UNIVERSITIES SYNFUELS R&D

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INTRODUCTORY REMARKS

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REMARKS FOR THE OPENING OF THE UNIVERSITY SYNFUELS R AND D PANEL

by

Samuel S. Lestz
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Good morning ladies and gentlemen:

Back in the early part of August when John Russell approached me for my thoughts pertaining to the organization of a University Panel for this conference, I tried in vain to tell him of my ignorance concerning the subject matter; namely, that I really didn't know anything about the composition of finish synfuels for transportation. However, John did prevail and I agreed to help organize this panel and serve as its moderator. In this, the organizing proved to be a relatively easy task because, fortunately, we were able to assemble a panel of three highly qualified people whom I will introduce in just a few moments. The other part of my agreement to serve as panel moderator, while appearing to be a most enjoyable undertaking, did leave me somewhat apprehensive. To overcome this, I felt that it might be a good idea to organize my thoughts and, once having done this, perhaps there may be an idea or two that would be worth sharing with you all this morning. So if you would please bear with me for just a little bit, I would like to inject two of these ideas that I came up with.

<u>First</u> - I asked myself, why hold such a conference as this. Isn't the answer to this question obvious? The scope of this conference is clearly set forth on the cover of the program announcement. But really are all the reasons for holding this conference obvious? I think not! I personally feel that a

most important reason for this conference is to arouse an awareness of the urgency to set a high priority on the development of the commercial capacity for producing finished synfuels for transportation. Strange as it seems, even though the social, economic, political, and military reasons for doing so are most compelling, there doesn't in my opinion appear to be the kind of commitment directed toward ensuring a future supply of transportation synfuels that one might expect. I feel as others of you have already indicated that this is critical, and therefore, concluded that an important goal for this conference would be to strive to bring about increased recognition of just how crucial it is to have a national commitment for the development of a viable production capability.

Second - The idea that I would like to throw out also seems to turn about an obvious notion. Namely, that in order for a synfuel to be generally acceptable in the near future as a transportation fuel, it necessarily will have to be a liquid and probably not too terribly different from present day fuels. That near future fuels will be liquids arises out of logistical (energy density) and hardware considerations. That they will not be too different from present fuels arises out of my reading of the current literature. If I am correct then, I think it is appropriate to ask what research involving transportation fuels can and should we in the universities by doing now? I do not presume to have the wisdom or the knowledge to provide a wholly satisfactory answer to this question. However, my experience and history does say that we must continue to do the basic research that will ultimately supply the fundamental physical characteristics that will be vitally needed in the future so that combustion and fuel management systems might be altered to accommodate synfuels as they become available. In the near future, the next five to ten years, while I can see the impact of synfuels becoming appreciable, I cannot see during this same period the immergence of an alternative prime mover for transportation (over the road) that will displace the internal combustion engine of today. True, we are apt to see in certain applications a shift from one kind of an engine to another as for example we are now witnessing the Diesel engine moving into the light duty automotive field, but it is doubtful that we will shortly witness a wholly new type engine moving into this same field.

A vital task then for university researchers is to supply fundamental information that will enable us to model the behavior of future synfuels as a function of their composition whatever that may be. This is a formidable task, but not I think an impossible one. Currently at our university, an interdisciplanary team of researchers is attempting to do this in the area of environmental compatibility for future Diesel engine fuels. If this effort is successful, it will provide a model which will alow one to predict the mutagenic activity of a given fuel based upon the composition of that fuel. The model itself will be based on data obtained while burning various blends of pure compounds in a diesel engine. There are other areas that can be approached in the same way and certainly the attempt should be made.

Thank you for listening to my comments, and now we should move on to the panel presentation and discussion. So, without further delay, let me now introduce our panel. They are:

Professor Otto A. Uyehara - University of Wisconsin
Professor Richard T. Johnson - University of Missouri-Rolla
Professor Arthur M. Mellor - Purdue University

TRANSPORTATION FUELS — 1978 CRUDE OIL SCENE

Dr. O.A. Uyehara
University of Wisconsin

TRANSPORTATION FUELS - 1978 CRUDE OIL SCENE

by

O. A. Uyehara

ABSTRACT

Estimation of depletion dates of natural crude oil for the U.S. and the World, the type of chemical structured fuel to expect from coal derived synthetic fuels and the questions that need to be answered to use fuels refined from synthetic crude oil, for transportation use.

TRANSPORTATION FUELS - 1978 CRUDE OIL SCENE

by

O. A. Uyehara

Even with fuel conservation practice the demand for crude oil in the United States has not decreased.

Federal law now states the automobiles produced by a particular manufacturer must satisfy the fleet average gas mileage of each model year so that by the year 1985 the average fleet must meet 27.5 miles per gallon. To comply, automobile manufacturers have been reducing the weight of the vehicles of certain models in their fleet yearly. The requirement of low pollutant emission is still very stringent. The Federal government, however, has relaxed the NO_x requirement from .4 gram per mile to 1.0 gram per mile for future.

In order to comply with the regulations, that is more miles per gallon and at the same time to comply with the emission restriction, the following methods are being tried depending on the manufacturer: lean burn engines, the use of two combustion chambers, use of catalytic mufflers, use of lower rolling resistance tires, lower differential gear ratios. These methods have been integrated to satisfy the yearly Federal and State of California laws.

Passenger Car Economy

The writer presented a paper entitled "Diesel Vehicles? Crude Oil", (I)* at the 1976 SAE February meeting showing miles

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*Numbers in parentheses designate references at end of paper.

per gallon data of spark ignited vehicles and diesel engine vehicles vs. curb weight plus 300 pounds. These plots for urban and highway driving modified by drawing the line for 1978 passenger cars using spark ignition engines are shown in Figures 1 and 2. The improvement in economy can be seen by inspecting Figure 1 and Figure 2.

Figure 1 contains data for urban driving of the 1974 and 1975 vintage new automobiles. Figure 2 gives similar information for highway driving. Additional data are shown in both Figure 1 and Figure 2 giving the mpg vs. vehicles curb weight plus 300 pounds for the 1978 spark ignited equipped vehicles. It shows increased mpg for 1978 vehicles of the same weight. Limited data was used to draw the line so care must be exercised in interpreting the plot. Also there is the question whether the EPA (2) published mileage data, which was determined in a different manner, could be higher in mpg than can be obtained in actual vehicle operation on the road. The improvement in mpg is between 20 to 40 percent which indicates substantial improvement. When data were given for both automatic transmission and manual transmission the manual transmission data were used.

Air Transportation

In air transportation field, the jet engines have been using turbo-fan (fan jets) to improve the propulsion efficiency. It is well known that the thrust is proportional to $\dot{M}\Delta V$ where

$\dot{M}$ is the mass rate of flow of fluid through the jet engine and ΔV is the difference in velocity of the jet leaving the jet engines to the velocity of the air frame. With the use of a turbo fan, the mass rate $\dot{M}$ of the fluid through the jet engine is increased and for the same thrust, ΔV decreases. The improvement in quantity of jet fuel consumed for the same payload and speed is about 15 to 20 percent.

Fuel Consumption Trends

Even with improvements shown by new automobiles and improvement in the propulsive efficiency of airplanes the consumption of total crude oil in the United States has not decreased. It can probably be attributed to the rate of new cars purchased to the rate of old cars taken out of service in such that the total population of vehicles is still increasing. The older cars (pre 1976) with lower value of mpg are still a large proportion of the automobile population.

Figure 3 is being presented to show the trends of petroleum demand (consumption), production, gasoline consumption and import of crude oil and products. From inspecting this plot the rate of demand of petroleum had decreased during the period from 1973 to 1976, but it started to increase again in 1977 and the yearly rate of consumption seems to be leveling off at about 18.5 million barrels a day. Looking at the import curve during the years between 1973 and 1976, the rate of consumption stayed, on the average, about constant. During the period from October 17, 1973 to March 18, during the oil embargo we had a shortage of import of crude oil. During this period the import stayed fairly constant at about 5 1/2 million barrels a day. The percentage of the import to the daily rate of consumption was roughly 5 1/2/17 or about 33%. However, looking at the import curve of 1977, the percentage of import to consumption increased to about 8 1/2 to about 18 1/2 or about 46%. The import seems to be taking a strong downward trend in 1978 but the year is not complete. If the quantities indicated at mid-year are used to make the estimate, the percentage import is about 42% which is in trend of the right direction.

Observing the trend in gasoline consumption we can see after a lull from 1973 to 1975 the trend is a gradual increase in consumption even with the addition of improved gasoline mileage automobiles introduced with new automobiles. At the present time the gasoline consumption is about 7.2/18.5, about 39% of the total petroleum consumption.

Definition Used in Crude Oil Industry

Figure 4 shows a "barrel" of oil estimated as being found. The quantity 433 billion barrels then is termed resources.

I, being a layman, may not be giving the absolute correct answer but my understanding is that the terms have the following connotation. The term reserve is the quantity of crude oil that can, at that period of time, be economically pumped from the ground.

During the life of a producing oil well the first 20 to 25 percent of crude oil is recovered by the effect of the dissolved gases in the crude oil generating enough pressure to maintain flow without any external devices. The second period called secondary recovery or water-flooding period, water is injected around the producing well to displace the oil and to increase its pressure. Using water flooding produces an average of about 10% additional crude oil. There are many intricate pores of minute size in the oil bearing structure. Special solvents followed by water flooding, pumping in inert gas such as CO_2, partial oxidation underground by limiting oxygen supply, etc., are some of the methods that can and if economic conditions warrant are used. This third stage is called tertiary recovery method. An additional 15 percent of the original 100% can be recovered. Secondary and tertiary recovery methods are termed enhanced recovery. There is about 50% of the original oil in the ground that cannot be recovered by any known technique of today.

In Figure 4 which depicts a "barrel" of oil, it is assumed that the location of 433 billion barrels of crude oil, which was given to us by nature is known in the United States. If the estimate of all oil given to us, but of unknown locations, the resource is higher - 800 billion barrels (see Figure 5). Using the data of 433 billion barrels as 100% then by 1975 we had recovered (quite easily) 106 billion barrels or about 24.5% of the "barrel." By January 1979, we will have recovered 120 billion barrels or about 28%. Some of the oil recovered since 1975 has cost more to recover since the new oil wells are much deeper and hence were made expensive to drill, more of the new oil wells are located off shore where platforms are required. Wells of the future many of which will be located many miles from the shore on the outer continental shelf both in the Atlantic and Pacific Ocean will require elaborate drilling techniques and platforms which will make then even more expensive. New wells and by using enhanced recovery methods (waterflooding and tertiary recovery) we can expect about 79 billion barrels of oil that can be recovered. This quantity is somewhat higher than the lowest recoverable oil line shown in Fig. 5.

U.S. Crude Oil Scene

In Figure 5, the U.S. oil scene is presented. The demand (consumption) is much greater than the supply (production) from our oil wells. To make up the difference crude oil and products must be imported. The import data as function of time was presented in Figure 3. Let us continue to look at the trends. If we continue to produce more crude oil trying to limit our import, and if we keep on producing by use of enhanced recovery methods, dig more wells and dig deeper wells, the production to date line, will cross the lowest of the USGS recoverable crude oil line by 1988 just a scant eight years away. If the more optimistic recoverable reserve line is used the date will be about the year 1988, which is shown in Fig. 5.

World Crude Oil Scene

Let us now look at the world petroleum scene which is shown in Fig. 6. Two estimates of recoverable oil in billion barrels are shown. These estimates are roughly 1300 and 2100 billion barrels. The bottom curve is the rate of production in barrels per year since 1920. A rough value of the peak rate shown on the plot is about 20 billion barrels per year which was reached about the year 1973. The rate of production (controlled by oil producing countries) and to pricing dropped to about 16.4 billion barrels per year in 1976. The production rate per year has increased to about 17.7 billion barrels per year in 1977. When the second peak in production rate will occur is difficult to estimate.

If the assumption is made that the same trend but at a slightly slower rate of consumption growth, the total oil produced to date curve crosses the estimate, made by King Hubbert's (3) of recoverable oil during the approximate year of 2010 - a short period of time of about 32 years. If the more optimistic recoverable oil estimate of Ryman's is used the year when it crosses is about 2025 or about 47 years away.

Let us see what the consumption of petroleum of the United States is to the total world production in the year 1978. U.S. consumption was about 3 billion barrels per year. The world consumption (includes Russia and the rest of the Communist countries) is about 17.7 billion barrels. U.S. consumes 3/17.7 x 100 or about 17% of the world crude oil with a percentage population of about .2/4.1 x 100 or 4.8 percent of the world's population.

It is alarming to the author that more effort is not being made to set up large conversion plants whereby coal (estimated reserve about 300 years) can be converted to synthetic crude. The effort is there, but at a fairly low effort. We do have several DOE co-sponsored small to medium size conversion plants of pilot plant size to obtain experimental data. The estimated cost for a barrel of oil is in the $25.00 range which is about twice the cost of imported oil. Even if the cost of a barrel of synthetic crude cost $28.00 a barrel, it is the opinion of the author that we meet the capability of producing about 2 million barrels per day of synthetic crude. If the supply of imported oil should suddenly be shut off, we can with storage system in operation get by for about 6 months, but by that time we should be producing synthetic crude at the above rate. The economic consequence of petroleum shortage will be devasting.

Sooner or later we will be making synthetic crude from coal and from shale. In Figure 7 is presented, in greatly simplified form, the conversion of coal to syncrude plant.

Required is a source of oxygen to keep the gas pumping to a minimum, a source of hydrogen to increase the H/C ratio of coal to the required H/C ratio to produce the liquid hydrocarbon.

The timely and informative paper by J. P. Longwell (4) which was presented at the 1976 Combustion Institute Meeting held at MIT, Cambridge, Massachusetts during August 1976, gives some of the cost involved and the problems that can be encountered. The amount of hydrogen required to liquify the coal depends upon what type of fuel structure we need to have to satisfy the transportation fuels. The cost of generating hydrogen gas is quite expensive. One of the methods is to use part of the coal and the left over material called char, in the process of producing synthetic crude.

In Figure 8 is shown a simple table giving the hydrogen to carbon atom ratio for a 10 carbon atom liquid fuel hydrocarbons of different chemical structures. The normal parraffins has the highest H/C ratio with a value of 2.2.

The olefin has an H/C of 2.0. Both diolefin and cyclo paraffins have H/C ratio 1.8. The alkyl benzene, for the structure shown, has a H/C ratio of 1.4. Napthalene, structured of 2 benzene rings, has the lowest H/C ratio of 0.8.

Longwell (4) gives the hydrogen gas requirement to convert coal with the value of H/C of .75 to synthetic crude. The H/C ratio of one of the synthetic crude mentioned in his paper is 1.27, made from coal with an H/C ratio of .75. The volume of hydrogen gas consumed in producing synthetic liquid petroleum by the H-coal process is given as 4100 cubic feet. His next example of hydrogen gas requirement to further increase the H/C ratio from 1.27 to 1.53 by cracking and hydrogeneration.

The additional volume of hydrogen gas required was given as 3500 ft^3. To produce synthetic crude with an H/C of 1.53 requires 7600 ft^3 per barrel of synthetic crude produced. He also gives the approximate percent aromatic content in the synthetic crude with H/C = 1.27 as about 80% and for 1.53 H/C ratio synthetic liquid petroleum as about 50%. He also states the Jet fuels specification specifies air aromatic content of no more than 20%.

Mr. Longwell gave the cost of hydrogen (in 1980) of $2.00 per 1000 cubic feet. Extrapolating the hydrogen required, I would guess to convert coal with air H/C of .75 to syncrude with an H/C 1.68 would require about 10,000 cubic feet. At a price of $2.00 per 1000 cubic feet, the cost of hydrogen gas alone would be $20.00 per barrel of synthetic crude. The $2.00 cost by Longwell for converting coal to hydrogen, I am assuming included the cost of O_2-N_2 separation from air, the cost of coal, and included the capital cost for the air separation and coal to H_2 equipment. In the above cost of hydrogen gas, the cost of coal, I am quoting Longwell, "assuming the cost of coal is $20.00 per ton in 1982". Let us perform a little simple arithmetic. Let us assume 2.75 barrels of synthetic crude can be produced per ton of coal. The:

Cost of coal = about $7.30

Cost of hydrogen (which includes some coal say to produce 1.53 H/C synthetic crude = 7.6 x 2.00 = 15.20.

The cost per barrel of synthetic petroleum with an H/C ratio of 1.53 produced from coal with an H/C ratio of .75 is then 15.20 + 7.30 or $22.50. The $22.50 cost does not include the cost of H-process plant (but does include the hydrogen producing section of Figure 7.)

In the SAE paper 760210, I made a guess it would cost about $20.00 a barrel. This rough estimate was made in 1975 when the paper was in preparation so my guess was too low.

Now let us look at some of the problems that one can encounter using synthetic crude for making transportaion fuels.

Porter (5,6) in his classic work of using photoflash pyrolysis technique, satisfied himself that carbon is formed in the manner given in Figure 9. The last step for hydrocarbons other than the aromatic structure, is C_2H_2 (acetylene) which then forms carbon and hydrogen. For the aromatic compounds, the carbon formation step need not go through only the C_2H_2 step but can be formed directly from the benzene ring structure as well as going through the C_2H_2 step.

The question arises why can't we produce benzene type structure hydrocarbon as transportation fuels, from coal which then will require the least quantity of hydrogen and be the least expensive to produce.

To answer this question Figure 10 is presented. In Figure 10 the tendency to smoke of a flame burning under steady state condition as function of fuel structure for carbon atoms fuels between 10 to 13 are presented. In Figure 10 it can be seen paraffin type of fuel which has the highest H/C ratio has the lowest tendency to smoke, whereas naphthlenic type of fuels which has the lowest H/C ratio has the highest tendency the smoke.

Even though liquid fuels of naphthalenic structure require the least quantity of hydrogen to produce from coal , it seems that certain types of transportation engines cannot use them. For example, at present the specification of aromatic content for jet engine fuels is limited to about 20%. The reason for this is probably the smoking tendency. The aromatic content of diesel engine fuels, I think, are kept below 30% by the refinery.

The spark ignited homogeneous mixture burning engine can probably tolerate higher aromatic content fuels if the fuel mixture entering the combustion chamber is in a homogeneous vapor state. This however is a guess, so further experimental research is required. From background material presented in this paper, let us see what information is needed to be able to use synthetic fuels of low H/C ratio in various types of engines. Some of the questions are:

1. Will a homogeneous fuel mixture spark ignited engine tolerate high napthelenic type of fuels if properly vaporized and mixed?
2. What effect does turbulence have on the capability of SI engines to burn high aromatic structured fuels.

3. What effect will EGR have on high aromatic type of fuel?
4. How much deposits will these fuels form in the combustion chamber?
5. What effect will air to fuel ratio have on the operation of the engine with these fuels?
6. Can diesel engines be designed to burn these fuels?
7. Can jet engines combustion chambers be designed to burn these fuels?
8. Can a more efficient method be devised to generate H_2?
9. What is the economics of using power plants (electricity) during periods of low demand to generate hydrogen by electrolysis. (It will generate both H_2 and O_2) both useable for the H-coal process given in Figure 7.
10. How much HC would be formed in reciprocating engines using this type of fuel?
11. Could water in fuel emulsified fuel help in reducing the tendency to smoke?

Further Comments

Is it time (1979) now to start to plan and construct a large (4 million barrels per day capacity) coal to syncrude plant, which will probably take about 5 years from the drawing board to operational stage. The output of the syncrude plant

(H/C = 1.27) can then be mixed with the crude oil from the ground. In this manner we can produce an average crude oil an average produce with an H/C of between 1.7 to 1.9 range which can have a much better chance of satisfying the transportation fuel requirements and at the same time reduce our petroleum import.

In my own opinion we do not have much time to dilly dally around before we take some action. I know the cost is very high but the cost will probably be much higher in the future if no action is taken.

In appendix a very rough estimate of the cost of the raw material (H_2) is given for producing a barrel of syncrude of various H/C compositions. The cost is very very high if the syncrude H/C ratio requirement is in the 1.9 range.

REFERENCES

1. "Diesel Vehicles? - Crude Oil Scene", O. A. Uyehara, presented in 1976 SAE meeting in Detroit. SAE Paper No. 760210.

2. 1978 Gas Mileage Guide, First Edition, Fuel Economy - FEA/D-77/372, U.S. Environmental Protection Agency.

3. "Resources and Man", M.K. Hubbert, W. H. Freeman and Company, San Francisco, 1969.

4. Synthetic Fuels and Combustion, Plenany Lecture, presented at the 16th Symposium (International) on Combustion, August 1976 at MIT, Cambridge, Mass.

5. "The Mechanism of Carbon Formation", George Porter, Agard - Memorandom AG 13/M19, May, 1954.

6. "Carbon Formation in the Combustion Wave", 4th Combustion Symposium, Williams and Wilkins, pg. 248, 1952.

7. "Coal Liquification by the Exxon Donor Solvent Process", L. E. Furlong, E. Effron, L. W. Vernon, E. L. Wilson, 1975 National AIChE Meeting, Los Angeles, California, November 18, 1975.

8. "The H-Coal Pilot Plant Program", H. H. Stotter, Coal Process Technology, Vol. 2, New York, AIChE, 1975.

9. The data points for constructing the petroleum plots were taken from the following publications:

    a. Oil and Gas Journal
    b. World Oil

LIST OF FIGURES

ACKNOWLEDGEMENT

I wish to thank Mrs. Sally Radecke for typing the manuscript, to John Olson for preparing the drawings and the Mechanical Engineering Department for letting us pursue our interests.

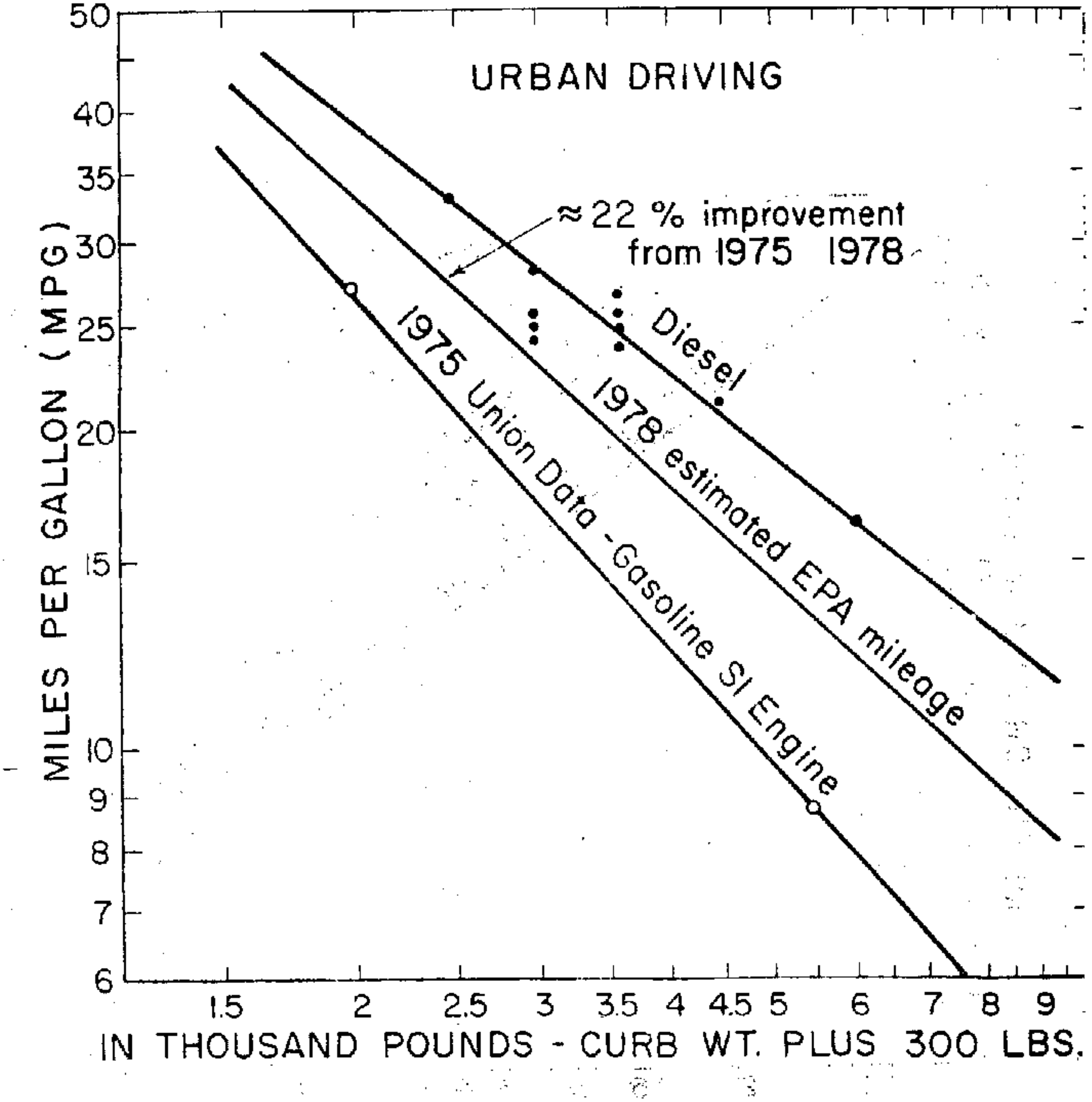

URBAN DRIVING
≈ 22 % improvement from 1975 1978
Diesel
1978 estimated EPA mileage
1975 Union Data - Gasoline SI Engine
MILES PER GALLON (MPG)
50
40
35
30
25
20
15
10
9
8
7
6
1.5
2
2.5
3
3.5
4
4.5
5
6
7
8
9
IN THOUSAND POUNDS - CURB WT. PLUS 300 LBS.

Fig. 1

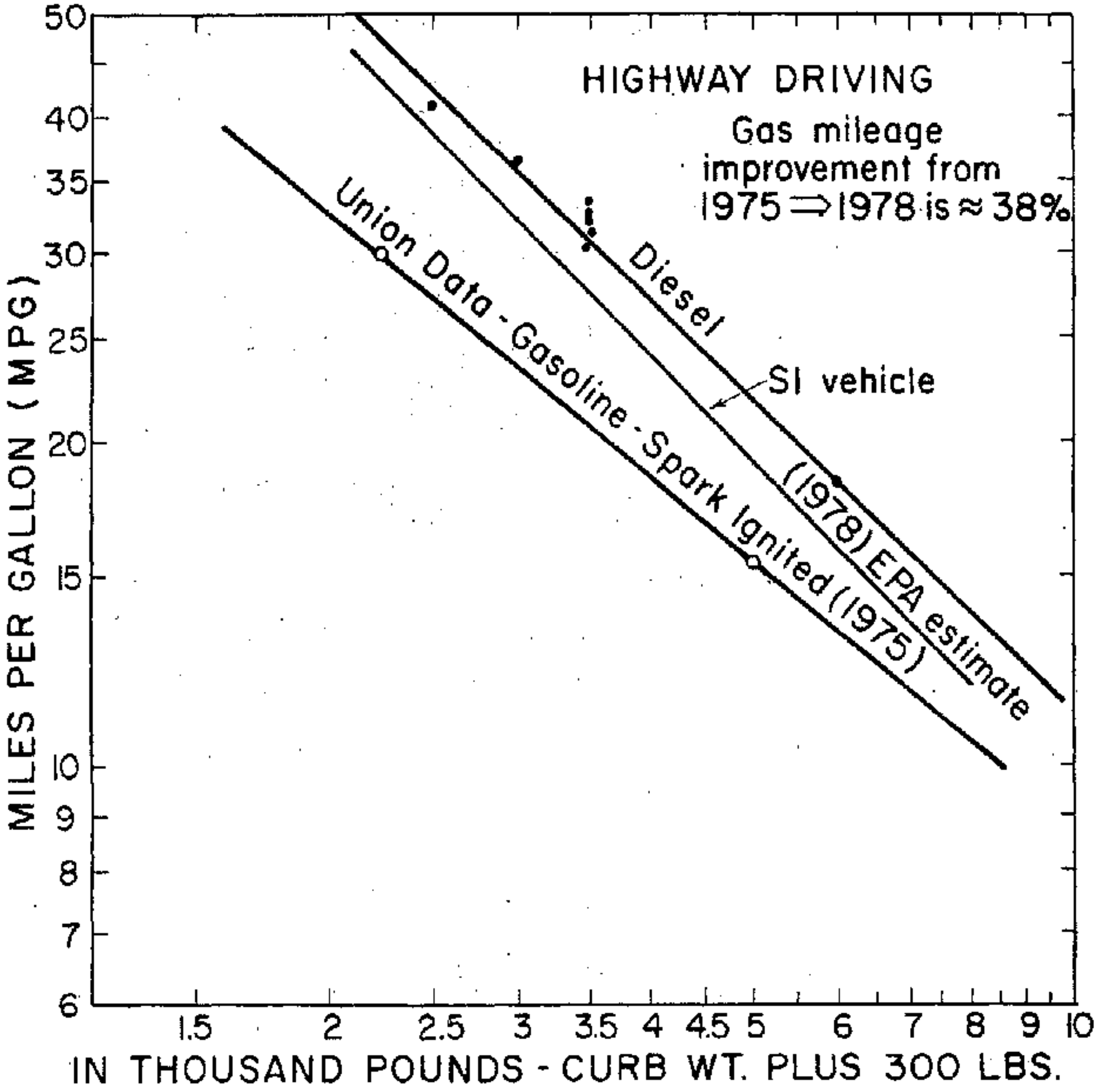

HIGHWAY DRIVING
Gas mileage improvement from 1975 ⇒ 1978 is ≈ 38%
Diesel
SI vehicle
(1978) EPA estimate
Union Data - Gasoline - Spark Ignited (1975)
MILES PER GALLON (MPG)
50
40
35
30
25
20
15
10
9
8
7
6
1.5
2
2.5
3
3.5
4
4.5
5
6
7
8
9
10
IN THOUSAND POUNDS - CURB WT. PLUS 300 LBS.

Fig. 2

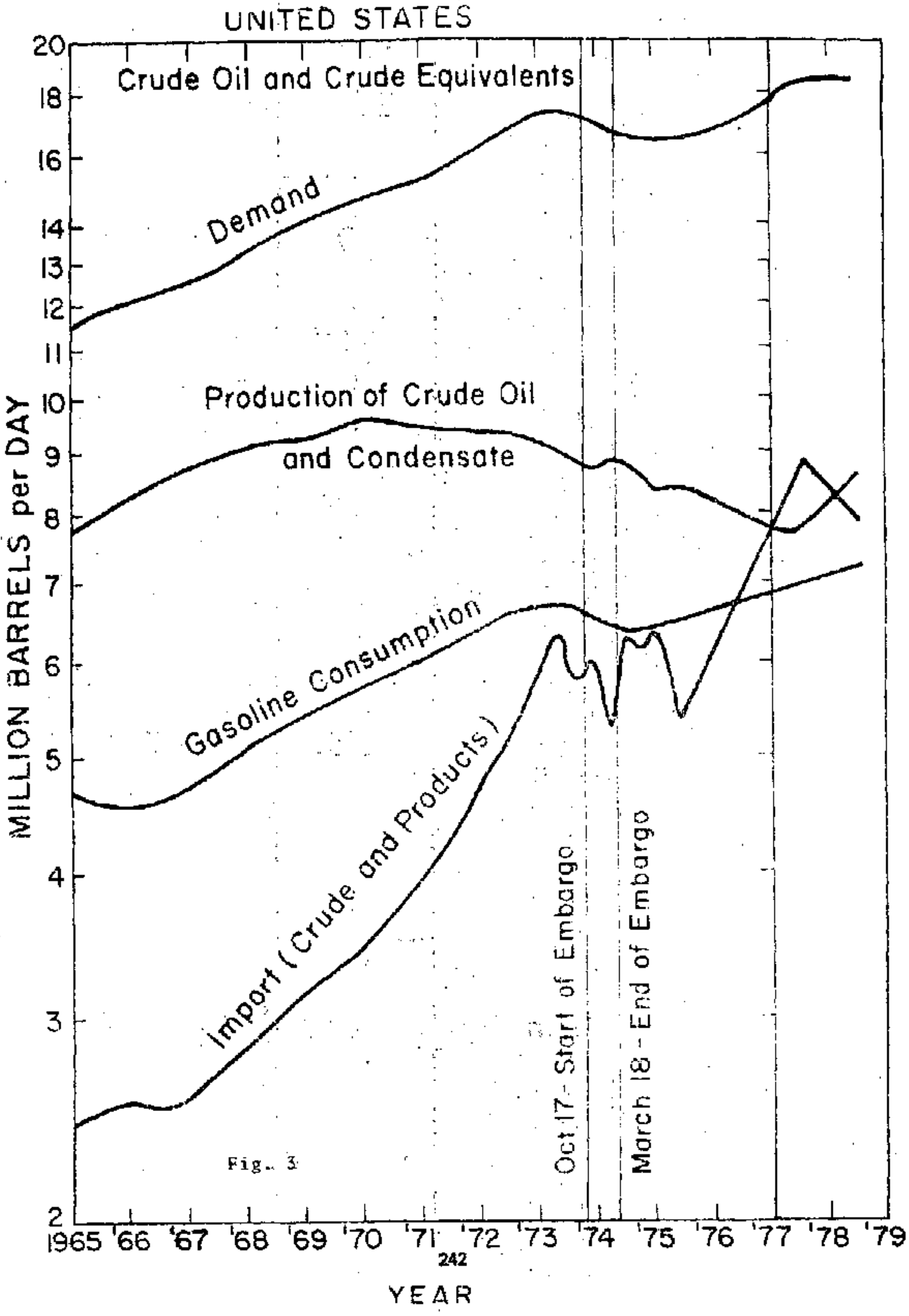
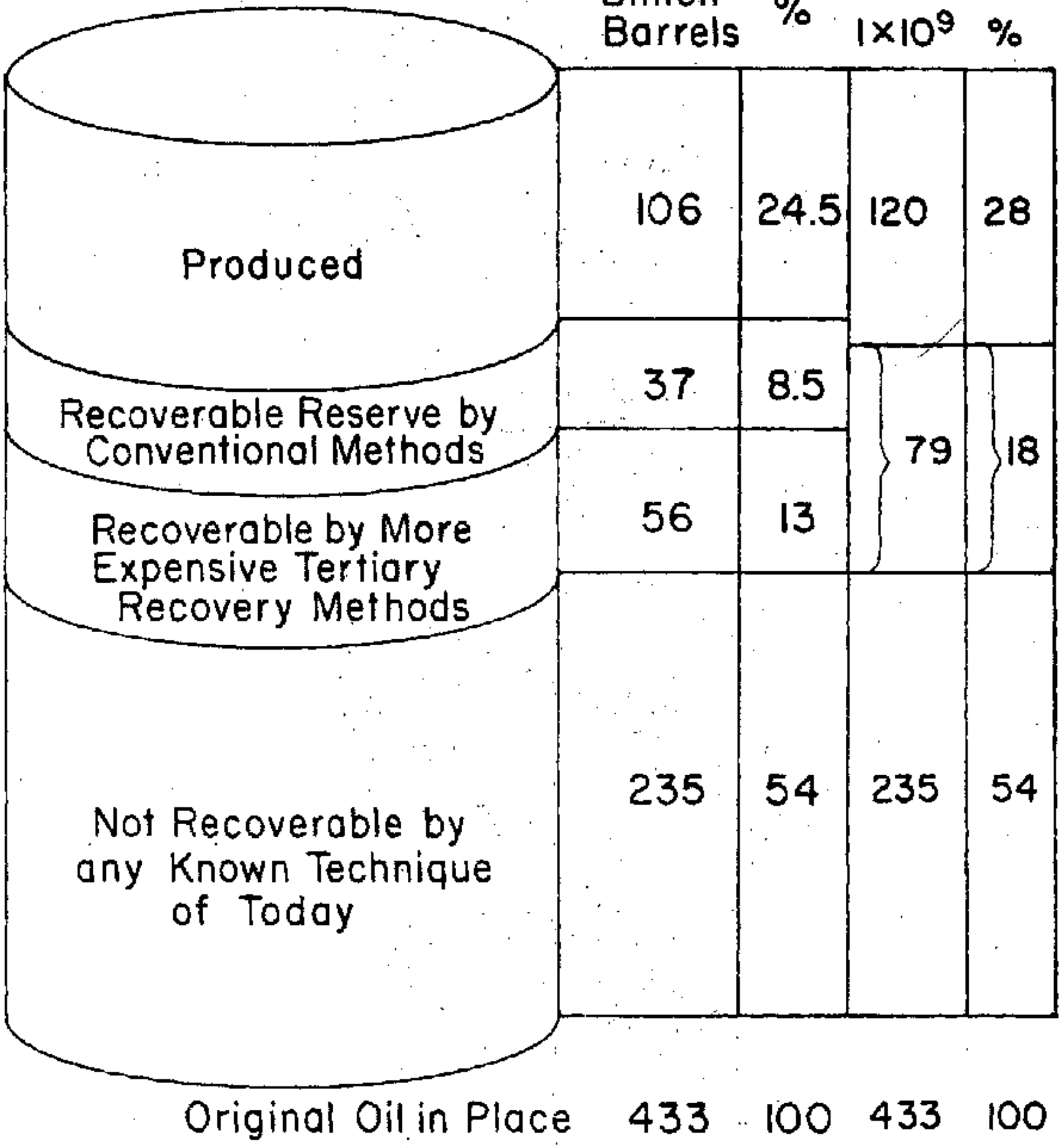

UNITED STATES
Crude Oil and Crude Equivalents
Demand
Production of Crude Oil
and Condensate
Gasoline Consumption
Import (Crude and Products)
Oct 17 - Start of Embargo
March 18 - End of Embargo
MILLION BARRELS per DAY
20
18
16
14
13
12
11
10
9
8
7
6
5
4
3
2
1965
'66
'67
'68
'69
'70
'71
'72
'73
'74
'75
'76
'77
'78
'79
YEAR

Fig. 3

US Crude Oil "Barrel"
as of Nov 1975



			Jan '79	
	Billion Barrels	%	1×10^9	%
Produced	106	24.5	120	28
Recoverable Reserve by Conventional Methods	37	8.5	79	18
Recoverable by More Expensive Tertiary Recovery Methods	56	13		
Not Recoverable by any Known Technique of Today	235	54	235	54
Original Oil in Place	433	100	433	100

Fig. 4

UNITED STATES PETROLEUM

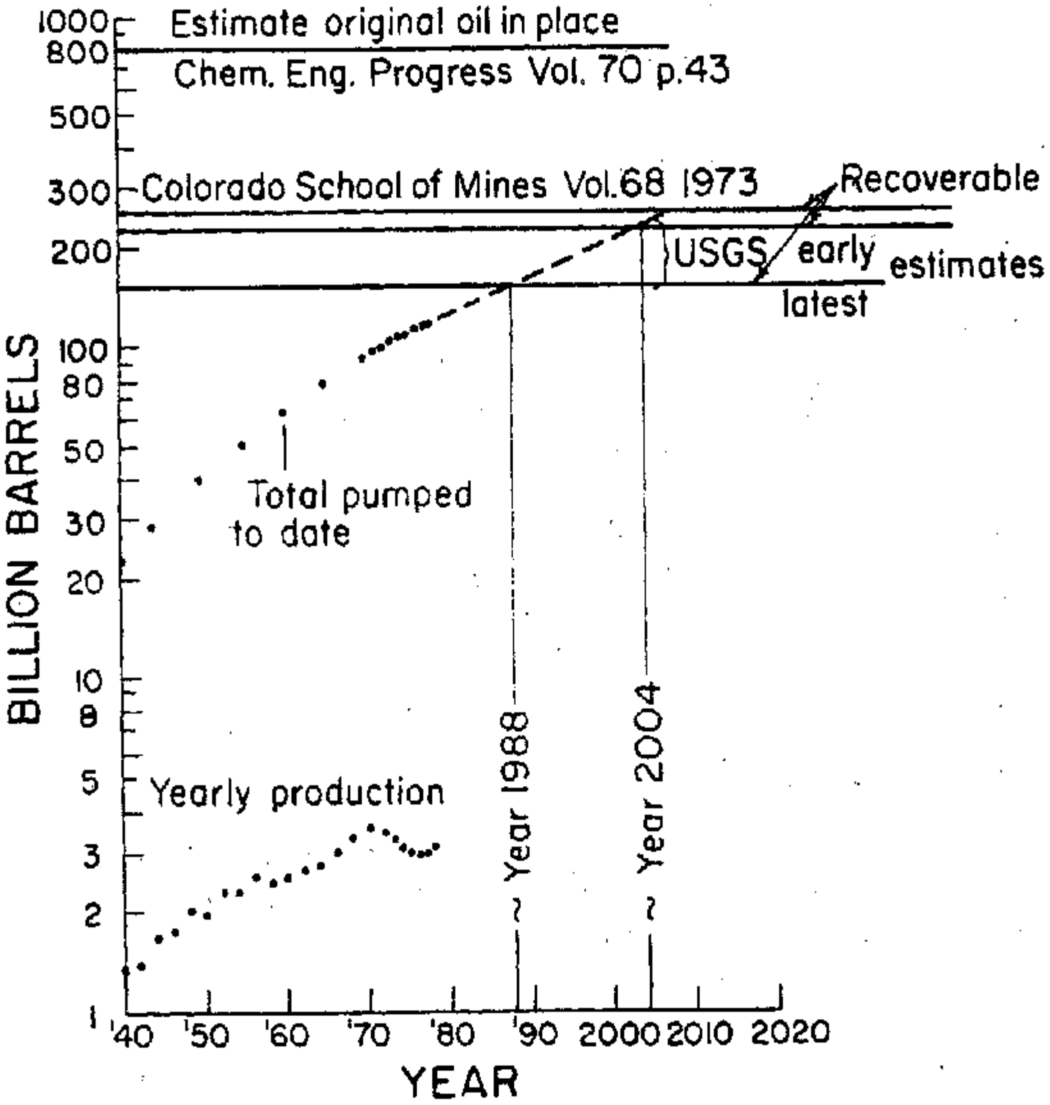


Fig. 5

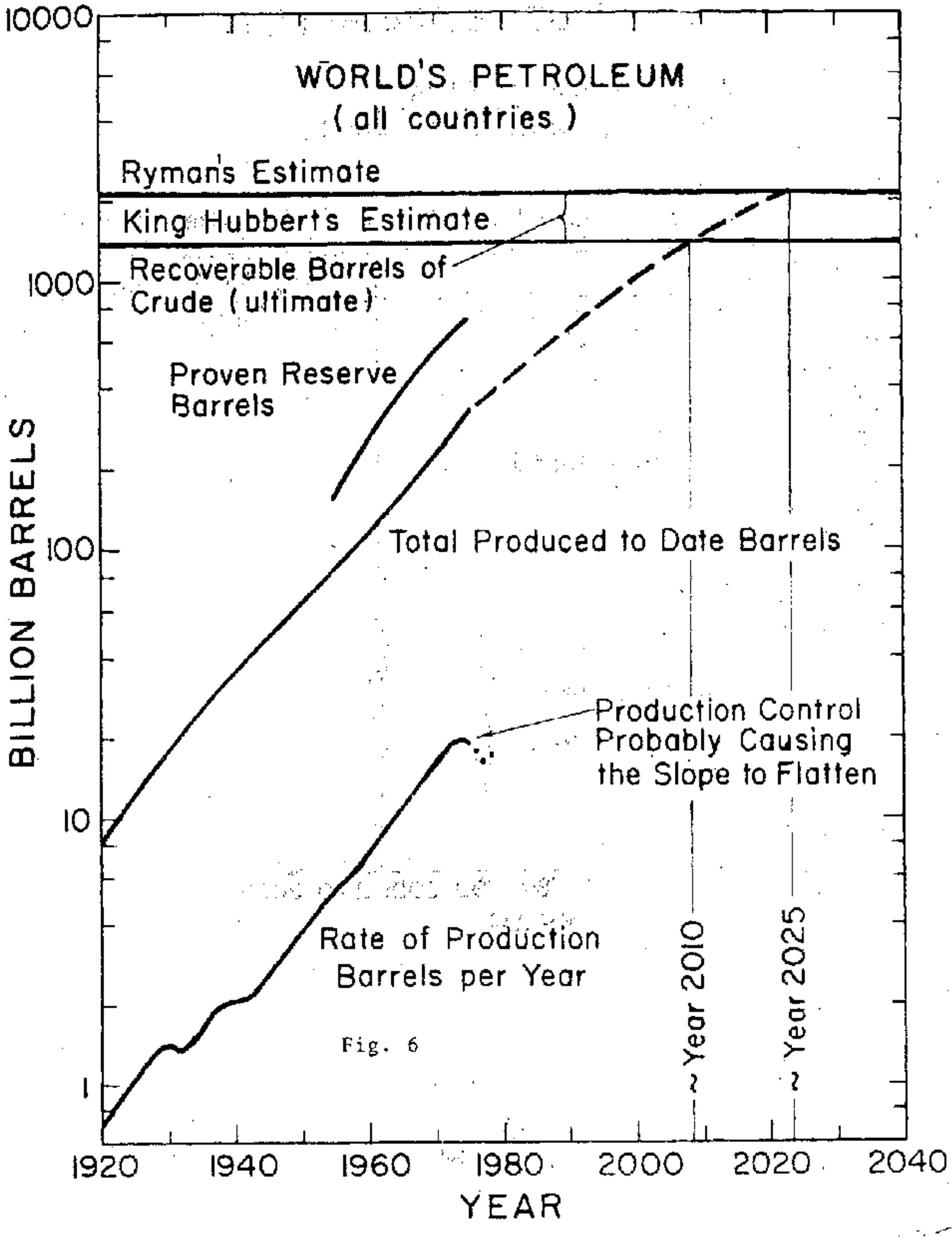
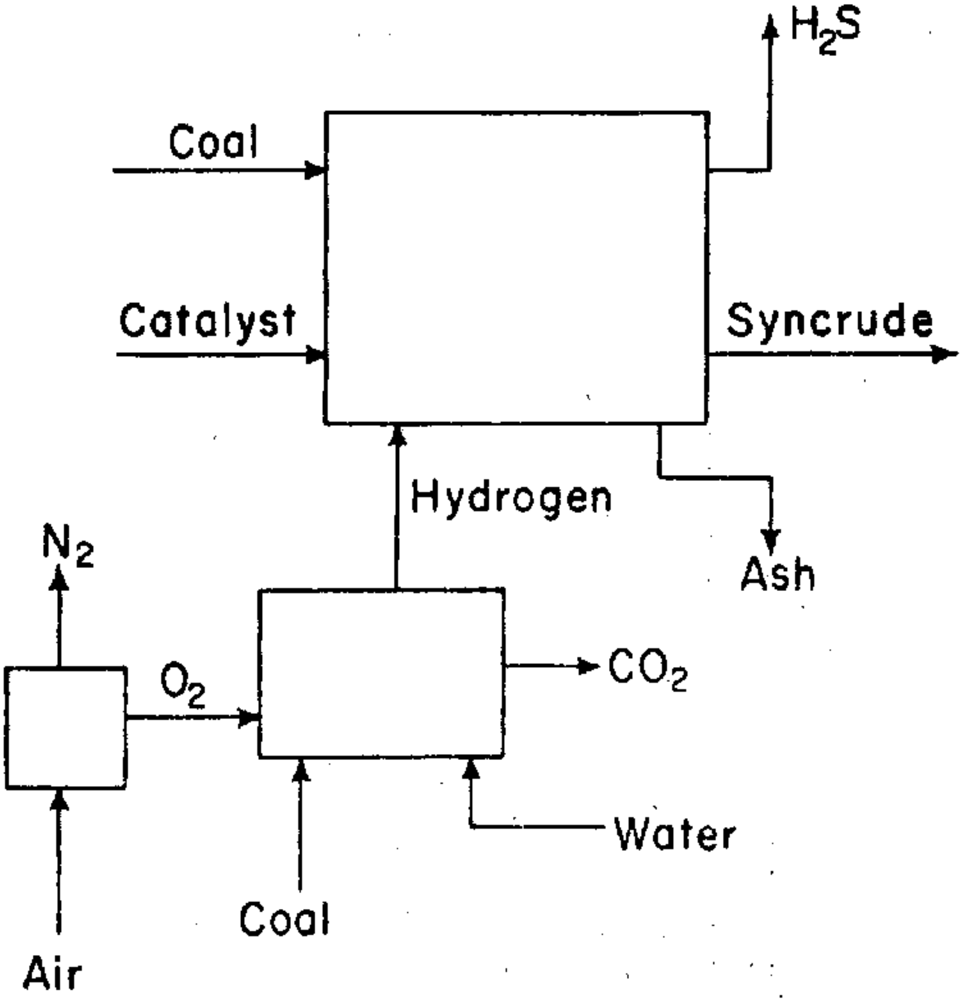

WORLD'S PETROLEUM
(all countries)
Ryman's Estimate
King Hubbert's Estimate
Recoverable Barrels of Crude (ultimate)
Proven Reserve Barrels
Total Produced to Date Barrels
Production Control Probably Causing the Slope to Flatten
Rate of Production Barrels per Year
~ Year 2010
~ Year 2025
BILLION BARRELS
10000
1000
100
10
1
1920
1940
1960
1980
2000
2020
2040
YEAR

Fig. 6



2000 lb Coal → 2.75 Barrels of Syncrude

% Chemical Energy Lost ≅ 30 %

Fig. 7

Liquid hydrocarbons atomic H/C ratio for different structures containing 10 carbon atoms

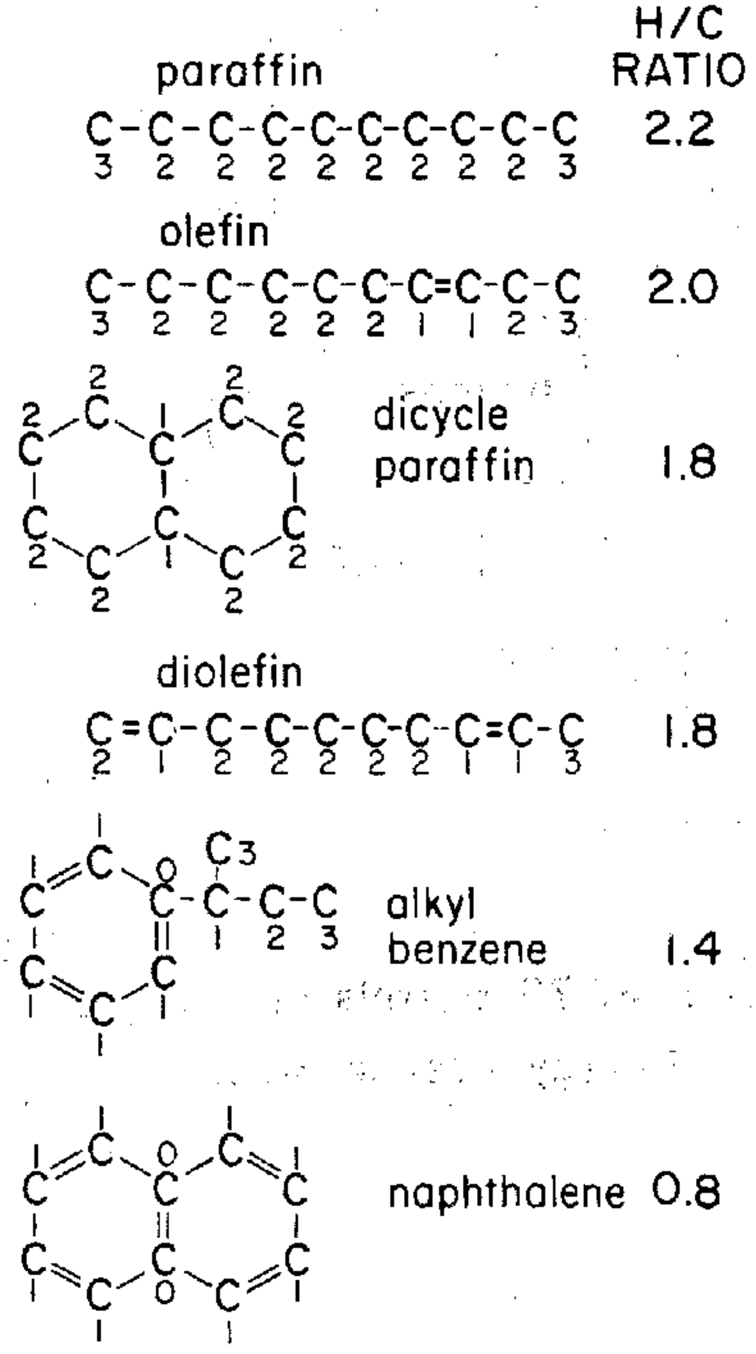


Fig. 8

From Porter :

$2CH_4 \Rightarrow C_2H_6 + H_2$

$C_2H_6 \Rightarrow C_2H_4 + H_2$

Higher paraffins ⇒ Lower paraffins + olefins

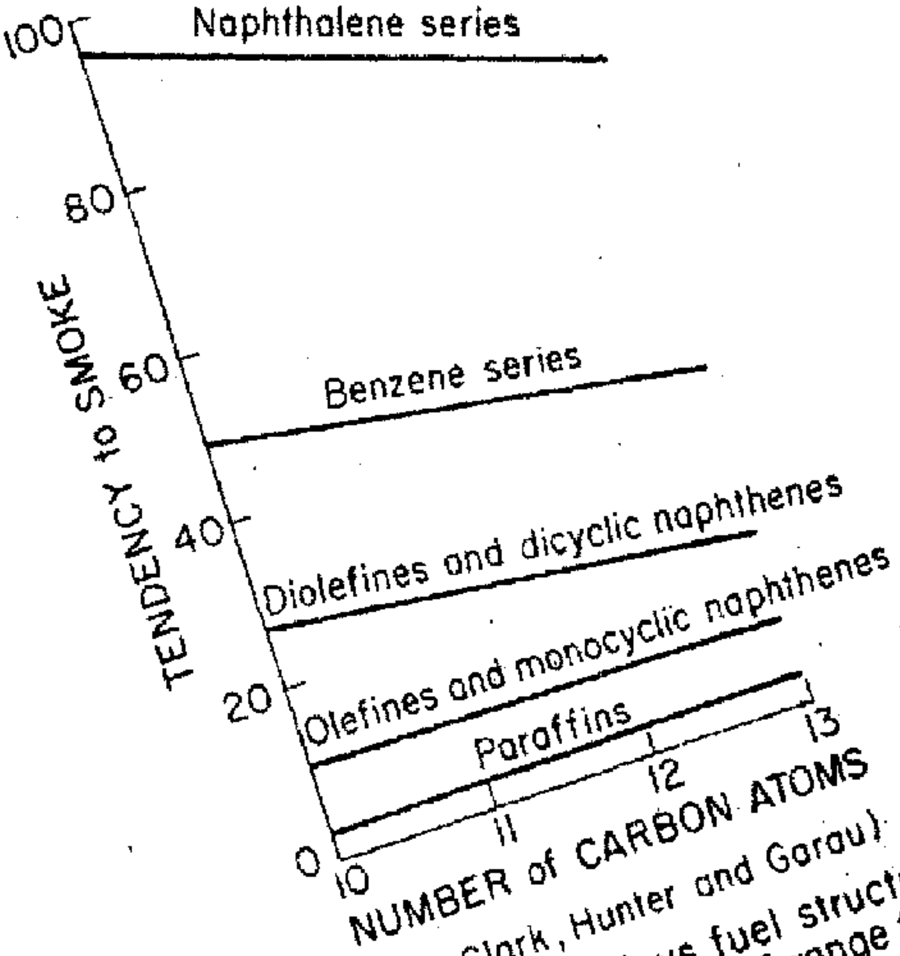
Higher olefins ⇒ Lower olefins + paraffins + acetylene

$C_2H_4 \Rightarrow C_2H_2 + H_2$

Aromatics ⇒ Carbon + CH_4 + C_2H_2 + H_2

$C_2H_2 \Rightarrow C + H_2$

Fig. 9



(after Clark, Hunter and Garau)

Tendency of various fuel structure with carbon in the 10 to 13 range to smoke

Fig. 10

ESTIMATE - H_2 COST vs H/C SYNCRUDE

Data base - Longwell (4)
H_2(gas) cost \$2.00/1000 ft^3 (1980)
Coal cost \$20.00/ton (1982)
Coal H/C = 0.75
H_2 required, coal $\Rightarrow$ H/C = 1.27 sync = 4100 ft^3
H_2 required, syn. H/C = 1.27 $\Rightarrow$ syn. H/C = 1.53 (3500)
$\therefore H_2$ required coal $\Rightarrow$ syn. H/C = 1.53 = 7600 ft^3

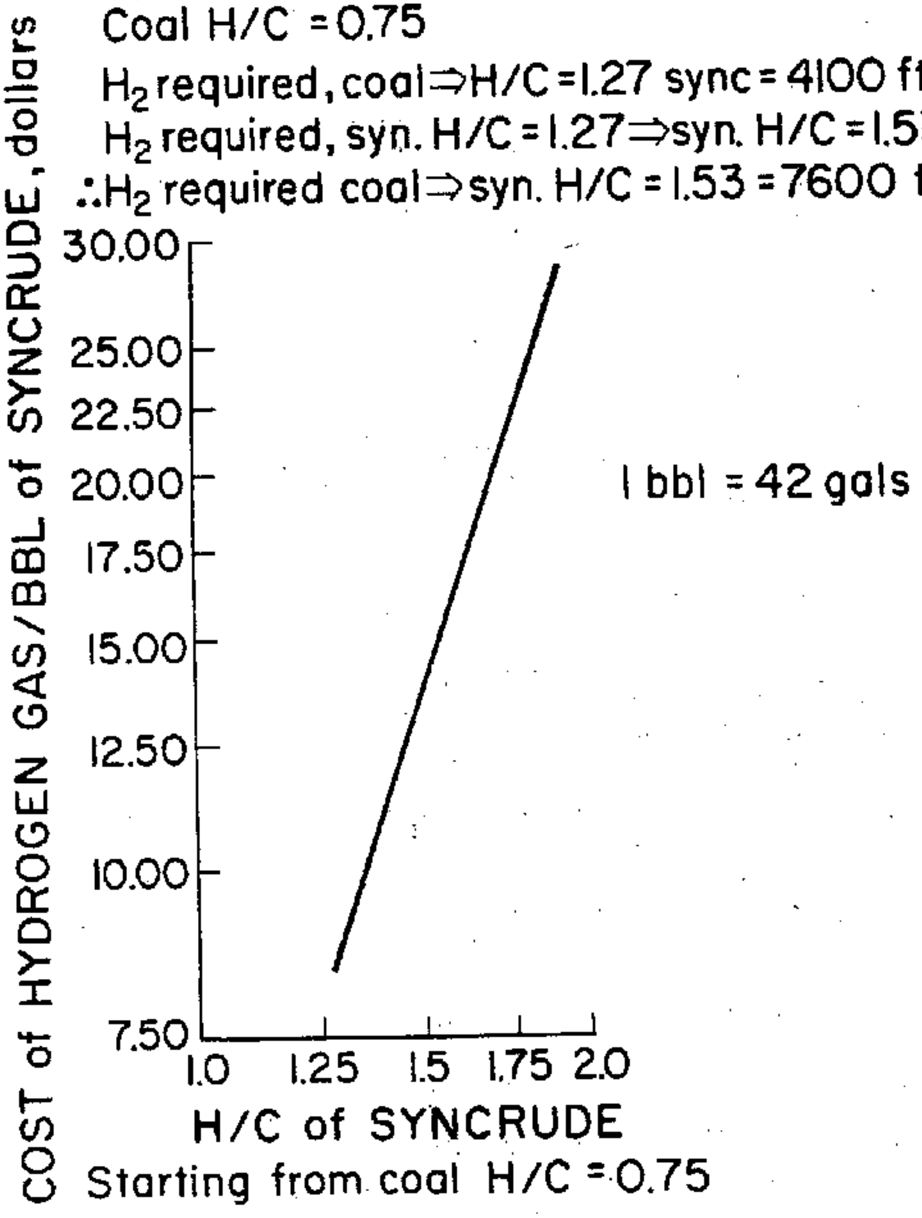
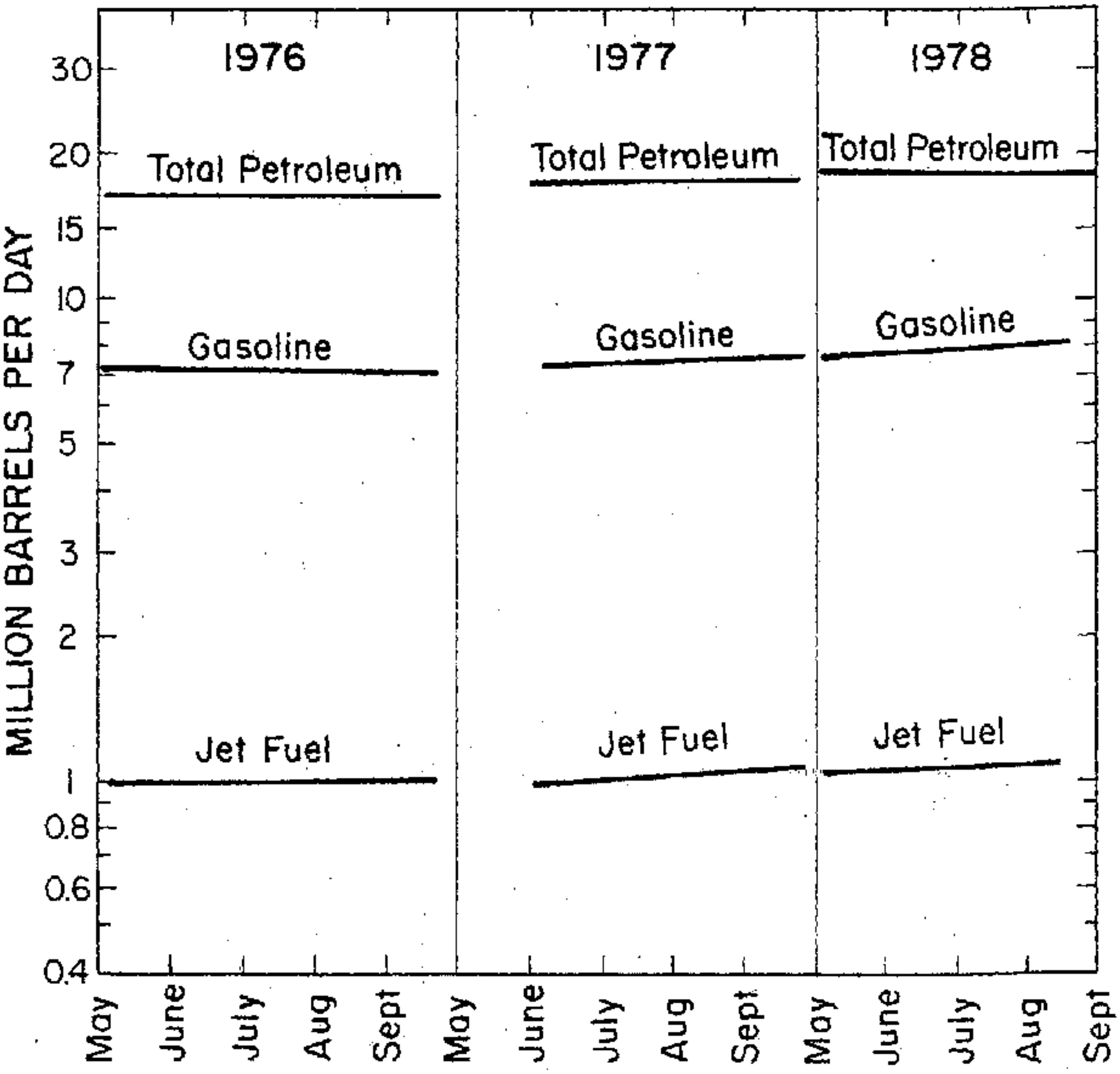


Fig. I-A


1976
1977
1978
Total Petroleum
Total Petroleum
Total Petroleum
Gasoline
Gasoline
Gasoline
Jet Fuel
Jet Fuel
Jet Fuel
MILLION BARRELS PER DAY
30
20
15
10
7
5
3
2
1
0.8
0.6
0.4
May
June
July
Aug
Sept
May
June
July
Aug
Sept
May
June
July
Aug
Sept

TRANSPORTATION FUELS—CRITICAL RESEARCH PROBLEMS

A.M. Mellor
Purdue University

Pulsed Spray Ignition

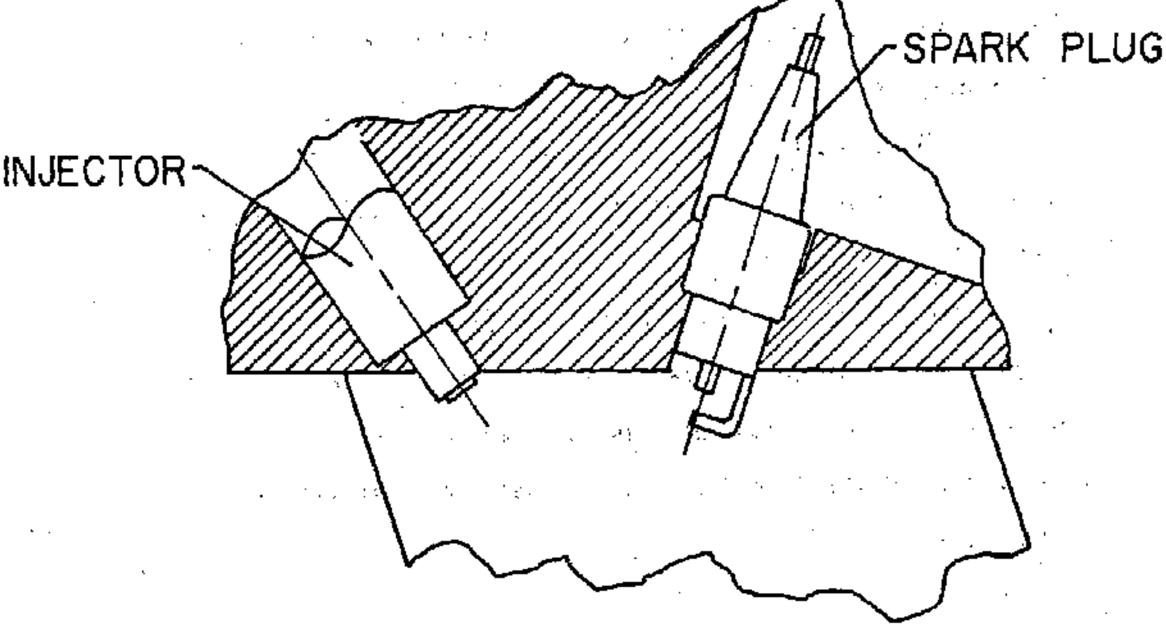
Due to the prospects of improved combustion efficiency and reduced emissions burning with very lean mixtures in reciprocating engines is highly desirable. However, as the lean limit is approached misfire in one or more cylinders becomes a severe problem due to the obvious performance degradation. Fuel injection is one means of burning with a lean overall equivalence since locally high equivalences are provided near the spark plug.

Fuel properties can affect the lean limit in a fuel injected engine in a variety of ways. For example, when misfire is occurring at the onset of ignition due to the inability of the spark to evaporate the fuel and heat the mixture to a temperature high enough for reactions to proceed unaided, an increase in volatility or decrease in viscosity would enhance evaporation and hence ignition as discussed for the continuous combustors. If, on the other hand, misfire is caused by poor fuel distribution or the lack of mixing, increasing the drop size can improve penetration of the fuel jet and reduce the lean limit. Obviously, these factors are strongly dependent on the fluid mechanics in the cylinder which are not well understood and require much more experimental work.

There are, of course, several factors which influence ignition other than fuel properties such as spark and injection timing, cylinder geometry, and injector performance. Depending on the type of injector, spray quality can be poor during the beginning and end of the injection cycle and this change of drop size with time can inhibit ignition.

PULSED SPRAY IGNITION

- FUEL VOLATILITY
- FUEL VISCOSITY
- FUEL PENETRATION AND MIXING
- INJECTION AND IGNITION TIMING
- SPRAY QUALITY TIME DEPENDENCE



PURDUE

Heavy Fuels Increase Combustion Inefficiency

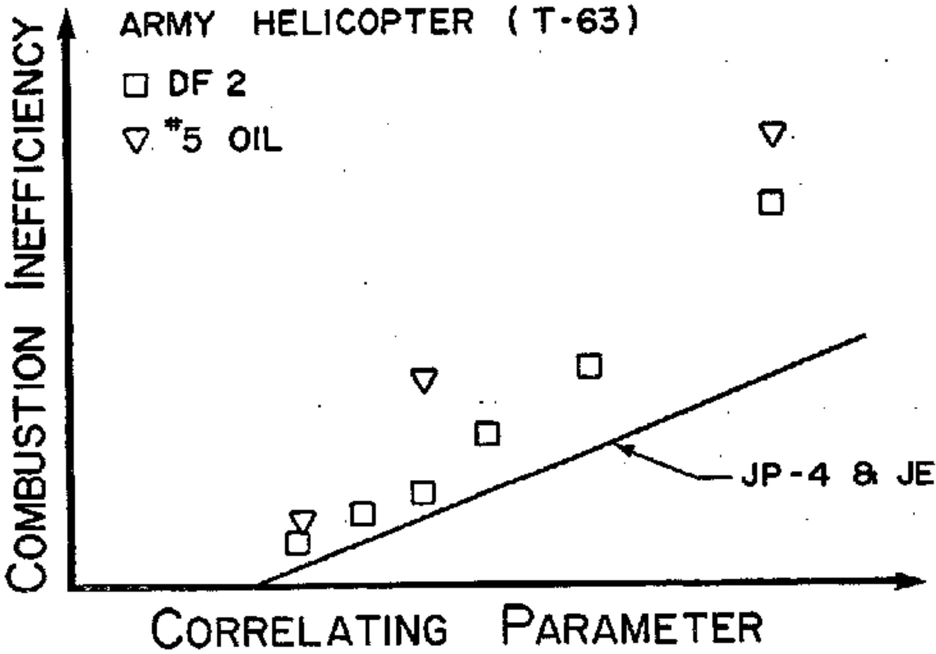
The selection of a gas turbine engine (the AGT 1500) as the power source for the next generation main Army battle tank and this engine's multi-fuel and long range (fuel economy) requirement has stimulated investigation into the effect of fuel type upon combustion inefficiency (i.e. CO and unburned HC emissions). Typically combustion inefficiency increases with heavier fuels; that is, as fuel volatility decreases (and viscosity increases), fuel droplets become more difficult to vaporize and combust.

A relationship has been developed (and is incorporated in the accompanying graph) which correlates combustion inefficiency from conventional gas turbine combustors (such as the T-63 Army helicopter liner) burning light (i.e. volatile and non-viscous) fuels only (such as liquid propane, JP-4, and Jet A). This correlation accounts for variation in fuel type, inlet air temperature, fuel-air ratio, pressure, reference velocity, and liner configuration.

However, this correlation does not predict the increased combustion inefficiency from heavy fuels (such as #2 Diesel fuel or #5 oil). Hence, more work is required in order to include the effect of droplets from heavier fuels upon combustion inefficiency.

HEAVY FUELS INCREASE COMBUSTION INEFFICIENCY

- INLET TEMPERATURE, PRESSURE, FUEL-AIR RATIO, & FUEL TYPE ARE CORRELATED (LIGHT FUELS ONLY)
- HEAVY FUELS (DF 2 & #5 OIL) INCREASE COMBUSTION INEFFICIENCY
- REQUIRE FURTHER WORK TO CORRELATE HEAVY FUEL EFFECTS

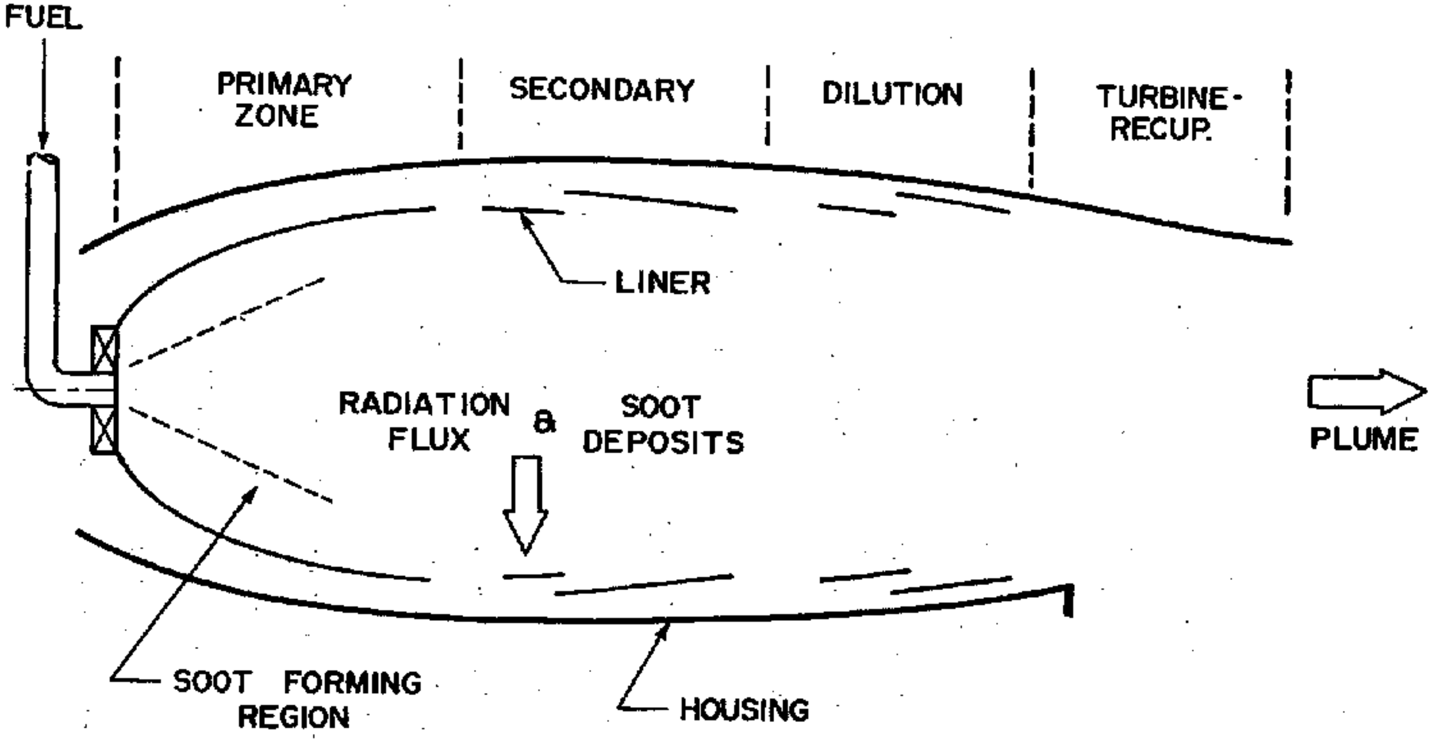


Effects of Soot Formation

Depicted in this viewgraph is a generalized gas turbine combustor. Combustion in the primary recirculation zone yields the majority of total heat released. In the secondary and dilution zones combustion is completed and the temperature traverse stabilized. Fluid then travels through the turbine and recuperator sections where energy is extracted before exhausting to the atmosphere.

Early in the progression of events shown on encounters the soot forming region. This region corresponds primarily to the volume in and near the fuel spray. The effect of this soot formation is felt at all locations downstream. Growth of soot deposits and increased radiant flux to the linear wall may critically reduce the effectiveness of film cooling. Detached soot deposits may damage turbine blades as well as clog passages in the recuperator. Visibility of the exhaust plume in conjunction with its infrared signature is of considerable importance in tactical situations.

EFFECTS OF SOOT FORMATION



- Deposition
- Visible Plume
- Liner Heat Flux

PURDUE

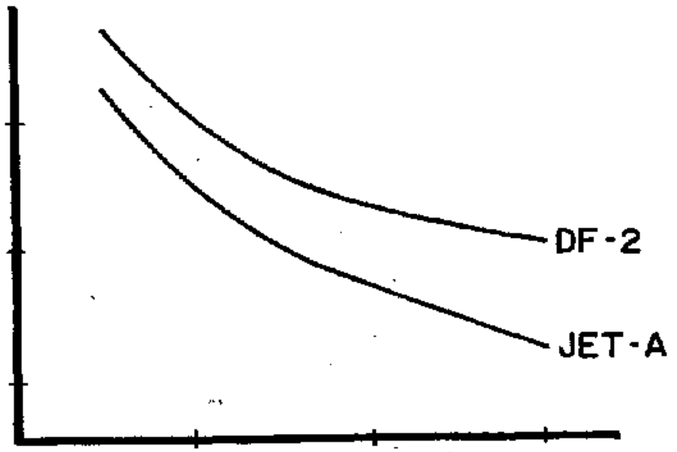
Heavy Fuels Increase Smoke and Radiation

In clean flames, little soot is produced and most of the radiation received by the combustor liner is band radiation, from water and carbon dioxide. In sooty, or luminous, flames the majority of radiation absorbed by the liner emanates from the smoke particles. The magnitude of this soot radiation is normally much greater than the magnitude of the band radiation. Thus, soot is the single most important source of combustor radiation. To demonstrate the relative "brightness" of clean and sooty flames, this picture of a clean flame (upper left corner) was taken at Purdue with an exposure time of 1/30th of a second. The sooty flame picture was also taken at Purdue, and the exposure time was 1/1000th of a second.

It has been shown that smoke particles and their associated high level of radiation produce three undesirable effects in gas turbine combustion. First, heavy sooting can lead to deposit formation. Second, smoke production means exhaust visibility, which is especially undesirable for military applications. Finally, high levels of combustor radiation lead to decreased liner lifetime.

The graph in the upper right corner is a plot of smoke mass concentration data measured at Purdue versus axial distance from the fuel injector. The lower curve is for Jet-A fuel and the upper curve is an indication of the increased smoke forming tendencies of heavier fuels like Diesel Fuel #2.

HEAVY FUELS INCREASE SMOKE & RADIATION



SMOKE MASS VS AXIAL DISTANCE

CLEAN FLAME
SOOTY FLAME

SMOKE & RADIATION EFFECTS

- DEPOSIT FORMATION
- EXHAUST VISIBILITY
- DECREASED LINER LIFETIME

PURDUE

Parameters Affecting Ignition Limit

For ignition to occur in a gas turbine engine the energy from the spark plug must evaporate a portion of the fuel and then heat the fuel vapor and air mixture so combustion can proceed unaided.

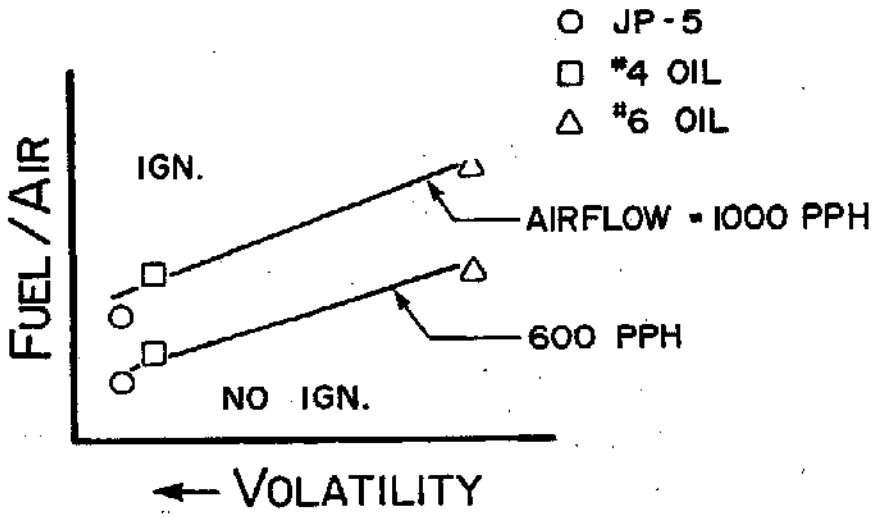
The volatility of a fuel is simply a measure of how readily the fuel changes from a liquid to a gas and thus increased volatility eases ignitability. The average drop size of a spray strongly depends on the viscosity of the fuel -- as viscosity decreases so does the average drop diameter. A reduction in the average drop diameter of a spray creates more surface area for the evaporation process. Consequently, decreasing the viscosity of a fuel increases the ignitability of that fuel. In addition, the average drop size of a spray is influenced by injector performance (pressure drop across the nozzle, for example).

The air flow rate near the igniter should be held to a minimum since increases in the velocity will promote heat loss from the spark area, reducing the energy available for ignition. The igniter will obviously affect the ignition process through variables such as energy per spark, spark repitition rate, and igniter location.

As an example of the importance of fuel volatility and the effect of air flow rate (in pounds per hour), the figure contains ignition limit data for the AGT -- 1500 obtained by Avco-Lycoming and correlated at Purdue. As previously noted, ignition is enhanced as the volatility increases.

PARAMETERS AFFECTING IGNITION LIMIT

- Fuel Volatility
- Fuel Viscosity
- Air Flow Rate
- Injector Performance
- Igniter Performance



Purdue Correlation of AGT-1500 Ignition Limit

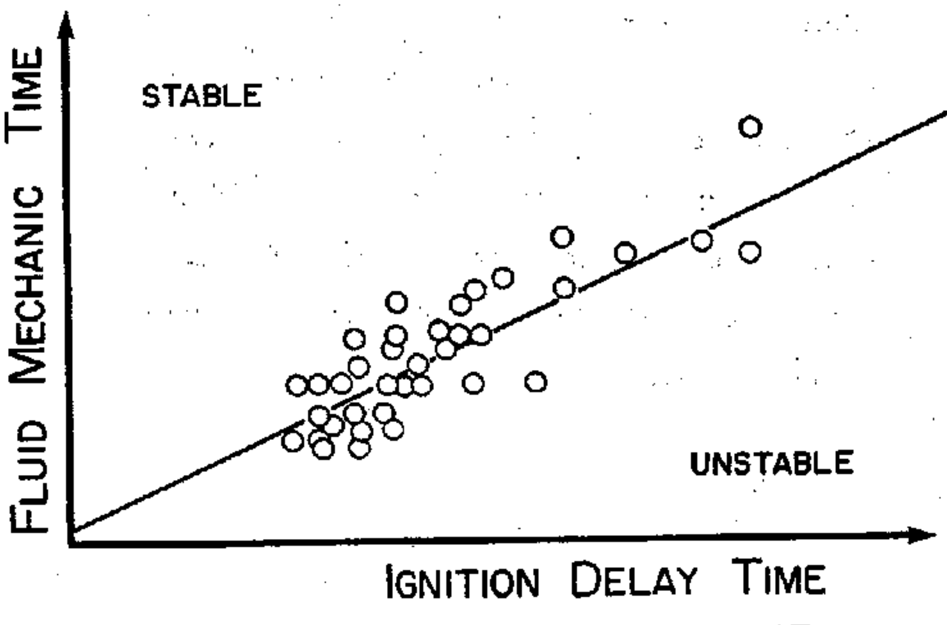
PURDUE

Light Fuel Correlation for Flame Stabilization

This slide illustrates the Purdue correlation for lean blow off. Flame stabilization involves the competition between a fluid mechanic and chemical time. For a given combustor operating point (consistent fluid mechanic time), too long an ignition delay time precludes stable combustion; therefore, one approaches the lean blow off limit by increasing the air velocity (decreasing the fluid mechanic time) or decreasing the fuel flow rate (increasing the ignition delay time). The correlation shown in the slide includes variations in combustor pressure, inlet temperature, velocity and geometry (disc-in-duct configuration) for flames in which heterogeneous effects are negligible. The model does not yet properly include heavy fuel effects which have been encountered with fuels such as DF-2. In an effort to include heterogeneous effects, appropriate time scales are being considered which incorporate fuel properties such as volatility and viscosity.

LIGHT FUEL CORRELATION FOR FLAME STABILIZATION

- Model Correlates Pressure, Inlet Temperature, Velocity And Geometry (Light Fuels Only)
- Heavy Fuel Effects Are Significant (DF-2)
- Require Further Work To Correlate Heavy Fuels



Purdue Correlation For Lean Blowoff
(Light Fuels)

PURDUE

Fuel Property Influence on Combustor Performance

Military preparedness in an era of limited petroleum resources requires that the multifuel capability of various propulsive devices be known quantitatively. For example, how wide a variation in fuel viscosity and boiling point range can be accommodated in the standard AGT-1500 Army main battle tank gas turbine engine in both emergency and long term substitutions?

In general, the heat release rate of a flame in a conventional gas turbine burning an aviation specification fuel is controlled by the rate of mixing between fuel vapor and air. Although liquid fuel is used, the fuel evaporation rate is normally much greater than this mixing rate. However, the use of aviation nonspecification fuels precludes the assumption that fuel evaporation rate exceeds this mixing rate. Thus, fuel viscosity and volatility are important determinants of gas turbine combustor performance in that they affect fuel evaporation rate. As is shown in this summary table, other fuel properties are also important, and performance criteria must be defined for combustion efficiency, blow off, exhaust smoke, flame radiation and ignition.

FUEL PROPERTY INFLUENCE ON COMBUSTOR PERFORMANCE

	PROBABLY IMPORTANT IN			
FUEL PROPERTY	COMB. EFF.	IGN.	LEAN BLOW OFF	SMOKE AND RAD.
VOLATILITY	X	X	X	X
VISCOSITY	X	X	X	X
HEAT OF COMBUSTION	X		X?	
AROMATIC CONTENT	X?			X

PURDUE

TRANSPORTATION FUELS RESEARCH AND TECHNICAL EDUCATION

R.T. Johnson
University of Missouri-Rolla

TRANSPORTATION FUELS RESEARCH
AND
TECHNICAL EDUCATION

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Mechanical Engineering Department
University of Missouri-Rolla

INTRODUCTION

Academic research has long been one of the more important aspects of university life. It is one of the basic mechanisms for increasing the scope of knowledge and keeping faculty current in their area of specialization. In addition, the active participation of faculty members in a research program leads to continual upgrading of the educational program as they bring new methods and information to the classroom. Basically, university engineering research has two objectives:

1. To pose and investigate technical problems and thus add to the general knowledge of the field.
2. To educate people in an area of technical specialization - in this case the area of transportation energy and fuels.

Since these objectives are somewhat different than those of a corporate or government research organization, a portion of this paper is devoted to describing the advantages and disadvantages of engineering research at the university level. With this information as a background, the current and near future program of alternative vehicle fuels and propulsion system research at the University of Missouri-Rolla is discussed.

ADVANTAGES AND DISADVANTAGES OF UNIVERSITY LEVEL ENGINEERING RESEARCH

DISADVANTAGES - As with any scientific endeavor, many problems confront the university research investigator. To begin with, most university research efforts are only part time. The faculty member who is the project director normally has many other duties during the academic year and cannot devote substantial time to research except during the summer recess and other periods when classes are not in session. There is some relief for this situation if the faculty member receives a portion of his academic year salary from grants and contracts outside the university. This outside support allows lighter teaching and administrative loads for the faculty member so that he can devote a greater portion of his time to the research effort. However, his effort is still only a part time committment.

Student assistants are a major part of most university research efforts. Both graduate and undergraduate students are involved in the fuels research program at UMR. Most graduate research assistants are working on a part time basis. The normal graduate appointment is for "half-time" effort. This half-time appointment allows the student to earn a subsistence wage working on the research project and spend the other half of his time trying to complete required course work. In most cases the research assistant will spend approximately one semester working full time on the research project (for half-time pay). This is due to his need to complete that portion of the work that constitutes his thesis for the graduate degree. Senior level undergraduate students are often employed on an hourly basis for the more routine aspects of a research project. In most cases they can work only a maximum of 10 to 15 hours per week. Usually they do not work the maximum number of hours per week because of the demands of their full-time course load. Considering the part-time effort of all the people involved, it takes substantial organization on the part of the faculty member to keep the project moving in the forward direction.

Since a great deal of the work done on a university research project is done by graduate and undergraduate students, the use of inexperienced personnel is a part of almost any research project. The training and self education of the advanced undergraduate and graduate students involved in the typical engineering research project is a time consuming and error prone process. The quality of the final work rests heavily on the faculty investigator and his ability to analyze results, ask the right questions, and keep the student's attention focused on the importance of consistent and reproducible results. Once the student has developed the experience and background to exhibit some degree of expertise and self confidence, he graduates and is eagerly recruited by industry, and the faculty research director once again returns to square one. Of course the other side of this coin is the fact that the faculty research director is providing people with specialized training and experience to the technical manpower of the country, which is one of the fundamental purposes of any engineering faculty member.

It is a well known and well advertized fact that university investigators, particularly in the engineering fields, have the perpetual problem of developing and maintaining adequate financial and equipment resources to keep a research program going. These problems are particularly acute for the experimentally oriented investigator who is not subsidized by the university as are many more theoretical investigators whose major research tools are the library and the computer. This condition leads to resourcefulness on the part of the faculty investigator and he learns how to apply the alchemy of converting sow's ears into silk purses. (Well, maybe not silk purses but certainly something that is functional and effective if it is not asthetically pleasing.) A significant amount of good quality scientific equipment has been assembled from surplus apparatus obtained from corporations and government agencies. This is not to imply that government and industrial research organizations do not have a problem in maintaining adequate resources to accomplish their mission. The problems there are very similar to those in the university, the only difference is the orders of magnitude involved.

The educational aspects of any university research program are also one of the problems that must be considered very carefully. Graduate students are most directly affected by university research projects because they are involved as assistants. Their involvement must not only be productive to the project but satisfy educational objectives in the graduate program of study, usually the thesis requirement. From the pedagogical point of view our objective is to produce a person with somewhat specialized technical skills who can conceive and formulate his own research or engineering efforts and carry them to a successful conclusion. For the faculty member trying to supply the motivation and guidance, this aspect of the educational process can indeed be trying. On the other hand there is great satisfaction in contributing to the professional development of the young individuals that we deal with. If, at the completion of his program, our student can write an intelligent and informative report, we have succeeded beyond our wildest dreams.

ADVANTAGES - Now that some of the better known problems of university research have been reviewed, let's examine some of the positive features of university research efforts. One of the most significant aspects of university research is the general freedom for a faculty member to investigate any topic that takes his interest. In fact, we may even pursue work outside the general area of our formal training. Of course if we want support in our work (and we all do) we may have to consider some bounds for our ideas. However, if we have a good idea, we are free to seek support from federal agencies, foundations, corporations, and sometimes our own university.

Another important plus for university research is that we can place the emphasis on information rather than results. Since we are not producing a commercial product, our work does not have to produce positive results. Although positive results provide a boost to the ego (and to the chances for additional outside funding), a thorough examination of a concept or project that produces results other than our expectations is still valuable information. Publishing this information in the open literature may save wasted effort by many other investigators. In addition, very few projects are completely negative and many important ideas and new areas of investigation have resulted from efforts that did not produce the anticipated results.

The potential to provide objective answers is another strong point for university research efforts. Since we are not selling a product and do not have the resources for exhaustive, detailed, and comprehensive programs, one of the major things that we have to offer is objectivity. We do not always succeed in being objective but the potential is there. There is also a certain amount of public acceptance of the objectivity of our work, particularly when contrasted to industrial results provided by companies that might have some financial interest in the nature of the results. This is in no way meant to cast any doubt on the published results of corporate research efforts, it is simply an attempt to point out how university research results can be perceived compared to those provided by companies having a financial interest in the results.

Another nice feature about university research is that it does not have to have direct economic justification. After all, our major products are educated people and information. A significant portion of the cost of university research can be charged against the education of skilled technical people. Therefore, very basic and fundamental projects or "high risk" projects can be undertaken in the university research program. These projects are those of significant interest that can not be justified by corporate product needs and available resources. Engineering research projects of this nature can be conducted very effectively in the university atmosphere.

One of the more compelling advantages of university research is the cost factor. Overall, university research is a bargain. Not only do we produce objective information and trained people, we do it at low cost. Where else can you employ a graduate engineer that will earn $19,000 in industry for $5000 to $6000 per year. Not only do we get him for a low rate but we expect him to put in a lot of free overtime in getting the job done. Now couple the low cost of our engineering help with the typical salary situation for our faculty investigator and the reason for our cost advantage is obvious.

In the preceding paragraphs I have attempted to illustrate the important factors that influence engineering research at schools such as the University of Missouri-Rolla. Keeping this background in mind, I would now like to briefly describe the current and near future programs in fuels and engine research at UMR.

TRANSPORTATION VEHICLE FUELS AND ENGINE RESEARCH AT UMR

The majority of the effort in transportation vehicle fuels and engine research at UMR is based upon the premise that the spark ignition and diesel engines will remain the primary power plants for ground transportation vehicles in the near and mid terms. The thrust of our work is devoted to three major areas:

1. Conservation of fossil fuels through improved engine efficiency.
2. Characterization of synthetic and alternate fuels, additives, and blending materials that may be used to extend fuel supplies or modify fuel properties.
3. Examination of engine modifications needed to optimize the use of synthetic and alternate fuels, additives, and blending materials with particular attention to emissions and fuel economy performance.

A fourth item on the above list might be "all of the above" since the interrelation of the three areas is obvious.

CONSERVATION - The conservation efforts now underway are primarily related to improving the efficiency of spark ignition and diesel engines. One of the "high risk" projects that is now in preliminary stages is the lean supercharge operation of spark ignition engines. The objective of this project is a feasibility study of recovering exhaust energy through the use of a turbo-supercharger and lean operation. More specifically, we hope to provide power levels equivalent to the naturally aspirated engine but at significantly leaner air-fuel ratios. Improved cycle efficiency and potentially reduced NO_x emissions are hoped for. Figure 1 shows some very preliminary results from a single cylinder research engine. In this case the supercharged power level was maintained at the same level as maximum power for the naturally aspirated engine. Since the supercharged condition is a substantial leaning of the air-fuel ratio from the rich mixture required for naturally aspirated maximum power, the results are about what could be anticipated: The efficiency is substantially increased, the HC and CO emissions are drastically decreased, and NO_x emissions are increased. Figure 2 illustrates the case when the supercharged power level is maintained at the power level for maximum efficiency in the naturally aspirated engine. For this condition the efficiency is increased, HC and CO emissions are virtually unchanged, and NO_x emissions are dramatically reduced. These tests were all conducted at equal manifold and inlet conditions, MBT spark timing, and with no EGR. We are now in the process of upgrading our research engine to undertake a significantly more extensive investigation.

FUELS - Our fuels work is based upon the assumption that liquid hydrocarbons are going to remain the major transportation fuels for the near and mid term. Liquid fuels will be produced from the substantial coal and shale resources in the United States. From my viewpoint, the major problems with the syncrude fuels produced from the coal and shale resources will be the lack of hydrogen and the presence of fuel nitrogen and sulfur, not to mention the trace metallic compounds and other inorganic materials. The availability of process energy and water required for the hydrogen upgrading of these fuels is certainly in question. Efforts to minimize refinery energy consumption, water, and siting problems will lead to changes in the properties of finished fuels produced from these resources. After considering the raw materials, the refining processes, and some of the current trends in finished fuels, I can speculate that spark ignition engine fuels will become more aromatic in content and diesel fuels possibly more paraffinic. Because of the special problems associated with jet aviation fuels, changes in these materials will be slower and less dramatic.

Another facet of near term future fuels is the question of alcohols. Methanol from waste, coal, or natural gas currently being flared is a distinct possibility. Ethanol from agricultural products and waste is also receiving a great deal of attention. If these materials are available we should seek ways to utilize them for transportation. The alcohol/gasoline blend has been examined extensively in the last few years and its use and problems are reasonably well understood. Blends, solutions, and other combinations of alcohols and diesel fuel have not received the same attention as the "Gasohol" combinations. Figures 3, 4, and 5 illustrate some very preliminary results that we have obtained with a combination of number 2 diesel fuel, 10% methanol, and 7% higher alcohol. These tests were conducted on a commercial diesel engine equipped with a turbocharger. No adjustments were made to the engine to compensate for the altered properties of the alcohol/diesel fuel blend. Examination of figures 3 and 4 indicates that, other than reducing maximum power, the addition of alcohol to the fuel had relatively minor effects on the engine efficiency and the NO emissions. Figure 5 illustrates that some slight reduction in the particulate emissions might be attributed to the presence of alcohol in the fuel. However, caution should be used before drawing any conclusions on this point. The alcohols have displaced 17% of the diesel fuel and the apparent reduction in particulates could be related to these lighter, more hydrogen rich alcohol molecules, rather than to any alteration in the combustion process. Nevertheless, these results are promising in that 17% alcohol was added to the diesel fuel and no substantial degradation of engine efficiency, NO or particulate emissions was observed. We hope to be conducting a more extensive investigation of stable alcohol/diesel fuels in the near future.

In the longer term, some thought should be given to the possibility of using ethanol and methanol from non-fossil resources to provide the hydrogen for upgrading future synfuels from coal and shale. UMR is now beginning something called the "Coors" project aimed at the conversion of Missouri wood waste into producer gas. One aspect of the project currently under consideration is the conversion of this producer gas into methanol. Given this type of source for methanol and ethanol, a more effective utilization of the resources might be achieved at the refinery level rather than in blended fuels. A current example of the possibilities is Methyl tert-Butyl Ether (MTBE) formed from methanol and Isobutene. This material shows promise as a high octane blending component for unleaded gasoline.

Non-conventional fuels is another area where some of our efforts are directed. Currently, a joint program between the Mechanical Engineering and Chemistry Departments is being implemented to study the possibilities of microemulsions of water and diesel fuel as diesel engine fuel. This will be a comprehensive program to seek optimum water/fuel microemulsions and evaluate the fuel properties of these microemulsions. In addition, engine parameter studies are planned to optimize the engine fuel combination for emissions and efficiency. Preliminary published information indicates the possibilities of reduced NO_x and soot emissions, and/or efficiency increases.

ENGINES - Our efforts concerning engines are related to modifications of current technology spark ignition and diesel engines to optimize engine-fuel combinations. Currently a program is underway to evaluate the prechamber stratified charge engine as a way to minimize external power requirements for cold starting of low vapor pressure fuels such as methanol. As previously mentioned, diesel engine efforts will deal with the water/diesel and alcohol/diesel fuels currently under consideration. The relationship of engine variables such as compression ratio and injection timing on emissions, efficiency, and power output will be examined.

SUMMARY

The advantages and disadvantages of engineering research in the university atmosphere provide unique opportunities for fundamental research that are generally not available in corporations or government agencies. In addition, the specialized training of technical personnel is a vital aspect of university research. In this paper I have attempted to describe this framework that university investigators must work within and provide illustrations of the transportation energy and fuels work being done at the University of Missouri-Rolla.

I feel that universities are going to contribute importantly to synfuel research and development. By the nature of their basic goals, objectives, and operation they can and will contribute in three significant ways:

1. Basic research into the fundamentals of synfuel production, refining, and combustion.
2. Undertaking of "high risk" projects.
3. Providing trained technical personnel for the transportation fuel segment of our economy.

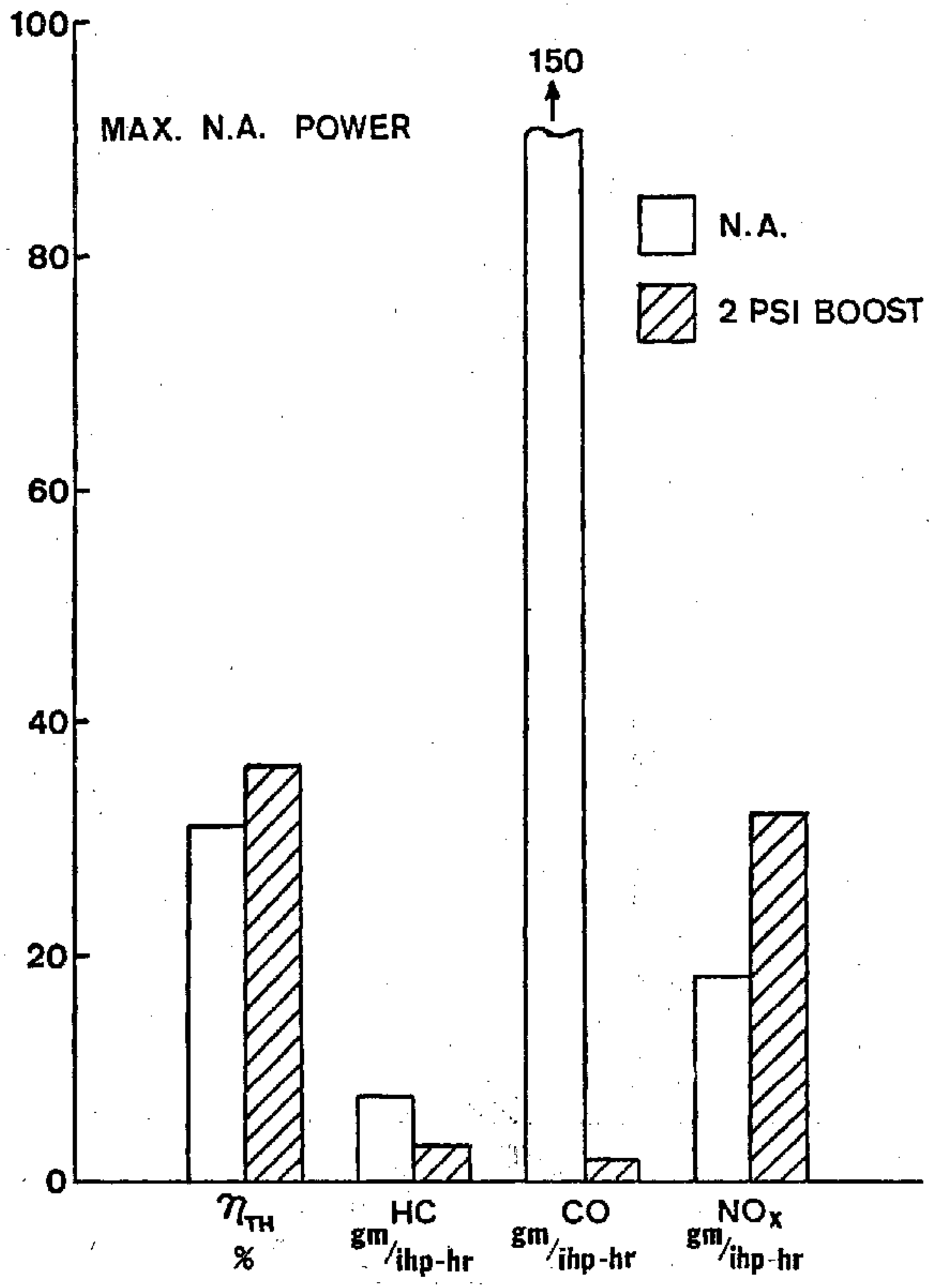

Figure 1 - Lean Supercharged Engine at Maximum Naturally Aspirated Power.

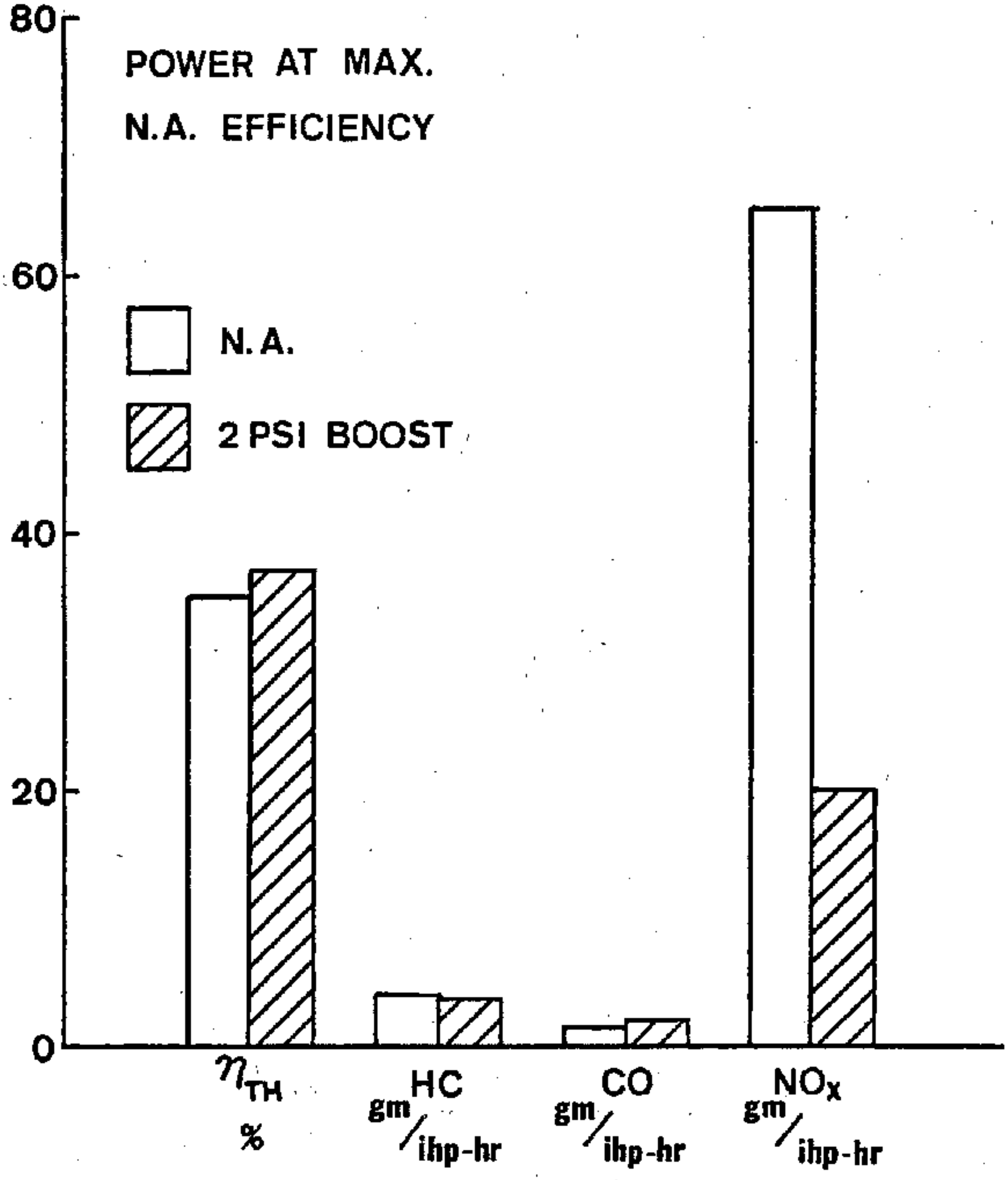

Figure 2 - Lean Supercharged Engine at Power Level for Maximum Naturally Aspirated Efficiency

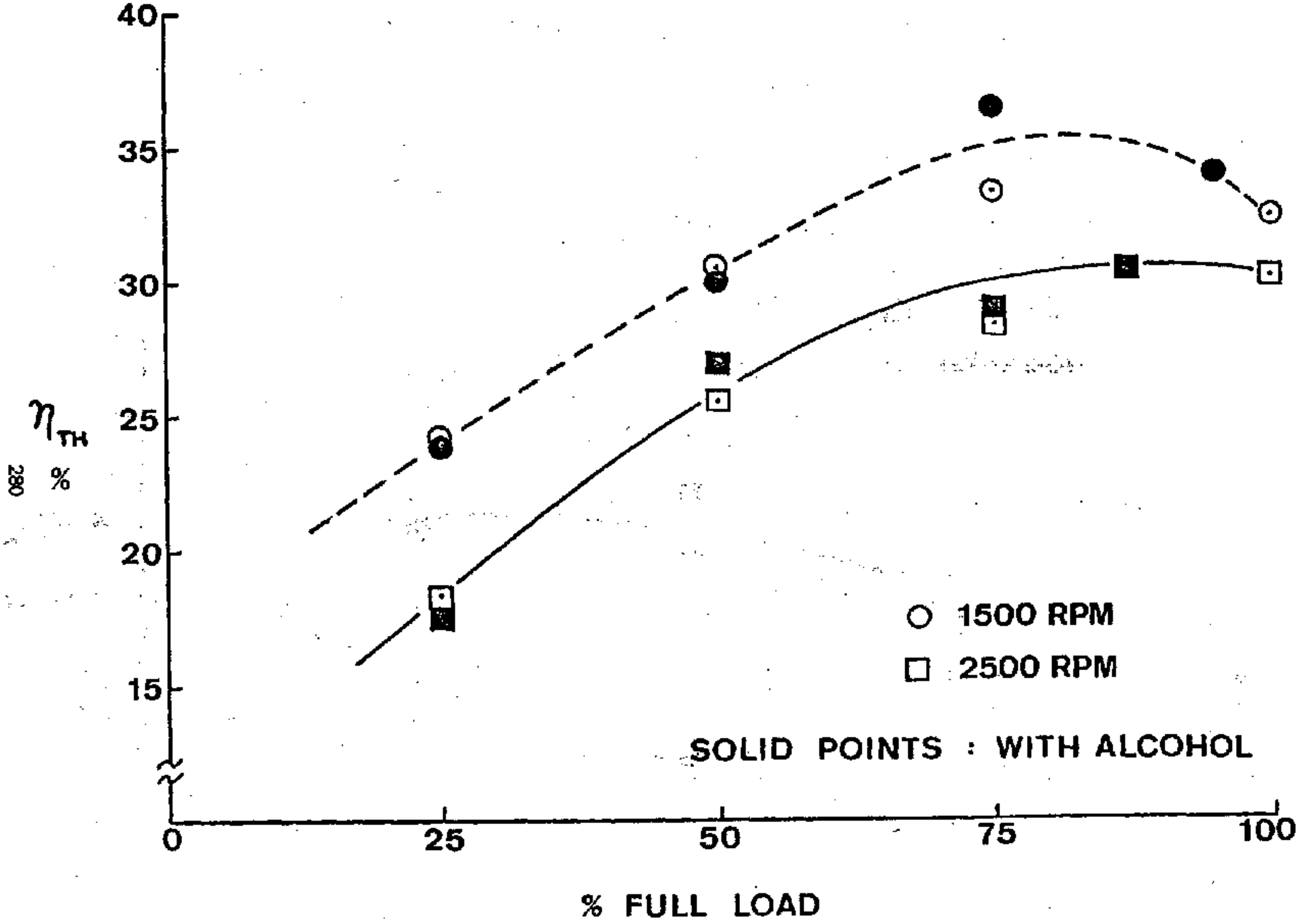

Figure 3 - Alcohol/Diesel Fuel Blend - Efficiency

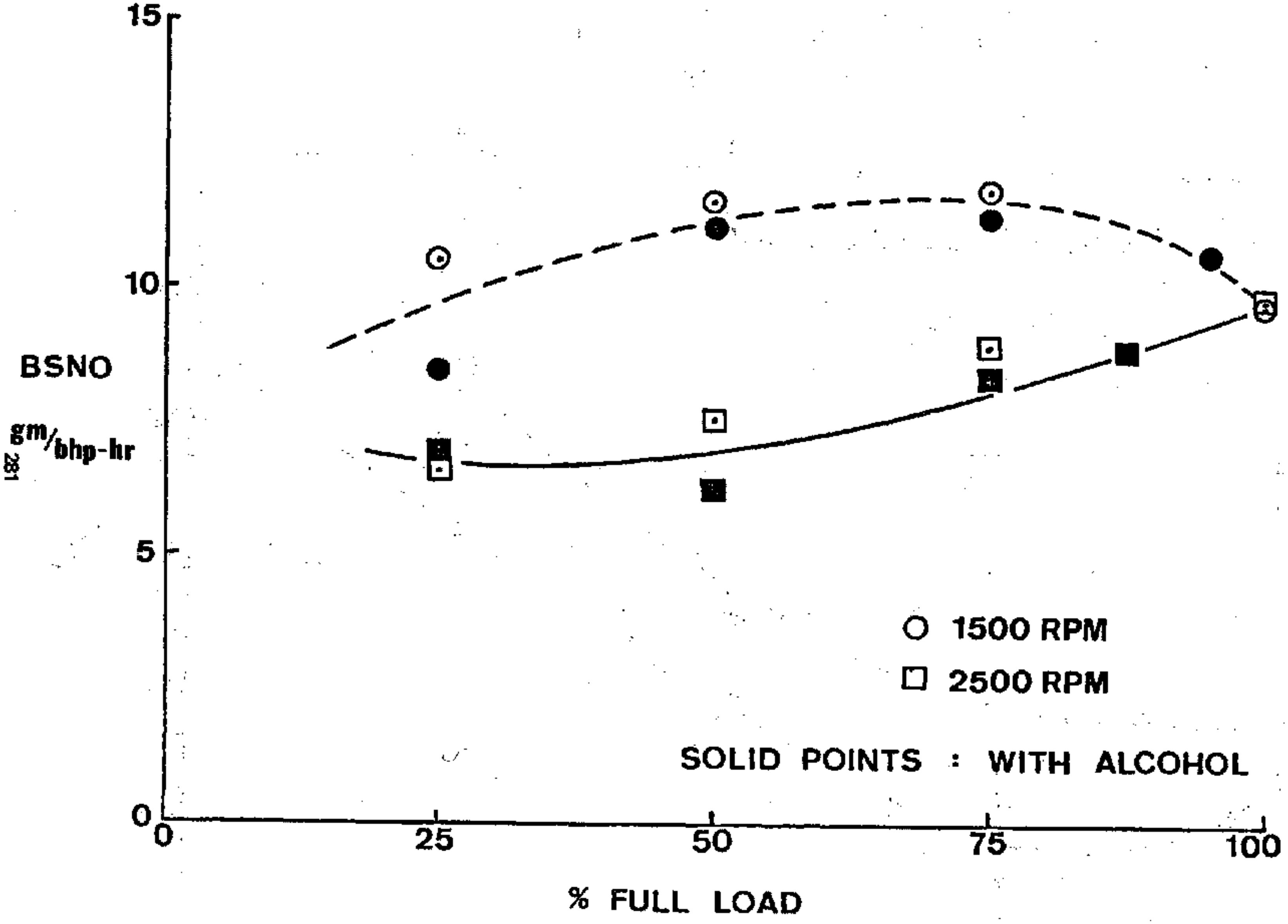

Figure 4 - Alcohol/Diesel Fuel Blend - NO Emissions

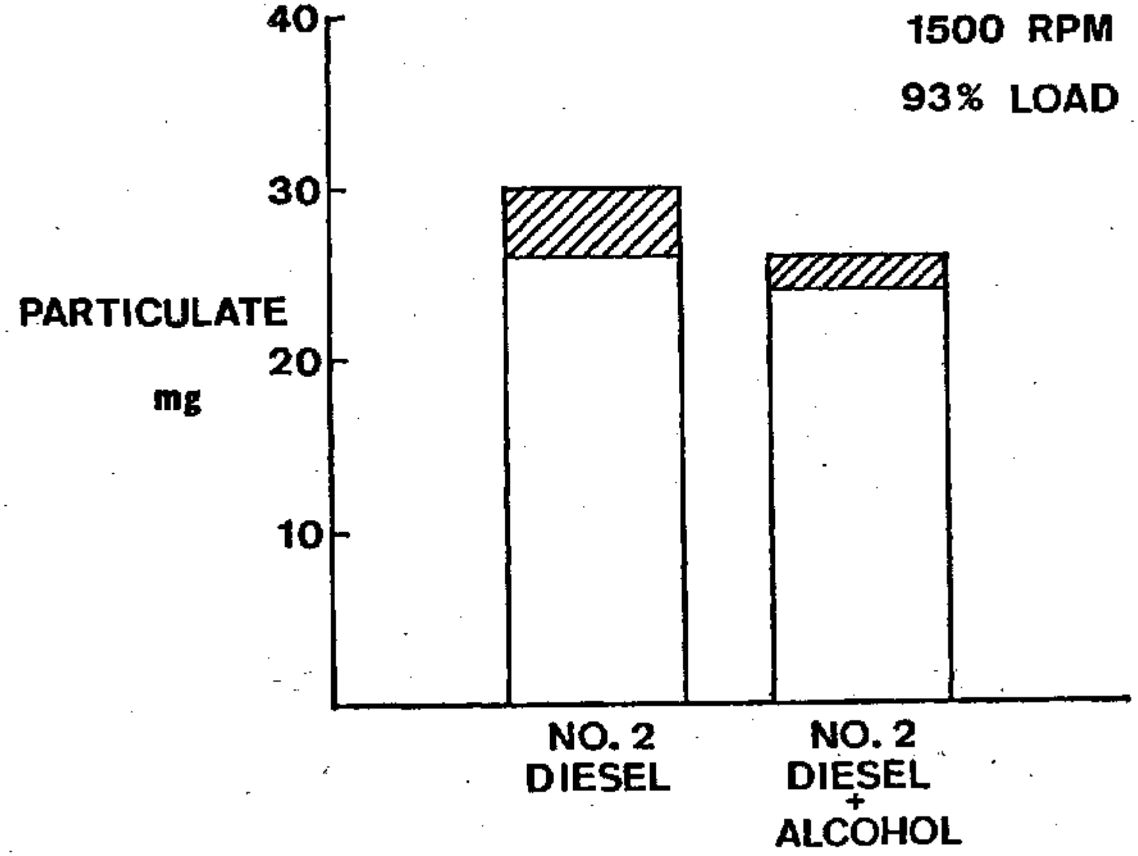

Figure 5 - Alcohol/Diesel Fuel Blend - Particulate Emissions

COMPOSITION AND PERFORMANCE OF PARAHO SYNFUELS

E.T. Robinson
The Standard Oil Company

S. Kumar Kunchal
SOHIO Natural Resources Company

PRESENTED AT THE CONFERENCE ON
COMPOSITION OF TRANSPORTATION SYNFUELS
IN SAN ANTONIO, TEXAS

11-13 OCTOBER 1978

COMPOSITION OF SHALE OIL
AND SHALE OIL DERIVED FUEL

The information provided in this presentation is the result of pilot plant studies conducted by The Standard Oil Company (Ohio) for the U.S. Navy under contract N00014-77-C-0750. Part of this report was presented at the Navy's Workshop on Synthetic Jet Fuels on June 15, 1978. ("Pilot Plant Refining Studies" by L. W. Kruse, E. T. Robinson, The Standard Oil Company, Ohio).

Attached are copies of the slides and back-up tables used in this presentation. The tables are included to provide additional data not shown on the slides.

E. T. Robinson

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10/11/78

S. Kumar Kunchal
SOHIO Natural Resources Company

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TOPICS OF DISCUSSION

I. SHALE OIL ANALYSES

II. SHALE OIL REFINING PROCESS

III. SHALE OIL HYDROTREATING RESULTS

IV. COMPOSITION OF SHALE DERIVED FUELS

V. CONCLUSIONS

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AVERAGE PARAHO SHALE OIL ANALYSES

(SETTLED)

API GRAVITY	20.6
HYDROGEN, WT.%	11.55
CARBON, WT.%	84.66
NITROGEN, WT.%	2.15
OXYGEN, WT.%	1.31
SULFUR, WT.%	0.66
IRON, PPM	33
ARSENIC, PPM	8
NICKEL, PPM	2
VANADIUM, PPM	0.2

TBP DISTILLATION	VOLUME, %
IBP-650°F	32.6
650°F-750°F	14.1
750°F⊕ BOTTOMS	53.1
	100%

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SETTLING OF PARAHO SHALE OIL

	BEFORE	AFTER
BS&W, VOL.%	0.85	0.38
ASH, WT.%	0.70	0.01
IRON, PPM	40.5	32.6
ARSENIC, PPM	11.8	13.3

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SIGNIFICANT CONSIDERATIONS IN REFINING SHALE OIL

1. HIGH NITROGEN CONTENT (≈ 2.15 WT.%).
2. LOW HYDROGEN CONTENT (≈ 11.5 WT.%).
3. SMALL VOLUME OF 650°F MINUS MATERIAL (≈ 32 VOL.%).
4. IRON AND ARSENIC LEVELS.

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EFFECTS OF HYDROTREATING

WHOLE SHALE OIL

	SHALE OIL	HYDROTREATED WHOLE SHALE OIL
API GRAVITY	20.3	34.4
HYDROGEN, WT.%	11.32	12.96
CARBON, WT.%	84.71	85.93
NITROGEN, WT.%	2.14	0.30
OXYGEN, WT.%	1.35	0.53
SULFUR, WT.%	0.68	< .002
MOLECULAR WEIGHT	297	261
TBP 650° PT, VOL.%	32%	65%

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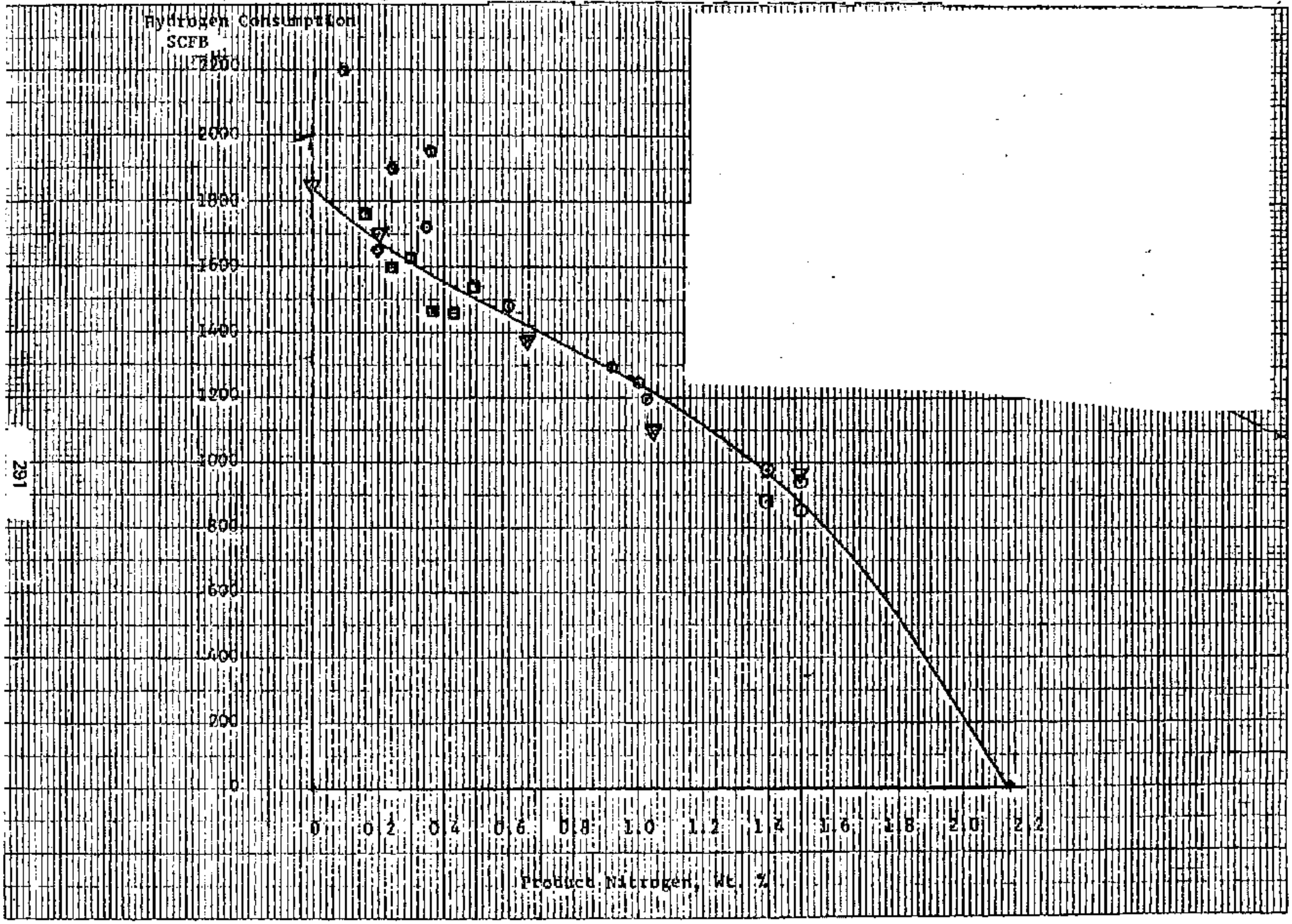
Figure 5. - HYDROGEN CONSUMPTION V S. PRODUCT NITROGEN



CATALYST DEACTIVATION

- DEACTIVATION OF CATALYST (W.R.S.T. DENITRIFICATION) DID NOT SIGNIFICANTLY ALTER TBP FUEL YIELDS.

- CAUSES OF CATALYST DEACTIVATION:

  1. COKING
     - HYDROGEN PARTIAL PRESSURE
     - REACTOR TEMPERATURE
  2. METALS DEPOSITION
     - GUARD BED EFFECTIVENESS
     - FEED METALS CONTENT

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COMPOSITION OF SHALE OIL DERIVED GASOLINE

	BEFORE REFORMING	AFTER REFORMING
API GRAVITY	57.5	48.7
C WT.%	85.51	87.74
H WT.%	14.54	11.89
N PPM	402	0.5
RESEARCH OCTANE, CLEAR	47	93
PARAFFINS	58.9	42.1
NAPHTHENES	30.7	6.8
AROMATICS	10.4	51.1
D-86 IBP, °F	190	115
D-86 50%, °F	258	264
D-86 EP, °F	332	377

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COMPOSITION OF SHALE DERIVED JP-5

	BEFORE ACID/CLAY	AFTER ACID/CLAY
API GRAVITY	40.9	43
CARBON, WT.%	85.96	86.64
HYDROGEN, WT.%	13.38	13.68
NITROGEN, PPM	3200	8.3
OXYGEN, PPM	63	≤53
SULFUR, PPM	0.4	1.3
D-86 IBP,°F	343	350
D-86 50%,°F	414	414
D-86 EP, °F	477	487
PARAFFINS, VOL.%	43.9	46.0
NAPHTHENES,VOL.%	33.2	33.1
AROMATICS, VOL.%	22.9	20.9
FREEZE PT,°F	-53.5	-52.6
SMOKE PT, MM	19	20

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STABILITY OF SHALE DERIVED JP-5

	BEFORE ACID/CLAY TREAT	AFTER ACID/CLAY TREAT
EXISTENT GUM, Mg/100 cc	12.2	0.6
POTENTIAL GUM, Mg/100cc	47.8	3.9
D-3241 (JFTOT) @ 500°F		
VISUAL	4 (FAIL)	< 2
ΔP MM	5	1.0

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ACCELERATED AGING TEST OF SHALE DERIVED JP-5

1-MONTH @ 140°F

	BEFORE AGING	AFTER AGING
LOW NITROGEN		
12 PPM NITROGEN		
	JFTOT @ 500°F	
VISUAL	<2	<3
ΔP MM	1.0	1.0
MAX TDR	4.5	7.0
	JFTOT @ 550°F	
VISUAL	<2	<2
ΔP MM	0	2.0
MAX TDR	4.0	2.0
HIGH NITROGEN		
189 PPM NITROGEN		
	JFTOT @ 500°F	
VISUAL	2	1
ΔP MM	0	1.0
MAX TDR	11.5	3.0
	JFTOT @ 550°F	
VISUAL	No Sample	<3
ΔP MM		10
MAX TDR		22.5

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COMPOSITION AND STABILITY OF
SHALE OIL DERIVED DIESEL FUEL MARINE

	BEFORE ACID/CLAY	AFTER ACID/CLAY
API GRAVITY	33.4	34.8
POUR, °F	15	5
CLOUD, °F	20	16
CARBON, WT.%	86.44	86.75
HYDROGEN, WT.%	12.91	13.02
NITROGEN, PPM	4000	90
CETANE NUMBER	50.1	55.3
D-86 IBP, °F	507	506
D-86 50%, °F	553	555
D-86 EP, °F	628	631
PARAFFINS, VOL.%	32.8	42.2
NAPHTHENES, VOL.%	18.2	25.8
AROMATICS, VOL.%	49.0	32.0
STABILITY, Mg/100cc (ASTM 2274)	8.3	0.4

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COMPOSITION OF SHALE OIL DERIVED

#5 OR #6 FUEL OIL

API GRAVITY	30.3
POUR PT, °F	105
VIS @ 122°F, CST	25.7
VIS @ 210°F, CST	6.5
CARBON, WT.%	87.32
HYDROGEN, WT.%	12.59
NITROGEN, PPM	3300
SULFUR, PPM	5
D-1160, IBP, °F	572
50% PT, °F	814
87% (EP), °F	951
PARAFFINS, VOL.%	23.5
NAPHTHENES, VOL.%	33.6
AROMATICS, VOL.%	42.9

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CONCLUSIONS

1. PROCESS FLOW REQUIRES SETTLING PRETREATMENT AND GUARD BED TO PROTECT CATALYST.

2. HYDROTREATING REQUIRED TO INCREASE H/C, IMPROVE FUELS YIELD AND REMOVE HETEROATOMS.

3. PRODUCT YIELDS FROM HYDROTREATED SHALE OIL ARE:

	VOL. %
GASOLINE	6%
JET FUEL	24%
DIESEL FUEL MARINE	35%
HVY FUEL OIL	35%

4. ACID/CLAY TREATING REQUIRED TO MEET THERMAL AND STORAGE STABILITY REQUIREMENTS.

5. SPECIFICATION MILITARY FUELS CAN BE PRODUCED.

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TABLE I

COMPOSITE SETTLED
WHOLE SHALE OIL

T.S. Number	78-3245-5B
API Gravity	20.3
BS&W, Vol. %	0.10
Water by Dist, wt.%	Trace
Ash, D-482, wt. %	0.013
Iron, PPM	38
Arsenic, PPM	9.6
Carbon Residue, wt. %	0.842
Asphaltenes, wt. %	1.099
Aniline Pt, T.F., °F	137°F
Pour Pt, °F	85°F
Vis @ 140°F, CST	16.68
Vis @ 210°F, CST	6.13
Molecular Weight	297
Vapor Pressure @ 212°F (Reid)	6.9 psi
C.O.C. Flash Pt., °F	265°F
C, wt. %	84.71
H, wt. %	11.32
N, wt. %	2.13 (C.E.)
O, wt. %	1.35
S, wt. %	0.68
DISTILLATION	D-1160
IBP	376
2	436
5	464
10	524
30	655
50	791
70	878
90	1015
95	--
EP	--
% RCVRD	90%
% Residue	10%

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TABLE II

DISTILLATION AND INSPECTIONS OF RAW SHALE OIL FEED TO THE HDN

77-2349-5

PHYSICAL INSPECTIONS

API GR	20.9	C, Wt. %	84.60
Pour Pt.	85	H, Wt. %	11.77
ASH - D-482, wt. %	0.004	N, Wt. %	2.17
TAN MG KOH/GM	2.029	O, Wt. %	1.27
BS&W, Vol., %	0.06	S, Wt. %	0.63
Asphaltenes, wt. %	0.576	As PPM	5.6
Vis @ 100 CST	46.09	Fe PPM	52.8
Vis @ 210 CST	5.74	V PPM	0.20
		Ni PPM	1.98

D-1160 DISTILLATION

IBP/5	410/478
10/30	521/670
50	799
70/90	855/---
EP	---

DISTILLATION AND ELEMENTAL ANALYSES

	API	Wt. %	Vol.%	Cum. Vol.%	H	C	N	O	S
IBP-250	50.0	0.27	0.32	0.32	12.56	84.93	0.59	0.81	0.97
250-300	47.5	0.37	0.44	0.76	12.53	84.35	1.25	0.90	1.29
300-350	43.0	1.29	1.48	2.24	12.42	83.75	1.70	1.47	1.03
350-400	38.5	1.26	1.41	3.65	12.36	84.19	1.44	1.54	0.88
400-450	34.6	6.22	6.81	10.46	12.26	84.35	1.18	1.67	0.79
450-500	30.8	3.67	3.92	14.38	12.05	84.36	1.51	1.38	0.93
500-550	28.2	2.73	2.87	17.25	11.80	83.86	1.75	1.85	0.83
550-600	27.1	9.79	10.23	27.48	11.75	84.66	1.77	1.45	0.73
600-650	22.9	5.07	5.16	32.64	11.41	84.71	2.01	1.32	0.76
650-700	20.9	6.22	6.25	38.89	11.38	85.04	2.11	1.24	0.75
700-750	17.5	8.14	7.99	46.88	11.17	84.96	2.20	1.23	0.70
750+	15.2	54.95	53.12	100.00	10.65	84.98	2.36	1.14	0.57

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TABLE I

EFFECTS OF SETTLING ON WHOLE SHALE OIL

Production Period	May-Oct., 1975		Nov., 1975		Jan.-Feb., 1977		Aug., 1977					
Drum Grouping	A		B		C		D		Before		After	
Settling T.S. Number	Before 2155	After 1313	Before 2160	After 1312	Before 2165	After 1310	Before 2170	After 1311	Mean	Std. Dev.	Mean	Std. Dev.
API Gravity	20.5	N.A.	20.4	N.A.	20.8	N.A.	20.8	N.A.	20.63	.206	--	--
Water by DIST, Wt.%	Trace	.12	Trace	.12	Trace	.12	3.0	1.2	0.75	1.5	0.39	0.54
BS&W, Vol. %	.06	.12	0.08	.12	.05	.06	3.20	1.2	0.848	1.568	0.375	0.551
Ash, D-482-Wt. %	.336	.030	1.117	.001	.853	.011	.472	.011	0.695	0.357	0.013	0.012
Arsenic, PPM	10.34	11.7	10.67	14.0	14.37	15.0	11.79	12.6	11.79	1.83	13.33	1.46
Iron, PPM	36.0	24.2	51.0	42.2	38.0	35.5	37.0	28.5	40.5	7.05	32.6	7.91
Vanadium, PPM	0.3	0.19	0.3	0.19	0.30	0.28	0.4	0.09	0.325	0.05	0.188	.078
Nickel, PPM	1.64	1.5	2.45	2.0	3.04	2.2	2.87	1.9	2.50	0.625	1.90	0.294

N.A. = not analyzed.

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TABLE III

DETAILED MATERIAL BALANCES AT LOW PARTIAL PRESSURE

	Near Start of Run				Near End of Run			
	WT %	°API	VOL %	WT% N	WT %	°API	VOL %	WT% N
H_2	- 2.6				- 2.5			
$NH_3/H_2S/H_2O$	4.0				3.3			
C1	1.0				1.2			
	1.0				1.5			
C3	0.9				1.1			
C4	0.9	111.0	1.5		1.1	111.0	1.8	
C5	1.0	92.7	1.6		1.1	92.7	1.8	
C6-315°F	6.3	58.0	7.9	0.05	4.8	56.2	6.0	0.06
315-480°F	22.2	42.2	25.3	0.25	21.8	41.9	24.9	0.40
480-650°F	31.9	33.3	34.5	0.43	33.5	33.3	36.4	0.76
650+ Btms.	33.4	28.7	35.2	0.22	33.1	27.5	34.7	0.59

TABLE IV

DETAILED MATERIAL BALANCE AT HIGH PRESSURE

	WT %	°API	VOL %	WT% N
H_2	- 2.8			
$NH_3/H_2S/H_2O$	4.2			
C1	1.4			
C2	1.1			
C3	0.7			
C4	1.2	111.0		
C5	2.2	92.7		
C6-315°F	4.6	56.2	5.7	0.02
315-480°F	19.9	43.0	22.9	0.11
480-650°F	30.2	33.9	32.9	0.23
650+ Btms.	37.3	29.0	39.9	0.18

TABLE 1A

	Paraho Shale Oil Feedstock	Mid Run Hydrotreater Products 650°F –	Mid Run Hydrotreater Products 650°F +
Hydrogen - wt %	11.32	13.04	12.83
Carbon - wt %	84.71	85.84	86.09
Nitrogen - wt. %	2.13	0.3	0.27
Oxygen - wt. %	1.35	0.4	0.28
Sulfur - wt. %	0.66		*
Metals - ppm			
As	9.6	Nil	Nil
V	0.2	Nil	Nil
Fe	38.0	Nil	Nil
Ni	1.9	Nil	Nil
°API	20.3	37.8	35.7
Mole Weight	297	218	338
Ash	0.011	—	
BS&W	0.1	—	1.8
Carbon Residue - wt. %	0.842	—	
Asphaltenes - wt. %	1.084	—	0.186
Aniline Point °F	137	148.5	217
Pour Point °F		10	110
Distillation	D-1160	D-86	D-1160
	IBP 376	IBP 262	IBP 710
	5 464	10 369	5 767
	30 608	50 526	30 799
	50 701	90 642	50 827
	70 878	EP 670	90 904
	90 1015	Residue 1%	93 962
	Residue 10%	Loss 0%	Residue 7%
	Loss 0%		Loss 0%

*Sulfur on hydrotreated products was less than 20 ppm.

Table XV

ANALYSES OF GASOLINE FEEDSTOCK, REFORMATE AND BLENDED PRODUCTS

Sample Description T.S.#	Type I-MOGAS MIL-G-3056D		Hydro.Shale Oil IBP-320 78-5050-5		Reformed IBP-320 78-5951-5		Final Blended Product 2 78-5951-5 A	
API Gravity	-		57.5		46.7		50.1	
DISTILLATION	D-86	D-2887	D-86	D-2887	D-86	D-2887	D-86	D-2887
IBP °F	-	-	190	108	115	3	102	6
10	122-158	-	226	202	201	160	177	130
50	192-239	-	258	274	264	280	262	276
90	270-356	-	288	320	317	339	317	336
EP	-	-	332	352	377	398	379	398
Vol. % Rcvrd	-	-	99.0	-	98	-	97.0	-
Vol. % Res	2.0	-	1.0	-	1	-	1.0	-
Vol. % Loss	-	-	0.0	-	1	-	2.0	-
RVP @ 100°F, PSI	7-9		1.3		3.8		7.5	
V/L Ratio = 20, °F	140°F min.		200		190		200.5	
Research Octane Number	91 min.		47^1		≈ 93^1 (avg.)		92.6^4	
Motor Octane Number	83 min.		-		-		84.2^5	
Lead, Gms/liter	0.65 max.		None		None		0.60	
Water and Sediment, Vol.%	0.01 max.		-		-		Trace	
Corrosiveness @ 122 °F	1 max.		1B		1B		1B	
Oxidation Stability, min.	480 min.		960⊕		960⊕		480⊕	
Unwashed Gum, mg/100 ml	4 max.		1.0		4.0		34.6	
Potential Gum, mg/100 ml	-		1.5		-		32.6	
C wt.%	-		85.51		87.74		87.36^3	
H wt.%	-		14.54		11.89		12.30	
N PPM	-		402		0.51		0.46	
O PPM	-		55		260		234.0	
S PPM	1000 max.		<20		0.50		0.45	
Hydrocarbon Type Analyses	Vol.%		Vol. %		Vol. %		Vol.%	
Paraffins	-		55.87		42.06		47.85^3	
MCP	-		29.61		6.54		5.89	
DiCP	-		1.11		0.28		0.25	
ABZ	-		9.97		49.99		44.99	
Indans + Tetralins	-		0.11		1.00		0.90	
Naphthalenes	-		0.33		0.22		0.20	
Carbon # Par./Carbon #ABZ	-		8.01/7.81		7.63/7.97			

1 No lead

2 Final Product: 90% Reformate + 3% n-pentane + 7% n-butane and includes 24 mg/liter A029 anti-oxidant + 5.7 mg/liter DMD metal deactivator and 0.60 gm/liter lead.

3 Calculated from 78-5951-5 Data to include the 3% pentane + 7% butane

4 RON with $C_4 + C_5$, additives but no lead = 88.0

5 MON with $C_4 + C_5$, additives but no lead = 80.3

Table XVIII

JP-5 FEEDSTOCK ANALYSES

	MIL-T-5624K Amendment 1		78-5049-5		78-5540-5	
API Gravity	36 < API < 48		41.8		40.9	
Freeze, °F	-51°F max		-51.7		-53.5	
Flash, P.M. °F	140 min		157		144	
TAN mg KOH/gm	0.015 max		0.022		0.054	
Aniline Pt., °F	-		127.5		128.5	
Heat of Comb, MJ /Kg[3]	42.6 min		42.97		42.96	
Molecular Wt. gm/mole	-		192			
Vis @ -30°F, cst	-		8.58		8.00	
Vis @ -20°C (-4°F), cst	8.5 max		-		-	
Smoke Pt., MM[1]	19 min		19		19	
Explosiveness, %	50% max		-		-	
Copper Strip Corr. 2 hr @ 212°F	1B max		1B		1B	
Existent Gum mg/100 ml	7 max		10.2		12.2	
Potential Gum mg/100 ml	-		20.7		47.8	
WSIM	85 min		-		27	
JFTOT @ 500°F, Visual	<3		>4		-	
JFTOT @ 500°F, ΔP MM Hg	25 max		5.0		-	
DISTILLATION, °F	D-86	D-2887	D-86	D-2887	D-86	D-2887
IBP	R	R	356	288	343	285
10	401 max	265 max	380	248	376	244
20	R	R	390	371	387	366
50	R	R	415	430	464	426
90	R	R	456	490	456	479
EP	554 max	608 max	477	523	477	520
% Res	1.5	-	1.0	-	1.0	-
% Loss	1.5	-	0.0	-	0.0	-
Carbon, Wt. %	-		86.07		85.96	
Hydrogen, Wt. %[1]	13.5 min		13.45		13.38	
Nitrogen PPM	-		3100		3200	
Oxygen PPM	-		251		63	
Sulfur PPM	10 max[2]		1.4		0.38	
Total Saturates	-		77.03		77.10	
Total Aromatics	25% max		22.97		22.90	
Total Olefins	5% max		0.00		0.00	

R - Report
1 - Smoke Pt or Hydrogen Content
2 - 10 PPM Mercaptan Sulfur
3 - Aniline Gravity Correlation ASTM-1405

Table XXI

FINAL JP-5 BLEND

	MIL-T-5624-K Amendment-1		Final JP-5 Product 78-3775-5DI[1]	
API Gr.	36 ≤ API ≤ 48		43.0	
Freeze °F	-51°F Max		-52.6	
Flash °F	140°F Min		136	
TAN mg KOH/gm	0.015 Max		Nil	
Aniline Pt. °F	-		134	
Heat of Comb. MJ/Kg[2]	42.6 Min		43.06	
Vis @ 0°F, CST	-		4.77	
Vis @ -30°F, CST	-		7.86	
Vis @ -20°C, CST[4]	8.5 Max		5.06	
Color, Saybolt	R		+20	
Smoke pt, MM[3]	19 Min		20	
Copper Strip Corrosion	ASTM No. 1 Max		1B	
Existent Gum mg/100 cc	7 Max		0.6	
Potential Gum mg/100 cc	-		3.9	
Particulate Matter mg/liter	1.0 Max		1.67	
JFTOT @ 500°F, Visual	< 3		< 2	
JFTOT @ 500°F ΔP MM	25 Max		1.0	
WSIM	85 Min		86	
Explosiveness, %	50% Max		I.S.	
DISTILLATION	D-86	D-2887	D-86	D-2887
IBP	R	R	350	285
10	401 (max)	365	380	346
20	R	R	389	369
50	R	R	414	426
90	R	R	458	486
EP	554 (max)	608	487	529
% Res	1.5 (max)	-	1	-
% Loss	1.5 (max)	-	0	-
Carbon, Wt. %	-		86.64	
Hydrogen, Wt. %[3]	13.6 Min		13.68	
Nitrogen, PPM	-		8.3	
Oxygen, PPM	-		≤53	
Sulfur, PPM	4000 (max); 10 mercaptan		1.3	
Total Saturates	-		79.97	
Total Aromatics	25 Max		20.93	
Total Olefins	5 Max		0.00	
% Napthalenes	3 Max		0.22	

1. With 0.10 Vol. % De-Icer
2. Aniline Gravity or Heating Value Acceptable
3. Smoke Point or Hydrogen Content
4. Calculated ASTM D-341 (Appendix)

I.S. = Insufficient Sample

Table XXIII

DIESEL FUEL MARINE FEED AND PRODUCT INSPECTION

	MIL-F-16884-	Feed to Acid/Clay 78-5799-5		Final Treated Product[1] 78-3792-5A	
API Gravity	R	33.4		34.8	
Flash	140°F min	-		290	
Pour °F	20°F max	15		5	
Cloud °F	30°F max	20		16	
Aniline °F	R	150°F		155	
RI @ 140, °F	-	1.4625		1.4582	
TAN, mg KOH/gm	0.30 max	0.078		0.029	
Color, ASTM	5 max	4.5		<1.5	
Molecular Wt.	-	201.		209	
Car.Res. 10% Btms, wt.%	0.20 max	0.512		0.176	
Ash, D-482, wt. %	0.005 max	0.011		Nil	
Vis @ 100°F cst	1.8<vis@100<4.5	4.33		4.16	
Vis @ 210°F cst	-	1.55		1.61	
Cetane Number	45 min	50.1		55.3	
Demulsification Minutes	10 max	-		10 min	
Neutrality Fed.-5101.6	Neutral	-		Neutral	
Corrosion 3 hr @ 212	No.1 ASTM max	1B		1B	
Accelerated Oxid, ASTM 2274 mg/100 cc	2.5 max	8.32±0.63		0.371	
DISTILLATION	D-86	D-86	D-2887	D-86	D-2857
IBP	-	507	454	506	459
10	-	529	497	530	501
50	R	553	577	555	577
90	675 max	595	642	598	643
EP	725 max	628	684	631	691
% Res + Loss	3% max	1%	-	1	-
% Loss	-	-	-	0	-
Carbon Wt. %	-	86.44		86.75	
Hydrogen Wt. %	-	12.91		13.02	
N PPM	-	4000		90	
O PPM	-	454			
S PPM	-	24		32	
Saturates Vol. %	-	51.0		68.0	
Aromatics Vol. %	-	43.2		32.0	
Olefins Vol. %	-	5.8[2]		0.00	
Fe PPM		0.64		0.025	
Arsenic PPM		0.17		< 0.01	
Vanadium PPM		0.41		< 0.01	
Sodium PPM		0.48		0.40	
Potassium PPM		<0.10		-	

1. Includes 24 mg/liter AO29 +5.8 mg/liter DMD (metal deactivator)
2. Results questionable - no olefins should be present.

Table XXIV

GRADE #6 FUEL OIL

	Fed.Spec. VV-F-815C Grade No. 6 Residual	650⊕ Btms 78-3773-5	
API Gr.	-	30.3	
Flash °F	150°F min	>300°F	
Ash - D482 wt. %	-	Nil	
BS&W Vol. %	2.00 max	0.60	
TAN mg KOH/gm	-	0.002	
Pour Pt., °F	-	105	
Color, ASTM	-	>8 Dil	
Molecular Wt.	-	351	
Aniline Pt., °F	-	214	
Asphaltenes, wt. %	-	0.244	
Vis @ 122°F, CST	92-638	25.71	
Vis @ 210°F, CST	-	6.45	
DISTILLATION	-	D-1160	D-2887
IBP °F		572	689
10	-	759	739
50	-	814	830
70	-	872	879
80	-	908	912
90	-	951	958
EP	-	-	1060
% Rec	-	87%	-
% Res	-	13%	-
C Wt. %	-	87.32	
H Wt. %	-	12.59	
N PPM	-	3300	
O PPM	-	102	
S PPM	-	5	
Total Saturates, Vol. %	-	57.1	
Total Aromatics, Vol. %	-	42.9	
Total Olefins, Vol. %	-	0.00	
Iron PPM	-	0.93	
Arsenic PPM	-	0.13	
Vanadium PPM	-	0.36	
Sodium PPM	-	0.79	
Potassium PPM	-	<0.10	