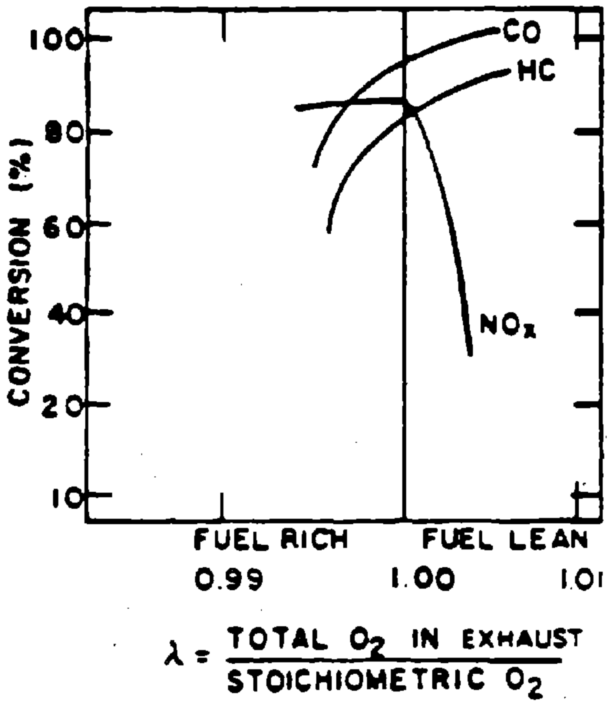

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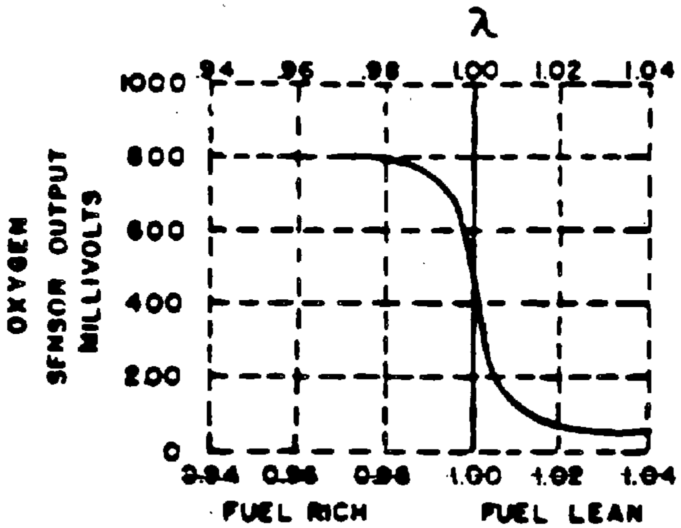
FIGURE 4.15. 3-WAY CATALYST CONVERSION EFFICIENCY FOR HC, CO AND NO_x AS A FUNCTION OF LAMBDA.



Ref. 4.6.

FIGURE 4.16. OXYGEN SENSOR MILLIVOLT OUTPUT AS A FUNCTION OF EXHAUST GAS COMPOSITION (LAMBDA).

exhaust is continuously monitored and the A/F ratio adjusted to maintain the stoichiometric A/F ratio. For unleaded gasoline, the average A/F ratio is controlled between 14.45:1 and 14.75:1. The oxygen content of the exhaust, which is related to the A/F ratio, is determined by an oxygen sensor placed in the exit of the exhaust manifold (4.7) (4.8). The oxygen sensor produces a signal of 0 to 500 mv when the A/F ratio is slightly lean, and 500 to 800 mv when slightly rich as shown in Figure 4.16. The response of the oxygen sensor is very rapid, detecting changes in the exhaust gas within a few milliseconds and responding with a very steep voltage characteristic at $\phi=1$. The response of the oxygen sensor to the stoichiometric mixture is independent of fuel composition (4.6).

The effect of blending gasoline with alcohols on the type of emission control using a 3-way catalyst was studied by Mooney et al (4.6), on a Volvo 244 car. The car had a 4-speed manual transmission and a 2.1 liter, 4-cylinder engine, without EGR. The fuel-metering was by a R. Bosch K-Jetronic fuel injection system controlled by a closed-loop system with an oxygen sensor. The fuels used in Mooney's tests were:

Ethanol:

Ethyl Alcohol	97%
Ethyl Acetate	1%
Methyl Iso-Butyl Ketone	1%
Aviation Gasoline	1%

Methanol:

Reagent Grade	99.9%

Unleaded Gasoline

Research Octane Number	91.8%
API Gravity 60/60°F	64
Vapor Pressure (100°F)	8.4 psi
Lead	0.023gm/gal.
Sulfur	300 ppm
Phosphorous	0.5 ppm

Distillation ASTMD-86

IBP	99°F
50%	212°F
EP	400°F

The results of the emissions produced from the vehicle with the baseline gasoline fuel, and with different blends of gasoline and alcohols are given for FTP in Table 4.6, and plotted in Figure 4.17. The FTP results indicate the following:

(a) For Ethanol-Gasoline Blends

(i) At 10 percent ethanol, HC and CO increased significantly from the baseline while NO_x remained constant.

(ii) At higher ethanol concentrations, the emissions behaved in different ways: (a) the CO emissions decreased to values lower than the baseline, 3.19 gm/mile, and reached a minimum of 0.78 gm/mile at 40% ethanol, (b) the HC emissions decreased and reached a minimum of 0.11 gm/mile at 30% ethanol, (c) the NO_x emissions increased from 0.11 gm/mile at the baseline to 0.14 gm/mile with 20 percent ethanol, after which it dropped to 0.07 gm/mile at 30 percent ethanol and reached 1.55 gm/mile at 50 percent ethanol.

The emissions results indicate that the 3-way catalyst with the closed loop control system was able to produce a high conversion efficiency for $HC/CO/NO_x$ for ethanol mixtures of 30 percent. For higher percentage mixtures, it appears that the closed-loop system (as set) could not maintain maximum conversion efficiency for $HC/CO/NO_x$.

(b) For Methanol-Gasoline Blends

Mooney's (4.6) tests on methanol-gasoline mixtures demonstrated that the system can operate satisfactorily with blends of up to 20 percent methanol. Similar results have been recently reported by Seiffert of VW (4.18).

(c) For Ethanol-Diesel-Gasoline Blends

The results of tests conducted with blends of gasoline, ethanol, diesel fuel, and water are given in Table 4.7. These results indicate that adding 30 percent ethanol increased the RON

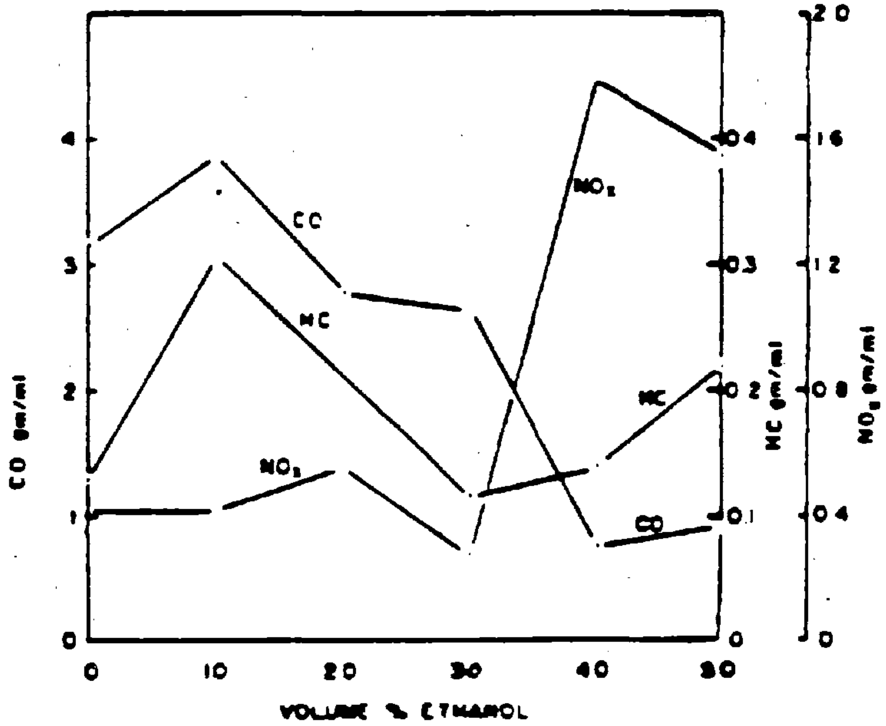
TABLE 4.6. EMISSIONS FOR FTP PROCEDURE WITH ETHANOL - GASOLINE BLENDS

HC gm/mi	CO gm/mi	NO_x gm/mi	Blend
Baseline No Catalyst			
0.93	13.68	2.47	100% Gasoline
Ethanol/Gasoline Blends			
0.14	3.19	0.11	100% Gasoline
0.31	3.90	0.11	10% Eth./90% Gas
0.24	2.77	0.14	20% Eth./80% Gas
0.11	2.61	0.07	30% Eth./70% Gas
0.14	0.78	1.77	40% Eth./60% Gas
0.22	0.90	1.56	50% Eth./50% Gas
Methanol/Gasoline Blends			
0.14	3.19	0.11	100% Gasoline
0.16	3.20	0.09	10% Meth./90% Gas
0.15	3.20	0.05	20% Meth./80% Gas

Note: Data for car having 3-way catalyst with closed loop control.

Ref. 4.6

15%



Ref. 4.6.

FIGURE 4.17. EMISSIONS ON THE FTP AS A FUNCTION OF ETHANOL IN AN ETHANOL/GASOLINE BLEND.

TABLE 4.7. EMISSIONS OF FTP PROCEDURE FOR A 3-WAY CATALYST CAR WITH CLOSED LOOP CONTROL, WITH BLENDS OF GASOLINE, DIESEL FUEL AND WATER

HC gm/mi	CO* gm/mi	NO_x gm/mi	Blend	Research Octane Number	Fuel Viscosity (Centipoise)
0.32	5.74	0.08	100% Gasoline	92.9	0.41
Without Catalyst					
1.22	17.99	2.70	100% Gasoline	92.9	0.41
0.33	3.55	0.10	70% Gasoline 23% Ethanol 7% Diesel Fuel	98.6	0.57
Without Catalyst					
1.39	15.87	2.34	Same as Above	98.6	0.57
0.38	5.76	0.09	70% Gasoline 25% Ethanol 2.5% Diesel Fuel 2.5% Water	NA	NA
0.30	3.83	0.16	70% Gasoline 30% Ethanol	102.6	0.57

Reference 4.6.

of gasoline from 92.9 to 102.6. Also, 23 percent ethanol could offset the poor octane characteristics of 7 percent diesel fuel.

Mooney concluded from his studies that the closed loop control system automatically provided a stoichiometric A/F ratio of 12.8 for the 30 percent ethanol/gasoline blend and a 14.6 A/F ratio for the 100 percent gasoline. Also, methanol/gasoline fuel blends containing up to 20 percent methanol provided excellent vehicle operation and low HC, CO and NO_x exhaust emissions.

4.1.7. Effect of Exhaust Aldehydes and Acetone Emissions

The effect of blending gasoline with methanol or ethanol on the individual aldehydes and acetone was reported by Harrenstein, et al (4.9). The engine used was a 1963, four-cylinder Pontiac engine, which had been modified to simulate a modern engine, using a 1974 cylinder head and camshaft. The C.R. was 8.1:1. During exhaust sampling, the engine was operated at steady-state conditions, 2000 rpm, MBT spark advance, and with F/A equivalence ratios (ϕ) of 0.96, 0.90 and 0.82. During operation at $\phi = 0.82$, the engine experienced lean-limit misfiring. The DNPH method with a gas chromatographic finish was employed to obtain exhaust gas concentrations of aldehydes and acetone.

Harenstein's experiments indicated that the use of alcohol-gasoline blends results in the following effects:

i. An increase in total aldehydes (including acetone) levels. The increase is 25 percent for 20 percent ethanol, 10 percent for 20 percent methanol, and 30 percent for 30 percent methanol.

ii. The aldehyde emissions are generally a stronger function of fuel blend than of equivalence ratio.

iii. Formaldehyde is the largest component of the total aldehydes; up to 70-90 mole % of the total.

iv. The emissions of formaldehyde and acetaldehyde are strongly controlled by the content of methanol and ethanol in the fuel respectively.

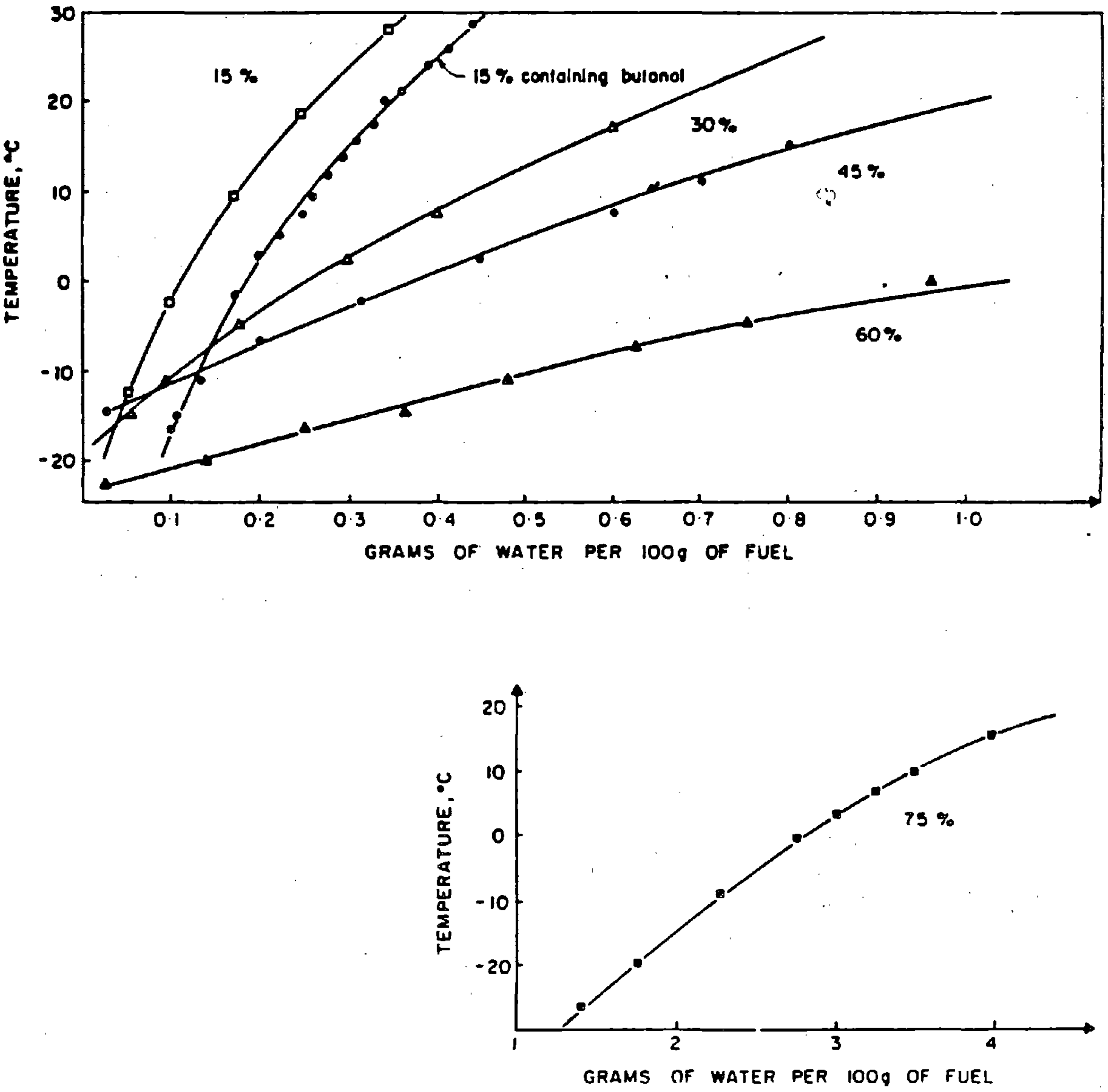
v. Acetone concentration increases as the lean misfire limit is approached. (ϕ = 0.82).

vi. Acrolein concentration decreases slightly with increasing alcohol blend level.

vii. Aldehydes and acetone are partially destroyed in the exhaust system and virtually completely destroyed in the catalyst.

4.1.8 Phase Separation

4.1.8.1 Nature of the Problem - A study of the methanol/gasoline phase separation problem was conducted by Lawson et al (4.5). Reagent grade methanol was dried and used in various proportions. Mixtures of dry gasoline, dry methanol and water were mixed in a sealed conical flask, fitted with a thermometer and a magnetic stirring bar. This flask was cooled until the cloud point temperature was reached as observed by the eye. Figure 4.18 shows the cloud point expressed as grams of water added per 100 grams fuel to reach cloud point (or onset of phase separation) at selected temperatures and for various methanol contents. Figure 4.18 indicates that at above-freezing temperatures, the presence of more methanol imparts a greater water tolerance to the mixture. At lower temperatures in the range -10°C to -20°C, there is relatively little difference in the behaviour of blends with methanol content of up to 45 percent. The cloud point is approximately at 0.05 gram per 100 grams of fuel. Lawson attributed this separation at 30 percent and 45 percent methanol to the drop in temperature rather than to the presence of water. For example, a 30 percent methanol blend will phase separate at approximately -20°C even if no water is present. Increasing the methanol content to 45 percent provides greater phase separation, increasing that temperature to -15°C. Lawson, et. al., concluded that phase separation phenomena below the freezing point is controlled by the combined tendency toward immiscibility exhibited by both the water and the methanol.



Ref. 4.5.

FIGURE 4.18. CLOUD POINT FOR VARIOUS METHANOL-GASOLINE BLENDS

At higher methanol contents of 60 percent and 70 percent, there is a reversal towards more miscibility which can be interpreted as the solubility of the gasoline in the methanol. This solubility becomes relatively insensitive to the water content as is illustrated by the low slopes of the 60 and 70 percent curves.

The "crossover" temperature at which methanol insolubility equals that of water (where the cloud point lines intersect) is between -10°C and -15°C. This has been found by Lawson et al to agree well with the range -12 to -18°C reported by Eccleston and Cox (4.10) for 30 percent aromatic gasoline.

4.1.8.2 Effect of Aromatic Contents on Phase Separation - Lowering the aromatic content tends to induce more phase separation, i.e., the same effect occurs at a higher temperature. Eccleston and Cox (4.10), found that a 25 percent aromatic gasoline had a crossover at 0 to 5°C, and 15 and 20 percent aromatic gasoline at 7 to 13°C. The presence of aromatics causes a marked increase in solubility of methanol in gasoline and of gasoline in methanol.

4.2 METHANOL NEAT

The main differences in the fuel properties of neat methanol as compared to the current production gasoline are:

(i) high octane number

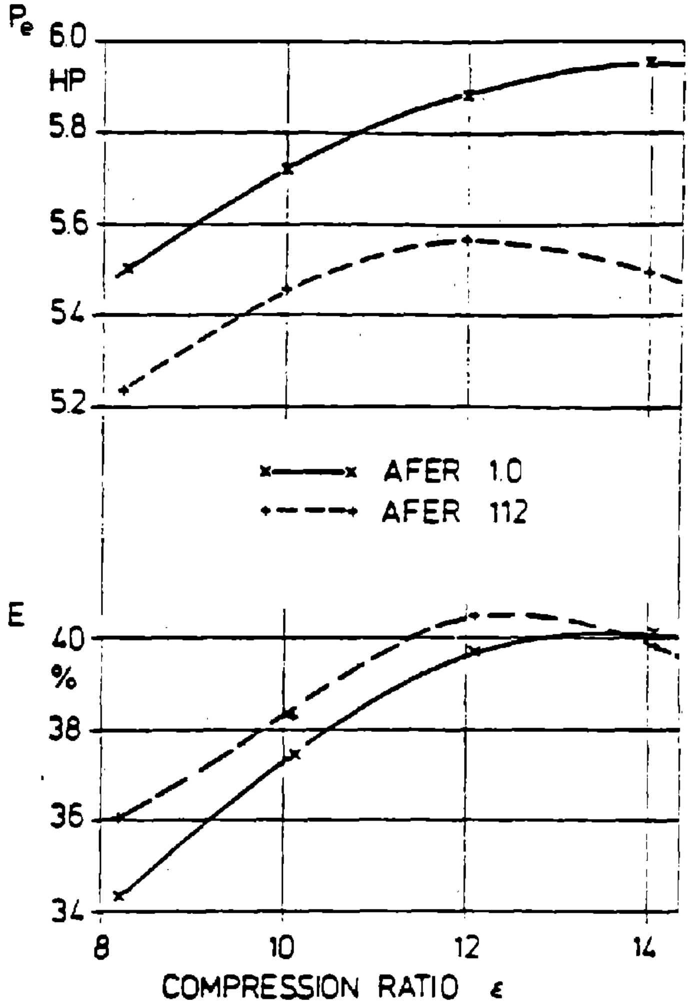
(ii) low heating value

(iii) high latent heat of evaporation

(iv) low vapor pressure

4.2.1 Single Cylinder Engine Sensitivity

The high octane number of methanol allows the engine to run at compression ratios higher than 8:1 to 9:1 used in the current production gasoline engine. This results in higher brake thermal efficiency and mean effective pressure. Figure 4.19 shows the effect of increasing the C.R. in a single cylinder engine, with



Ref. 4.11.

FIGURE 4.19. EFFECT OF C.R. ON POWER AND EFFICIENCY

MBT spark timing and full throttle opening, on the power output and brake thermal efficiency. The results are shown for A/F equivalence ratios of 1.0 (stoichiometric) and 1.12 (lean). For both the A/F ratios, best brake thermal efficiency is at a C.R. between 12:1 and 13:1. The power output of the lean mixture peaks at about 12:1. For the stoichiometric mixture, the power output increases at a decreasing rate as the C.R. increases. The saving in specific energy consumption with the increase in C.R. is given in Figure 4.20 at loads equivalent to 37 mph and 62 mph road loads. At 37 mph load, the fuel consumption can be reduced up to 5 percent by increasing the C.R. from 8.2:1 to 13:1. At a 62 mph equivalent load, the saving in fuel consumption amounts to 11 percent. Figure 4.21 shows the improvement in specific energy consumption at a load equivalent to that of 37 mph, with increasing compression ratio for methanol fueled engines in comparison to the current production gasoline engine. The gain in efficiency ranges from 18 to 23 percent according to compression ratio.

The effect of C.R. on the emissions was reported by Meurad (4.11) as follows:

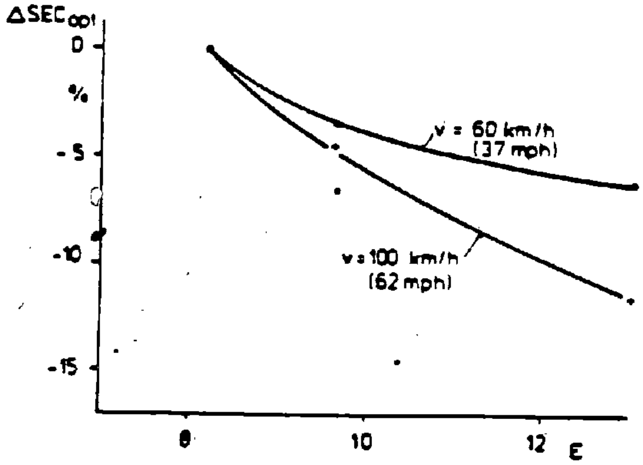
(i) CO is mainly a function of A/F ratio and not on the C.R.

(ii) HC (UBF) increased with C.R. as indicated in Figure 4.22. This increase is a result of the increase in the effective S/V ratio which results in more HC in the quench zone, and the drop in the exhaust temperature which results in a reduction in the oxidation reactions during exhaust.

(iii) The increase in NO_x with C.R. was insignigicant.

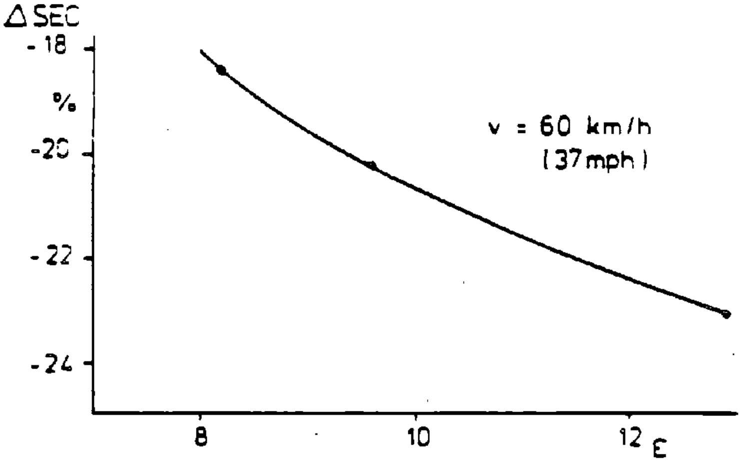
4.2.2 Comparison Between the Single Cylinder Engine Results and Cycle Computations

The increase in power output of gasoline engines has been calculated for methanol as compared to isooctane by detailed computer analysis. An example of the cycle analysis results is shown



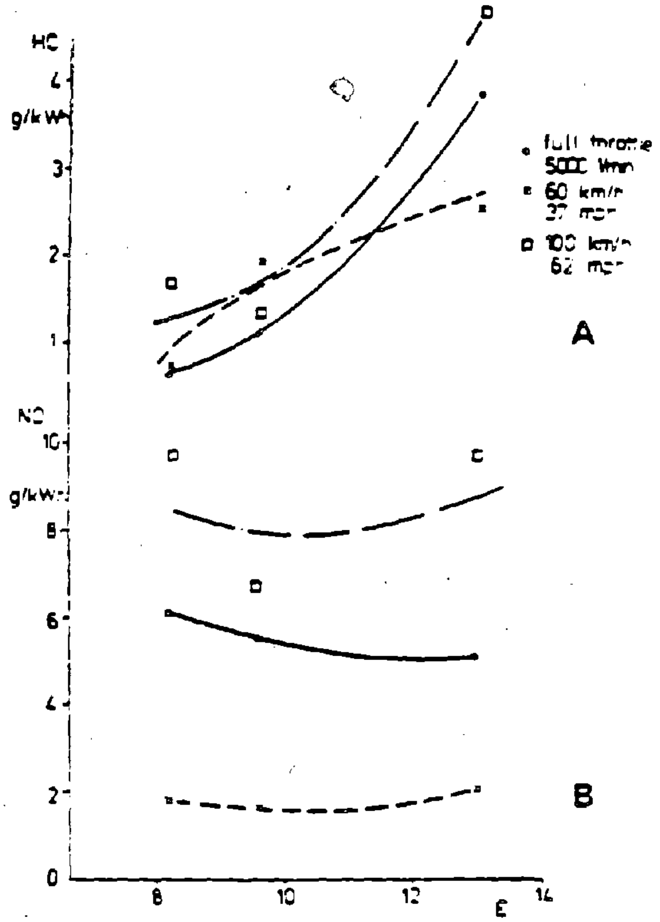
Ref. 4.11.

FIGURE 4.20. EFFECT OF C.R. ON SAVINGS IN FUEL-ENERGY, AT 37 MPH AND AT 62 MPH ROAD LOADS.



Ref. 4.11.

FIGURE 4.21. PERCENTAGE DECREASE IN FUEL-ENERGY IN A METHANOL FUELED ENGINE IN RELATION TO A PRODUCTION GASOLINE ENGINE.



Ref. 4.11.

FIGURE 4.22. HC AND NO$_x$ EMISSIONS VERSUS C.R.

TABLE 4.8. CHART CALCULATIONS OF CYCLE CHARACTERISTICS

	Peak Temperature °R	Peak Pressure psia	Cu. Ft. of Mixture per lb of Air	Compression Work BTU/lb
Isooctane	5200	1240	13.92	130
Methanol	4870	1300	13.92	101
Ethanol	5000	1255	14.09	111

C.R. = 9.1, Intake Air = 100°F
14.7 psia, ϕ = 1

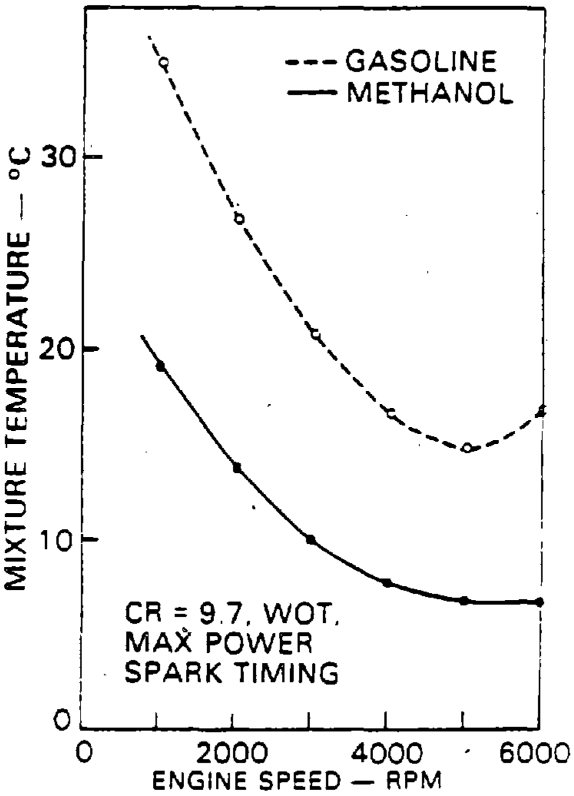
in Table 4.8. This example shows that at equal equivalence ratio (ϕ = 1) and C.R. = 9:1 the calculated compression work for methanol is 101 BTU/lb as compared to 130 BTU/lb for isooctane. The peak combustion temperature is lower: 4870°R for methanol compared to 5200°R for isooctane. The peak pressure is higher: 1300 psia for methanol as compared to 1240 psia for isooctane. Thus, it follows that a methanol-fueled engine can achieve power boost over a gasoline-fueled engine at the same equivalence ratio, or equal power at a leaner equivalence ratio.

These computed results agree with the experimental work on the single cylinder engine discussed earlier.

4.2.3. Multicylinder Engine Sensitivity

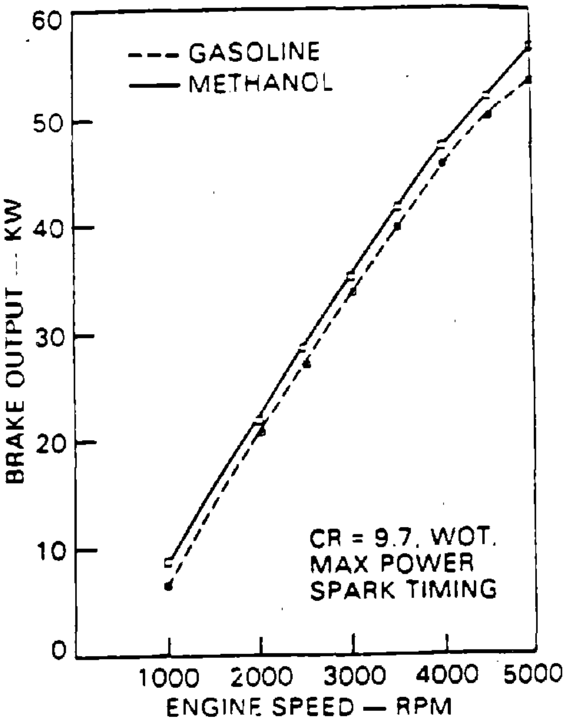
Berhardt and Lee of VW (4.13) reported the results of laboratory and road tests on a number of VW production vehicles which have been converted to methanol operation through the use of a modified carburetor and an exhaust-heated intake manifold combined with a heating feature using engine coolant. The engines used were water-cooled 4-cylinder, 1.6 liter VW engines. The standard carburetor was modified to improve the atomization of the fuel-air spray. The intake manifold was heated by a constant flow of hot exhaust gases, and, in addition, by hot engine coolant after warm-up. In spite of this heating, Bernhardt reported that it was impossible to get completely identical mixture temperatures with methanol and gasoline. Figure 4.23 shows the results reported by Berhardt for the intake charge temperature for methanol and gasoline.

4.2.3.1 Effect on Power Output - Figure 4.24 shows the engine brake power with methanol and with gasoline at different engine speeds. The methanol engine had about 10% higher output than the gasoline engine, both with MBT spark. This is related to the increase in the mass of the fuel-air charge with methanol caused by its higher latent heat of evaporation. This results in lower charge temperatures as indicated in Figure 4.22.



Ref. 4.13.

FIGURE 4.23. MIXTURE TEMPERATURE WITH METHANOL AND GASOLINE



Ref. 4.13.

FIGURE 4.24. ENGINE OUTPUT WITH METHANOL AND GASOLINE

4.2.3.2 Effect on Brake Thermal Efficiency

- Berhardt compared the brake thermal efficiency of the gasoline engine with that of methanol engine, both having the same compression ratio of 9.7:1. The results are shown in Figure 4.25 for a speed of 2000 rpm, and WOT, at different air-fuel equivalence ratios, and show that the methanol engine is more efficient than the gasoline at the same C.R.

Because of the high octane rating of methanol (RON ≈ 110, MON ≈ 92) (21), the C.R. could be boosted to 14.0, resulting in higher brake thermal efficiency as indicated in Figure 4.25.

4.2.3.3 Cold Start Problems

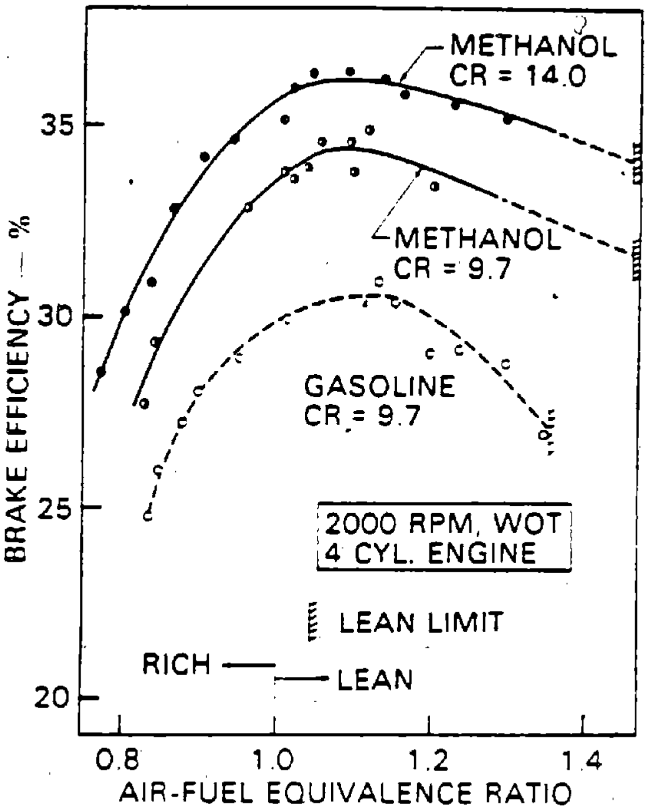
- With methanol, a cold starting aid is absolutely essential for starting the engine at temperatures below 8°C (4.13). Cold start aids could be in the form of volatile starting additives (such as butane, methyl ether, or gasoline) to be sprayed into the intake air during starting. A small methanol-fueled flame preheater may be used in the intake manifold to solve the cold starting problem.

4.2.3.4 Effect of Methanol on Emissions

Figure 4.26 shows the effect, as reported by Bernhardt, of air-fuel equivalence ratio on the NO_x emissions of the gasoline and methanol-fueled cars, at 2000 rpm, WOT, and MBT spark. The methanol cars, with C.R. = 9.7:1, or C.R. = 14.1 had lower NO_x than the gasoline car. The reduction in NO_x is caused by the lower peak temperature with methanol than with gasoline.

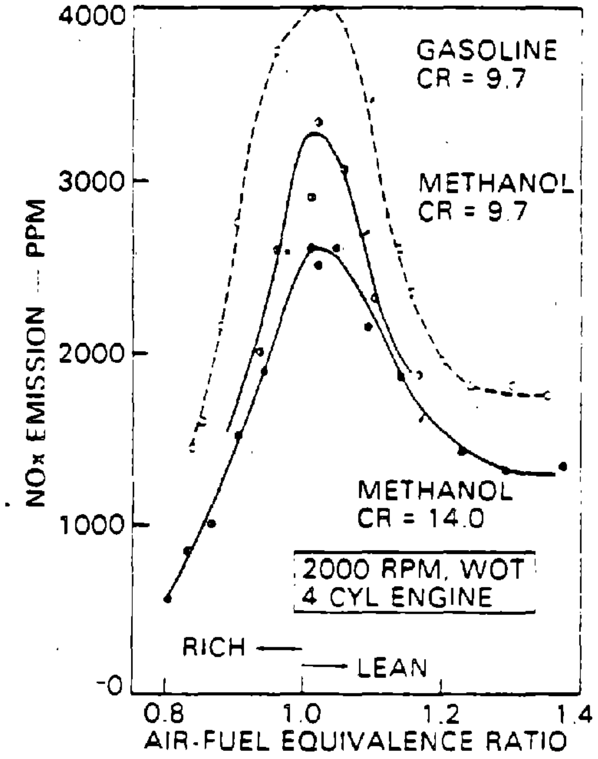
The CO emissions from the methanol-fueled engine corresponded approximately to those from the gasoline-fueled engine as indicated by Bernhardt as shown in Figure 4.27. At 2000 rpm and a stoichiometric mixture ratio between $\phi = 1$ and $\phi = 0.9$, methanol produced less CO emissions.

The hydrocarbons in the methanol-fueled car consisted of the original fuel, aldehydes and other hydrocarbons. The hydrocarbons in the methanol-fueled car were found to be less than those from the gasoline-fueled car as shown in Figure 4.28.



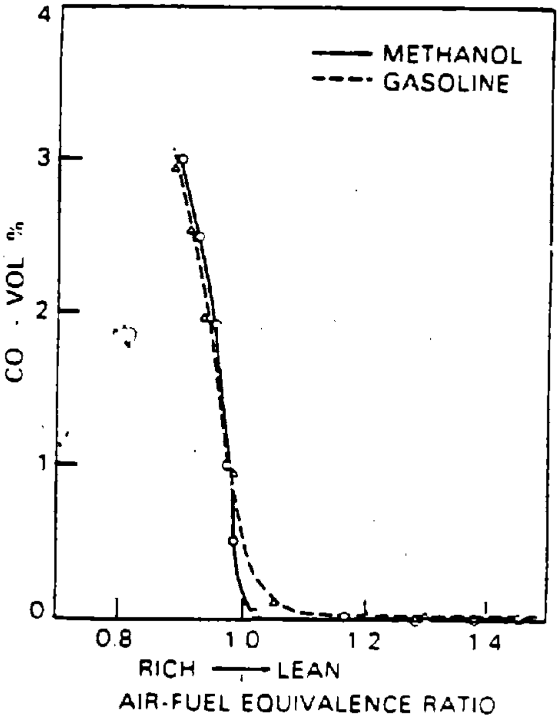
Ref. 4.13.

FIGURE 4.25. BRAKE THERMAL EFFICIENCY WITH METHANOL AND GASOLINE.



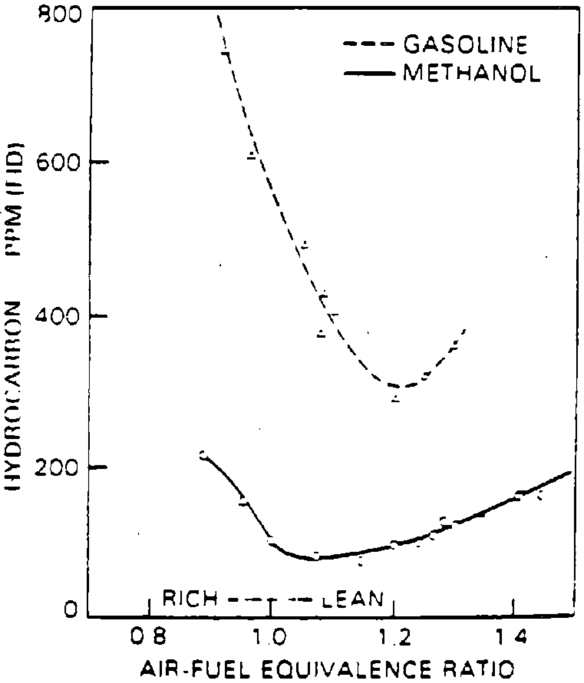
Ref. 4.13.

FIGURE 4.26. EXHAUST NO_x WITH METHANOL AND GASOLINE.



Ref. 4.13.

FIGURE 4.27. EXHAUST CO WITH METHANOL AND GASOLINE.



Ref. 4.13.

FIGURE 4.28. EXHAUST HC WITH METHANOL AND GASOLINE.

The total aldehydes emitted from the methanol-fueled engine were higher than from the gasoline-fueled engine when the same C.R. (C.R. = 9.7) was used, as shown in Figure 4.29. The total aldehydes of the methanol-fueled car were reduced by increasing the C.R. from 9.7:1 to 14:1 as shown in Figure 4.29. Bernhardt reported that the total aldehydes may be reduced by adding water to methanol. This resulted in a NO_x reduction as shown in Figure 4.30, with some sacrifice in power output.

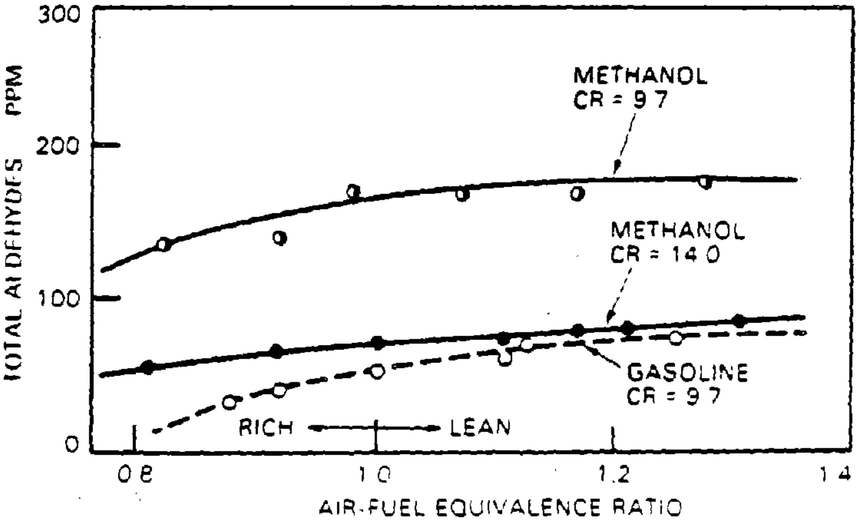
Polynuclear aromatics (PNA) obtained from a gasoline-fueled car were compared with those from a methanol-fueled car by Bernhardt (4.13), on the European Test Procedure. The results are shown in Fig. 4.31 and indicate a much lower level of PNAs when methanol is used.

Figure 4.32 shows the variation in the emissions, with engine speed, at WOT, for methanol and for gasoline.

4.2.4 Sensitivity of a Vehicle to Neat Alcohol

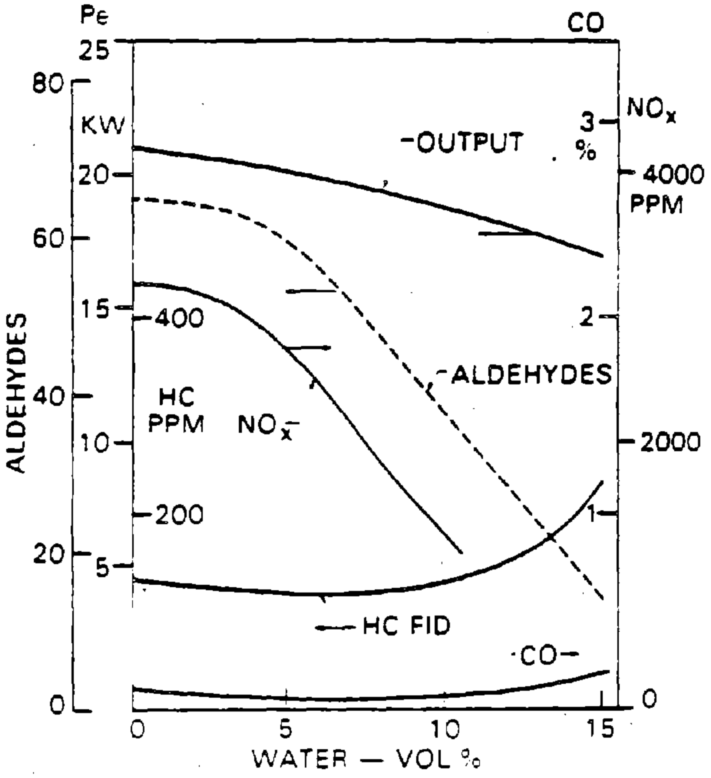
VW reported the results of tests conducted on a number of standard production vehicles which were converted from gasoline to methanol operation. To improve cold starting, gasoline or other volatile fuel was injected into the intake manifold. Vehicle evaluation has been conducted mainly under simulated road conditions using the CVS cold-hot emissions tests and the ECE Test Procedure. The results for methanol-fueled cars indicated an improvement in energy consumption of 4 percent when compared with gasoline operation during the ECE cold-start test, and 12 percent for the hot start.

The effect of using methanol on the ECE cold test cycle is to reduce the CO emissions by 25 percent, but to increase (HC) by 22 percent. In the hot-start test, the CO emissions were reduced by 68 percent and HC by 28 percent (24), and NO by 20 percent.



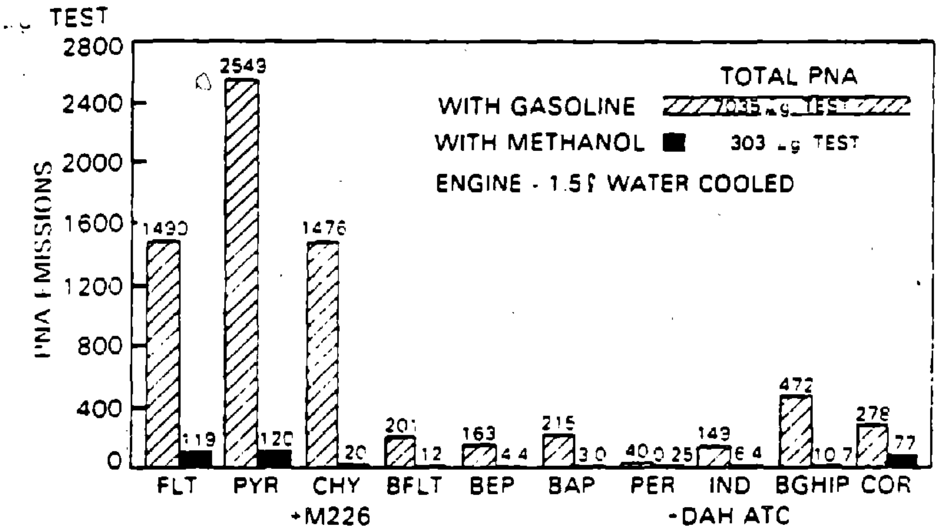
Ref. 4.13.

FIGURE 4.29. EXHAUST ALDEHYDES WITH METHANOL AND GASOLINE



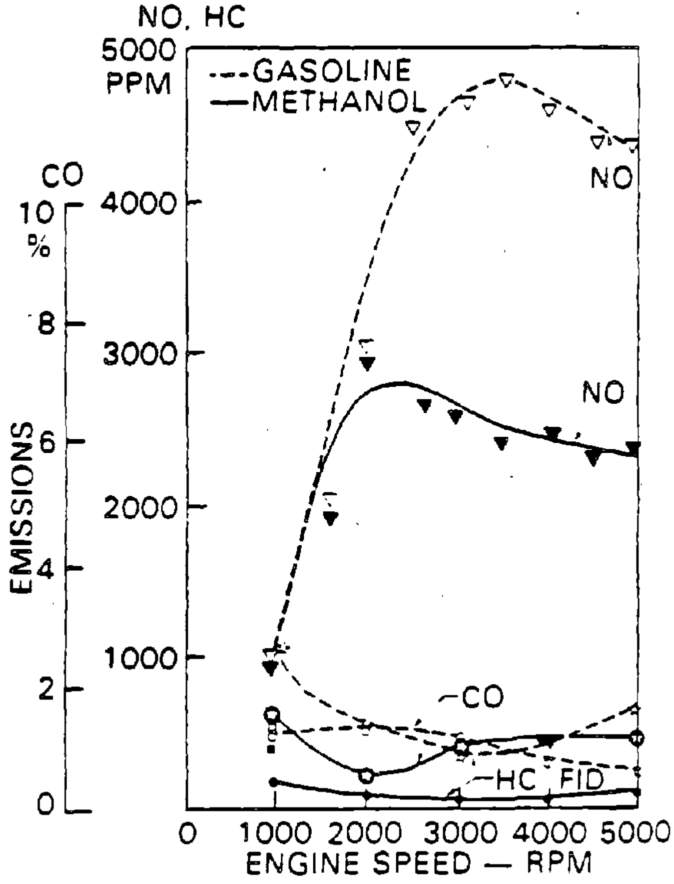
Ref. 4.13.

FIGURE 4.30. EFFECT OF WATER ADDITION TO METHANOL ON EXHAUST EMISSIONS AND ENGINE POWER.



Ref. 4.13

FIGURE 4.31. PNA HYDROCARBONS WITH METHANOL AND GASOLINE.



Ref. 4.13.

FIGURE 4.32. EXHAUST EMISSIONS WITH METHANOL AND GASOLINE AT FULL THROTTLE.

4.3 SHALE-DERIVED AND COAL DERIVED GASOLINE IN GASOLINE ENGINES

Hurn (4.14) reported experimental data concerning physical properties and engine performance characteristics for a gasoline derived from oil shale and for a gasoline containing a coal-derived component. The properties of gasoline derived from shale oil are given in Table 4.9. The emissions and fuel economy results with shale-derived gasoline are compared with Indolene and given in Table 4.10. Hurn reported that the differences between the results with the shale-derived gasoline and the regular gasoline were mainly related to poor octane quality which resulted in engine knock.

Hurn reported the results of tests on gasoline produced from blends of coal derivative components and refinery stocks. The naphtha from catalytic reacting (51 percent yield) of a coal syncrude, was blended with refinery stocks. The naphtha was usable as 44 percent by volume of a finished, 96 RON, unleaded gasoline.

The results showed no significant differences between the emissions and fuel economy characteristics of reference and test fuels. The data show somewhat elevated CO and HC emissions for the fuel containing coal-derived components. Hurn indicated that the differences may be attributable to a slight difference in the stoichiometry of the fuel mixtures.

4.4 GASOLINE EMERGENCY BLENDS

In case of a national emergency, the available gasoline fuel may need to be extended in order that gasoline engines providing essential services continue operation. Under such emergency conditions, blends of gasoline and other fuels may be formed to stretch-out the base gasoline fuel. Russell, et al (4.16) of Southwest Research Institute (SWRI) conducted an extensive study of such emergency blends and published the results in a guidebook. Several blends of gasoline and extenders were tested in single and multicylinder engines and in a very

TABLE 4.9. PROPERTIES OF SHALE OIL-DERIVED GASOLINE

API Gravity, 60°F	87
ASTM Distillation, °F:	
IBP	114
10 percent	125
30 percent	158
50 percent	194
70 percent	261
90 percent	328
End point	387
Reid Vapor Pressure, psia	10.5
Sulfur, wt. percent	0.024
Nitrogen, wt. percent	0.03
Oxygen, wt. percent	0.52
Hydrocarbon types (FIA), vol. percent:	
Aromatics	28.0
Olefins	14.0
Saturates	58.0
Motor Octane No. (MON)	76.0
Research Octane No. (RON)	81.1
Stability data:	
ASTM induction period, min	1140-*
ASTM existent gum. mg/100 ml	25
Accelerated gum (4 hr.) mg/100 ml: 2.0 lbs DMD per 1.000 bbl	32

*40 lbs of pressure was lost during the entire 24-hr period: however, at no time did it lose 2 lbs in a 15-minute period.

Ref. 4.14.

TABLE 4.10. EMISSIONS AND FUEL ECONOMY RESULTS WITH SHALE-DERIVED GASOLINE

						Fuel Economy, mpg	
		Emissions, g/mile					
Fuel	Vehicle	CO	HC	NO_x	Aldehydes	Urban Cycle	Highway
Shale gasoline	1974 Model, 351-CID	25.8	2.2	2.6	0.14	11.2	17.4
Indolene		25.9	2.3	2.7	0.15	10.9	17.7
Shale gasoline	1975 Model, 318-CID	7.4	1.3	2.7	0.18	12.3	21.1
Indolene*		8.7	1.2	2.5	0.17	12.2	20.6

*Represents one analysis, all other data represent the average of 3 replicates.

Ref. 4.14.

limited number of vehicles, both on the road and by chassis dynamometers. SWRI developed "Tradeoff Charts" for engine performance, fuel economy and emissions for each of the emergency blends. Figures 4.33 to 4.44 are compiled from the charts developed by SWRI. The following indexes are used:

1. BSGC = BSFC x w gasoline

   where

   BSGC = brake specific gasoline consumption

   BSFC = brake specific fuel (blend) consumption

   m gasoline = mass fraction of gasoline

   $$= \frac{\text{mass of gasoline}}{\text{mass of blend}}$$

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

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

4. Tradeoff Index = Conservation Index + Power Index

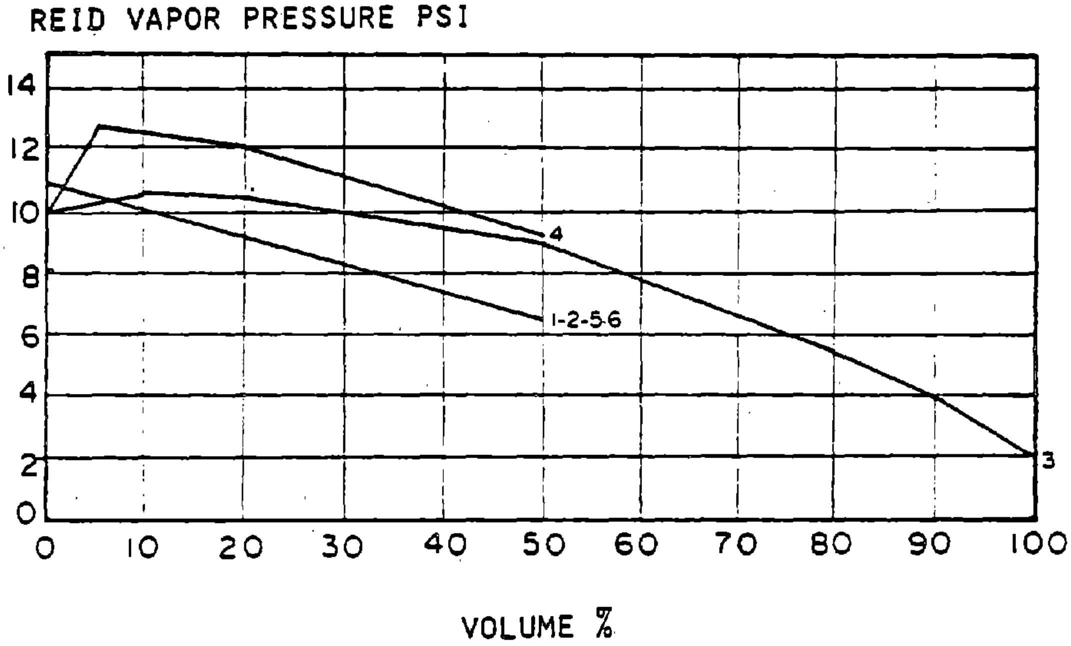
Russell et al (4.16) indicated that the tradeoff index reflects the balance between increase in base fuel conservation and drop in power (if any) with increasing extender concentration. A maximum in the Tradeoff Index curve indicates a maximum advisable extender concentration. Beyond this concentration, there is reason to believe base fuel may be wasted.

5. Emission Index $= \frac{\text{Emission (blend)}}{\text{Emission (base)}}$

The emergencey gasoline extenders tested by SWRI are shown in Table 4.11.

4.4.1 Effect on Reid Vapor Pressure

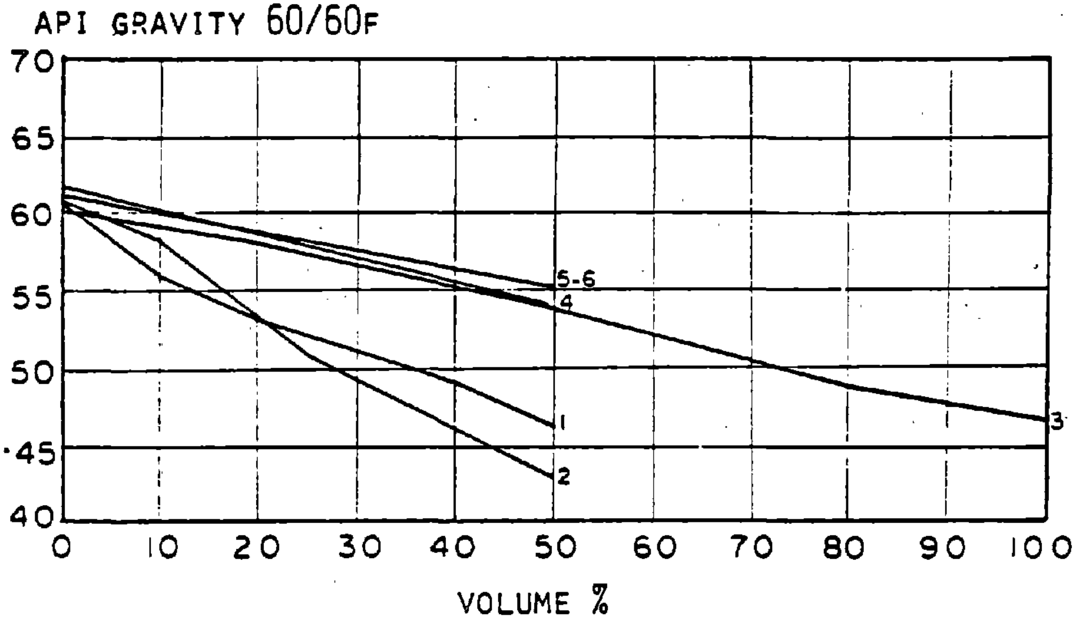
Figure 4.33 shows the effect of blending gasoline with different extenders on the Reid Vapor Pressure (RVP). Alcohols are the only extenders which result in an increase in the RVP at concentrations less that 42 percent for methanol and 30 percent



1 Extender = No. 2 Diesel Fuel
2 = Marine Diesel Fuel
3 = Ethanol
4 = Methanol
5 = Naphtha
6 = Kerosene

Ref 4.16.

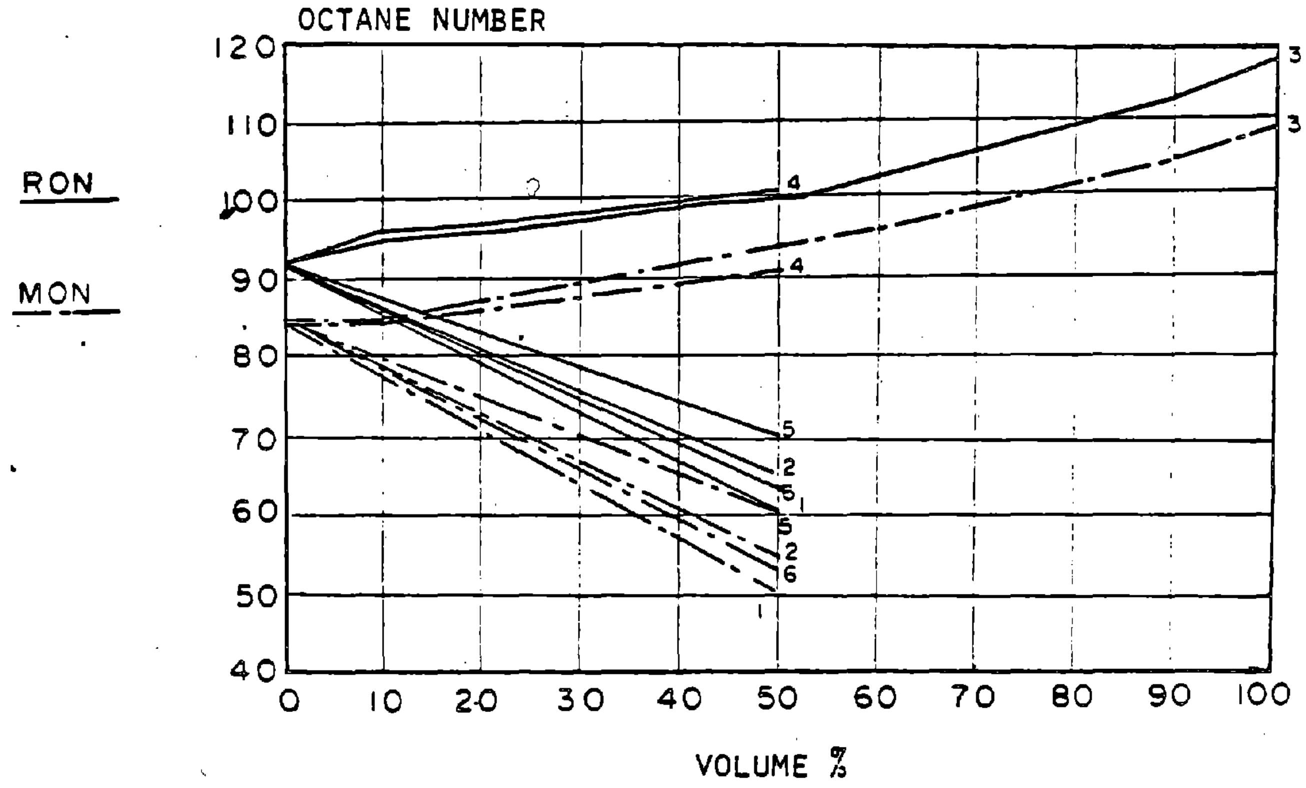
FIGURE 4.33. EFFECT OF GASOLINE EXTENDERS ON RVP.



1 Extender = No. 2 Diesel Fuel
2 = Marine Diesel Fuel
3 = Ethanol
4 = Methanol
5 = Naphtha
6 = Kerosene

Reference 4.16.

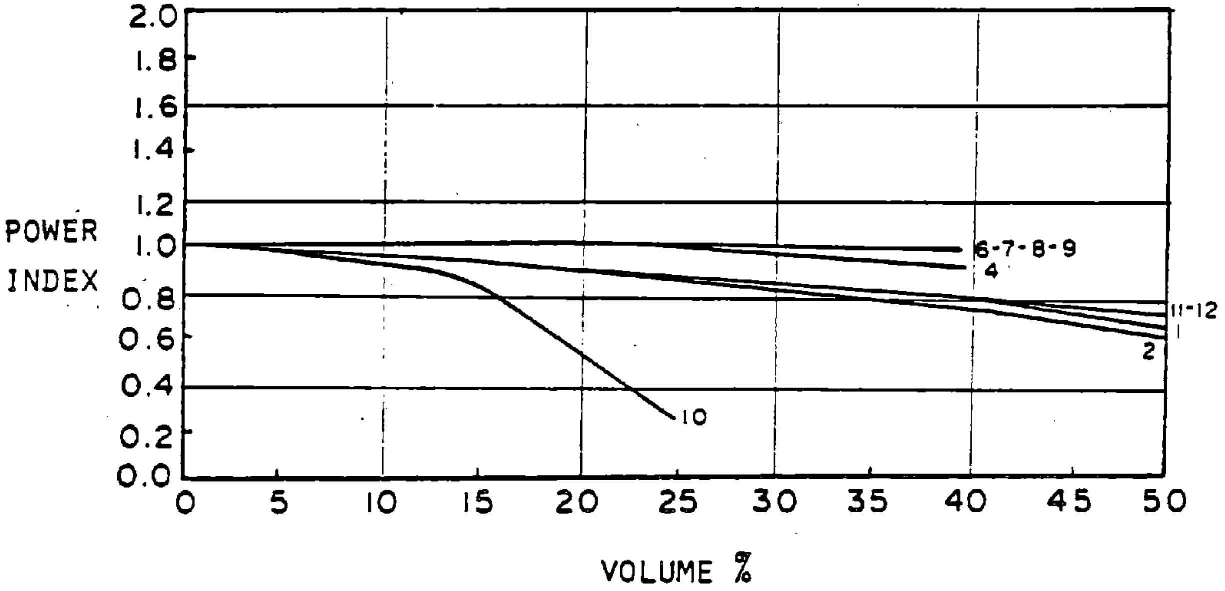
FIGURE 4.34. EFFECT OF GASOLINE EXTENDERS ON API GRAVITY.



1 Extender = No. 2 Diesel Fuel
2 = Marine Diesel Fuel (DFM)
3 = Ethanol
4 = Methanol
5 = Naphtha
6 = Kerosene

Reference 4.16.

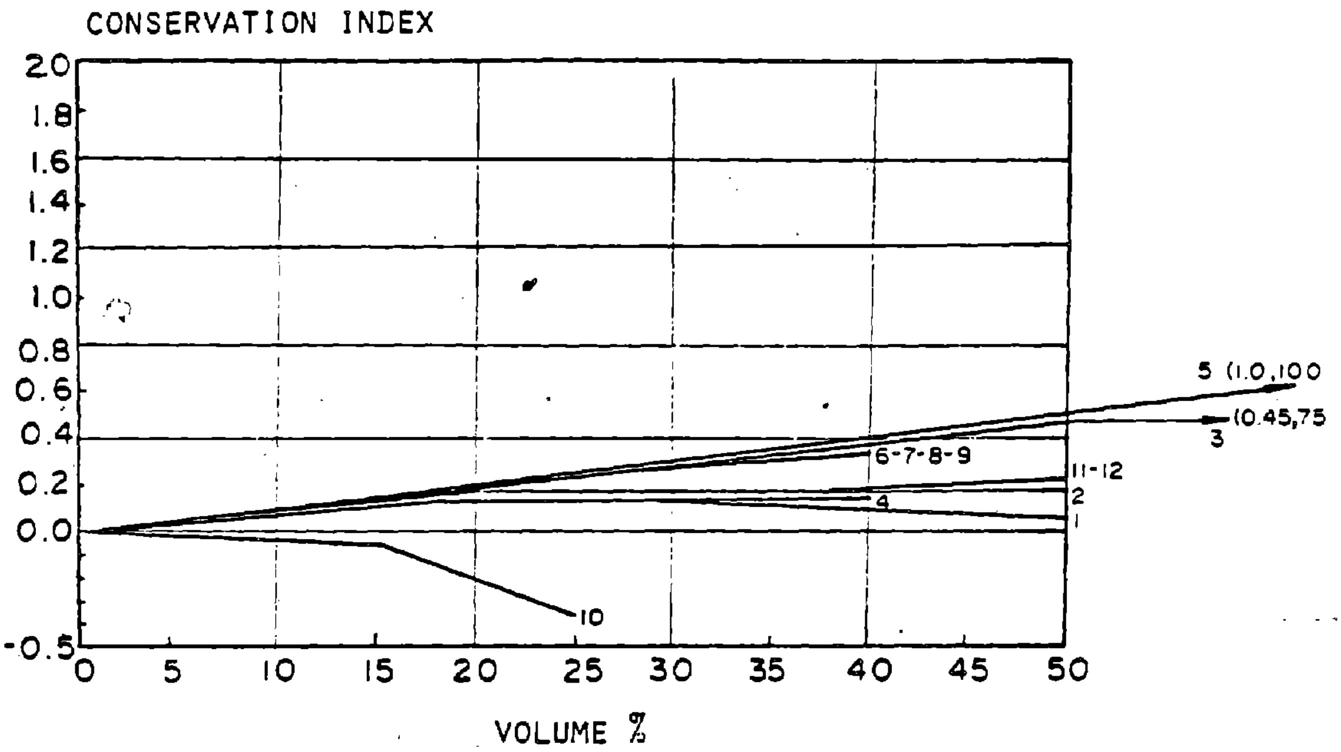
FIGURE 4.35. EFFECT OF GASOLINE EXTENDERS ON OCTANE NUMBER



1 Gasoline Emergency Blend Extender = No. 2 Deisel Fuel
2 = Marine Diesel Fuel
3 = Ethanol
4 = Methanol
5 = MBTE
6 = Naphtha-Ethanol
7 = DFM-Ethanol
8 = No. 2 Diesel Fuel-Ethanol
9 = Kerosene-Ethanol
10 = Ethanol Extended with Water
11 = Naphtha
12 = Kerosene

Reference 4.16.

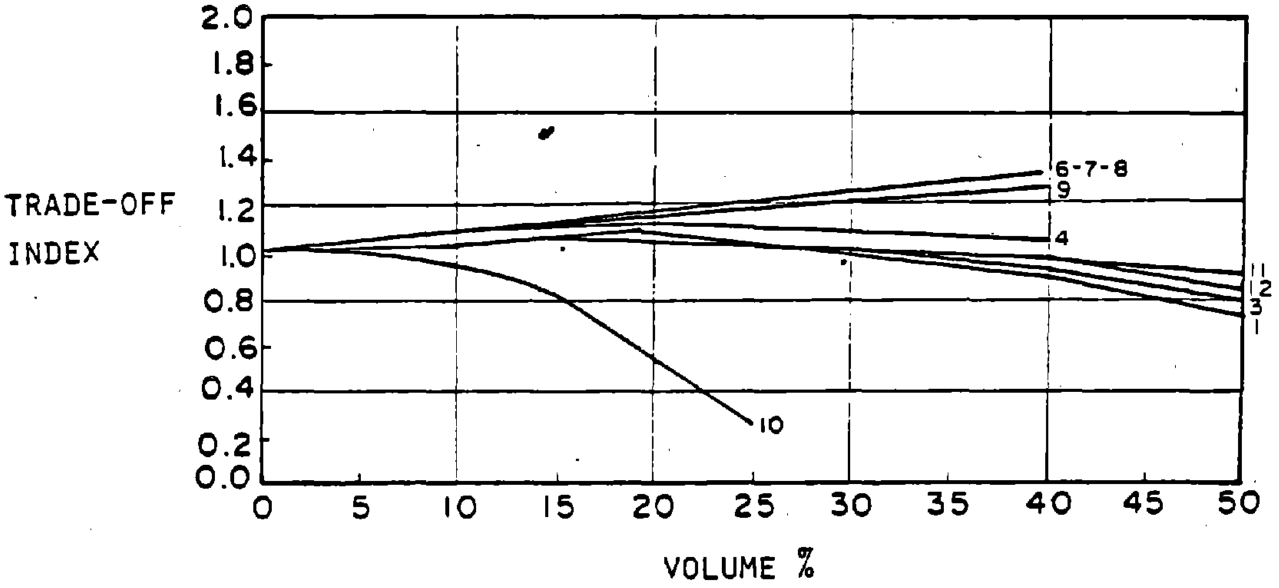
FIGURE 4.36. EFFECT OF GASOLINE EXTENDERS ON POWER INDEX.



1 Extender = No. 2 Deisel Fuel
2 = Marine Diesel Fuel
3 = Ethanol
4 = Methanol
5 = MTBE
6 = Naphtha-Ethanol
7 = DFM-Ethanol
8 = No. 2 Diesel Fuel-Ethanol
9 = Kerosene-Ethanol
10 = Ethanol Extended with Water
11 = Naphtha
12 = Kerosene

Reference 4.16.

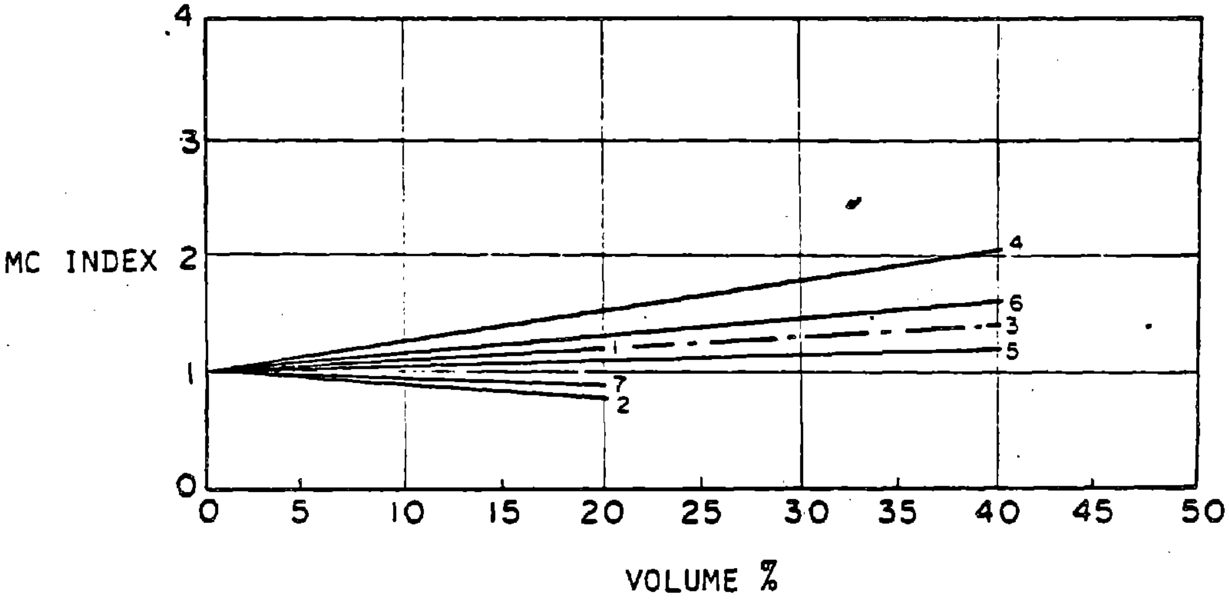
FIGURE 4.37. EFFECT OF GASOLINE EXTENDERS ON CONSERVATION INDEX.



1 Extender = No. 2 Diesel Fuel
2 = Marine Diesel Fuel
3 = Ethanol
4 = Methanol
5 = MTBE
6 = NaphthaEthanol
7 = DFM-Ethanol
8 = No. 2 Diesel Fuel-Ethanol
9 = Kerosene-Ethanol
10 = Ethanol Extended with Water
11 = Naphtha
12 = Kerosene

Reference 4.16.

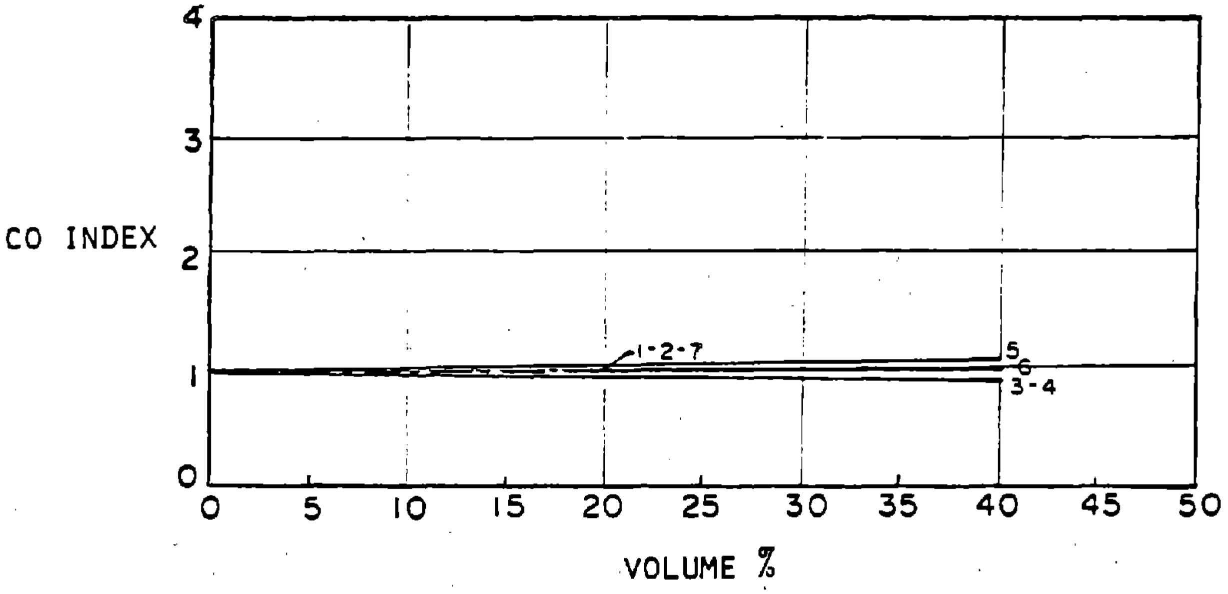
FIGURE 4.38. EFFECT OF GASOLINE EXTENDERS ON TRADEOFF INDEX.



1 Extender = No. 2 Diesel Fuel
2 = Marine Diesel Fuel
3 = Ethanol
4 = Methanol
5 = Naphtha-Ethanol
6 = DFM-Ethanol
7 = Naphtha

Reference 4.16

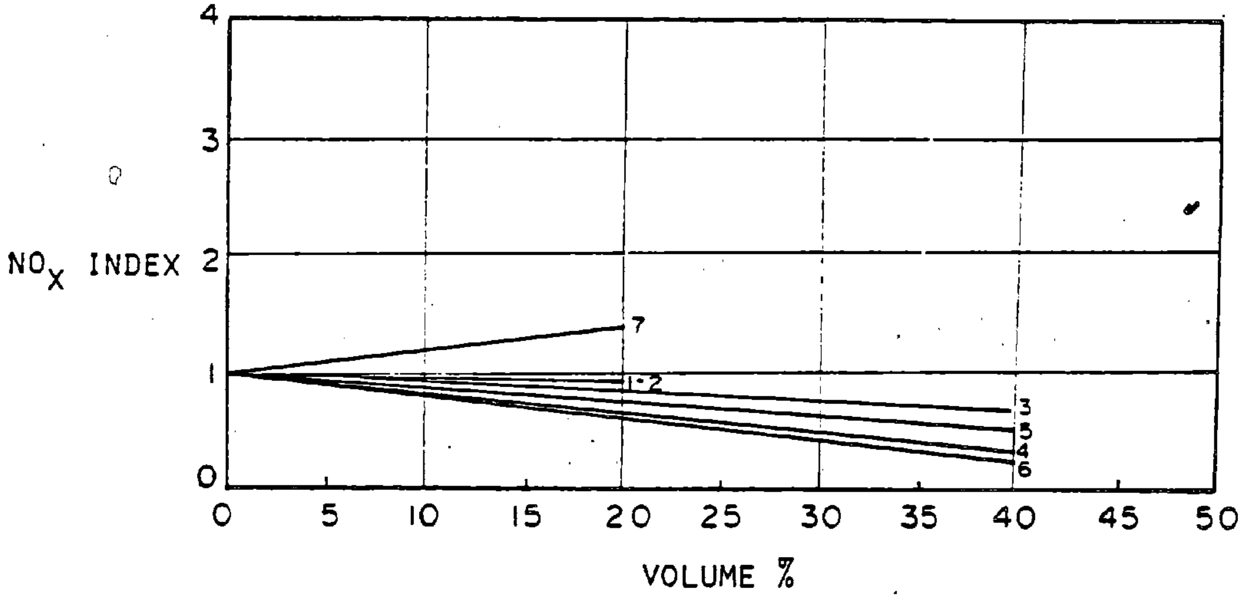
FIGURE 4.39. EFFECT OF GASOLINE EXTENDERS ON THE HYDROCARBONS INDEX AT IDLE.



1 Extender = No. 2 Diesel Fuel
2 = Marine Diesel Fuel
3 = Ethanol
4 = Methanol
5 = Naphtha-Ethanol
6 = DFM-Ethanol
7 = Naphtha

Reference 4.16.

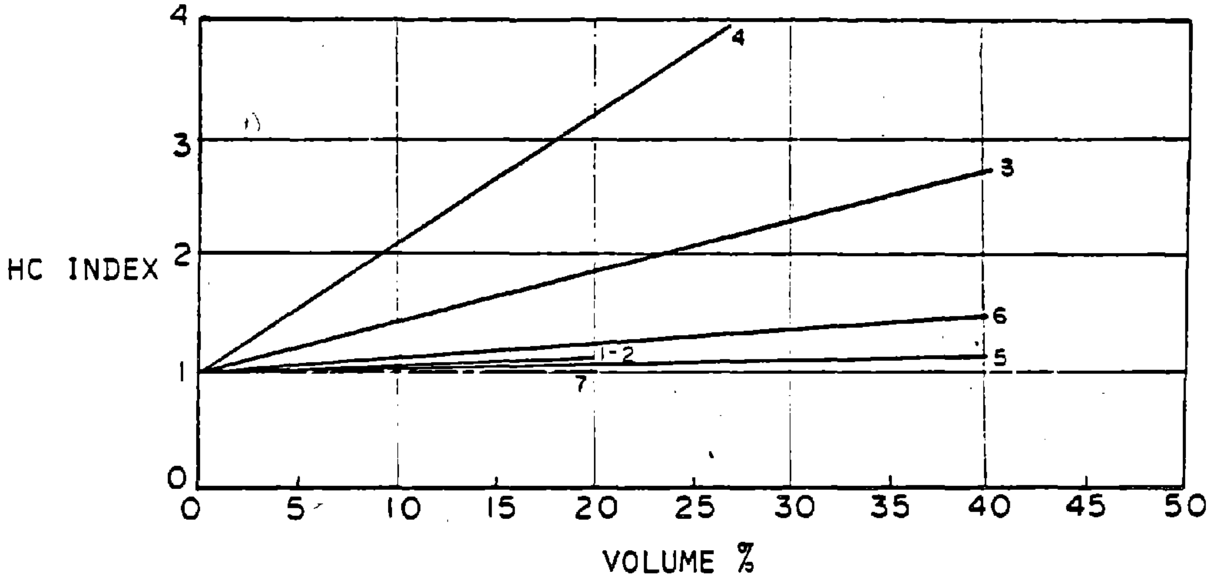
FIGURE 4.40. EFFECT OF GASOLINE EXTENDERS ON CO INDEX AT IDLE.



1 Extender = No. 2 Diesel Fuel
2 = Marine Diesel Fuel
3 = Ethanol
4 = Methanol
5 = Naphtha-Ethanol
6 = DFM-Ethanol
7 = Naphtha

Reference 4.16.

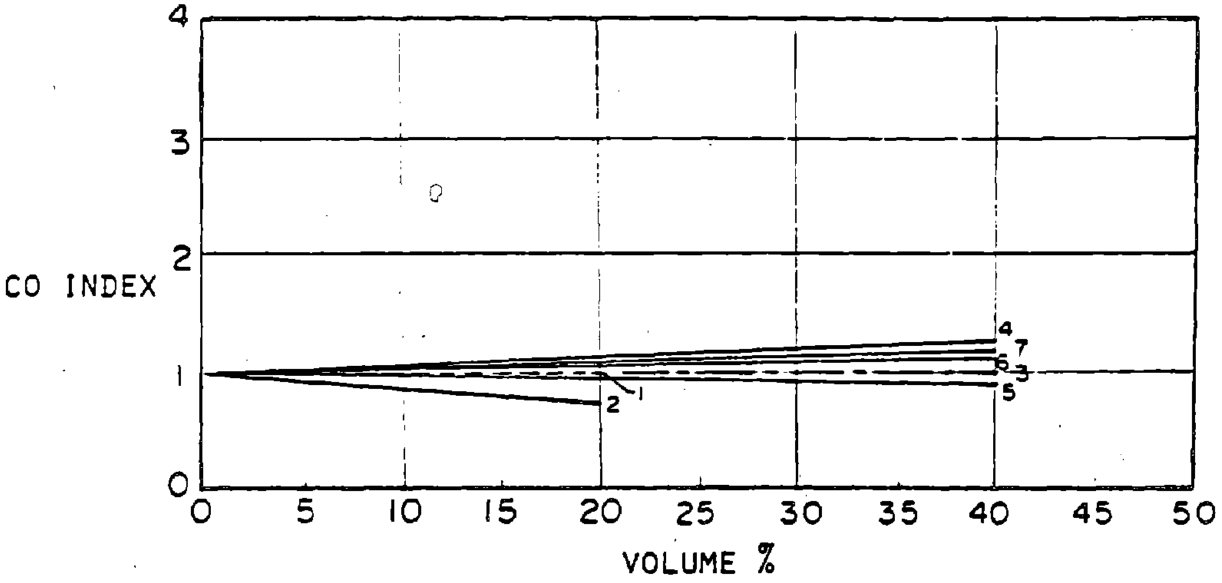
FIGURE 4.41. EFFECT OF GASOLINE EXTENDERS ON NO_x INDEX AT IDLE.



1 Extender = No. 2 Diesel Fuel
2 = Marine Diesel Fuel
3 = Ethanol
4 = Methanol
5 = Naphtha-Ethanol
6 = DFM-Ethanol
7 = Naphtha

Reference 4.16.

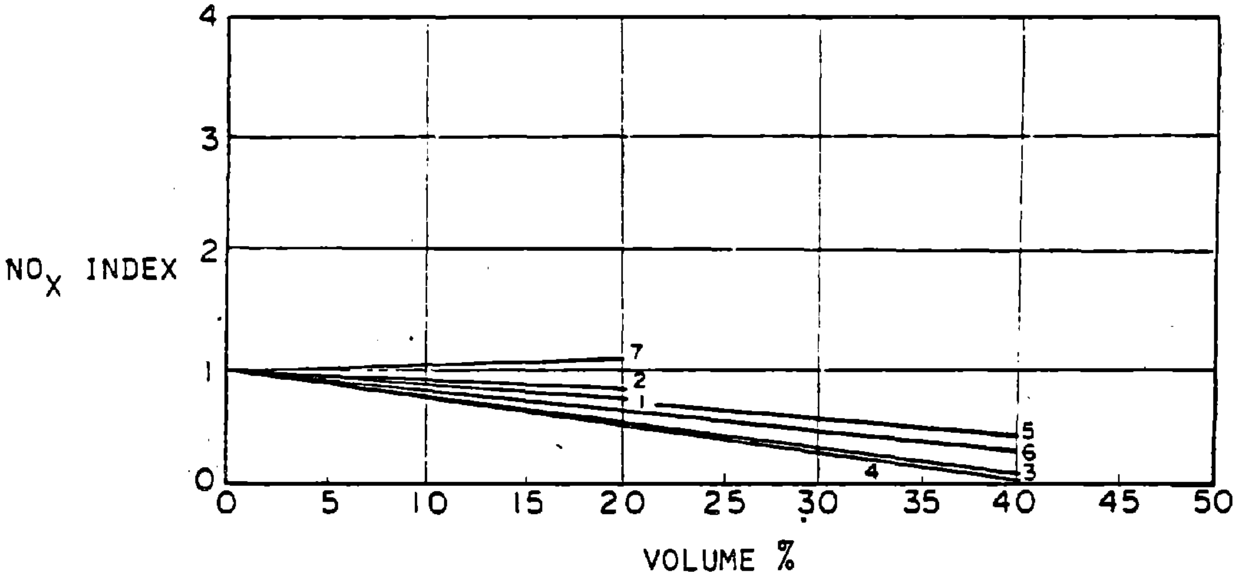
FIGURE 4.42. EFFECT OF GASOLINE EXTENDERS ON HYDROCARBON INDEX AT ROAD LOAD.



1 Extender = No. 2 Diesel Fuel
2 = Marine Diesel Fuel
3 = Ethanol
4 = Methanol
5 = Naphtha-Ethanol
6 = DFM-Ethanol
7 = Naphtha

Reference 4.16.

FIGURE 4.43. EFFECT OF GASOLINE EXTENDERS ON CO INDEX AT ROAD LOAD.



1 Extender = No. 2 Diesel Fuel
2 = Marine Diesel Fuel
3 = Ethanol
4 = Methanol
5 = Naphtha-Ethanol
6 = DFM-Ethanol
7 = Naphtha

Reference 4.16.

FIGURE 4.44. EFFECT OF GASOLINE EXTENDERS ON NO_x INDEX AT ROAD LOAD.

for ethanol. Higher concentrations of alcohols cause a drop in the RVP.

TABLE 4.11. EMERGENCY GASOLINE EXTENDERS

(I)	No. 2 Diesel Fuel	Diesel
(II)	Marine Diesel Fuel (DFM)	
(III)	Ethanol	Alcohol
(IV)	Methanol	
(V)	MTBE (Methyl Tert Butyl Ether)	Ether
(VI)	Naphtha - Ethanol	Complex Extender
(VIII)	No. 2 Diesel Fuel - Ethanol	
(IX)	Kerosene - Ethanol	
(X)	Ethanol Extended with Water	(Lower Proof Ethanol)
(XI)	Naphtha	Solvent
(XII)	Kerosene	(Solvent)

4.4.2 Effect on API Gravity

Figure 4.34 shows the effect of extender concentration on API gravity. All extenders used in this figure result in a drop in the API gravity, or an increase in the blend specific gravity.

4.4.3 Effect on Octane Number

Figure 4.35 shows that only alcohols produce an increase in the octane number of a blend. Blending with diesel fuel No. 2 has the worst effect on octane number of all the extenders shown.

4.4.4 Effect on Power Index

Figure 4.36 shows that gasoline extenders have either no effect on, or decrease the power index of the blend.

4.4.5 Effect on Conservation Index

Figure 4.37 indicates that the conservation index increases with the increase in the concentration of all the extenders except ethanol extended with water.

4.4.6 Effect on Tradeoff Index

Figure 4.37 indicates that all extenders, other than ethanol mixed with water, increase the tradeoff index, up to a volume ratio of 25 percent. At higher volume ratios of diesel fuels, naphtha and kerosene the tradeoff index decreases.

4.4.7 Effect on Emissions Index

The effects of the volume percent of the extenders on the emissions at idle are shown in Figure 4.39 for the unburned hydrocarbons, Figure 4.40 for CO, and Figure 4.41 for NO_x.

The effects on the emissions at road load are shown in Figure 4.42 for the unburned hydrocarbons, Figure 4.43 for CO, and Figure 4.44 for NO_x.

5. SENSITIVITY OF AUTOMOTIVE DIESEL ENGINES TO VARIATIONS IN FUEL PROPERTIES

5.1 D.I. FOUR-STROKE-CYCLE DIESEL ENGINE

5.1.1 Effect of Cetane Number

The major effect of cetane number is related to the length of the ignition delay. Lower C.N. fuels result in longer ignition delays, more fuel injected before autoignition, more premixing of the fuel with air, and higher rates of pressure rise. The increased premixing results in more fuel in the lean flameout region of the spray and increased unburned hydrocarbon exhaust emissions. The increase in the HC emissions with the drop in C.N. has been observed by Bertodo (5.1) in tests on a 3.86 liter, 4 cylinder, D.I., high swirl toroidal engine. The higher rates of pressure rise resulting from the longer I.D., result in higher temperatures and more premixed combustion, which increase the NO_x emissions. This effect has been observed by Bertodo (5.1). Bertodo reported the sensitivity of the engine to variations in parameters which control the I.D. as follows:

a. Delaying injection timing by 10°C.A. reduced the I.D. by about 30 percent, and allowed operation down to C.N. 40, but resulted in increased smoke equivalent to a derate requirement of 2.5 percent.

b. Increasing C.R. from 16:1 to 18:1 reduced the I.D. by about 15 percent, and allowed operation down to about C.N. 45, but increased the NO_x level by 5.7 percent to 9.5 percent.

c. Changing the mixing rate by using a "Squish Lip" combustion chamber design instead of the high swirl toroidal design: (a) reduced the I.D. from 0.75 to 0.5 ms when tuned for best fuel economy, which allowed the operation down to C.N. 42, and (b) reduced the I.D. by 50 percent when tuned for minimum emissions, and allowed operation down to C.N. = 35.

Bertodo (5.1) reported that reducing the C.N. from 55 to 22 resulted in the following:

a. Acceptable operation down to C.N. 48, at which point, severe white smoke and light load misfire occurred. This trebled the HC level.

b. C.N. lower than 48 led to severe roughness and piston erosion.

5.1.2 Effect of Aromatic Content

Aromatics are known to be low cetane number fuels, and to contribute to the smoke particulate emissions. Bertodo (5.1) reported that as the aromatic contents were raised from 15 to 30 percent, black smoke levels became unacceptable, and particulate concentrations doubled. Similar effects are reported in I.D.I. engines, which will be discussed later.

5.1.3 Effect of Mixing DF-2 With Shale Distillates

Bertodo (5.1) reported tests conducted on a D.I. high swirl, toroidal diesel engine, with DF-2 mixed with shale distillates. The shale distillates had the following approximate split:

Light Distillates	IBP < 200°C	10%
Kerosenes	IBP < 315°C	20%
Middle Distillates	IBP < 375°C	20%

The rest of the shale distillates were heavy fractions with IBP > 375°C and were not mixed with the DF2. The cetane rating of shale distillates with IBP < 375°C is about CN 25. The ASTM gums level was in the range 27-35 mg/ml. The DF2 was obtained from a refinery practicing extensive cracking to maximize gasoline production. The fuel contained 35 percent aromatics, and had the following properties:

C_6 - 190°C Raffinates	2%
200 - 300°C Kerosenes	70%
200 - 300°C Hydrocrackates	4%
300 - 350°C Distillates	24%

TABLE 5.1. TYPICAL PERFORMANCE DEGRADATION OF SHALE OIL DILUTION

Engine	Baseline Engine 16:1 Compression Ratio 22° BTDC Dyn. Inj. Timing	Baseline Engine 18:1 Compression Ratio 8° Retarded
Fuel Specification	BS 2869 Class A1	ASTM D975 No 2
Dilution	Nil	20% Shale Oil
Aromatic Content, %	∼20	32
Centane Rating	> CN 50	CN 39 - 45
Power, Kw*	61.6	60.3
s/f/c/. ml/Kwh	281	282
NO_x, g/Kwh$^+$	13.1	14.3
HC, g/Kwh$^+$	2.6	2.4
CO, g/Kwh$^+$	10.2	11.7
Black Smoke, %USPHS	9 1/4	9 1/4
Particulates, mg/m^s	220	267
Noise, dB re - 2x10^{-5} N/m^2	100	102

* at 2500 rev/min and BS Au 141a : 1971 conditions

\+ at CARB 13-mode cycle conditions

The C.R. of the baseline engine had to be increased from 16:1 to 18:1, and the injection retarded by 8°C.A., in order to account for the lower C.N. of the DF2-shale distillate mixture. The results are given in Table 5.1, and indicate the following trends:

a. The power had to be derated by 2 percent from 61.6 kW to 60.3 kW in order to keep black smoke at a constant level of 9.25 percent USPHS opacity.

b. The specific fuel consumption was almost constant.

c. NO_x, CO, particulates and noise increased.

d. HC decreased slightly

The operating problems experienced, after testing for 250 hours on a mixed duty cycle, were restricted to lacquering and sticking of precision components exposed to high temperatures, notably injectors and needles. This was attributed to the high gum content of the fuel.

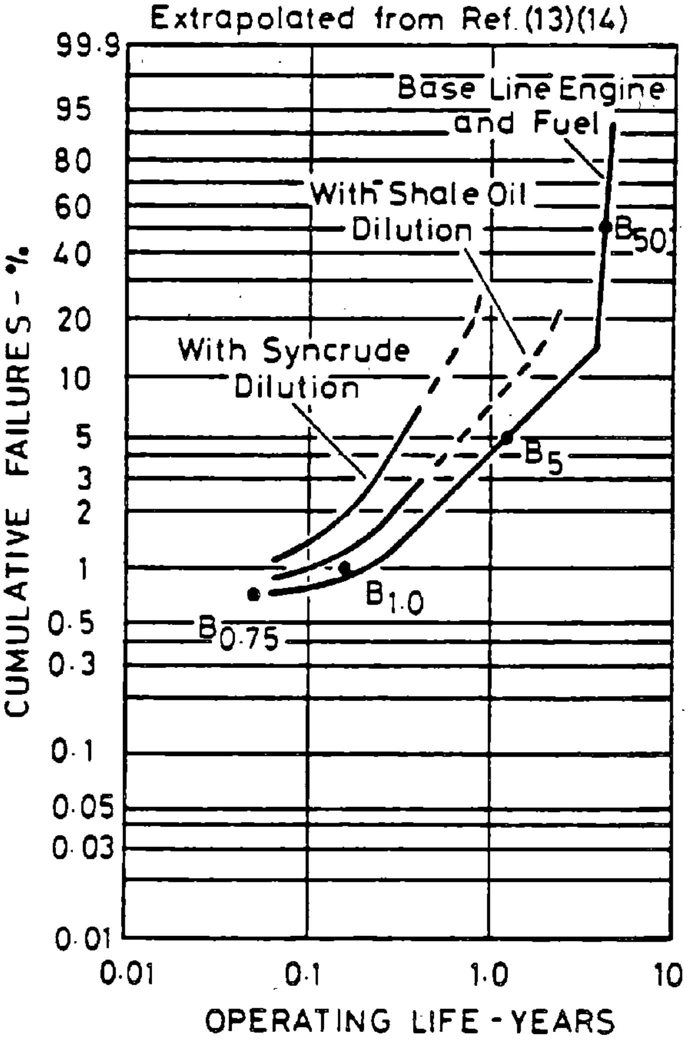
5.1.4 Effect of Mixing DF2 With Coal Distillates

Bertodo (5.1) conducted tests on coal distillates-DF2 mixtures on a D.I. high swirl torodial type diesel engine. Two types of coal distillates were used: low pressure pyrolysis tar oil, and hydrogenated creosote oil. The properties of these coal distillates are shown in Table 5.2. The test results with blends of 25 percent coal distillates, and 75 percent BS2869 Class A2 diesel oil are shown in Table 5.3. The results indicate the following:

a. Blending with 25 percent coal distilates lowered the C.N. of the fuel. This results in a longer I.S. Operation with dilution above 25 percent straight tar oil or above 50 percent hydrogenated creosote oil was impossible.

b. Derating of the power was necessary to keep the black smoke at 10 percent USPHS capacity.

c. The NO_x, HC, and CO increased.



Reference 5.1.

FIGURE 5.1. PREDICTED WEIBULL FAILURE PROFILE FOR ENGINES OPERATING ON DILUTED DIESEL FUELS.

TABLE 5.2. SELECTED PROPERTIES OF COAL DISTILLATES

	Premium Diesel Oil	Low Pressure Pyrolysis Tar Oil	Hydrogenated Creosote Oil
Specific Gravity	0.857	1.06	0.87
Cetane Rating	50	<20	40
Conradson Carbon, on 10% residue, % wt.	0.05	0.26	0.19
Distillation temperature, °C for 90% volume recovery	273	260	264
Flash point, closed cup Pensky-Martens °C	90	112	107
Benzole Insolubles, %	0.05	4.8	-
Hard asphalt, %	0.11	2.5	-

Reference 5.1.

TABLE 5.3. TYPICAL PERFORMANCE DEGRADATION WITH TAR OIL AND HYDROGENATED CREOSOTE OIL

	Baseline Engine 16:1 Compression Ratio 22°BTDC Dyn. Inj. Timing	Stratified Diesel 18:1 Compression Ratio 8°BTDC Dyn. Inj. Timing	Baseline Engine 18:1 Compression Ratio 14°BTDC Dyn. Inj. Timing
Fuel Specification	BS 2869 Class A1	BS 2869 Class A2	BS 2869 Class A2
Dilution	Nil	25% Tar Oil	25%Hydrogenated Creosote Oil
Aromatic Content, %	~20	N/A	N/A
Cetane Rating	>CN 50	36	41
Power, Kw*	61.6	58.4	55.1
s.f.c., ml/Kwh	281	336	323
NO_x, g/Kwh+	13.1	14.8	16.3
HC, g/Kwh+	2.6	4	2.9
CO, g/Kwh+	10.2	12	11.7
Black Smoke, % USPHS	9 1/4	10	10
Noise, dB re - $2x10^{-5}$ N/m^2	100	N/A	N/A

* at 2500 rev/min and BS Au 141a: 1971 conditions

\+ at CARB 13-mode cycle conditions

Reference 5.1.

Reference 5.1.

d. The specific fuel consumption increased.

Problems reported by Bertodo are related to nozzle fouling, lubricating oil sludging, and consequent wear. This resulted in poorer reliability and durability as shown in Figure 5.1. The low pour point of the coal-derived liquids, typically 4°C on the ASTM 975 test, made it necessary to introduce some fuel line heating to minimize waxing, filter plugging and line blockage. Table 5.4 shows the pour point of diesel oils diluted with coal-derived crudes.

5.1.5 Effect of Using Alcohols

Alcohols can be utilized as fuels for diesel engines by using the following techniques:

1. Neat alcohols mixed with a cetane improver.
2. Emulsion of alcohols with diesel fuel.
3. Carburetion of alcohols and ignition by diesel injection.
4. Two separate injection systems.
5. Spark ignited alcohols injected in diesel engines.

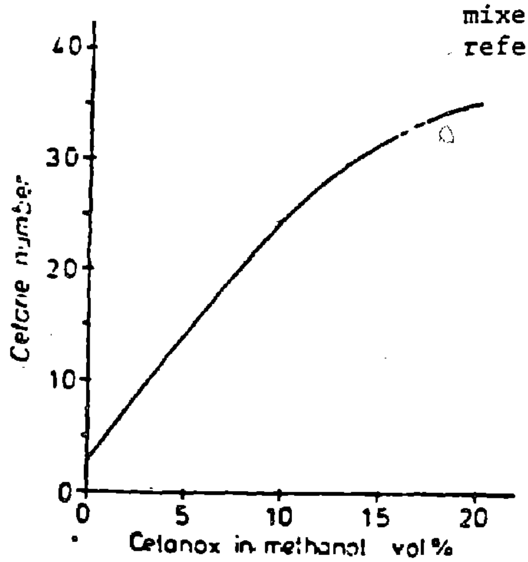
5.1.5.1 Neat Alcohols Mixed With a Cetane Improver

An improvement of the ignition quality of some alternate fuels can be achieved by using cetane improving additives (5.2). Figure 5.2 shows the effect on cetane number of adding cetanox to methanol. Cetane number increased linearly from 3 to 24 with the addition of up to 10 percent cetanox. The rate of increase of C.N. decreased as cetanox was added above 10 percent. Figure 5.3 shows the effect of the additive on the hydrocarbon emissions at part load in an automotive turbocharged direct injection diesel engine (displacement = 10 liters, C.R. = 15:1). At any BMEP, the increase in the percentage additive resulted in a reduction in the hydrocarbon emissions. This is probably due to the shorter ignition delay periods and the decrease in the amount of fuel in the lean flame-out regions. The problems associated with this

TABLE 5.4. POUR POINT (ASTM D975) OF DIESEL OILS DILUTED WITH COAL DERIVED CRUDE

	BS 2869 A2 Diesel Oil Only	Diluted 25%	Diluted 50%	Diluent Only
Low Pressure Pyrolysis Tar Oil as Diluent	-17°C	-12°C	-6°C	4°C
Hydrogenated Creosote Oil as Diluent	-17°C	-14°C	-9°C	0°C

Reference 5.1.

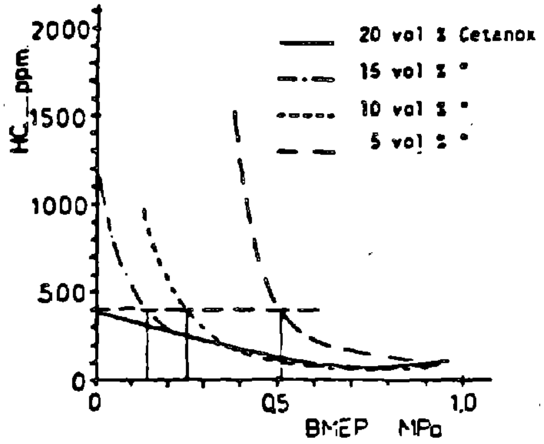


Test on a
CFR engine with equal contents of energy in the
mixed methanol and in the
reference fuel.

Reference 5.2.

FIGURE 5.2. CETANE NUMBER VERSUS PERCENTAGE OF CETANOX IN METHANOL

Part load
at engine speed 2220 rpm.



Reference 5.2.

FIGURE 5.3. EFFECT OF THE AMOUNT OF CENTANOX IN METHANOL ON HC EMISSIONS.

approach are related to low durability due to excessive wear.

The amount of additive needed can be reduced by preheating the intake air by engine coolant. At partial loads, when the coolant is relatively cool, the exhaust gases can be recirculated by increasing the back pressure. This may reduce the hydrocarbon emissions.

Cold starting represents a problem and calls for preheating the intake air by an electrical element or by using an intake air burner.

The effect of increasing the back pressure on the hydrocarbon emissions at partial load is shown for the engine of Figure 5.2 in Figure 5.4. These results are for methanol with 5 percent centox by volume. The reduction in the HC at any BMEP can be attributed to two factors. The first is the reduction in the ignition delay period caused by the increase in the gas temperature. The second factor is the improvement in the oxidation reactions caused by the higher mass average temperature.

Bertodo (5.1) conducted two types of tests with ethanol. The first consisted of ethanol neat mixed with 8 percent ethyl nitrate and 2 percent lubricating oil. Mixing with ethyl nitrate increased the C.N. to 45. In the second type, blends containing 30 percent ethanol were used, either premixed or manifold injected with the injection timing retarded by 10°C.A. The results are shown in Table 5.5 and indicate the following trends:

a. Mixing with ethanol reduced the C.N.

b. Power decreased very slightly

c. Specific fuel consumption on a volume/kW basis increased due to the lower energy content of ethanol. On an energy basis, the fuel economy did not change.

d. NO_x, CO, black smoke, decreased.

e. HC increased.

TABLE 5.5. PERFORMANCE IMPACT OF ETHANOL FUELING

Engine	**Baseline Engine** **16:1 Compression Ratio** **22° BTDC Dyn. Inj. Timing**	**Baseline Engine** **16:1 Compression Ratio** **12° BTDC Dyn. Inj. Timing**	**Baseline Engine** **16:1 Compression Ratio** **12° BTDC Dyn. Inj. Timing**
Fuel Specification	BS 2869 Class A1	90% Ethanol 8% Ethyl Nitrate 2% Lub. Oil	BS 2869 Class A1
Dilution	Nil		30% Ethanol
Aromatic Content, %	~ 20	-	~ 15
Cetane Rating	>CN 50	CN 40	CN 38 - 43
Power, Kw*	61.6	60.1	60.4
s.f.c., ml/Kwh	281	477	340
NO_x, g/Kwh+	13.1	10.2	12.8
HC, g/Kwh+	2.6	4.1	2.9
CO, g/Kwh+	10.2	6.9	9.0
Black smoke, % USPHS	9¼	4½	7
Noise, dB re - 2×10^{-5} N/m^2	100	-	-

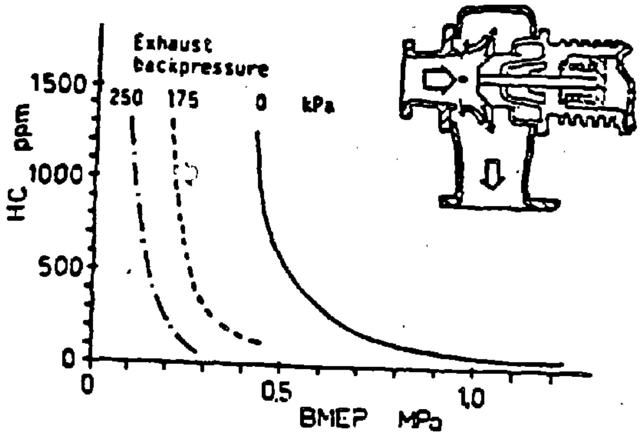
* at 2500 rev/min and BS Au 141a : 1971 conditions

+ at CARB 13-mode cycle conditions

Reference 5.1.

Aldehydes were reported to increase. Bertodo reported problems related to lubricating oil contamination by organic acids (mainly formic) and unidentified aldehydes. This resulted in higher wear in critical engine parts such as bearings.

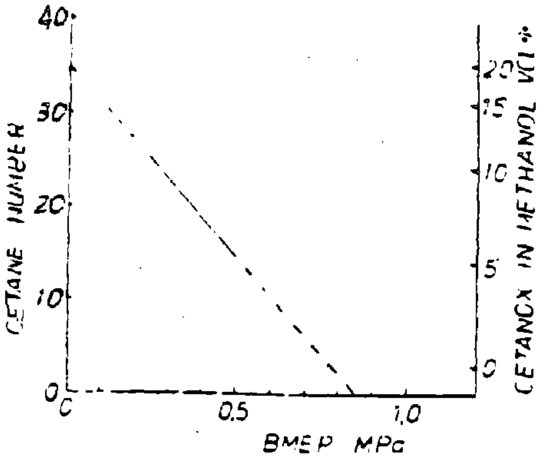
5.1.5.2 Emulsions of Alcohols With Diesel Fuel - Injecting methanol or ethanol under high pressure in diesel fuel was found by Holmer, et.al. (5.2) to form an emulsion, which remains stable long enough to be uniform until injected. This results in a drop in the cetane number of the fuel. The cetane number demand is much lower at full load than at low load as as shown in Figure 5.5. Therefore, a load-dependent emulsion can be used, which increases the amount of emulsified methanol with load. One such system was developed in which the emulsion was produced. It was found that with this system, emulsions of methanol and ethanol



Part load at 1500 rpm. Methanol with 5 vol.% centanox.

Reference 5.2.

FIGURE 5.4. EFFECT OF THE BACK PRESSURE ON HC EMSSIONS.



Part load at engine speed 2220, ambient air temperature 25 C.

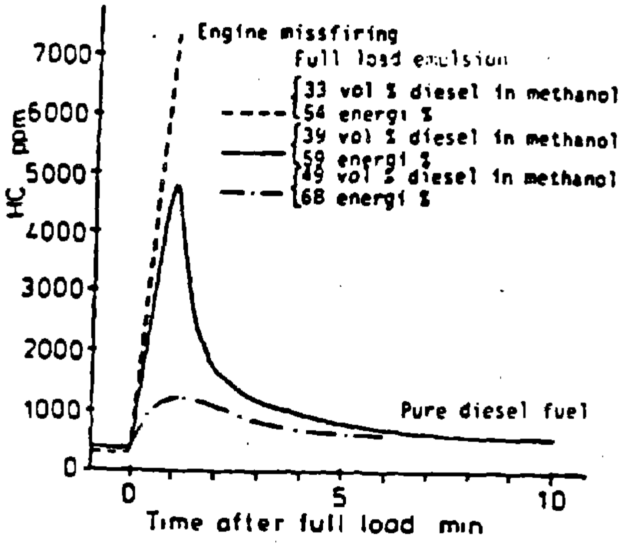
Reference 5.2.

FIGURE 5.5. PERCENTAGE NEEDED OF CENTANOX IN METHANOL AND CETANE NUMBER TO MINIMIZE HC EMISSIONS TO 400 PPM.

with diesel fuel are only useful under steady state, full load conditions. Under transient conditions, the capacity of the gallery of the injection pump does not allow the quick adjustment of the methanol/diesel ratio to meet the cetane requirements at different loads. Figure 5.6 shows the variation of the hydrocarbon emissions with time after unloading the engine. Holmer, et.al. found that only 32 percent diesel fuel could be substituted by methanol under full load conditions to avoid peaks of HC above 1000 ppm. Holmer stated that with such emulsions, the diesel fuel will give reasonable wear protection of the injectors and fuel pump providing the alternative fuel has a low acid content. .

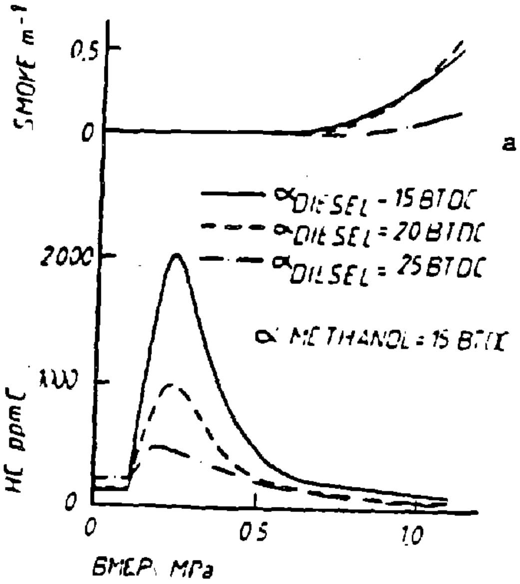
5.1.5.3 Carburetion or Manifold Injection of Alcohols and Ignition by Diesel Injection - Alcohols have a latent heat of evaporation much higher than gasoline. Therefore, carburetion of alcohols results in a larger drop in the intake air temperature which affects the autoignition process and tends to cause misfire at low loads. At high loads the carburetted mixture tends to self-ignite (5.3, 5.4, 5.5). Manifold injection of ethanol was found by Bertodo (5.1) to require elaborate and expensive control of the metering and timing of the two fuels.

5.1.5.4 Two Separate Injection Systems - The methanol, ethanol or gasoline is injected, separate from the diesel fuel, by a separate injection system. The relative timing of the start of injection in the two injection systems has a great effect on performance and emissions. The effect of the dynamic injection timing of diesel fuel on the HC and smoke is shown in Figure 5.7, at a fixed injection timing for methanol. It is clear from this figure that earlier diesel injection results in lowering the HC at light loads and the smoke at the higher loads.



Ref. 5-2.

FIGURE 5.6. HC-EMISSIONS VERSUS DRIVING TIME AT NO-LOAD AFTER FULL LOAD AT ENGINE SPEED 1500 RPM.



Part load
at engine speed 900 rpm.

Ref. 5.1

FIGURE 5.7. EFFECT OF DIESEL DYNAMIC INJECTION TIMING ON SMOKE AND HC EMISSIONS WITH FIXED METHANOL TIMING.

The relative amounts of fuel injected can be varied according to the cetane requirements at the different loads. At idling and light loads the fuel should be diesel fuel in order to reduce HC emissions and improve the cold starting characteristics.

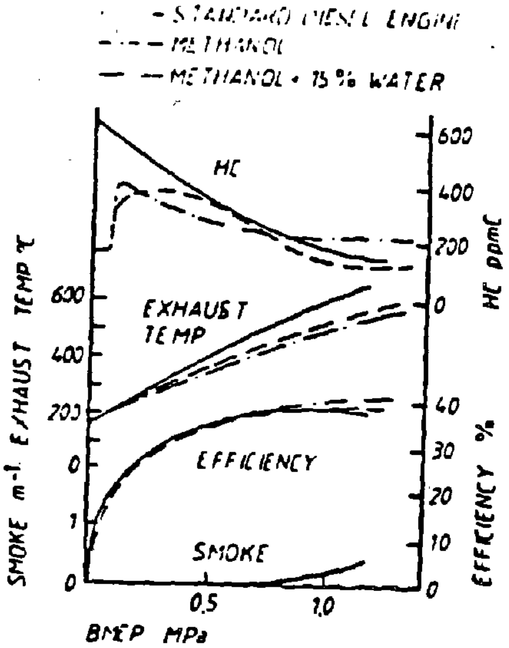
A comparison between the performance of the standard diesel engine and the diesel/methanol engine is given in Figure 5.8. This figure also shows curves for methanol with 15 percent water, which represents an alcohol distilled at a low concentration and relatively lower cost. Figure 5.8 indicates that with methanol, there is a slight improvement in thermal efficiency, low load hydrocarbons, and high load smoke.

Figure 5.9 is for a diesel/ethanol engine and is similar to the corresponding figure for methanol.

5.1.5.5. <u>Spark Ignited Alcohols in Diesel Engines</u> - A commercial spark ignited diesel engine running on diesel fuel was used by Volve (5.2). To make a light engine, a low compression ratio (12:1) was used. The problems with this engine were cold starting, high emission of hydrocarbons at idling, and low reliability, as the spark plug could be wetted by the fuel, thus causing misfire.

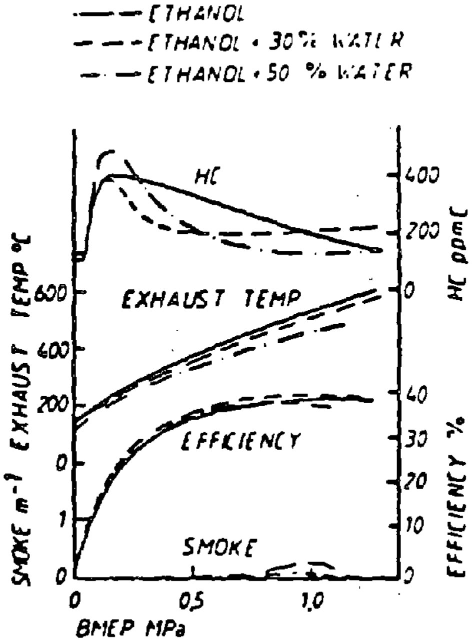
Spark ignited diesel engines running on gasoline, methanol, and ethanol have been developed (5.6) (5.7), but are not commercially available. In these engines, a much higher voltage is needed for the spark because of the high compression ratio.

The effect of using methanol on the endurance of diesel engines during two 1000-hour cycling bench tests was reported by Holmer, et.al., (5.2). Wear was observed between the injection needle and the spring washer causing the opening pressure to fall from 14.7 MPa to between 4.1 and 11.8 MPa. An attempt was made to solve the wear problem in the injector by increasing the back pressure in the fuel leakage pipe in order to maintain the methanol in a liquid phase at the temperatures which exist in the injector. This attempt did not solve the problem. Other problems reported by Holmer are related to cracked plunger liners.



Reference 5.2.

FIGURE 5.8. COMPARISON OF PART LOAD PERFORMANCE BETWEEN STANDARD DIESEL AND DIESEL/METHANOL ENGINES AT 1500 RPM.



Reference 5.2.

FIGURE 5.9. PART LOAD PERFORMANCE WITH DIESEL/ETHANOL ENGINE AT 1500 RPM.

5.1.6 Effect of Mixing DF-2 With Vegetable Oils

Results of tests on blends of DF2 and several types of vegetable oils are given in Table 5.6. The vegetable oils tested are:

- Soya Oil
- Babco Oil
- Palm Oil
- Peanut Oil

The results with 10 percent and 20 percent cotton seed oil are given in Table 5.7. Bertodo concluded that:

i. Most vegetable oils except castor oil are directly miscible with middle distillates.

ii. High viscosity and acidity were general problems with all vegetable oils.

iii. Castor oil, readily mixed up to 2 percent concentration, was too viscous (297.5 CS at 37.8°C) and tended to cause fouling (carbon residue 44 percnet), and proved excessively acidic.

5.1.7 Effect of Mixing DF-2 with Gasoline - The main problem of using gasoline as an alternate fuel in diesel engines is related to its very poor ignition property resulting in very long ignition delays. This results in late start of combustion at low speeds and misfire at high speeds. Techniques to reduce ignition delay are heating the inlet air, raising the compression ratio, or mixing a high ignition quality additive with the gasoline such as diesel fuel or lubricating oil. Figure 5.10 gives the cetane number drops from 50 to 32 as the percentage gasoline in the mixture increases from 0 to 50 percent. The effect of mixing gasoline and diesel fuels on the ignition delays is shown in Figure 5.11. This figure shows that an inlet air temperature of 100°F, mixing with 30 percent gasoline increased the I.D. by 50 percent. Figure 5.12 shows results reported by Scott for tests of a 300 cu. in., 6 cylinder D.I. truck engine, with diesel fuel

TABLE 5.6. PERFORMANCE IMPACT OF EXTENSION WITH VEGETABLE OIL

Engine	Baseline Engine 16:1 Compression Ratio 22° BTDC Dyn. Inj. Timing				
Fuel Specification	BS 2869 Class A1	BS 2869 Class A1	BS 2869 Class A1	BS 2869 Class A1	BS 2869 Class A1
Extender	Nil	20% Soya Oil	20% Babaço Oil	20% Palm Oil	20% Peanut Oil
Aromatic Content, %	~20	~15	~15	~15	~15
Cetane Rating	>CN 50	CN 48	CN 48	CN 47	CN 47
Power, Kw*	61.6	61.1	61.1	61.1	61.0
s.f.c., ml/Kwh	281	286	284	281	280
NO$_x$, g/Kwh$^+$	13.1	-	-	-	-
HC, g/Kwh$^+$	2.6	-	-	-	-
CO, g/Kwh$^+$	10.2	-	-	-	-
Black Smoke, % USPHS	9¼	8 - 9	8 - 9	8 - 9	8 - 9
Noise, dB re - 2x10^{-5} N/m^2	100	-	-	-	-

* at 2500 rev/min and BS Au 141a : 1971 conditions

\+ at CARB 13-mode cycle conditions

Reference 5.1.

TABLE 5.7. PERFORMANCE IMPACT OF COTTON-SEED OIL EXTENSION

Engine	Baseline Engine 16:1 Compression Ratio 22° BTDC Dyn. Inj. Timing		
Fuel Specification	BS 2869 Class A1	BS 2869 Class A1	BS 2869 Class A1
Extender	Nil	10% Cotton Seed Oil	20% Cotton Seed Oil
Aromatic Content	~ 20	~18	~16
Cetane Rating	>CN 50	CN 49	CN 47
Power, Kw*	61.6	61.0	60.9
s.f.c., ml/Kwh	281	280	278
NO$_x$, g/Kwh$^+$	13.1	-	-
HC, g/Kwh$^+$	2.6	-	-
CO, g/Kwh$^+$	10.2	-	-
Black Smoke, % USPHS	9¼	8 - 9	8 - 9
Noise, dB re - 2x10^{-5} N/m^2	100	-	-

* at 2500 rev/Min and BS Au 141a : 1971 conditions

\+ at CARB 13-mode cycle conditions

Reference 5.1.

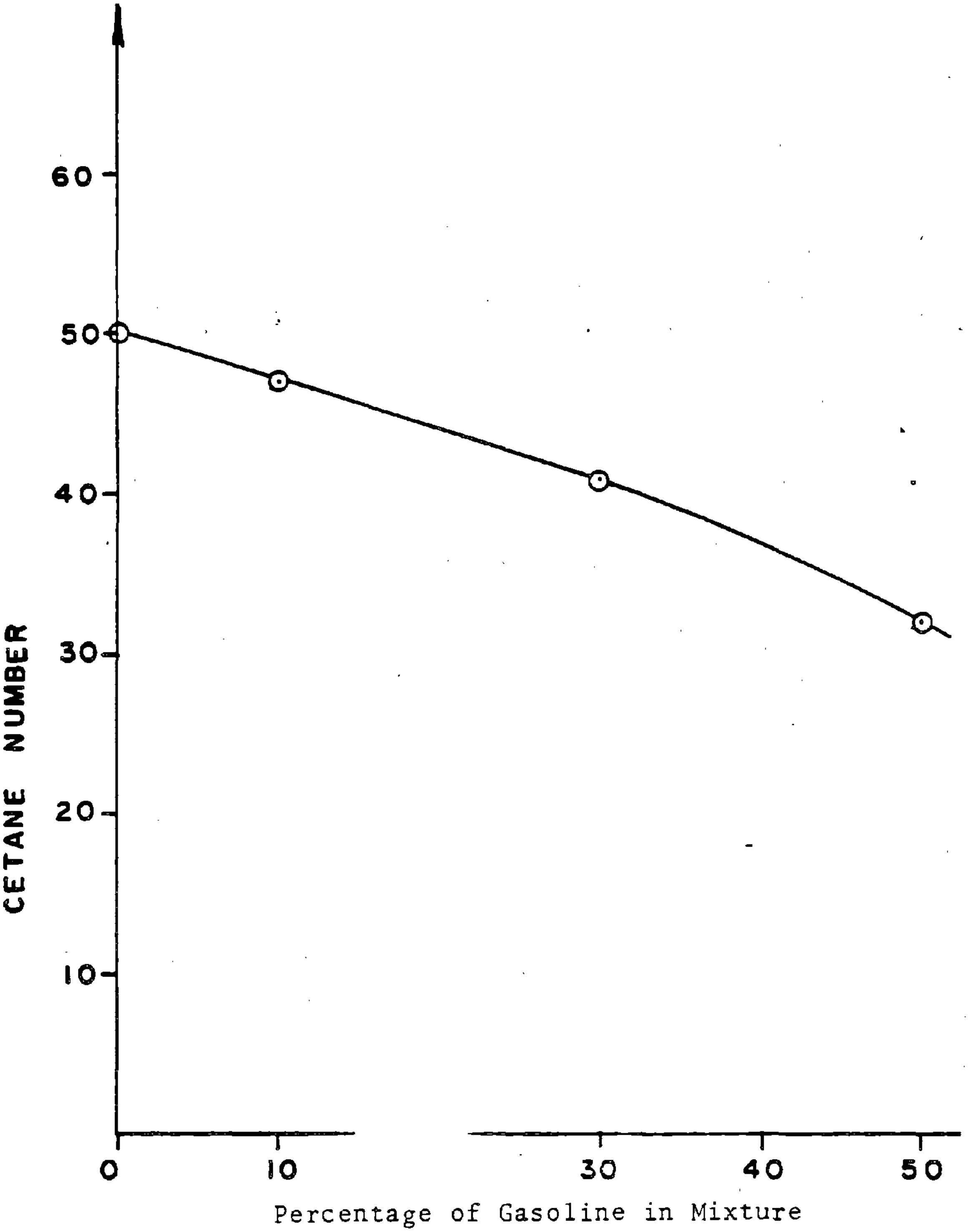


FIGURE 5.10. CETANE NUMBER OF DIESEL-GASOLINE MIXTURES

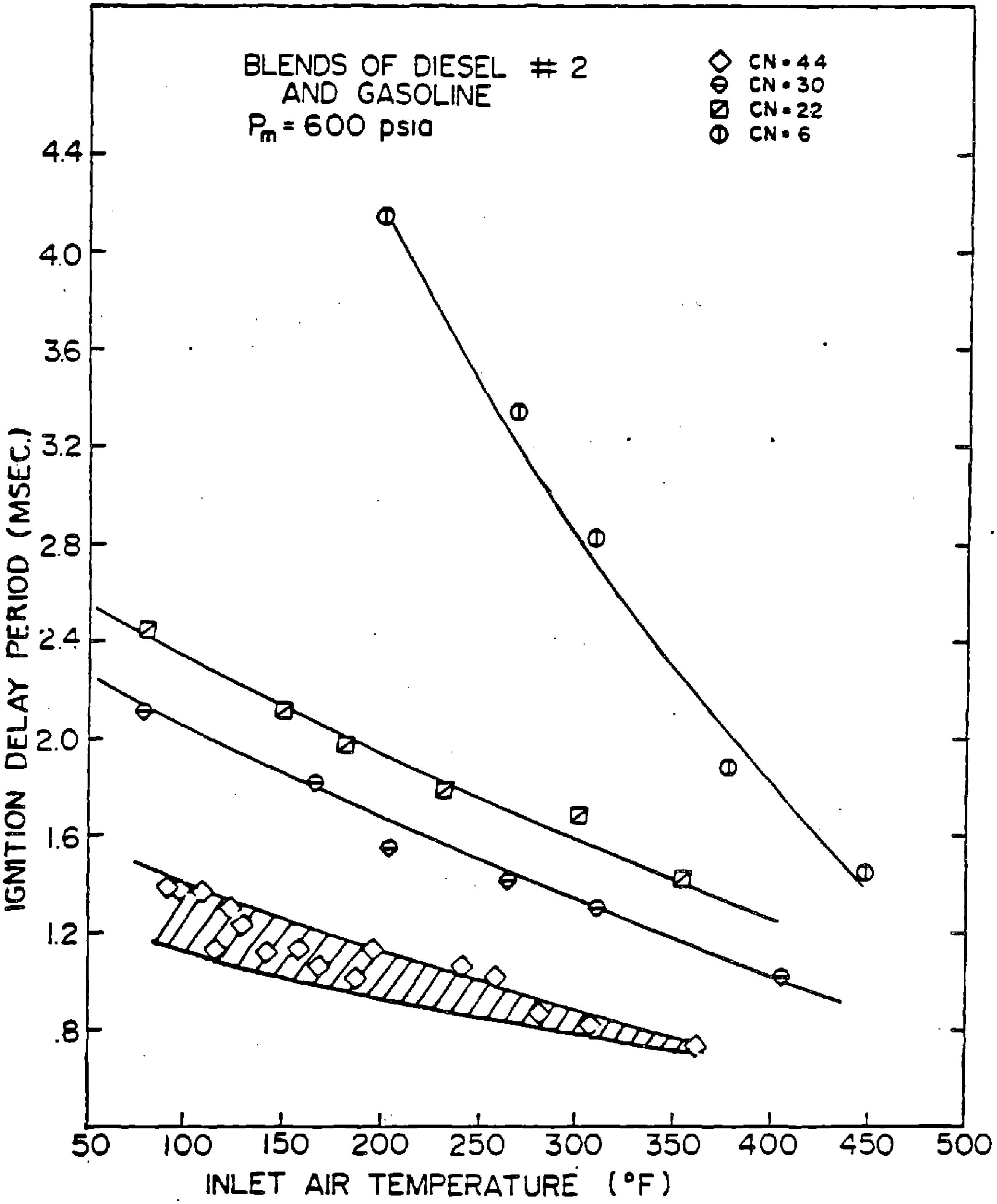
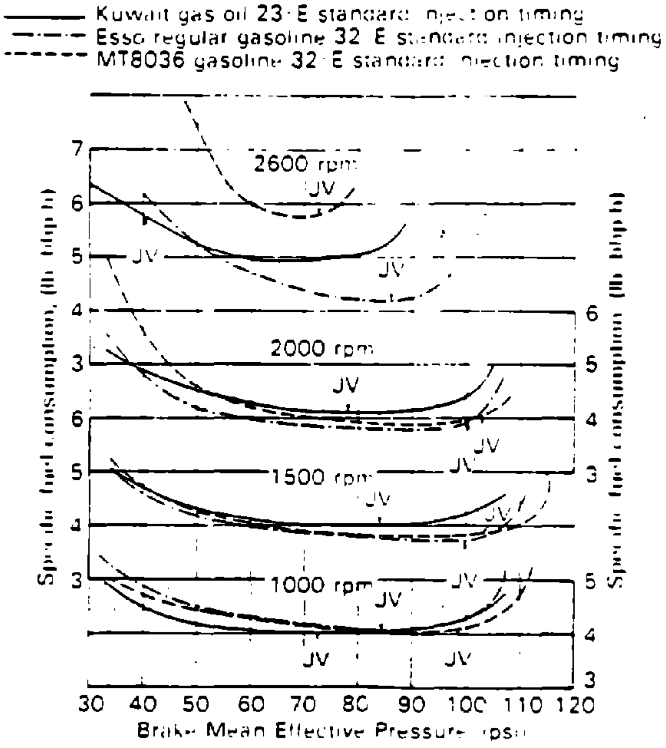


FIGURE 5.11. EFFECT OF MIXING GASOLINE WITH DIESEL FUEL ON IGNITION DELAY.



Reference 5.18.

FIGURE 5.12. TYPICAL DIESEL FUEL AND GASOLINE LOAD RANGE CURVES FROM A 6 CYLINDER 300 CID DIESEL ENGINE.

and two types of gasoline. The C.R. was raised from 17 to 19:1. The BMEP at which just visible smoke is indicated by the symbol JV on the figure for each fuel. Figure 5.13 shows very clearly that gasoline produced higher BMEP at the smoke limit. This is caused by the increase in the portion of the fuel which is injected during the longer ignition delay, and the increase in the pre-evaporated and pre-mixed part of the charge. The deterioration in fuel economy at high speed and light load is due to misfiring due to the long ignition delays of gasoline. Combustion photographs taken by Scott (5.8) indicated the occurence of premixed burning with long ignition delays.

One of the problems associated with the use of gasoline in direct injection diesel engines is the formation of pockets of end gas outside the combustion bowl, which detonate causing damage to the piston crown.

The use of additives can reduce the ignition delay period. Adding 5 percent lubricating oil to the gasoline was found to increase the cetane number of a primary reference fuel from 19 to 22 and to decrease the R.O.N. of gasoline from 93.1 to 89.5 (5.8). Adding 5 percent lubricating oil was found by Scott (5.8) to eliminate the damage in the piston caused by detonation, and to provide necessary lubricity to the gasoline in the fuel injection pump.

Another problem associated with the use of highly volatile fuels in diesel engines is vapor lock in the fuel injection pump. This may be avoided by using pressurized recirculating feed to the pump gallery (5.8).

The use of gasoline in divided chamber automotive engines was reported by Scott (5.8) to be far less successful than in D.I. engines. This is attributed to the high rate of evaporation and premixing, coupled with high rates of heat loss, which result in excessive delay and unreliable ignition, particularly at partial loads.

5.1.8 Effect of Using Two Separate Injection Systems in a Diesel/Gasoline Fueled Engine

A comparison between the partial load performance of a diesel/crude low octane gasoline engine and a diesel engine running on gasoline has been reported by Holmer et.al., (5.2) and is given in Figure 5.13. This figure shows an increase in the thermal efficiency and reduction in smoke in the diesel engine when run on low-octane gasoline. However, the HC emissions are much higher with pure gasoline, particularly at light loads. To reduce these emissions and improve the cold starting characteristics, pilot injection of diesel fuel is used at light loads and at starting. At high loads, the pilot injection is stopped as the cetane requirements are less.

5.1.9 Effect of Using Wide Cut Distillates

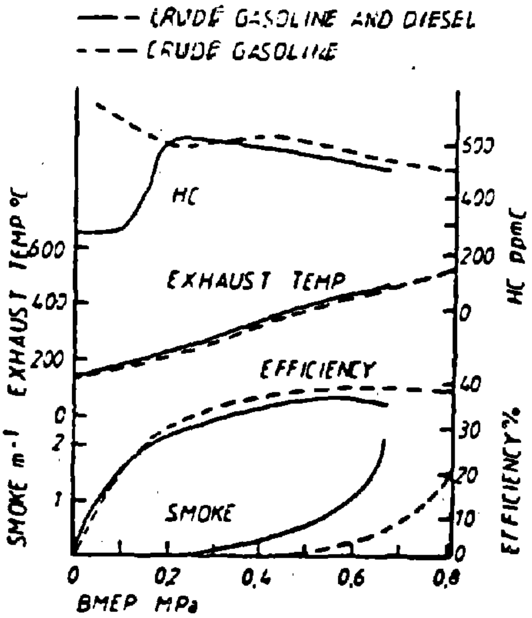
Holmer (5.2) indicated that wide cut fuels can be obtained by mixing crude gasoline with diesel fuel, and can be produced at the refinery with less energy than that required to produce high octane gasoline. Broadening the distillation range of the fuel, by including both lighter and heavier fractions than those normally associated with DF2, is the simplest and most expedient method to increase the diesel fuel stocks (5.1). According to Bertodo (5.1), the benefits from such a fuel are:

a. Reduce the refinery losses by 17-25 percent.

b. Increase crude barrel yield as "road fuel" by 5-25 percent.

c. Improve the mileage potential per barrel of crude by 11-21 percent.

d. Raise crude to drive-wheel conversion efficiency by about 30 percent.



Reference 5.2.

FIGURE 5.13. COMPARISON OF PART LOAD PERFORMANCE WITH DIESEL/ CRUDE GASOLINE AND CRUDE GASOLINE AT 900 RPM.

5.2 D.I. TWO-STROKE-CYCLE DIESEL ENGINE

5.2.1 Effect of Using Off-Specification Diesel Fuels

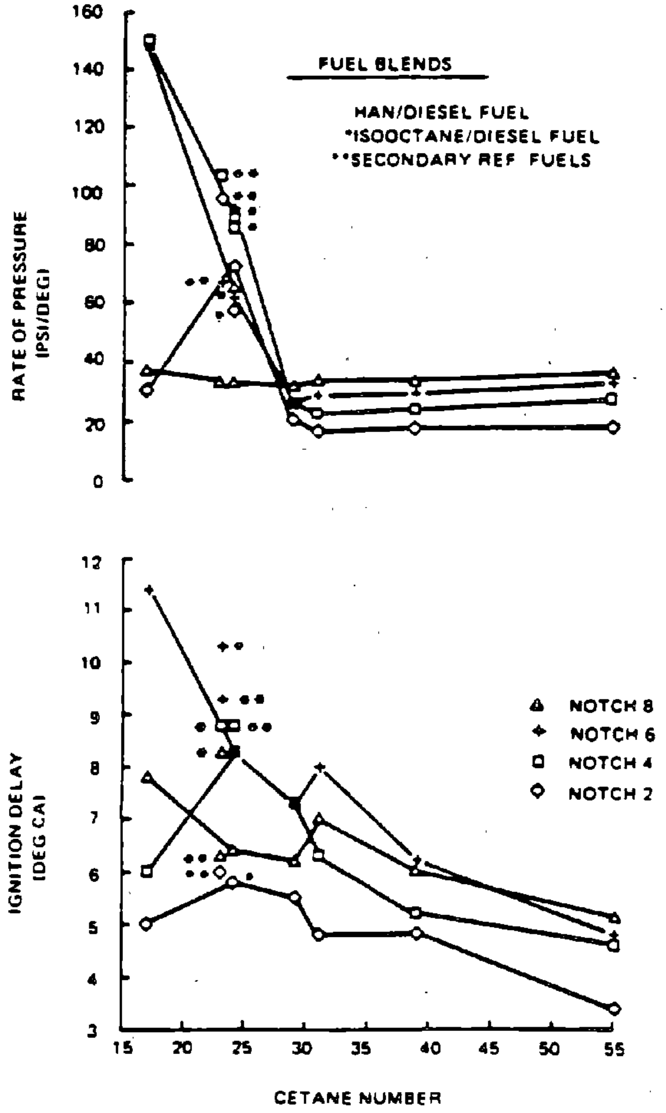
Baker (5.9) performed tests on a two-stroke-cycle medium-speed diesel engine by using off-specification diesel fuels. One or more properties of these fuels did not lie in the currently accepted range of specifications for Number 2 diesel fuel. The fuel properties varied were cetane number, viscosity and distillation range.

The engine used was a two-cylinder version of the Electro-Motive Division (EMD): 8.5" bore, 10.0" stroke, 2-stroke-cycle, blower scavenged, maximum governed speed of 835 rpm, 16:1 C.R.

Fuels were produced by blending various components, and compared to No. 2 diesel fuel which met all requirements of ASTM D-975 shown in Table 5.8.

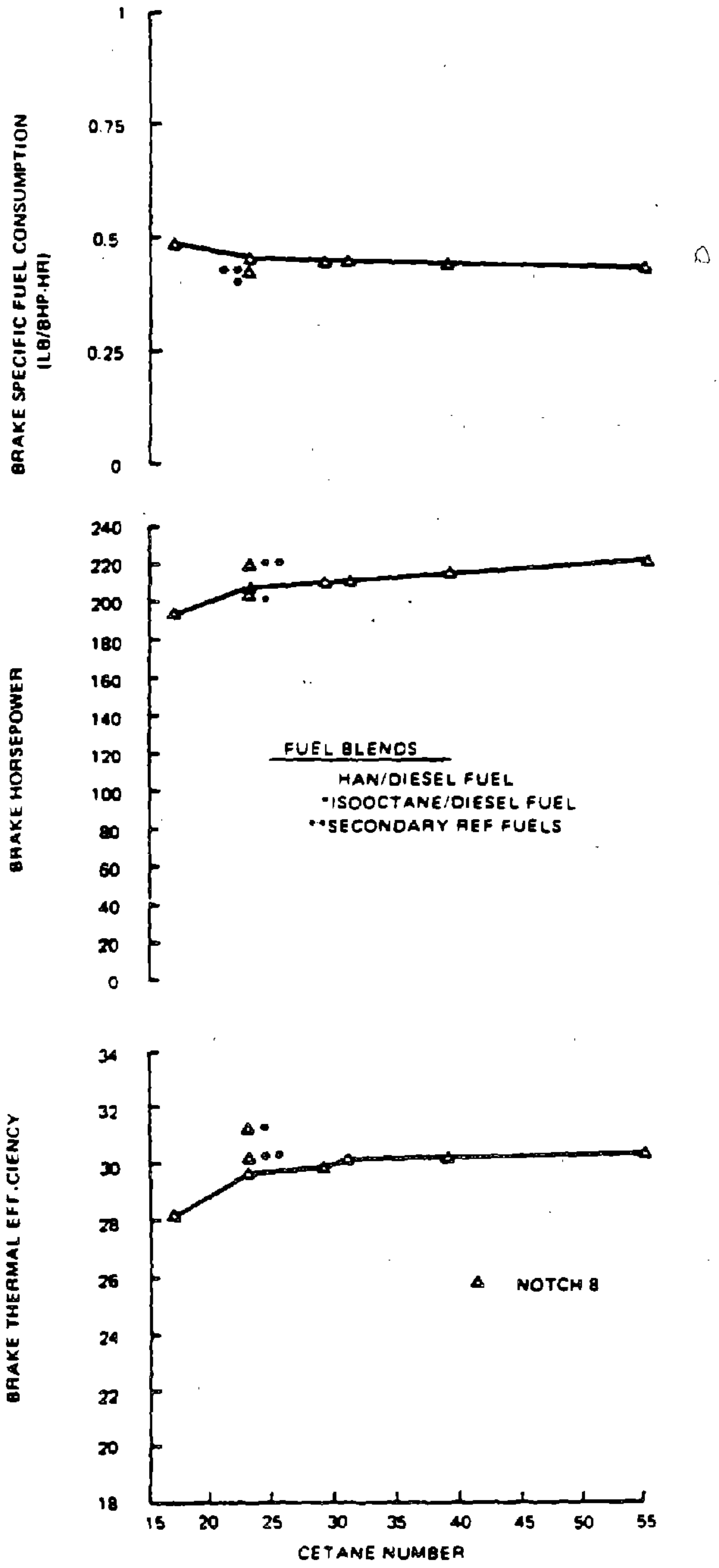
Effect of Cetane Number. The effect of cetane number was to reduce the I.D. and rate of pressure rise as shown in Figure 5.14. For fuels with a C.N. above 30, the decrease in I.D. was not sufficient to result in a significant penalty in engine performance, brake horsepower, thermal efficiency, BSFC, and rate of pressure rise as shown in Figure 5.15. Below a C.N. of 30, rate of pressure rise increased dramatically. The effect of the variation in C.N. on the emissions is shown in Figure 5.16. In this figure, Notch 8 indicates full load rated speed and load. All other notches indicate partial load conditions.

Effect of Viscosity. The viscosity was varied independently of the other fuel properties by heating an extremely viscous lube stock. Probably, heating the oil resulted in variations in density. Engine power, fuel consumption, thermal efficiency, and combustion characteristics were almost constant. The effect of viscosity is shown in Figure 5.17. Brake specific particulates increased as viscosity increased from 38 to 65, at the high load. (This load was limited by the inability of the injection system to supply sufficient fuel for normal operation). At partial loads,



Reference 5.9.

FIGURE 5.14. EFFECT OF C.N. VARIATIONS ON I.D. AND RATE OF PRESURE RISE (2-CYLINDER ENGINE).



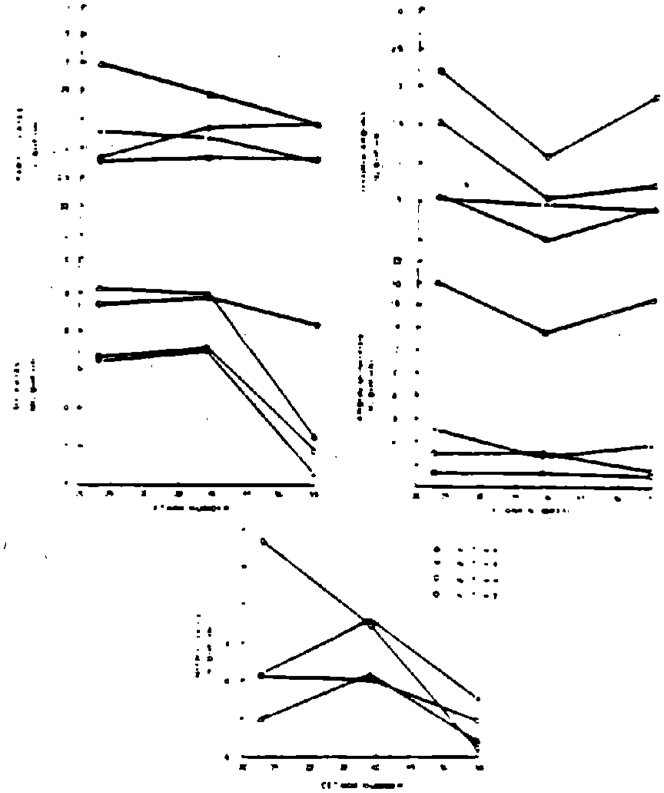
Reference 5.9.

FIGURE 5.15. EFFECT OF C.N. ON ENGINE PERFORMANCE (2-CYCLE ENGINE)

TABLE 5.8. NO. 2 DIESEL FUEL PROPERTIES

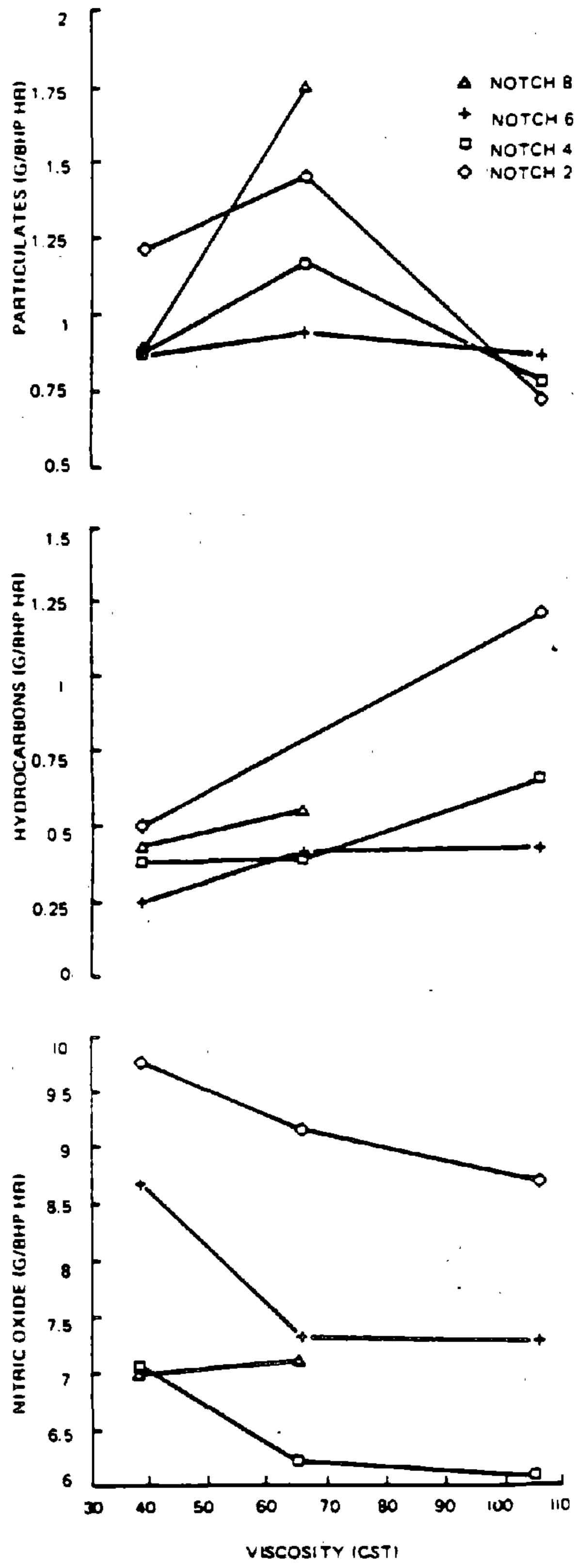
Fuel Property	ASTM D975 Specifications	Baseline No. 2 Diesel Fuel
Cetane Number	min. 40	55
API Gravity	no spec.	37.7
Kinematic Viscosity (cst. at 40°C)	min. — max. 2.0 4.3	3.3
Heat of Comb. (BTU/lb)	no spec.	19685
Distillation (°F)		
10%	no spec.	460
90%	min. — max. 540 675	640
Sulfur (% mass)	1.0	0.15
Ash (% mass)	0.02	—
Water, Sed. (% vol.)	0.10	—
Flash Pt. (°F)	min. 125	161

Reference: 5.9.



Reference 5.9.

FIGURE 5.16. EFFECT OF C.N. ON EMISSIONS IN A 2-CYCLE ENGINE.



Reference 5.9.

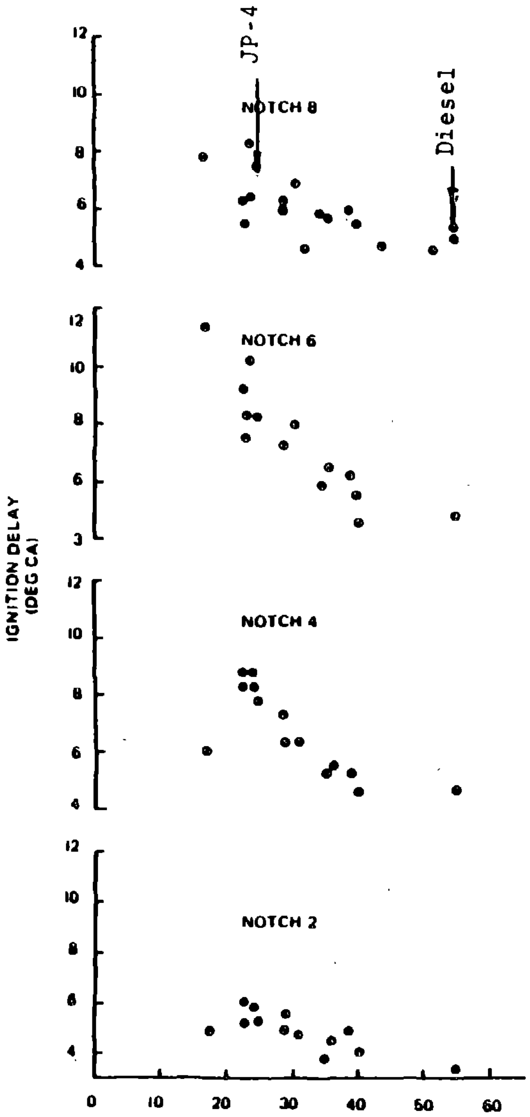
FIGURE 5.17. EFFECT OF VISCOSITY ON EMISSIONS IN A 2-CYCLE ENGINE

the brake specific particulates increased with viscosity up to 65 CS, after which they decreased. This variation in particulate emissions is related to the change in the spray characteristics and the degree of premixing of the fuel and air.

Brake specific hydrocarbons generally increased with viscosity, particularly at the lightest loads (Notch 2). Brake specific nitrogen oxides decreased with increased viscosity. Carbon monoxide and sulfates did not show a definable relation to viscosity.

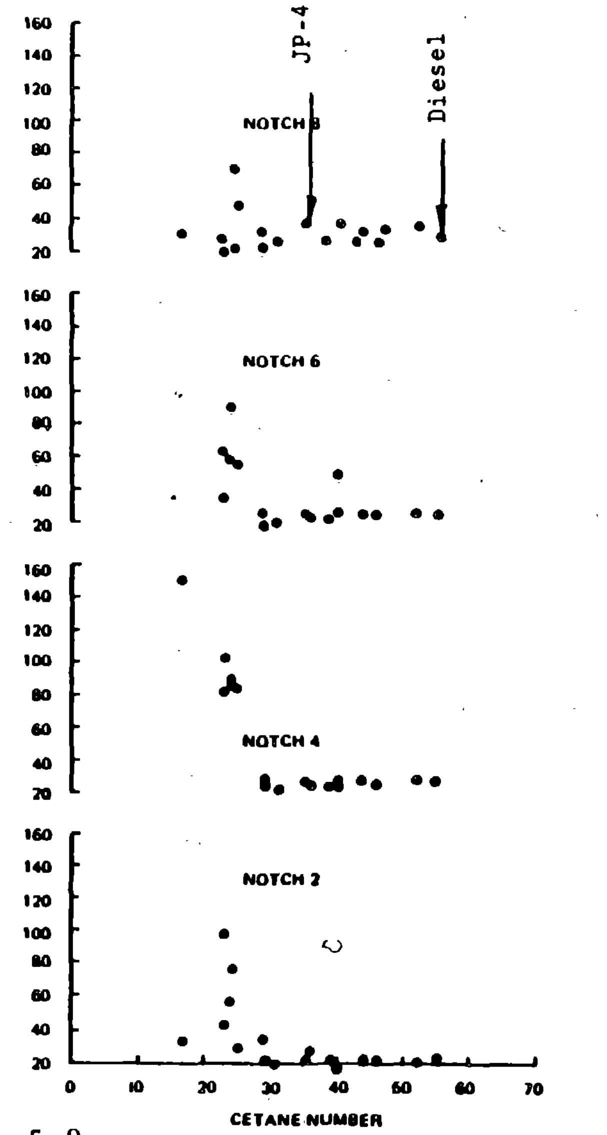
Effect of Distillation Range. Fuels of different distillation range were produced by blending various combinations of unleaded gasoline, a lube stock, and No. 2 diesel fuel. This resulted in variations in the other fuel properties, and a multi-variate statistical analysis was used to find the effect of each fuel property. This analysis indicated that the distillation range was not a primary factor in B.H.P. and BSFC, but rather, the C.N., API gravity and the heating value are the major factors. In a second analysis, each of the performance parameters was plotted in terms of each fuel property, and the results were then cross-referenced to isolate the pertinent properties. The effect of C.N. on I.D. is shown in Figure 5.18, and on the rate of pressure rise in Figure 5.19. Below a C.N. of 30, the increase in I.D. resulted in a high rate of pressure rise. The effect of API gravity on brake thermal efficiency is shown in Figure 5.20. The effects of API gravity on the brake horsepower are shown in Figure 5.21. It should be noted that the engine was not optimized for fuels of different distillation ranges. Accordingly, it is expected that the engine thermal efficiency and power output are not optimized for these fuels. Baker (5.9) observed that the maximum brake horsepower and brake thermal efficiency resulted from the use of fuels whose properties approximated those of the baseline diesel fuel.

The effect of viscosity on the brake thermal efficiency is shown in Figure 5.22. The effect on brake horsepower is shown in Figure 5.23. The relationship between the API gravity and the viscosity for the different blends used by Baker is given in



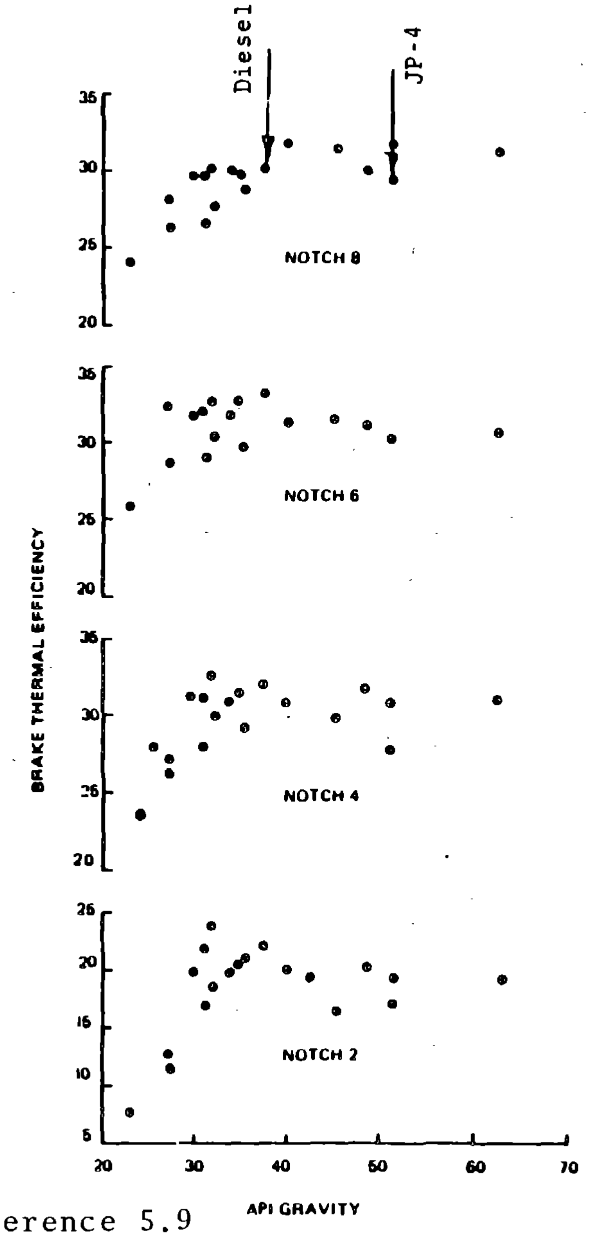
Reference 5.9

FIGURE 5-18. EFFECT OF C.N. ON I.D. FOR VARIOUS DISTILLATION RANGE FUELS.



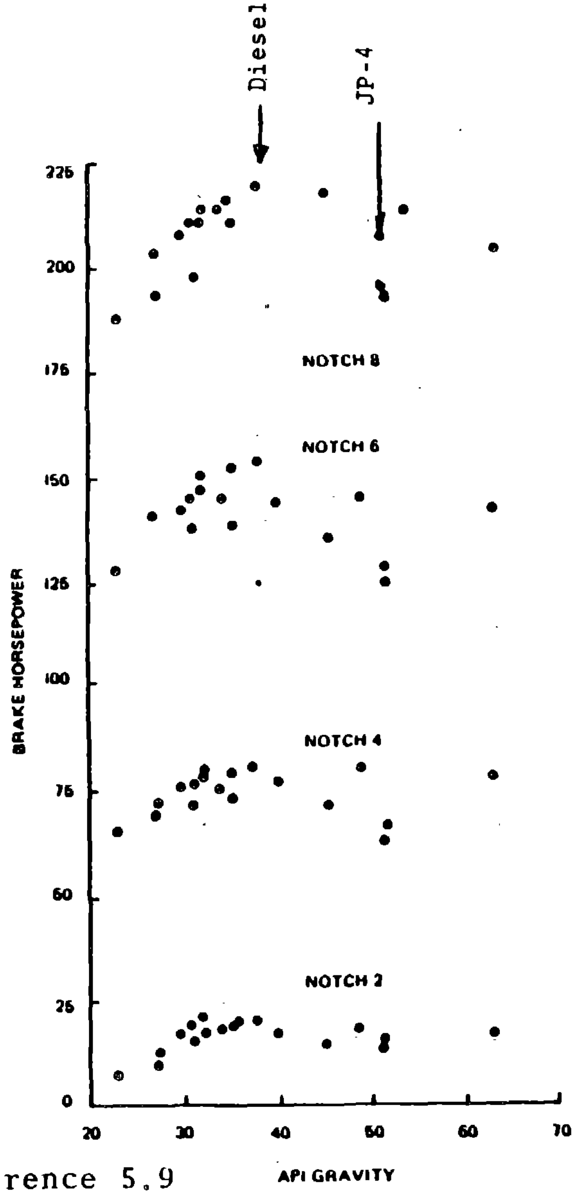
Reference 5.9

FIGURE 5.19. EFFECT OF C.N. ON RATE OF PRESSURE RISE-DISTILLATION RANGE SERIES.



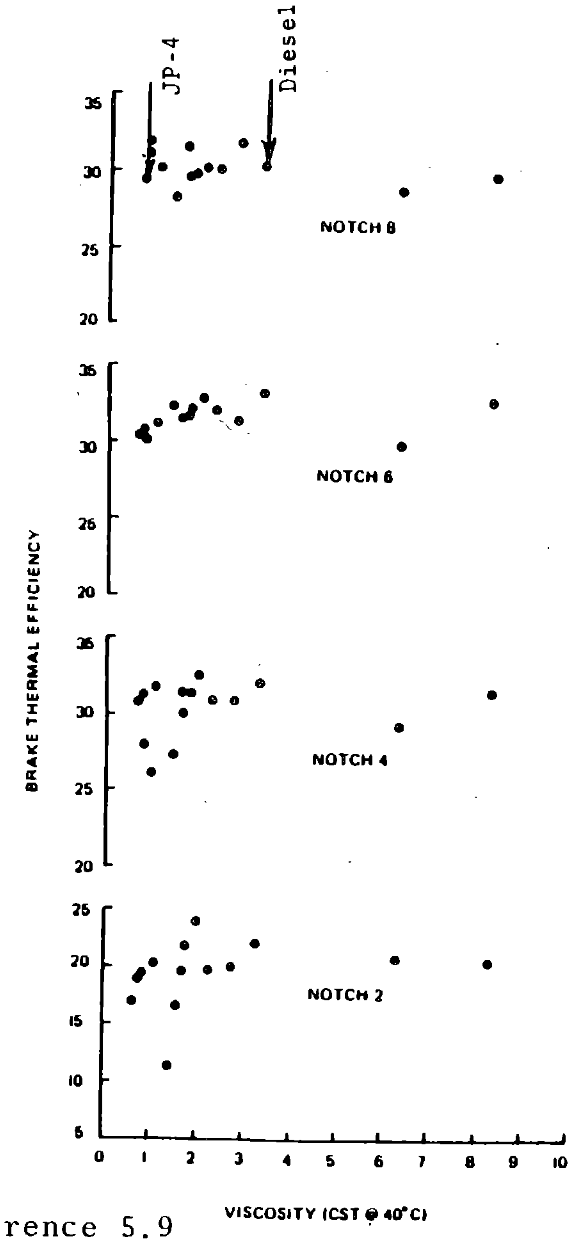
Reference 5.9

FIGURE 5.20 EFFECT OF API GRAVITY ON BRAKE THERMAL EFFICIENCY DISTILLATION RANGE SERIES



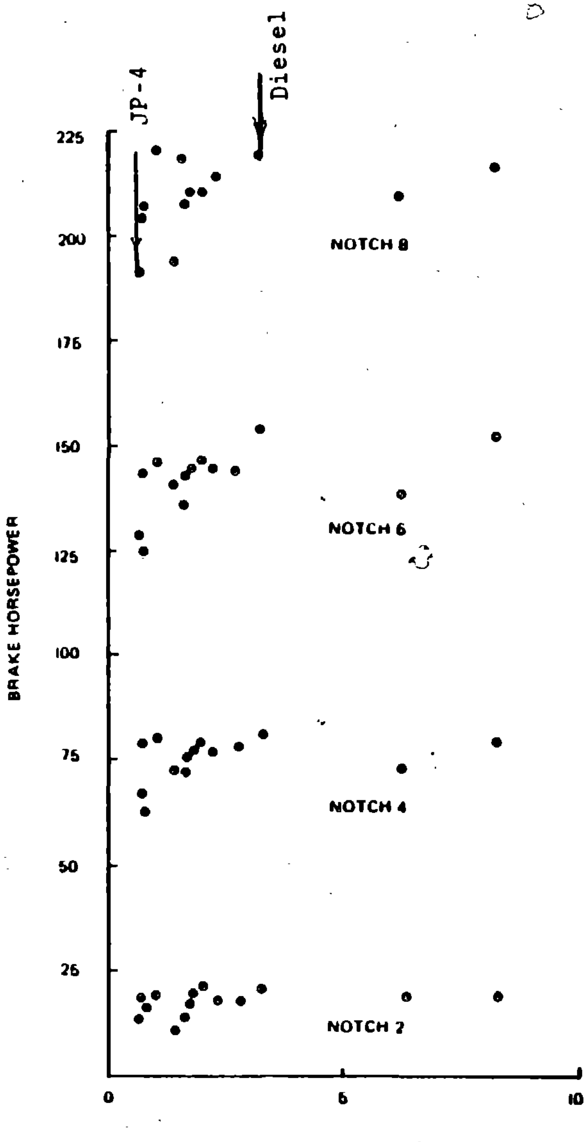
Reference 5.9

FIGURE 5.21. EFFECT OF API GRAVITY ON BRAKE HORSEPOWER - DISTILLATION RANGE SERIES



Reference 5.9

FIGURE 5.22 EFFECT OF VISCOSITY ON BRAKE THERMAL EFFICIENCY DISTILLATION RANGE SERIES



Reference 5.9

FIGURE 5.23. EFFECT OF VISCOSITY ON BRAKE HORSEPOWER DISTILLATION RANGE SERIES.

Figure 5.24. This figure shows that heavy fuels are more viscous. Accordingly, high viscosity fuels have more BTU per unit volume and, in general, should produce more power for the same volumetric rate of fuel injection.

Effect of Fuel Properties on Emissions. The effect of API gravity on the brake specific hydrocarbons is shown in Figure 5.25. In general, lighter fuels produced more hydrocarbon emissions. This is caused by the longer I.D. of the lighter fuels, in addition to their higher vapor pressure and results in more HC in the lean flame-out region of the spray.

The effect of viscosity on the brake specific hydrocarbon emissions is given in Figure 5.26. This figure shows that the fuel which has a viscosity slightly lower than diesel fuel produced less BSHC. For less viscous fuels, BSHC were higher than for diesel fuel. Fuels which are more viscous than diesel fuel produced less BSHC, particularly at the lighter loads.

The effect of viscosity on the BSHC is related to the lean flame-out region of the spray and to the fuel in the sac volume of the nozzle.

Baker reported that neither particulates nor nitric oxide emissions could be specifically defined in terms of the influence of a single fuel property. However, carbon monoxide displayed a dependence on both cetane number and total BTU input; in both cases, the trends observed were also a function of load (or notch position), as indicated in Figures 5.27 and 5.28.

Baker concluded that no single fuel property could be classified as the primary variable which affected performance and emissions when all fuel properties were allowed to vary simultaneously; rather it was the combined influence of several variables that ultimately determined engine behavior.

5.2.2 Effect of Using Fuels Derived From Tar Sands and Shale Oil

Tuteja and Clark (5.11) studied the sensitivity of a D.I., 2-stroke-cycle diesel engine to variations in fuel source. Diesel

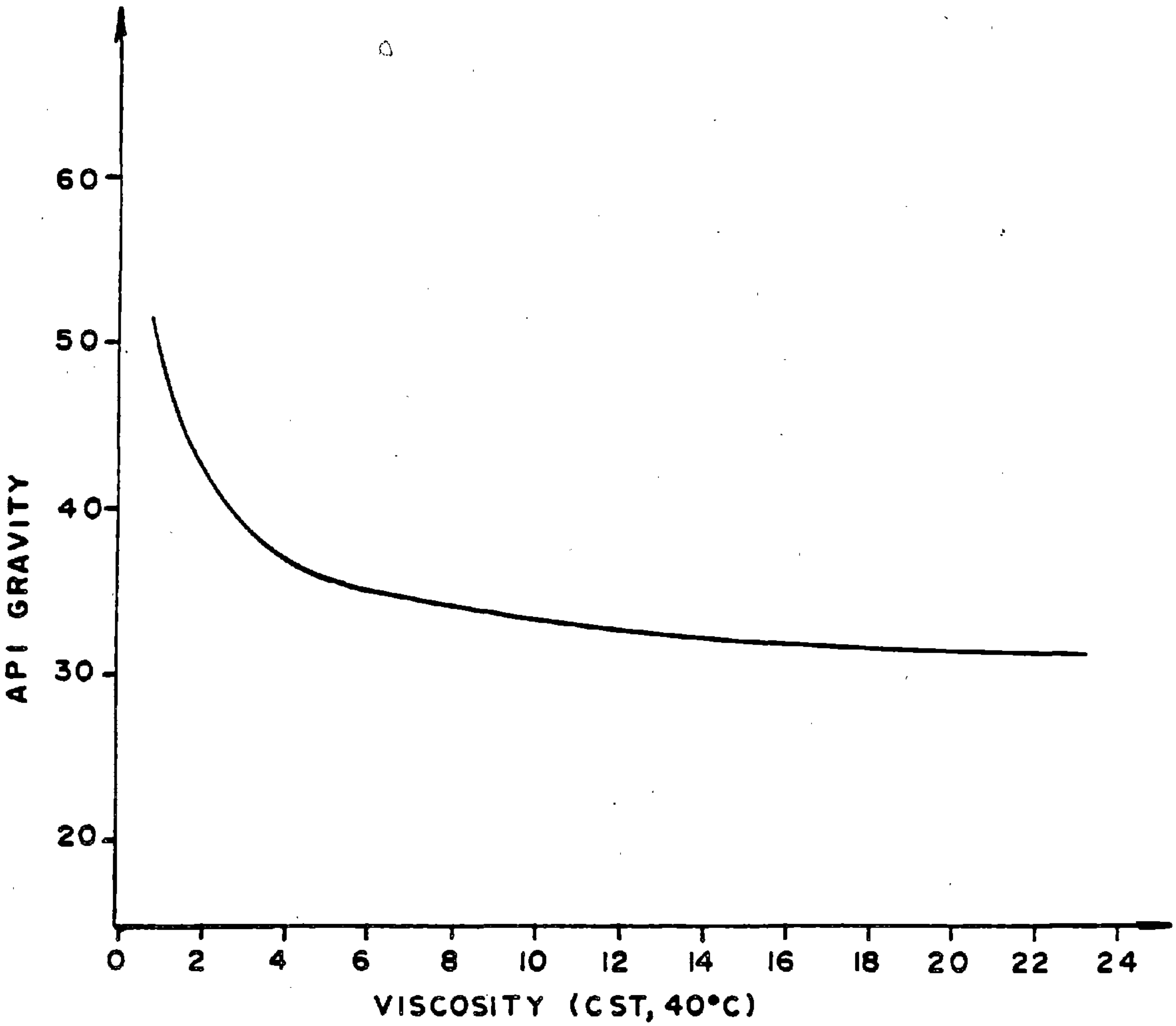
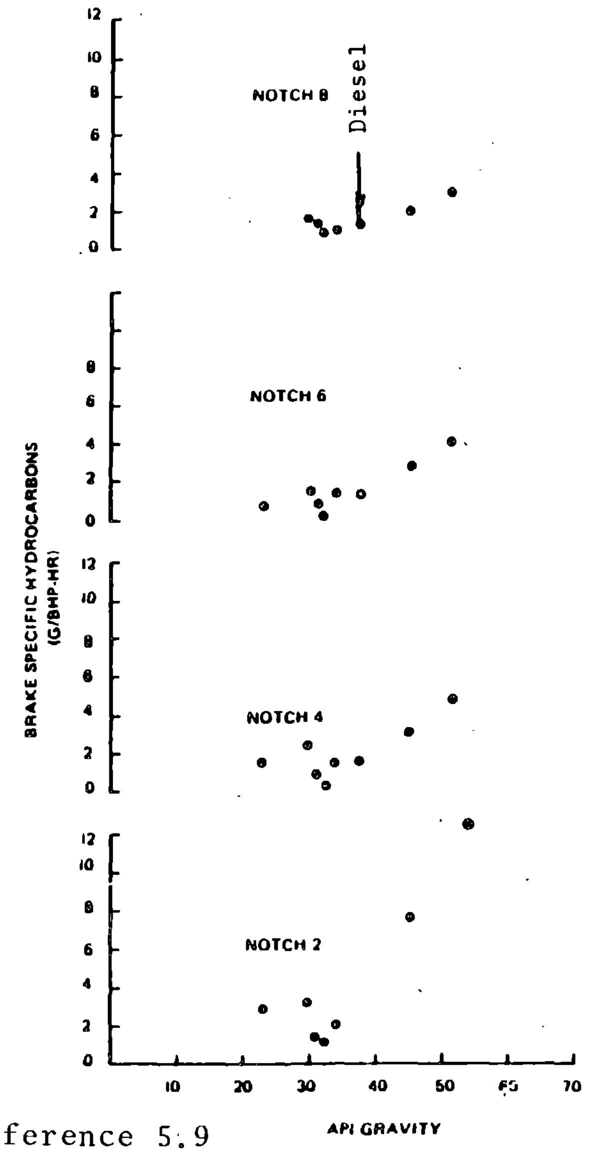
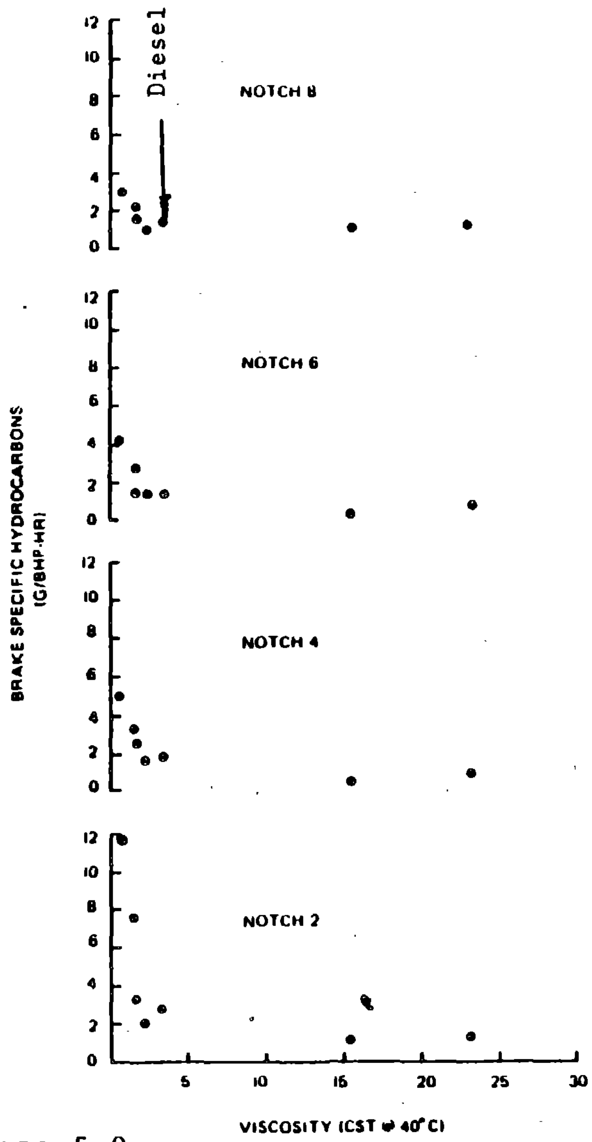


FIGURE 5.24. RELATIONSHIP BETWEEN VISCOSITY AND API GRAVITY FOR DIFFERENT DISTILLATES.



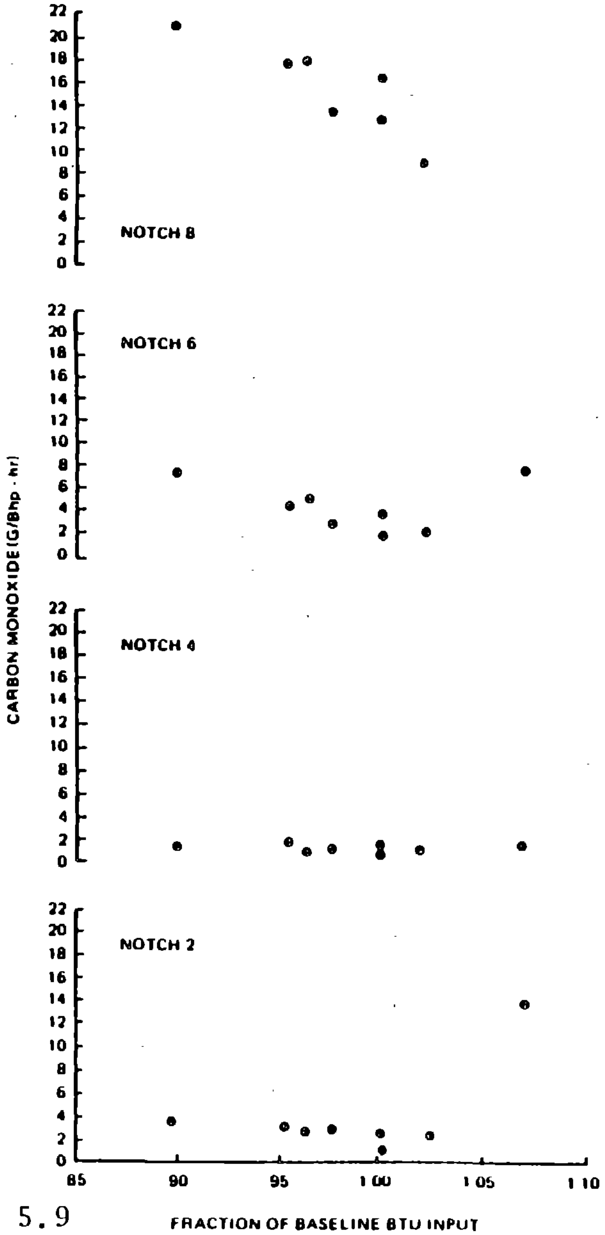
Reference 5.9

FIGURE 5.25. EFFECT OF API GRAVITY ON BRAKE SPECIFIC HC - DISTILLATION RANGE SERIES



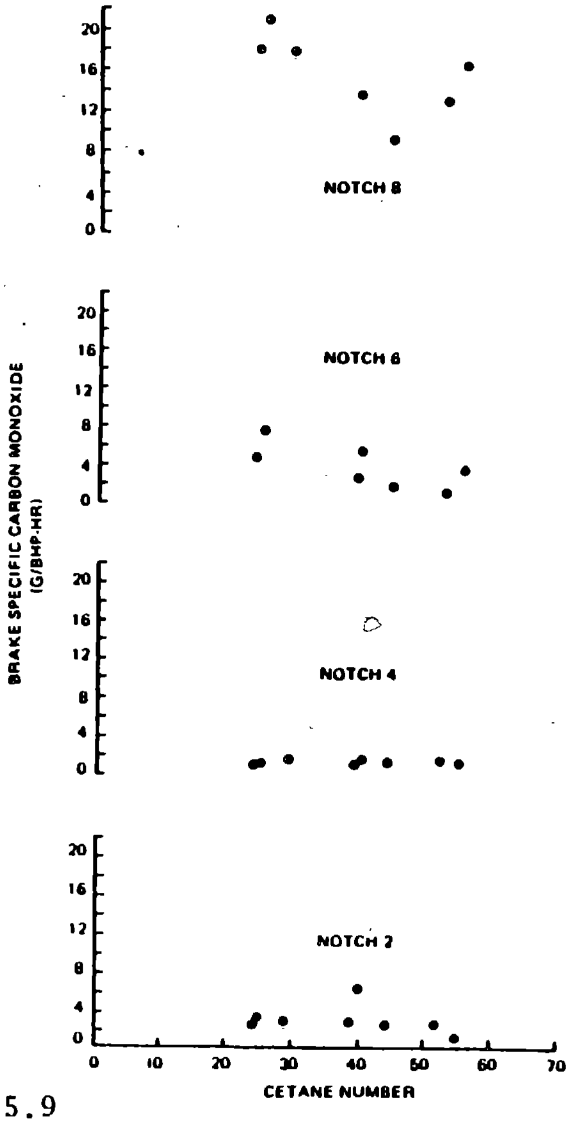
Reference 5.9

FIGURE 5.26. EFFECT OF VISCOSITY ON BRAKE SPECIFIC HC - DISTILLATION RANGE SERIES



Reference 5.9

FIGURE 5.27. EFFECT OF TOTAL BTU INPUT ON BRAKE SPECIFIC CARBON MONOXIDE EMISSIONS - DISTILLATION RANGE SERIES



Reference 5.9

FIGURE 5.28. EFFECT OF C.N. ON BRAKE SPECIFIC CARBON MONOXIDE - DISTILLATION RANGE SERIES.

fuels derived from oil shale and tar sands were compared with the commercial DF-2 diesel fuel derived from crude petroleum. The properties of these fuels are shown in Table 5.9. The DF-2 has the lowest viscosity and distillation range, while shale fuel has the highest. Tar sands fuel has the lowest cetane number, sulfur content and atomic H/C ratio while shale fuel has the highest. The fuel nitrogen content was low for regular DF-2 and tar sands fuel, but substantially higher for the shale fuel.

The engine used was a three cylinder, D.I., 18.7 C.R., naturally aspirated, 213 CID, 2-stroke-cycle diesel engine. The injectors used were of the N-60 needle valve type modified to maintain constant beginning of injection. In this work, NO was measured by using an NDIR analyzer, and NO_2 by using a long path NDUV. These values were corrected for temperature and humidity.

The effect of load on I.D. for the three fuels is shown in Figure 5.29 for three different speeds. The I.D. decreased with the increase in cetane number.

The maximum rates of pressure rise, shown in Figure 5.30 followed a trend similar to the ignition delay.

The BSFC relative to DF-2 fuel is shown in Figure 5.31 and shows a slight loss in fuel economy with the alternate fuels, particularly at the high loads. This is believed to be caused by the injection and combustion systems which were developed for the DF-2 and not for the other two fuels. For example, in this work, the injection timing was kept constant and corresponds to the I.D. of DF-2 fuel. The I.D.s for the alternate fuels are longer than for the diesel fuel and a slight advance of the injection timing would have improved the engine fuel economy.

The exhaust smoke obtained for the three fuels is given in Figure 5.32. Tar sands fuel showed the highest smoke, followed by regular DF-2, and shale fuel respectively. The differences are generally small and possibly not significant at lower speeds. At higher speeds, the fuel from tar sands produced the highest smoke. In general, smoke is related to the injection timing,

TABLE 5.9. PROPERTIES OF REGULAR DF-2 FUELS DERIVED FROM SHALE AND TAR SANDS

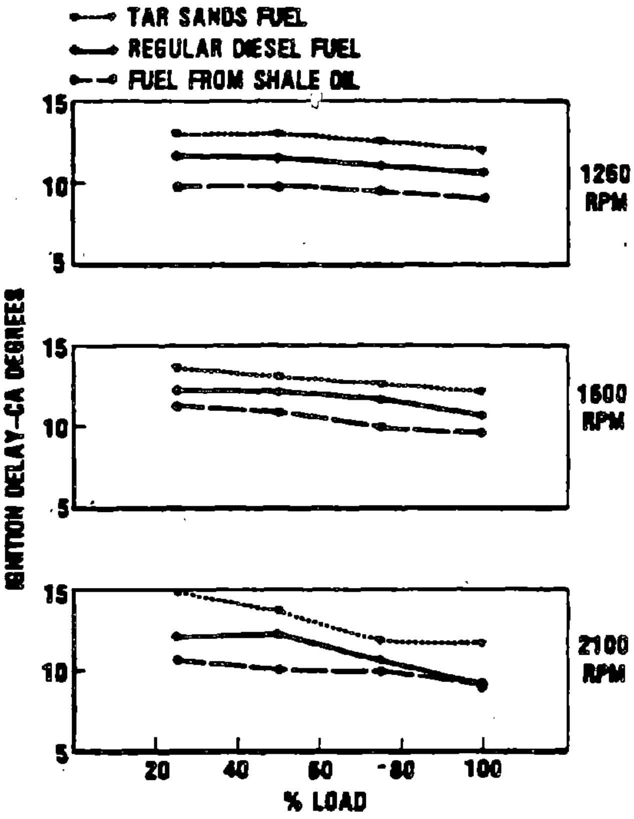
	TAR SANDS	REGULAR DF-2	SHALE MARINE
WT. %:			
S	0.16	0.25	0.50
N	0.022	0.014	0.26
C	87.64	87.34	86.02
H	12.56	12.87	12.79
Aromatic	43.6	42.6	33.7
Naphthenes	43.7	24.0	-
Olefins	0.0	0.5	-
Paraffins	12.7	32.3	-
Ash		.0016	.001
TRACE METALS/ (PPM)			
V	0.2	<.01	0.2
Na	0.3	0.6	3.6
Mg	0.9	0.1	0.7
Ca	0.2	0.1	1.2
K	<0.1	0.1	<0.1
Pb	<0.1	0.5	<0.1
OTHERS:			
Aniline Pt. (°C)	52.0	37.8	67
H/C	1.71	1.76	1.77
Cetane No.	36.8	43.0	52.2
IBP °F	358	357	410
10% °F	446	425	533
50% °F	555	509	594
90% °F	630	605	656
EP °F	658	649	681
°API	28.9	34.1	37.9
Viscosity CS at 100°F	4.35	2.50	5.58
Lower Heating Value (BTU/lb)	18133	18263	18247

TABLE 8

PROPERTIES OF FUELS USED IN N_2 DOPING TESTS

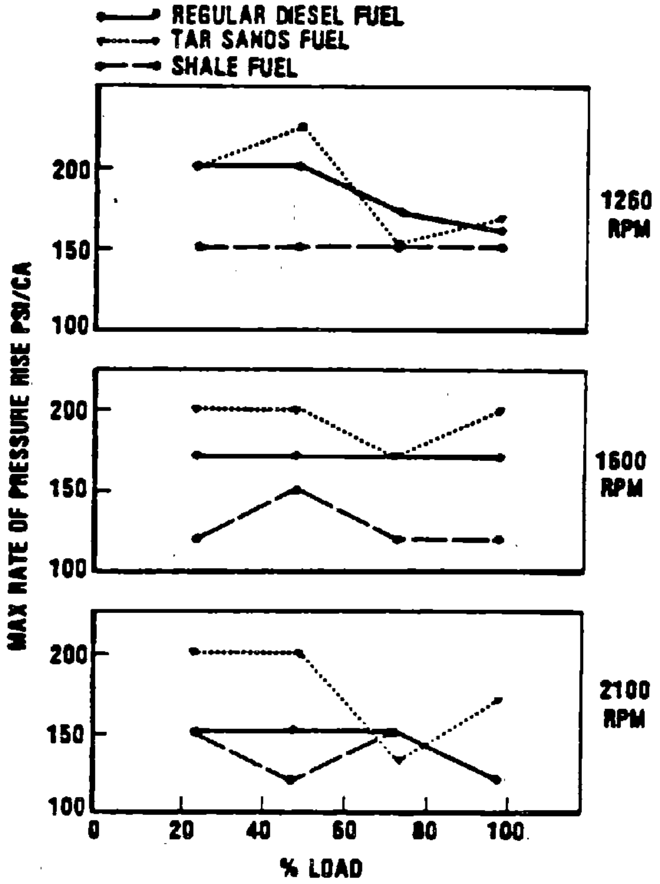
Wt. %	High Aromatic DF-2	Low Aromatic DF-2	DF-1	JP-Cetane
S	0.25	0.25	.07	.015
N	0.014 (0.96)*	0.017 (0.92)	<.005 (1.02)	<.00[illegible] (1.[illegible]
C	87.34	86.73	86.02	85.34
H	12.87	12.62	13.84	14.66
Aromatic	42.6	35.5	13.0	6.5
Naphthenes	24.0	25.3	25.1	26.0
Olefins	0.5	0.0	0.0	0.0
Paraffins	32.3	39.2	61.9	67.5
Ash	.0016	.0004	.0004	.0008
TRACE METALS/ (PPM)				
V	<.01	<.05	<.05	0.21
Na	0.6	1.2	.15	.87
Mg	0.1	0.03	.05	.55
Ca	0.1	0.23	.09	.09
K	0.1	0.03	.02	.03
Pb	0.5	0.25	0.37	.21
OTHERS:				
Aniline Pt. (°C)	37.8	52	68	70
H/C	1.76	1.73	1.92	2.05
Cetane No.	43.0	45.0	51.6	53.9
IBP °F	357		374	168
10% °F	425	402	396	236
50% °F	509	472	419	373
90% °F	605	558	468	524
EP °F	649		514	536
°API	34.1	35.8	42.9	53.6

* Values in ( ) are Kjeldahl nitrogen analyses for 1.0% pyridene doped fuels.



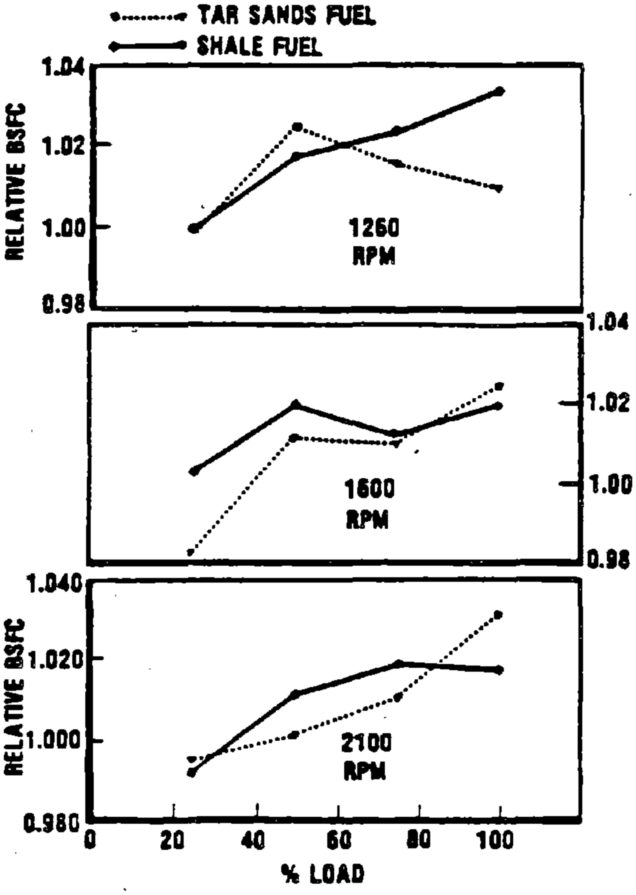
Reference 5.11.

FIGURE 5.29. COMPARISON OF I.D. WITH REGULAR DIESEL FUEL AND FUELS DERIVED FROM SHALE AND TAR SANDS.



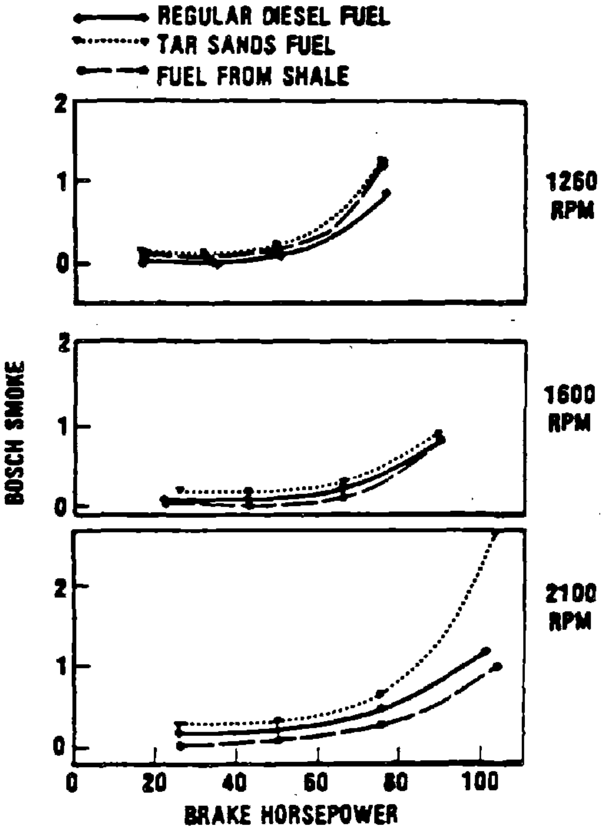
Reference 5.11.

FIGURE 5.30. COMPARISON OF MAXIMUM RATE OF PRESSURE RISE WITH REGULAR DIESEL FUEL AND FUELS FROM SHALE AND TAR SANDS.



Reference 5.11.

FIGURE 5.31. BSFC WITH SHALE AND TAR SANDS FUELS RELATIVE TO REGULAR FUEL.



Reference 5.11.

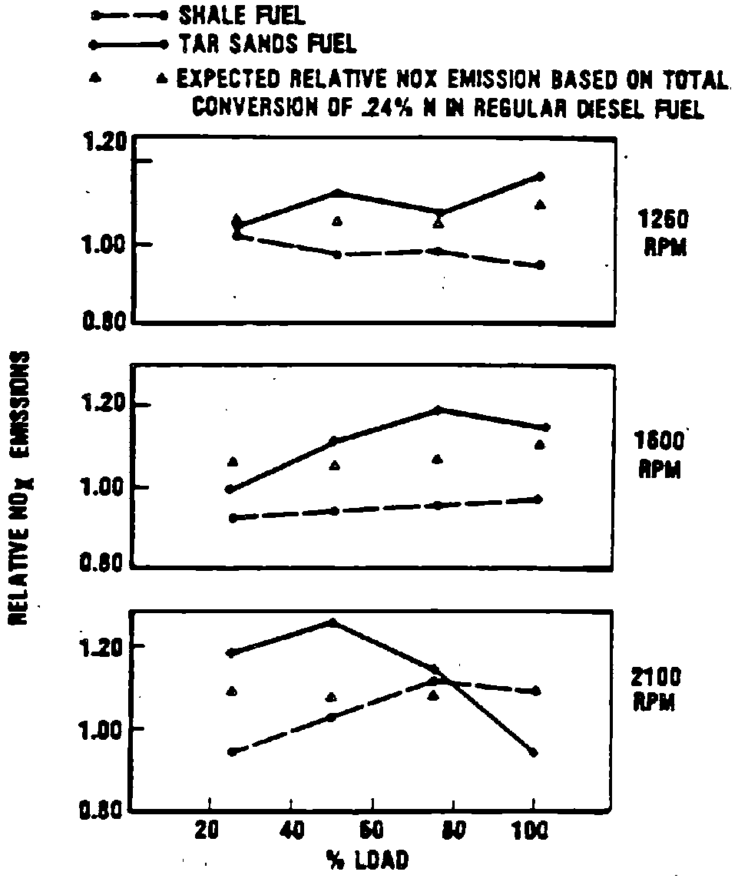
FIGURE 5.32. COMPARISON OF SMOKE WITH REGULAR DIESEL FUEL AND FUELS DERIVED FROM SHALE AND TAR SANDS.

injection pressure, 95 percent, and aromatic contents. Table 5.9 indicates that the fuel from tar sands has an aromatic content slightly higher than DF-2 and much higher than the shale-derived fuel. The 95 percent point does not indicate a trend in these tests. It appears that the reason for the highest smoke with the fuel from tar sands is related to the unoptimized injection timing. The longer ignition delay with this fuel, without advancing the timing allows the combustion to take part later in the expansion stroke and result in higher smoke concentrations.

The NO_x emissions are given in Figure 5.33 for the two fuels relative to DF-2 fuel. In general, over the speed range, NO_x emissions were highest with tar sands fuel, and least with the shale fuel, except at full load at the highest speed. The difference between DF-2 and shale fuel is small. However, the difference between NO emissions from regular DF-2 and tar sands fuels is significant. The differences between the two fuels which contribute to the high NO_x emissions are: (i) the lower cetane number of tar sands fuel, which results in longer I.D., and premixed combustion, (ii) the slightly higher aromatic content of the tar sands fuel as compared to that of DF-2 and the resulting higher combustion temperature, (iii) the higher nitrogen content of the tar sands fuel as compared to that of DF-2.

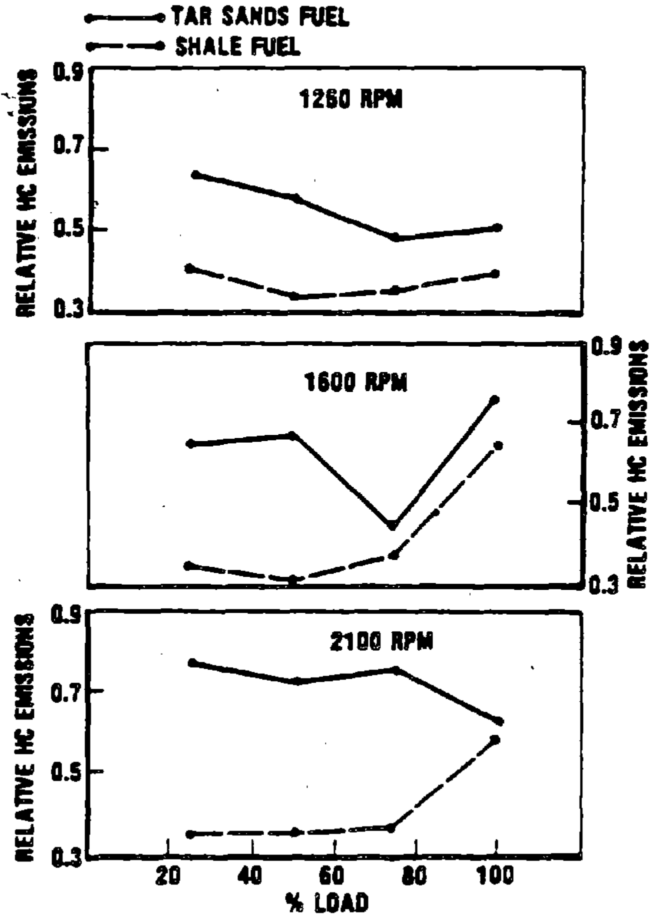
The unburned hydrocarbons from the tar sands fuel and shale fuel are given by Tuteja and Clark (5.11) in Figure 5.34, relative to the hydrocarbons from DF-2. The HC emissions with tar sands fuel are about 60-70 percent of HC emissions with regular DF-2, whereas, with shale fuel, these emissions are about 30-40 percent of those with regular DF-2, over all the speed and load ranges. The factors that might have contributed to the lower HC emissions from the alternate fuels are related to the higher viscosity and 50 percent points of these fuels, which reduces the HC related to the volume of fuel in the sac and injection nozzle.

The CO emissions are shown in Figure 5.35 for the alternate fuels relative to the CO from the regular DF-2. In general, tar sands fuel shows the highest CO followed by regular DF-2 and shale



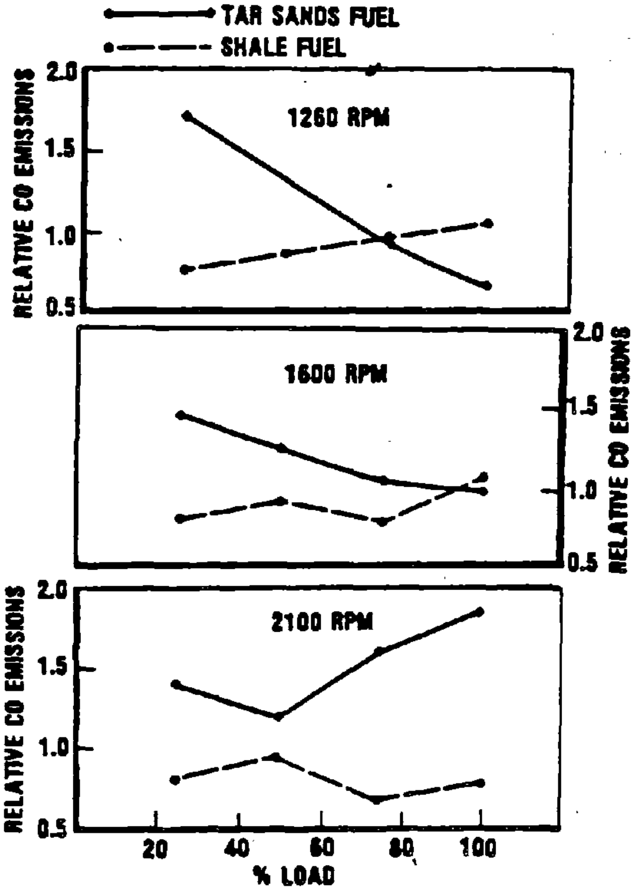
Reference 5.11.

FIGURE 5.33. NO_x EMISSION BY MASS WITH SHALE AND TAR SANDS FUELS RELATIVE TO REGULAR DIESEL FUEL



Reference 5.11

FIGURE 5.34. HC EMISSIONS BY MASS WITH TAR SANDS FUEL RELATIVE TO REGULAR DIESEL FUEL.



Reference 5.11.

FIGURE 5.35. CO EMISSION BY MASS WITH SHALE AND TAR SANDS FUELS RELATIVE TO REGULAR DIESEL FUEL.

fuel. The factors which contributed to this behaviour are related to the cetane number of the fuel. According to Broering and Holtman (5.12), and Gross and Murphy (5.13), CO increases with the increase in the 90 percent distillation point.

Tuteja, et. al., observed no significant contribution due to fuel bound nitrogen in NO emissions. Their tests were conducted at an injection timing of 18.6° BTDC, and they attributed the insignificant N conversion due to NO attaining its equilibrium concentration in the main NO producing regions. However, at relatively retarded timing necessary for low emission engines, significant conversion of fuel bound nitrogen might take place.

5.3 I.D.I. SWIRL TYPE 4-STROKE-CYCLE ENGINE

5.3.1 Effect of Fuel Properties on Fuel Economy and on Particulates and Other Emissions

Many attempts have been made to find out which constituents of the fuel (i.e. paraffins, aromatics or olefins) were most responsible for particulates.

Burley and Rosebrock (5.14) reported the results of a carbon-14 fuel tracer study, in which radioactive C-14 tagged fuel constituents were blended, one at a time, with the standard baseline D-2 fuel. These fuels were run in a 2.1 liter I.D.I. 4 cylinder Opel engine, modified to run on one cylinder. All the particulates were collected on an 8 x 10 inch filter mounted in a tunnel and analyzed for the presence of C-14. Tests were at the equivalent of 25 mph road load and 55 mph road load for each fuel.

The petroleum compounds used in C-14 fuel tracer studies are shown in Table 5.10. The quantity of C-14 compound added to the test fuel was so small that the general physical properties of the fuel were unchanged. The results of these tests, given in Figure 5.36, show the following:

1. Each of the compounds (paraffins, olefins and aromatics) made a contribution to particulates.

TABLE 5.10. PERFORMANCE IMPACT OF ETHANOL FUELING

COMPOUND	CARBON NUMBER	FORMULA & STRUCTURE
DECANE	C-10	$CH_3-(CH_2)_8-{}^{14}CH_3$
HEXADECANE	C-16	$CH_3-(CH_2)_{14}-{}^{14}CH_3$
OCTADECANE	C-18	$CH_3-(CH_2)_{16}-{}^{14}CH_3$
DECENE	C-10	$CH_2=CH-(CH_2)_7-{}^{14}CH_3$
ORTHO METHYL XYLENE	C-8	
1-METHYLNAPHTHALENE (RING LABEL)	C-11	
1-METHYLNAPHTHALENE (METHYL LABEL)	C-11	

Reference 5.1.

2. Particulate emissions from the paraffins were independent of boiling point over the range 174°C to 317°C.

3. Aromatics, as a group, were the greatest contributors to particulates. The ring-labeled 1-methyl naphthalene was the largest contributor.

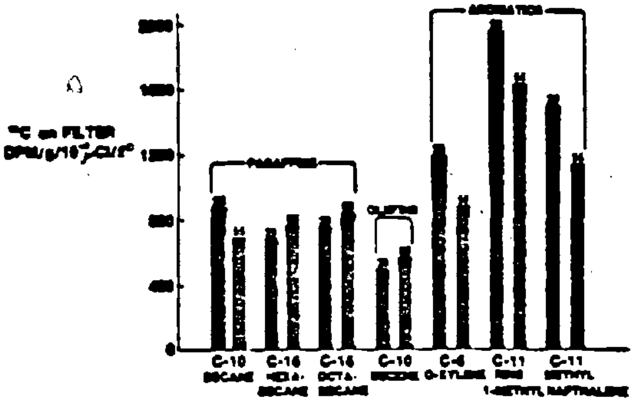
4. Most of the C-14 appeared in the insoluble fraction. Less than 20 percent appeared in the soluble fraction.

In another extensive study, Burley and Rosebrock found the effect of fuel composition on fuel economy and emissions. Forty-six fuels including D-1 and D-2 fuels were tested. The range of distillation characteristics of these fuels is shown in Figure 5.37. The engine used was an Oldsmobile, 5.7 liter, I.D.I. V-8, 4-stroke-cycle, C.R. = 22.5:1 light duty diesel, with C.A.V. poppet-type injectors. Each fuel was tested at the standard timing, 5 engine degrees advance, and 5 engine degrees retard. The tests were conducted under steady state conditions at 5 speed-torque points in the FTP cycle, and a weighting factor applied to calculate the performance and emission parameters. Particulates were collected from the exhaust of one cylinder diluted in a 300 CFM constant volume tunnel. The sampling time was 20 minutes at each point. The HC and NO_x emissions and the fuel economy were also measured.

The physical properties of the fuels and their range are shown in Table 5.11.

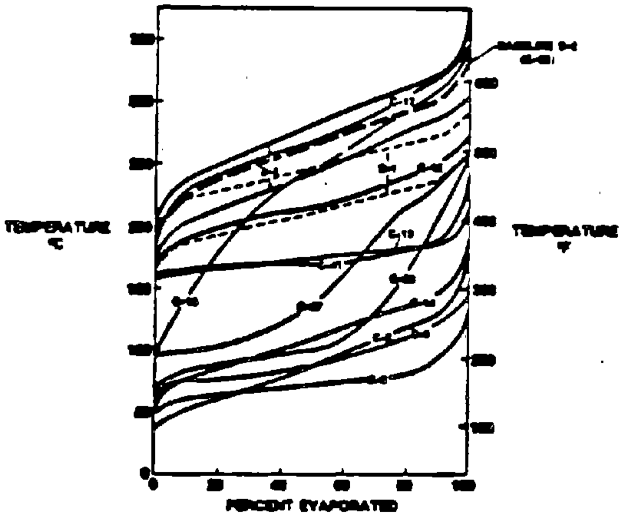
TABLE 5.11. PHYSICAL PROPERTIES OF G.M. STUDY FUELS

Physical Property	Range of Test Fuels
Specific Gravity	0.678 - 0.879
Viscosity	0.50 - 3.5 CS at 40°C
10% Boiling Point	48 - 233°C
50% Boiling Point	71 - 267°C
90% Boiling Point	92 - 365°C
Cetane Number	21 - 80
Aromatic Content	0 - 95%
API Gravity	27.13 - 77.20
Sulfur Content	0.002 - 1.25%



Reference 5.14.

FIGURE 5.36. CONTRIBUTION OF VARIOUS COMPONENTS OF DIESEL FUEL TO PARTICULATE EMISSIONS.



Reference 5.14.

FIGURE 5.37. DISTILLATION RANGE OF SOME OF THE FUELS TESTED.

A multiple linear stepwise regression analysis was employed to relate the fuel properties to the various emissions, and fuel economy.

5.3.2 Effect of Fuel Properties on Particulates

The regression analysis showed the following:

1. Aromatic content and 90 percent boiling point were the fuel properties most closely related to particulates, as shown in Figures 5.38 and 5.39.

2. Fuel volatility factors such as the 10 percent and 50 percent boiling point showed a weaker correlation to particulates than the 90 percent boiling point.

3. Particulate emissions increased with addition of cetane improvers to the light fuels.

4. A typical D-1 fuel produces 25 percent less particulate emissions than D-2 fuel.

Burley and Rosebrock tested a light, narrow distillation range, low aromatic fuel (C-40) in two vehicles on the FTP cycle. The vehicles were equipped with 5.7 liter engines similar to the ones used in the fuel test program conducted on the dynamometer. The injectors in the engines were conventional two-hole pencil injectors rather than the CAV poppet type injectors previously used. The properties of the C-40 fuel are given in Table 5.12 together with those for D-1 and D-2 fuels. The particulates formed on the FTP cycle from the C-40 fuel are reduced to 57.4 percent of those from the regular D-2 fuel (Table 5.13).

Burley and Rosebrock (5.14) studied the effect of aromatics on the 5.7 liter Oldsmobile diesel engine on a dynamometer under 5 different steady load-speed points with the two-hole, pencil-type injectors. The armoatic contents of the fuel were changed

TABLE 5.12. PROPERTIES OF D-1, D-2 & C-40

	C-11 Diesel No. 1	C-28 Diesel No. 2	C-40 Low Aromatic Narrow Distillation Range Fuel
Distillation:			
BIP	170.5	179.0	209.0
10%	201.0	221.5	214.5
50%	226.0	256.0	221.5
90%	254.0	303.0	232.5
EP	276.0	333.5	244.0
Gravity, °API	41.69	36.35	49.91
Cetane No.	49.0	44.5	36
Sulfur, Wt%	0.23	0.32	0.005
Flash Point, °C	76.7	93.3	85
Viscosity at 40°C	1.75	2.40	2.15
Gum, mg/100 ml	-	-	-
Paraffins %	79	68	96
Olefins %	4	4	2
Aromatics %	17	28	2
H/C	1.9	1.79	2.11
Specific Gravity	0.817	0.843	0.780
Energy, MJ/kg	46.28	46.33	46.16

TABLE 5.13 PARTICULATES WITH D-2 AND C-40 FUELS - FTP CYCLE.

Diesel No. 2	0.826 grams/mile
C-40	0.474 grams/mile

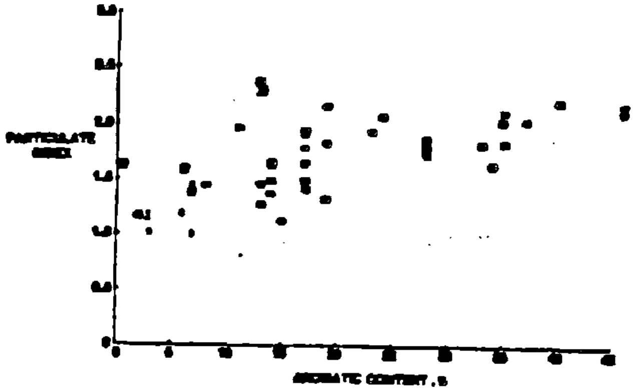
by blending various amounts of 95 percent aromatic fuel (C-42: solvent #150) to D-2 fuel. The results given by Burley and Rosebrock are shown in Figure 5.40. From this figure, it is noted that:

1. Increase in the aromatic contents up to 55 percent had little effect on the particulates and hydrocarbons. Above 55 percent, the particulates and hydrocarbons increased at a very high rate.
2. NO_x increased continuously with the increase in the aromatic contents.
3. The increase in aromatic contents improved the fuel economy (on a volume basis) up to an aromatic content of 45 percent, above which there was no effect.

In another test, Burley and Rosebrock (5.14) found the effect of increasing the aromatic content of the fuel by blending the 95 percent aromatic product (C-42) with the low aromatic narrow distillation range fuel (C-40). The tests were at steady state at 5 speed-torque points of the FTP cycle. The results are shown in Figure 5.41.

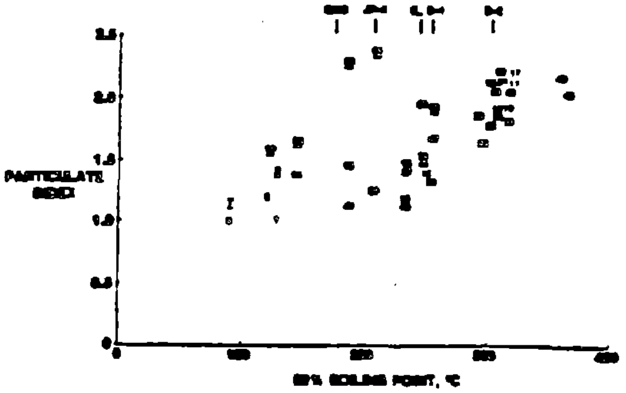
The NO_x, HC and particulates increased steadily with increasing aromaticity, while the fuel consumption remained relatively constant on a volume basis in spite of a density change.

Burley and Rosebrock concluded that the soluble content of the particulates did not correlate well with fuel properties. Soluble contents tend to decrease as cetane number increases. Also, the hydrocarbons decrease with the increase in specific gravity, viscosity, 90 percent boiling point and cetane number. The NO_x did not correlate well with the fuel properties, but appeared to decrease with the drop in the aromatic content, specific gravity, and 90 percent boiling point. The fuel economy, on a work done per



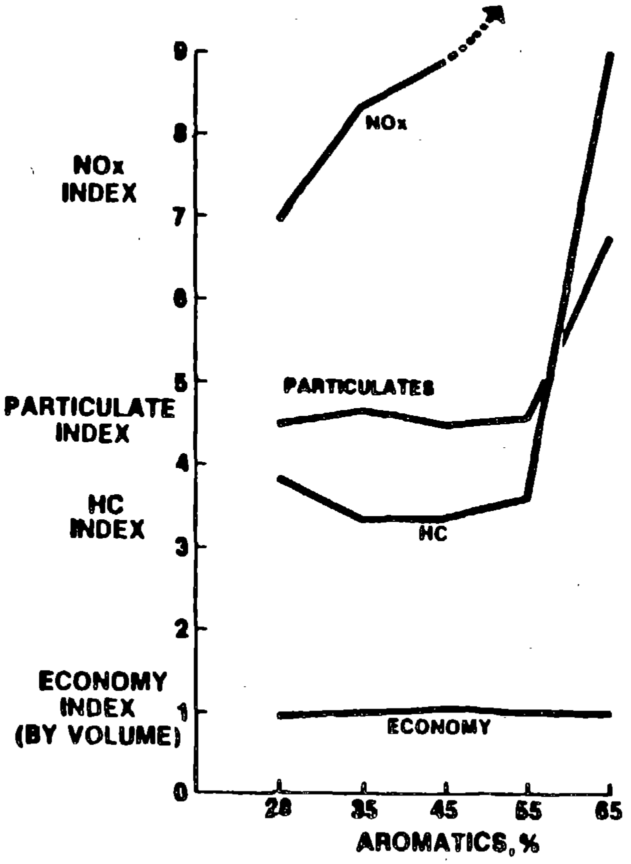
Reference 5.14.

FIGURE 5.38. PARTICULATE INDEX IN ARBITRARY UNITS VS. FUEL AROMATIC CONTENT.



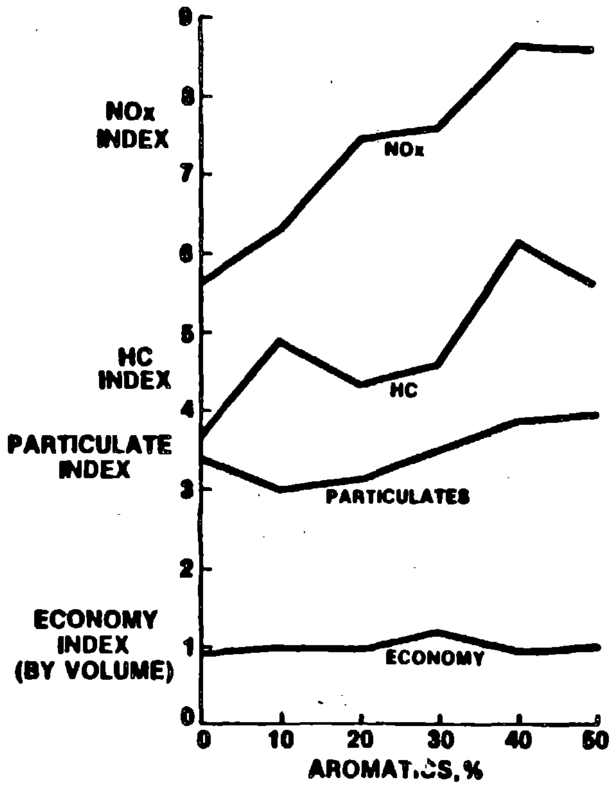
Reference 5.14.

FIGURE 5.39. PARTICULATE INDEX IN ARBITRARY UNITS VS. FUEL 90% BOILING POINT.



Reference 5.14.

FIGURE 5.40. EMISSIONS AND ECONOMY VARIATION WITH FUEL BLENDS OF INCREASING AROMATICITY AND SPECIFIC GRAVITY STARTING WITH D-2 FUEL.



Reference 5.14.

FIGURE 5.41. EMISSION AND ECONOMY VARIATION WITH FUEL BLENDS OF INCREASING AROMATICITY AND SPECIFIC GRAVITY STARTING WITH LOW-AROMATIC NARROWCUT PRODUCT

unit volume basis, improved with the increase in specific gravity, 90 percent boiling point, cetane number and viscosity.

5.4 DIESEL EMERGENCY BLENDS

Similar to the gasoline emergency blends discussed in section 4.4 of this report, diesel blends were tested by Russell et.al. (4.16) and the results reported in the "Emergency Fuels Utilization Guidebook". The tests were conducted on a DD4-53 Detroit diesel 2-stroke-cycle engine, and LD-465-1 multifuel engine. The diesel extenders are listed in Table 5.14. The indexes used in this section are the same as those in Section 4.4 except for the BSDC.

$$BSDC = BSFC \times w_{diesel}$$

where

$$BSDC = \text{Brake specific diesel consumption}$$

$$w_{diesel} = \text{mass fraction of diesel fuel} = \frac{\text{mass of diesel fuel}}{\text{mass of blend}}$$

5.4.1 Effect on Cetane Number

The effect of blending diesel fuel with different extenders on C.N. is shown in Figure (5.42). All the extenders used decreased the C.N. except No. 4 fuel oil which resulted in a slight increase in C.N. The worst extender is gasoline which resulted in a sharp decrease in C.N.

5.4.2 Effect on API Gravity

Figure 5.43 shows that all the extenders used by Russell et.al., (4.16), except No. 6 fuel oil and South Texas sour crude, increased the API gravity of the blend.

5.4.3 Effect of Heat on Combustion

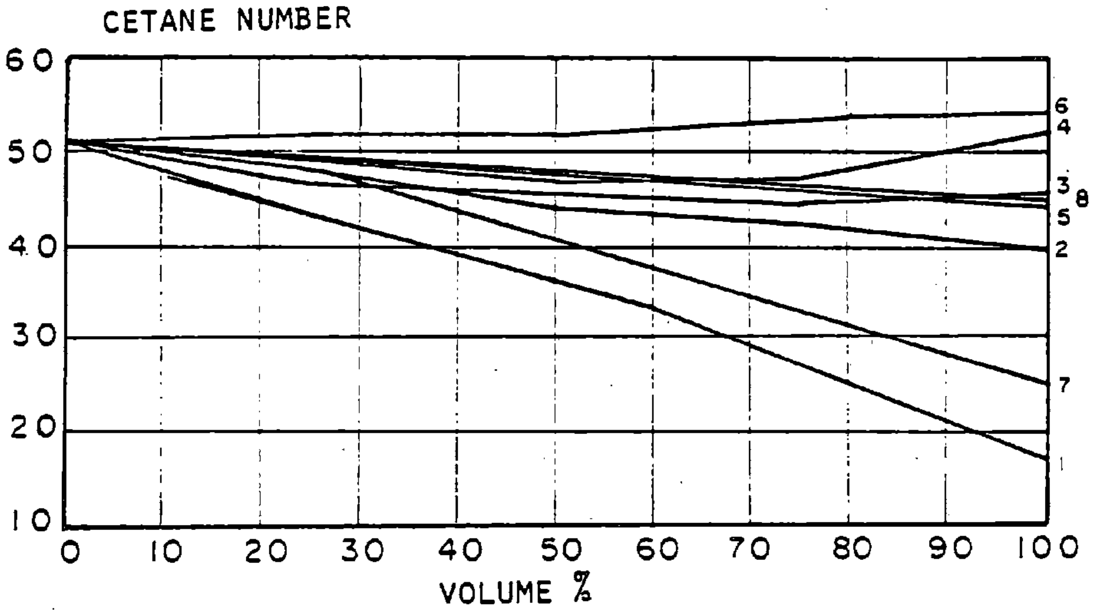
Figure 5.44 shows that all the extenders used increased the heat of combustion except No. 6 fuel oil.

TABLE 5.14. EMERGENCY DIESEL EXTENDERS

1.	Gasoline	
2.	Ethanol	Alcohol
3.	Medium Naphtha	Solvent
4.	Heavy Naphtha	
5.	Jet A	Jet Fuel
6.	Jet A-1	
7.	Kerosene	Kerosene (Solvent)
8.	No. 4 Fuel Oil	Heating Oil
9.	No. 5 Burner Oil	Residual Fuel
10.	No. 6 Fuel Oil	
11.	TX Sour	Crude Oil
12.	LA Sweet	
13.	CA Sour	
14.	UT Sweet	
15.	Peanut Oil	Vegetable Oil
16.	Soy Oil	
17.	Sunflower Oil	
18.	Corn Oil	

The reference fuel used is neat baseline fuel (CAT 1 H reference diesel fuel).

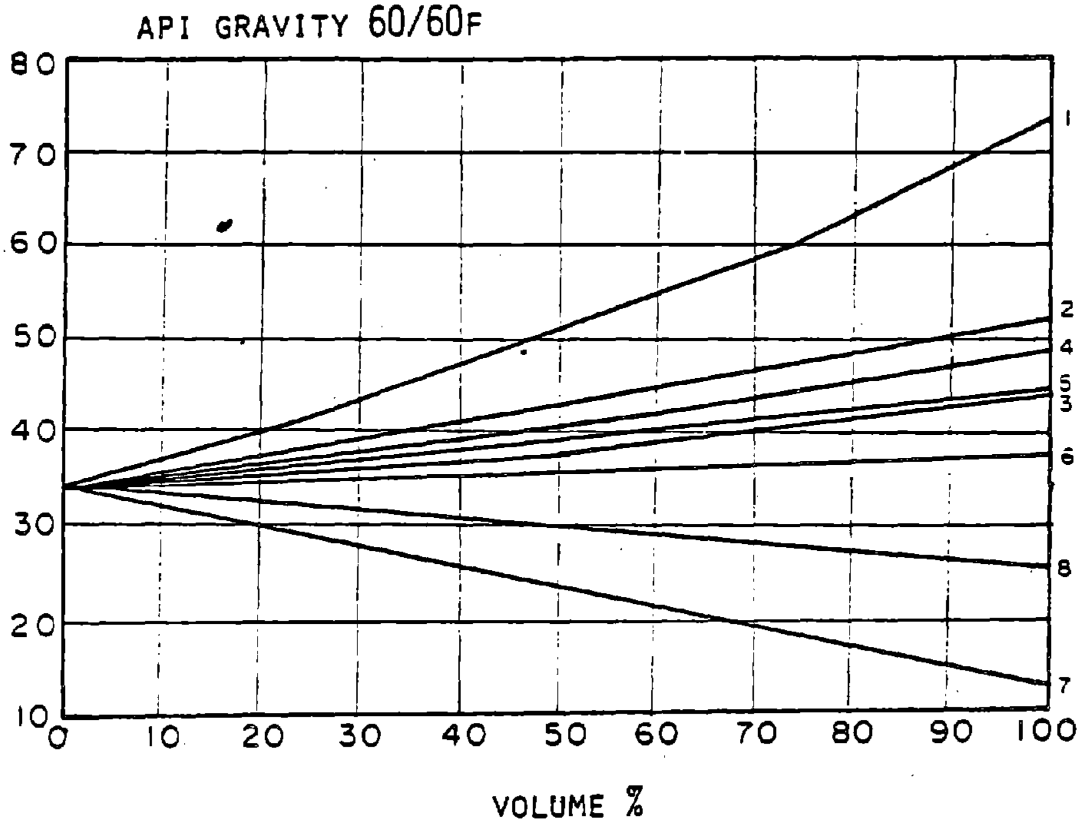
Reference 4.16.



1 Extender = Gasoline
2 = Medium Naphtha
3 = Jet A
4 = Jet A-1
5 = Kerosene
6 = No. 4 Fuel Oil
7 = No. 6 Fuel Oil
8 = South Texas Sour Crude

Reference 4.16.

FIGURE 5.42. EFFECT OF DIESEL EXTENDERS ON C.N.



1 Extender = Gasoline
2 = Medium Naphtha
3 = Jet A
4 = Jet A-1
5 = Kerosene
6 = No. 4 Fuel Oil
7 = No. 6 Fuel Oil
8 = South Texas Sour Crude

Reference 4.16.

FIGURE 5.43. EFFECT OF DIESEL EXTENDERS ON API GRAVITY

5.4.4 Effect on Viscosity

Figure 5.45 shows that all the extenders used reduced the viscosity of the blend except No. 6 fuel oil and South Texas sour crude.

5.4.5 Effect on Power Index

Figure 5.46 shows that all the extenders used reduced the power index at concentrations higher than 65 percent. The gasoline and ethanol caused the sharpest drop in power index at all concentrations. Some extenders, such as No. 6 fuel oil resulted in a slight increase in the power index at concentrations less than 65 percent.

5.4.6 Effect on Conservation Index

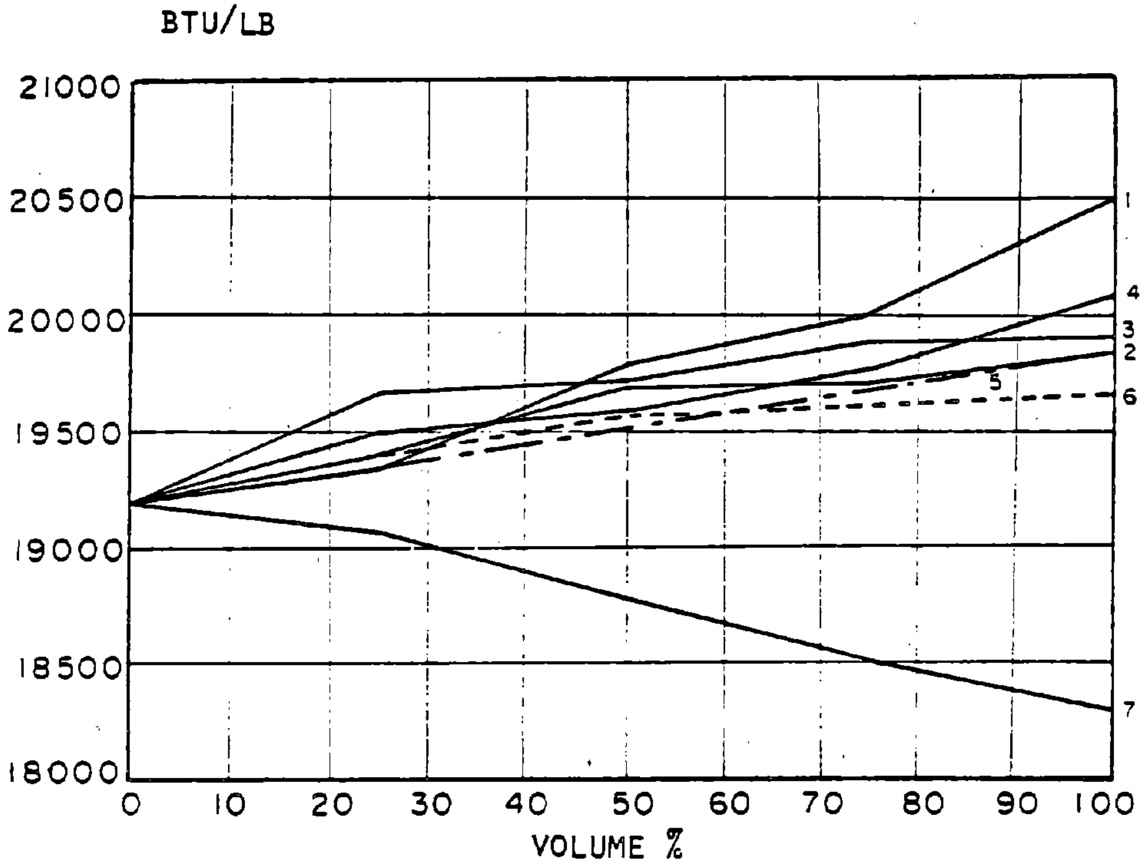
Figure 5.47 indicates that extending the diesel fuel with any extender results in an increase in the conservation index.

5.4.7 Effect on Tradeoff Index

Figure 5.48 indicates that the tradeoff index increases with all the extenders, except with gasoline at concentrations higher than 60 percent.

5.4.8 Effect on Emissions Indexes

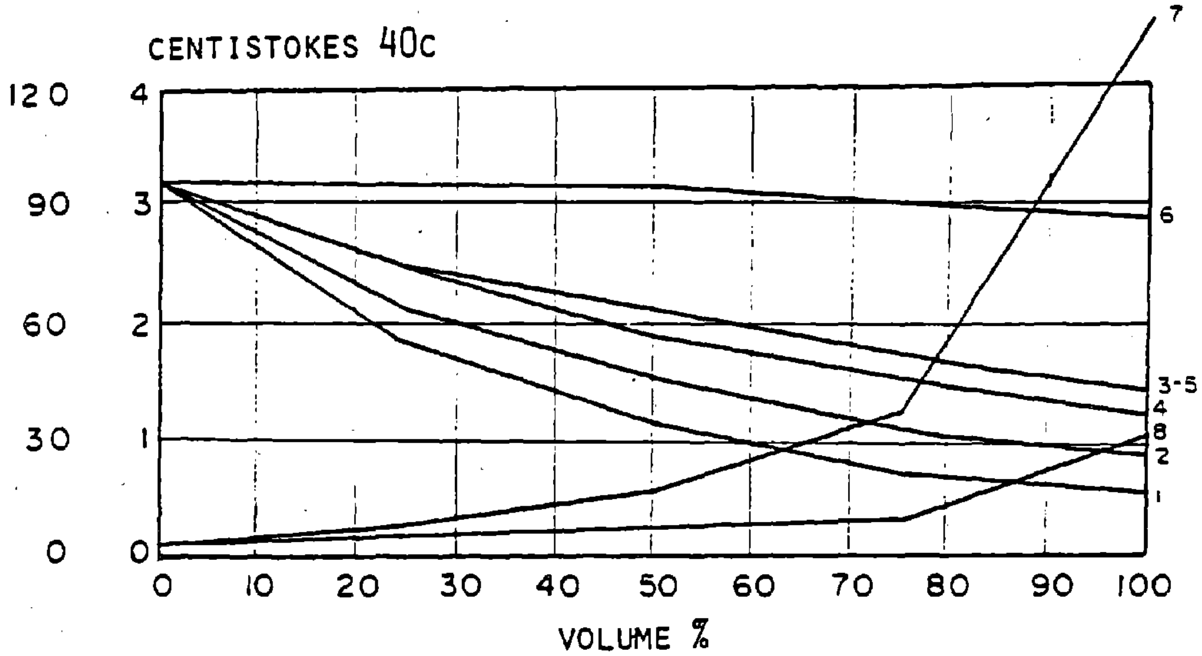
The effect of blending diesel fuel with different extenders is shown in Figure 5.49 for hydrocarbons, Figure 5.50 for CO, Figure 5.51 for NO_x, and Figure 5.52 for smoke. It is clear from these figures that the hydrocarbons are the most sensitive, and increase with the use of extenders. The CO increases when heavier fuels such as No. 6 fuel oil, No. 5 burner oil, No. 4 fuel oil, and heavy naphtha fuels, are used. The NO_x index increases with the lighter fuels, and remains almost constant with the heavier fuels. The smoke index decreases with gasoline and ethanol, and tends to increase with the heavier fuels.



1 Extender = Gasoline
2 = Medium Naphtha
3 = Jet A
4 = Jet A-1
5 = Kerosene
6 = No. 4 Fuel Oil
7 = No. 6 Fuel Oil

Reference 4.16.

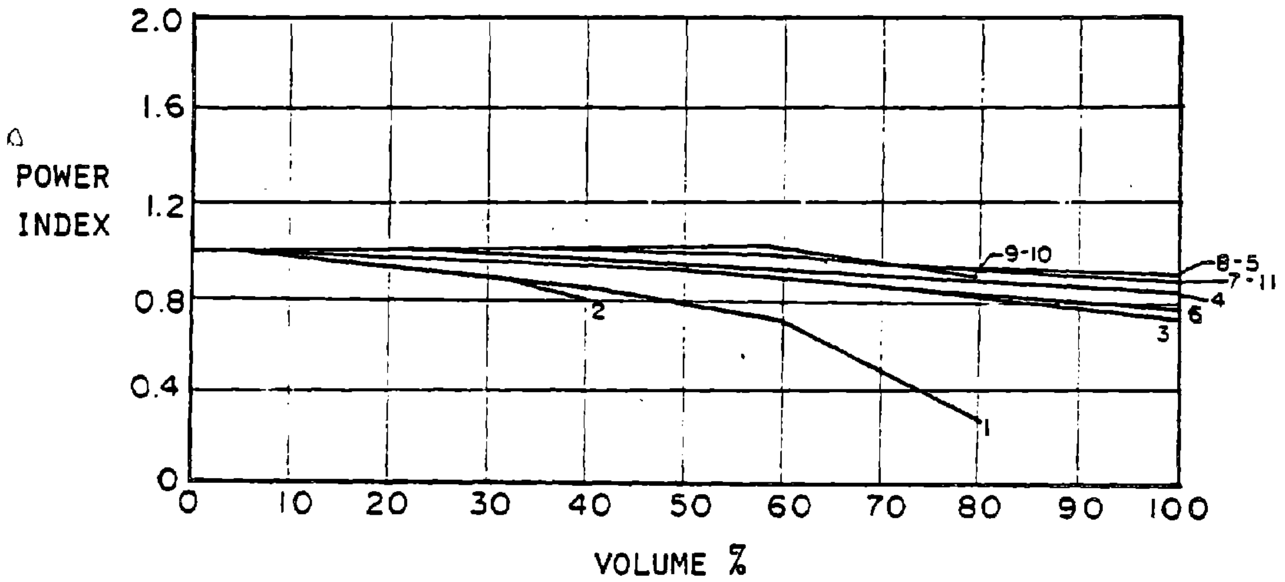
FIGURE 5.44. EFFECT OF DIESEL EXTENDERS ON THE HEAT OF COMBUSTION



1 Extender = Gasoline
2 = Medium Naphtha
3 = Jet A
4 = Jet A-1
5 = Kerosene
6 = No. 4 Fuel Oil
7 = No. 6 Fuel Oil
8 = South Texas Sour Crude

Reference 4.16.

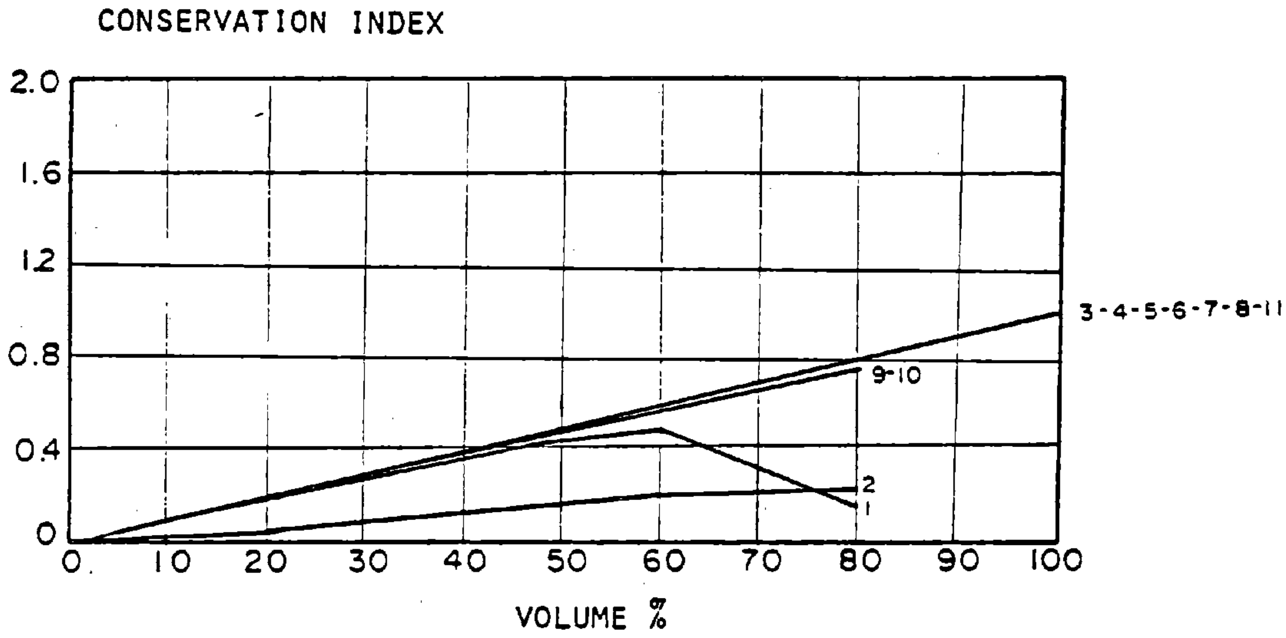
FIGURE 5.45. EFFECT OF DIESEL EXTENDERS ON VISCOSITY



1 Diesel Emergency Blend Extender = Gasoline
2 = Ethanol (Dieselhol)
3 = Medium Naphtha
4 = Heavy Naphtha
5 = Jet A
6 = Jet A-1
7 = Kerosene
8 = No. 4 Fuel Oil
9 = No. 5 Burner Oil
10 = No. 6 Fuel Oil
11 = South Texas Sour Crude

Reference 4.16.

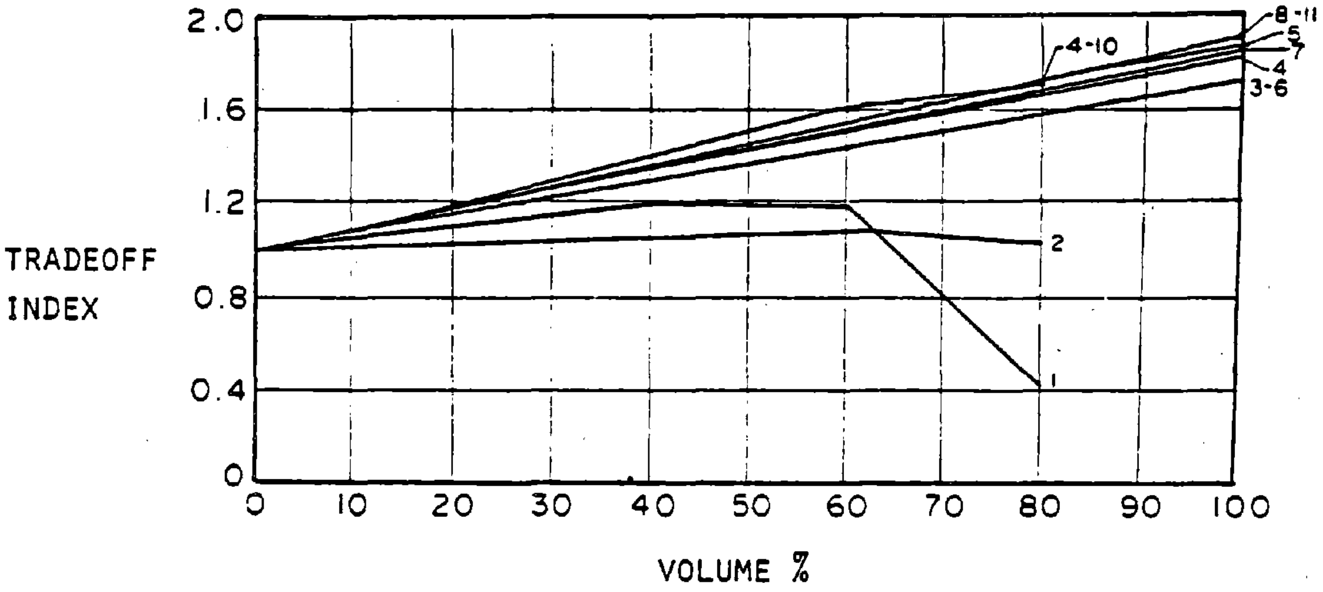
FIGURE 5.46. EFFECT OF DIESEL EXTENDERS ON POWER INDEX.



1 Extender = Gasoline
2 = Ethanol (Dieselhol)
3 = Medium Naphtha
4 = Heavy Naphtha
5 = Jet A
6 = Jet A-1
7 = Kerosene
8 = No. 4 Fuel Oil
9 = No. 5 Burner Oil
10 = No. 6 Fuel Oil
11 = South Texas Sour Crude

Reference 4.16.

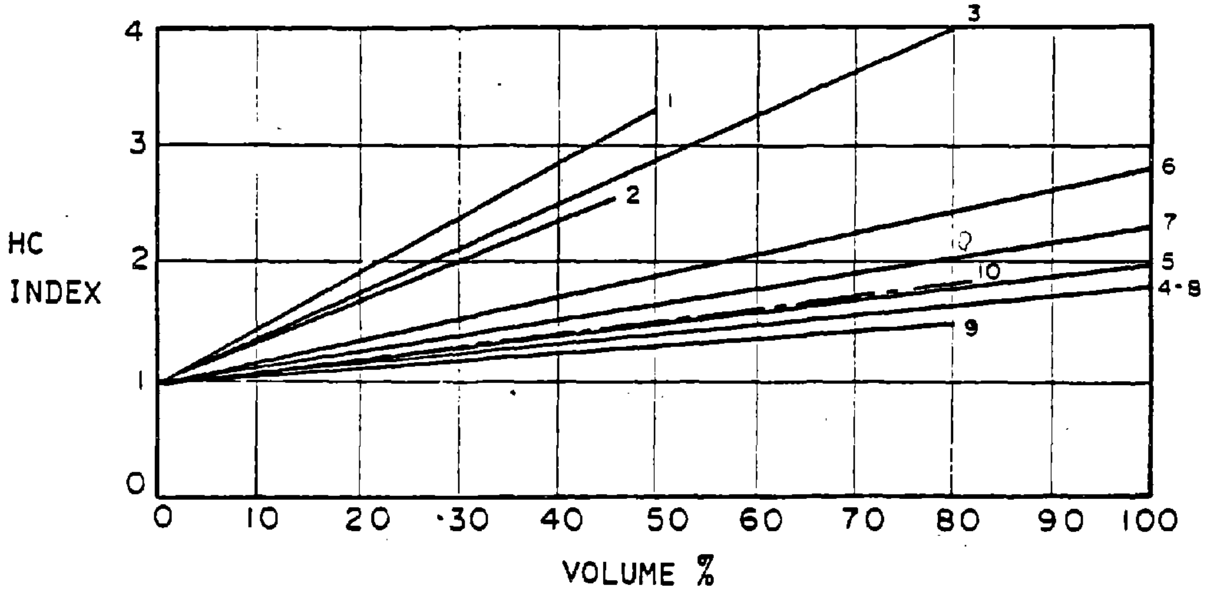
FIGURE 5.47. EFFECT OF DIESEL EXTENDERS ON CONSERVATION INDEX.



1 Extender = Gasoline
2 = Ethanol
3 = Medium Naphtha
4 = Heavy Naphtha
5 = Jet A
6 = Jet A-1
7 = Kerosene
8 = No. 4 Fuel Oil
9 = No. 5 Burner Oil
10 = No. 6 Fuel Oil
11 = South Texas Sour Crude

Reference 4.16.

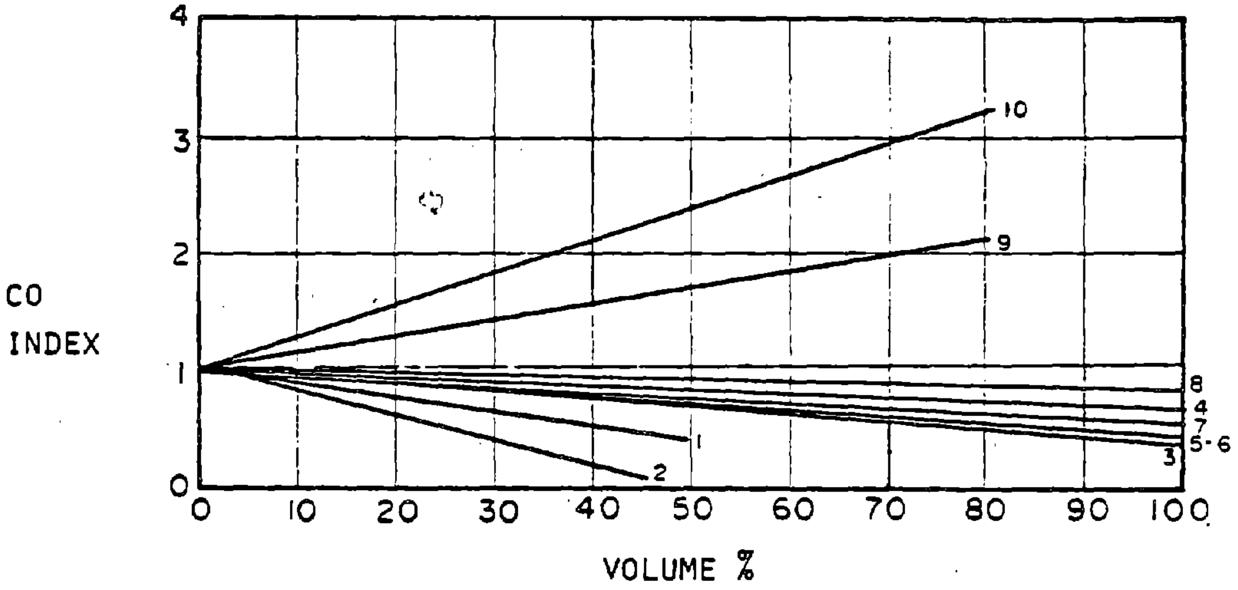
FIGURE 5.48. EFFECT OF DIESEL EXTENDERS ON TRADEOFF INDEX



1 Extender = Gasoline
2 = Ethanol
3 = Medium Naphtha
4 = Heavy Naphtha
5 = Jet A
6 = Jet A-1
7 = Kerosene
8 = No. 4 Fuel Oil
9 = No. 5 Burner Oil
10 = No. 6 Fuel Oil

Reference 4.16.

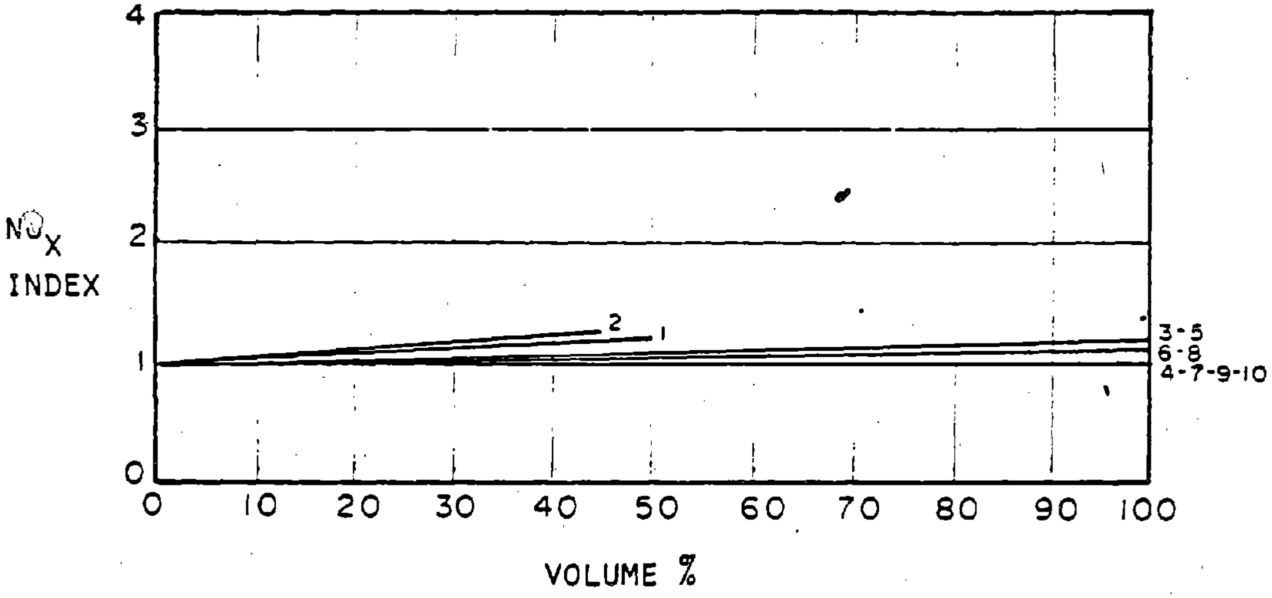
FIGURE 5.49. EFFECT OF DIESEL EXTENDERS ON HC INDEX



1 Extender = Gasoline
2 = Ethanol
3 = Medium Naphtha
4 = Heavy Naphtha
5 = Jet A
6 = Jet A-1
7 = Kerosene
8 = No. 4 Fuel Oil
9 = No. 5 Burner Oil
10 = No. 6 Fuel Oil

Reference 4.16.

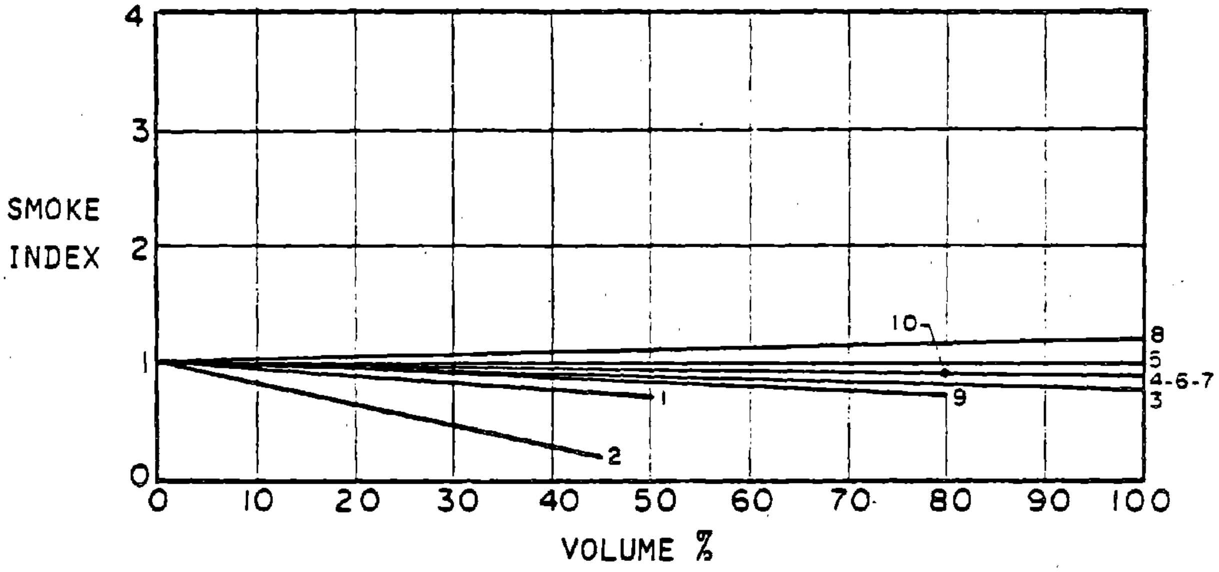
FIGURE 5.50. EFFECT OF DIESEL EXTENDERS ON CO INDEX.



1 Extender = Gasoline
2 = Ethanol
3 = Medium Naphtha
4 = Heavy Naphtha
5 = Jet A
6 = Jet A-1
7 = Kerosene
8 = No. 4 Fuel Oil
9 = No. 5 Burner
10 = No. 6 Fuel Oil

Reference 4.16.

FIGURE 5.51. EFFECT OF DIESEL EXTENDERS ON NO$_X$ INDEX.



1 Extender = Gasoline
2 = Ethanol
3 = Medium Naphtha
4 = Heavy Naphtha
5 = Jet A
6 = Jet A-1
7 = Kerosene
8 = No. 4 Fuel Oil
9 = No. 5 Burner Oil
10 = No. 6 Fuel Oil

Reference 4.16.

FIGURE 5.52. EFFECT OF DIESEL EXTENDERS ON SMOKE INDEX.

6. SENSITIVITY OF ENGINE LUBRICATION TO VARIATIONS IN FUEL PROPERTIES

6.1 INTRODUCTION

Variations in fuel properties might result in increased oil contamination and intensify some of the lubrication problems such as lubricant degradation, deposits, corrosion and wear. Crankcase oil contamination is caused by one or a combination of the following:

a. Direct contact of the combustion products with the lubricating oil film on the cylinder walls past the piston ring or along the valve stems. This contaminated oil returns to the crankcase.

b. Blow-by gases in contact with the lubricating oil in the crankcase. The blow-by gases, during the compression stroke in gasoline engines, contain fuel vapors. During the expansion stroke the blow-by gases contain combustion products.

c. Exhaust gas recirculation.

d. In some engine models, the fuel vapors are vented in the crankcase.

The PCV valve directs the crankcase gases into the intake manifold, which reduces the lubricant contamination problems.

The fuel properties which affect the concentration of contanimants are related to nigrogen and sulfur contents, and the incomplete and complete combustion products. The type of contamination depends on the combustion process, and is different in gasoline and diesel engines.

6.2 GASOLINE ENGINES

The main lubricating oil contaminants in gasoline engines are listed in paragraphs 6.2.1 and 6.2.5. Effects of alcohol fuels on lubrication and engine wear are described in paragraph 6.2.6.

6.2.1 Nitrogen Oxides

The nitrogen oxides are formed as a result of the high temperatures reached in the combustion process, from the atmospheric nitrogen, or from nitrogen in the fuel. Most of the nitrogen oxides are in the form of nitric oxide, and the rest is nitrogen dioxide. The latter is more reactive than nitric oxide, in contaminating the oil (6.1).

If the nitrogen content of the fuel increases, the nitrogen oxides concentration in the blow-by gases and in the exhaust gases used for EGR will increase, resulting in more oil contamination.

6.2.2 Sulfur Compounds

The sulfur compounds are mainly sulfur dioxide (SO_2) and sulfur trioxide (SO_3). These are formed during the combustion process, and depend mainly on the sulfur content of the fuel and the air-fuel ratio. The sulfur content of the conventional crude petroleum based gasoline is 0.07 percent.

The sulfur compounds contribute to the corrosive wear caused by the condensation of acids on the cylinder walls with subsequent chemical attack of the metal and removal of corrosion products by the wiping action of the rings. The corrosive wear is different from abrasive or rubbing wear caused by mechanical interaction between two metallic surfaces with relative sliding motion. The corrosive wear is significant during low temperature operation.

Syncrudes are known to contain more sulfur than conventional crudes. Reducing the sulfur content of gasoline made from syncrude will require the expenditure of more energy and money in the refinery.

6.2.3 Partial and Complete Oxidation Products

The partial oxidation products consist of aldehydes, RCHO (mainly formaldehyde, HCHO), ketones ($R_2C=O$) and acids (RCOOH). These are products of preflame reactions and partial combustion which takes place as a result of flame quenching near the walls or of incomplete flame propagation.

The complete combustion products, water and carbon oxides, are, of course, present in higher concentrations in the blow-by and EGR contaminants.

It is expected that the partial and complete oxidation products of future fuels will be nearly the same as those of conventional gasoline.

6.2.4 Hydrocarbons

The higher boiling point hydrocarbons of fuels represent a major contaminant because of their lower molecular weight as compared with that of the lubricating oil molecules. These higher boiling point hydrocarbons adhere to the cylinder wall, particularly under cold starting and warmup periods, and are mixed with the lubricating oil film.

If the end-point of future gasolines is increased, more oil contamination can be expected

Low temperature operation problems in the form of deposits occur whenever complete warmup of the engine is not achieved, particularly in cold weather. These deposits appear as "varnish" and sludge.

Varnishes which coat various engine parts such as valve-lifters, pistons, piston rings, and PCV valves, may cause troublesome adhesion of parts or interference between close-fitting parts. These varnishes have been found to contain significant amounts of nitrogen, sulfur and oxygen.

Sludge is colloidal in nature and separates from the crankcase oil in the more stagnant regions of the engine, or is deposited in places critical to oil supply and distribution, such as the piston oil control ring or the oil screen in the sump. The sludge forms as a water-in-oil emulsion, stabilized and thickened by finely divided solids, such as lead salts, soot, and resin forming surfactants.

6.2.5 Corrosion

Corrosion occurs on ferrous surfaces, particularly if gasoline engines are operated under light-duty conditions and with frequent shut-down periods. The factors favoring corrosion are a dispersed water phase in the oil, the presence of sulfur compounds in the fuel, and high dilution of the crankcase lubricant with raw fuel.

The high temperature operation problems result from exposing the lubricant to high temperatures and to high nitrogen oxide concentration, in the combustion chanber or as a result of contract with the blow-by gases. Oil oxidation under high temperature operation result in carbonyl-type compounds, which are acidic in character and may attack and dissolve corrodible metals. Also, nitrogen oxides can be involved in high temperature accelerated oxidative degradation. This is particularly true with increased blow-by rates (6.1).

6.2.6 Effect of Alcohol Fuels on Lubrication and Engine Wear

Owens and co-workers (6.6) of the U.S. Army Fuels and Lubricants Research Laboratory at S.W.R.I. investigated the effects of methanol fuel on spark ignition engine wear and deposits. The engine used was a 2-3 liter Ford overhead cam, four-cylinder design and was tested on a dynamometer, according to a modified ASTM sequence V-D test procedure. Owens, et al., indicated that the use of pure methanol as a fuel can result in large increases in engine wear and wear-metal accumulation during low temperature operating periods. This increased wear occurs primarily in the piston ring and upper cylinder bore area. In addition to wear, methanol was found to form rust. The extent of rust formation is dependent on the materials present and the metal and lubricant temperatures during engine operation. Therefore, this rusting phenomena would be design dependent and vary in intensity from engine to engine. Owens, et al indicated that the blow-by produced from methanol contains at least formaldehyde and formic acid, which are capable of corrosive attack within the ring zone, the area of highest concentration. The methanol, or its intermediate combustion products, directly attack the piston ring and cylinder bore area rather than first degrading the lubricant.

6.3 DIESEL ENGINES

Diesel lubrication problems are mainly related to the oil contamination by soot particulates, in addition to the factors described in 6.2., Gasoline Engines.

6.3.1 Soot Particulates

The soot particulate formation is one of the characteristics of the diffusion type flame in heterogeneous, combustible mixtures. The particulates formed during the different stages of combustion can be picked up by the lubricating oil and contaminate the crankcase lubricating oil by the approaches discussed in Section 6.2. The lubricating oil can be contaminated by soot particulates, even when the final engine exhaust is clear (6.2).

The fuel properties which affect the soot particulates have been explained in detail in another part of this report.

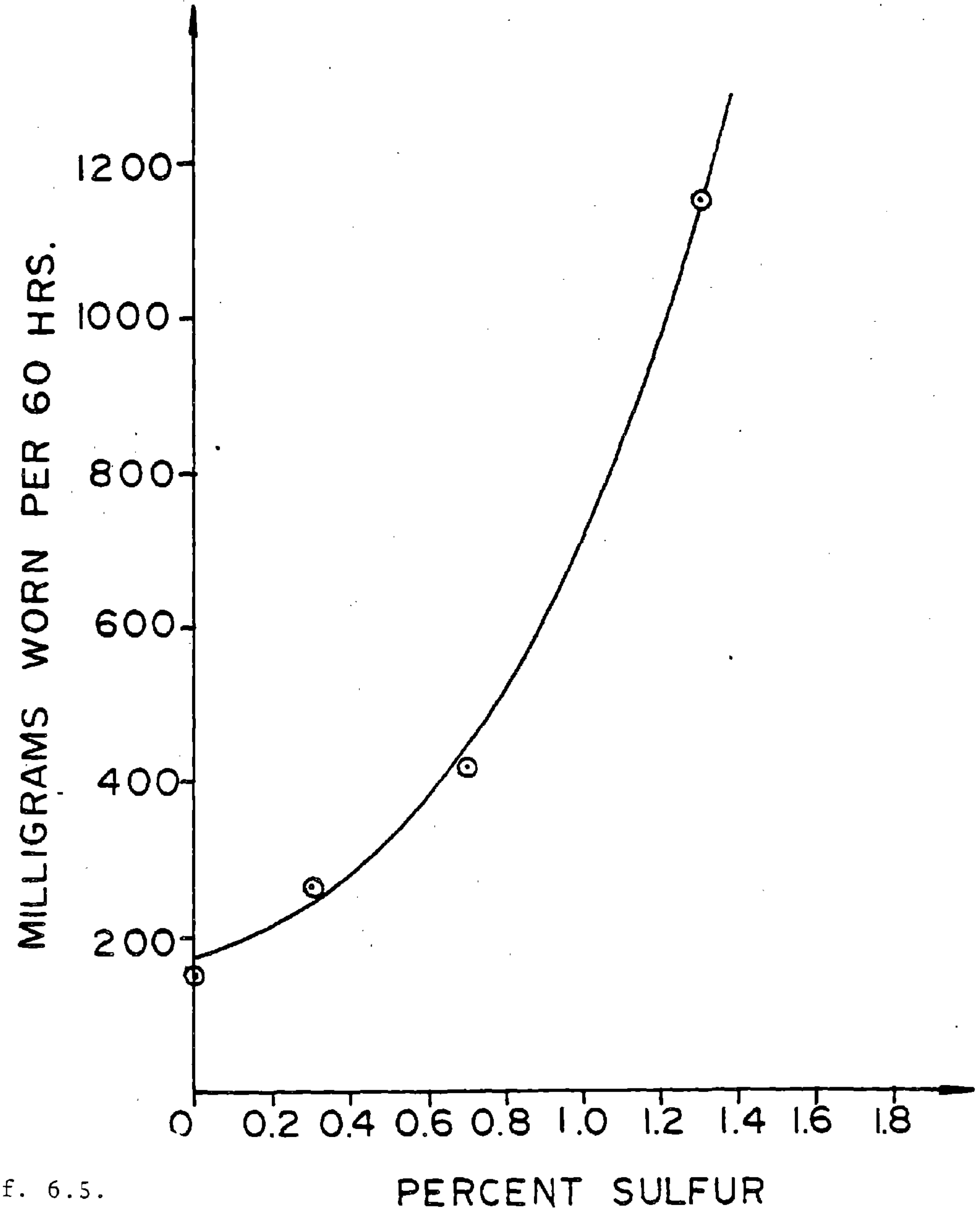
The soot contributes to the formation of different types of deposits in the engine, such as piston groove carbon, piston lacquer, and crankcase sludge. The piston groove carbon and lacquer are the result of combinations between the soot particulates and resins. The sludge is the result of combinations between soot, oil, oxygenates and water (6.3). Formation of deposit resins arises both from partial combustion products of the fuel, and from oxidative-thermal degradation of the lubricating oil and its additives.

6.3.2 Sulfur

The problem of the contamination of the lubricating oil with sulfur is much more serious in the diesel engines than in gasoline engines because of the much higher sulfur content of diesel fuels.

There is some evidence that formation of deposit resins is favored by increases in fuel sulfur except at very high temperatures where thermal effects predominate. Increasing the fuel sulfur content from 0.4 to 1.0 percent was reported to increase the level of piston deposits by 100 percent, in Caterpillar L-1 Test procedures by Deen and Schetelich (6.4).

Figure 6-1 shows the effect of sulfur on wear, obtained by Moore and Kent (6.5), using a single cylinder 5-3/4 inch bore, 4-inch stroke, Caterpillar test engine. The sulfur content of the fuel was varied from 0 to 1.3 percent by adding different amounts of thiophene to the light commercial fuel of originally low sulfur content. Figure 6-1 also shows the wear rates of two heavy diesel fuels, and it is seen that the points fall reasonably well on the curve. Figure 6-1 shows that, with all other conditions constant, the rate of wear with a diesel fuel of 1.0 percent sulfur content is approximately 400 percent greater than that with a fuel of 0 percent sulfur content.



Ref. 6.5.

FIGURE 6-1. EFFECT OF SULFUR CONTENT ON WEAR

7. CONCLUSIONS

Automotive gasoline and diesel engines are sensitive to certain fuel properties. Currently, the baseline automotive gasoline and diesel fuels are highly processed to the American Society of Testing Material (ASTM) specifications from natural crude petroleum. The current automotive engines are tailored to meet certain performance and emission goals when run on these fuels. Some variations in the properties of the baseline automotive fuels are anticipated in the future because of the expected depletion of natural crude resources, the increase in the price of imported crude and the desirability of reducing the nation's reliance on foreign fuels. In the United States, alternate fuels can be produced from the abundant coal and shale oil reserves, or from biomass. At the present time, the properties of future alternate fuels cannot be well defined, because they have not been established; although, it is known that the distillates from shale oil are highly paraffinic in nature while those from coal are highly aeromatic in nature. Also, syncrudes from coal and shale oil contain impurities such as nitrogen and sulfur. Reducing these impurities in the final product will require expenditure of energy and dollars at the refinery. Less refined fuels are likely to have high nitrogen and sulfur contents.

The following conclusions are based on the available data published in the literature. The areas which need further research are noted.

7.1 GASOLINE ENGINES

The important fuel properties which affect gasoline engines are summarized in Table 7-1. The gasoline engines are sensitive to the fuel volatility, octane number, H/C ratio, latent heat of evaporation, energy content, and sulfur and nitrogen contents. The engine parameters which are sensitive to each of the above properties are also listed in Table 7-1.

TABLE 7-1. IMPORTANT FUEL PROPERTIES FOR GASOLINE ENGINES

Fuel Property	Dependent Engine Parameter	
1 - Distillation range		
0 - 20% point	Cold starting	
	Hot starting	
	Vapor lock	
	Evaporative emissions	
20 - 80% point	Warm up	
	Hot stalling	
	Carburetor icing	Fuel economy
80 - 100% point	Crank-case oil dilution	Acceleration
	Deposits	Power
	Gum	
	Plug fouling	
	Hydrocarbon emissions	
2 - Octane number	Compression ratio	
	Engine efficiency	
3 - H/C ratio	Stoichiometry	
	Combustion temperature	
4 - Latent heat of evaporation	Cold starting	
	Volumetric efficiency and power	
5 - Gravimetric energy content	Brake specific fuel consumption	
6 - Volumetric energy content	Storage cost	
	Transportation cost	
7 - Nitrogen content	NO_x emissions	
	Lubricating oil contamination	
	Corrosion and wear	
8 - Sulfur content	Sulfates emissions	
	Lubricating oil contamination	
	Corrosion and wear	

7.1.1 Alternate Fuel Options

The gasoline engine alternate fuel may be one of the following options, or their blends with gasoline:

1. Synthetic gasoline from syncrude produced from oil shale or coal
2. Alcohols:
    - i. methanol produced from coal, biomass or wastes
    - ii. ethanol produced from biomass.
3. Hydrogen produced from coal.

The synthetic gasoline in the first option is expected to be produced at specifications close to those of baseline gasoline. The synthetic gasoline produced from shale is low in octane number and needs to be improved by high octane extenders such as MTBE or TBA. The synthetic gasoline produced from coal is highly aromatic and has a high octane number. Gasoline engines can be designed to run on these gasolines with relatively higher compression ratios in order to improve their fuel economy. The effect of the use of the extenders MTBE and TBA will be summarized in the following item.

The hydrogen in the third option is constrained in its use as an alternate fuel by the development of safe and economically competitive distribution and storage systems. Hydrogen is not expected to be a viable alternate fuel in the near term (1980-2000), or mid-term time frame (2000-2020). This report has not dealt with hydrogen as a fuel for automotive engines.

7.1.2 Gasoline - Alcohol Blends

The effects of blending gasoline with methanol, ethanol, MTBE and TBA on the fuel physical properties, and the performance of gasoline cars is summarized in Table 7-2. This table indicates the following:

TABLE 7-2. GASOLINE ENGINE ALTERNATE FUELS: GASOLINE - ALCOHOL BLENDS

Fuel or Engine Parameter		Gasoline Extender			
		Methanol 10%	Ethanol 10%	MTBE* 7%	TBA* 7%
Physical Properties	Volatility				
	RVP	↑	↑	↑	↑
	10% point	↓	↓	↓	↓
	Specific gravity	↑	↑	↑	↑
	H/C ratio	↑	↑	↑	↑
	Volumetric Energy content	↓	↓	↓	↓
	Octane number	↑	↑	↑	↑
	Latent Heat of evaporation	↑	↑	↑	↑
Oxidation Catalyst 1978 Cars, FTP	Miles per gallon	↓	↓	↓	↓
	Miles per BTU	↓	↓	↓	↓
	Emissions g/m				
	HC	↓	↓	↓	↓
	CO	↓	↓	↓	↓
	NO_x	↑	↔ ↑	↓	↑
	Aldehydes	N/A	N/A	N/A	N/A
	Acetone	N/A	N/A	N/A	N/A
	Evaporative g	↑	↑	↑	↑
3-Way Catalyst 1978 Cars, FTP	Miles per gallon	↓	↓	↓	↓
	Miles per BTU	↓	↑	↓	↓
	Emissions g/m				
	HC	↓	↓	↓	↓
	CO	↓	↓	↓	↓
	NO_x	↑	↑	↑	↑
	Aldehydes	N/A	N/A	N/A	N/A
	Acetone	N/A	N/A	N/A	N/A
	Evaporative	↑	↑	↑	↑

* MTBE: Methyl tetriarybutyl ether

TBA: Tetriarybutyl alcohol

1. The fuel economy in miles per gallon decreased mainly because of the lower volumetric energy content of the blends.
2. The fuel economy in miles per BTU decreased because the cars used were not calibrated for the blends. A major adjustment which would have improved the fuel economy is the spark timing (which could have been slightly advanced).
3. The NO_x and evaporative emissions increased with the blends.

It is clear from Table 7-2 that both the volatility and octane number of a fuel increased after blending with alcohols. The results shown are for baseline cars and do not reflect the full potential of the blends since the cars were tailored to run on the baseline gasoline. For example, the baseline cars have C.R. less or equal to 8.5:1, which is limited by the octane number of Indolene ().N.=91). The C.R. could be increased to 9.5 or 10 with these blends without producing knock. Increasing the C.R. of the engine improves the fuel economy of the vehicle.

The major problems associated with the use of alcohol - gasoline blends are:

1. Phase separation with methanol - gasoline blends
2. Cold starting problems caused by the higher latent heat of the blends
3. Increase of the NO_x exhaust emissions and the hydrocarbon evaporative emissions
4. Incompatibility of some materials which are used successfully with gasoline and deteriorate seriously with alcohol - gasoline blends.

7.1.3 Neat Alcohols

The sensitivity of gasoline engines to the use of neat alcohols, contrasted with Indolene is given in Table 7-3.

TABLE 7-3. GASOLINE ENGINE NEAT ALCOHOLS COMPARED TO INDOLENE

Fuel or Engine Parameter		Methanol	Ethanol
Physical Properties	Volatility	↓	↓
	Specific gravity	↑	↑
	H/C ratio	↑	↑
	Volumetric Energy Content	↓	↓
	Octane Number	↑	↑
	Latent Heat of evaporation	↑	↑
	Stoichiometric A/F	↓	↓
	Power	↑	N/A
	Brake Thermal	↑	N/A
	Emissions		
	HC	↓	↓ *
	CO	↔ ↓	↓ *
	NO_x	↓	↔ ↓ *
	Aldehydes	↑	↑ *
	PNA	↓	
	Evaporative		

* CVS - Hot Driving cycle only.

Most of the work conducted has been on methanol, and showed the following advantages for methanol:

1. Methanol has a high octane rating (RON = 110, MON = 92) which allow the C.R. of the gasoline engine to reach 13:1 or 14:1 and achieve better thermal efficiency than the current gasoline engine. VW reported an improvement of 4 percent during the ECE cold start test, and 12 percent for the hot start test.
2. Tests over the whole speed range indicated that with methanol, the brake output of the engines is 10 percent higher than for gasoline engines, both with MBT spark.
3. Tests over the operating range of the equivalence ratio (0.8 to 1.2) indicated that the methanol-fueled engine produced less NO_x, CO and HC than the gasoline fueled engine. However, the aldehydes emissions were higher with methanol than with gasoline.

Operation on methanol on the ECE cold test system resulted in a reduction of 22 percent in CO, but an increase of 22 percent in HC. In the hot-start test, the CO emissions were reduced by 68 percent HC by 28 percent, and NO_x by 20 percent.

Problems

A cold starting aid is absolutely essential for starting the engine at temperatures below 8°C. Cold starting aid could be in the form of volatile starting additives (such as butane, methyl ether, or gasoline) to be sprayed into the intake air during starting. A small methanol-fueled flame preheater can also be used in the intake manifold.

7.2 DIESEL ENGINES

The important fuel properties which affect the automotive diesel engine are summarized in Table 7-4. Automotive diesel engines are sensitive primarily to the cetane number which affects almost every aspect of combustion such as: ignition delay,

TABLE 7-4. IMPORTANT FUEL PROPERTIES FOR DIESEL ENGINES

Fuel Property	Dependent Engine Parameter
1 - Cetane Number	Ignition delay engine noise Hydrocarbon emissions NO_x emissions exhaust smoke, and particulates cold starting
2 - Distillation range	
Light ends	cold starting Hycrocarbon and aldehyde emissions Vapor lock Cavitation in the injection system
Heavy ends	Smoke emissions particulate emissions waxing and filter plugging
3 - Aromatic content	Smoke and particulate emissions Polynuclear aromatic hydrocarbons
4 - Viscosity	Spray formation and combustion Injection system lubrication Flow through the fuel system
5 - Sulfur content	Sulfate emissions corrosion and wear
6 - Nitrogen content	NO_x emissions corrosion and wear
7 - Gravimetric energy content	B.S.F.C.
8 - Volumetric energy content	Miles per gallon

engine noise, cold starting problems, and emission of hydrocarbons, nitrogen oxides, smoke, and particulates. Automotive diesel engines are also sensitive to the distillation range, aromatic content, viscosity, sulfur content, nitrogen content, gravimetric energy content and volumetric energy content of their fuels.

7.2.1 Alternate Diesel Fuel Options

The diesel engine alternate fuels may be one of the following:

1. Wide cut distillates from petroleum crude
2. Synthetic diesel fuel from syncrude produced from oil shale or coal
3. Alcohols.

7.2.1.1 Distillates from Petroleum Crude - The increase in demand for jet fuel and heating oil will put pressure on the diesel fuel production to include heavier compounds. To this effect, DF-3 is being considered for transportation diesel engines. No work has been conducted so far to find the sensitivity of automotive diesel engines to DF-3 fuel. Another approach to reduce energy expenditure in the refinery is to produce a wide cut fuel which will contain lighter and heavier compounds than DF-2. Very limited work has been reported so far on the performance of automotive diesel engines on wide cut fuels. The following applies:

1. D.I. truck engines are more sensitive to variations in fuel properties than I.D.I. engines used in passenger cars.

2. The increase in the volatility of the distillate by lowering the 10 percent point results in a drop in C.N., increase in I.D., increase in HC and NO_x emissions and increase in combustion noise. Some of these problems can be solved by increasing the C.R. of the D.I. engine, retarding the injection timing, turbocharging, or redesigning the combustion chamber. The increase in volatility is usually associated with a reduction in viscosity which might result in poor lubrication and fuel leakage in the injection pump, particularly at low speeds.

3. The increase in the heavy components of the distillate, by increasing the 90 percent point, results in more smoke. Derating the engine power may be needed to limit the smoke. Heavy fuels, which need to be heated to flow readily, increase the ignition delay, HC, NO_x, and smoke particulate emissions and noise. These effect are more pronounced in D.I. engines than in I.D.I. engines.

7.2.1.2 DF-2 Gasoline Blends - Some work has been conducted on DF-2 gasoline blends and the results are summarized in Table 7-5. The main advantage of DF-2 gasoline blends is the drop in smoke formation resulting from the increased portion of premixed combustion. This results, however, in increasing the combustion-generated noise, and the unburned hydrocarbon emissions. Other problems associated with the use of diesel-gasoline blends are the difficulty in cold starting, misfire at light loads and high speeds, vapor lock in the fuel injection system, crankcase oil dilution and lack of proper lubrication of the fuel injection parts.

7.2.1.3 DF-2/Synfuels Blends - The effect of blending DF-2 with synfuels from shale oil and coal - derived crude have not been well studied. The limited studies conducted in this area show unfavorable results as summerized in Table 7-6. The major problems with shale-derived synfuels are lacquering, needle sticking and poor reliability. The major problems with coal-derived synfuels are filter plugging, waxing, nozzle fouling, lubricating oil sludging and poor reliability.

7.2.1.4 DF-2/Alcohol Blends - The third option is to use alcohols, as blends with DF-2 or as neat compounds. Very little work has been conducted in this area. The limited work completed so far showed some effects which are summarized in Table 7-7.

The major problems associated with the use of alcohols to extend the diesel fuel are:

TABLE 7-5. DF-2 GASOLINE BLENDS

1 - Cetane Rating	↓
2 - Smoke limited power	↑
3 - BSFC	↑
4 - BSEC	↔
5 - Emissions	
HC	↑
CO	↔
NO_x	↑
Noise	↑
Smoke	↓
Aldehydes	N/A

Major Problems:

- Cold starting
- Misfire at high speeds and light loads
- Vapor lock in fuel injection system
- Crankcase oil dilution
- Lack of proper lubrication of the fuel injection parts
- increase in combustion generated noise

TABLE 7-6. DIESEL ENGINE ALTERNATE FUELS (DF-2/SYNFUELS BLENDS)

	Shale Derived Synfuel	Coal Derived Synfuel
1 - Cetane Rating	↓	↓
2 - Gum Content	↑	N/A
3 - Smoke-limited Power	↓	↓
4 - BSFC	↔	↑
5 - Aromaticity	↓	↑
6 - Emissions		
HC	↔ ↑	↑
CO	↑	↑
NO_x	↑	↑
Noise	↑	↑
Smoke	↑	↑
7 - Pour Point	N/A	↑
8 - Major Problems	Lacquering Needle sticking Poor reliability	Filter plugging Waxing Nozzle fouling Lub. oil sludging Poor reliability

TABLE 7-7. DF-2/ALCOHOL BLENDS

	Methanol	Ethanol
1 - Cetane Rating	↓	↓
2 - Smoke-limited Power	↔ ↓	↔ ↓
3 - BSFC	↑	↑
4 - BSEC	↔	↔
5 - Emissions		
HC	↑	↑
CO	↓	↓
NO_x	↓	↓
Noise	↑	↑
Smoke	↓	↓
Aldehydes	↑	↑

a. Blends of Alcohols - DF-2

   i. cold starting

   ii. lubricating oil contamination and engine wear

   iii. injection system wear

b. Alcohols - DF-2 Emulsions

Some of the above problems can be reduced by using pure DF-2 at cold starting and increasing the emulsion concentration with load. This requires difficult control techniques particularly under transient modes.

c. Alcohol Carburetion or Manifold Injection and Diesel Injection

This results in a large drop in the intake air temperature which causes misfire at low loads. On the other hand, self-ignition may occur at high loads. Also, elaborate control techniques are needed to optimize the timing and metering of the two fuels

d. Two Separate Injection Systems

This allows varying the relative amounts of the two fuels. The main problem associated with two high pressure injection systems is the initial cost, and the elaborate and expensive control systems needed to optimize the timing and metering of the two systems.

The major problems associated with the use of neat alcohols in diesel engines are:

a. <u>Autoignited Alcohols</u>

1. Alcohols have a very low C.N. (about 3). They require to be mixed with cetane improving additives, such as 8 percent ethyl nitrate.

2. Alcohols have very poor lubricity. They must be mixed with about 2 percent lubricating oil.

3. Lubricating oil contamination with alcohols may cause

increased engine wear.

4. A starting aid such as intake air heating or using diesel fuel is required under cold starting conditions.

b. Spark Ignited Alcohols in Diesel Engines

The major problems are:

1. Alcohols have high latent heats of evaporation which result in severe cold starting problems.
2. High emission of hydrocarbons at idling and low loads.
3. Low reliability due to wetting of spark plugs and misfiring.
4. Requires a much higher voltage for ignition because of the high compression ratios used.
5. Wear due to cavitation in the injection system.
6. High hydrocarbon and aldehyde emissions.

7.3 EMERGENCY FUELS

7.3.1 Gasoline Engine Emergency Fuels

One research program conducted on the use of emergency fuels in a limited number of automotive gasoline engines indicated that only alcohols can be used as gasoline extenders without the need to reduce the compression ratio of the engine. The emergency fuels studied are DF-2, marine diesel fuel, ethanol, methanol, MTBE (Methyl Tert Butyl Ether), naphtha - ethanol, DF-2 ethanol, kerosene - ethanol, ethanol extended with water, naphtha, and kerosene.

7.3.2 Diesel Engines Emergency Fuels

Tests on a limited number of diesel engines showed the following results:

1. The following fuels were found to be suitable emergency

fuels for diesel engines and had minor effects on smoke emissions: Jet A, Jet A-1, medium naphtha, and kerosene.

2. Blending with gasoline and alcohols decreased the C.N. sharply, however, it decreased smoke. The problems with these fuels are mainly related to their poor lubricity, particularly in the fuel injection system, and the increase in combustion noise and cold starting difficulties.

3. Blending with heavier distillates such as No. 4, and No. 5 fuel oil, resulted in an increase in smoke.

8. RECOMMENDATIONS

Research is needed in the following areas to determine the sensitivity of automotive engines to variations in fuel properties.

8.1 FUTURE FUEL CHARACTERISTICS

1. Develop scenarios for future automotive fuels based on the most energy- and cost-efficient refining techniques, and the availability of the energy sources.

2. Develop a data base for the variation in fuel properties as a function of blending the base fuels with different types of extenders.

3. Develop a data base for the effect of variations in fuel properties on their autoignition properties (cetane number and octane number). The fuels should cover a wide range of the following:

   i. Carbon to hydrogen ratio,
   ii. aromatic content,
   iii. distillation range,
   iv. density,
   v. sulfur content
   vi. nitrogen content.

4. Study the impact of the use of alternate fuels on the lubrication process in automotive engines and find techniques to reduce lubricating oil contamination.

8.2 GASOLINE ENGINES

1. Investigate the effect of variations in the base fuel properties on gasoline engine performance, fuel economy and emissions. Develop engine maps to cover the expected variations in future fuel properties.

Emphasis should be on the properties which cost more to control in the refinery.

3. Study the economy of producing ethanol from U.S. grown grain, the energy expenditure, and the efficiency of converting the source energy into useful mechanical work. A system approach should be taken in this study.

4. Study the use of neat alcohols and blends with gasoline in gasoline engines. The following should be optimized: compression ratio, spark timing, and fuel metering. Most of the studies conducted so far are on mass produced engines calibrated for gasoline (Indolene).

5. Investigate techniques to solve the cold starting problems of gasoline engines when run on neat alcohols or alcohol-gasoline blends.

8.3 DIESEL ENGINES

1. Investigate the effect of variations in the base fuel properties on the automotive diesel engine (D.I. and I.D.I) performance, economy and emissions. Develop engine maps to cover the expected variations in future fuel properties. The engine systems should be optimized for each fuel.

2. Make an assessment of the tradeoffs in economy, performance, emissions and variations in fuel properties which cost more to control in the refinery.

3. Develop a modified cetane scale to rate the autoignition quality of alternate fuels. The current scale is unsuitable for alternate fuels.

4. Study the problem of cycle-to-cycle variation in the autoignition of alternate fuels in diesel engines, and methods of reducing their effect on engine reliability.

5. Determine the effect of cetane improvers on increasing the C.N. of alcohols. These improvers include commercially

available additives, diesel fuel, and lubricating oil. This study needs to be done on a CFR-Cetane engine with the Modified Cetane Scale which is capable of measuring the C.N. of fuels in the range 0-20.

6. Study the use of neat alcohols, and alcohol-diesel blends in optimized diesel engines. The main design parameters which should be optimized are: compression ratio, injection pressure, injection nozzle, intake system, and combustion chamber design.

APPENDIX A
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APPENDIX B
REPORT OF INVENTIONS

The work presented in this report is of a review nature. No invention or application for patent rights evolved from the performance of this work.

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