ECT UTILIZATION OF CRUDE OILS AS FUELS IN U. S. ARMY DIESEL ENGINES

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by

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Crude oils with a wide range of properties were investigated for direct use as fuel in U. S. Army high-speed diesel engines. The distribution and availability of crude oil properties throughout the world were investigated, and these properties were divided into two groups (1) Those properties which would be of importance for short-term operational effects, and (2) Those properties whose effects would manifest during longer term operation. Effects of crude oil use on engine subsystem hardware such as fuel filters and fuel injection pumps were investigated, with particular attention being paid to the TCCS injection system. Performance and combustion data were determined using pre-cup and direct injection configurations of the single cylinder CLR

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diesel engine operating on various crude oils. Performance data, wear, and deposition effects of crude oil use were obtained using the TACOM single-cylinder diesel engine. Results of this investigation showed that a wide range of crude oils with proper selection and pretreatment are feasible emergency energy sources for U. S. Army four-cycle high-speed diesel engines.

FOREWORD

The work reported herein was conducted at the U.S. Army Fuels and Lubricants Research Laboratory (AFLRL), located at Southwest Research Institute, San Antonio, Texas, under Contract DAAK02-73-C-0221, during the period July 1973 through April 1975. The work was funded by U.S. Army Mobility Equipment Research and Development Center (USAMERDC), Ft. Belvoir, Virginia, and by U.S. Army Tank Automotive Command (USATACOM), Warren, Michigan. Project monitors were Maurice LePera, USAMERDC, AMXFB-GL, and Walter Bryzik, USATACOM, AMSTA-RGR. Contract monitor was F.W. Schaekel, USAMERDC, AMXFB-GL.

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INTRODUCTION

The Army, to be able to maintain the national security, must be able to operate its fleet of combat vehicles throughout the world. This could often mean long supply lines for vehicle fuels, particularly when considering the present world-wide energy shortage which could restrict local fuel procurement. This project was conducted under contract with MERDC to assess the feasibility of direct utilization of crude oil as an energy source in times of dire emergency when no other adequate supplies of fuel are available.

The approach taken was to make an evaluation of crude oil sources to determine the geographic distribution of the world crude oil reserves and determine the range of crude oil properties within geographic areas. Concurrently, laboratory experimentation was undertaken to establish some general crude oil composition limits which would allow direct crude oil utilization and determine what effects direct usage would have on fuel related engine subsystems and on engine operational characteristics such as power, wear and operating life. Once some limiting crude oil properties were established, it was then possible to combine these limits with the crude sources information to estimate the percent of world crude oil reserves available for direct usage in military diesel engines. In conjunction with this, work was done under contract with TACOM to evaluate the suitability of crude oils for use in the Texaco Controlled Combustion System (stratified charge) engine. In particular, the effects of crude oils on various diesel combustion parameters and the ability of the TCCS fuel injection system to handle crudes were evaluated.

APPROACH

The program was divided into the following major segments: (1) a crude oil sources evaluation to determine the worldwide distribution and composition of crude oils; and (2) an investigation of the effects of various crude oil characteristics on the operation of diesel engines and their related components. Initially, the crude sources evaluation focused on gathering and analyzing crude oil characterization data. Based on analysis of these collected data, several CONUS crude oils were obtained which were felt to be representative of a range of usable world crudes that might be found. One of the crudes had a history of direct use in the oilfield as a diesel engine fuel.

The effects of using fuels with characteristics outside of the normal specifications on various engine subsystems were evaluated either by using crude oils or by blending various fluids to obtain the desired characteristics. Tests were conducted to determine the effect of fuel viscosity on fuel injector pump life and delivery rate, and spray patterns; high boiling point material content on injector deposits; water, sediment and viscosity on fuel filter delivery rate; and crude oil composition effects on engine power, combustion chamber deposits and wear. From these studies and from the literature, a set of crude oil general limits were formulated. These general limits are a rough estimate only and have not been tested on full scale engines. Throughout this program crude oils have been considered as a fuel of *last resort*, only to be used when other more satisfactory fuels are unavailable.

Use of crude oils in diesel powered equipment generally would not be considered until standard specification fuels and the following alternate and emergency fuels[(1)*] are exhausted or critically low, although use of crude oils as blending agents to extend available fuel supplies should not be neglected when considering emergency fuel supplies. The following alternate fuels: No. 2 fuel oil, NATO F-54, No. 1 fuel oil, JP-5, NATO F-44; and the following emergency fuels: kerosenes, Jet-A, Jet A-1, Jet-B, JP-4, DFM, NATO F-34, F-35, F-76, F-85; should always be used before crude oils. However, these emergency fuels can result in some performance degradation.

Some general property limits for direct use of crude oils were developed from our experimental work and from the literature. In general, crude oil properties can be divided into two groups: (1) those properties which are of importance for short-term operational effects, and (2) those properties whose effects manifest during longer term operation.

Short-term crude oil properties are those properties which either allow or prevent the direct use of crude oil, regardless of operating time, and are mainly related to fuel handling and fuel delivery characteristics. The following short-term properties and their proposed limits will be discussed individually:

- Pour point
- Viscosity
- Fuel cleanliness
- Volatility

*Superscript numbers in parentheses indicate references at end of report.

The following crude oil properties are important for long-term effects such as engine deposition and wear:

- Sulfur content
- High boiling material
  - residuum
  - estimated asphalt content
- Ash

Assuming that a crude oil has satisfactory short-term properties, the long-term properties will determine the length of trouble-free operation that can be expected. Each of the long-term properties will also be discussed and limits proposed.

SUMMARIZED GENERAL LIMITS

Short-Term Property Limits

Pour Point–Limit: The crude oil pour point should be at least 11°C (20°F) below the lowest expected ambient operating temperature.

This property determines the lowest permissible operating temperature at which a particular crude oil could be used. Crude oils having too high a pour point are nearly solid and will not flow as liquids which makes bulk handling and dispensing impossible. Should a crude oil be cooled to near its pour point while in a vehicle, fuel delivery problems caused by the accumulation of solidified crude in the fuel filter element and fuel lines would result. This condition would lead to reduced fuel flow to the engine with resulting power loss or complete stoppage.

Viscosity–Limits: (a) For rotary type distributor pumps, less than 75 cS at the fuel injector pump inlet or less than 32 cS at 38°C (100°F).

(b) For piston type injection pumps, less than 55 cS at 38°C (100°F).

Rotary distrubutor fuel injection pumps of the Roosa-Master type are viscosity critical because if the inlet viscosity exceeds some limiting value, the pump seizes. Bosch type piston pumps reduce delivery as viscosity increases with a resulting loss of maximum power. High viscosity fuels can also result in restricted fuel flow through filters, poor injector spray patterns, and rapid wear of injection system components. Nearly all crude oils have sufficient viscosity to avoid problems associated with using a fuel of too low viscosity.

Fuel Cleanliness–Limit: Crude oil should be dewatered and prefiltered. Water, salt and particulate matter should be kept to a minimum.

Crude oils typically contain the following range of impurities:[(2)]

Salts	30–300 mg/liter [10–100 lb/1000 bbl]
Water	0.1–2% vol
Sediment	3–1500 mg/liter [1–500 lb/1000 bbl]

It was evident that an initial crude oil cleanup would be necessary to remove particulate matter (sediment) and reduce water and salt content. Therefore, throughout the program when considering direct use of crudes, they were assumed to have some initial cleanup at the oilfield storage location. A final external filtration before the crude enters the vehicle would be highly desirable. Excess particulate and water content would be expected to plug vehicle fuel filters causing reduced fuel flow resulting in power loss or engine stoppage. Should particulate matter by pass the fuel filters, high pump and injector wear could occur and pumps could experience seizure at critical points.

Volatility–Limits: $<5\%$ light ends (including dissolved gases).

No vapor lock problems were encountered with crude oils that contained less than 5% light ends, which were defined as all material boiling up to 66°C (150°F). Some vapor lock problems causing erratic fuel delivery were observed when using Bosch injection pumps with crudes having greater than 5% light ends. No problems were encountered with the TCCS pump.

Long-Term Property Limits

Sulfur Content–Limits: 0-1.5% for long-term use, no limit for short-term usage.

When using fuels with high sulfur contents, problems related to corrosive engine wear and increased engine deposition have been documented in the literature(3-8). Cloud and Blackwood(3) have reported that increasing fuel sulfur level from 0.2 to 1.0% in high-speed diesel engines may result in a 40 to 80% increase in engine deposits and a two to sixfold increase in engine wear. Furstoss(6) reported that medium-speed diesel engines operated on fuels having greater than 0.5% sulfur content were subject to abnormal wear and combustion-chamber deposits. Recent work by Perry and Anderson(8) representing the U.S. Navy showed that in 1000-hr tests, independent of the type of engine and operating speed, the increase in wear rate using 1.3% sulfur fuel was approximately twice that of 1.0% sulfur fuel. In the present study, despite the use of high quality lubricants (MIL-L-2104C)(24) which should neutralize much of the corrosive sulfur combustion products, increased wear rates were observed using high sulfur fuel (1.95%) in relatively short-term (120-hr) tests. The proposed sulfur limits and operational durations are by no means absolute, they represent broad general limits based upon these experiments and the results reported in the literature.

Active Sulfur–Limits:(10) Copper strip corrosion (ASTM D-130) it would be *preferable* to have a maximum rating of no more than 2 after 1 hr at 100°C (212°F). Alternate Limit: The Doctor test for mercaptans should be negative.

Active sulfur compounds have been defined as those sulfur containing fuel components which are actively corrosive before they are combusted. Corrosive attack would generally appear in the fuel related subsystems such as fuel tank, pump and injectors.

High Boiling Material–Limits: Residuum (material with BP > 427°C) Longer-term use: 0-15%, short-term use: 0-45%

Estimated asphalt content(11) (4.9 × carbon residue of entire crude) is a component of the residuum and should be kept to a minimum. High boiling material would be expected to cause increased engine deposits in the fuel system, combustion chamber, injector tips, top of piston and piston ring belt and land areas. Also, increased exhaust smoke levels would be expected. Once again, as with the sulfur limits, broad general limits on residuum content and operating durations are proposed because precise definite limits could not be determined without extensive additional work.

Ash–Limit:(10) 0.05% wt

Ash level determines the amount of noncombustible metallic or inorganic material in a fuel which contributes to overall engine deposits. Some crude oils contain large amounts of nickel and/or vanadium. Sodium, from the salt content of some crude oils, and iron also contribute to crude oil ash. Unfortunately, the crude oils which we obtained were relatively low in nickel and vanadium content and also had low ash content, thus the effects of using crude oil of high ash content were not determined.

These general limits are intended for four-cycle diesel engines and it should be kept in mind that the military high output two-cycle diesels are more fuel sensitive[12] and could be expected to have more problems.

DISCUSSION

World Crude Oil Properties

Crude oil characterization data were obtained from Bureau of Mines Reports RI 6819[13] and IC 8542[14] and other sources[15,16,17]. A computer program was written which allows rapid retrieval and selection of CONUS and OCONUS crude oil characterization data.[18] The crude oil characterization data computer program consists of fourteen categories of crude oil data including geographic location, production rate, reserves quantity and physical properties such as distillation, gravity, sulfur content, pour point, and viscosity. The crude oil data computer program and other data sources[15,16,17] formed the basis of the crude oil properties survey.

In considering crude oils as direct use energy sources, the location distribution and various characteristics of the world crude oil supply were investigated. As might be expected, crude oil is found widely distributed throughout the world. Table 1 shows the quantity of crude oil reserves found in various geographical location areas, as given by two different sources[15,16]. The figures in parentheses are the percent of total world crude oil reserves found in each area. The two sources of world crude oil reserves data compare favorably, with the major differences being the more recent source (B) had higher estimates of Communist area reserves, increased Western Europe reserves due to North Sea discoveries and also increased African reserves. The bar graph of Figure 1 shows the percent reserves distribution for each geographic area. It is quite apparent that with respect to crude oil reserves, the world is divided into two groups: (1) the Middle East, and (2) all other areas (whose sum total of reserves do not equal the Middle East reserves).

TABLE 1. WORLD CRUDE OIL RESERVES

Area	Reserves Billions of bbl (Percent of total world reserves) Source A[a]		Source B[b]	
USA	36	(6.4)	34.7	(5.5)
Canada	8	(1.4)	9.4	(1.5)
Latin America	30	(5.3)	31.6	(5.1)
W. Europe	10	(1.8)	15.9	(2.5)
USSR	42	(7.5)	80	(12.8)
Africa	54	(9.6)	67.3	(10.8)
Middle East	353	(62.8)	350	(56.1)
Asia-Pacific	16	(2.9)	15.6	(2.5)
Far East (China)	13	(2.3)	20	(3.2)
Total	**562**	**(100.0)**	**625**	**(100.0)**

[a]Source A – Data from *Hydrocarbon Processing*, 9/73.
[b]Source B – Data from *Oil and Gas Journal*, 12/73.

Having established the distribution of world crude oil reserves, the characteristic crude oil properties of each area will now be considered. Crude oil properties vary significantly depending on the geographic location of the crude. Sulfur content is one of the most important methods of classifying crude oils. Figures 2 and 3 show the distribution of the world crude oil reserves by sulfur content. It is significant to note that about 66% of the world crude oil reserves contain greater than 1.0% sulfur, and about 28% of the reserves contain greater than 2.0% sulfur. In Figure 4, the sulfur distribution bar graphs of Figure 4-2 have been subdivided to visually illustrate the contribution of each geographic area to the overall sulfur distribution. The significant points of Figure 4 are the fact that most North America, Asia-Pacific, and Africa crudes contain 1.0% or less sulfur, while most Middle East and Latin America crudes contain greater than 1.0% sulfur. From a refining standpoint and from a direct use standpoint crudes of lower sulfur content are more desirable.

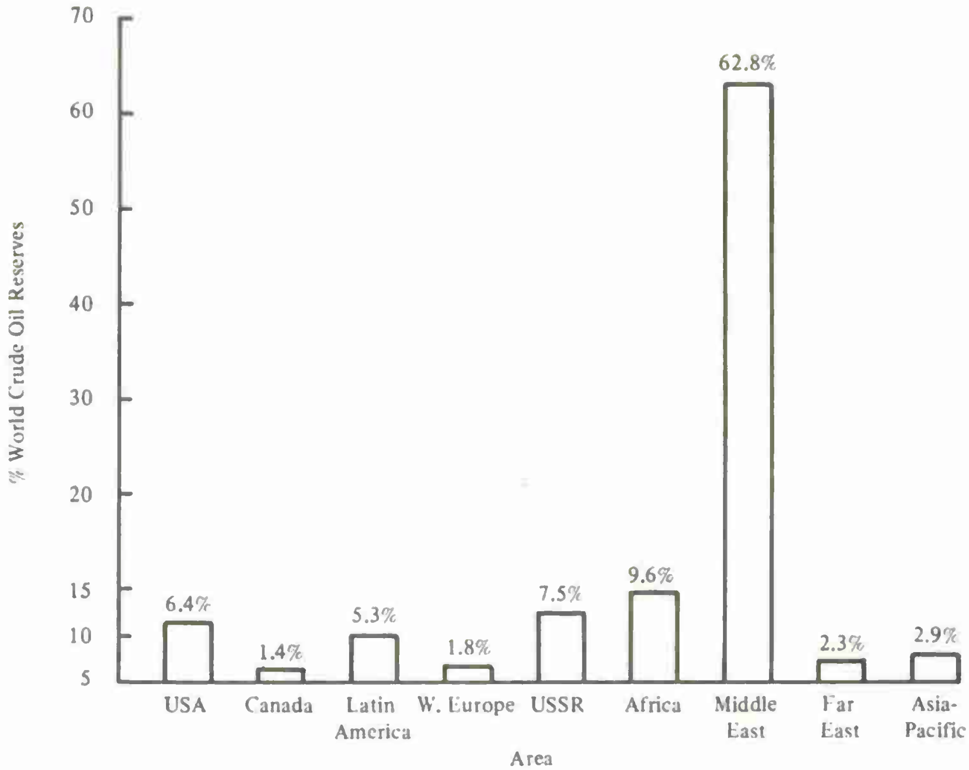


FIGURE 1. DISTRIBUTION OF WORLD CRUDE OIL RESERVES BY GEOGRAPHIC AREA (RESERVES–SOURCE A)

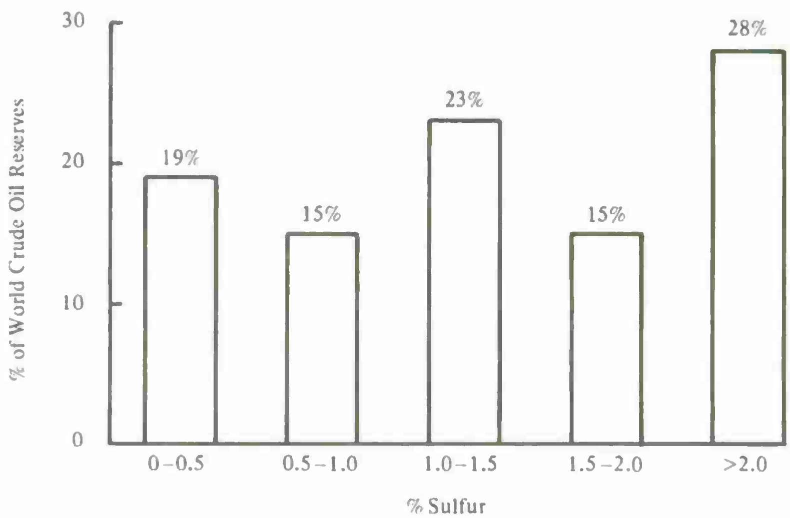


FIGURE 2. DISTRIBUTION OF WORLD CRUDE OIL RESERVES BY SULFUR CONTENT

With the sulfur distribution established, various other properties were investigated to determine in general which properties were most critical for a given geographic area. By critical properties, it is meant those properties which would eliminate from direct use the most crude in a given area, based on either long- or short-term effects.

Geographic distributions based on maximum pour point and maximum viscosity values were made. These properties are related to short-term effects and the use of fuels having

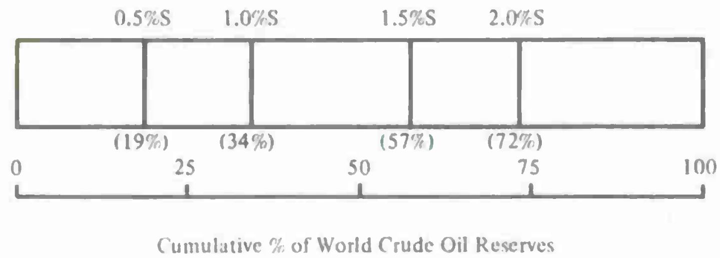


FIGURE 3. SULFUR CONTENT OF WORLD CRUDE OIL RESERVES

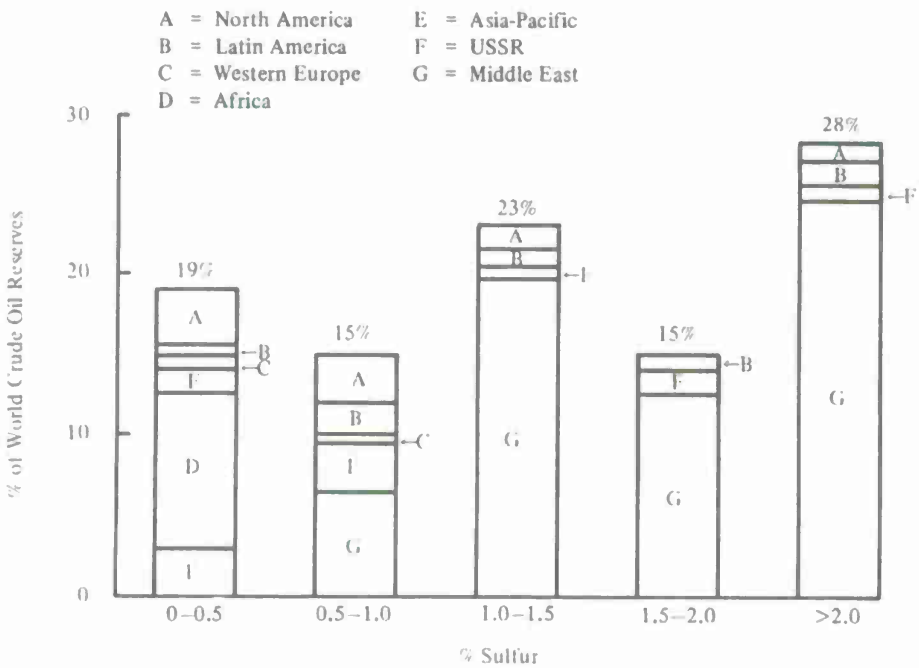


FIGURE 4. DISTRIBUTION OF CRUDE OIL RESERVES BY SULFUR AND GEOGRAPHIC AREA

pour points and/or viscosities in excess of some limiting values would be expected to result in immediate problems such as poor fuel delivery leading to power loss or complete engine stoppage. Based on experimental work conducted during this project, a maximum viscosity limit of 32 cS at 38°C was used which would allow operation with the more viscosity sensitive rotary distributor fuel injection pump. A pour point limit of −7°C (+20°F max) was chosen to allow operation in all but severe environments.

Sulfur content and estimated asphalt content were assumed to be important properties for longer term operation. Expected long-term engine effects would be corrosive wear from high sulfur content and deposition from the high boiling, resinous asphaltic material. It would be expected that the higher the sulfur and/or estimated asphalt content, the shorter the trouble-free operation time will be. Distributions of the world crude oil reserves for various areas were determined for three sulfur levels and three estimated asphalt contents.

Table 2 shows the percent of reserves in each area that satisfy each of the given individual limits. For example, considering the Middle East reserves, if an intermediate length of operation on crude oil was expected, a limit of 1.0% sulfur maximum might be

TABLE 2. CRUDE OIL CRITICAL PROPERTIES
(Percent of reserves meeting various property limits)

Area	Percent Sulfur			Percent Estimated Asphalt			Pour pt < –7°C (+20°F max)	K. Vis. at 38°C 32cS max
	1.0 Max	1.5 Max	2.0 Max	10 Max	15 Max	20 Max		
Middle East	10	40	60	2	20	47	94	95+
Asia-Pacific	95	95+	95+	23	52	95+	2	80
Latin America	50	70	80	4	5	27	71	40
Africa	95	95+	95+	43	90	95+	39	90
W. Europe	95	95+	95+	NA	NA	NA	70	75+
USA	70	90	90	—	—	—	—	—

[a]NA–Not Available.

chosen. As shown in Table 2, there would only be approximately 10% of the Middle East reserves which meet this particular limit. Considering estimated asphalt content, if a relatively high limit were selected (20% max), still only 47% of the Middle East reserves would meet this requirement. Both sulfur and estimated asphalt content are considered critical properties for Middle East reserves because many crudes are eliminated from potential long-term use based on these properties. The Asia-Pacific reserves are an example of a short-term property being the critical property, because a pour point limit of –7°C (+20°F max) allows direct use of only about 2% of the reserves from this area. Analysis of the data of Table 2 revealed the following critical crude oil properties by geographic area:

Area	Critical crude oil properties
Middle East	Sulfur, estimated asphalt
Asia-Pacific	Pour Point
Latin America	Viscosity, estimated asphalt
Africa	Pour point
W. Europe	Pour point, unknown estimated asphalt

The next step was to determine the distribution of reserves within geographic areas when considering sulfur level, estimated asphalt content, pour point and viscosity properties collectively instead of individually as was done in determining the critical properties. A single set of limits were estimated for the short-term properties, since they determine go or no go use of crude, while several different sets of limits were considered for the long-term properties, to reflect the various trade offs between operation time using crude versus engine deterioration. The short-term property maxima selected were –7°C (+20°F) for pour point and 32 cS at 38°C for viscosity. Distributions of reserves were then determined for various combinations of long-term properties (sulfur and estimated asphalt content). Figures 5, 6, and 7 show the results of this investigation in matrix form for the Middle East, Africa, and Latin America reserves. Each block in the matrix represents a particular sulfur level-estimated asphalt content combination, with the pour point and viscosity at their given maxima. The percent of reserves meeting this exact combination of properties is given for each block. For example, Figure 5 shows that 27.9% of the Middle East crudes are in the range of 1.5 to 2.0% sulfur with 10 to 20% estimated asphalt content and are also within the given pour point and viscosity maxima.

This matrix set-up can also be used to determine the *total* percent of reserves in an area meeting selected limits based on the two constant and two variable properties. This is done

% Sulfur

% Estimated Asphalt	0–1.0 max	1.0–1.5 max	1.5–2.0 max	2.0–2.5 max	>2.5 max
30–40 max	–	–	–	–	–
20–30 max	–	–	12.5	4.4	33.0
10–20 max	–	5.9	27.9	11.8	–
0–10 max	1.3	1.1	–	–	0.3

Constants

Viscosity @ 38°C (100°F) = 32cS (150 sus) max

Pour Point = >–7°C (20°F) max

Total of 98.2% of Middle East crude reserves have properties within this matrix

Example:

To calculate total % of reserves meeting a set of limits (e.g., 2.0% max and 30% est. asphalt max): (1) find this matrix box, (2) sum values of it and all matrix boxes directly below it, directly to the left of it, and to lower left (all boxes in shaded area) TOTAL = 45%

Legend:

% Sulfur

% Est. Asphalt	0–1.0 max	1.0–1.5 max	1.5–2.0 max	2.0–2.5 max	>2.5 max
30–40 max	–	–	–	–	5
20–30 max	–	10	10	25	10
10–20 max	5	15	5	–	–
0–10 max	–	–	–	–	–

FIGURE 5. MIDDLE EAST CRUDE OILS
(Percent of area reserves meeting various requirements)

% Sulfur

% Estimated Asphalt	0–1.0 max	1.0–1.5 max	1.5–2.0 max	2.0–2.5 max	>2.5 max
30–40 max	–	–	–	–	–
20–30 max	–	–	–	–	–
10–20 max	1.5	–	–	–	–
0–10 max	42.3	–	–	–	–

Constants

Viscosity @ 38°C (100°F) = 32cS (150 sus) max

Pour Point = >–7°C (20°F) max

Total of 43.8% of Africa crude reserves have properties within this matrix

FIGURE 6. AFRICA CRUDE OILS
(Percent of area reserves meeting various requirements)

% Sulfur

% Estimated Asphalt	0–1.0 max	1.0–1.5 max	1.5–2.0 max	2.0–2.5 max	>2.5 max
30–40 max	–	–	–	1.3	–
20–30 max	4.3	5.6	–	–	–
10–20 max	3.9	22.0	–	–	–
0–10 max	–	–	–	–	–

Constants

Viscosity @ 38°C (100°F) = 32cS (150 sus) max

Pour Point = >–7°C (20°F) max

Total of 37.1% of Latin America crude reserves have properties within this matrix

FIGURE 7. LATIN AMERICA CRUDE OILS
(Percent of area reserves meeting various requirements)

by selecting the matrix block which has the desired combination of maximum sulfur and estimated asphalt limits, and then summing the percentages in the following matrix blocks:

1. The selected maximum limits block
2. All blocks directly below the selected block
3. All blocks directly to the left of the selected block
4. All blocks to the lower left of the selected block.

For example, if we wanted to determine the total percent Middle East reserves with a maximum sulfur level of 2.0%, and a maximum estimated asphalt of 20%, we first find this matrix block in Figure 5. It contains 27.9%. The block(s) directly below it are empty, while directly to the left are 5.9% and an empty block. To the lower left are blocks containing 1.3% and 1.1%. Summing the values of all these matrix blocks (27.9 + 5.9 + 1.3 + 1.1) we find that 36.2% of the Middle East reserves fall within the following limits:

% Sulfur	2.0 max
% Est. asphalt	20 max
Viscosity @ 38°C	32 cS max
Pour point	−7°C (20°F) max

As additional data for diesel engine operation on crude oil are obtained, and *definite* crude oil property limits are developed which correlate engine deterioration with operation time and crude oil properties, the distribution information presented here can be used to find the quantities and locations of crudes having the desired properties.

CRUDE OIL EVALUATION

The evaluation part of the program was divided into a number of sections, each of which will be discussed separately. Physical property inspections were conducted on the crude oils obtained from various CONUS locations.

Compatibility determinations were performed with various engine subsystems plus operation in single cylinder engines. Fuel injection pumps and total systems, particularly the pump from the TCCS engine, were evaluated to determine the effects of viscosity on fuel delivery and pump life. Unit fuel injectors from a 6V53T engine were operated for extended periods on crudes to evaluate any deposit tendencies. Fuel filter systems from the LDS-465 and 6V53T engine were used to evaluate filterability. Spray pattern studies with both pencil and unit injectors were attempted and single cylinder engines, the CLR diesel in both the precup and direct injection configurations and the TACOM ER-3 direct injection engine, were operated using crude oils. The remainder of this report will be devoted to detailed discussions of this work.

Crude Oil Analysis

Oil industry contacts were made to obtain a wide variety of selected CONUS crude oils. Complete physical inspections were made of each crude oil, and are shown in Table 3. Standard inspection tests included gravity, sulfur, viscosity, pour point and flash point. A gas chromatographic technique was developed to enable the determination of crude oil boiling point distributions. Percent residuum, defined as all material with a boiling point greater than 427°C, was determined from GC boiling point distributions. Estimated asphalt content was determined by using the following Bureau of Mines correlation[11]

% estimated asphalt = 4.9 X % Conradson carbon residue.

Cetane number and heat of combustion were determined to give an indication of the combustion quality of the crude oils. It was apparent from particulate matter content that initially the crude oils required filtering before use in engines. The technique and results of the filtration study are discussed in a separate section of this report. Most of the crudes had been dewatered at the oilfield; however, they still had a higher water content than typical refined fuels.

The wide variety of the crude oils investigated is illustrated by the following summary table which shows the range of properties (minimum and maximum values) observed:

Property	Minimum	Maximum
Gravity, API°	15.4°	41.8°
Sulfur, % wt	0.05	1.95
Viscosity, cS, 37.8°C	2.0	397
Pour point, °C (°F)	−37 (−35)	32 (90)
Residuum, %	11	64
Estimated asphalt, %	1	41
Cetane number	21	51

Based on the range of properties of the crudes which were investigated, it is estimated that they are representative of about 70% of the total world crude oil reserves.

TABLE 3. CRUDE OIL INSPECTIONS

Oilfield State AL-designation	ASTM method	Conroe TX 5253	N. Alazan TX 5250	KMA TX 5277	TXL TX 5283	Eugene Is. LA 5300	Caillou Is. LA 5301	Venice LA 5296	Greeley CA 5267	Wilmington CA 5795	Inglewood CA 5810	Red Wash UT 5709	Reference diesel DF-2
Physical properties													
Specific gravity		0.84	0.82	0.82	0.84	0.82	0.84	0.85	0.90	0.96	0.93	0.91	0.86
(°API)	D 287	(37.2)	(41.8)	(41.2)	(37.2)	(40.8)	(36.5)	(35.9)	(26.4)	(15.4)	(21.4)	(24.1)	(33.2)
Sulfur, % w	D 129	0.05	0.06	0.20	0.43	0.07	0.13	0.17	0.67	1.73	1.95	0.12	0.42
Viscosity, cS, 37.8°C	D 445	2.2	2.0	2.6	4.6	3.1	4.6	4.6	24.5	397	41.2	89.2	3.2
Pour point, °C	D 97	−12	−29	−34	−18	−4	2	−12	−1	−15	−37	32	−8
Flash point, °C	D 92	−3	−6	−8	2	−4	0	−9	28	99	43	32	85
Copper corrosion	D 130	1A	1A	3[a]	1-A	1-A	1-A	1-A	1-A	—	—		1A
GC BP distribution	—												
10% recovered at °C		122	112	97	97	150	127	131	174	242	177	222	242
30% recovered at °C		202	189	195	207	228	223	232	293	363	291	386	259
50% recovered at °C		266	244	301	319	283	303	312	410	463	400	496	271
70% recovered at °C		324	293	436	456	356	380	420	603	568	510	610	286
90% recovered at °C		454	443	—	—	535	496	604	—	—	—	—	317
Estimated asphalt, % w	—	2	2	7	8	1	8	6	26	41	31	14	—
Residuum, % (BP > 427°C)	—	13	11	31	34	19	21	29	48	58	45	64	—
Heat of combustion (gross) MJ/kg	D 240	48.4	46.2[b]	46.2[b]	45.9[b]	45.6[b]	45.8[b]	46.1[b]	45.0[b]	—	43.2	—	45.5[b]
Cetane number	D 613	45	44	42[c]	46[c]	51	47	46	39	21	28	27	47[b]
Water, ppm	D 1744	500	300	300	500	300	5800	1800	1100	—	2700	—	—
Solids on 5×10^{-4} cm filter before filtered, mg/100 ml	—	104	15	42	20	7	210	26	—	114	88	115	—
Ash, % w	D 482	0.003	0.002	0.004	0.005	0.002	0.001	0.009	0.035	—	—	—	0.006
Elemental analyses													
Ni, ppm	D 2788	<5	<5	<5	5	<5	<5	<5	40	65	43	20	—
V, ppm		<5	<5	<5	7	<5	<5	<5	30	40	52	<40	—

[a]Dark tarnish.
[b]Calculated value.
[c]Vapor problems encountered.

EFFECTS OF CRUDE OILS ON DIESEL FUEL INJECTORS AND FUEL INJECTION PUMPS

TCCS Pump

Equipment and Procedures

The fuel injection pump intended for use with the TCCS stratified charge engine was mounted on a Unitest fuel pump calibration machine for determining the pump's fuel delivery characteristics with changing fuel viscosity and to assess the effects of fuel viscosity on pump life. Work had already been done on the effects of low viscosity fuels[19] so this work concentrated on fluids with viscosities greater than the typical reference DF-2[20]. The standard TCCS injectors and lines were used to connect the pump to reservoirs for measurement of the pump fuel delivery volume (Figure 8). After an initial pump seizure, the pumps were instrumented with pressure gauges connected to a fuel transfer passage and to the overflow reservoir. An exposed junction iron-constantine thermocouple was inserted into a fuel outlet passage in the hydraulic head near the rotor, and the internal fuel temperature was recorded continuously with a strip chart recorder (Figure 9). Inlet fuel temperature was measured by a partial immersion type thermometer. The test fuels were initially blended from DF-2 and a qualified MIL-L-2104C grade 50 motor oil (AL-4654) and later from DF-2 and white mineral oil. The pumps, which normally run at half engine speed, were operated at 500, 750, 1000, 1250, 1500, and 1750 pump rpm while the fuel delivered by the injectors was collected for approximately 1000 revolutions.

Discussion of Results

Determinations of the fuel delivery vs. viscosity characteristics had just begun when the first pump seized. This pump had been operated on DF-2 and just began operation using a grade 50 motor oil with a viscosity of approximately 200 cS at 38°C (100°F) when the failure occurred. Disassembly revealed that the seizure occurred between the rotor and the hydraulic head at the fuel discharge ports, Figure 10a. While this type of failure was expected with high viscosity fuels, the 50 grade oil had been expected to perform satisfactorily and the location of the seizure directly at a port brought up the possibility of fuel contamination being the cause.

A second pump was then mounted on the test stand and three fuels were blended from the 50 grade oil and DF-2 to have viscosities at 38°C (100°F) of approximately 50, 100 and 150 cS. The same delivery determinations were made as before with increasing fuel viscosities. The fuel delivery per injection, fuel temperature near the outlet port and transfer pump pressure were monitored.

There was no fall-off in delivery per stroke for any of the blends tried (Figure 11), thus indicating that the fuel viscosities were low enough to allow complete filling of the pumping section. The transfer pump pressure never exceeded that of DF-2 and was substantially under the 862 kPa (125 psi) limit set by the manufacturer. However, the temperature of the injected fuel increased with increasing fuel viscosity (Figure 12) until the second pump seized.

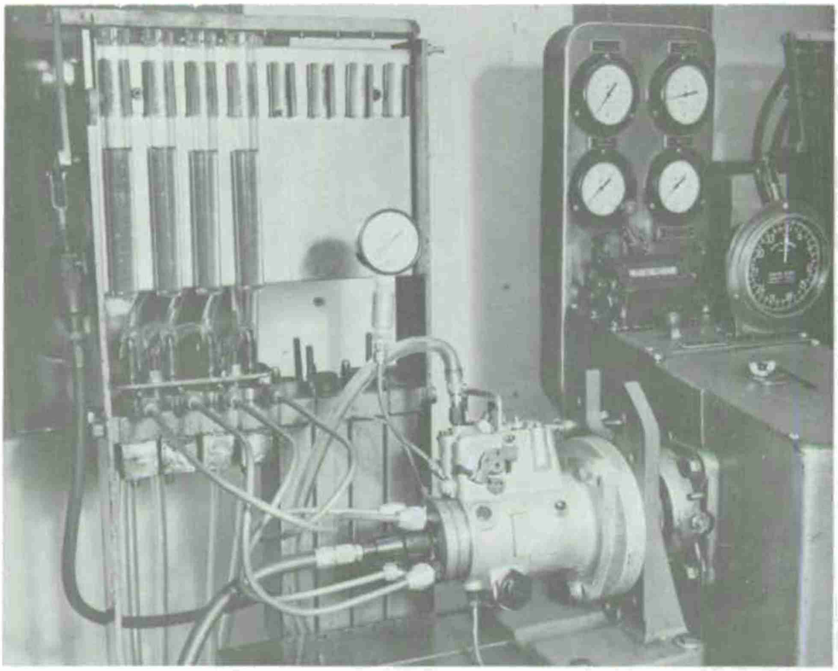


FIGURE 8. TCCS FUEL INJECTION SYSTEM
INSTALLED ON TEST STAND

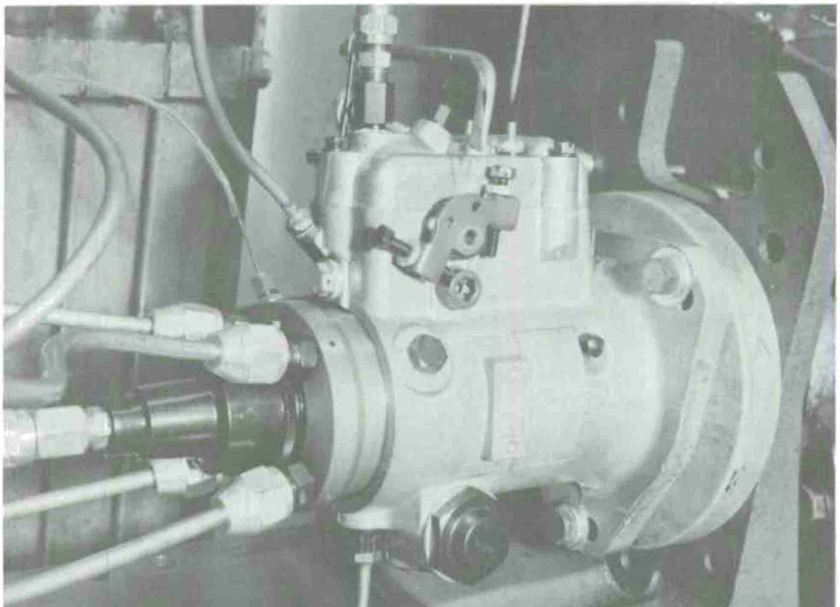


FIGURE 9. INSTRUMENTED TCCS FUEL INJECTION PUMP

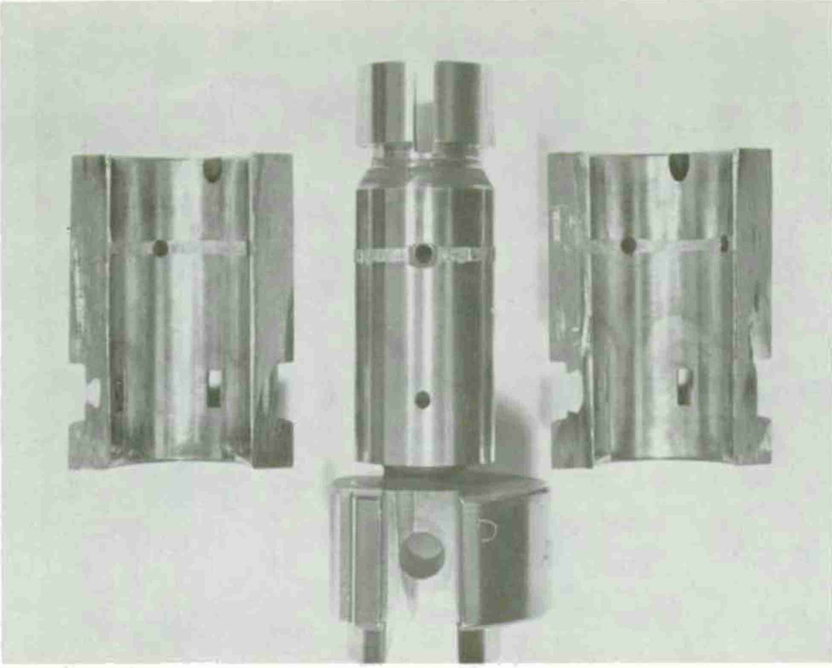


FIGURE 10a. SEIZURE NO. 1 TCCS PUMP OPERATED ON 50 GRADE MOTOR OIL

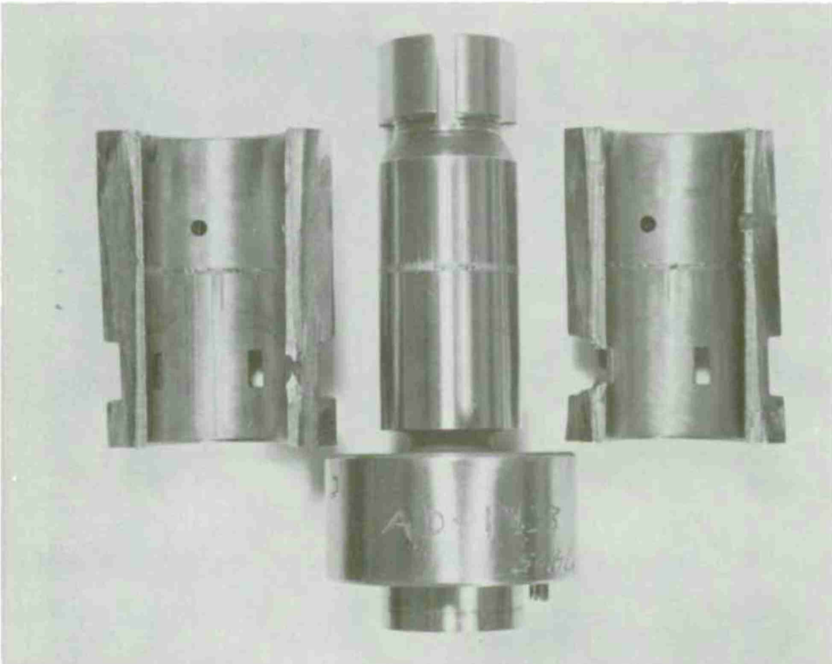


FIGURE 10b. SEIZURE NO. 2 TCCS PUMP OPERATED ON DF-2/50 GRADE OIL BLEND WITH VISCOSITY OF 128 cS AT 38°C

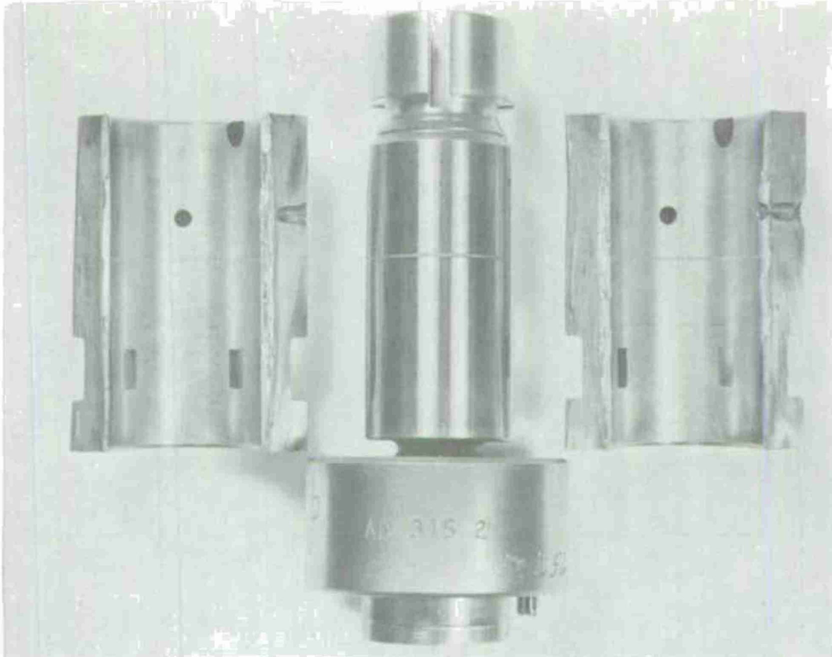


FIGURE 10c. SEIZURE NO. 3 TCCS PUMP OPERATED ON DF-2/WHITE MINERAL OIL BLEND WITH VISCOSITY OF 72 cS AT 38°C

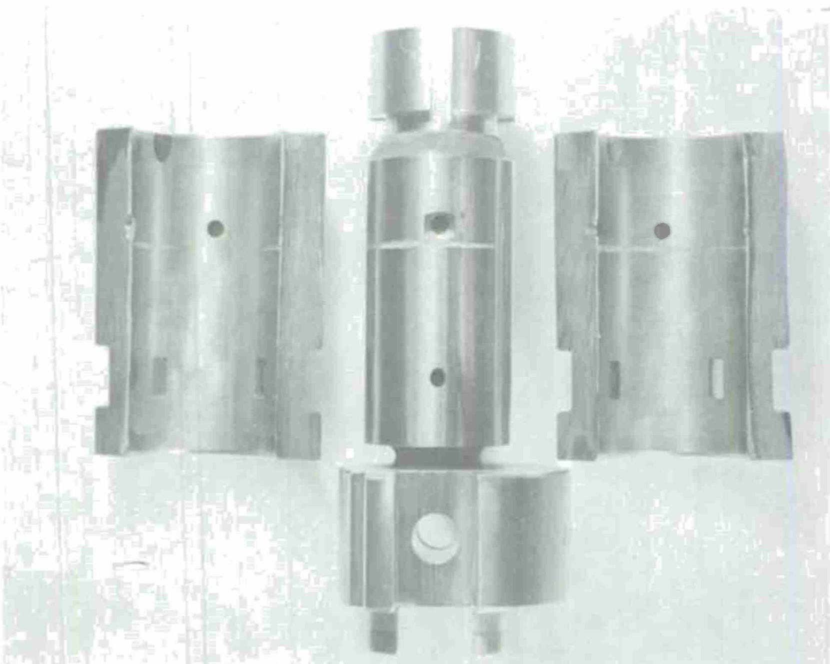


FIGURE 10d. SEIZURE NO. 4 TCCS PUMP OPERATED ON DF-2/WHITE MINERAL OIL BLEND WITH VISCOSITY OF 40 cS AT 38°C

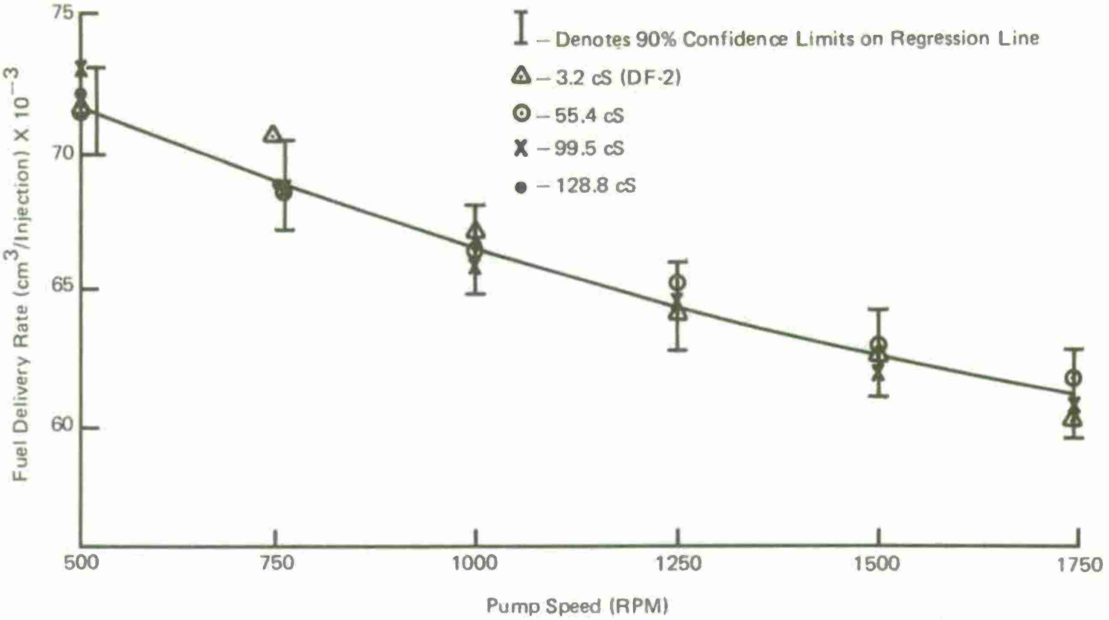


FIGURE 11. TCCS PUMP DELIVERY WITH VARYING VISCOSITY FUELS

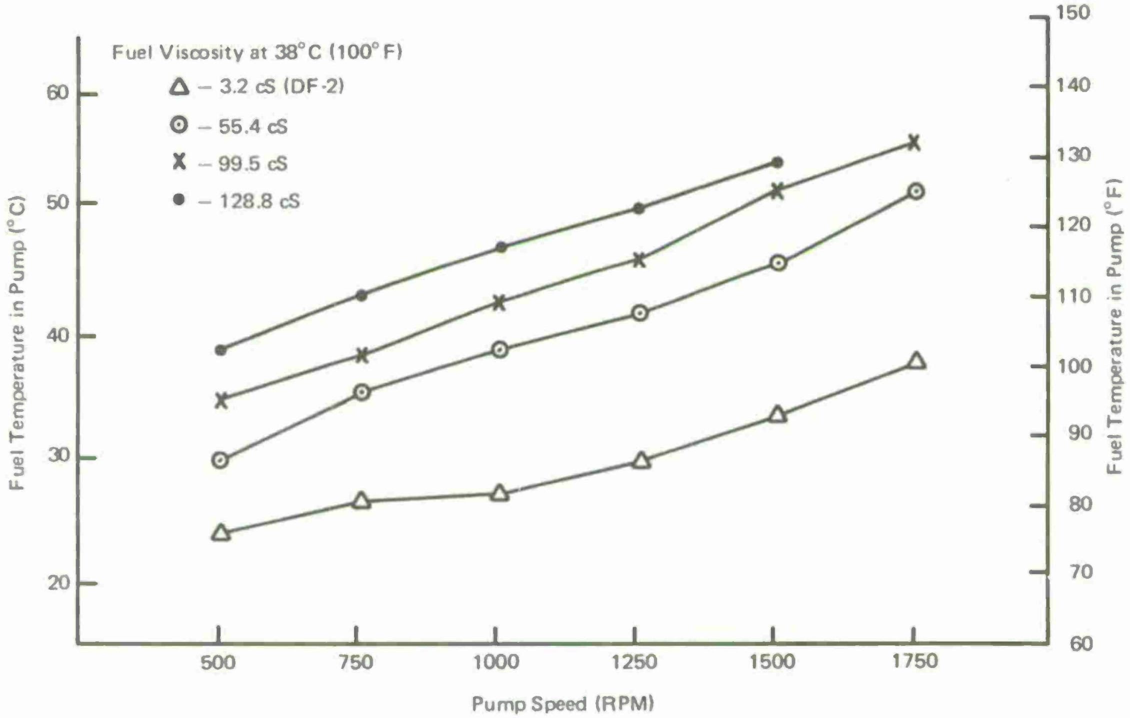


FIGURE 12. EFFECT OF FUEL VISCOSITY ON INTERNAL FUEL TEMPERATURE–TCCS PUMP

The second seizure occurred while using a fuel with a viscosity at 38°C (100°F) of 128.8 cS. The pump was being brought to 1750 pump rpm at the time. The transfer pump pressure was approximately 552 kPa (80 psi) and the fuel temperature peaked at 62°C (143°F).

This pump was disassembled and it was found that the seizure occurred between the charging and the outlet ports in the rotor, well away from any port, Figure 10B. Thus, the failure was probably due to fuel effects, since contamination at this point was unlikely. This seizure also tended to substantiate the premise that the first failure was also viscosity related, since the earlier failure had occurred at a higher viscosity but a lower pump speed.

At this point it was felt that a limiting viscosity, approximately 100 cS at 38°C (100°F) had been reached, so one of the TCCS pumps was rebuilt using new parts and was used to take pictures of the injector spray pattern using the liquid injector technique.[21] The pump was operated for a number of days using DF-2 while injection pictures were made at varying speeds and fuel delivery rates. A second fuel blended from white mineral oil and DF-2, having a viscosity of 72 cS at 38°C (100°F) was then used. Spary pictures were made at 500 pump rpm and as the pump was being brought to 750 rpm, it seized.

Disassembly revealed that the seizure had once again occurred in the hydraulic head section, at the same location as the second seizure, Figure 10c. Thus, it appeared that this, too, was a viscosity related failure, at a lower viscosity and much lower pump speed than before. It appears that the additive package in the engine oil used in the earlier work may have been protecting the pump to some extent.

Another TCCS pump was ordered and mounted on the test stand. Discussions with the pump manufacturer had indicated that fuels with a viscosity of 40 cS at 38°C (100°F) had been used successfully with pumps of this type. Thus, four fuels were blended from DF-2 and mineral oil to have viscosities at 38°C (100°F) of 10, 20, 30, and 40 cS. DF-2 and these fuels, in order of increasing viscosity, were then run through the pump. All these fuels except the 40 cS blend operated satisfactorily. The pump seized at 1500 pump rpm with the 40 cS fuel, with the seizure line immediately below the high pressure outlet ports (Figure 10d) and, consequently, contamination could not be ruled out as a cause, even though the fuel had been filtered. Based on these tests and discussions with the pump manufacturer, a fuel viscosity of 75 cS at inlet conditions appeared to be a reasonable upper limit. This viscosity limit, when applied at the 23°C (74°F) inlet temperature of these tests, thus allows use of fuels with viscosities of slightly over 30 cS at 38°C (100°F). This viscosity limit is of value when applied to the rotary distributor type pumps and need not be used when dealing with barrel and plunger type pumps, as discussed in the following section.

It should be noted that crude oils were never run in the TCCS pumps, primarily because of difficulties in obtaining a sufficient number of pumps within the necessary time period. The varying viscosity fluids used, particularly the white mineral oil and DF-2 blends, would be expected to produce results similar to crude oils with some possible exceptions in that crude oils contain a variety of components which may either provide some protection[22] or could cause other problems.

Single Cylinder Barrel and Plunger Pump

Equipment and Procedure

A single cylinder pump, with a 7-mm barrel and plunger, was mounted on the Unitest machine to determine the pump's response to varying fuel viscosity. A pintle type injector was used and the fuel control rack on the pump was fixed at a convenient position. Test fluids were blended from combinations of VV-G-001690A unleaded gasoline, DF-2, white mineral oil and 50 grade engine oil.

The pump was run at 500, 1000, 1500, and 1750 rpm while the amount of test fluid delivered during approximately 1000 injections was collected. The inlet fuel temperature was measured using a partial immersion thermometer. The fluids were collected in graduated glass tubes.

Discussion of Results

The delivery curves for the various fuels are given in Figure 13. The pump delivery decreases with increasing viscosity as might be expected when considering the port control arrangement used in the barrel and plunger pump. A plot of average delivery versus viscosity, Figure 14, can be used to set a limiting fuel viscosity for adequate engine power. The decrease in fuel delivery with increasing viscosity has little effect except at near full rack conditions. At partial rack settings, a decrease in delivery rate can be compensated for by increasing the rack setting. At full rack, however, a decrease in fuel delivery is reflected in a direct decrease in power. Based on this, and assuming that the energy content per volume of the various fuels are essentially constant, an upper viscosity limit was set to limit the fuel rate loss to 10%. A fuel with a maximum viscosity of 55 cS at 38°C (100°F) would not cause a loss of greater than 10% power attributable to pump filling effects.

When gasoline was used, the average delivery of the pump dropped approximately 12% even though the viscosity of gasoline is less than that of DF-2. However, when water was used in the pump, the delivery increased almost 5% above DF-2 and water and gasoline have similar viscosities. Apparently the volatile components of the gasoline were vaporizing inside the pump and causing a partial vapor lock that impeded filling of the pumping section. This vapor problem was also observed with crude oils that had 5% or more material with a boiling point less than 66°C (150°F).

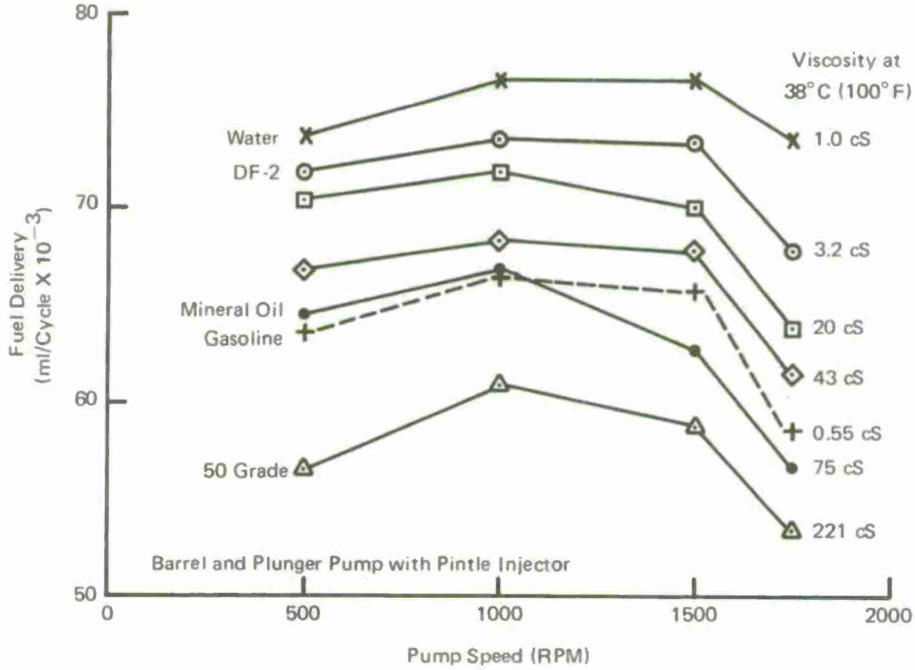


FIGURE 13. EFFECT OF SPEED AND FUEL VISCOSITY ON PUMP DELIVERY, BARREL AND PLUNGER PUMP

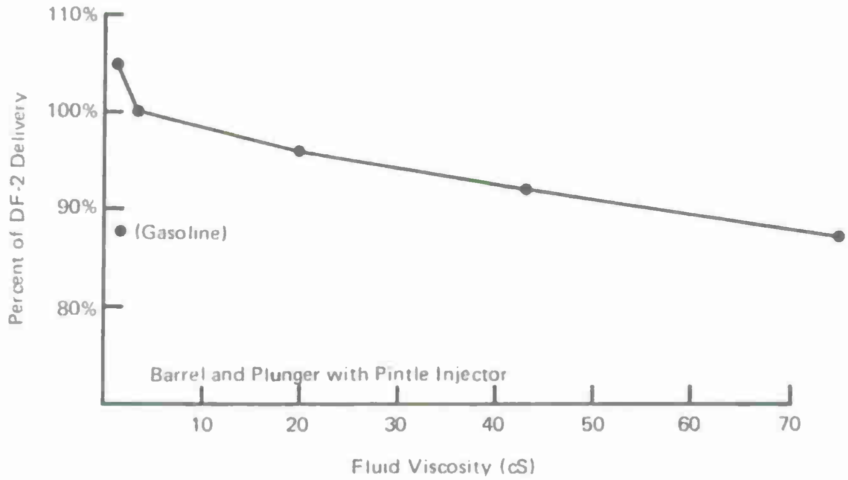


FIGURE 14. AVERAGE DELIVERY WITH VISCOSITY, BARREL AND PLUNGER PUMP

It is also of interest that during this program a barrel and plunger type pump was operated with a crude oil which had a viscosity of over 500 cS at the pump inlet conditions. While there were difficulties in fuel pickup and there was a large reduction in delivery rate, the pump continued to operate and was later used without any problem. Fluids with this high viscosity would have seized the rotary pump, thus demonstrating the potential differences in fuel handling capability between injection pump designs.

Unit Injectors

To evaluate the deposit formation and seizure tendencies of unit injectors, the injectors from the U.S. Army 6V53T engine were mounted in a rig normally used for observing injector spray patterns. The rig consisted of a holder for an injector and a 6V53T camshaft to actuate it. The camshaft was driven by a 0.6 kW (0.75 hp) motor through a variable speed transmission. The fuel system included filters, flow and pressure regulating equipment, and provisions for fuel heating and cooling and a 5-gal fuel tank. An aluminum heating block was attached to the lower end of the injector to simulate engine heat. The injector was run for 12 hr with each test fuel, then disassembled and inspected. During the 12-hr test, the camshaft was turned at 700 rpm, the fuel pressure to the injector was maintained at 173 kPa (25 psi) and the injector rack control set so that the injected fuel flow rate was 6.5 ml/min (0.103 gal/hr) at 260°C (500°F). These conditions maintained the fuel recycle temperature at 52°C to 54°C (125°F to 130°F) and the tank temperature at 49°C (120°F). To increase the fuel degradation rate and increase deposition tendencies, the injected fuels were collected, cooled and returned to the fuel tank. DF-2, the Greely, and the Inglewood, California crude oil, were used. No operational difficulties were encountered. After each 12-hr test, the injector spray patterns were studied using DF-2 as the test fluid and no differences in spray patterns were detected for any of the injectors. Disassembly of the injectors showed no differences between injectors as deposit levels were essentially identical and, also, no wear was evident. However, this type of test would not be expected to emphasize sulfur effects nor would it simulate the higher temperatures and combustion pressures experienced in an operating diesel engine.

Spray Patterns Determined By Liquid Injection Technique

Equipment and Procedures

Spray pattern studies were made using a single hole pencil injector from the TCCS engine, using the liquid injection technique in which the injector sprays into a clear fluid and the resulting cavitation plume can be photographed and studied.[21] Unfortunately, the dark crude oils clouded the receiving fluid so rapidly that taking pictures was impossible.* As a result, the assumption was made that the viscosity of the injected fluid was the most important variable in injector sprays, thus a series of clear fluids of varying viscosities were used.

The injector spray patterns were studied by using a high intensity strobe light, capable of producing a 44-million beam candle flash, and was triggered by a magnetic pickup. The adjustable trigger delay of the strobe light was used in conjunction with a black and white television camera with video recording and playback capability. Using this camera and the strobe light, photographs were made while manually varying the strobe delay. In this manner, measurements of the spray pattern could be made from the television monitor when the spray penetrations were identical and estimations of the maximum spray penetrations were possible. Maximum penetration was considered to be the point furtherest from the injector where the injected fluid could be clearly distinguished from the receiving fluid.

Discussion of Results

Initial spray studies were conducted using the TCCS fuel injection system and a specially constructed receiving box. Tests were completed using DF-2, but when a test fluid with a viscosity of 72 cS at 38°C was tried, the pump seized, as noted previously. In an effort to continue this spray work, a Bosch APE single cylinder pump was then substituted for the TCCS pump. A series of clear fluids, varying from unleaded gasoline to mineral oil, were then tested in the system. These fluids, their viscosities, and the resulting spray measurements are given in Table 4. It should be kept in mind that although there were some differences in spray patterns, and these differences might affect engine power and economy, for emergency fuels all that is really required is that the fuel be delivered into the combustion chamber in some semi-atomized state. All of the fuels tried exceeded this requirement.

TABLE 4. SPRAY PATTERN CHARACTERISTICS WITH VARIOUS VISCOSITY FLUIDS LIQUID INJECTION TECHNIQUE[21)a]

Fluid	Viscosity at 38°C, cS	1000 rpm		1750 rpm	
		Cone angle	Est. penetration	Cone angle	Est. penetration
Gasoline	0.55	23°	16 cm	20°	15 cm
DF-2	3.20	24°	19 cm	21°	21 cm
Mineral Oil	75	16°	23 cm	19°	18 cm
Naptha	1.02	23°	18 cm	23°	18 cm
DF-2/polyisobutylene V.I. improver	41.1 cS	12°	NA[b]	10°	NA

a Bosch APE pump w/TCCS injecter
a JP-4 receiving fluid
b NA–Not available

*Attempts at spraying into air produced similar results.

Only when an insufficient amount of fuel can be atomized so that combustion cannot be initiated or sustained for a sufficiently long period will spray characteristics be a major factor. And, as will be seen elsewhere in this report, a number of other component limits will probably have been reached before this point.

Crude Oil Filtration

Equipment and Procedure

A fuel filter system from the 6V53T engine and a system from an LDS-465 engine were used to evaluate the ability of crude oils to pass through standard fuel filters without large pressure losses or a reduction in fuel flow to the injector pump. Throughout this work, the assumption was made that all crudes would in some way be pretreated, even if only by holding the crude oil in storage tanks for a time to allow water and sediment to settle. A more positive method of pretreatment would be preferred.

Initial tests were conducted using the filter system from the 6V53T engine, which consists of a 30-μm sock type primary filter followed by a 10-μm pleated paper secondary filter. The fuel pump, which was located between the two filters so that the primary filter was under suction and the secondary filter was under pressure, was held at constant speed while 208 liters (55 gal) of the test fuel was filtered. The flow rate through the system was measured by determining the amount of time required to filter 3.8 liters (1 gal). Flow rate measurements were made initially and after every 38 liters (10 gal) until a 208-liter (55-gal) sample had been filtered.

Tests were then conducted using the fuel filters from the LDS-465 engine. The system consisted of a variable speed, positive displacement pump with a built-in variable pressure bypass, the standard 1-1/2μm filters with pressure gauges installed before, between, and after the filters, and a flow regulating valve and pressure relief valve after the filters. The fuel temperature was held constant at 38°C (100°F). The upstream pressure was set at 450 kPa (65 psi) and the downstream relief valve set at 415 kPa (60 psi). The relief line returned fuel to the 19-liter (5-gal) tank while the flow regulating valve controlled the flow from the system. The fuel was removed from the system at 41 kg/hr (90 lb/hr), the maximum fuel requirement of the turbocharged LDS-465 engine.

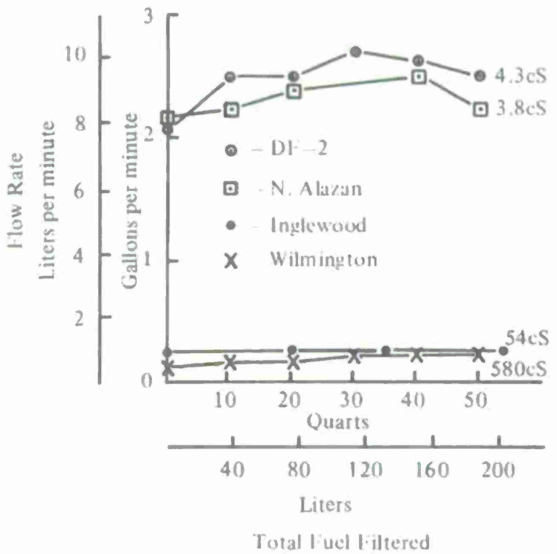


FIGURE 15. FLOW RATE OF CRUDE OILS THROUGH 6V53T FILTER SYSTEM

Discussion of Results

Three crudes and the DF-2 were used in the 6V53T system and the resulting flow rates are shown in Figure 15. This system, which was intended to be used to filter crude oil samples in preparation for other work, was instrumented to obtain filter plugging rate information. Although there was a substantial variation in the flow rates obtained with DF-2 and the crude oil samples, it should be noted

TABLE 5. AVERAGE FLOW RATE THROUGH 6V53T FILTER SYSTEM USING CRUDE OILS

Temperature, °C (°F)	Fuel	Viscosity, cS	Avg flow rate, ℓ/min (gal/min)
26 (78)	DF-2	4.3	9.5 (2.5)
16 (60)	N. Alazan	3.8	8.7 (2.3)
32 (90)	Inglewood	54	1.02 (0.27)
35 (95)	Wilmington	580	0.76 (0.20)
32 (90)	Red Wash	100	0.64 (0.17)

that the flow rates obtained did not decrease with time. This would tend to indicate that the reason for the low flow rates was not filter plugging as had been anticipated. Examination of the average flow rates of each fluid, along with its viscosity indicated that the low flow rates appeared to be viscosity related.

The fuel system from the LDS-465 engine was then simulated in an attempt to examine the effect of fuel viscosity on fuel filter pressures and flow rate. The variable of interest during these short-term tests was whether the filters would pass enough fuel to satisfy the LDS-465 turbocharged engine's maximum fuel requirement of 41 kg/hr (90 lb/hr) while still maintaining the 310 kPa (45 psi) minimum fuel pressure required to ensure adequate filling of the engine's fuel injector pump. As can be seen in Table 6, only one of the crude oils failed to satisfy these criteria and, in fact, the first attempt with this crude (Red Wash) totally plugged the filters and stopped flow completely. As previously noted, this crude oil has a pour point of 32°C (90°F) and it was the wax crystals in the crude, collecting on the filters, which reduced the flow. This crude oil was rerun at 66°C (150°F), well above the pour point, with no problems or high pressure drop, thus confirming the wax problem.

TABLE 6. PRESSURE LOSS THROUGH LDS-465 FILTER SYSTEM USING CRUDE OILS

Fuel	Viscosity at 38°C (100°F), cS	Pressure drop, kPa (psi)		Final pressure, kPa (psi)
		Filter 1	Filter 2	
DF-2	3.4	6.9 (1)	6.9 (1)	434 (63)
Inglewood crude	41.2	28 (4)	14 (2)	407 (59)
Red Wash crude[a]	89.2	172 (25)	55 (8)	221 (32)
50 grade engine oil	222.	34 (5)	28 (4)	386 (56)
Wilmington crude	397.4	21 (3)	14 (2)	414 (60)

[a]The first attempt with this crude totally plugged the filter.

It is of interest to note the performance of the fuel filters used during the 120-hr TACOM engine endurance tests. A modified filter system from the 6V53T engine was used, in which the fuel pump was after both filters so that they were both under suction. The engine operator used this pump and filter system to fill a reservoir on a weigh scale. The fuel system of the engine removed fuel from this reservoir and by knowing the time required for removal of a known weight of fuel, the fuel consumption rate of the engine could be determined. The operator changed one or both of these fuel filters whenever he began having trouble filling the reservoir fast enough to keep up with the engine's consumption of 5 kg/hr (11 lb/hr) while still allowing time for the flow rate to be determined.

The average filter replacement interval was 15 hr or approximately 80 liters (21 gal) of the Inglewood crude, which has a particulate matter content of 87.5 mg/100 ml on 5 μm filter paper. However, the amount of solids in the crude oil was not the only factor influencing filter life. The Inglewood crude contained a moderate amount of water which, when allowed to reach the fuel filters, appeared to reduce the flow rate appreciably. This water content problem observed by the engine operator helps explain the longer filter replacement interval of 100 hr or 520 liters (140 gal) observed when later using the Conroe crude, which had a slightly higher particulate matter content of 104 mg/100 ml.

As illustrated by this study, some method of crude oil pretreatment other than the on-board vehicle fuel filters, would be desirable. The crude oils used in this program were obtained from field storage tanks so some settling of contaminants had already occurred, and additionally some of the crudes were dewatered and desalted. However, the settling rate for small particles (10-20 μm) is slow, especially in high viscosity fluids.[23] Generally, more frequent replacement of the vehicle fuel filters should be anticipated, although in many cases replacement of the primary filter alone can alleviate the fuel starvation problem.

CLR Engine Performance Evaluation

Equipment and Procedure

Initial evaluations of crude oil performance were conducted using the CLR diesel engine manufactured by the Laboratory Equipment Corporation (LABECO), the characteristics of which are shown in Table 7. This engine was chosen for the initial crude performance test because it allowed evaluation of crudes in both a pre-cup and a direct injection combustion chamber configuration which are the predominant diesel combustion systems at the present time. While the engine provided relatively low power output for a diesel of this displacement, the low fuel rate required allowed the use of small crude oil samples and the engine, nevertheless, provided an adequate research tool for comparing the relative combustion performance of fuels.

TABLE 7. CLR OIL TEST ENGINE

Configuration	Direct Injection	Pre-Cup
Base, cm (in.)	9.65 (3.80)	9.65 (3.80)
Stroke, cm (in.)	9.53 (3.75)	9.53 (3.75)
Displacement, cm^3 ($in.^3$)	696.5 (42.5)	696.5 (42.5)
Compression ratio	16.36:1	16:1
Valve timing (IN)	5° BTC to 38° ABC	5° BTC to 38° ABC
(EX)	55° BBC to 20° ATC	55° BBC to 20° ATC
Fuel injection system	Bosch APE	Bosch APE
Barrel and plunger	10 mm	7 mm
Injector	Sims NL-141, 4-hole	Bosch 1250-12, single-hole

The cooling water in and out of the block, the oil sump, ambient air and fuel temperatures were measured using iron-constantine thermocouples. A four-channel oscilloscope was used to measure combustion pressure, fuel injector needle lift and engine rotation.

In a diesel engine an essentially constant volume of air is inducted each cycle, then compressed and the fuel in injected. At constant engine speed, as more fuel is injected, it produces more power in an almost linear relationship until the readily available air is utilized. At that point, each incremental increase in the fuel rate produces a progressively smaller increase in power, due to the greater difficulty in finding available oxygen. During the linear portion of this process, the relationship between energy input and power is a measure of the combustion efficiency of both the fuel and the engine. This was the process utilized for evaluating the crude oils in the CLR engine.

Discussion of Results

An initial series of runs at speeds between 1200 and 1800 rpm were made using DF-2, varying the fuel rate at each speed to obtain fuel rate versus BMEP curves. The data points were fitted to a linear equation by least squares regression analysis. The condition that allowed the best fit, i.e., correlation coefficient nearest to unity, was chosen as the condition to be used in evaluating the various crude oils. Table 8 gives the results of these tests.

Based on these tests, 1200 rpm was chosen as the test speed. With each test fuel, the engine was held at constant speed while the measured dynamometer load was increased in increments of 2.3 kg (5 lb) or 93.1 kPa (13.5 psi) BMEP. In this manner, a curve of fuel rate versus BMEP was obtained. This curve indicates the ability of the engine to convert the available fuel into power, and when extrapolated to zero fuel rate, gives a rough estimate of engine MEP lost to friction. If the engine friction is assumed constant at any one speed, and the various fuel-BMEP curves are shifted so that the BMEP intercept or friction points are equal, then the curve slopes are a measure of the conversion efficiency. Unfortunately, the CLR engine had a large amount of test-to-test variation using DF-2. This variation tended to mask minor performance differences when using crude oils, although gross changes, greater than 7%, could be noted. Figure 16 shows the range of DF-2 performance and some of the more significant fuels.

TABLE 8. CLR PERFORMANCE–CONSTANT SPEED DIRECT INJECTION CONFIGURATION

Speed	Correlation coefficient	Std error of estimate	Intercept	Regression coefficient
1200	0.999	1.015	−36.5	14.944
1400	0.998	1.571	−27.8	13.220
1600	0.984	4.452	−33.6	17.275
1800	0.939	7.646	−30.4	14.330

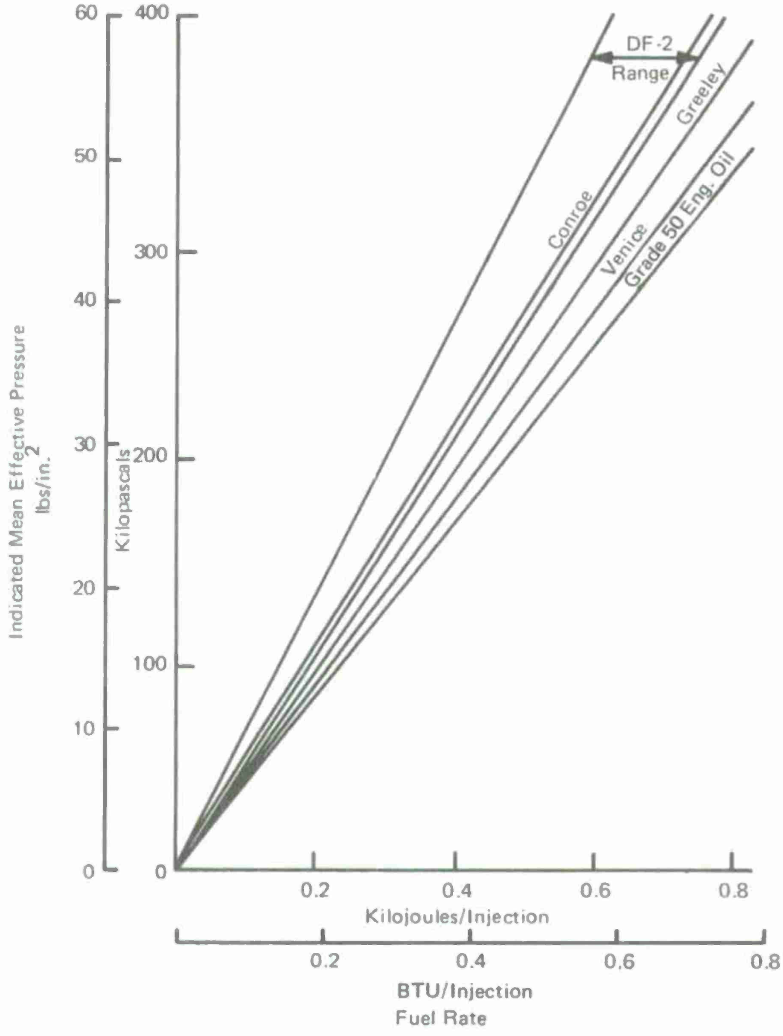


FIGURE 16. CRUDE OIL PERFORMANCE–CLR DIRECT INJECTION ENGINE

TABLE 9. CLR COMBUSTION DATA

Fuel	DF-2	Conroe	Greeley	Venice	TXL	N. Alazan	Caillou Is.
1200 rpm, 370 kPa (54 psi) BMEP, direct injection							
Beginning of injection, deg	18	17	18	18	21	17	21
Ignition delay, deg	10	11	11	12	11	11	13
Avg rate of pressure rise, kPa/deg (psi/deg)	228 (33)	269 (39)	248 (36)	179 (26)	193 (28)	310 (45)	165 (24)
Maximum pressure, kPa (psi)	4960 (720)	4960 (720)	4960 (720)	5100 (740)	5100 (740)	4960 (720)	5030 (730)
1800 rpm, 370 kPa (54 psi) BMEP, Pre-Cup Configuration							
Beginning of injection, deg	13.0	13.0	13.0	9.7	12.0		
Ignition delay, deg	11.0	11.0	11.0	8.6	9.7		
Avg rate of pressure rise, kPa/deg (psi/deg)	640 (93)	640 (93)	510 (74)	480 (70)	640 (93)		
Maximum rate of pressure, kPa/deg (psi/deg)	1790 (260)	1580 (230)	1380 (200)	1450 (210)	1450 (210)		
Maximum pressure, kPa (psi)	7170 (1040)	7300 (1060)	7720 (1120)	7450 (1080)	7170 (1040)		

In conjunction with this work, combustion measurements were made at high load conditions at two engine speeds, 1200 and 1800 rpm. Table 9 gives the ignition delay, average rate of pressure rise and peak pressure measured for each of the crude oils examined.

While there was some variation in peak pressure and average rate of pressure rise, no gross differences were observed. To some extent, increases in peak pressures observed correlated with reduced performance but the correlation was not consistent. The Greeley crude oil, with the highest peak pressure, produced the lowest power output at constant fuel rate. Other variables did not appear to correlate to power output but the differences observed were minimal.

CLR 24-Hr Tests

Three 24-hr tests were made with the CLR engine in its open chamber configuration. The test length was dictated by the amount of crude oil available. The engine was operated at 1800 rpm, 20.3 N-m (15 ft-lb) torque for 2 hr, followed by a 1-hr 1800-rpm minimum load period. This cycle was repeated for a total of 24 hr. The three fuels used were DF-2, Greeley crude oil and Caillou Island crude oil. The engine variables examined were piston ring wear, deposit levels and equipment durability. The results of these short-term tests are summarized in Table 10. The performance and fuel consumption data are for the loaded portion of the test.

All three tests were run without problems and there were no signs of distress in the engine. Since the engine was operated at constant power output, any differences in fuel performance are reflected in the specific fuel consumption. Thus, in these tests, the Caillou Island crude oil has essentially the same specific fuel consumption as the DF-2 while the Greeley crude resulted in a 2.6% increase in fuel consumption. However, this was not a significant difference since the specific consumption rate varied as much as 6% during the DF-2 test. The only significant differences between the three tests are the deposit weights on the intake and exhaust valves. The weight gains of the valves due to deposits increased with increased residuum content of the fuel. This increase in deposits was not seen on the piston, and further testing would be required to determine the significance of these valve deposits to engine performance and wear. The fuel system (pump, injector, filters) showed no signs of distress or wear and performed normally in all tests.

TABLE 10. 24-HOUR TEST RESULTS–CLR DIRECT INJECTION ENGINE

Fuel	DF-2	Greeley	Caillou Is.
Speed, rpm	1800	1800	1800
Average power, kW (BHp)	3.88 (5.20)	3.88 (5.20)	3.88 (5.20)
BSFC, kg/kW-hr (lb/BHp-hr)	0.393 (0.645)	0.404 (0.662)	0.396 (0.649)
Top ring gap change[a], cm (in.)	0	0.0025 (0.001)	0.0051 (0.002)
Piston deposit weight, kg (lb)	0.2065 (0.4553)	0.2265 (0.4993)	0.3011 (0.6638)
Exhaust valve weight gain, kg (lb)	0.0011 (0.0024)	0.0818 (0.1803)	0.0322 (0.0710)
Intake valve weight gain, kg (lb)	0.0413 (0.0911)	0.1566 (0.3452)	0.1317 (0.2903)

[a]In all three runs, the second ring was broken during removal.

Utilization of Crude Oils in the TACOM ER-3 Engine

The TACOM ER-3 engine, a 1170 cm^3 (71.5 in^3), displacement single cylinder direct injection, compression ignition research engine developed by International Harvester Co., TACOM, and Laboratory Equipment Corp., was chosen for further crude oil studies. The engine was coupled to a Eddy Current dynamometer with 93-kW (125-hp) absorption and 22.4-kW (30-hp) motoring capacities. Engine load was measured by cradling the dynamometer and measuring its torque reaction with a 136-kg (300-lb) load cell and transducer indicator. The dynamometer load was controlled by a solid-state control chassis capable of holding engine speed to within 5 rpm.

Fuel was delivered to the engine either through a mass flow meter capable of measuring the fuel flow to within 0.045 kg/hr (0.1 lb/hr) or when crude oils were used, through a weighing system consisting of a beaker, a 0.9-kg (2-lb) balance and pumping system. The engine was equipped with a single cylinder pump with a 8-mm barrel and plunger and a four-hole fuel injector.

The engine was equipped with an intake and exhaust air treatment system that could be used to simulate turbocharged (or supercharged) operating conditions. Air was supplied by two compressors at up to 415 kPa (60 psi) through a 30-kW heater capable of maintaining inlet air temperatures up to 200°C (400°F). The intake air pressure was controlled by a system of air operated valves, a pressure sensor and transmitter and a recording control station, and the intake and exhaust pressures were measured with a two-sweep 338 kPa (100 in Hg) absolute pressure gauge. The exhaust back pressure was controlled by a surge tank followed by an air operated valve and a control system identical to that of the intake system, capable of maintaining pressure to 415 kPa (60 psi). Surge tanks having volumes of approximately 48 cylinder volumes are in both the intake and exhaust lines immediately adjacent to the engine to reduce any pulsating gas flow. All temperatures were measured using iron-constantine thermocouples and a 24-point recorder.

The operating conditions chosen are shown in Figure 17. These conditions were chosen to simulate present turbocharged conditions although no corrections for variations in fuel flow were made. All injection timing settings were made from the needle lift indicator with the engine at the proper speed. After an initial series of constant speed variable fuel flow tests the barrel and plunger in the fuel injector pump was changed to 5 mm to allow full rack operation without overfueling. Power checks were then made at

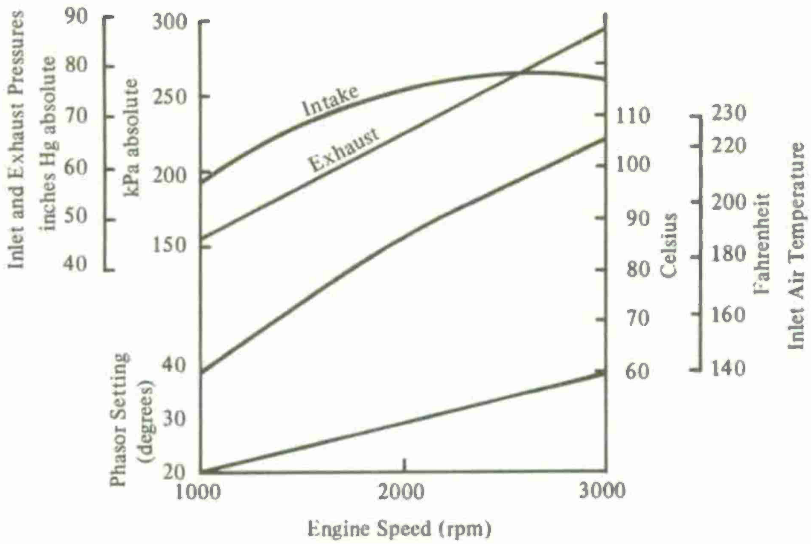


FIGURE 17. SIMULATED TURBOCHARGED CONDITIONS TACOM ER-3

full rack with both DF-2 and various crude oils. Finally, two crude oils were chosen for use in an extended duration, constant speed test.

The conditions chosen for the 120-hr tests are summarized in Table 10. The test length and fuel rate were dictated by the amount of crude oil available. Engine wear was determined by measuring the various parts both before and after the test, deposits were rated visually by standard CRC methods,[24,25] and engine blowby was measured using a calibrated dry gas meter.

Discussion of Results

Based on the experience obtained from the CLR engine, additional crude oil samples were obtained. Crudes from Red Wash, Utah, Wilmington, and Inglewood, California along with the Greeley and Conroe crudes, which were previously evaluated in the CLR engine, were to be evaluated for combustion performance in the TACOM engine.

Initially, the same approach was taken with the TACOM engine as was used with the CLR engine. The TACOM engine was run normally aspirated at constant speed while the fuel rate was varied and indicated mean effective pressure obtained at each fuel rate. However, initial results did not indicate as much separation between fuel types as was desired.

Comparisons were then made by developing speed versus IMEP curves at constant fuel delivery (full rack conditions). At this time, the barrel and plunger in the injector pump was changed from an 8 mm to a 5 mm so that overfueling would not occur. At each speed, the inlet and exhaust air conditions and oil sump temperature were varied to correspond to what might be expected in production engines. The chosen conditions gave an almost linear indicated horsepower curve from 1600 to 3000 rpm. Each crude oil run was both preceded and superseded by a run using DF-2 and the crude oil was compared to the resulting two baseline curves.

Operation using the Red Wash, Utah crude was not attempted due to handling problems resulting from its high pour point. The wax in this crude made standard handling impossible. The Wilmington, California crude was also impossible to use without special handling because of its high viscosity of 397 cS at 38°C (100°F). The barrel and plunger type pump could only deliver approximately one third of the normal volume per injection with this crude, and it is doubtful if the injector could atomize or even approach a spray with this crude. All three of the other crude oils operated satisfactorily and there were no discernable differences in indicated power or indicated specific fuel consumption between any of these crudes and DF-2 (Figure 18). This seems inconsistent when the delivery curves developed with the barrel and plunger type pump are considered, but the fuel delivery rates on the engine test stand were substantially different from those obtained with the pump alone. One possible explanation is that the fuel system in the test stand maintained approximately 6 kPa (24-in. of water) pressure at the pump at all times instead of relying totally on the transfer pump.

As a further check, engine output was measured at constant rack setting with conditions more carefully controlled than normal (Table 11). The fuel temperature was held within 0.5 degree of 29°C (85°F), the inlet air pressure varied no more than 0.34 kPa (0.1 in. Hg) while the exhaust back pressure was held within 0.68 kPa (0.2 in. Hg). At this condition, the Conroe crude had a 14 kPa (2.1 psi) loss in BMEP from the 827 kPa (120 psi) BMEP of DF-2 or approximately a 2.2% reduction. The Inglewood and Greely crude oils each produced an approximate 28 kPa (4 psi) or 3.5% power loss. The three crude oils were then run at a constant fuel delivery rate, 3.9 kg/hr (8.6 lb/hr), with all other conditions being held constant. At this fuel rate, DF-2 produced 827 kPa (120 psi) BMEP and a BSFC of 0.300 kg/kW-hr (0.494 lb/BHp-hr), while the Conroe crude oil had a 3.5% loss in power, or produced 800 kPa (116 psi) BMEP and 0.312 kg/kW-hr (0.512 lb/BHp-hr) BSFC. At the same condition, the Inglewood crude had a 5% loss in power and a 5% increase in specific fuel consumption, 786 kPa (114 psi) BMEP and 0.317 kg/kW-hr (0.521 lb/BHp-hr). Based on this, there appears to be a relatively small power decrease using the crude oils but it is particularly interesting how small (5%) the power loss was with a crude like that from the Inglewood field, whose properties are far removed from those of standard diesel fuel. It is important to remember that these tests were of very short duration, none longer than four hours, and any gradual degradation in performance would be unnoticed.

Endurance Tests

Endurance tests were run with the crude oils from Inglewood, California and Conroe, Texas, and with DF-2. The Inglewood was chosen as a crude near the limit of wide usability and had long-term properties such that as much as 60% of the world's supply was at least as suitable for direct utilization. The Conroe, Texas crude was chosen as an example of an almost ideal crude for direct usage, and in fact had been used in oil field engines for many years. It should be noted that the Conroe crude had a lower sulfur level than the DF-2. The lubricant chosen for the tests was REO-203, grade 30, a qualified MIL-L-2104C/MIL-L-46152 lubricant (Appendix A). The engine was run for 16 hr per day, 5 days per week, with an 8-hr overnight shutdown to accentuate any sulfur corrosion problems. The engine was rebuilt using a new piston and cylinder liner before each test and the fuel injection pump was thoroughly cleaned and inspected. Test one used the Inglewood crude oil, test two the DF-2 and test three used the Conroe crude. All three completed the scheduled 120 hr without major incident. Complete test results are given in Appendix C. Summarized operating conditions, new and used oil analyses, wear measurements and deposit ratings are shown in Table 11.

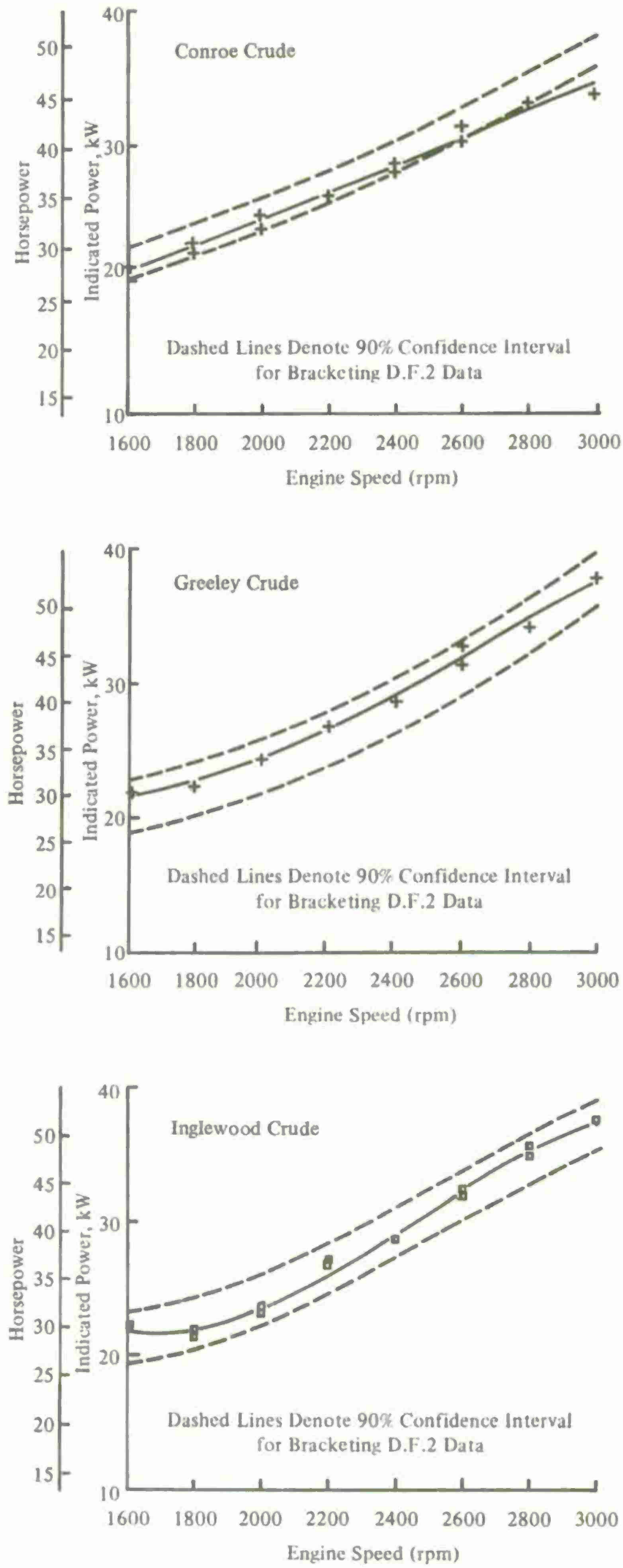


FIGURE 18. PERFORMANCE CURVE–TACOM ER-3 SIMULATED TURBOCHARGED CONDITIONS

TABLE 11. 120-HOUR TACOM ENGINE TESTS

Test number	1	2	3
Fuel name	Inglewood	DF-2	Conroe
Oil	REO 203	REO 203	REO 203
Operating conditions, avg			
Test hours	120	120	120
Torque, N-m (ft-lb)	61 (45)	72 (53)	69 (51)
Rpm	2200	2200	2200
Brake power, kw (BHp)	14.1 (18.9)	16.5 (22.1)	15.8 (21.2)
Blowby, m^3/hr (CFH)	0.81 (28.6)	0.87 (30.7)	0.86 (30.4)
Oil sump, °C (°F)	88 (190)	88 (190)	88 (190)
BMEP kPa (psi)	65.8 (95.4)	76.7 (111.2)	73.6 (106.8)
Fuel rate Kg/hr (lb/hr)	4.9 (10.9)	5.0 (11.0)	4.9 (10.9)
BSFC kg/kW-hr	0.350 (0.575)	0.304 (0.500)	0.313 (0.515)
Inlet pressure, kPa (in. Hg)	261 (77.2)	261 (77.2)	261 (77.2)
Inlet air, °C (°F)	910 (195)	910 (195)	910 (195)
Exhause pressure, kPa (in. Hg)	240.4 (71.2)	240.1 (71.1)	240.4 (71.2)
Exhaust temperature, °C (°F)	429 (805)	419 (787)	409 (769)
Total oil consumption, ℓ (qt)	1.9 (2)	2.4 (2.5)	1.9 (2.0)
Piston deposit CRC F-ratings, weighted			
Ring grooves	132.5	190	165
Lands	42.45	20.3	28.75
Undercrown	7.5	0.9	0
Total deposits	182.45	211.2	193.75
Wear			
Piston ring end gap change, cm (in.)			
No. 1 Compression	0.0076 (0.003)	0.0051 (0.002)	0.0076 (0.003)
No. 2 Compression	0.0330 (0.013)	0.0127 (0.005)	0.0137 (0.005)
No. 3 Compression	0.0279 (0.011)	0.007 (0.003)	0.0152 (0.006)
Oil control	0.0127 (0.005)	0.0051 (0.002)	0.0051 (0.002)

Oil analyses	ASTM method	New oil	Test 1	Test 2	Test 3
K. vis., cS, 38°C	D 445	121.60	140.00	144.35	132.08
K. vis., cS, 99°C	D 445	12.61	14.02	14.02	13.34
Total acid no.	D 664	3.6	3.60	4.86	3.83
Total base no.	D 2896	5.4	2.66	3.12	4.96
Carbon residue, %	D 524	1.19	1.65	1.72	1.40
Sulfated ash, %	D 872	0.93	0.98	1.15	1.05
Iron, ppm		—	181	55	70
Chromium, ppm		—	23	8	4

Test 1—Inglewood Crude Oil

Brake power for the test was 14.1 kW (18.9 bhp), a 14.5% reduction from that of DF-2; however, power remained constant throughout the test after the 24th hour. During the early part of the test a lock screw in the injector pump broke, allowing the injection timing to shift. At hour 24 this was discovered and repaired. From this point on, the injector pump was repeatedly inspected for signs of rapid wear but nothing abnormal was found. Blowby increased from 0.57 m^3/hr (20 ft^3/hr) to approximately 1.0 m^3/hr (35 ft^3/hr) by the 120-hr mark, although the average blowby was the lowest of the three tests. As would be expected from the power loss, the BSFC of 0.350 kg/kW-hr (0.575 lb/bhp-hr) was the highest of the three tests. Exhaust emissions (Table 12) and exhaust gas temperature both tend to confirm the picture of reduced combustion efficiency with this crude oil.

Disassembly revealed moderate deposit levels, with the lowest overall weighted deposit level of the three tests using the CRC F-rating method.[25] However, the piston land deposits, most indicative of fuel effects, were the heaviest of the tests, with a total weighted rating of 42.25. The ring groove deposits, which are more oil related, were relatively low at 132. There were tar-like deposits in the piston bowl and across the head and the fuel injector nozzle had tar-like whiskers about each injection hole. Second and third ring wear was almost three times that of the other two tests. Used oil analyses also confirmed this rapid wear by higher levels of iron and chrome in the oil, although the sulfated ash had not increased. In general, the higher sulfur level of this crude produced more ring and liner wear and used oil wear metals and more reduction in the base number of the oil due to acid formation. Higher fuel related combustion deposits (combustion chamber and lands), were noted due to the amount of high boiling point material present. However, the lower piston ring groove deposits in grooves 2, 3 and 4 were less, reflecting the lower oil consumption during this test as compared to test two. Higher undercrown deposits are apparently due to overriding fuel property effects even though power output and piston temperatures were lower. Infrared analysis of the oil showed reduced transmittance probably attributable to higher soot contaminatioon.

Test 2—Reference No. 2 Diesel Fuel

While DF-2 produced the highest average power of the three tests, it was also the only fuel that showed a consistent loss of power during the test, down 7.7% after 120 hr. This test also had the highest piston deposits of the three, but this can be attributed to the 25% greater oil consumption as compared to the other two tests. This conclusion is reinforced by the fact that this test had the highest ring groove deposit rating of 190 and the lowest ring land deposits with 20.3, indicating oil rather than fuel related deposits.

Test 3—Conroe Crude Oil

Due to the low sulfur content of this crude few acidic combustion products were formed, and as a result the used oil base number was 4.96, the highest of the three tests. Piston deposit levels, both ring groove and land, were intermediate to the other tests. There were some heavy deposits in the piston bowl, but the injector tip was almost free of any buildup. Ring and liner wear was essentially equivalent to that of DF-2. The only obvious difference between this test and test two was power loss, down 4% from DF-2, with a corresponding 3% increase in average BSFC. This could be due in part to the natural gasoline in the crude.

Endurance Test Comparisons

The following group of figures and tables compare the three endurance tests. Table 12 summarizes the three test results. Note that the total base number of the used oils decreases with increasing fuel sulfur concentration, due to the formation of combustion acids. Table 13 compares the average exhaust emissions for each test, and these tend to substantiate the observed power losses with the two crudes. The decrease in NO_X and CO_2

TABLE 12. SELECTED CRUDE OILS PERFORMANCE IN TACOM ER-3

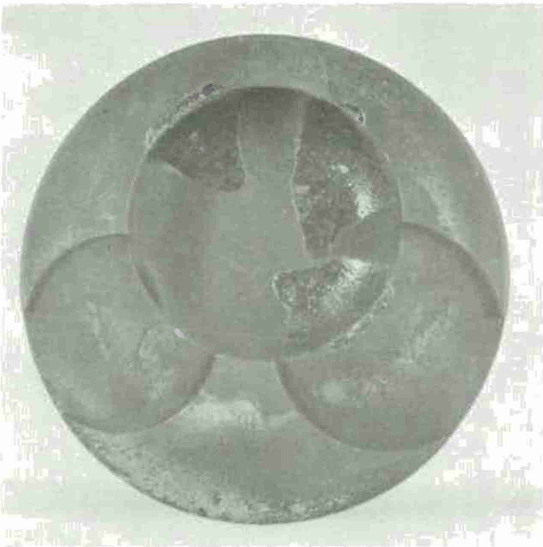
Fuel	DF-2	Conroe	Greeley	Inglewood
Constant Rack				
Speed, rpm	1600	1600	1600	1600
Inlet air pressure, kPa (in. Hg)	238.1 (70.5)	237.7 (70.4)	238.1 (70.5)	238.1 (70.5)
Inlet air temp., °C (°F)	79 (174)	79 (174)	79 (174)	79 (174)
Exhaust pressure, kPa (in. Hg)	195.8 (58.0)	195.2 (57.9)	195.2 (57.8)	195.8 (58.0)
Torque, N-m (ft-lb)	77 (57)	76 (56)	74 (55)	74 (55)
BMEP, kPa (psi)	827 (120)	813 (117.9)	800 (116)	800 (116)
Brake power, kW (BHp)	13.0 (17.4)	12.8 (17.1)	12.5 (16.8)	12.5 (16.8)
Constant Fuel Rate				
Speed, rpm	1600	1600	—	1600
Fuel rate, kg/hr (lb/hr)	3.9 (8.6)	3.9 (8.6)	—	3.9 (8.6)
Inlet air pressure, kPa (in. Hg)	237.0 (70.2)	237.4 (70.3)	—	237.0 (70.2)
Inlet air temp., °C (°F)	79 (174)	79 (174)	—	79 (174)
Exhaust pressure, kPa (in. Hg)	195.2 (57.8)	195.8 (58.0)	—	195.2 (57.8)
Torque, N-m (ft-lb)	77 (57)	74 (55)	—	73 (54)
Brake power, kW (BHp)	13.0 (17.4)	12.5 (16.8)	—	12.3 (16.5)
BMEP, kPa (psi)	827 (120.0)	800 (116)	—	785 (113.9)
BSFC, kg/kW-hr (lb/BHp-hr)	0.300 (0.494)	0.312 (0.512)	—	0.317 (0.521)

TABLE 13. EXHAUST EMISSIONS FROM TACOM ER-3 ENDURANCE TESTS

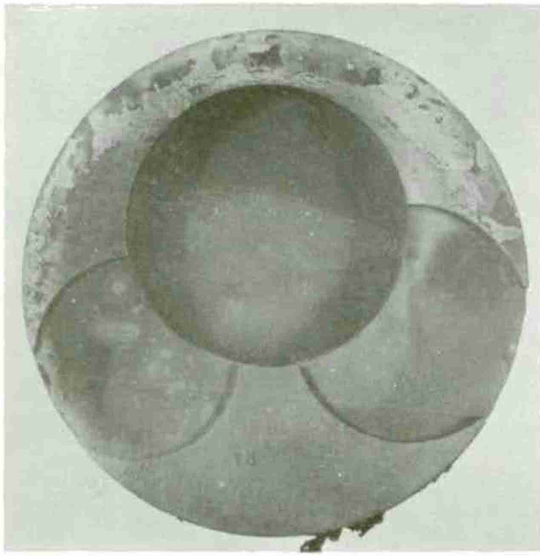
Test no.	1		2		3	
Fuel	Inglewood		DF-2		Conroe	
Test Hour	6	120	1	119	4	120
NO, ppm	230	455	640	710	450	655
NO_X, ppm	280	490	655	820	610	674
HC, ppm propane	35	24	30.3	16.2	120	71.0
CO, percent	0.046	0.078	0.026	0.037	0.030	0.037
CO_2, percent	4.90	5.6	5.3	5.2	5.0	5.2
O_2, percent	15.3	13.3	13.6	13.4	14.0	13.6

concentrations in conjunction with an increase in CO tend to indicate reduced combustion efficiency. Figures 19, 20, and 21 show the deposit buildup on the piston top, piston ring belt, and fuel injectors for each test while Figure 22 is a closeup of the piston ring faces. The extent of ring wear is clearly visible.

While fuel related deposits and wear were increased with the crude oils, particularly the Inglewood, it should be kept in mind that no major engine problems developed and that the engine produced usable power. Approximately 640 liters (170 gal) of fuel were run through this single cylinder engine during a 120-hr test. If the results of this test could be extrapolated to a six cylinder engine of the same type, then at least 3780 liters (1000 gal) of fuel would have been used during the 120 hr. If this engine was placed in a 4.5-Mg (5-ton) truck, operating under emergency high-output conditions and assuming 58.8 liters / 100-km (4-mpg) consumption rate, then the Inglewood crude oil should operate for at least 6400 km (4000 miles). Of course, this mileage is based on a number of questionable assumptions but it illustrates the point that a wide range of crude oils, with proper selection and pretreatment, are feasible energy sources for four cycle military diesel equipment.



Test 1
Inglewood Crude



Test 2
DF-2

Test 3
Conroe Crude

FIGURE 19. TACOM ENGINE PISTON TOPS–120 HOUR TESTS

Test 1
Inglewood Crude, Thrust

Test 2
DF-2, Thrust

Test 3
Conroe Crude, Thrust

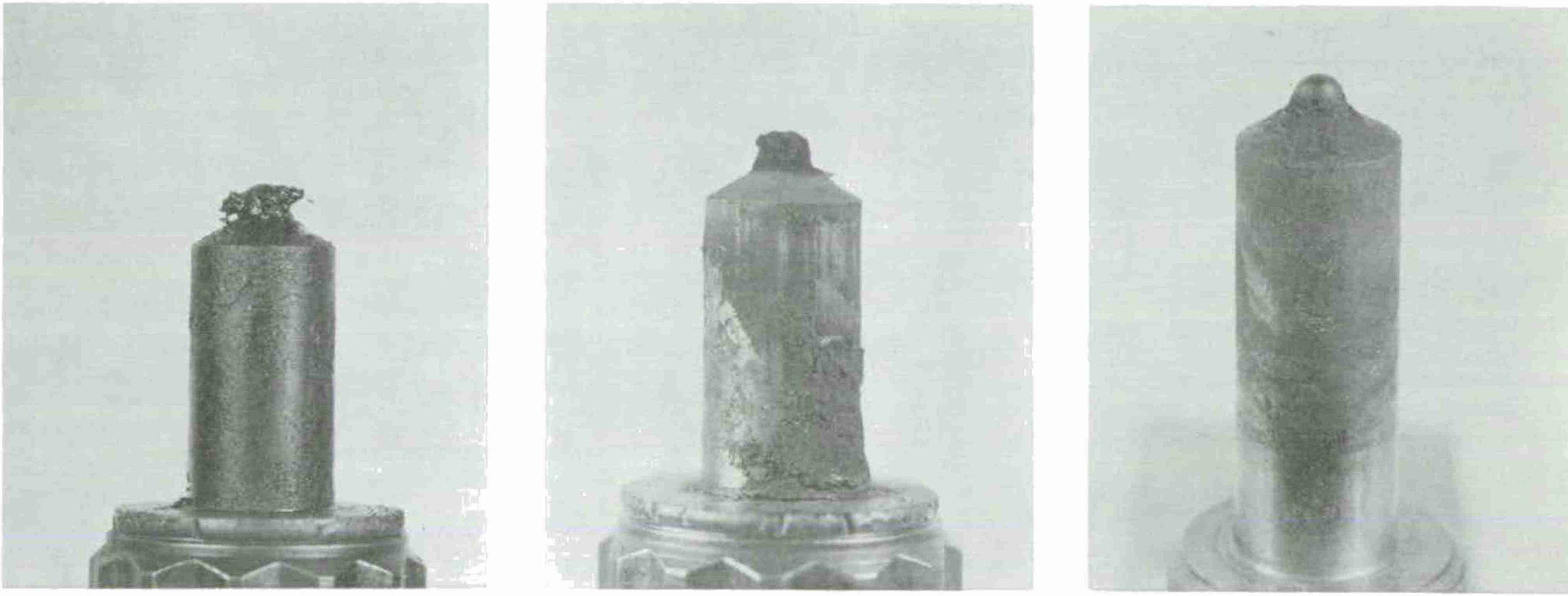
FIGURE 20. TACOM ENGINE PISTONS–120 HOUR TESTS

Test 1
Inglewood Crude, Anti-Thrust

Test 2
DF-2, Anti-Thrust

Test 3
Conroe Crude, Anti-Thrust

FIGURE 20. TACOM ENGINE PISTONS–120 HOUR TESTS (Cont'd)

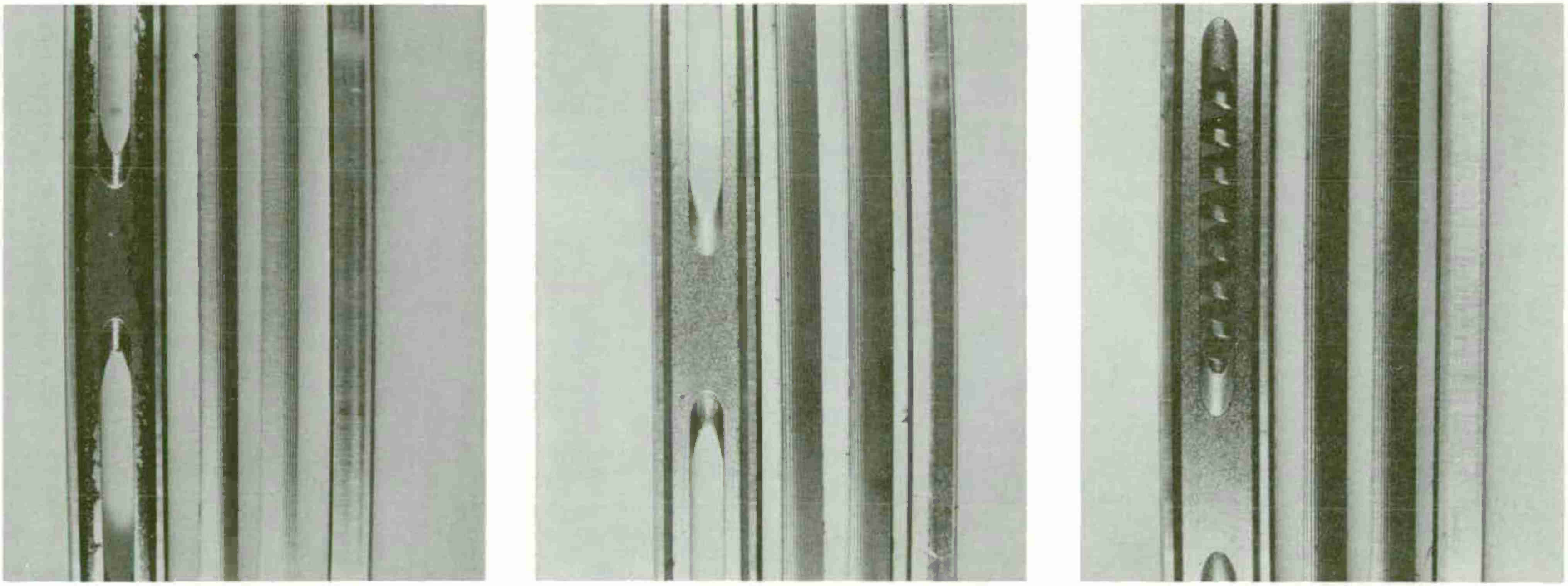


Test 1
Inglewood Crude

Test 2
DF-2

Test 3
Conroe Crude

FIGURE 21. TACOM ENGINE INJECTOR TIPS–120 HOUR TESTS



Test 1
Inglewood Crude

Test 2
DF-2

Test 3
Conroe Crude

FIGURE 22. TACOM ENGINE PISTON RING FACES–120 HOUR TESTS

OVERVIEW OF RESULTS

Crude oils with widely varying properties appear feasible for short-term emergency direct utilization in military diesel engines. A number of problem areas need to be resolved before any definite operational limits can be made, but the potential short-term usage on a go or no go basis of approximately 70 to 75% of the world crude oil reserves, with a wide geographic distribution, makes further investigation desirable.

Prior to direct crude oil utilization, some type of crude oil pretreatment must be employed. This treatment could range from dewatering and filtration as a minimum to some type of field portable crude oil topping unit. Portable crude oil topping units are commercially available[26] and are capable of filtration, water removal and rapid distillation. A broad middle cut would be made which would eliminate the very light and heavy ends of the feed crude oil. Light ends, which appear to cause problems in some types of fuel injection pumps, and heavy ends which cause engine deposition could be used to power the portable units. Pour point reduction is a difficult problem area; dilution of the crude oil with DF-2 or other fuels is a possible solution.

Throughout this report the phrases short-term and long-term have not been strictly defined. It should be realized that when using non-standard fuels in a fleet of vehicles, there is a possibility that some vehicles will not even be able to be started. As operation continues, increasing numbers of vehicles would be expected to experience failures. The length of time required for a majority of the vehicles to fail will be dependent on fuel properties, environmental conditions and the operating cycle. Although additonal work needs to be done on predicting deposit and wear rates with nonstandard fuels of various compositions, due to the number of fuel and operating variables involved, it will always be difficult to accurately predict long-term equipment failure rates when using nonstandard fuels.

As this work progressed, it became evident that fuel filters and fuel injector pumps were limiting factors in direct crude oil usage. The fuel filters restrict the flow of high viscosity fluids, particularly when wet from entrained water, and develop high pressure drops across the filter elements. Collapse of the filter elements could lead to fuel starvation or injestion of filter particles by the fuel pump, resulting in pump seizure. In any case, more frequent element changes will probably be required unless the fuel is well pretreated.

Fuel injection pumps by their nature are high precision close tolerance parts and are probably the most vulnerable part of the engine. Only two types of pumps were examined, and the barrel and plunger pump was a single-cylinder unit. Much care must be exercised when comparing these two units to the multitude in service. It should be noted that the TCCS pump appears to be viscosity limited at the high end, while the barrel and plunger pump experienced repeated difficulties in handling fuels with volatile components. Long-term wear was not examined with either pump. Another fuel injection system that was examined briefly and appeared to alleviate some of the fuel property problems was the unit injector system used on the 6V53T engine, which is common to the U.S. Army two-cycle diesel engine family. With unit injectors there is no close tolerance pump common to the entire engine and while the injectors themselves are precision parts, failure of one injector would not necessarily stop the engine.

The single-cylinder engine tests showed the four-cycle diesel engine to be more fuel tolerant than originally anticipated. It should be realized that the results from single-cylinder tests do not necessarily extrapolate well to multicylinder engines. Also, two-cycle diesels were not examined, and these engines appear to be more fuel sensitive. Also, in all engine work, a very high quality MIL-L-2104C/MIL-L-46152 lubricant was used which helped minimize the wear and deposit effects of using poor quality fuel.

Most importantly, the results outlined here do not apply strictly to crude oils. Any hydrocarbon fluid that burns and meets the handling criteria outlined could be considered as a nonstandard fuel. For example, motor oils or heavy residual fuels diluted with DF-2 would be expected to yield short-term results similar to those observed with crude oils.

CONCLUSIONS

- High pour point values of crude oils represents a major problem in some areas of the world. In the Asia-Pacific area in particular, direct crude utilization is very limited because of this property.

- It appears that present U.S. Army four-cycle diesel-powered tactical and combat equipment have the ability to tolerate a wide variety of crude oils and heavy distillate (BP > DF-2) fuels on a limited term basis.

- The engine fuel systems are the critical component when contemplating the use of emergency fuels for the short-term, but some systems appear more tolerant than others.

- Some fuel filter systems presently used on U.S. Army vehicles, while appearing to have adequate strength, could cause flow restriction when used with high viscosity fuels containing entrained water.

- Single cylinder high speed four-cycle diesel engines have been operated successfully using various crude oils as fuel.

- Approximately 70 to 75% of the world crude oil reserves appear to be directly usable in diesel engines on a short-term go or no go basis with minimal pretreatment.

RECOMMENDATIONS

- A wider range of fuel injection systems should be examined to determine sensitivity to high viscosity fuels. In particular, the Cummins P-T system was not considered in this work and would appear to have some fuel tolerance.
- Additional work should be done on the sensitivity of U.S. Army fuel filter systems to water and high viscosity fuels, particularly when the fuel contains substantial amounts of contaminants.
- Particular emphasis should be given to the problem of pour point reduction of crude oils. In some areas of the world, crude oil pour point problems represent the most severe limiting characteristic restricting direct utilization. A field portable method for rapid large-scale wax removal would allow much higher utilization percentages in certain areas.
- Field portable crude oil topping units should be evaluated for potential U.S. Army use. Commercially available portable units are capable of handling 800 to 1000 bbl/day crude feed. The light and heavy ends of the crude oil could be easily removed, leaving a broad cut of useable fuel.
- Additional work is needed to define engine endurance limits for longer term operation with non-standard fuels.
- Full scale engine/vehicle testing with non-standard fuels including crude oils should be performed.

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APPENDIX A
TEST LUBRICANTS

TEST LUBRICANTS

Designation	REO-203	WS8636
MIL Spec.	MIL-L-2104C/MIL-L-46152	MIL-L-2104C
Viscosity, cS		
at 99°C (210°F)	12.61	221.2
at 38°C (100°F)	121.6	17.93
Viscosity Index	94	96
Flash Point, °C (°F)	241 (465)	238 (460)
Pour Point, °C (°F)	−21 (−5)	−17 (+2)
Gravity, °API	27.4	26.7
Sulfated Ash, %	0.93	0.92
Total Acid Number	3.3	1.55
Total Base Number	5.4	5.80
Additive Content, % wt		
Zinc	0.093	0.069
Calcium	0.24	0.13
Barium	nil	0.16

APPENDIX B
TEST FLUIDS OTHER THAN CRUDE OILS

TEST FLUIDS OTHER THAN CRUDE OILS

Description	Viscosity @ 38°C (100°F), cS	Specific Gravity
Gasoline (MS08)	0.555	0.742
Mineral Oil	73.3	0.885
Naptha	1.024	N. D.
Polyisobutylene V.I. Improver	6200	N. D.

N. D.–Not Determined.

APPENDIX C

120-HOUR TACOM ER-3 TEST DATA

TACOM ER-3 Engine
Test 1
120 Hours

Fuel: Inglewood Crude Oil
Lubricant: REO-203

Summary of Operating Data - Test 1

	Minimum	Maximum	Average
Engine Speed, RPM	2195	2205	2201
Torque, N-m (lb-ft)	57 (42)	64 (47)	61 (45)
Power, kW (BHp)	13.0 (17.5)	14.7 (19.7)	14.1 (18.9)
BMEP, KN/m^2 (psi)	610 (88.5)	683 (99.1)	658 (95.4)
BSFC, kg/kW-hr (lbs/BHp-hr)	.332 (.546)	.373 (.613)	.349 (.574)
Fuel Rate, kg/hr (lbs/hr)	4.77 (10.5)	5.04 (11.1)	4.95 (10.9)
Blowby, m^3/hr (ft^3/hr)	.561 (19.8)	1.118 (39.5)	.810 (28.6)
Temperatures, °C (°F)			
Intake Air	90 (194)	91 (196)	90.6 (195)
Exhaust	407 (765)	429 (805)	416 (780)
Jacket-in	81 (177)	83 (182)	82 (179)
Jacket-out	84 (184)	86 (186)	85 (185)
Oil Sump	87 (189)	89 (192)	88 (190)
Pressures, Abs, KN/m^2 (in. Hg)			
Intake Air	297 (76.7)	264 (78.2)	261 (77.2)
Exhaust	239 (70.7)	243 (71.9)	240 (70.2)

Exhaust Emissions Data - Test 1

Test Hour	NO (ppm)	NO_x (ppm)	HC (ppm propane)	CO (%)	CO_2 (%)	O_2 (%)
6	230	280	35	.046	4.90	15.30
21	220	238	3.0	.023	4.05	15.70
50	450	457	18	.053	5.05	14.45
120	455	490	24	.078	5.60	13.25

CRC DIESEL RATING SYSTEM

STANDARD COMPUTATION SHEET FOR PISTON RATING

TEST PROCEDURE TACOM ER-3
TEST HOURS 120
TEST LABORATORY ARLRL
LUBRICANT REO 203

RATER E.R. Lyons DATE 19 March 1975
LABORATORY TEST NUMBER TACOM-1
STAND NO. ______ ENGINE NO. ______
FUEL AL-5810-L (Inglewood)

PISTON NO. 1

NO. 1 GROOVE, VOLUME-%	--
PISTON WTD* RATING	182.25

	DEPOSIT TYPE	DEPOSIT FACTOR	GROOVES NO. 1		GROOVES NO. 2		GROOVES NO. 3		GROOVES NO. 4		LANDS NO. 1		LANDS NO. 2		LANDS NO. 3		LANDS NO. 4		UNDER-CROWN	
			AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT
CARBON	HC	1.00	90	90	25	25														
CARBON	MHC	0.75																		
CARBON	MC	0.50																		
CARBON	LC	0.25									25	6.25								
CARBON	VLC	0.15									55	8.25	25	3.75	100	15				
CARBON	CARBON RATING		90		25						14.50		3.75		15					
LACQUER	BL	0.100					100	10	75	7.5			75	7.5						
LACQUER	DBrL	0.075									20	1.5							100	7.5
LACQUER	AL	0.050																		
LACQUER	LAL	0.025																		
LACQUER	VLAL	0.010																		
LACQUER	RL	0.001																		
LACQUER	LACQUER RATING						10		7.5		1.5		7.5							
CLEAN		0																		
ZONAL RATING																				
LOCATION FACTOR																				
WEIGHTED RATING			90		25		10		7.5		16.0		11.25		15.0		0		7.5	

*WEIGHTED TOTAL DEPOSITS

TACOM ER-3 Engine
Test 2

Fuel:	Reference No. 2 Diesel Fuel
Lubricant:	REO-203

Summary of Operating Data - Test 2

	Minimum	Maximum	Average
Engine Speed, RPM	2197	2205	2200
Torque, N-m (lb-ft)	66 (49)	76 (56)	72 (53)
Power, kW (BHp)	15.3 (20.5)	17.5 (23.5)	16.5 (22.1)
BMEP, KN/m^2 (psi)	712 (103)	814 (118)	767 (111)
BSFC, kg/kW-hr (lbs/BHp-hr)	.282 (.464)	.329 (.541)	.304 (.499)
Fuel Rate, kg/hr (lbs/hr)	4.91 (10.8)	5.09 (11.2)	5.00 (11.0)
Blowby, m^3/hr (ft^3/hr)	.532 (18.8)	1.611 (56.9)	.869 (30.7)
Temperatures, °C (°F)			
Intake Air	90 (194)	93 (200)	91 (195)
Exhaust	404 (760)	427 (800)	419 (787)
Jacket-in	82 (180)	86 (186)	84 (184)
Jacket-out	88 (190)	91 (196)	88 (191)
Oil Sump	87 (188)	88 (190)	88 (190)
Pressures, Abs, KN/m^2 (in. Hg)			
Intake Air	260 (77.0)	263 (77.9)	261 (77.2)
Exhaust	239 (70.7)	243 (71.9)	240 (71.1)

Exhaust Emissions Data - Test 2

Test Hour	NO (ppm)	NO_x (ppm)	HC (ppm propane)	CO (%)	CO_2 (%)	O_2 (%)
1	640	655	30.3	.026	5.30	13.55
22	722	753	24.5	.042	5.15	13.45
50	423	725	22.1	.047	5.31	14.80
75	870	980	17.2	.038	5.51	13.6
100	715	795	7.0	.040	5.05	14.2
119	710	820	16.2	.037	5.25	13.45

CRC DIESEL RATING SYSTEM

STANDARD COMPUTATION SHEET FOR PISTON RATING

TEST PROCEDURE TACOM ER-3
TEST HOURS 120
TEST LABORATORY ARLRL
LUBRICANT REO 203

RATER E.R. Lyons DATE ______
LABORATORY TEST NUMBER TACOM-2
STAND NO. ______ ENGINE NO. ______
FUEL Reference No. 2 D.F.

PISTON NO. 1

NO. 1 GROOVE, VOLUME-%	--
PISTON WTD* RATING	211.2

DEPOSIT TYPE		DEPOSIT FACTOR	GROOVES								LANDS								UNDER-CROWN	
			NO. 1		NO. 2		NO. 3		NO. 4		NO. 1		NO. 2		NO. 3		NO. 4			
			AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT
CARBON	HC	1.00	90	90	90	90	10	10	0											
CARBON	MHC	0.75																		
CARBON	MC	0.50																		
CARBON	LC	0.25																		
CARBON	VLC	0.15									95	14.25	20	3.0	10	1.5				
	CARBON RATING		90		90		10				14.25		3.0		1.5					
LACQUER	BL	0.100											5	0.5						
LACQUER	DBrL	0.075													5	0.375				
LACQUER	AL	0.050									5	0.25			5	0.250				
LACQUER	LAL	0.025											25	0.625						
LACQUER	VLAL	0.010																	90	0.9
LACQUER	RL	0.001																		
	LACQUER RATING										0.25		0.675		0.625				0.9	
CLEAN		0																		
ZONAL RATING																				
LOCATION FACTOR																				
WEIGHTED RATING			90		90		10		0		14.50		3.675		2.125		0		0.9	

*WEIGHTED TOTAL DEPOSITS

TACOM ER-3 Engine
Test 3

Fuel: Conroe Crude
Lubricant: REO-203

Summary of Operating Data - Test 3

	Minimum	Maximum	Average
Engine Speed, RPM	2197	2204	2200
Torque, N-m (lb-ft)	62 (46)	72 (53)	69 (51)
Power, kW (BHp)	14.3 (19.2)	16.1 (21.7)	15.8 (21.2)
BMEP, KN/m^2 (psi)	669 (97)	770 (112)	736 (107)
BSFC, kg/kW-hr (lbs/BHp-hr)	.284 (.468)	.355 (.583)	.312 (.514)
Fuel Rate, kg/hr (lbs/hr)	4.95 (10.9)	5.09 (11.2)	4.99 (11.0)
Blowby, m^3/hr (ft^3/hr)	.566 (20.0)	1.127 (39.8)	.861 (30.4)
Temperatures, °C (°F)			
Intake Air	90 (194)	91 (196)	90 (195)
Exhaust	396 (745)	452 (845)	409 (769)
Jacket-in	84 (183)	86 (186)	85 (185)
Jacket-out	88 (190)	89 (192)	88 (190)
Oil Sump	88 (190)	88 (190)	88 (190)
Pressures, Abs, KN/m^2 (in. Hg)			
Intake Air	257 (76.2)	263 (77.8)	261 (77.2)
Exhaust	238 (70.5)	245 (72.5)	240 (71.2)

Exhaust Emissions Data - Test 3

Test Hour	NO (ppm)	NO_x (ppm)	HC (ppm propane)	CO (%)	CO_2 (%)	O_2 (%)
4	450	610	120.4	.030	5.01	14.0
20	498	532	136.0	.040	5.12	13.65
50	550	700	116.0	.042	5.00	14.35
75	489	572	67.7	.053	5.15	14.25
120	655	674	71.0	.037	5.15	13.65

CRC DIESEL RATING SYSTEM

STANDARD COMPUTATION SHEET FOR PISTON RATING

TEST PROCEDURE TACOM ER-3
TEST HOURS 120
TEST LABORATORY ARLRL
LUBRICANT REO 203

RATER E.R. Lyons DATE
LABORATORY TEST NUMBER TACOM-3
STAND NO. ENGINE NO.
FUEL AL-5884-L (Conroe)

PISTON NO. 1

NO. 1 GROOVE, VOLUME-%	--
PISTON WTD* RATING	198.75

	DEPOSIT TYPE	DEPOSIT FACTOR	GROOVES NO. 1 AREA-%	GROOVES NO. 1 DEMERIT	GROOVES NO. 2 AREA-%	GROOVES NO. 2 DEMERIT	GROOVES NO. 3 AREA-%	GROOVES NO. 3 DEMERIT	GROOVES NO. 4 AREA-%	GROOVES NO. 4 DEMERIT	LANDS NO. 1 AREA-%	LANDS NO. 1 DEMERIT	LANDS NO. 2 AREA-%	LANDS NO. 2 DEMERIT	LANDS NO. 3 AREA-%	LANDS NO. 3 DEMERIT	LANDS NO. 4 AREA-%	LANDS NO. 4 DEMERIT	UNDER-CROWN AREA-%	UNDER-CROWN DEMERIT
CARBON	HC	1.00	95	95	75	75														
CARBON	MHC	0.75																		
CARBON	MC	0.50																		
CARBON	LC	0.25									10	2.5								
CARBON	VLC	0.15									25	3.75	95	14.25						
CARBON	CARBON RATING		95		75		0		0		6.25		14.25							
LACQUER	BL	0.100																		
LACQUER	DBrL	0.075																		
LACQUER	AL	0.050									65	3.25			100	5.0				
LACQUER	LAL	0.025																		
LACQUER	VLAL	0.010																		
LACQUER	RL	0.001																		
LACQUER	LACQUER RATING										3.25				5.0					
	CLEAN	0																		
	ZONAL RATING																			
	LOCATION FACTOR																			
	WEIGHTED RATING		95		75		0		0		9.50		14.25		5.0		0		0	

*WEIGHTED TOTAL DEPOSITS

Consolidated Oil Analyses,
Wear Measurements, and
Deposit Ratings

TACOM ER-3 Engine Tests

Used Oil Analyses
120-Hour TACOM ER-3 Tests
Lubricant: REO-203

Test Number Fuel Used	New Oil	1 Inglewood	2 DF-2	3 Conroe
Viscosity at 38°C (100°F), cS	121.6	140.0	144.35	132.08
Viscosity at 99°C (210°F), cS	12.61	14.02	140.02	13.34
Total Acid Number (D664)	3.60	3.60	4.86	3.83
Total Base Number (D2896)	5.40	2.66	3.12	4.96
Carbon Residue (D524), %	1.19	1.65	1.72	1.40
Sulfated Ash (D872), %	0.93	0.98	1.15	1.05
Insolubles (D893), %				
Pentane B	0.03	0.75	0.94	0.28
Benzene B	0.02	0.51	0.63	0.19

TACOM Single-Cylinder ER-3 Engine Measurements (Wear)
Tests No. 1, 2, and 3

Cylinder Bore Change, cm (inches)

Top Ring Position	Transverse		
	Test No. 1	Test No. 2	Test No. 3
T.D.C. at 90° BDC	.0013 (.0005)	.0013 (.0005)	.0018 (.0007)
	.0013 (.0005)	.0005 (.0002)	0 (0)
	.0013 (.0005)	.0020 (.0008)	-.0005 (-.0002)
	Longitudinal		
	Test No. 1	Test No. 2	Test No. 3
	.0005 (.0002)	.0005 (.0002)	-.0008 (-.0003)
	.0010 (.0004)	.0005 (.0002)	-.0003 (-.0001)
	.0010 (.0004)	.0013 (.0005)	.0015 (.0006)

PISTON RINGS

End Gap Change, cm (inches)

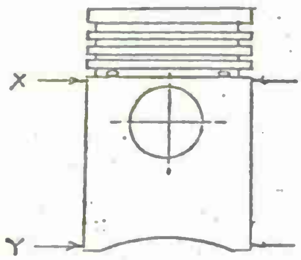
	Test No. 1	Test No. 2	Test No. 3
#1 Compression	.008 (.003)	.005 (.002)	.008 (.003)
#2 Compression	.033 (.013)	.013 (.005)	.013 (.005)
#3 Compression	.028 (.011)	.008 (.003)	.015 (.006)
Oil Control	.013 (.005)	.005 (.002)	.005 (.002)

Side Clearance (In Groove) Change, cm (inches)

	Test No. 1	Test No. 2	Test No. 3
#2 Compression	.0025 (.0010)	.0012 (.0040)	.0038 (.0015)
#3 Compression	.0025 (.0010)	.0050 (.0020)	.0038 (.0015)
Oil Control	.0025 (.0010)	.0013 (.0005)	.0013 (.0005)

Piston Skirt Diameter Change, cm (inches)

	Test No. 1	Test No. 2	Test No. 3
at "X"	.0038 (.0015)	.0025 (.0010)	-.0008 (-.0003)
at "Y"	.0025 (.0010)	.0018 (.0007)	-.0005 (-.0002)



RING STICKING

Engine Model TACOM Serial No. ______ Date 3/18/75
Fuel ______ Lubricant REO 203 Observer E.R. Lyons

TEST NUMBER

Ring No.	1	2	3
1	F	F	F
2	F	F	F
3	F	F	F
4	F	F	F

Indicate by letter – Free or Sluggish, or by number and letter – percent Pinched (cold stuck) or percent Hot stuck (Pages 6 and 7 of Manual).

RING DEPOSITS

Engine Model TACOM Serial No. ____ Date 3/18/75
Fuel ____ Lubricant REO 203 Observer E.R. Lyons

Test Number			1		2		3	
			CARB	LACQ	CARB	LACQ	CARB	LACQ
Piston Ring	Top	1	0	5	0	10	5	5
		2	0	100	60	40	0	0
		3	0	100	0	100	0	0
		4						
	ID	1	100	0	60	40	100	0
		2	100	0	100	0	100	0
		3	0	100	10	90	0	0
		4						
	Bottom	1	0	0	0	0	5	10
		2	0	95	0	100	0	0
		3	0	100	0	100	0	0
		4						

See pages 4, 36 and 37 of Manual. Areas previously rated for carbon, rate 0 for lacquer

Test No. 1 #2 ring has carbon buildup in the step

RING FACE CONDITION

Engine Model TACOM Serial No. ______ Date 3/18/75
Fuel ______ Lubricant REO 203 Observer E.R. Lyons

	TEST NUMBER		
	1	2	3
First Ring	Normal	Normal	Normal
Second Ring	Medium Wear	Normal	Normal
Third Ring	Medium Wear	Normal	Normal
Fourth Ring	--	Normal	Normal
Oil Ring Slots—% Open	100	100	100

Pages 1 and 2 and 59 through 65 of Manual.

#1 ring is chrome face

PISTON SURFACE DEPOSITS

Engine Model TACOM Serial No. ______ Date 3/18/75
Fuel ______ Lubricant REO 203 Observer E.R. Lyons

		TEST NUMBER		
		1	2	3
Top*		20%-A 80% ½-A	20%-A 80% ½-A	100½-A H
Combustion Chamber*		25%-A 75% ½-A	15-C 5-B 80-A	100½-A H
Under Head*		#6 Lacquer	90-2	0
Skirts*	Thrust	Clean	5% #3	0
	Anti-Thrust	Clean	Clean	0
Relief Areas*		--	Clean	--
Lands	1	25%BHC 65%AHC 20% #7	95-A 5-5	10-BH 25-AH 65-½ 5
	2	25%-½AHC 75% #9	20-A 5-9 25-3	50-½AH 45-AH
	3	100% ½AH HC	10½-A 5-5 5-6	100-4
	4			Clean

Lacquer—Pages 4, 36, 37 of Manual.
*Carbon and Ash: Use Volume Factor (Pages 5 and 40 through 47)
Indicate H, M, or S (Page 5)

Test No. 1 - The deposit where the injector pattern shows is a shiney almost tacky substance

PISTON RING GROOVE DEPOSITS

Engine Model TACOM Serial No. ______ Date 3/19/75

Fuel ______ Lubricant REO 203 Observer E.R. Lyons

		TEST NUMBER					
		1		2		3	
		CARB	LACQ	CARB	LACQ	CARB	LACQ
Top of Groove*	1	15	85	50A HC	40-9	100½ AH	
	2	15	85	0	60-9	95-8	
	3	0	0	0	0	0	
	4	0	0	0	0	0	
Back of Groove†	1	90	0	90-H	0	95-H	
	2	25	0	90-H	0	75-H	
	3	0	100	10-H	0	0	
	4	0	75	0	0	0	
Bottom of Groove*	1	0	0	0	25-9	50-7	
	2	0	0	0	0	0	
	3	0	0	0	0	0	
	4	0	0	0	0	0	
Drain Holes—% Blocked		0		0		0	

Lacquer: Pages 4, 36, and 37

*Carbon and Ash: Use Volume Factor (Pages 5 and 40 through 47)
Indicate H, M, or S (Page 5)

†Carbon and Ash: Indicate Percent Filled and H, M, or S (Page 5)

PISTON GROOVE INSIDE DIAMETER–% RING SUPPORTING CARBON

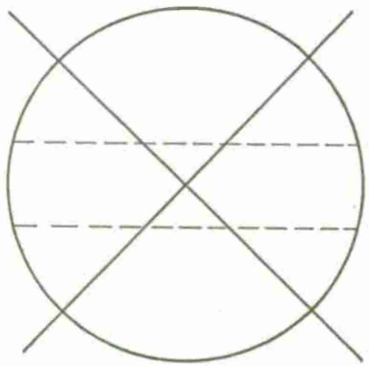
6

Engine Model TACOM | Serial No. | Date 3/19/75
Fuel | Lubricant REO 203 | Observer E.R. Lyons

Piston Ring	Quadrant	TEST NUMBER 1	2	3
1	1	75	0	100
	2	50	5	75
	3	20	5	85
	4	50	20	75
2	1	0	0	0
	2	0	0	0
	3	0	10	25
	4	0	100	90

1 Thrust Side

4 Front



2 Rear

3 Anti-Thrust Side

PISTON SURFACE CONDITION

Engine Model TACOM Serial No. ______ Date 3/18/75
Fuel ______ Lubricant REO 203 Observer E.R. Lyons

	TEST NUMBER		
	1	2	3
Top Land	Normal	Normal	Normal
Skirt	Normal	Normal	Normal
Piston Pin	Normal	Normal	Normal

Pages 1 through 2 and 59 through 65 of Manual.

VALVE DEPOSITS

Engine Model TACOM   Serial No. ____________   Date 3/19/75

Fuel ____________   Lubricant REO 203   Observer E.R. Lyons

		TEST NUMBER					
		1		2		3	
		CARB	LACQ	CARB	LACQ	CARB	LACQ
Head*	INT	100% ½A	0	100% ½A	0	100% ½A	0
	EXH	100% ½A	0	100% ½A		100% ½A	0
Face	INT	0	100%	0	0	100% ½A	0
	EXH	100% ½A	0	0	0	100% ½A	0
Tulip†	INT	10-B 90-A	0	100%-A H	0	100% ½A	0
	EXH	100% ½A	0	100% ½A	0	100½ ½A	0
Stem	INT	0	0	0	0	0	0
	EXH	0	15	0	0	0	0

*Carbon and Ash: Use Volume Factor Technique (Pages 5 and 40 through 47 of Manual).

†Use Chart, Page 21—Indicate H, M, or S (Page 5).

Lacquer: Pages 4, 36 and 37.

Test No. 3 - All of carbon is like soot

VALVE SURFACE CONDITIONS

Engine Model TACOM Serial No. Date 3/19/75
Fuel Lubricant REO 203 Observer E.R. Lyons

Test Number	Intake			Exhaust		
	1	2	3	1	2	3
Freeness in Guide	F	F	F	F	F	F
Head	N	N	N	N	N	N
Face	N	N	N	N	N	N
Seat	N	N	N	N	N	N
Stem	N	N	N	N	N	N
Tip	N	N	N	N	N	N

See Pages 1, 2, 16 through 23, and 54 through 65 of Manual.

F = Free N = Normal

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