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RESIDUAL SHALE OIL/DIESEL ENGINE OPERATING COMPATIBILITY PROGRAM

Final Report

37

By
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Craig Derbidge
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October 1983
Date Published

Work Performed Under Contract No. AC19-80BC10114

Acurex Corporation
Mountain View, California

MASTER

U. S. DEPARTMENT OF ENERGY

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SECTION 1

INTRODUCTION

1.1 BACKGROUND

Shortages of conventional petroleum fuels can be alleviated by the use of alternate fuels in internal combustion engines. Power generation with medium-speed diesel engines is widespread throughout the United States, as well as other nations, and requires large volumes of light distillate petroleum products. An attractive alternative in the near term is to replace these dwindling and increasingly expensive fuels with synthetic coal-derived fuels and shale oils. This can be accomplished with minimal changes in engine design. Other fuels, such as highly cleaned, pulverized coal or coal-oil mixtures may become useful in the future, but they will require extensive system modifications.

The rapid and economic development and the efficient use of the available coal-derived liquids (CDL) and shale oil requires that they be used in a minimally processed form. The efficiency and cost of modifying medium-speed (300- to 1200-rpm) diesel engines must be established and weighed against the cost for further fuel refining. Also, performance and reliability of the engines with the alternate fuels must be established.

The Department of Energy, Bartlesville Energy Technology Center (DOE/BETC) has established a program to address some of these technological problems that exist in utilizing new fuels in diesel engines and to provide technical information to determine the need and direction for future diesel engine programs. Different fuels are to be examined as they become available. The objective is to obtain a broad base of technical information on fuel and engine systems, using fuels that may be expected to enter production in the next two decades. This must be achieved with commercially acceptable operational reliability, fuel efficiency, emissions levels, and engine life.

When coal- or shale-derived liquids are considered for medium-speed engines, the following problems, related to the fuel properties, are anticipated.

- Certain fuels must be heated and possibly blended with No. 2 diesel oil.
- The injectors may plug, wear excessively, or build up black "trumpets" of carbon that break off periodically. Carbon accumulation is due to the high carbon/hydrogen ratio.
- The ignition delay increases due to the potentially lower "cetane" index of the fuel.
- The amount of preignition fuel vaporization increases causing excessive rate-of-pressure-rise, noise, and peak pressure.
- Altered spray penetration and atomization occur because of shifted viscosity, density, and surface tension, and may lead to increased burn times or soot formation (e.g., from wall impingement).
- The NO_x emissions from certain coal-derived fuels are expected to increase due to high fuel-bound nitrogen.
- Ash or metal impurities may accumulate on the combustion chamber walls or cause excessive ring wear and piston scuffing.

- Some fuels have a high aromatic content which may lead to increased emissions of polynuclear aromatic hydrocarbons.

Limited tests with coal-derived liquids in medium-speed diesels have confirmed several of the problems anticipated.

The objective of the DOE/BETC study is to acquire engineering data from current technology engines using CDL, shale-derived liquids, or similar low-grade fuels. This will be accomplished by both laboratory and engine tests in areas of fuel handling, injection and initial combustion, fuel blending, performance characteristics, effect of additives, combustion exhaust emissions, and wear and corrosion of critical components. These data will serve two purposes: (1) enable technical appraisal of the potential adaptability and overall suitability of current diesel engines for using CDL-type fuels in the projected U.S. market, and (2) reveal critical problems to be addressed in further development of a CDL/diesel system.

To meet this objective, five different contractors are conducting experimental projects with medium-speed diesel engines, using a minimum of three different fuels. Three contractors are using minimally refined coal liquid, SCR-II, in the middle distillate range with a hydrogen content of approximately 9.3 percent by weight; two contractors are using a distillate shale oil with physical properties similar to no. 2 diesel fuel; two contractors are using shale oil bottoms fuel which has a higher viscosity than the other fuels. The engines are described in table 1-1. Additional fuels will be considered as they become available (e.g., EDS, H-Coal, full-range SRC-II, and higher hydrogenated SRC-II).

Table 1-1. Fuel and Diesel Selection for Test Program

Prime Contractor/ Subcontractor	Fuel Used	Engine Characteristics				
		Model	bhp @ rpm	B x S	CID	CR
Acurex/ Ricardo Engineering	Shale Residual	APE-Allen BSC 12 F 6-cylinder, in-line Turbocharged, 4-stroke	1,323 @ 1,000	9.5 x 12	5,101	12.0
A. D. Little/ Colt Industries	SRC-II Middle Distillate	Fairbanks Morse 38TD-8-1/8 6-cylinder, in-line Turbocharged, 2-stroke	1,050 @ 900	8.5 x 10	3,108	13.8
EER/(None)	Shale Distillate and Shale Residual	Superior 40-X-6 6-cylinder, in-line Turbocharged, 4-stroke	702 @ 900	9.125 x 10.5	4,122	13.5
General Electric/ (None)	SRC-II Middle Distillate Shale Distillate	GE FDL-8 8-cylinder, V Turbocharged, 4-stroke	1,750 @ 1,050	9 x 10.5	5,344	12.7
Transamerica Delaval/ (None)	SRC-II Middle Distillate	Delaval DSR 46 6-cylinder, in-line Turbocharged, 4-stroke	3,656 @ 450	17 x 21	28,600	12.0

1.2 OBJECTIVES

The objective of the Acurex program is to develop engineering data on the operation of a current technology, medium-speed, diesel engine on residual shale oil (RSO). The data will serve two purposes:

- Enable technical appraisal of the potential adaptability and overall suitability of RSO for use in diesels in the projected U.S. market.
- Reveal critical problems to be addressed in further development of fuel and engine systems.

1.3 OVERALL APPROACH

To perform this program Acurex teamed with Ricardo Consulting Engineers Ltd. Engine tests were conducted in Ricardo's large engine test facility at Shoreham-by-Sea, West Sussex England. The engine used was a medium-bore (9.5-in.), medium-speed (1,000-rpm) prototype version of the BSC 12F engine marketed worldwide by APE-Allen. Engine details are given in table 1-2.

Review of RSO fuel properties and test data indicate that potential problem areas are:

- Fuel handling
  - -- High pour point
  - -- Degradation of seals
- Engine degradation
  - -- Lube oil dilution
  - -- Sediment and water contamination
  - -- Vanadium/sodium corrosion
- Ignition
  - -- Cetane rating uncertain

Table 1-2. BSC 12F Engine Specifications

Make	APE/Allen
No. of cylinders	6
Bore	241 mm (9.5 in.)
Stroke	305 mm (12 in.)
Speed	1000 rpm
Brake Mean Effective Pressure (BMEP)	275 psi, distillate fuel 210 psi, heavy fuel
Combustion system	Direct injection diesel
Induction	Turbocharged and aftercooled
Cycle	Four stroke

To address these potential problems the following series of tests were conducted: fuel characterization, go/no-go, and performance/endurance.

The fuel tests included the determination of physical, chemical, and combustion properties as well as fuel pumpability and filterability tests. The primary objectives of the go/no-go tests were to select the best firing mode for RSO and to check the fuel delivery system design. Three potential firing modes were evaluated: dual-rate injection, pilot injection, and mixed fuel injection. A brief description of these methods is presented in figure 1-1. To conserve fuel during the go/no-go tests, only one cylinder was fired on RSO and the remaining five No. 2 on diesel fuel. The best fueling mode determined from the go/no-go tests was direct firing of 100 percent RSO and was used in the performance/endurance tests.

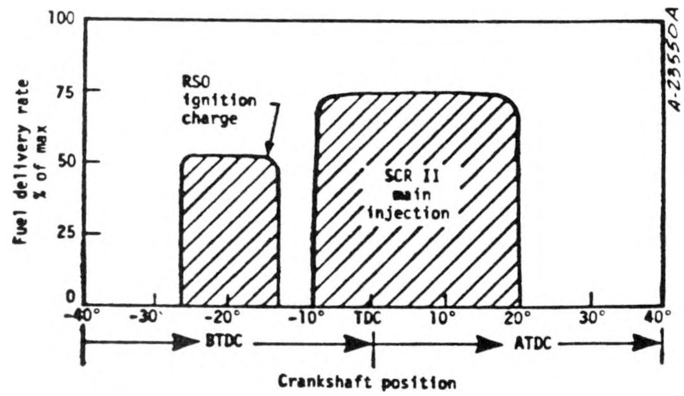
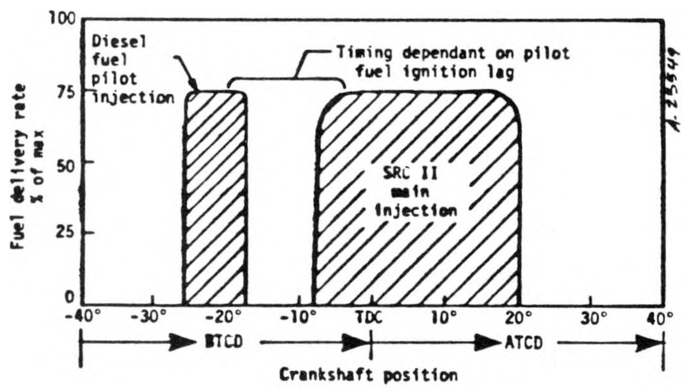
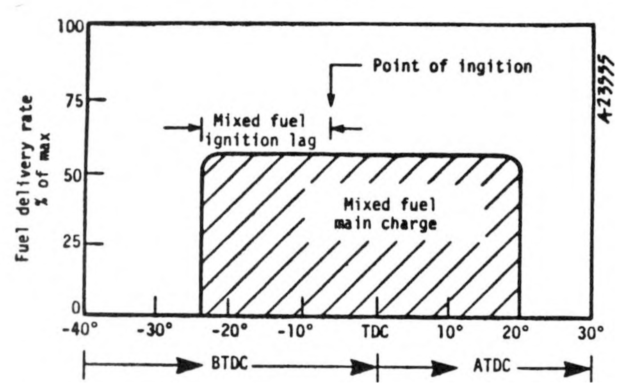
Approach	Description	Injection Profile
Dual-Rate Injection of RSO	Fuel injected initially at low rate to avoid accumulation during long ignition lag. Second injection at normal rate delivers main charge into combustion zone.	
Pilot Injection	Short duration injection of diesel fuel initiates burning. Second injection delivers RSO into combustion zone.	
Mixed Fuels Injection	Mixtures of up to 20 percent diesel with RSO to shorten ignition lag time.	

Figure 1-1. Fueling Methods to be Evaluated

Upon completion of the go/no-go tests, the engine was set up for testing RSO in all six cylinders. The objective of these tests was to provide engine performance/endurance data over a variety of load and speed ranges. Lube oil dilution was closely monitored and engine wear characterization evaluated -- particularly the fouling of fuel injection equipment, turbine nozzles, and exhaust manifolds.

A logic flow diagram of the test plan is shown in figure 1-2. The following sections contain a description and characterization of the RSO fuel, description of the Allen engine that was tested, detail design of the test setup, and test results and conclusions.

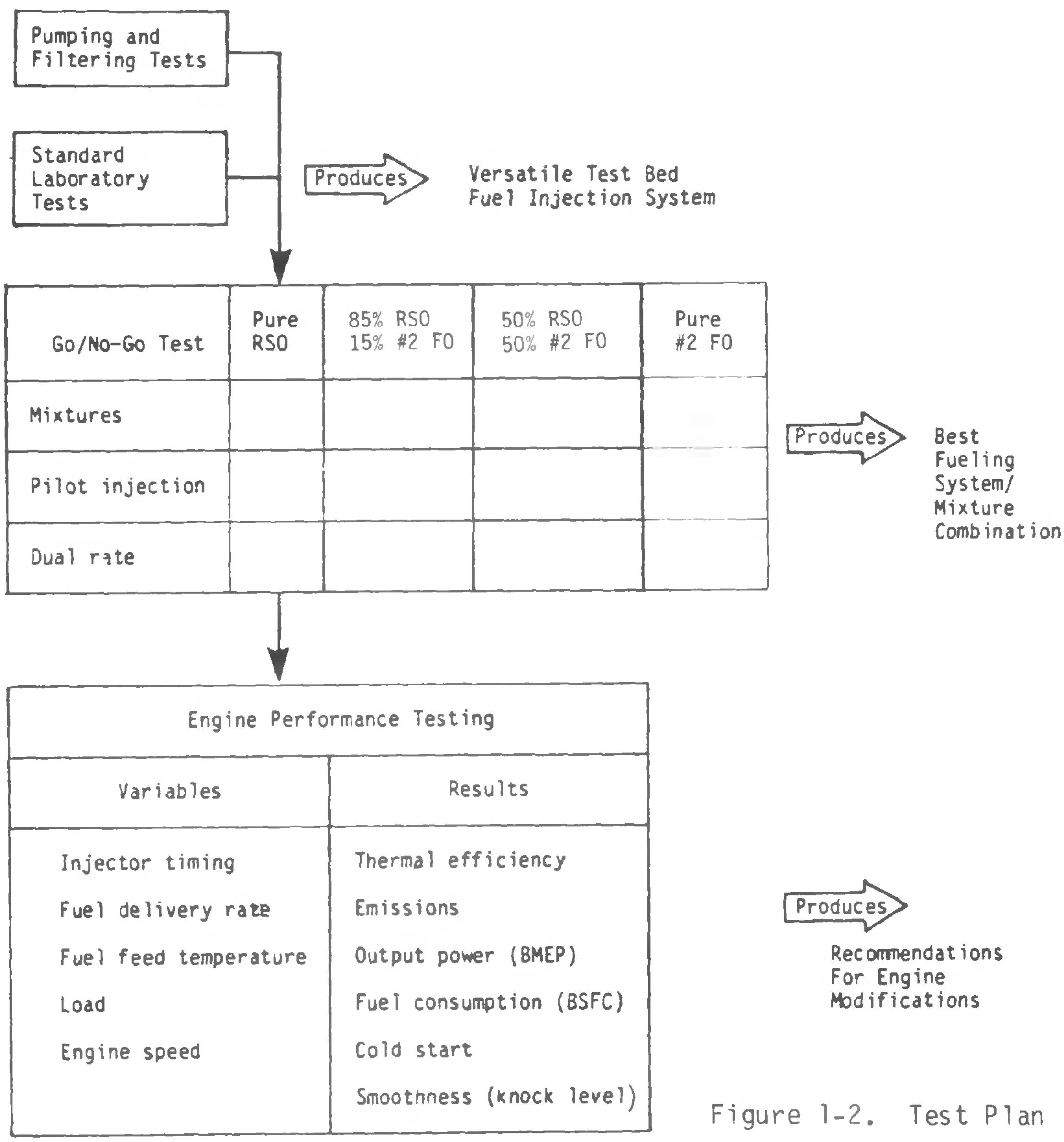


Figure 1-2. Test Plan

SECTION 2

FUEL CHARACTERIZATION

The residual shale oil (RSO) tested in this program was obtained from the U.S. Naval storage facility in Mechanicsburg, Pennsylvania, and is comprised of the refinery splitter bottoms from the Navy's 100,000-barrel shale test run (reference 2-1). The Navy's program involved the production of 100,000 barrels of shale syncrude from Green River Basin shale by the Paraho process. This syncrude was subsequently treated and refined for the purpose of producing military specification distillates for testing on military equipment. Also produced was a substantial quantity of hydrotreated residual shale oil which was used in the tests described herein.

The following section describes the process involved in producing the RSO fuel, as well as a discussion and comparison of the chemical, physical, and combustion properties of this fuel with selected other fuels and the fuel requirements of medium-speed diesel engines. Also included is an assessment of the availability of RSO as a commercial fuel.

2.1 PRODUCTION PROCESS DESCRIPTION

The extraction of the shale crude oil from the shale rock was accomplished in a vertical, refractory-lined retort equipped with shale- and gas-handling devices. In the Paraho retort shown in figure 2-1, crushed and sized shale moves downward through a combined mist formation

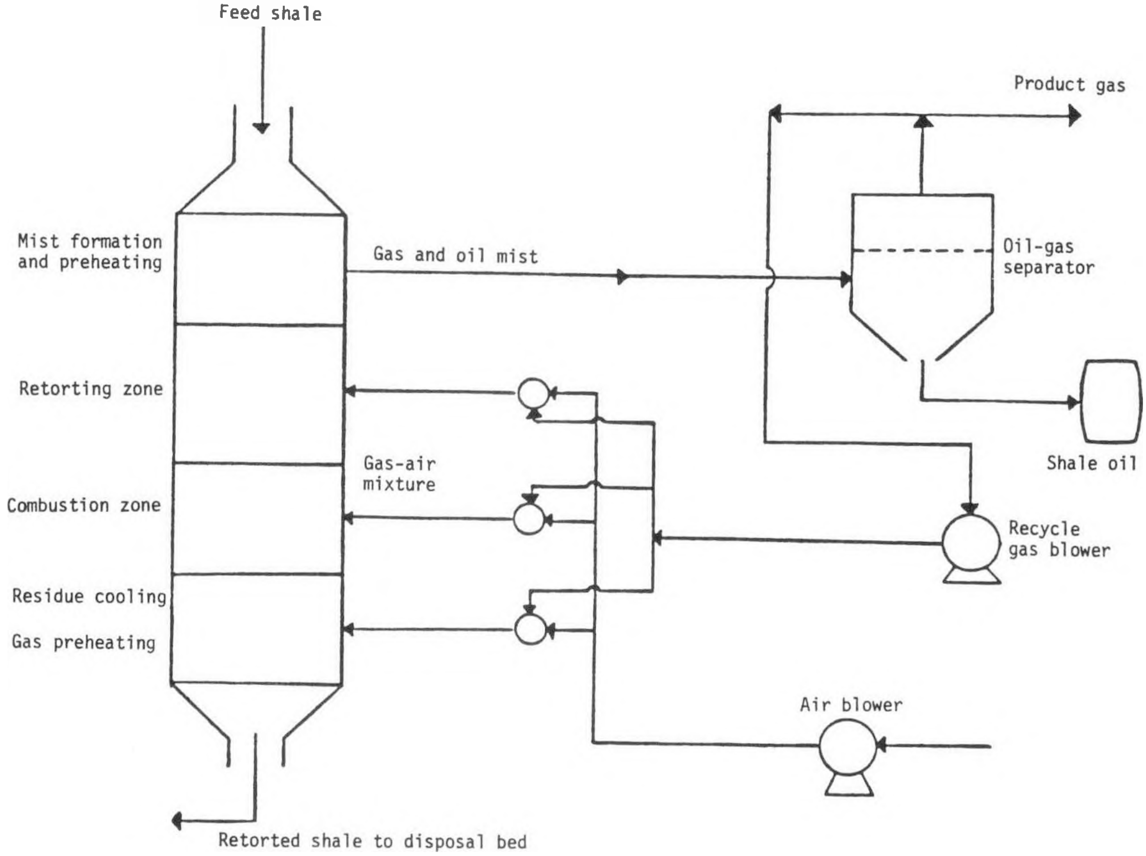


Figure 2-1. Paraho Retorting (Direct Heating) (Reference 2-1)

and cooling zone, above the top air-gas distributor, where the shale particles are heated by the rising gases from the retorting zone and the retorted oil and gas vapors are formed into a stable mist. The shale proceeds downward into the retorting zone, between the middle and top air-gas distributors, where the organic kerogen in the shale is decomposed by heat, forming oil vapor and gas. Conditions in the retort zone are sufficient for liberation of relatively light hydrocarbons only; the very heavy asphaltenes, coke, and other viscous macromolecules remain in the rock, providing fuel for the combustion zone (reference 2-2).

The retorted shale proceeds to the combustion zone; the heat required to retort the shale is produced by burning the organic residue in the shale plus a part of the product gas which is returned to the system. The spent shale moves downward from the hot zone to the cooling zone where the heat of the retorted shale is transferred to the rising stream of recycle gas. The cooled shale is then discharged from the retort by a grate mechanism at the bottom of the retort.

The recycle gas is injected at the bottom of the retort and rises through the retorting shale in the cooling zone. This zone acts as a simple counter-current gas-to-solids heat exchanger. Air-gas distributors are located at two levels near the center of the retort where air, diluted with retort recycle gas, is injected. The oxygen then reacts with the combustibles to produce hot gases. The resulting gas rises up through the raw shale in the retorting zone where the solids are heated to a temperature above $900^{\circ}F$ to cause the thermal decomposition of the kerogen in the shale.

The product gas stream from the retort then goes to an electrostatic precipitator where the shale oil is recovered. A portion of the product gas is returned to the retort for combustion. Other commercial syncrudes will be retorted in a similar manner, using surface or "in situ" retorts that utilize indirect heating (reference 2-3).

Syncrudes from shale are higher in sulfur, nitrogen, and oxygen, and lower in asphaltenes and carbon residue than conventional petroleum crudes. The levels of nitrogen, oxygen, and sulfur are of particular concern at the refinery, where they foul catalysts used in refining processes. The syncrude is, therefore, hydrotreated to reduce levels of these contaminants as well as saturate and selectively crack the oil to maximize the yield of distillate.

The hydrocracking schematic is shown in figure 2-2. The shale crude is hydrocracked in the reactor, the hydrogenated contaminants are stripped off as gases (e.g., H_2S, H_2O, and NH_3) and the resultant products separated by distillation. In this case four product cuts were produced: gasoline, jet fuel (JP-5), diesel fuel marine (DFM), and heavy fuel oil (RSO). The effects of hydrotreating are significant, as indicated by pilot plant results summarized in table 2-1. The distribution of yields from the actual SOHIO refinery run is presented in table 2-2; approximately 30 percent of the shale syncrude was produced as RSO. Maximization of the distillate cut with less severe processing of RSO may be an alternate refining tactic used by commercial shale oil refiners (reference 2-1).

2.2 RSO FUEL AS A DIESEL FUEL

A logical market for RSO would be as a fuel for medium-speed diesels, as the manufacturers of these engines currently allow residual fuels with viscosities up to 400 cst. The properties of fuels that significantly affect the operation of diesel engines are presented in the

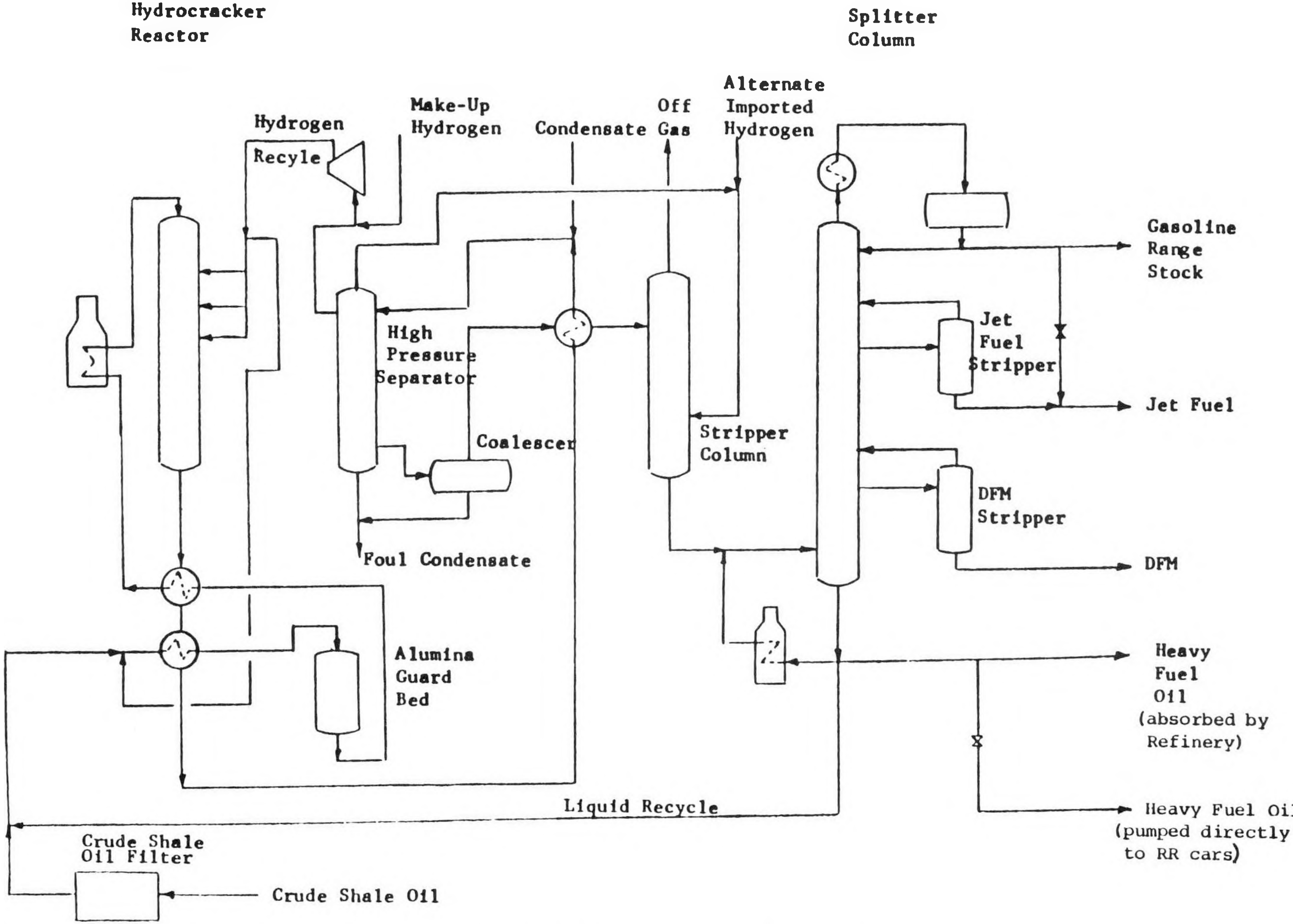


Figure 2-2. Hydrocracker Unit (Reference 2-1)

Table 2-1. Effects of Hydrotreating Whole Shale Oil (Prior to Distillation) Pilot Plant Results

Factor	Unhydrotreated	Hydrotreated
API Gravity	21.4	34.4
Hydrogen, Wt. %	11.4	13.0
Carbon, Wt. %	84.5	85.9
Nitrogen, Wt. %	2.0	0.3
Oxygen, Wt. %	1.3	0.5
Sulfur, Wt. %	0.6	0.002
Molecular Weight	297.0	261.0
Tbp 650°F Pt, Vol. %	32	65
H/C Molar Ratio	1.6	1.8

Table 2-2. Preliminary Normalized Reactor Yields From SOHIO Toledo Refinery Run (Reference 2-1)

Temperature	Percent of Yield
C_4 to 325°F (Gasoline)	11
325° to 480°F (JP-5)	26
480° to 650°F (DFM)	31
650°F and Bottoms	32
	100

following paragraphs, with an emphasis on the characterization of RSO as a diesel fuel in relation to other petroleum-derived fuels.

The term "residual shale oil" is used to indicate the splitter bottoms from the distillation process. In the case of petroleum-derived fuels, the maximization of the distillate yield from a crude requires severe treatment of the first-run residue, including catalytic cracking, visbreaking, and vacuum distillation which produce a residual that is mainly a dispersion of asphaltenes in an oily medium (reference 2-4). Residual shale oil is significantly different in that the extremely viscous, high molecular weight hydrocarbons are left in the shale and combusted in the retort. This results in a crude with lower quantities of carbon residue and asphaltenes which suggests that RSO, in this respect, is more like a distillate than a petroleum residual.

Properties of RSO and various fuel oil grades (a Phillips Petroleum No. 2 control diesel fuel and typical No. 4, 5 (light), 5 (heavy) and No. 6 fuel oils) are presented in table 2-3. The No. 2 diesel fuel is included as a reference fuel for diesel engines. The other fuels are included to characterize RSO in terms of other familiar fuels. The detailed properties of the RSO shown were obtained both from the reported values as given in the contract "Statement of Work" and from measurement on the fuel used in this program. The results of the different analyses performed on RSO indicate either an apparent change in some properties with time or that there was a variation among storage containers.

The first analyses were performed by the Radian Corporation in November of 1978 with subsequent analyses performed by Caleb Brett & Son, Ltd. concurrently with the engine testing in July of 1981. The later analyses show a decrease in nitrogen content, a significant increase in

Table 2-3. Comparison of Various Fuel Properties

Property	Units	ASTM Test Method	RSO[a]	RSO[b]	Shale[c] DFM	Phillips[d] Control 2-D	Ricardo Standard Diesel	No. 4[e]	No. 5[e] Light	No. 5[e] Heavy	No. 6[e]
Distillation											
IBP	°F	D86	365	446	402	372	442				
10%	°F		590	580.1	452	427					
20%	°F		671	622.4	470	--					
30%	°F		699	653	--	--					
40%	°F		733	675.5	--	--		--	--	--	--
50%	°F		776	698	508	504	566				
60%	°F		814	720	--	--					
70%	°F		844	736	--	--					
80%	°F		890	752	--	--					
90%	°F		931	--	563	568	680				
EP	°F		1,024	--	593	600	730				
Physical Properties											
API Gravity (60°F)	°API	D287	--	--	37.9	35.0		18-22	14-18	13-21	10-16
Specific Gravity		D1298	0.87	0.882			0.8445				
Viscosity	cst (100°F)	D445	23.48	23.08	2.71	2.67	3.74	6.0-26	46-59	85-142	90-675
Flash Point	°F	D93	208	221	176	172		158-276	152-236	148-250	150-366
Pour Point	°F	D97	77.5	89.6	0	--		10-85	0-65	0-90	15-90
Wax Content	% Mass			13.18							
Wax Melting Point	°F	D127	128	113							
Chemical Properties											
Total Nitrogen	Wt. %	D3228	0.44	.02	0.001	--		--	--	--	--
Total Sulfur	Wt. %	D129	0.02	0.13	0.004	0.34	0.31[h]	0.46-1.42	0.88-20	0.62-236	0.21-3.35

-- Not Available
[a]Analysis from "Statement of Work"
[b]Caleb Brett & Son Ltd Analysis, October 79
[c]Reference 2-3
[d]Written correspondence with Phillips Petroleum
[e]Reference 2-7
[f]Private communication from Ricardo
[g]Caleb Brett measured Cetane index of 61 using Aniline Gravity Point Method
[h]Test Method I.P. 242
[i]Test Method I.P. 12

Table 2-3. Concluded

Property	Units	ASTM Test Method	RSO[a]	RSO[b]	Shale[c] DFM	Phillips[d] Control 2-D	Ricardo Standard Diesel	No. 4[e]	No. 5[e] Light	No. 5[e] Heavy	No. 6[e]
Carbon	Wt. %	D524	86.33	--	--	86.54		--	--	--	--
Oxygen	Wt. %		0.38	--	0.37	--		--	--	--	--
Sodium			--	2	--	--		--	--	--	--
Vanadium			--	2	--	--		--	--	--	--
Bottom Sediment and Water	Vol. %	D2709	0.10	0.20	--	--		0-0.10	0.05-0.2	0.1-0.2	0.1-0.3
Carbon Residue (100% Sample)	Wt. %	D524	0.18	0.28	0.004 (10%)	--		1.0-4.3	2.0-4.5	3.1-5.3	3.3-16.8
<u>Combustion Properties</u>											
Heat of Combustion											
- Gross	Btu/lb	D240	19,331	19,700	--	--		19,000	18,850	18,775	18,725
- Net	Btu/lb	D240	--	--	18,271[i]	--	18,275[i]	--	--	--	--
Cetane Number		D613	--	48[fg]	54.2	47.8	54.2	--	--	--	--
Hydrogen Content	Wt. %	D1018	12.31	--	13.36	--		--	--	--	--
Saturates	Vol. %	D1319	54.53	--	--	--		--	--	--	--
Aromatics	Vol. %	D1319	44.25	--	30	30.5		--	--	--	--
Olefins	Vol. %	D1319	1.25	--	1	--		--	--	--	--
Ash	Wt. %	D482	0.001	--	0	--		.01-.04	0.0-0.01	.02-.03	--

-- Not Available
[a]Analysis from "Statement of Work"
[b]Caleb Brett & Son Ltd Analysis, October 79
[c]Reference 2-3
[d]Written correspondence with Phillips Petroleum
[e]Reference 2-7
[f]Private communication from Ricardo
[g]Caleb Brett measured Cetane index of 61 using Aniline Gravity Point Method
[h]Test Method I.P. 242
[i]Test Method I.P. 12

sulfur content and increases in bottoms sediment and water (BS&W) and carbon residue. Contamination of the RSO may be indicated from the higher sulfur and BS&W, as these constituents are at higher levels than any of the original Paraho samples (reference 2-1). There is no apparent explanation for the observed decreases in nitrogen content and increases in the carbon residue of this fuel. The distillation temperature profile indicates a decrease in the initial boiling point (possibly due to loss of the lighter end) but a decrease over the remainder of the measured range (0 to 80 percent boiling point). The loss of the lighter end is also manifested in the increased flash point. No consistent explanation for the differences is apparent.

Fuel properties of concern in the operation of diesel engines are well documented (references 2-5 and 2-6) and include: viscosity, cetane number, carbon residue/asphaltene content and to a lesser extent sulfur, trace elements (such as vanadium and sodium), pour point/wax melt point, and BS&W. A summary of manufacturers' recommended and absolute limits for these fuel properties is presented in table 2-4. From the fuels comparison shown in table 2-3, with respect to these salient properties, the RSO ranks:

- Considerably more viscous than No. 2, being at the high end of the range for No. 4.
- Cetane number is comparable to No. 2.
- Carbon residue content is low compared to other heavy fuel oils.
- Sulfur, sodium, and vanadium levels are also low.

Table 2-4. Recommendations and Limits on Fuel Properties for Medium-Speed Diesels

Fuel Property	RSO Value	Units/Specification		APE-Allen S12[a]	Other Manufacturers' Recommendations[b]	Manufacturers' Limits[b]
Specific Gravity	0.87	at $60^{\circ}F$	Max	0.985	0.970	0.980
Viscosity		SSU at $100^{\circ}F$	Max	4,000	1,600	4,000
	23.1	Cst at $100^{\circ}F$	Max	900	375	900
Sulfur	0.13	Wt percent	Max	3	2.5	4.0
Carbon Residue (100 Percent Sample)	0.28	Wt percent	Max	12	8	10
Bottom Sediment and Water	0.28	Vol percent	Max	0.25	0.2[c]	1.0[c]
Ash	0.0011	Wt percent	Max	0.10	--[d]	--[d]
Cetane No.	48		Min		40	40
Sodium	2	Ppm	Max	100	--[d]	--[d]
Vanadium	2	Ppm	Max	200	--[e]	--[e]

[a]Reference 2-8
[b]Reference 2-5
[c]Specification for water only
[d]Not specified
[e]Recommended vanadium levels as low as possible

- Pour point is relatively high, being at the high end of the typical range for heavy fuel oils; note that a wax melting point was also measured for the RSO and was 45°C (113°F).
- BS&W is comparable to a No. 4 fuel oil.

Table 2-4 shows that the RSO properties meet all APE-Allen recommendations and are within maximum limits set by manufacturers. A discussion of the effects of these properties follows.

Viscosity

Viscosity is indicative of the pumpability and atomization characteristics of a fuel, the atomization of the fuel being especially important; e.g., for medium-speed diesels utilizing Nos. 5 and 6 grade fuels any delay in the time-limited compression ignition process will effectively raise the cetane requirement. The viscosity ranges of the various grades of fuels are summarized in figure 2-3, with the viscosity limits acceptable to engine manufacturers indicated. The viscosity of RSO is low in comparison to a normal petroleum residual (e.g., No. 6 fuel oil) because it is less severely cracked, more highly saturated, and lower in high molecular weight hydrocarbons. However, the viscosity of RSO is sufficiently high that some heating is required to maintain the viscosity at levels suitable for filters and injectors, but the required temperatures are substantially lower than those required for petroleum residuals.

In addition to the higher viscosity (relative to No. 2 diesel fuel), preliminary analysis showed that the wax content of RSO was very high, giving rise to unfavorable pumpability and filter plugging, (tables 2-3, 2-5). As a result the fuel required heating, at least, above the wax melting point of 113°F throughout the fuel handling system. At

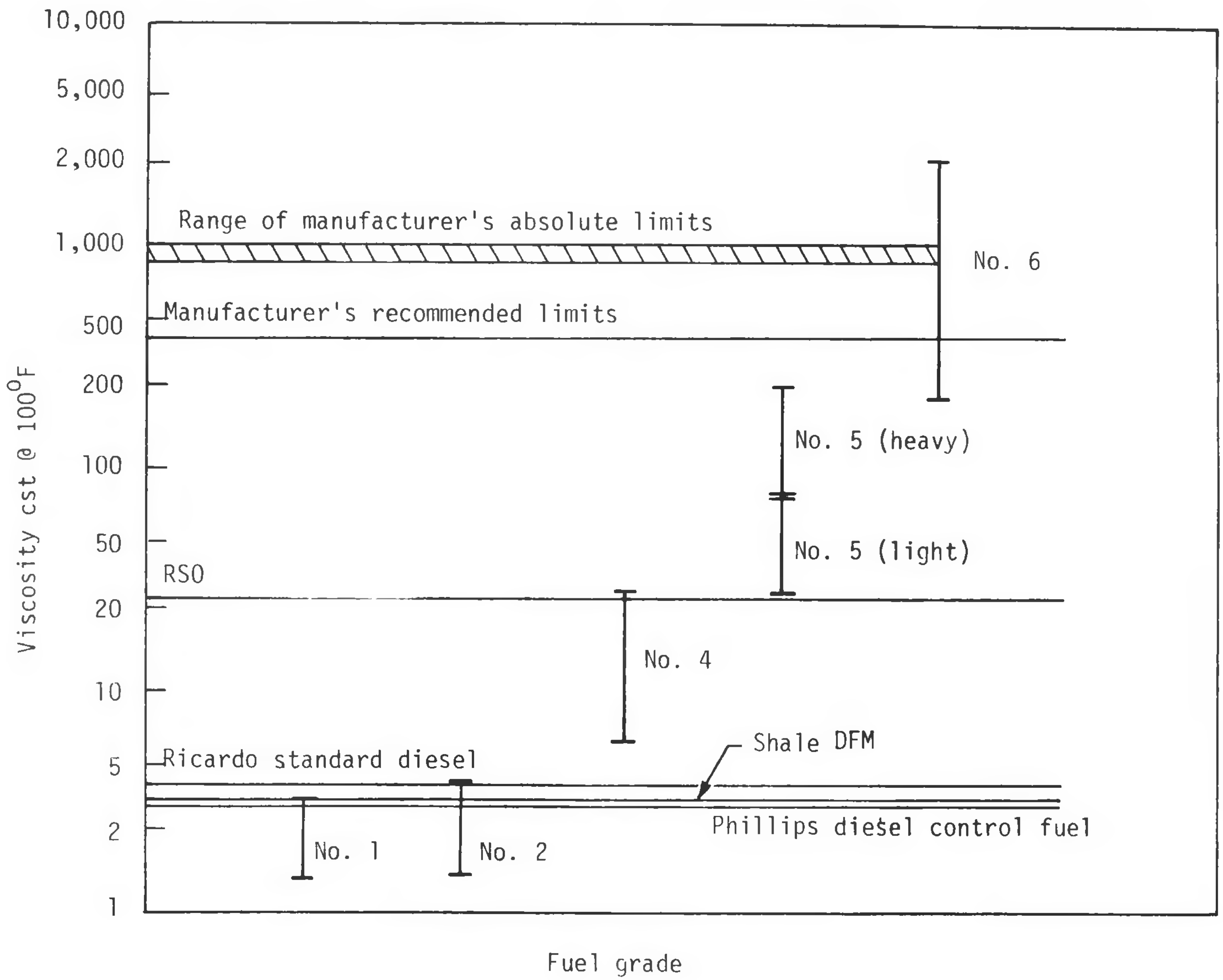


Figure 2-3. Comparison of Various Fuel Oil Viscosity Specifications and Requirements at 100°F U. S. Fuel Grade (References 2-3, 2-7, and 2-8)

Table 2-5. Preliminary Tests of Physical Properties Performed by Caleb-Brett Ltd.

Test	ASTM Method	Result
Cold Filter Plugging	309[a]	>110°F (>43°C)
Pour Point	D97	95°F (35°C)
Pumpability	230[a]	
Handling Point (6 poise)		82°F (28°C)
Storage Point (25 poise)		64.5°F (18.2°C)
Viscosity		
at 100°F (38°C)	D445	20.19 cst
at 122°F (50°C)		11.19 cst
at 176°F (80°C)		5.08 cst

[a]International Petroleum Method

the conditions maintained (i.e., approximately 140°F) the viscosity was reduced to an acceptable level for the fuel injection system, pump, and filters. Hence, higher temperature heating required by many residual fuels prior to injection is not necessary.

Cetane Number

Cetane Number is an indication of ignition quality. Residual fuels, in general, have a low Cetane Number. This was assumed to be the case for RSO. Cetane Number of a distillate can be determined by burning the fuel in a CFR engine. This technique is not normally available for residual fuels, but, at a late stage in the test program, Ricardo reached an agreement with a major oil company to conduct such a test on a sample of RSO. A specially modified CFR installation was used. Aniline point was also determined, enabling the Diesel Index to be calculated. The

Table 2-6. Cetane Number and Aniline Point Evaluation

Test	Method		Result
	I.P.	ASTM	
Aniline Point	2	D611	148.3°F (82.4°C)
Diesel Index	21	-	52.2
Cetane Number		Based on D613	47.8

results of these tests (table 2-6) indicate that the combustion characteristics of this batch of RSO were much better than anticipated. The resultant value of 47.8 is comparable to a standard No. 2 diesel fuel and well above minimum engine specifications.

A detailed analysis of RSO is presented in table 2-7. This analysis was obtained from the refinery splitter bottoms by mass spectrometry (MS) (reference 2-1). Although this analysis indicates a somewhat different breakdown between saturates and aromatics than that shown in table 2-3, both tables illustrate the same general distribution of hydrocarbons in RSO. Straight chain and cyclic paraffins comprise approximately 60 percent of hydrocarbons. These saturates have the lowest carbon-to-hydrogen ratio and, therefore, have high autogeneous ignition characteristics. Aromatic and polyaromatic compounds comprise the remaining 40 percent. These compounds are derivatives of benzene and do not have the compression ignition quality of the paraffins (reference 2-9).

In general, paraffins and cycloparaffins are known to have better self-ignition properties than the aromatics. Aromatic and olefin

Table 2-7. RSO Splitter Bottoms Hydrocarbon Type Analysis by Mass Spectrometry (Reference 2-1)

Hydrocarbon Type	Weight Percent
Paraffins	30.8
Cycloparaffins	
1 Ring	15.4
2 Ring	6.4
3 Ring	4.6
4 Ring	3.2
5 Ring	1.3
6 Ring	1.1
Total Saturates	62.9
Aromatics	
Alkyl Benzenes	13.0
Naphthene Benzenes	11.5
Dinaphthene Benzenes	3.4
Naphthalenes	3.3
Acenaphthenes, Biphenyls	0.2
Acenaphthylenes, Fluorenes	2.2
Phenanthrenes, Anthracenes	1.8
Naphthene Phenanthrenes	1.2
Pyrenes	0.1
Chrysenes	0.4
Perylenes	--
Dibenzo Anthracenes	--
Benzothiophenes	--
Dibenzothiophenes	--
Naphthobenzothiophenes	0.3
Total Aromatics	37.1

saturation was accomplished in processing RSO, which tends to increase the cetane rating by converting aromatics and olefins to paraffins. The cetane number is dependent on the paraffin/aromatic distribution to some extent and, as indicated below, evidence suggests it is also dependent on Conradson Carbon Residue (CCR)/asphaltene content. Figure 2-4 shows the normal boiling curves of the major constituents of RSO, the alkanes (paraffins), alkyl cyclopentanes (cycloparaffins), and alkyl benzenes (aromatics). From table 2-3, the 10 percent distillation point is 590^{0}F. Therefore, 90 percent of the hydrocarbons contained in the RSO have 16 carbon atoms or more, including the alkyl benzenes. This is important when comparing the normal boiling curves versus cetane number, as shown in figure 2-5. This figure indicates the dependence of cetane number on carbon number and structural complexity. It also indicates that most of the aromatic hydrocarbons (i.e., those with inherent low cetane numbers) have a cetane number greater than 40. In general, cetane improves with increasing number of carbon atoms but decreases with increasing structural complexity (reference 2-10). Data for cetane versus boiling point for the remaining hydrocarbon families listed in table 2-5 are unavailable. These constituents make up an increasingly smaller part of the RSO as a whole, but their contribution to cetane appears sufficient to keep the overall cetane number at 48 (reference 2-11).

A direct quantitative comparison of the cetane ratings of RSO and petroleum residuals is unavailable, mainly due to lack of information concerning the cetane rating of the petroleum residuals; however, the slow burning and poor ignition qualities of fuels containing asphaltenes and having high carbon residue are known qualitatively (references 2-2 and 2-4). Additional information for comparison is probably not forthcoming

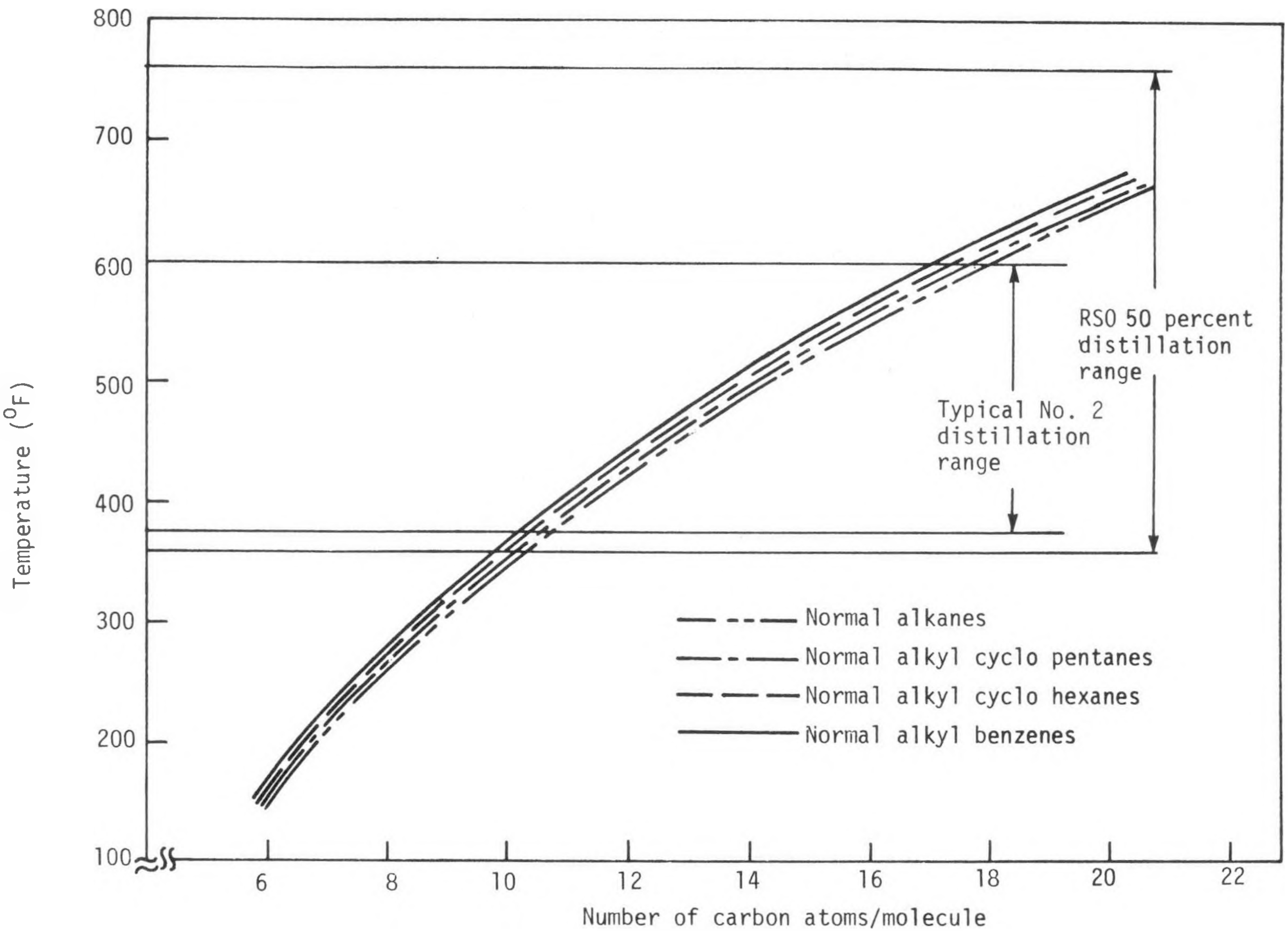


Figure 2-4. Approximate Boiling Curves of Various Hydrocarbon Families Contained In RSO (Reference 2-10)

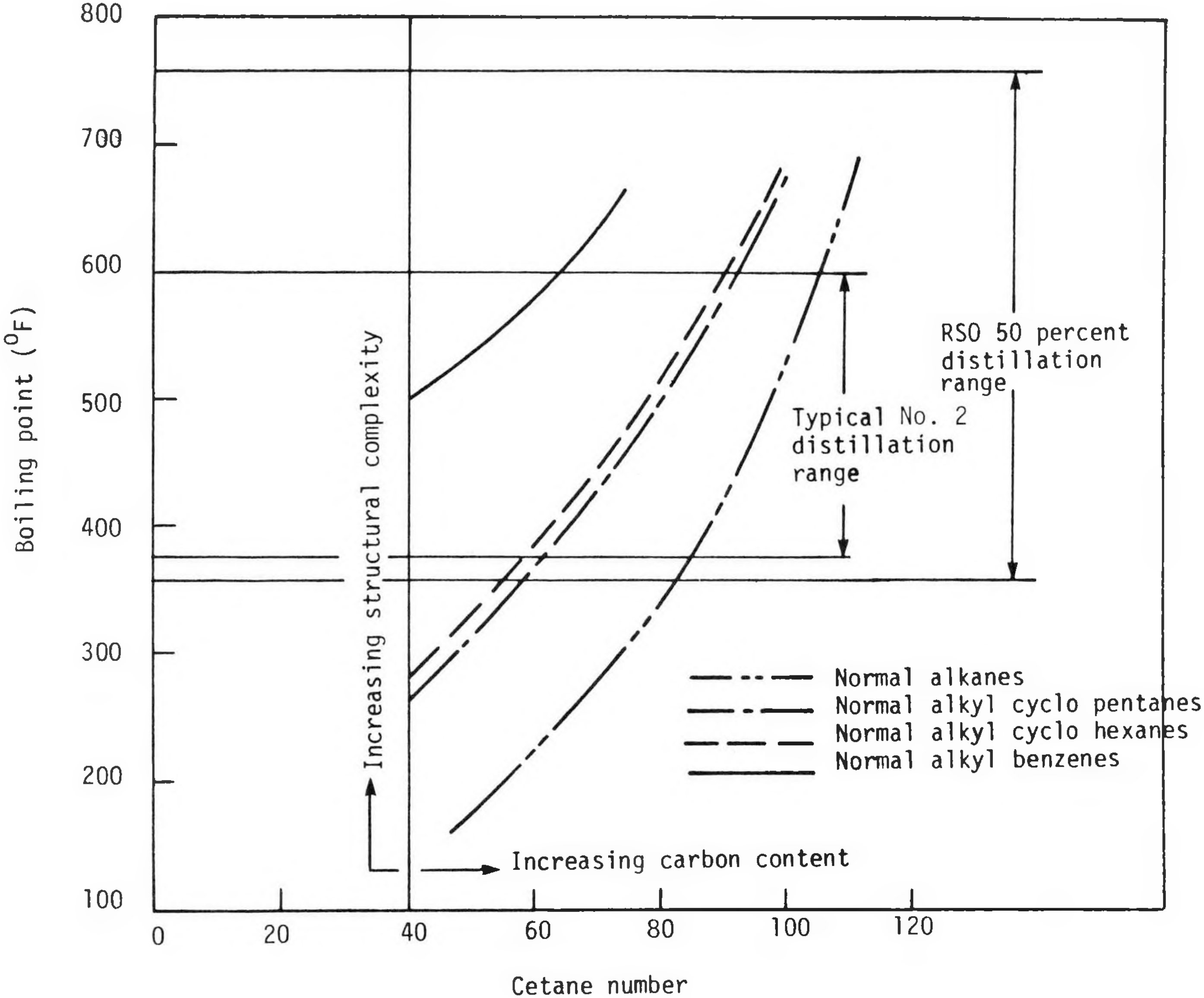


Figure 2-5. Boiling Points at Standard Pressure Versus Cetane Number for Various Hydrocarbon Families (Reference 2-10)

as the engines that burn the petroleum residuals are operating successfully on fuels with 4 to 15 percent carbon residue (reference 2-5).

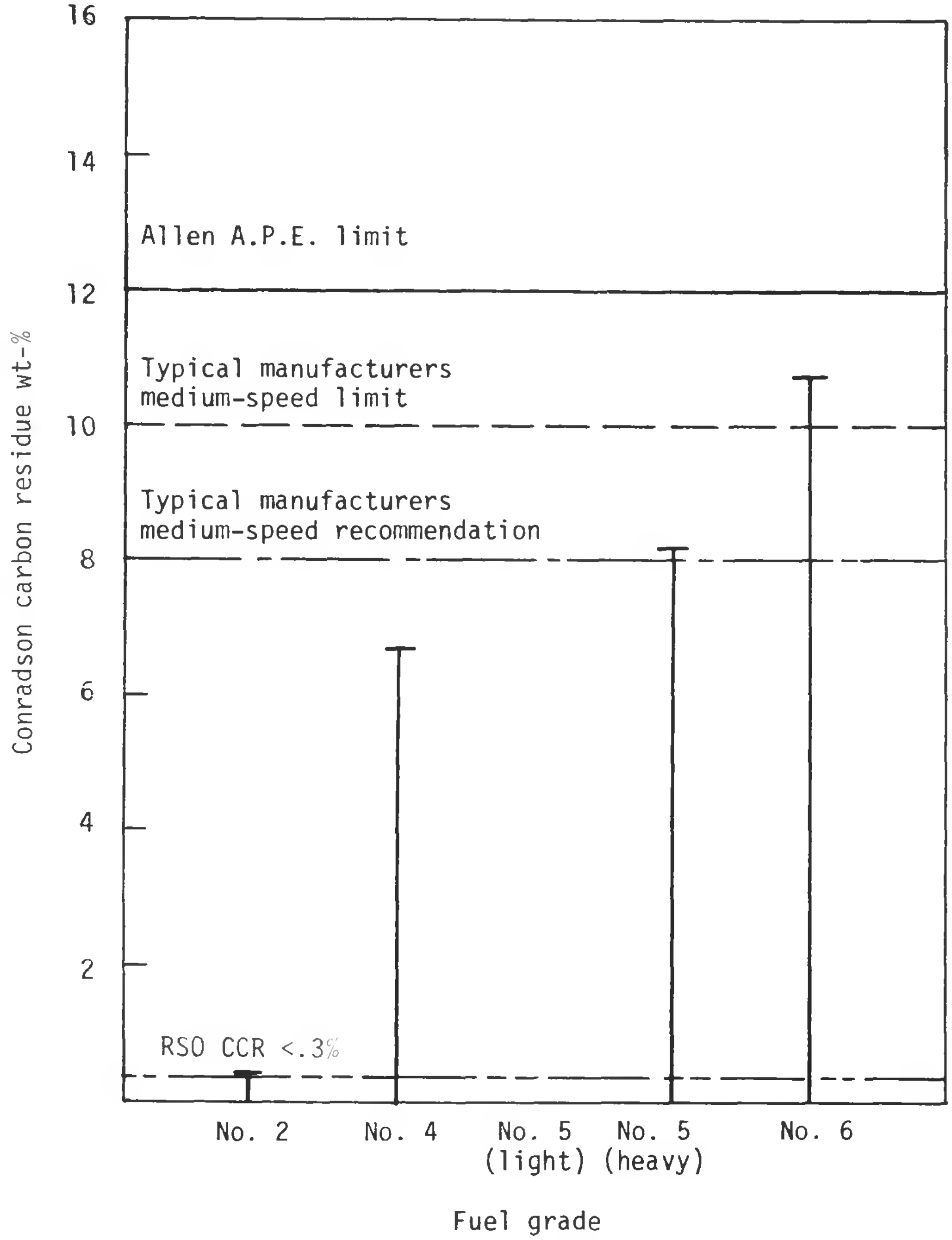
Carbon Residue/Asphaltenes

As already indicated, RSO has some exceptional properties compared to normal petroleum residuals due mainly to the low carbon residue and asphaltene content. These constituents of fuels are important in the successful operation of a diesel engine. Figure 2-6 summarizes the ranges of carbon residue for various grades of fuels and includes manufacturers limits.

CCR gives a rough indication of the deposit and wear behavior of a fuel. Asphaltenes, which are high molecular weight hydrocarbons, contribute extensively to deposits and abrasion. CCR percentage in RSO is less than 0.3 percent, placing RSO at the top of the No. 2 specification limits and well below the recommendation (8 percent) of the engine manufacturers. A direct correlation between CCR and engine wear, carbon deposit formation and nozzle coking problems does not exist; however, problems with RSO are expected to be closer to those with a No. 2 diesel fuel than to a No. 4, 5, or 6 fuel oil, i.e., CCR is more representative of a No. 2 fuel.

Contaminants

Sulfur levels are of concern in diesel engines as compounds containing this element are known to cause low temperature corrosion, leading to cylinder liner and piston wear. This element is not at problem-causing levels in RSO, mainly as a result of hydrotreating. RSO sulfur levels are less than the specification limits for a No. 2 fuel and are far below engine manufacturers recommended and absolute limits. A summary of the sulfur levels are presented in figure 2-7. Note that the



Note: Based on U.S. fuels (reference 2-7)

Figure 2-6. Conradson Carbon Residue Versus Fuel Grade

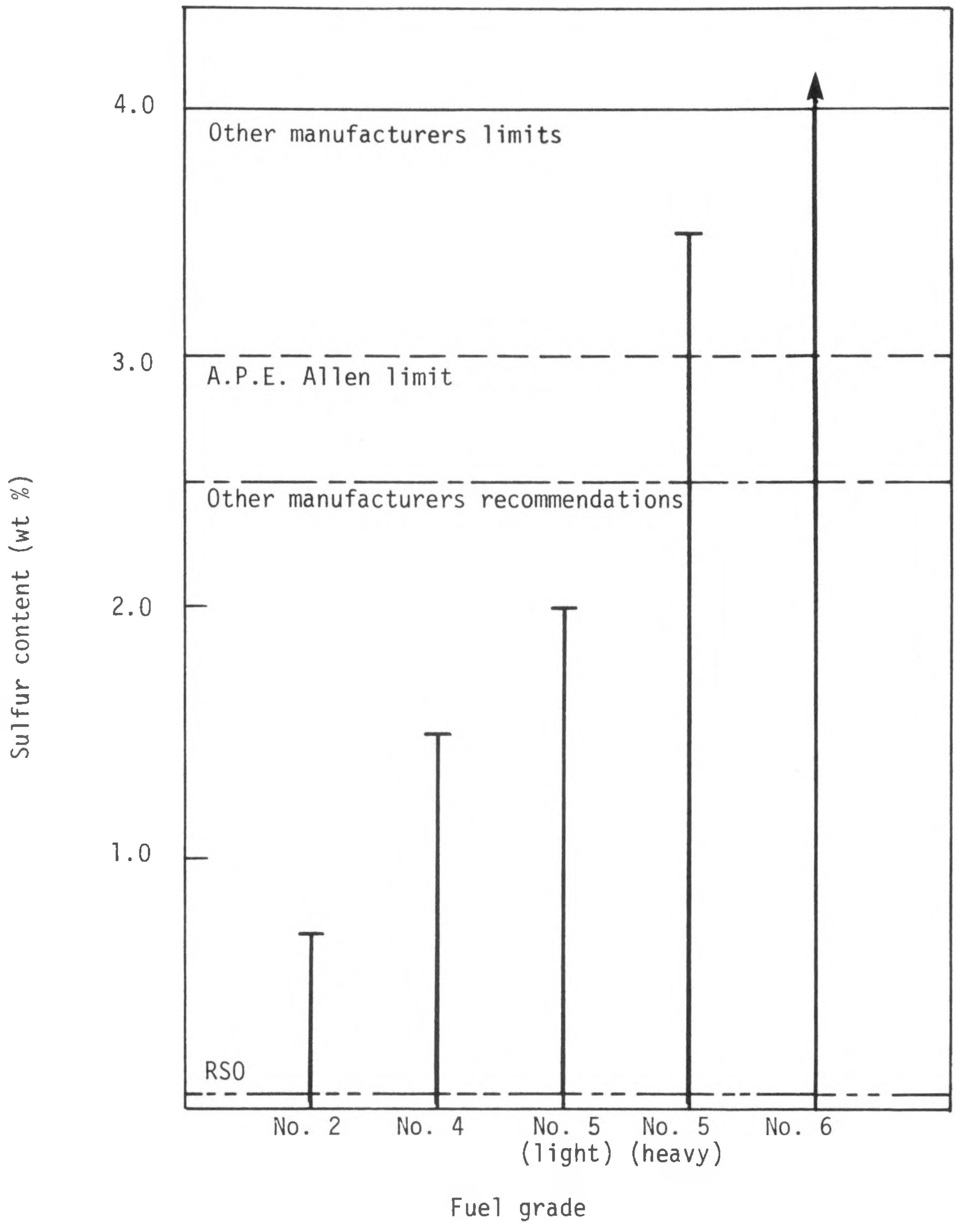


Figure 2-7. Summary of Typical Sulfur Ranges for Various Grades of Fuel

sulfur levels reported on the test fuel are considerably larger than the original measurements on the RSO product.

The levels of sodium and vanadium in the RSO are sufficiently low that diesel operation on this fuel should not suffer. Typically, engine manufacturers recommend that vanadium levels be as low as possible, with 200 ppm as an upper limit. Sodium control is recommended where levels are high; however, levels found in RSO are low enough that treatment is unnecessary. The levels of sodium in the RSO are actually within the No. 2 specification range. Measures normally taken to combat these problems, such as the use of special valve and seat materials and derating to reduce exhaust temperatures, should not be necessary.

BS&W/Ash

Particulate and water make up a total of 0.25 percent of the RSO by volume and are of concern to the erosion of fuel nozzles. Typically, upper limits on this fuel property are around 2 percent for a petroleum residual. The RSO has about twice as much particulate as a No. 2 fuel and would be expected to cause more wear as a result. The levels of particulate could be reduced by centrifuging or filtering to achieve a level closer to that of a No. 2 fuel.

Ash content in a fuel is an indicator of both solid, foreign material and dispersed organic metals such as vanadium, sodium, and nickel in the fuel. The latter form ash on combustion. Also included in ash are the polymerizea hydrocarbons (tars), which are not very stable. Ash deposits are responsible for localized overheating, abrasion, and plugging. Their deposits also provide convenient initiators for corrosion from sulfur and vanadium compounds. Ash levels above 0.1 percent are of general concern, this being the specification limit for Nos. 4 and 5 fuels. Again, the RSO is more similar to a No. 2 fuel in ash content as levels are below 0.01 percent.

Heat of Combustion

The heat of combustion (Btu/lb) for RSO is comparable to that of petroleum diesel fuels; however, an apparent decrease in fuel consumption can be realized from the utilization of fuels with lower API gravity. Analyses of the effects of the different heats of combustion in a medium-speed diesel have been done. The results indicated a 2.2 percent increase in specific fuel consumption (lb per horsepower hour) when switching from a 32 ^{o}API fuel to a 16 ^{o}API fuel. This fuel change accounted for approximately 8 percent more pounds per gallon. Engine efficiency was unaffected (reference 2-5). It should be pointed out that the results are engine-specific, and it is unclear whether performance adjustments (e.g., reduction of brake mean effective pressure) required for utilization of heavier fuels in other engines would enable users to realize a fuel savings from a consumption standpoint.

Summary

To summarize, RSO appears to be a relatively clean fuel suitable for use in medium-speed diesel engines. In fact, the major fuel properties of concern in the operation of a diesel engine are more representative of a No. 2 fuel than a normal petroleum residual. Those properties of RSO which are significantly less desirable are mainly of concern to the handling and injection systems. These deficiencies are easily controlled or modified in the fuels treatment system. Heating and purification of RSO will result in a fuel very similar to a No. 2 diesel. If RSO can be produced at a competitive price, there should be the potential for a viable market as a diesel fuel.

2.3 RSO AVAILABILITY PROJECTIONS

The use of synthetic fuels (fuels which are not petroleum based) as substitutes for DFM is not presently feasible since the synthetic fuels industry, which includes tar sands, coal gasification and liquefication, and shale oil, has not yet advanced to commercial-size operations. Therefore, the composition of industrial synthetic fuels and projections of their availability remain somewhat speculative. Estimates of the projected size of the synthetic fuels industry range from the equivalent of a few hundred thousand barrels per day to several million barrels of crude oil by the 1990's (references 2-12, 2-13, and 2-14).

Of the several synthetic fuel technologies under consideration as direct substitutes for large volumes of liquid fuels, the shale oil technology is perhaps the closest to commercialization in the U.S. Shale oil products will most likely be used as transportation fuel, while coal-derived liquid fuels are used in utility and industrial boilers, and coal gas in commercial, residential, and industrial heating applications.

Syncrudes obtained from shale oil and upgraded by hydrotreatment are well suited for refining into middle distillates and as the demand for transportation fuels increases, it is likely that shale-dedicated refineries will produce significant amounts of these fuels. The majority of shale distillates will be consumed by the military in the near term, with the possibility of a government synfuel purchase guarantee program (reference 2-5).

As a result of the military's interest in shale oil as well as plans to direct the U.S. away from dependence on foreign oil, several companies are undertaking shale oil projects. These are summarized in table 2-8. The marketability of RSO produced from these programs is

Table 2-8. U.S. Oil Shale Projects (Reference 2-15)

Project	Location[a]	Technology	Production Capacity Goal (bbl/day)	Status
Chevron	Piceance Basin	Undecided	50,000	Technical assessment phase
Colony (TOSCO, Exxon C)	Parachute Creek	Surface retorting	47,000	Construction of commercial modules scheduled for 1980
Equity Oil	Piceance Creek	Solution injection, modified in-situ	--	Steam injection feasibility
Geokinetics, Inc.	Unitah County	Horizontal modified in-situ	7 to 13 2,000 to 5,000	Several small retorts successfully operated; work on larger retorts in progress
Getty Oil	Piceance Basin	Surface thermal extraction	--	Getty R&D proposal being considered by DOE
Mobil	Piceance Basin	Undecided	50,000	May start module in 1987
Occidental Oil	Logan Wash	Vertical modified in-situ	70,000	Six retorts operated; 48,000 barrels produced. Retorts 7 and 8 scheduled for cluster burn
Occidental Oil (Tenneco)	Tract C-b, Piceance Basin	Vertical modified in-situ	57,000	Shaft sinking in progress; construction of initial retorts scheduled for 1982

[a]State locations: Piceance Basin - Colorado, Parachute Creek - Colorado, Unitah County - Utah, Logan Wash - Colorado, Anvil Points - Colorado

Table 2-8. Concluded

Project	Location[a]	Technology	Production Capacity Goal (bbl/day)	Status
Paraho (Development Engineering Inc.)	Anvil Points	Surface retorting	150 to 200	Shut down due to lack of funding; 88,225 barrels produced over about a one year period
Rio Blanco (Gulf, Amoco)	Tract C-a, Piceance Basin	Vertical modified in-situ, surface retorting	50,000	Modular program consisting of 5 retorts scheduled for completion by 1982
Superior Oil	Piceance Creek	Multimineral recovery, surface retorting	13,000	Company seeking land exchange with Federal Government which was denied in February 1980
TOSCO-Sand Wash	Uintah Basin	Modified in-situ, surface retorting	50,000	Feasibility studies in progress
Union Oil	Parachute Creek	Surface retorting	50,000	Construction of experimental mine and plant scheduled for 1982
White River (Sohio, Sunoco, Phillips)	Tracts U-a and U-b, Unitah Basin	Modified in-situ, surface retorting	100,000	Opeations suspended due to legal proceedings on ownership of lands

[a]State locations: Piceance Basin - Colorado, Parachute Creek - Colorado, Unitah County - Utah, Logan Wash - Colorado, Anvil Points - Colorado

dependent on the production costs. An argument for a valid market for RSO could be made if its selling price could be maintained somewhere between that of a normal petroleum residual and a No. 2 diesel. This would allow individual users to assess whether they could replace their current No. 2 fuel with RSO for a slight increase in maintenance and fuel treatment. Another market may be those users with unacceptable down-time due to increased maintenance related to operation with normal petroleum residuals. Here the user might be willing to accept an increase in fuel costs in return for an increase in the meantime between repairs for fuels-related problems.

The demand for residuals and blended fuels has increased during the last decade relative to distillates (reference 2-2), indicating further that commercially produced RSO may be in demand. Since fuels problems generally increase with decreasing quality, higher quality residuals are usually highest in demand. However, in the near term, finished specification-quality commercial synfuels may not differ significantly from today's fuels since suppliers may blend shale-derived syncrudes with dominant petroleum crudes at conventional petroleum refineries rather than produce commercial-grade synfuels at dedicated syncrude refineries. That way, undesirable compounds such as long-chain olefins and aromatics can be diluted to acceptable levels by blending with petroleum feedstocks (reference 2-16). The economics of production and demand should dictate the appropriate strategy.

Synfuel Availability Projections

On July 15, 1979, President Carter announced plans to decrease the U.S. dependence on imported oil which in part called for the investment of $88 billion in synfuel projects over the next decade. In mid-1980, President Carter signed into law the Energy Security Act which projected a synfuel production rate of 2.2 million bbl/day by 1992; of this quantity, shale oil production was earmarked at 400,000 bbl/day by 1990.

Several shale oil projects plan to begin operation during the 1980's. The retorting technologies, which are proprietary in many cases, have been demonstrated at pilot scale or larger, and appear sufficiently mature for commercialization. Geokinetics, Inc., Occidental Oil, Paraho, Union, and TOSCO have successfully operated several noncommercial retorts. Colony, Union Oil, and Occidental Oil have announced plans to begin commercial development in the 1980's.

Figure 2-8 shows the Department of Energy's (DOE) estimated cumulative production of shale oil projected for existing and currently proposed shale producers (reference 2-16). If all the projects come on line as projected, the production of shale oil will meet the goals set by President Carter. Oil-shale-derived synfuels will be introduced into the petroleum fuel market about 1985; based on figure 2-8, as much as 0.2 million bbl/day of shale oil can enter the market by 1987.

The synfuels market will initially target transportation fuels because hydrotreated shale oil can be refined at existing refineries into gasoline, jet fuel, diesel fuel, and marine fuels; the bulk of this supply will be middle distillates (i.e., jet fuel and diesel oil). The demand for transportation fuels during the late 1980's is expected to be around 10 million bbl/day. Of this, about 5 percent is likely to be consumed by the military sector. Projections for the shale oil industry are for continued growth to as much as 0.45 million bbl/day (or even 0.9 million bbl/day) by 1990.

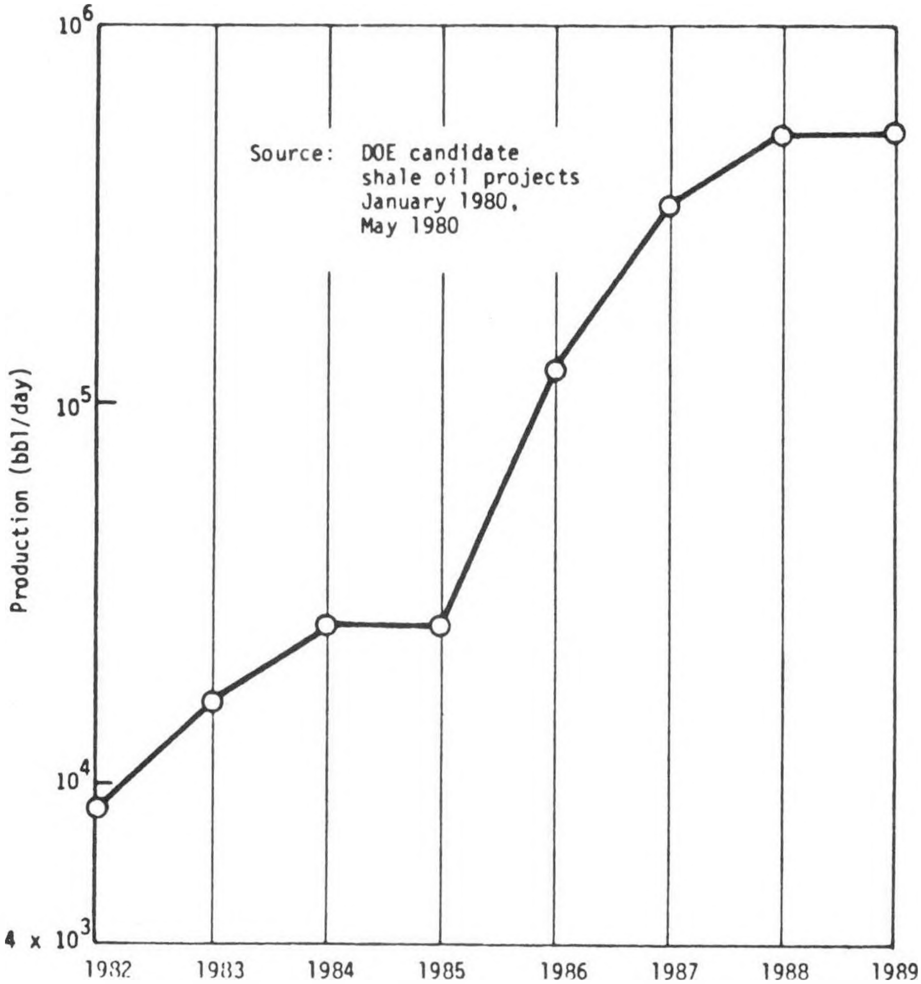


Figure 2-8. Department of Energy Projected Shale Oil Production

The production rate of 400,000 bbl/day by 1990, however, is subject to debate. Estimates from the U.S. Department of Energy (reference 2-17) and from the Congressional Office of Technology Assessment (OTA) (reference 2-12) place production anywhere from 200,000 to 2,000,000 bbl/day in 1990. These estimates come from a number of different scenarios, incorporating various capital costs, rates of technology development, legislative and tax incentives, environmental controls, natural resources availability, and socioeconomic considerations.

Estimates of a break-even price for shale oil depend on the real rate of return required on investment, cost of money, effective tax rates, etc. OTA computer simulations estimate the price of shale syncrude must attain $48 and $68 per barrel in 1979 dollars to achieve real, after tax rates of return of 12 and 15 percent, respectively. A March 19, 1981, article in Engineering News Record stated that, according to a report by the Congressional Research Service, even if the price of oil rises to $100 per barrel, a newly constructed synthetic fuels plant would not be economical. Therefore, the economics of competing energy sources, namely petroleum crude, have a significant impact on the prospects of synfuel development.

Other uncertainties and unknowns may constrain the development of the shale syncrude/synfuel industry, including:

- Availability of skilled manpower: the supply of engineers and construction labor will be severely taxed to meet the synfuel production goal set by President Carter.
- Availability of critical equipment: compressors, heat exchangers, and pressure vessels are expected to be in short supply unless corrective measures are taken now.
- Diversion of investment to competing technologies: demand on the limited available capital by competing energy supply technologies, such as coal liquefaction, coal gasification, and geothermal and solar technologies, could slow the build-up rates for shale oil technologies.
- Environmental data: environmental data are lacking for necessary regulatory approvals.

- Licensing: construction schedule constraints imposed by state and federal licensing and permitting requirements could hinder the synfuel industry build-up rate.
- Ecological concerns: state and municipal resistance to the spoiling of pristine open areas could limit synfuels expansion.
- Technology: some technologies are still considered developmental, such as the modified in-situ process.
- Land problems: the acquisition of off-tract disposal sites may take time to resolve.
- Water: the availability of this natural resource is critical to shale oil production.

Synfuel Summary and Conclusions

Pilot-scale plants have demonstrated the capability not only for extracting oil from shale but for refining products as well. Middle distillate fuels of good quality have been produced from syncrude, including near-specification DFM. Although the physical properties of products derived from shale oil during commercial scale production remain uncertain, syncrude from shale probably will have to undergo pretreatment of some kind to eliminate undesirable compounds before refining. Further upgrading will be required to obtain specification-quality fuels.

The availability of synfuels is uncertain, various scenarios predicting anywhere from 200,000 to 2,000,000 bbl/day. If the national goals set by President Carter in 1979 are met by 1990, the U.S. will have a 400,000 bbl/day shale oil industry producing middle distillate products. However, a number of significant concerns must be addressed if a synfuel industry is to come to fruition.

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SECTION 3

ENGINE APPLICATION AND DESCRIPTION

The incentive for the utilization of heavier fuels (grades 4 to 6) for medium-speed diesel engines has come mainly from the European marine industry. This industry has historically opted for slow- (approximately 75 to 300 rpm) and medium-speed (approximately 300 to 1,200 rpm) diesels as the main propulsion and auxiliary engines for ships. Since it is economically advantageous to have the auxiliary engine burn the same fuel as the main propulsion engine, European engine manufacturers have worked towards producing more fuel-tolerant medium-speed engines (reference 3-1).

The situation has been different for U.S. manufacturers. Operators of large U.S. vessels have relied mainly on steam powerplants for main propulsion. These power plants commonly burn residual fuel oil which is unsuitable for use in medium-speed engines. Coupled with the general availability of high quality distillate fuels, there has been little incentive for relaxing of fuel requirements for U.S. medium-speed engines. A review of the literature reveals only one U.S. engine manufacturer, Caterpillar, having an engine (<2500 HP) capable of burning blended (No. 4) fuels (reference 3-2).

Recent declines in distillate fuel quality, increases in distillate fuel costs, and interest by U.S. firms in purchasing foreign medium-speed engines have caused U.S. engine manufacturers to reevaluate their markets, resulting in development of more fuel-tolerant engines. Most large U.S. engine manufacturers are now introducing their versions of more fuel-tolerant engines (reference 3-3).

3.1 OPERATION OF MEDIUM-SPEED ENGINES ON HEAVIER FUELS

Extensive data are available concerning the operation of European medium-speed engines on heavier fuels. These operations data indicate satisfactory engine performance can be realized from fuels with viscosities as high as 400 cst (at 122^{o}F) and sulfur content as high as 4 percent (reference 3-4).

Most heavier fuels are cleaned with centrifugal purifiers to remove particulate and water before being fired in diesel engines. Also, proper fuel atomization requires the fuel be heated to a point where the viscosity is below 25 cst.

Lube oil treatment can also determine to a large extent the success or failure of medium-speed engines on heavier fuels. The total base number (TBN) of the lube oil is adjusted according to the sulfur levels of the fuel by using slightly alkaline motor oils. Control of TBN can significantly affect maintenance levels by controling the sulfuric acid created in combustion. A summary of the effects of lube oil alkalinity and fuel sulfur content is presented in figure 3-1.

Centrifugal purification and lube oil treatment were not necessary for the fuel utilized in this program because sediment, water, and sulfur levels of the as-received fuel are much lower than values typical of petroleum residual fuel (see section 2).

The actual combustion conditions also play a key role in heavy fuel operation. When firing heavy fuel, maximum load is usually limited to 90 percent of the maximum continuous rating (MCR) for distillate fuel.

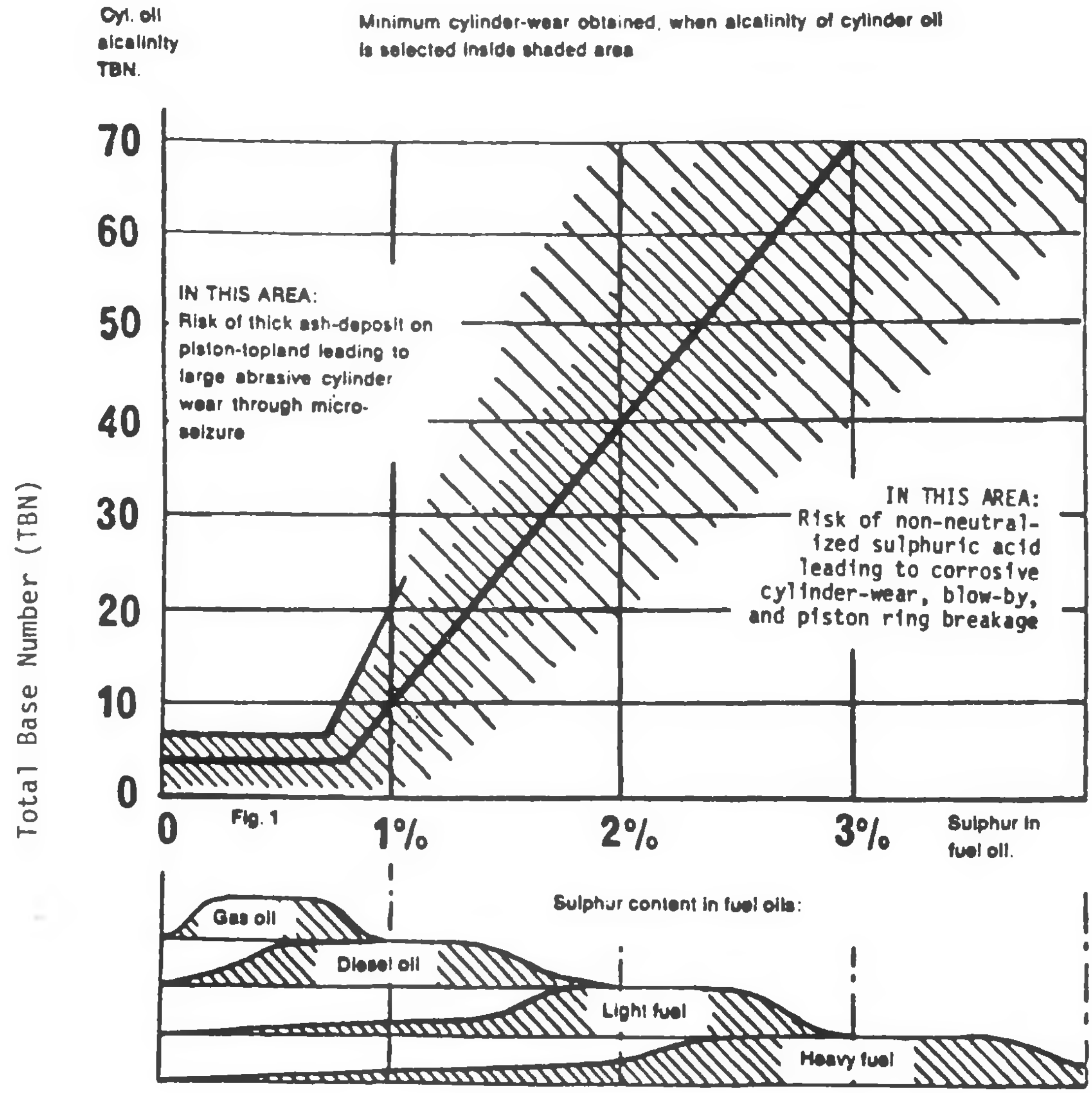

Figure 3-1. Relationship Between TBN and Fuel Concentration of Sulfur (Reference 3-5).

This is because heavy fuels cause higher combustion temperatures than distillate fuels, which can lead to valve overheat.

Similarly, low power levels (under 50 percent MCR) reduce available compression ignition pressures as well as engine temperature. This leads to incomplete combustion and formation of soot and gums which deposit on engine surfaces, causing scarring and poor heat transfer. As a result of these problems, the general consensus is that power levels for medium-speed diesels firing heavy fuel must be maintained between 40 and 90 percent of the MCR rating on distillate fuels (reference 3-4).

In addition to these operational measures, European engine manufacturers have incorporated design features that ease problems which would normally be associated with heavier fuels. Engines designed for heavier fuel operation are normally turbocharged with charge aftercooling. Turbocharged engines have higher air flow rates which allow for more complete combustion than in naturally aspirated engines. Aftercooling also increases the charge density by lowering the charge temperature. Turbocharged engines operate at higher output levels than normally aspirated engines which increase combustion intensity. The effects of turbocharging and aftercooling on engine performance are summarized in table 3-1 for a typical diesel engine.

Medium-speed engines firing heavy fuel are also commonly equipped with water-cooled fuel injector nozzles to prevent coking and deposit formation at the elevated temperatures required for proper atomization. In most applications cylinder liners are the wet type to facilitate heat transfer, rather than the dry type which require heat conduction through two metal surfaces.

Table 3-1. Effect of Turbocharging and Aftercooling on Brake-Specific Fuel Consumption (BSFC) and Brake Horsepower (BHP) of Diesel Engines (Reference 3-2)

ENGINE TYPE	1,400 rpm		Best BSFC and rpm
	BSFC (lb/hp-hr)	BHP	BSFC (lb/hp-hr)
Normally aspirated	0.380	156	0.380 at 1,500
Turbocharged	0.353	250	0.344 at 1,575
Turbocharged and aftercooled	0.347	285	0.338 at 1,700

Finally, exhaust valves are subject to the most severe combination of stress and heating and must withstand creep, corrosion, and thermal shock, each of which are more troublesome with the higher combustion temperatures associated with heavier fuels. Exhaust valves are made from austenitic steel coated with high strength facings at the valve seat. Many engines are designed with two exhaust valves per cylinder to further reduce valve heat. Valve rotators are commonly applied to even out loading (reference 3-4).

The cooling of engine components is a major area of concern with heavy fuel operation. Features introduced to improve engine cooling include the previously mentioned fuel injector cooling and direct cylinder liner cooling, as well as exhaust valve and piston oil cooling. Improved piston cooling is accomplished by oil jets which spray the piston bottom on each stroke, and the dripping oil cools the piston connecting rod and rings.

3.2 U.S. APPLICATIONS FOR MEDIUM-SPEED DIESELS OPERATING ON HEAVY FUELS

The first U.S. medium-speed diesels capable of burning heavier fuels are being placed in marine vessels as both main propulsion and auxiliary engines. Furthermore, although the marine industry is currently depressed, future commercial and military starts incorporating diesel engines will likely use the more fuel-tolerant designs (references 3-3).

Stationary applications include cogeneration facilities, oil and gas pumping stations, agricultural pumping facilities and small base-load, power-generating facilities. These applications are ideal for fuel-tolerant, medium-speed engines as they have a constant load profile and fuels handling systems are not space-limited (references 3-6, 3-7).

The application of heavy-fueled, medium-speed diesels to the land-based transportation segment is unlikely. These applications are characterized by frequent load fluctuations, which is undesirable with heavier fuels and medium-speed engines. An exception here is locomotive propulsion; recent studies indicate diesels with greater fuels capability are desirable for this industry (reference 3-8).

The current engine market as viewed by Diesel and Gas Turbine Progress (reference 3-9) is that:

- Demand for locomotive diesels will remain slow but steady.
- Marine demand is generally slow, military starts may have an effect on this.
- Demand in the oil and gas industry is increasing rapidly but will taper off within a few years.
- Topping and standby units for utilities will be in greater demand due in part to predicted peak shortages and shortages of reserve predicted for the 1980's.

- Cogeneration systems are expected to escalate rapidly, bringing a high demand for these engines in this application.

Apparently a market is available in the U. S. for medium-speed diesels capable of burning heavier fuels.

3.3 TEST ENGINE DESCRIPTION

The testing of RSO undertaken in this program was accomplished in a European-made APE Allen S300 six-cylinder engine. The S300 is the predecessor of the S12-G engine and the commercially available S12-F. Allen engine nomenclature consists of a series designation (in this case 'S') followed by the stroke length of the engine (i.e., S12 refers to 12-in. stroke, similarly S300 refers to 300 mm stroke); the final character (i.e., F or G) represents the current commercially available model. The S300 is a four-stroke, turbocharged, compression ignition, aftercooled engine. The commercially available S12-F is available in four, six, eight, or nine cylinders with brake horsepower ratings from 644 to 1,440 at 750 rpm. A summary of the APE Allen families of small medium-speed diesels is presented in table 3-2, along with various current models from U.S. manufacturers that would be considered competitors. Table 3-3 displays a few of the characteristics of these engines.

The S300 incorporates both standard and water-cooled fuel injectors to allow for dual-fuel operation during the RSO test. The nozzles are long stem with a 150^{0} spray angle and 0.0169 in. (0.43 mm) hole diameter. The fuel pumps are flange-mounted at the top of each cylinder and contain one plunger with a roller tappet and a 0.787-in. (20 mm) element diameter. The nozzle holders are 10.83 in. (275 mm) and are either water-cooled or uncooled.

The cylinder liners used in the S12-F are centrifugally cast from iron and are the wet type. The pistons are cast from aluminum, with an iron retaining carrier for the top ring.

Exhaust valves are equipped with rotators, and are made from austenitic steel incorporating high strength facings at the valve seat. The exhaust valves are mounted two per cylinder and seated on replaceable nickle-iron inserts.

The S families incorporate ample turbulent water flows to facilitate engine cooling; liners are directly cooled, and the valve seats are indirectly cooled. Oil jet cooling is utilized for the pistons.

Experience has shown that the S12-F engines are capable of burning heavier fuels, with current applications ranging from heavy fuel burning on board ships to the burning of crude oil being transferred in pipelines. As a result of this success, APE Allen has established facilities in the U.S. and is planning to sell 200 to 400 of their engines per year.

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3-6. Wilkinson, B. W. and R. W. Barnes, "Cogeneration of Electricity and Useful Heat," CRC Press, 1980.

3-7. "Stationary Internal Combustion Engines," EPA, 1978.

3-8. Bonzo, B. B., et al, "Future Propulsion Systems for Railroad Locomotives," Phase B Report, Advanced Diesel Engines and Alternative Fuels, Jet Propulsion Laboratory, December 1979.

3-9. Private communication, Rob Wilson, Diesel Progress Magazine, 10/1/81.

Table 3-2. Comparison of Various Competing Diesel Engines By Manufacturer

Manufacturer	Engine Series	No. of Cylinders	Rated BHP	Speed (rpm)
APE Allen	S12-D	3	387	750
		4	516	750
		6	774	750
		8	1,032	750
		9	1,161	750
	S12-F	4	708	750
		6	1,062	750
		6	1,416	1,000
		8	1,888	1,000
		9	2,124	1,000
Electromotive Division of General Motors (GM EMD)	645 E7B	8	1,462	900
		12	2,225	900
		16	2,976	900
Alco	6D251	6	1,350	1,100
	8F251	8	1,820	1,100
	12E251	12	2,675	1,100
	16E251	16	3,200	1,100
Fairbanks Morse Division of Colt (FM Colt)	38D8-1/8	6	1,750	750
		9	2,625	750
		12	3,500	750
Caterpillar	D353	6	425	1,225
	D379	8	565	1,225
	D398	12	850	1,225
	D399	16	1,125	1,225

Table 3-3. Summary of Engine Characteristics (Reference 1, 4)

Engine Type	Manufacturer	Series	Charging[a]	Bore/ Stroke (inches)	Compression Ratio	Valving Inlet/Exhaust	Injection Method	Rpm
Four-Stroke	APE Allen	S12-D	TC, AC	9.5 x 12	--[b]	Valved/Valved	Direct	750
Four-Stroke		S12-F	TC, AC	9.5 x 12	--[b]	Valved/Valved	Direct	750
Two-Stroke	GM EMD	645 E7B	TC or BS	9.1 x 10	16.0:1	Ported/Valved	Direct	720-900
Four-Stroke	Alco	251	TC, AC	9.0 x 10.5	11.5:1	Valved/Valved	Direct	1,100
Two-Stroke	FM Colt	38D 8-1/8	BS	8.1 x 10	16.1:1	Ported/Ported	Direct	750
Four-Stroke	Caterpillar	D353	TC, AC	6.25 x 8	15.5:1	Valved/Valved	Indirect	1,300
		D379	TC, AC	6.25 x 8	15.5:1	Valved/Valved	Indirect	1,300
		D398	TC, AC	6.25 x 8	15.5:1	Valved/Valved	Indirect	1,300
		D399	TC, AC	6.25 x 8	15.5:1	Valved/Valved	Indirect	1,300

[a]TC = Turbocharged, AC = Aftercooled, BS = Blower Scavenged
[b]The compression ratio of the S300 model is 12:1

SECTION 4

TEST SETUP

The test set-up consists primarily of the engine, the fuel system and instrumentation. The engine is described in section 3, and shown in Ricardo's large engine test shop (figure 4-1). This facility features separate test stands and control rooms for two engines which may be tested simultaneously. Figure 4-2 presents a plan view of this facility.

The following subsections describe the fuel system and instrumentation setup.

4.1 FUEL SYSTEM

To fulfill the fuel supply requirements of the various testing modes described in section 1, a free-standing module was designed and constructed to perform the following functions:

- Supply a homogenous blend of RSO and standard diesel, the RSO content being accurately maintained at any desired value between 50 and 100 percent.
- Heat both fuels before blending and maintain the supply to engine at a preset temperature.
- Provide adequately filtered recirculating fuel supplies to three discrete fuel injection systems on the engine during various modes of testing, as shown in table 4-1.

Table 4-1. Fuel Supply Requirements

Test Mode	Cylinder No. 6		Cylinder No. 1-5
	Main Injector	Pilot Injector	Main Injectors
Baseline	SD		SD
Go/No-Go Tests Blended Fuel	B		SD
Go/No-Go Tests Pilot Injection	RSO	SD	SD
Go/No-Go Tests Dual Rate Inj.	RSO	RSO	SD
Performance Tests (6 cylinders)	B		B
Startup and Shutdown	SD	SD	SD

SD = Standard Diesel Fuel
RSO = Residual Shale Oil
B = Blend of SD and RSO

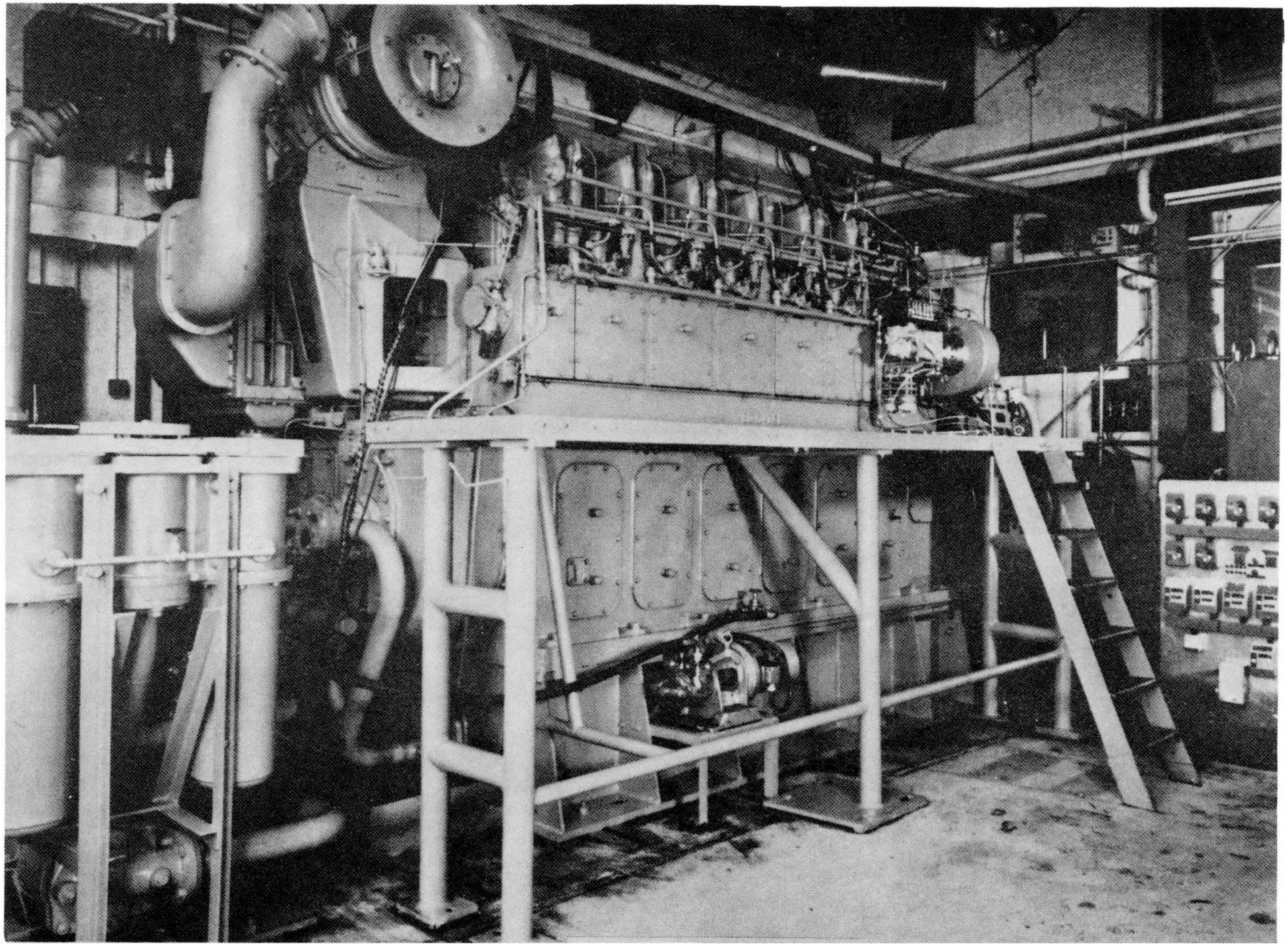


Figure 4-1. APE Allen Engine Set-Up in Test Cell

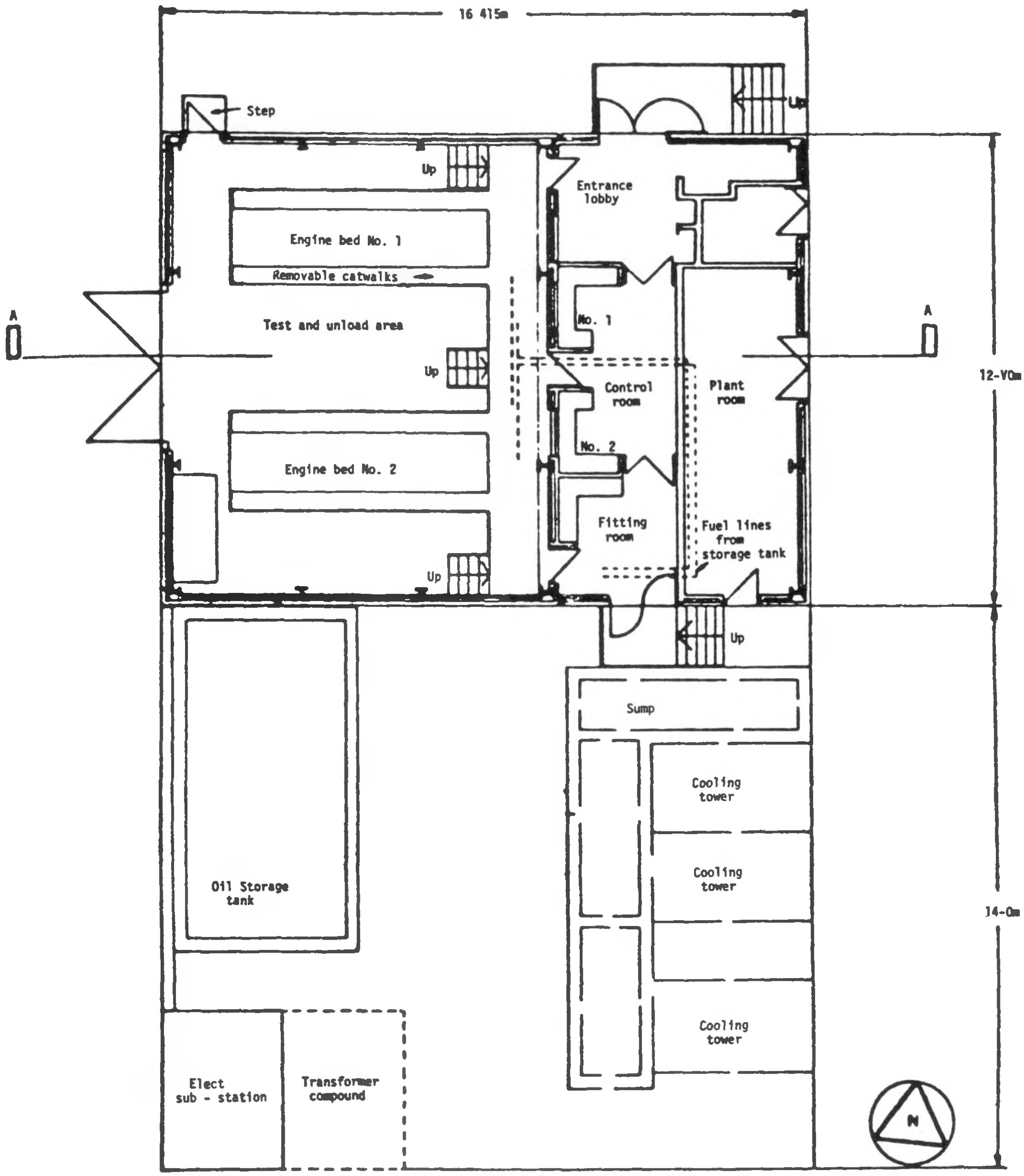


Figure 4-2. Ricardo Large Engine Test Shop

- Provide a means of changing the fuel supply from one test mode to another with a minimum of delay and without stopping the engine.
- Accurately meter the fuel supplied to each of the three injection systems.

A simplified schematic of the system is shown in figure 4-3.

The following subsections describe the fuel system in detail. Subsection 4.1.1 describes the components which prepare and transport the fuel, and subsection 4.1.2 describes the fuel injector pumps and injector nozzles.

4.1.1 Fuel Handling System

The fuel supply system is designed to ensure that all fuel transported to the engine is free of contaminants and that the fuel or fuel mixtures are homogeneous with relatively constant properties.

A detailed schematic diagram of the fuel handling system is shown in figure 4-4 and details of individual components are given in table 4-2. As figure 4-4 indicates, a portion of the fuel handling system consists of the previously existing Ricardo test stand fuel supply equipment, and the remainder is a free-standing module designed specifically for this program. The installed module can be seen beside the engine, on the right-hand side of figure 4-1. The following paragraphs describe the operating modes of the fuel handling system.

Fuel Mixing

The required amounts of RSO and standard diesel fuel (SD) were introduced into tanks A and B respectively. Both fuels were heated by immersion heaters (with integral thermostats) to 60^{o}C. (Float switches prevented heater operation unless fuel was present.) The fuels were then

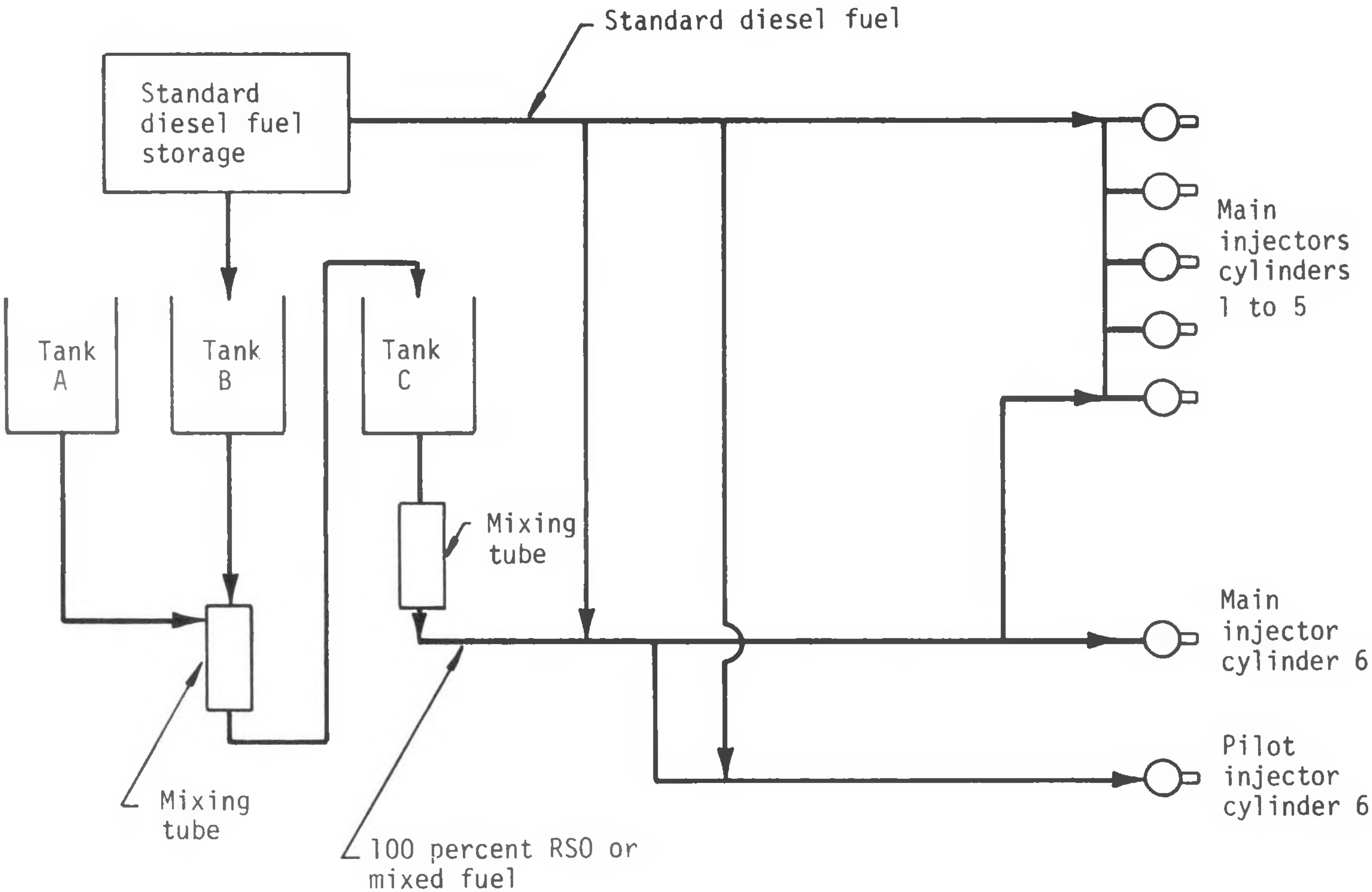


Figure 4-3. Simplified Fuel System Schematic

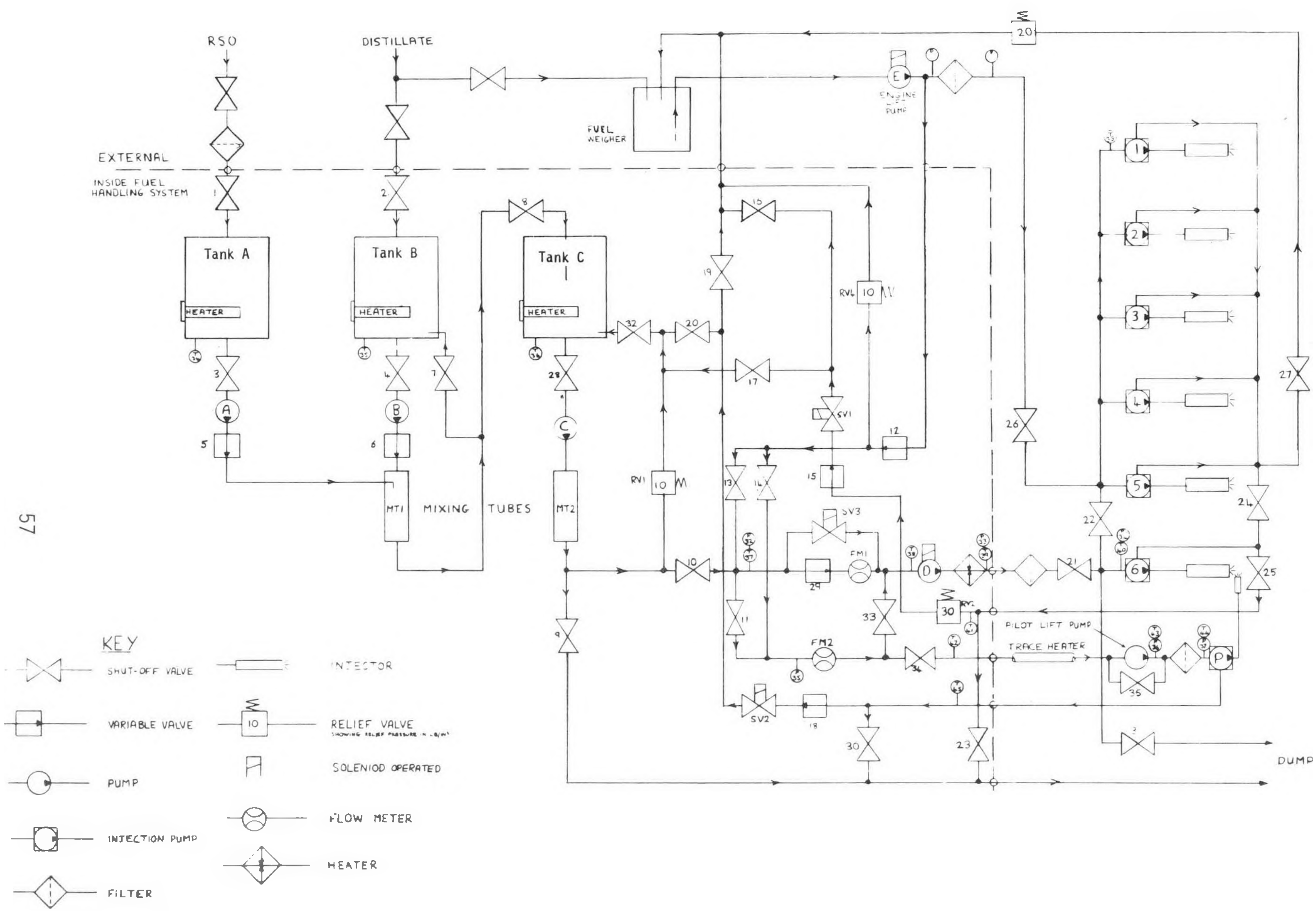


Figure 4-4. Detailed Fuel Handling System Schematic

Table 4-2. Fuel Handling System Components

Item	Manufacturer	Type	Description	Application
Mixing Tubes	Sulzer	1015-5V	Static (5 elements)	MT1 and MT2
Fuel Filter	Vokes	E229F	Felt element	Main Injection Pump Supply
Fuel Filter	CAV	2FSAL	2 parallel paper elements	Pilot Injection Pump Supply
Pumps	Peerlees Pumps	Varley 5MIT6R	Gear type 4 gpm, integral relief valve	Pumps A,B,C,D
Ball Valves	Worcester	Series 42		All valves (No. 1 - 35)
Relief Valves	Bailey	1640	Adjustable relief pressure	RV 1,2,3,4
Tanks	Metcraft	Fabricated Mild Steel	A and B 12.4 gal C 25 gal	Tanks A,B,C,
Heaters	Santon	Beaver 3 kW	Integral thermostat	Tanks A,B,C, and Main Line Heater
Trace Heating	Isopad	IZR30	30 W/m	Pilot Supply Line, Pilot and Main Filters
Temperature Controllers	Controls and Automation Ltd.	6103	Proportional Controller	Main Line Heater Pilot Trace Heater

mixed by opening valves 3, 4 and 7. This allowed the fuels to be pumped by pumps A and B through mixing tube MT1, valves 5 and 6 having previously been set to give the required mixing rate. The mixed fuel then returned to tank B. When tank A was empty, valve 3 was closed and pump A switched off. To prevent separation from occurring, the mixed fuel was continuously circulated through the mixing tube until required for use.

Mixed Fuel Supply

When the mixed fuel was required for use, it was transferred to tank C by closing valve 7 and opening valve 8. (On completion of transfer, a second batch of mixed fuel could then be prepared while that in tank C was being used.) Continuous circulation through a second mixing tube MT2 was maintained by pump C via valves 28 and 32. Temperature was maintained by an immersion heater.

Fuel was passed to the engine supply system by opening valve 10. Control of supply pressure was given by relief valve RV1. Unwanted fuel remaining at the end of a test could be dumped via valve 9.

The mixed fuel supply system could be used to supply 100 percent RSO when required.

Standard Diesel Fuel Supply

SD could be supplied directly to five cylinders (during go/no-go tests) or all six cylinders (baseline tests) from the test shop fuel weigher. Alternatively, SD could be supplied to the pilot injection system and/or the main injection system for No. 6 cylinder via the supply system in the fuel handlng module.

No. 6 Cylinder Main Injector Supply System

This was supplied with either mixed fuel or SD by opening valve 10 or 13, respectively. The fuel then passed through flowmeter FM1 to pump D, which supplied the required pressure for the fuel injection pump. A line heater after the pump was thermostatically controlled by a sensor at the injection pump, set to 60^{o}C. After the line heater, the fuel passed through a felt element filter to the injection pump via valve 21.

Excess recirculating fuel from the injection pump returned to the handling system module via valve 25. Relief valve RV2 controlled pressure at the injection pump. From RV2 the returning fuel passed through valve 15 (used to control volume flow) and solenoid valve SV1. (This was closed when fuel consumption measurements were being made with FM1). The fuel was then returned to tank C via valve 17 if it was mixed fuel, or to the fuel weigher via valve 16 if it was standard diesel.

No. 6 Cylinder Pilot Injector Supply System

This operated in much the same way as the main injection supply system. Fuel was introduced via valve 11 or 14. Because of the much lower circulation rates, trace heating was used on the line between the module and the engine.

Mixed Fuel Supply to All Six Cylinders

This system was required for performance tests. Because the capacity of one flowmeter was insufficient for the fuel quantities required by the whole engine, arrangements were made to connect the two flowmeters (FM1 and FM2) in parallel. This was accomplished by closing valve 34 and opening valves 11 and 33. Valve 29 was used to equalize the flows. (The pilot injector supply system was not required during performance tests.)

With valves 26 and 27 closed and 22 and 24 open, all six cylinders could then be supplied by the No. 6 cylinder supply system.

Fuel Changeover

Changing from mixed to standard diesel or vice versa could be readily accomplished without stopping the engine. Recirculation was stopped by closing valve 16 or 17. Fuel supply was then changed over by means of valves 10 and 13. To remove surplus quantities of the original fuel from the system, valve 23 was opened until the new fuel was seen to flow from the dump pipe. (Solenoid valve SV3 was open during this operation to prevent the flowmeter capacity from being exceeded.) Recirculation was then restarted by opening valve 16 or 17. The pilot supply could be changed over in a similar manner.

4.1.2 Pilot Injection Equipment

During the go/no-go tests, the fuel injection system must be able to accommodate the three injection modes to be evaluated: normal injection, pilot injection, and dual-rate injection. This required two injectors for cylinder, No. 6, with the capability to vary the timing and injection rate.

Since the engine was fitted with a mechanical injector system, a parallel mechanical pump system was added (figure 4-4). The additional injection pump injected the initial charge in the pilot and dual-rate injection modes and was driven from the power take-off at the free end of the crankshaft. Timing changes were accomplished by adjusting the driving pulley of the pump relative to the TDC of the crankshaft.

Technical details of the fuel injection equipment procured for the pilot injection system are given in table 4-3. A brief description of the system components and installation is given in the following paragraphs.

Table 4-3. Pilot Fuel Injection Equipment

Table 4-3a. Injection Pump -- Lucas-CAV Majormec Type P5347/1

Item	Serial No.	Size
Element No. 1	503348[a]	10 mm
No. 2	503350	11 mm
No. 3	512748	12 mm
Delivery Valve No. 1	504787	69.3 mm^3
No. 2	506242	88.0 mm^3
No. 3	507564[a]	88.0 mm^3
No. 4	505133	125.0 mm^3
no. 5	512235	150.0 mm^3
Camshaft No. 1	512020	0.3 mm/degree
No. 2	503547[a]	0.4 mm/degree

[a]Fitted to pump in "as received" build

Table 4-3b. Injector Nozzles[a] -- Lucas-CAV Type LRBX 67810

Nozzle No.	Serial No.	No. of Holes	Hole dia. (mm)	Hole Length (mm)	Spray Angle (degrees)
1	JBX6809533	3	0.25	1.0	120
2	JBX6809528	3	0.25	1.0	150
3	JBX6809529	3	0.30	1.0	120
4	JBX6809530	3	0.30	1.0	150
5	JBX6809531	4	0.25	1.0	120
6	JBX6809532	4	0.25	1.0	150

[a]All nozzles have 16° spray offset from center line

Table 4-3c. High Pressure Fuel Line

Internal/External dia. (mm)	2.25/6.0
Length (mm)	1,300
Length between pressure transducer and injector (mm)	500

Pilot Injection Pump

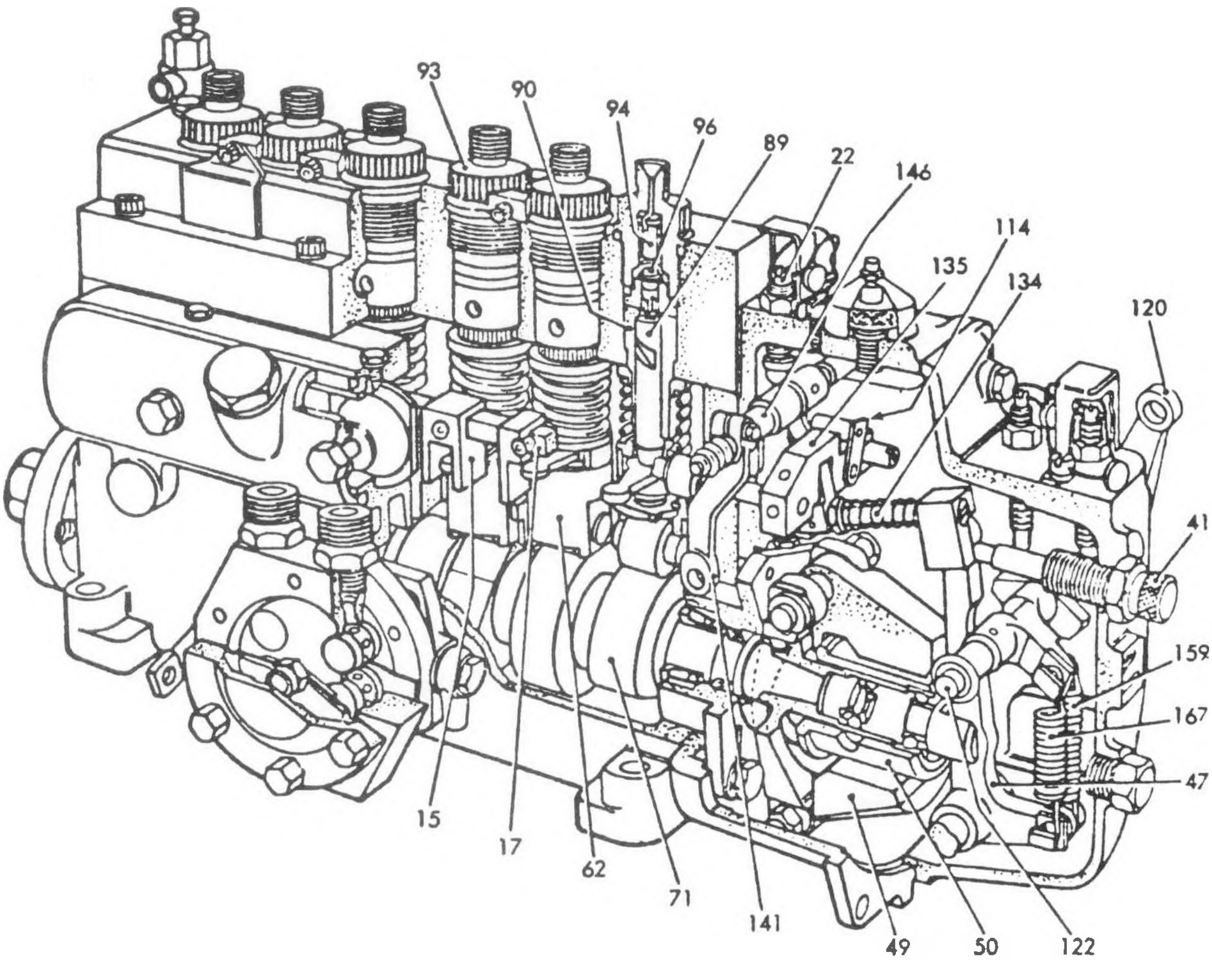
The pump chosen to provide pilot injection was a Majormec Type P5347/1, manufactured by Lucas CAV Ltd. This was a conventional six-cylinder block pump, widely used on truck engines (see figures 4-5 and 4-6). A major consideration in the choice of this pump was the availability of various elements, delivery valves and camshafts, enabling optimization of the system over the range of operating conditions required by the test program.

Since pilot injection was to be fitted to one cylinder only, the Majormec pump was modified by removal of five delivery valves. The corresponding five output lines were linked by short lengths of pipe to permit fuel to flow from one to another in order to prevent overheating. The one remaining output was used to supply the pilot injector.

The pump was supplied with a mechanical governor. Since this was not required, it was rendered inoperative and a manual rack control fitted. This was provided with a numbered scale, and the pump was then calibrated to determine output for any given rack setting. The object of this was to enable the pilot injection quantity to be set to the desired percentage of the main injector quantity during engine testing.

The pump was mounted on the camshaft side of the engine at the flywheel end (see figure 4-1). Drive for the pump was taken from the camshaft gear. A spare camshaft gear wheel was procured and arranged to mesh with the existing camshaft gear. A housing to support and enclose this gear was designed to bolt onto the engine gearcase in place of the existing camshaft gear cover.

The pump itself was mounted on a fabricated bracket bolted to a camshaft inspection door. The pump was driven from the shaft carrying the



15	Control Fork	93	Delivery Valve Holder
17	Control Rod	94	Volume Reducer
22	Max. Fuel Stop Screw	96	Delivery Valve
41	Damper	114	Trip Lever
47	Crank Lever	120	Speed Control Lever
49	Governor Flyweight	122	Speed Lever Shaft
50	Governor Sleeve	134	Telescopic Link
62	Tappet Assy.	135	Bridge Link
71	Camshaft	141	Stop Control Lever
89	Plunger	146	Excess Fuel Device
90	Barrel	159	Governor Idling Spring
		167	Governor Main Spring

Figure 4-5. Cutaway Section of Typical Six-Cylinder Majormec Pump

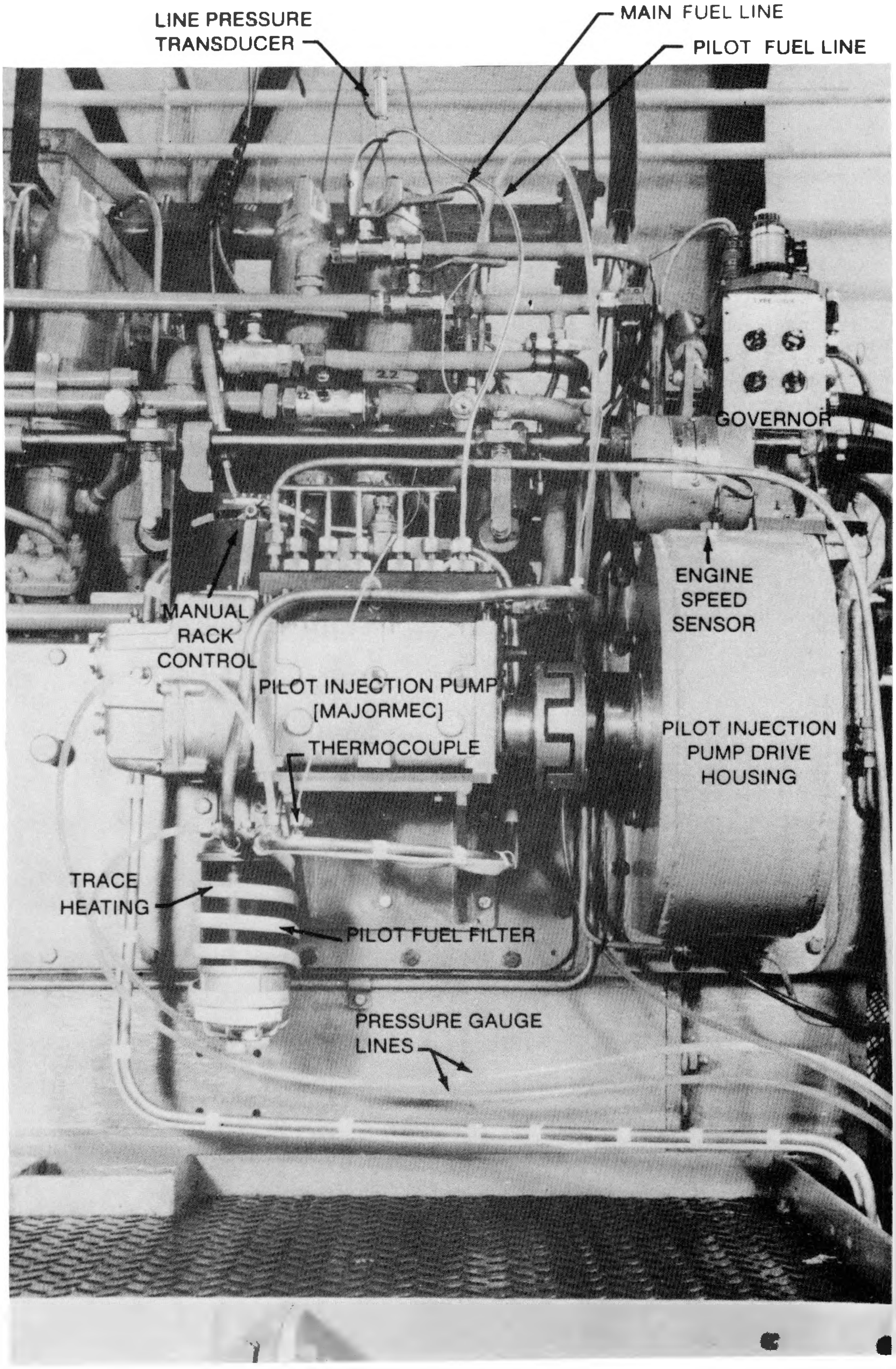


Figure 4-6. Majormec Pilot Injection Pump Mounted on APE Allen Engine

camshaft gear wheel via a flexible coupling with facilities for adjusting injection timing.

Pilot Injector

The pilot injector chosen for this application was a Lucas CAV type LR with an axial inlet. This was chosen for maximum length and minimum outside diameter (for ease of installation) compatible with the fuel delivery requirements. Two injector bodies (in order to have a spare available) and six different nozzles were procured. The nozzles were selected on the basis of spray penetration calculations (see appendix A) to provide a range of fuel delivery characteristics (compatible with the various injection pump builds available (see section 4.4.1)) to meet the fueling requirements of the pilot injection and 'dual-rate' injection test modes.

One of the injector bodies was fitted with a Ricardo needle lift transducer, as described in section 4.5.2.

Cylinder Head Modifications for Pilot Injector

The primary requirements of the pilot injector installation design were as follows:

- Injector to be as near the center of the combustion chamber and as near vertical as possible, to ensure a favorable fuel spray pattern.
- Injector to be easily and quickly removable, for cleaning and changing nozzles.

As shown in the design drawing of figure 4-7, both these requirements were met. The injector nozzle was as close to the center of the combustion chamber as the presence of the main injector allowed, and the injector was inclined at an angle of only 16^{0} from the vertical (offset nozzles were

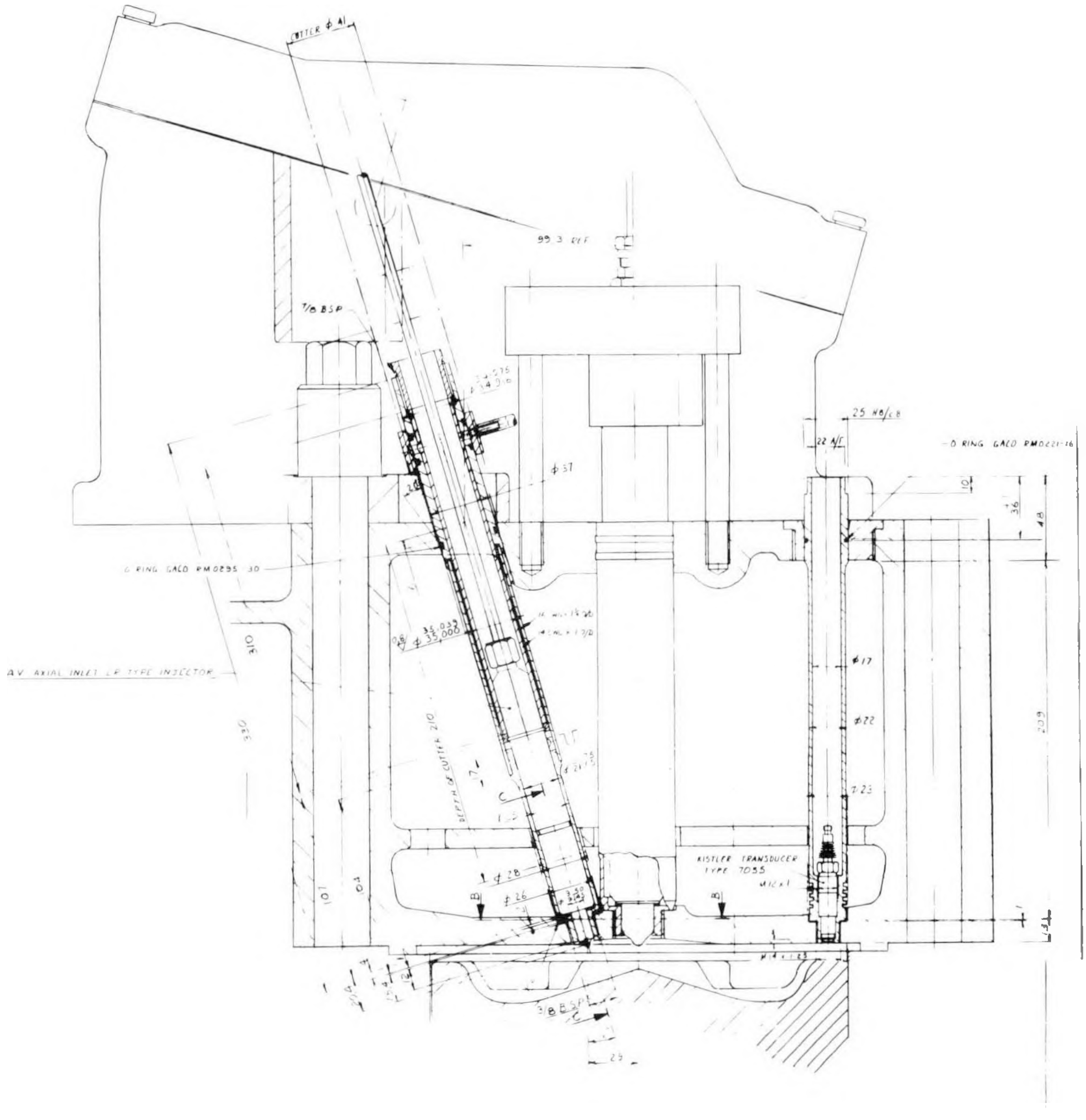


Figure 4-7. Layout of Pilot Injector and Pressure Transducer in Test Cylinder

used to correct for this, see appendix A). The injector could be withdrawn after releasing a single retaining nut.

Pilot Injection System Installation

A photograph of the pilot injection pump installation is shown in figure 4-6. The drive housing, pump mounting bracket, and pump were fitted to the engine, using shims as required to obtain correct gear meshing and alignment. When all parts of the system had been correctly aligned, dowels were fitted to ensure that alignment was retained.

Injection timing was set approximately by gear wheel teeth meshing. Fine adjustment was provided by an arrangement on the coupling between the gear wheel and pump.

A high pressure fuel line was made up to connect the pump to the injector, and this was fitted with an adaptor to accept a line pressure transducer located as close to the injector as possible. Dimensions of this line are given in table 4-3.

The fuel supply system for the pilot injection pump is shown schematically in figure 4-4, and some components can be seen in figure 4-6. (The fuel lift pump is concealed behind the injection pump.) Trace heating on the fuel feed line can be seen since this photograph was taken before any insulation was fitted.

4.2 INSTRUMENTATION

A complete list of all instrumentation used during the test program is given in table 4-4, with brief details of each item. Further details of selected items are given in the following sections.

4.2.1 Cylinder Pressure

Combustion performance was monitored during go/no-go testing by observing the cylinder pressure diagram. A piezoelectric pressure

Table 4-4. Instrumentation

Measured Quantity	Sensor (1) Signal Conditioner (2) Readout (3)	Type	Manufacturer	Model Number	Range(s)	Notes
Cylinder pressure	1 2 3	Piezo-Electric Charge amp. Oscilloscope	Kistler Kiag Phillips	7055B/122008 5001 3244	0-250 Bar	
Fuel line pressure	1 2 3	Strain gauge Bridge Oscilloscope	Intersonde Ricardo Phillips	XT44 -- 3244	0-1,000 Bar	Pressure measured in main and Pilot no. 6 cylinder
Crankcase pressure	1 2 3	Strain gauge Bridge Digital	Druck Druck Amplicon	DP1201 -- 55	9-99.9m Bar	
All other pressures		Bourdon tube Gauge	Wika	Series 2	0-1, 0-2.5 0-4, 0-6 Bar	
All temper-atures	1 2 3	Cr-Al thermocouple Linearizer + amp. Digital	Gulton Control and Readout Ltd.	K-3HT2 & K-6HT2 621	0-999°C	Single readout with 60-way switched input
Engine speed	1 2 3	Electro-Magnetic Counter/timer Analogue and digital	Orbit Ricardo Amplicon	80 D 1102 -- 55	0-1,500 rpm	
Turbine speed	1 2 3	Electro-Magnetic Counter/timer Digital	Disa Ricardo Amplicon	72K02 -- 55	0-99,999 rpm	
Fuel flow (1)	1 2 3	Load cell Microprocessor Digital (time for set mass)	Cussons	--	0-10 Kg	Test shop Meter, not used for RSO
Fuel flow (2)	1 2 3	Positive displacement Counter/Timer Digital	Transflo Ricardo Amplicon	TF101P -- 55	0-130 Liters/Hour	Incorporated in fuel handling system
Crankcase blowby	1 2 3	Rotating float inductance briged analog	A. V. L.	431C/2500 4032-01 3015	0-2500 Liters/Min	

Table 4-4. Concluded

Measured Quantity	Sensor (1) Signal Conditioner (2) Readout (3)	Type	Manufacturer	Model Number	Range(s)	Notes
Exhaust smoke	1 2 3	Pump and filter paper optical comparator analogue	Bosch	-- EFAW 68A	0-10	
Injector needle lift	1 2 3	Electromagnetic displacement transducer FM unit oscilloscope	Ricardo Ricardo Phillips	-- -- 3244	--	
Degree marker	1 2 3	Electro-Magnetic pulse shaper oscilloscope	Ricardo Ricardo Phillips	-- -- 3244	--	Synchronized reference for cylinder and fuel line pressure and needle lift
<u>Emissions</u>						
HC		FID	Ratfisch	RS5-108	0-10, 0-100 0-1,000, 0-10,000 ppm	
NO_x		Chemiluminescent		10AR	8 Ranges from 0-2.5 to 0-1,000 ppm	
O_2		Paramagnetic	Servomex	250	0-10, 0-25, 0-100 percent	
CO		NDIR	Analytical Development	140	0-0.05, 0-0.2, 0-0.5, 0-2 Percent	

transducer was fitted to No. 6 cylinder head, as shown in figure 4-7. The signal from this was displayed on an oscilloscope together with reference markings indicating crankshaft position, as shown in figure 4-8. Signal conditioning was provided by a charge amplifier having a linear pressure/voltage output relationship. Transducer and amplifier were calibrated before fitting, enabling actual pressure values to be determined from the diagram in addition to the qualitative information given by its shape. Permanent records of oscilloscope traces were obtained photographically.

4.2.2 Injector Line Pressure and Needle Lift

Fuel injector line pressure on both main and pilot injectors in No. 6 cylinder was obtained from strain gauge type pressure transducers fitted to the high pressure fuel lines. Electromagnetic position sensors were built into the injectors. The signals from these were displayed on the same oscilloscope as the cylinder pressure signal, as shown in figure 4-8.

The displayed signals from these sensors provided precise information on injection timing and duration, effect of fuel viscosity and injection system build on line pressure, and any adverse injection system characteristics such as pressure fluctuations and secondary injection.

4.2.3 Fuel Consumption

Two types of fuel consumption measuring equipment were used. One of these was a Cussons gravimetric fuel meter which was permanently installed as part of the standard test bed instrumentation. A schematic of this flow meter is shown in figure 4-9.

In addition, two Transflo positive displacement volumetric meters were incorporated in the fuel handling system module. These had four

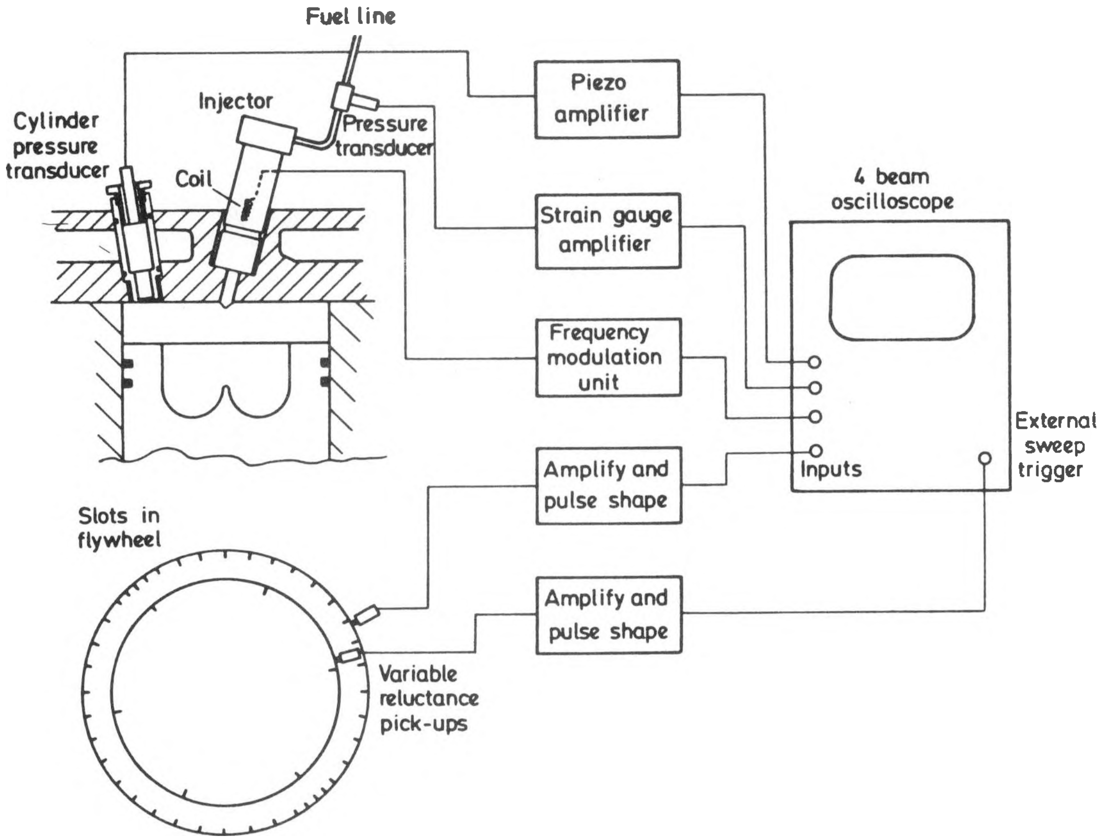


Figure 4-8. Schematic of Instrumentation for In-Cylinder Measurements

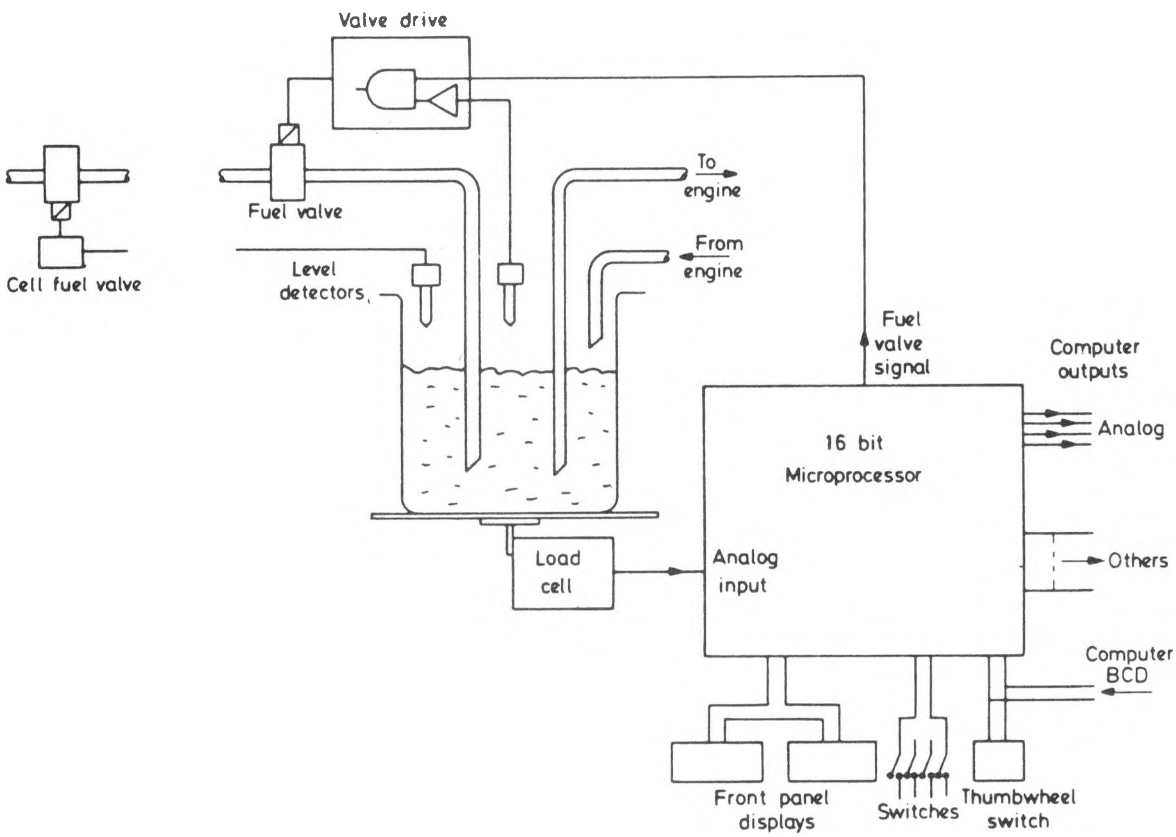


Figure 4-9. Schematic Diagram of Cussons Gravimetric Fuel Flow Meter

cylinders connected to a common crankshaft with a total displacement of 1 cc/rev. A transducer on the crankshaft provided output pulses. A pulse counter/timer was constructed to count the number of pulses in a preset time period and display this in terms of cubic centimeters.

The manner in which the three fuel meters were used to provide the required information in each of the various modes of testing is described in section 4.1.1.

4.2.4 Engine Load and Speed

A Heenan & Froude water-brake dynamometer provided the load for the engine. By measuring the brake torque and engine speed, the power output of the engine was determined. Torque was measured with a load cell and lever arm. Engine rpm was measured with a tachometer operated by a magnetic sensor mounted on the engine flywheel. This sensor also provided a trigger signal for the fuel injector monitoring oscilloscope (see figure 4-8).

4.2.5 Air Turbocharging and Aftercooling

The inlet air temperature and pressure was monitored at several points before entering the engine cylinders. Air temperature was first measured at the filter inlet and then at the turbocharger outlet to monitor the turbocharger performance and ensure overheating did not occur. Temperature and pressure were also measured downstream of the aftercooler to monitor its performance and measure the actual conditions of the air entering the engine cylinders. All temperature measurements were made with thermocouples, and pressures were measured with Bourdon tube gauges.

4.2.6 Exhaust

The exhaust gas temperature of each engine cylinder was measured individually. Temperatures were also measured immediately ahead of and after the turbine to evaluate its performance. These temperatures were all measured by thermocouples and displayed through a 30 channel multiplexer and single readout system.

The turbine was also instrumented with a magnetic sensor so that its rpm could be determined. This provided another, more sensitive indication of turbine performance.

4.2.7 Oil Cooling

The oil cooling system consisted of an external oil-to-water shell and tube heat exchanger and filter. Temperatures were measured on each side of the heat exchanger for both fluids. Measuring the oil temperature inlet provided an indication of engine overheating, while the outlet temperature provided an indication of heat exchanger performance and oil supply temperature. Measuring water temperature provided a means of heat exchanger control. Again, temperatures were measured with thermocouples.

Oil pressures ware measured ahead of and after the filter to determine when the filter was plugged. The engine block oil pressure measurement ensured that the oil pump was functioning properly. All pressure measurements were made with Bourdon tube gauges.

4.2.8 Engine Crankcase

The pressure within the engine crankcase was measured to determine the degree of engine cylinder blowby and indicate if dangerous pressures are building within the case. Measuring the flowrate of the vented gases also provided a quantitative indication of blowby.

4.2.9 Engine Coolant

The engine coolant inlet and outlet pressures and temperatures were measured to determine the performance of the cooling system and engine. Comparing the pressure measurements provided an indication of coolant flow, as well as any potential plugging within the engine. Temperatures also indicated the performance of the cooling system; a high temperature differential between the inlet and outlet provided an indication of engine overheating.

To determine the performance of the coolant pump, pressure was also measured at the pump inlet. All temperatures were measured with thermocouples, and pressures were measured with Bourdon tube gauges.

4.2.10 Particulate Emissions

A schematic diagram of the particulate sampling equipment is given in figure 4-10. A sample of the engine exhaust gas was drawn into the dilution tunnel and mixed with filtered air at ambient temperature to promote particle condensation. (This simulated the condensation process which occurs when exhaust gases emerge from an exhaust pipe into the atmosphere.) Two alternative systems were provided for sampling the developed particles.

Bulk Sampling System

Large quantities of samples were collected during endurance testing. A specially made holder for large filter papers (of an EPA-approved material) was provided, together with a high volume sample pump.

Quantitative Sampling System

This system was a standard fitting on the tunnel, designed for accurate removal of a small sample at a constant flowrate over a

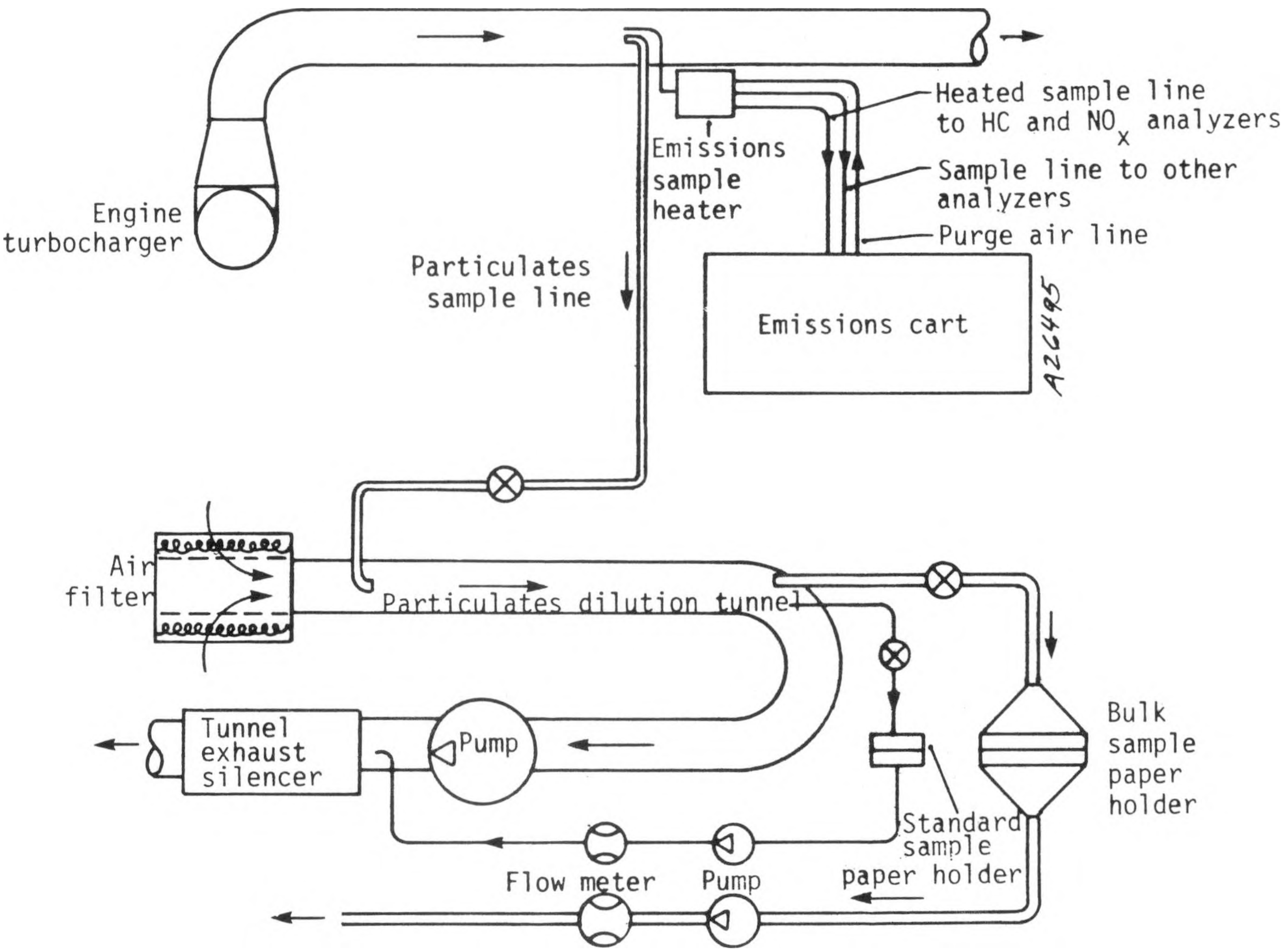


Figure 4-10. Schematic of Gaseous and Particulate Exhaust Emissions Sampling

relatively short time period. In this way a quantitative assessment of the particulate emissions could be obtained.

4.2.11 Gaseous Emissions and Smoke

Engine emissions were monitored for the following components:

- NO_x
- CO
- CO_2
- O_2
- Total hydrocarbons (HC)
- Smoke (Bosch)

Emissions were sampled downstream of the turbocharger turbine, using one of the several cart-mounted emissions benches currently in operation at Ricardo (figure 4-10). These portable emission benches are manufactured by G. Cussons, a manufacturing subsidiary of Ricardo.

Each analytical unit consists of a sample handling system which extracts the sample from the exhaust line, measures the flow, chills the sample to extract moisture, and delivers it sequentially to the analyzers. For the hydrocarbon measurement, the sample line between the exhaust and the analyzer is heated to prevent condensation of exhaust constituents.

In order to avoid contamination of the sample, the gas handling circuit is made entirely with stainless steel or poly-tetrafluoroethylene (PTFE) pipes and fittings. Provision is made for connecting span gas bottles for calibration of the analyzers.

SECTION 5

ENGINE TEST RESULTS

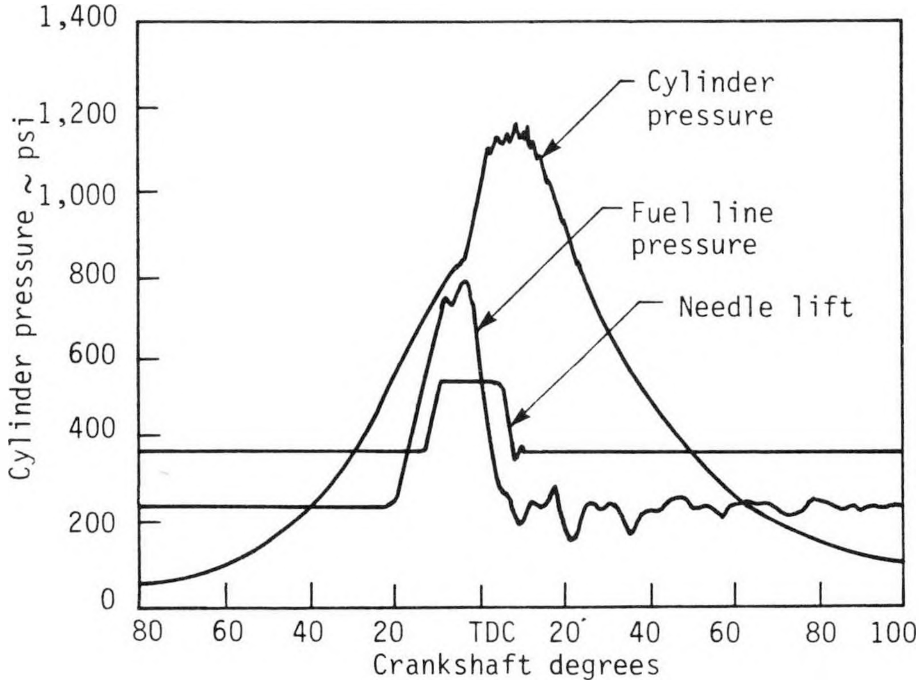
5.1 GO/NO-GO TESTS

These tests were performed with RSO supplied to one cylinder only (No. 6), with the quality of combustion and performance of fuel injection equipment monitored by oscilloscope traces of cylinder pressure, injector needle lift, and injector fuel line pressure. The remaining five cylinders operated on standard diesel fuel.

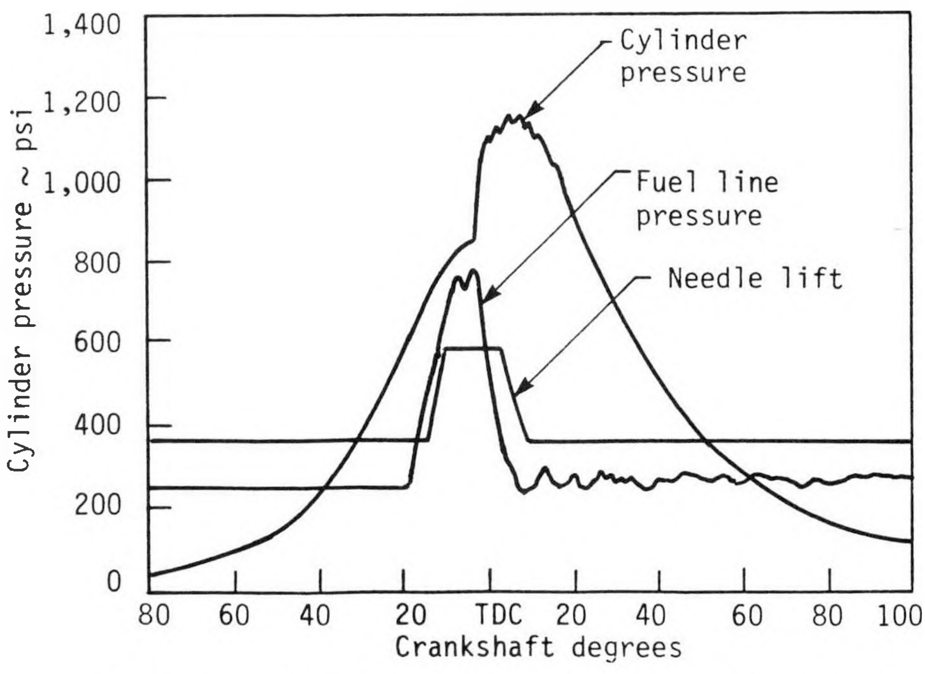
All go/no-go tests were conducted at a speed and load of 1,000 rpm, 158 psi (10.9 bar) BMEP, unless otherwise stated.

5.1.1 Mixed Fuel Tests

A blended mixture of RSO and standard diesel fuel was supplied to the No. 6 cylinder. Four tests were conducted, using 0, 50, 85, and 100 percent RSO blended with SD. The oscilloscope traces obtained are shown in figure 5-1. There was no perceptible difference in ignition delay, rate of pressure rise, or maximum pressure in any of the diagrams. To further demonstrate this unexpected result, the traces of 0 percent RSO (i.e., pure standard diesel fuel) and 100 percent RSO are overlaid, as shown in figure 5-2. This confirmed that the combustion performance of RSO was equal to that of standard diesel fuel. Since this result rendered the remaining planned mixed fuel tests redundant, a test over the full-load range of the engine was substituted. This was run first with

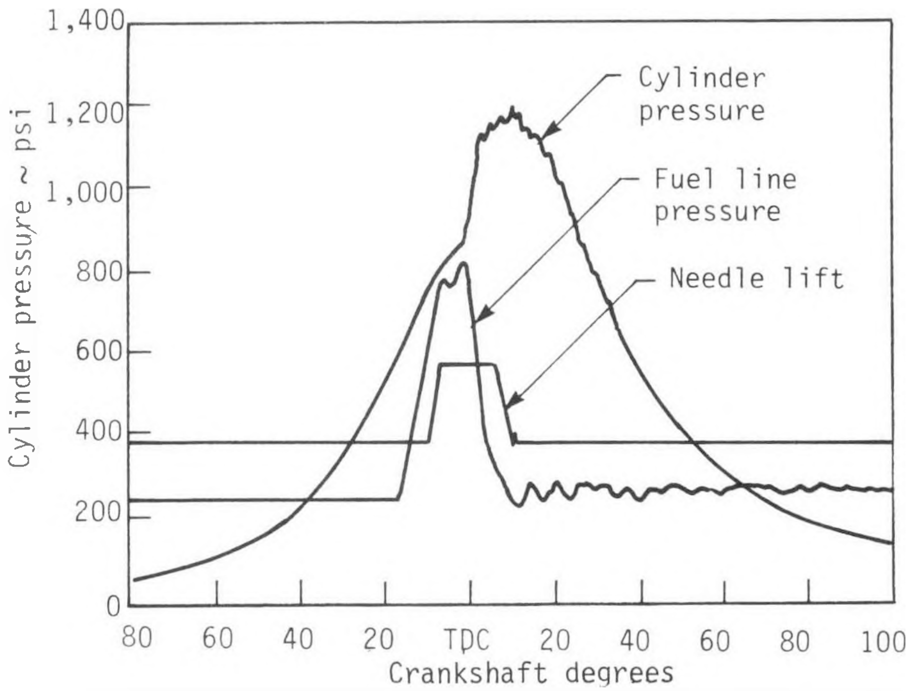


a) 100 Percent Standard Diesel Fuel

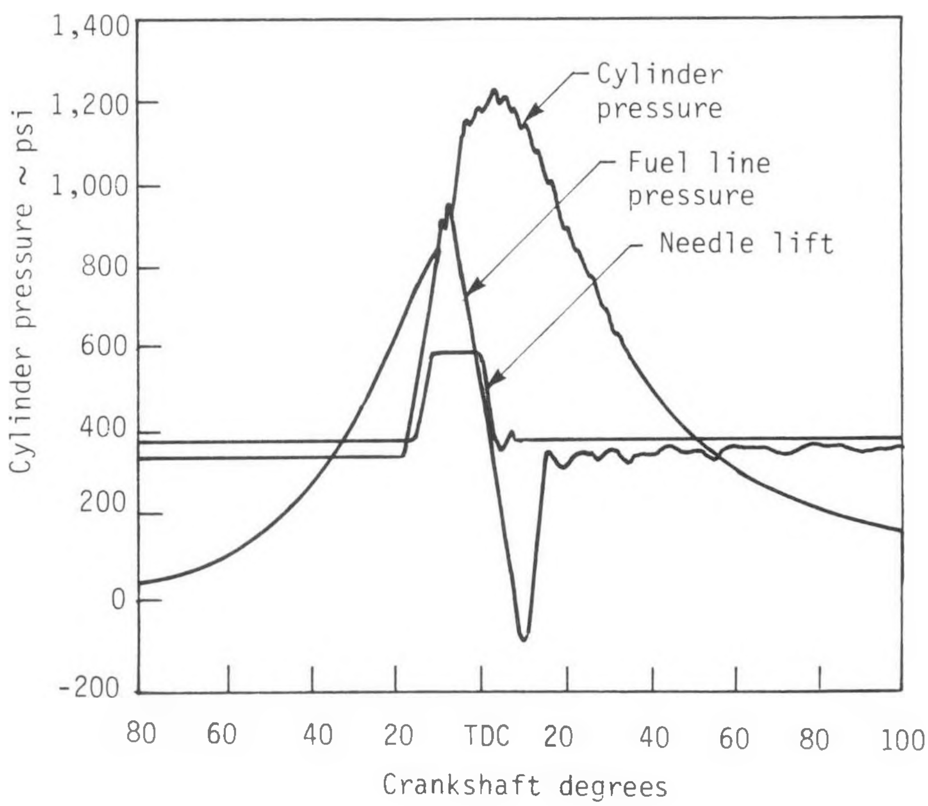


(b) 50 percent RSO, 50 percent Standard Diesel Fuel

Figure 5-1. Cylinder Pressure Trace for Mixed Fuel Tests
(BMEP = 158 psi, 75 percent load)



c) 85 percent RSO, 15 percent Standard Diesel Fuel



d) 100 percent RSO

Figure 5-1. Concluded

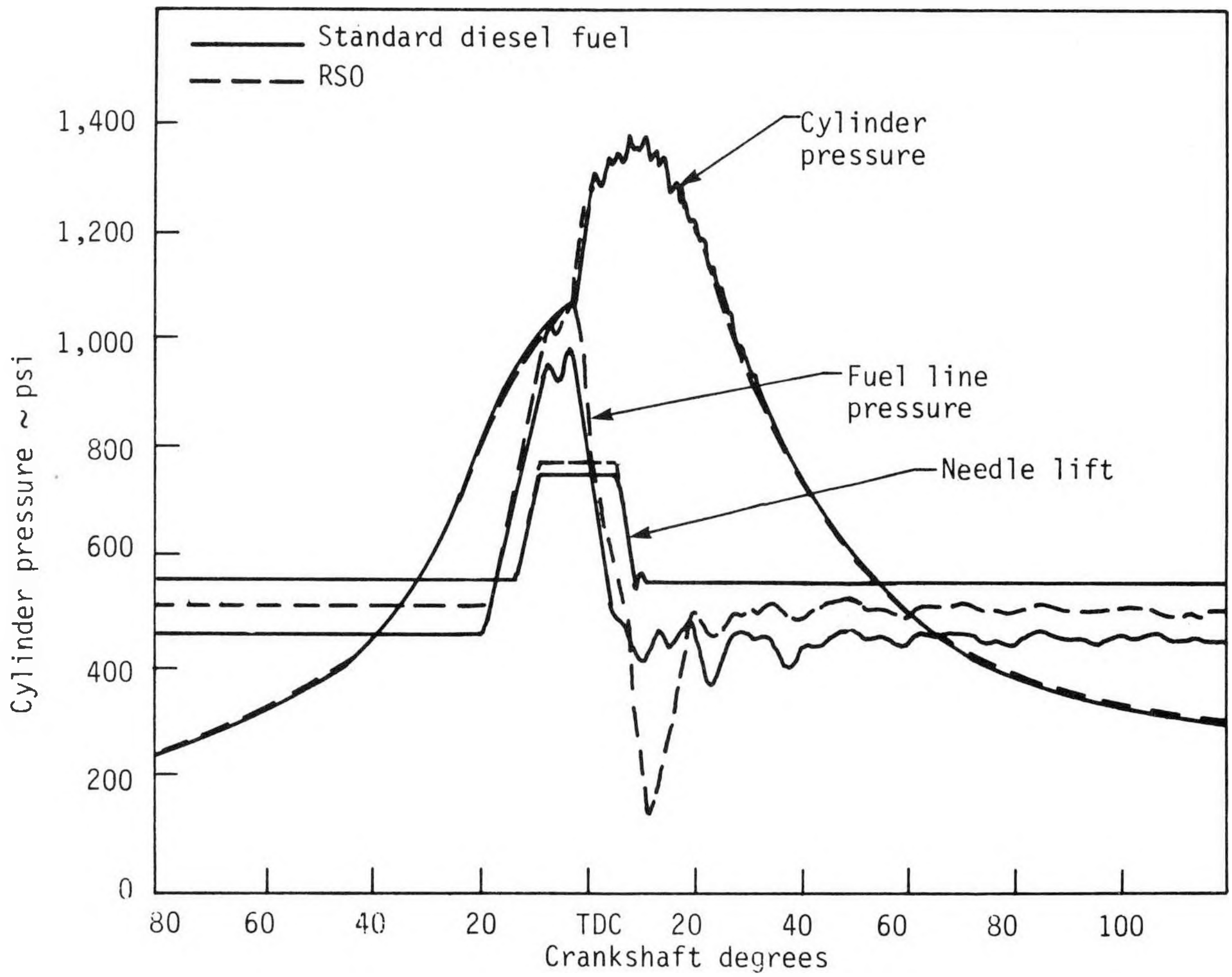


Figure 5-2. Comparison of Cylinder and Fuel Pressure for Standard Diesel Fuel and RSO (BMEP = 158 psi, 75 percent load)

100 percent standard diesel fuel, then with 100 percent RSO. Differences in cylinder pressure only became apparent at very low loads, as shown in figure 5-3. At 45 psi (2.9 bar) a slight increase in maximum pressure when burning RSO became apparent, and at 13 psi (0.9 bar) and 9 psi (6.1 bar) a small increase in ignition delay could be detected. However, these were very minor changes and would not have any significant effect on engine performance.

A slight increase in fuel line pressure when using RSO was noted, due to RSO having a higher viscosity than standard diesel fuel.

5.1.2 Pilot Injection Tests

Results of the mixed fuel tests described in the previous section showed that RSO could be fired satisfactorily without any form of ignition assistance. However, as the pilot injection equipment had already been procured and partially fitted to the engine, it was considered worthwhile to proceed with an abbreviated series of pilot injection tests.

The pilot injection pump was installed in its 'as received' build and nozzle No. 6 was fitted to the pilot injector. (Pump build and nozzle details are given in table 4-3). Two tests were conducted with standard diesel fuel supplied to the pilot injector in quantities corresponding to 5 and 15 percent by mass of the main charge of RSO.

Pilot injection timing was arranged so that pilot needle lift occurred 8^0 before main needle lift, this being the delay period between needle lift and start of combustion observed in earlier tests as shown by figure 5-1. This ensured that combustion of the pilot charge would occur during the early stages of main charge injection.

The oscilloscope traces obtained during these tests are shown in figure 5-4. Two diagrams were required for each test, as only four traces

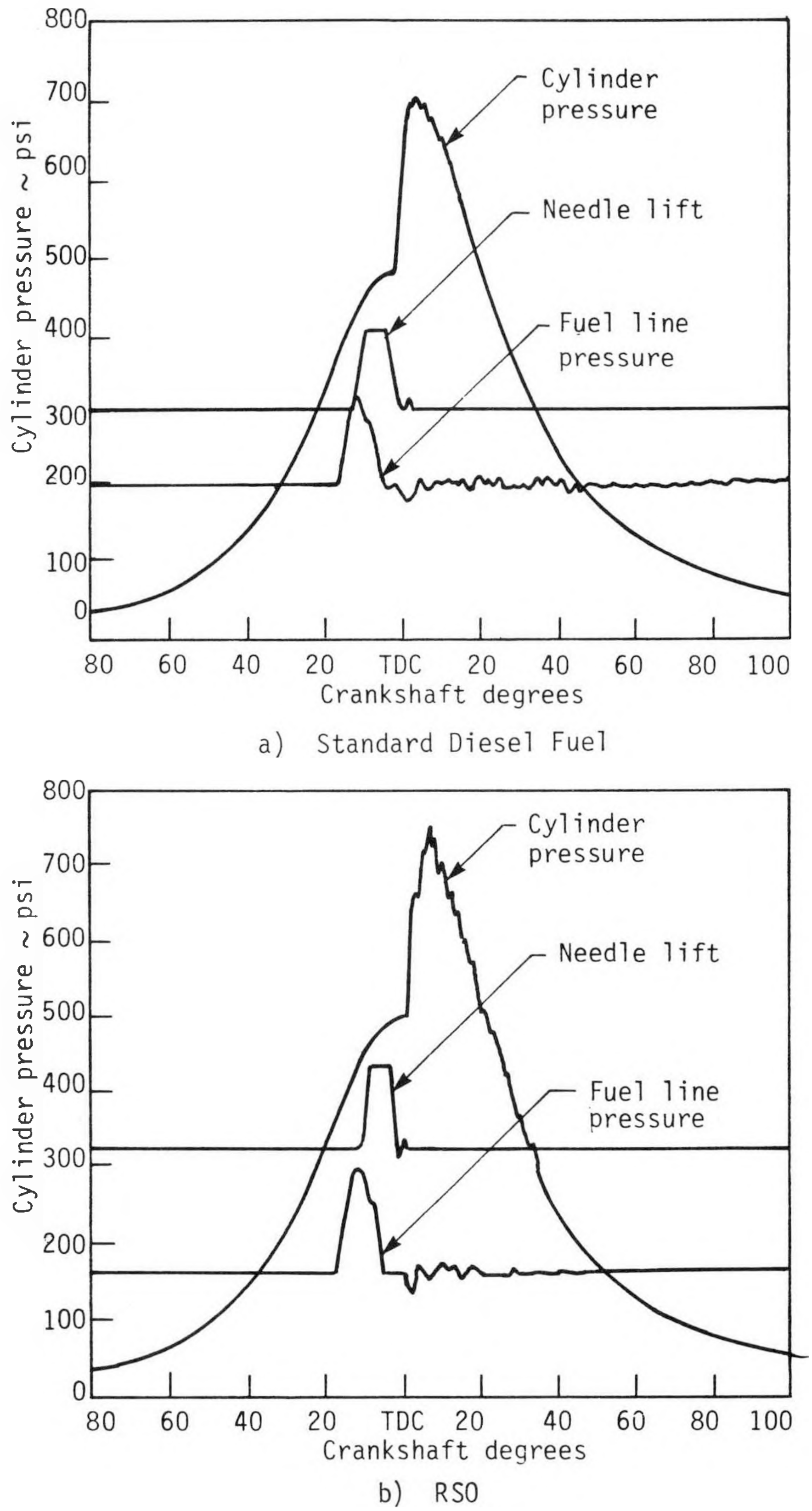
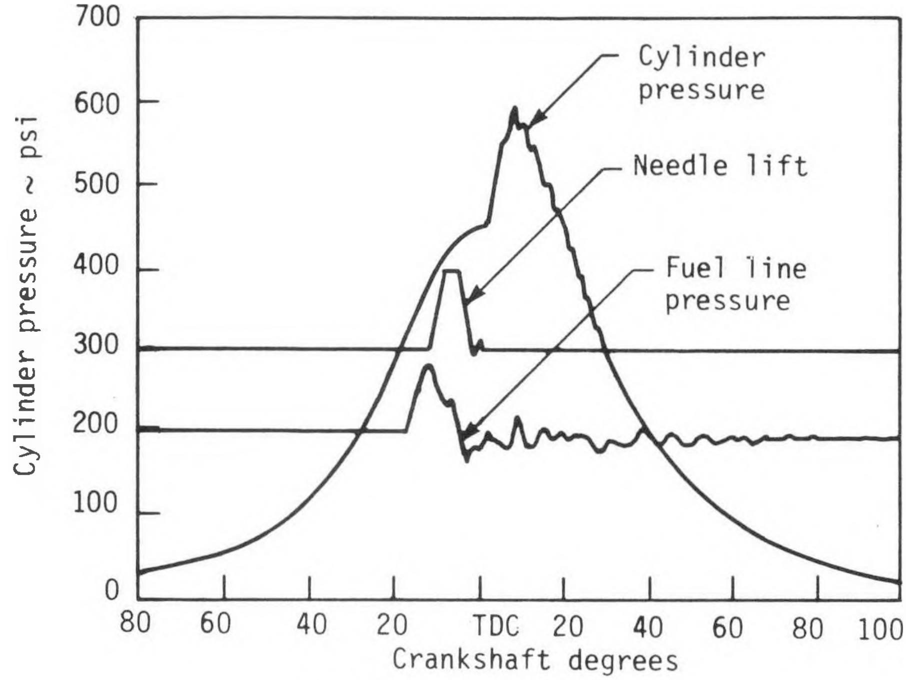
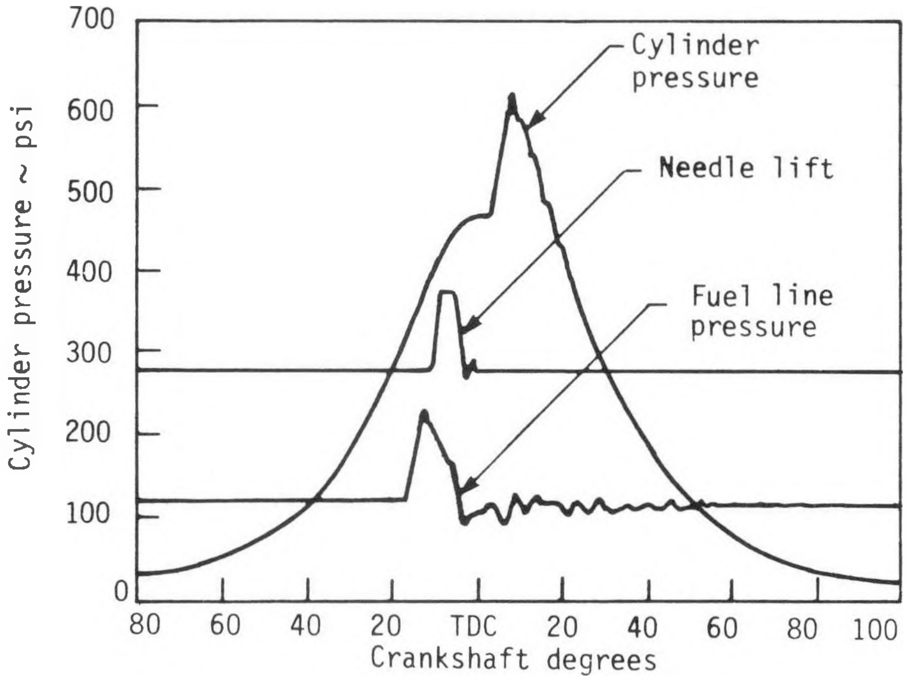


Figure 5-3. Comparison of Cylinder Pressure Between Standard Diesel Fuel and RSO at Reduced Load (BMEP = 45 psi, 21 percent load)

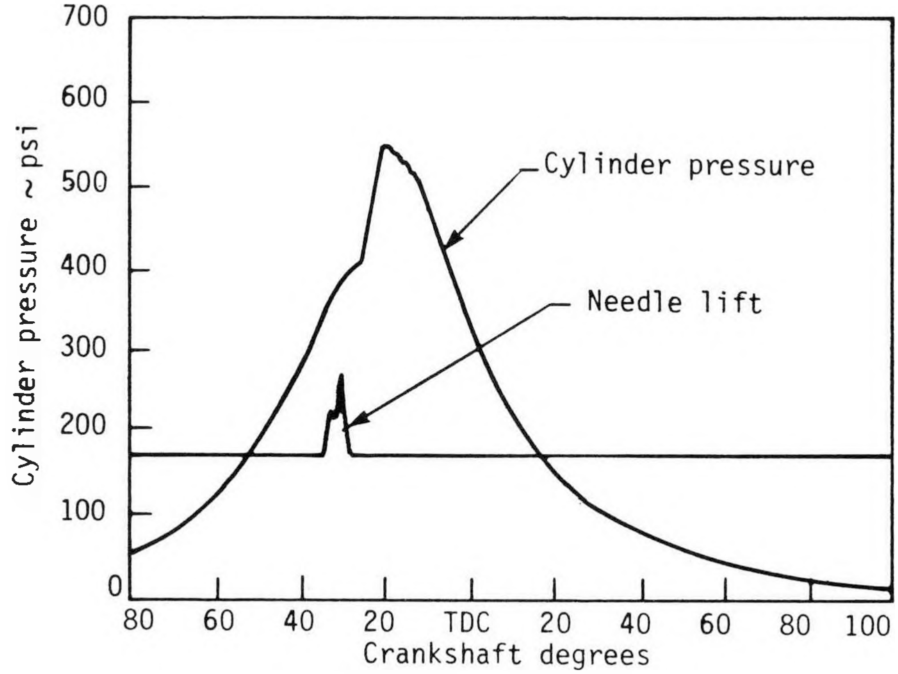


c) Standard Diesel Fuel

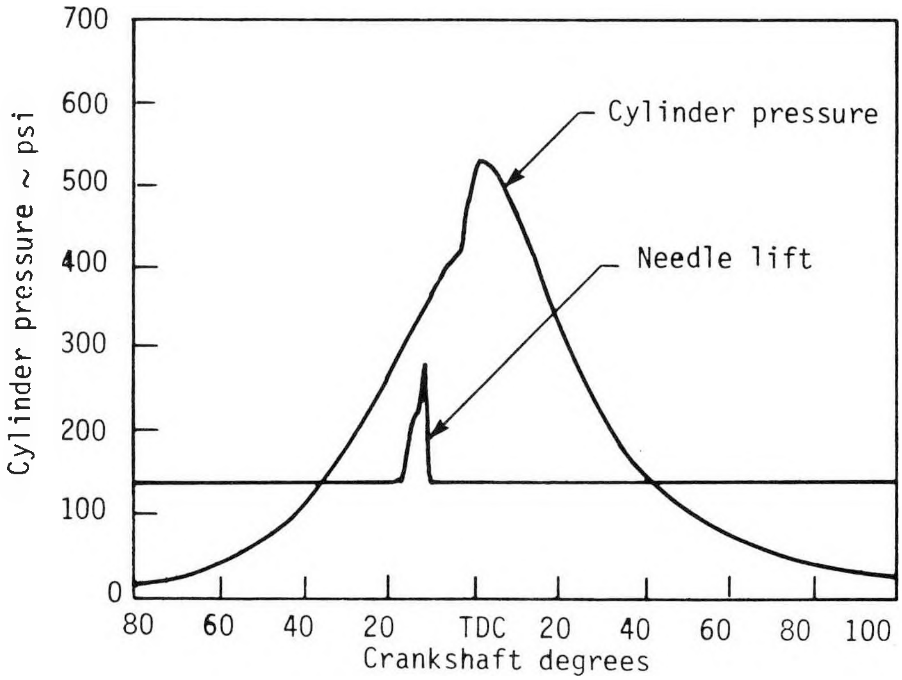


d) RSO

Figure 5-3. Continued (BMEP = 13 psi, 6 percent load)

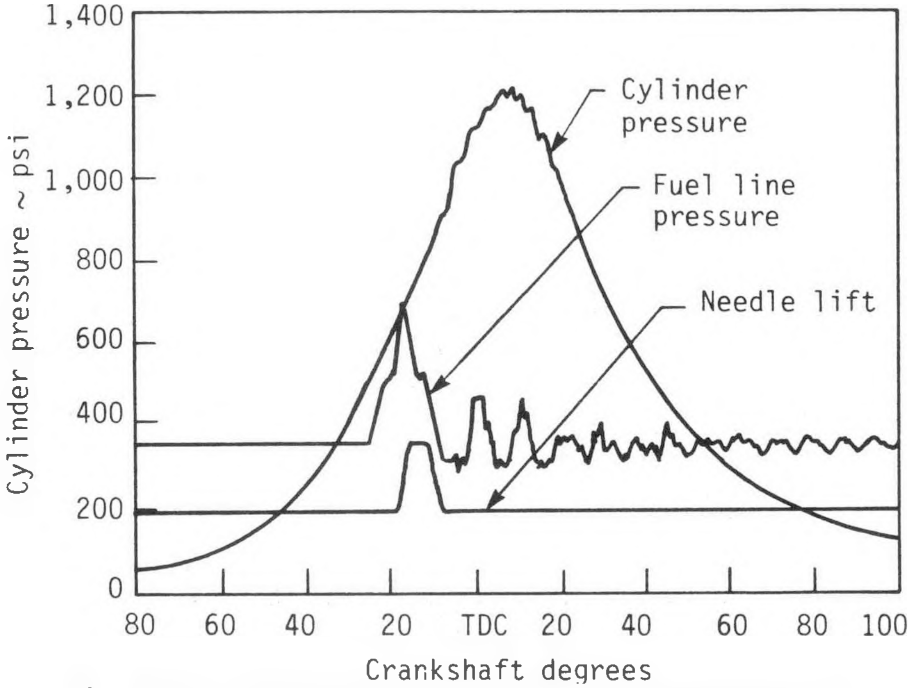


e) Standard Diesel Fuel

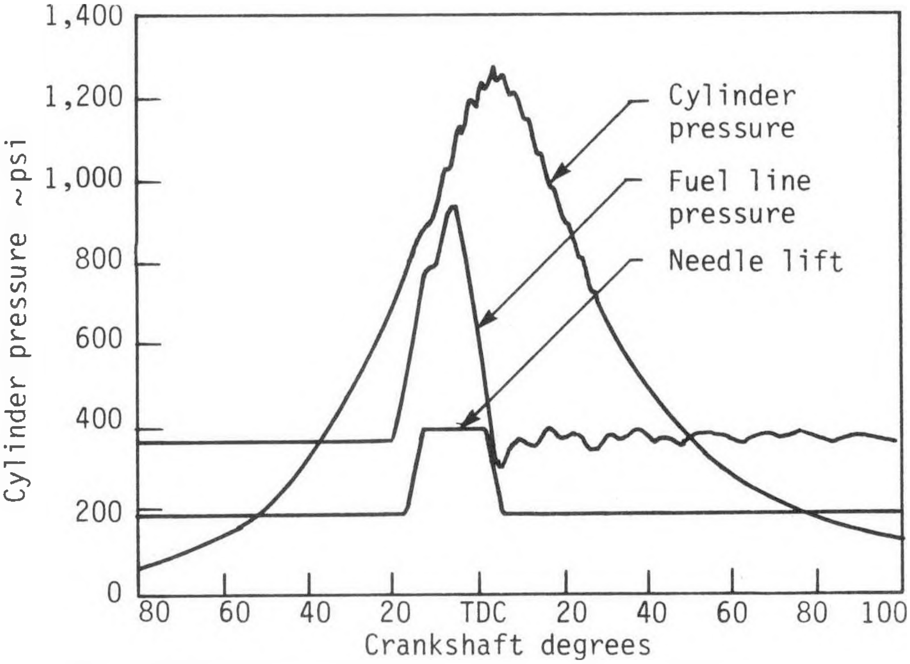


f) RSO

Figure 5-3. Concluded (BMEP = 9 psi, 4.3 percent load)

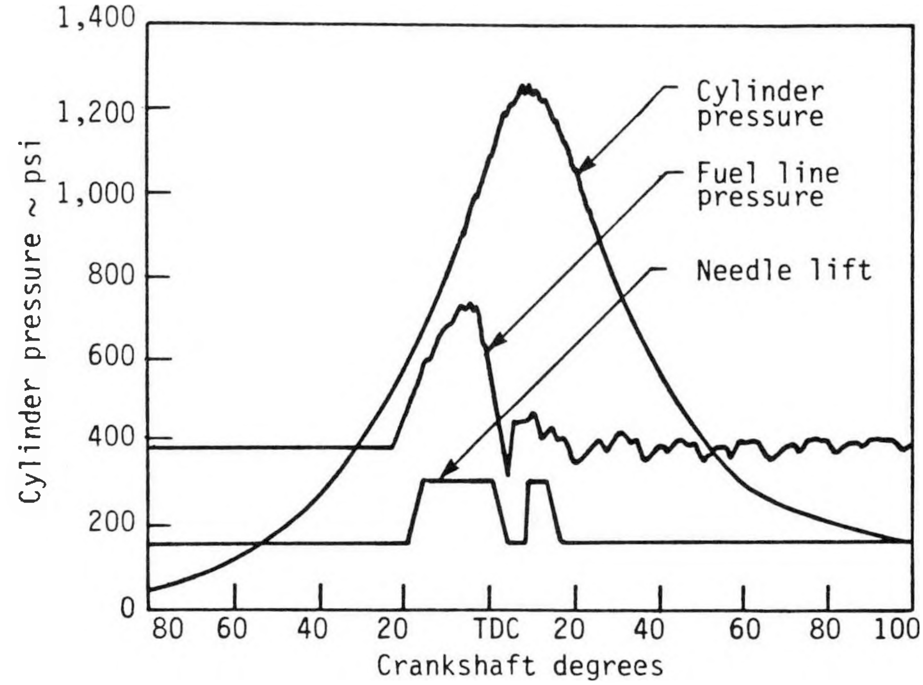


a) Pilot Injector Needle Lift and Fuel Pressure

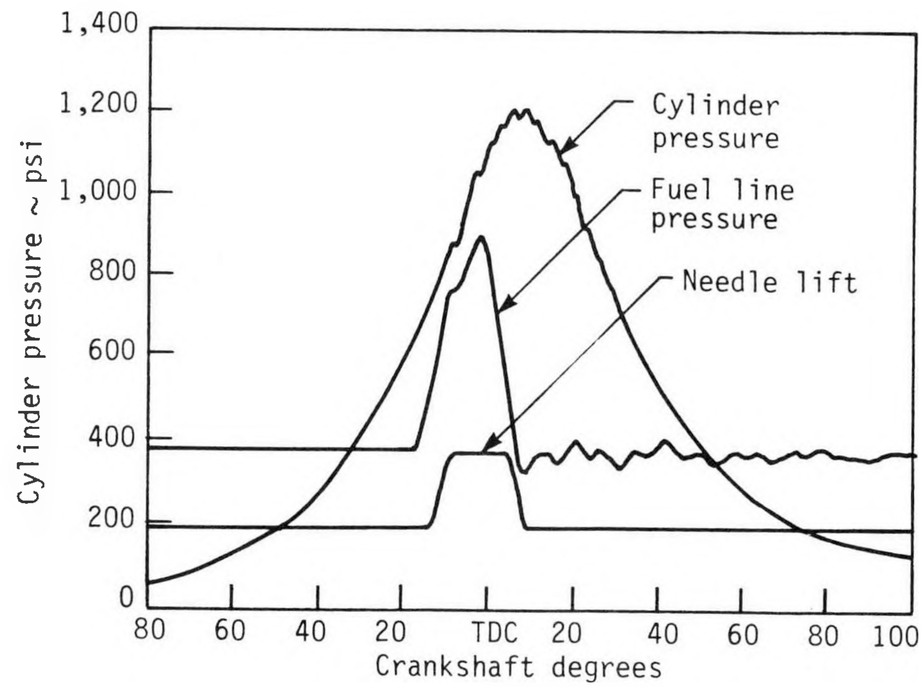


b) Main Injector Needle Lift and Fuel Pressure

Figure 5-4. Cylinder and Fuel Pressure Trace for Pilot Injector Test. (Pilot Injection of Standard Diesel Fuel Corresponding to 5 percent of the Main Charge of RSO)



c) Pilot Injector Needle Lift and Fuel Pressure



d) Main Injector Needle Lift and Fuel Pressure

Figure 5-4. Concluded. (Pilot Injection of Standard Diesel Fuel Corresponding to 15 percent of the Main Charge of RSO) could be displayed simultaneously. Both diagrams show cylinder pressure and degree markers; the top diagram shows pilot injector needle lift and line pressure, and the bottom diagram shows main injector needle lift and line pressure.

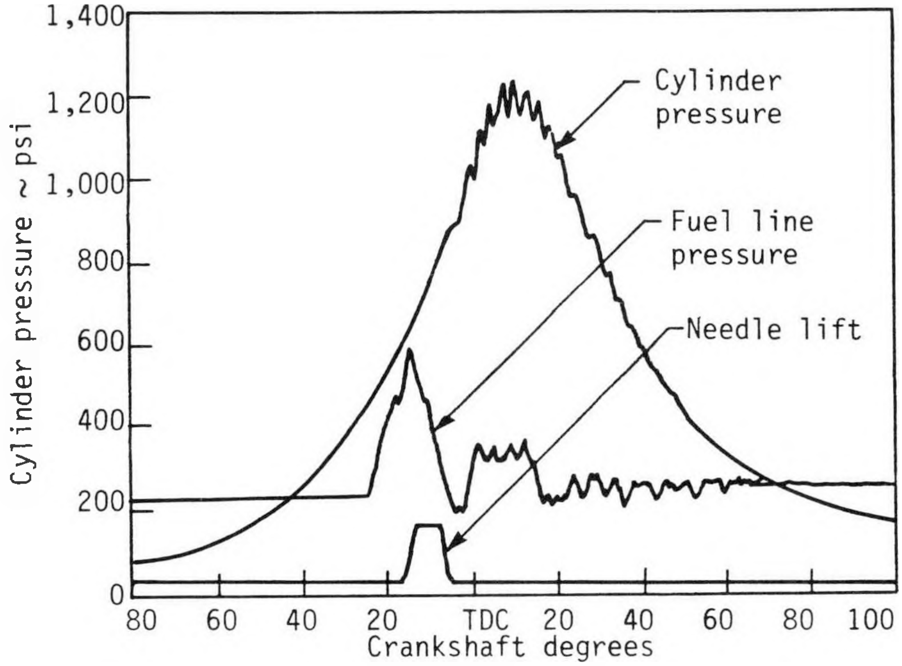
These results show that the normal ignition delay period was almost entirely eliminated, and lower rates of pressure rise were obtained, as was the objective. There appeared to be no advantage in using 15 percent pilot injection, as 5 percent achieved the desired result. Furthermore, severe secondary injection occurred when 15 percent was used, as can be seen from the needle lift diagrams in figure 5-4c. However, this could almost certainly have been eliminated by modifications to the injection pump build, had it been considered necessary.

5.1.3 Dual-Rate Injection

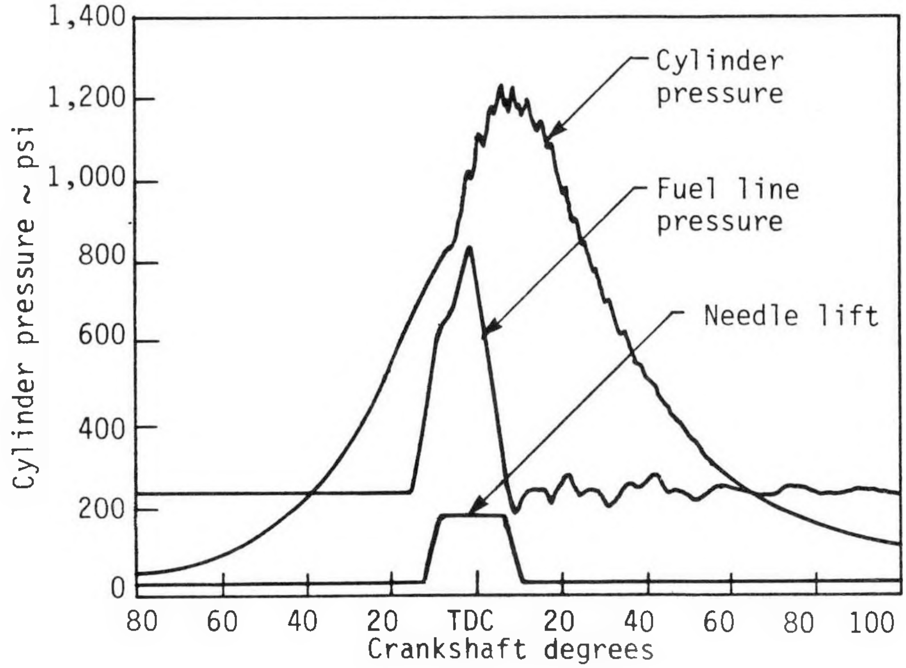
No true dual-rate injection tests were conducted, as this would have required extensive modifications to the injection pump build to provide a prolonged supply of RSO at a low rate from the pilot injection system. However, two tests were conducted with RSO supplied to the pilot injector, using the same build as for the pilot injection tests. The results of these tests are shown in figure 5-5 and are very similar to the results of the pilot injection tests, providing further evidence that the combustion properties of RSO closely resemble those of standard diesel fuel.

5.1.4 Injector Inspection

After completion of the pilot and dual-rate injection test work, both main and pilot injectors were removed from the engine for inspection. Large deposits of soft carbon were found on both injector nozzles, as shown in figure 5-6a. At this time, the main injector had

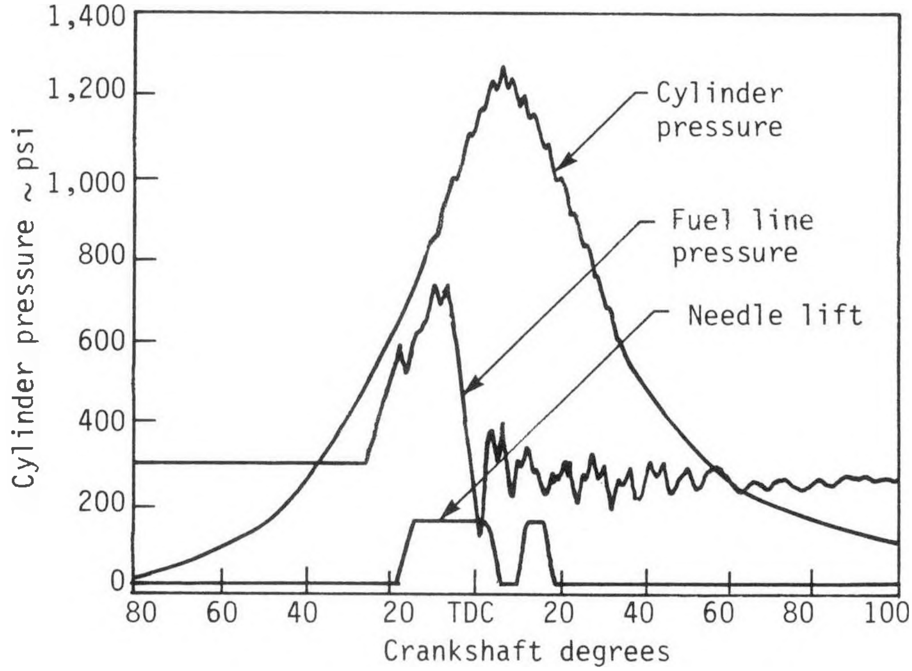


a) Pilot Injector Needle Lift and Fuel Pressure

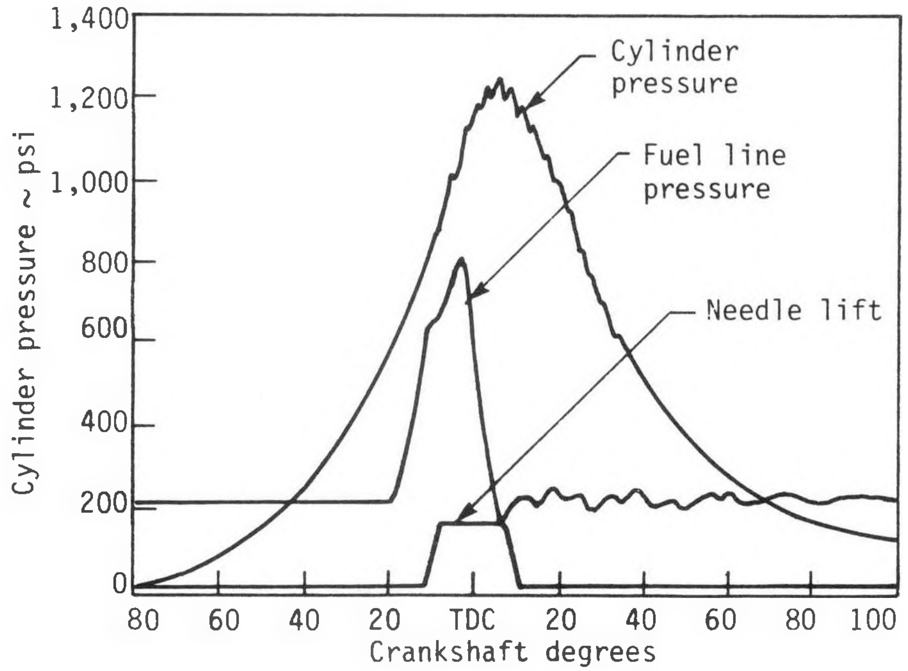


b) Main Injector Needle Lift and Fuel Pressure

Figure 5-5. Cylinder and Fuel Pressure Trace for Dual-Rate Injection Tests. (Pilot Injection of RSO Corresponding to 5 percent of the Main Charge of RSO)

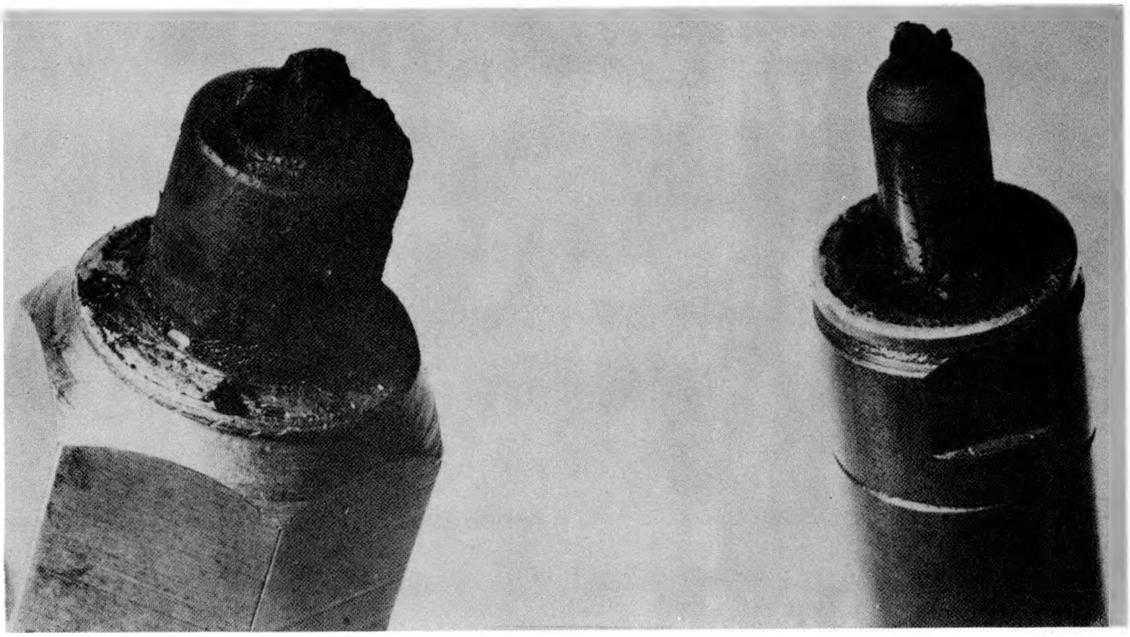


c) Pilot Injector Needle Lift and Fuel Pressure

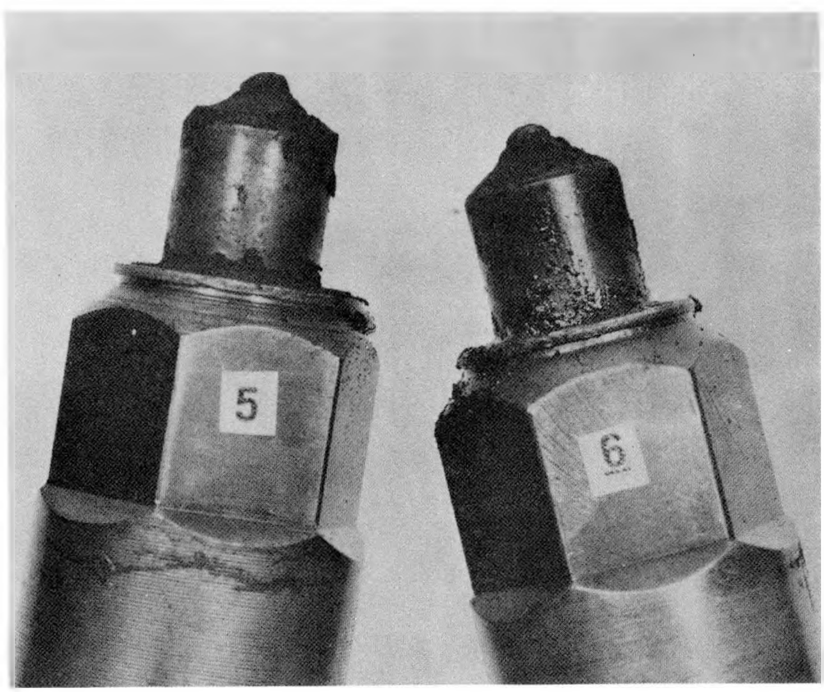


d) Main Injector Needle Lift and Fuel Pressure

Figure 5-5. Concluded. (Pilot Injection of RSO Corresponding to 15 percent of the Main Charge of RSO)



a) Soft Carbon Deposits Found on Test Cylinder Injectors (Cylinder No. 6) After Go/No-Go Tests



b) Carbon Deposits on Cylinder Injectors After Endurance Test

Figure 5-6. Injector Carbon Deposits

been used to supply RSO for a total of 8 hours, the pilot injector just 1.5 hours. The nozzle opening pressure, spray pattern, and atomization of both nozzles were checked and found to be unaffected by the deposits. However, such a large accumulation of carbon in a very short space of time suggested a possible major durability problem; although, the very soft nature of the deposits could result in flaking off after reaching a certain level, particularly during operation at high load.

5.2 PERFORMANCE TESTS

Following the abbreviated series of pilot and dual-rate injection tests, the pilot injection pump was removed. The main injector from No. 6 cylinder was cleaned and replaced, and a dummy pilot injector was fitted.

As was the case with the go/no-go tests, the favorable combustion characteristics of RSO rendered much of the planned performance test matrix redundant. Therefore, performance test work was restricted to a series of tests over the full-load range of the engine at 1,000 rpm, with a check point at 900 rpm, 75 percent load. These tests were conducted first with standard diesel fuel to provide a baseline, then with 100 percent RSO. Full performance and emissions data were recorded at each test point.

The performance tests were repeated after turbocharger and combustion chamber cleaning work and injector nozzle changes prior to endurance testing (see section 5.3). Similar results were obtained, and the results of this second test series are presented in figures 5-7, 5-8, and 5-9.

The engine build was such that specific fuel consumption on standard diesel fuel was typical of this class of engine. (It should be

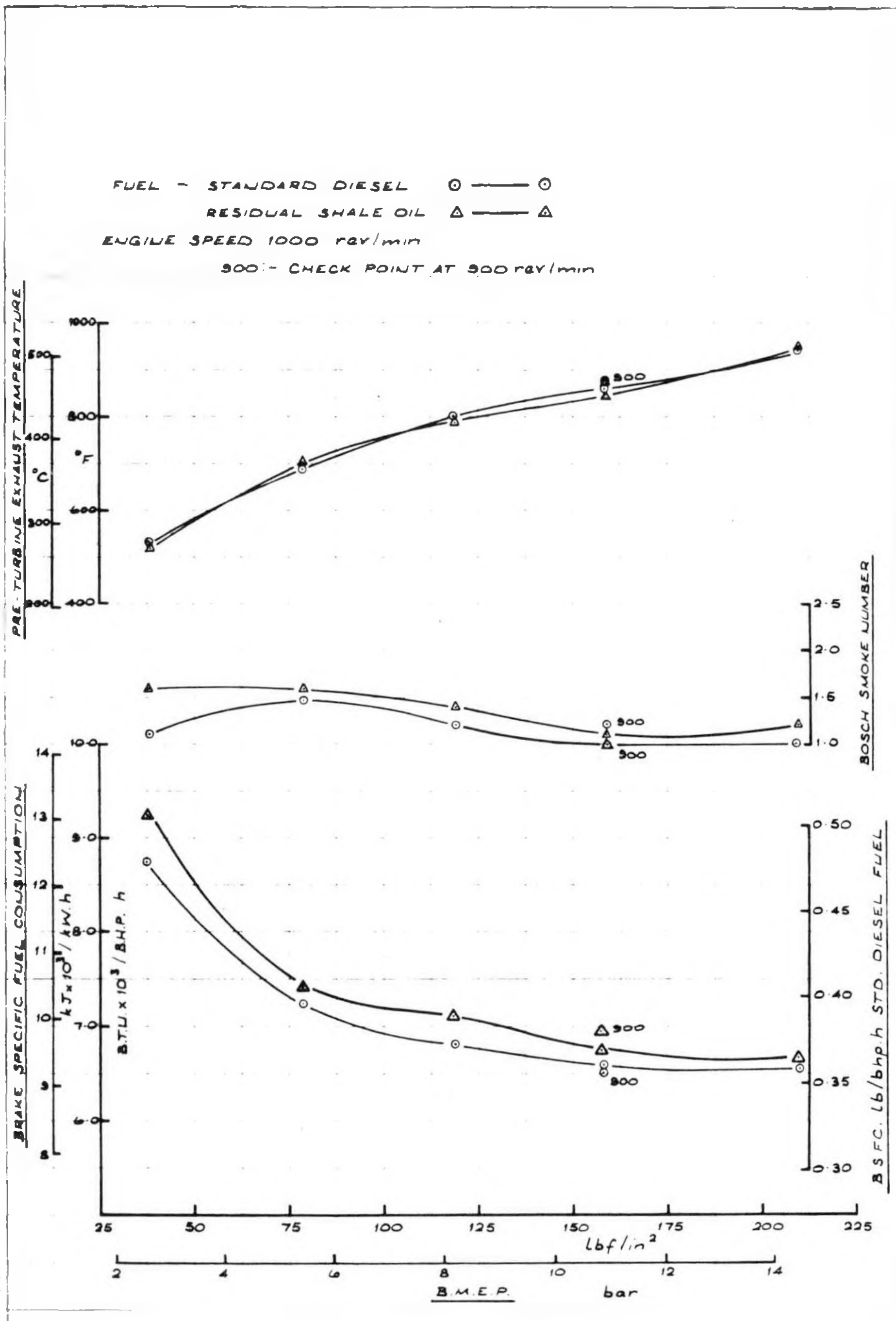


Figure 5-7. Performance Test Results Conducted Prior to Endurance Tests (Exhaust Temperature, Bosch Smoke Number, and BSFC versus BMEP)

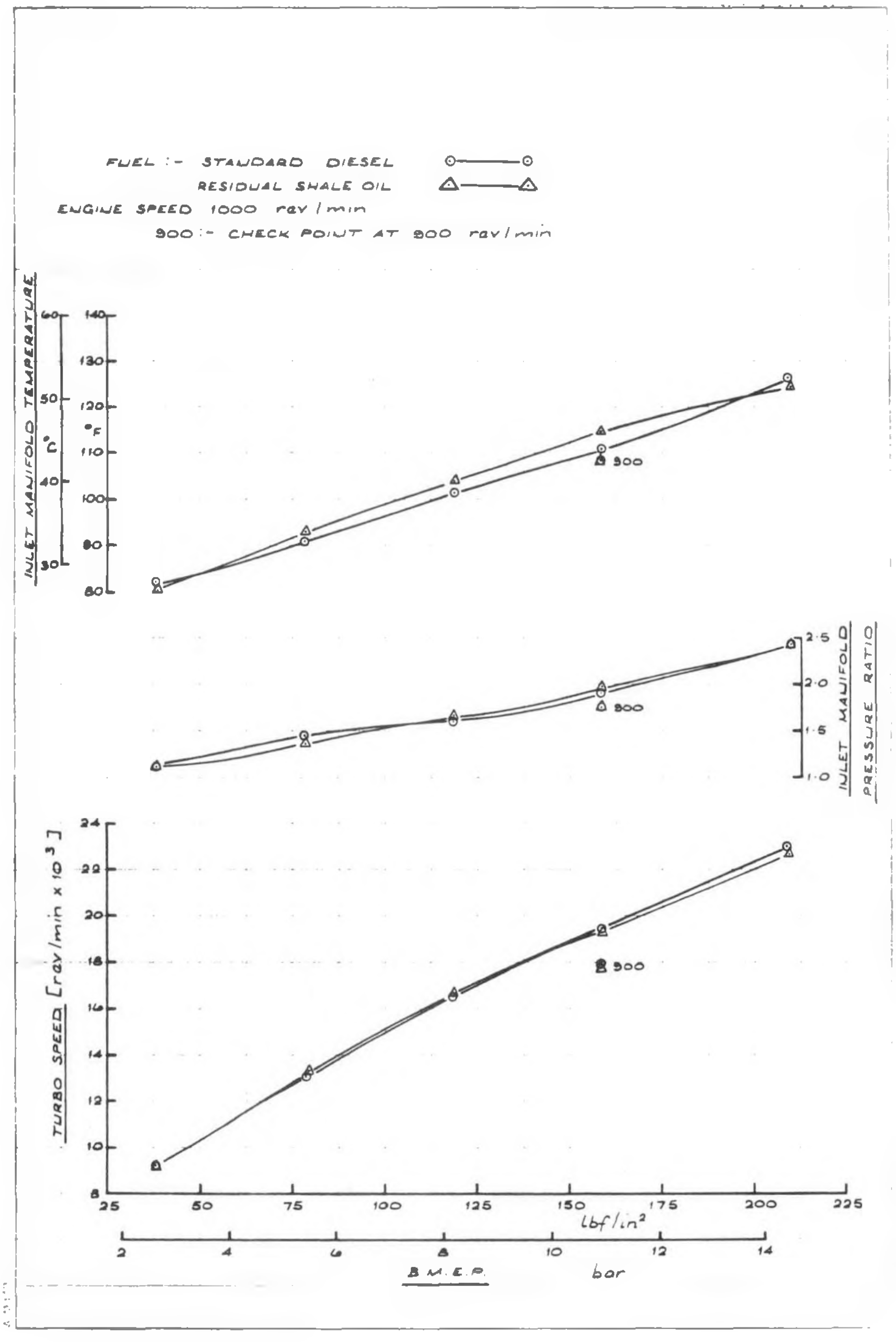


Figure 5-8. Performance Test Results Conducted Prior to Endurance Tests (Inlet Temperature, Inlet Pressure Ratio and Turbo Speed versus BMEP)

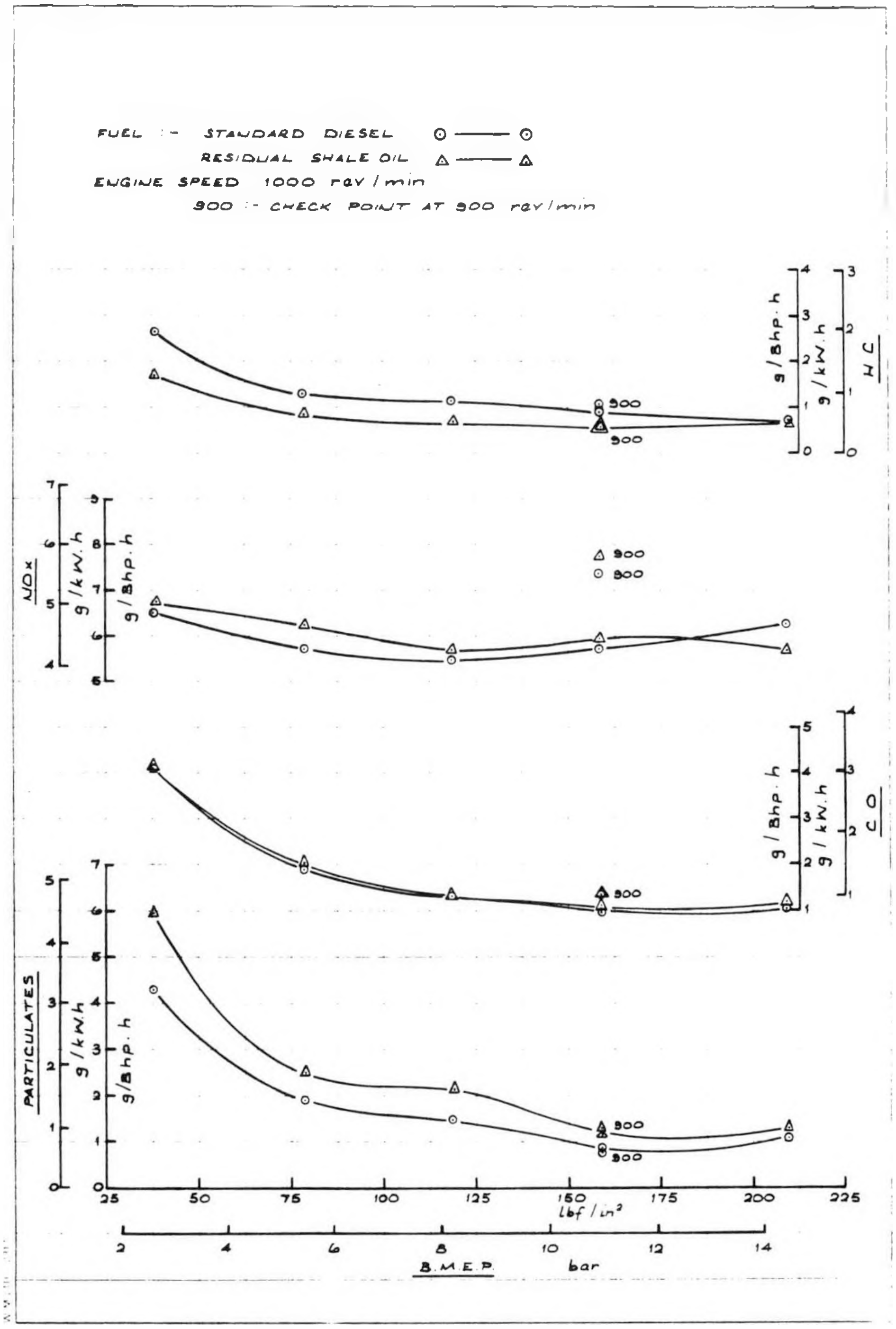


Figure 5-9. Emission Test Results Conducted Prior to Endurance Tests (Unburned Hydrocarbons, NO_X, CO, and Particulates versus BMEP)

noted that the engine was rated at, and optimized for, 275 psi (19 bar) BMEP on standard diesel fuel.)

Specific fuel consumption (on a net calorific value basis) and Bosch smoke number increased slightly when RSO was used, suggesting poorer combustion. However, the hydrocarbon emissions seemed to contradict this, being somewhat lower for RSO. Particulate emissions were higher when RSO was used, especially at light loads. However, the increase was much less than would be expected from a typical residual fuel with a high value of Conradson Carbon Residue. Other performance parameters showed no significant difference in results for the two fuels. NO_x emissions were relatively low for an uncontrolled engine of this class.

Hot-starting tests were conducted with RSO, the engine being shut down for 30 minutes before restarting. Circulation of the heated fuel was maintained through the injection pumps and fuel supply system during this time. The engine restarted normally.

5.3 ENDURANCE TEST

As a result of the savings in time, cost, and fuel by curtailing the go/no-go and performance test programs (made possible by the unexpectedly favorable combustion properties of RSO), it became possible to conduct a short endurance test. This, it was considered, would provide valuable data on possible long-term effects of using RSO, in particular the deposit build-up noted after the go/no-go tests.

To enable accurate assessment of deposit accumulation during the endurance test, the turbocharger and two cylinder heads (No. 5 and No. 6) were removed, stripped, and cleaned immediately before the endurance test was started. All six fuel injectors were removed, cleaned along with the two piston crowns, and tested. One injector (from cylinder No. 4) was found to give poor atomization; therefore, a new nozzle was fitted.

To investigate the effect of nozzle cooling on deposit formation, three of these were fitted to the injectors for cylinder Nos. 1, 3, and 5. A cooling circuit was installed, utilizing engine coolant.

Following this work, the performance tests previously described were repeated in case the cleaning work and injector nozzle changes had affected the engine performance. It was, of course, essential to establish an accurate performance baseline before commencing the endurance test.

A test cycle of 1-1/2 hours at 1,000 rpm, 100 percent load, followed by 1/2 hour at 500 rpm, no load, was used throughout the endurance test. It was felt that this would provide a high rate of deposit accumulated while including a realistic amount of transient operation. At the beginning of each day of testing, the engine was started and warmed up to normal operating temperature on standard diesel fuel before switching to RSO. At the end of each day, the fuel supply was changed to standard diesel approximately 15 minutes before engine shutdown. A full set of readings was taken during each cycle at the full load condition to ensure that any adverse trends could be quickly identified. Also, samples of the engine lubricating oil were taken at regular intervals for spectrographic analysis.

During the endurance test, after approximately 60 hours operation, a loss of fuel supply pressure occurred. The felt element of the fuel filter was found to be plugged with wax. This was attributed to the filter being unheated. Also, during startup and shutdown, cool, standard diesel fuel was being passed through the filter. The filter element was replaced and a heating element fitted around the filter housing and lagged. The startup and shutdown procedure was altered to provide for heating of the standard diesel fuel.

Throughout the endurance test, a high exhaust smoke level was observed during transient operation from idle to full load (duration of transient was approximately 40 seconds). The smoke began as white smoke and became brown in color as load increased, reducing to the normal level of smoke at full load.

After 100 hours of endurance testing, performance tests over the load range were repeated with both fuels. The results are shown in figures 5-10, 5-11, and 5-12. These tests were carried out at this point to eliminate the possibility of having insufficient fuel left to conduct the performance tests as only a small quantity of RSO fuel remained. Following the performance tests, the endurance test was continued until all remaining RSO had been consumed, which occurred at 115 hours. The results of readings taken throughout the endurance test are shown in figure 5-13 for those parameters likely to be most sensitive to deposit accumulations. Analysis results of oil samples are shown in table 5-1.

The engine was partially stripped for inspection after completion of the endurance test. All six injectors were removed, and the quantity of carbon deposits on cooled and uncooled nozzles was found to be similar. Two representative nozzles, from cylinder No. 5 (cooled) and No. 6 (uncooled) are shown in figure 5-6b. These deposits were of a lesser quantity than those found after the go/no-go tests (see figure 5-6a) after only 8 hours of running on RSO, suggesting that the deposits flake off during engine operation at high load.

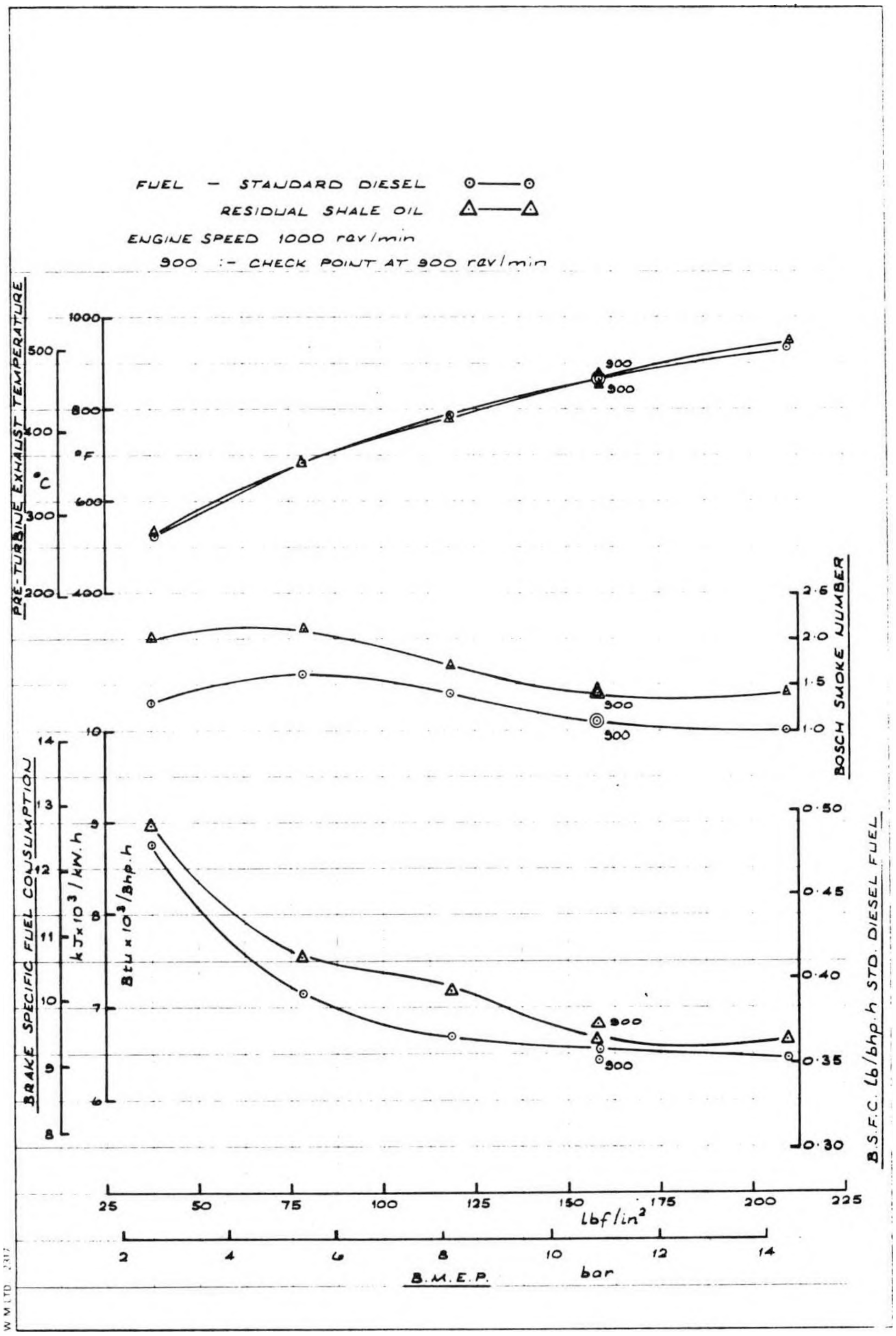


Figure 5-10. Performance Test Results Conducted After Endurance Tests (Exhaust Temperature, Bosch Smoke Number, and BSFC versus BMEP)

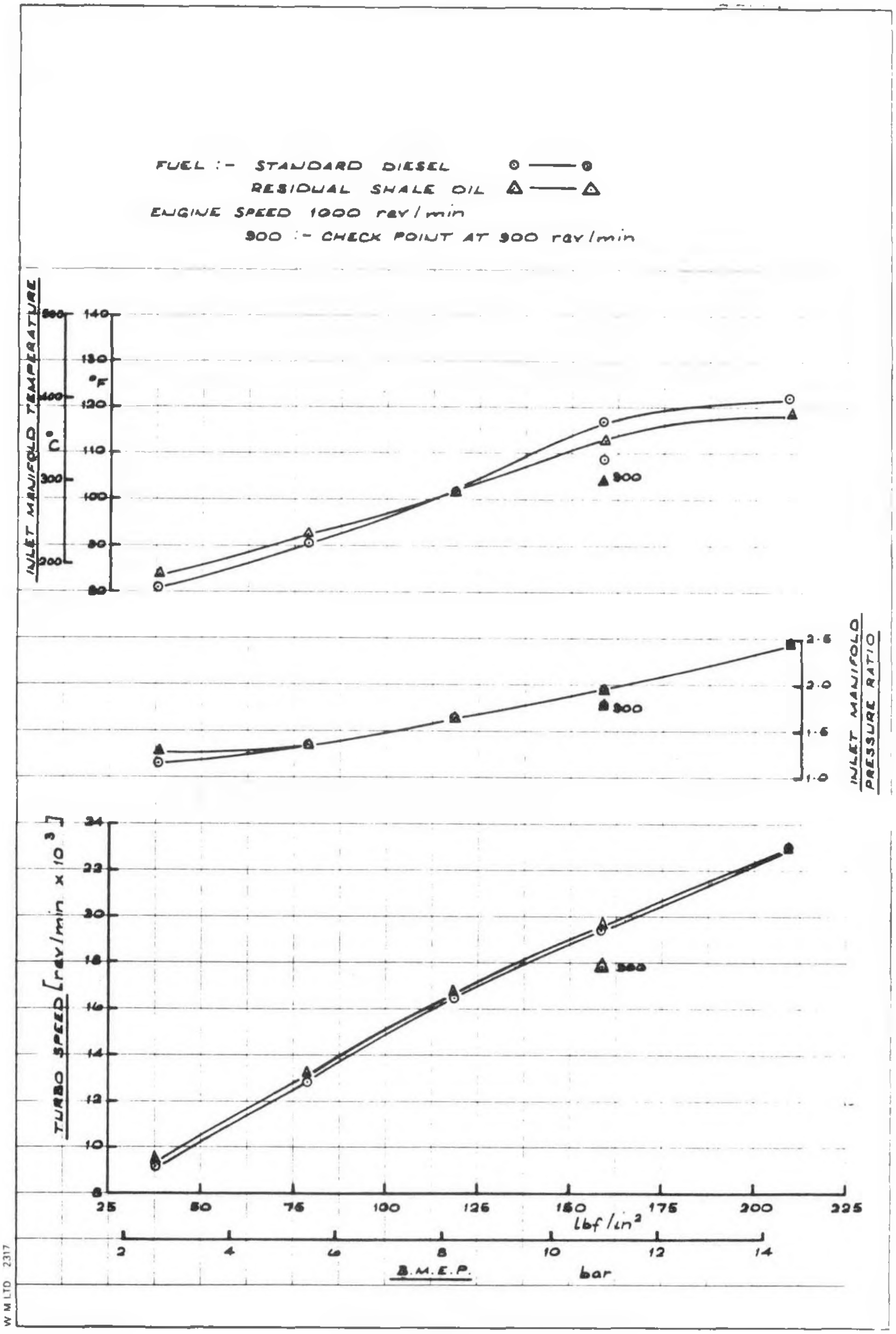


Figure 5-11. Performance Test Results Conducted After Endurance Tests (Inlet Temperature, Inlet Pressure Ratio and Turbo Speed versus BMEP)

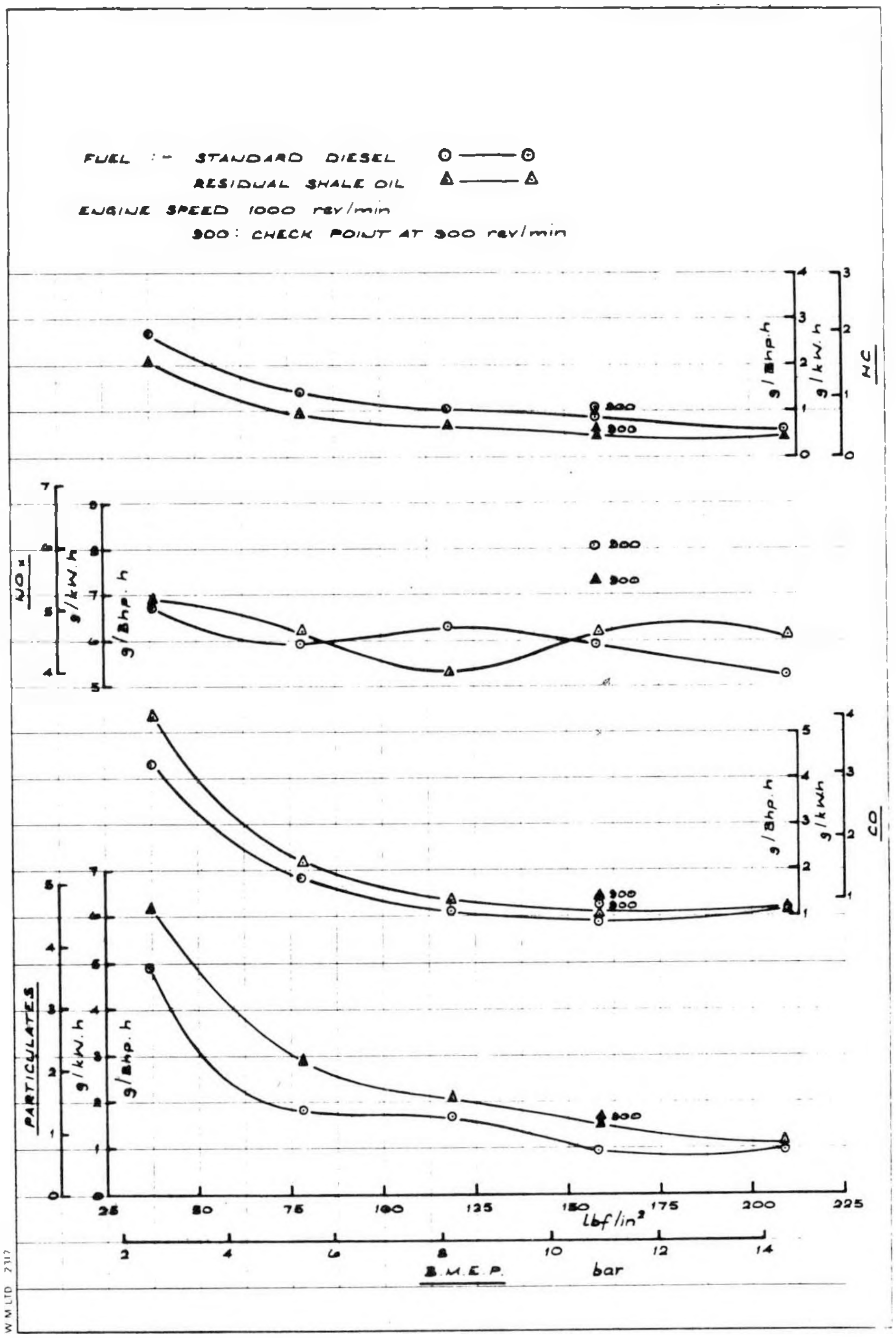
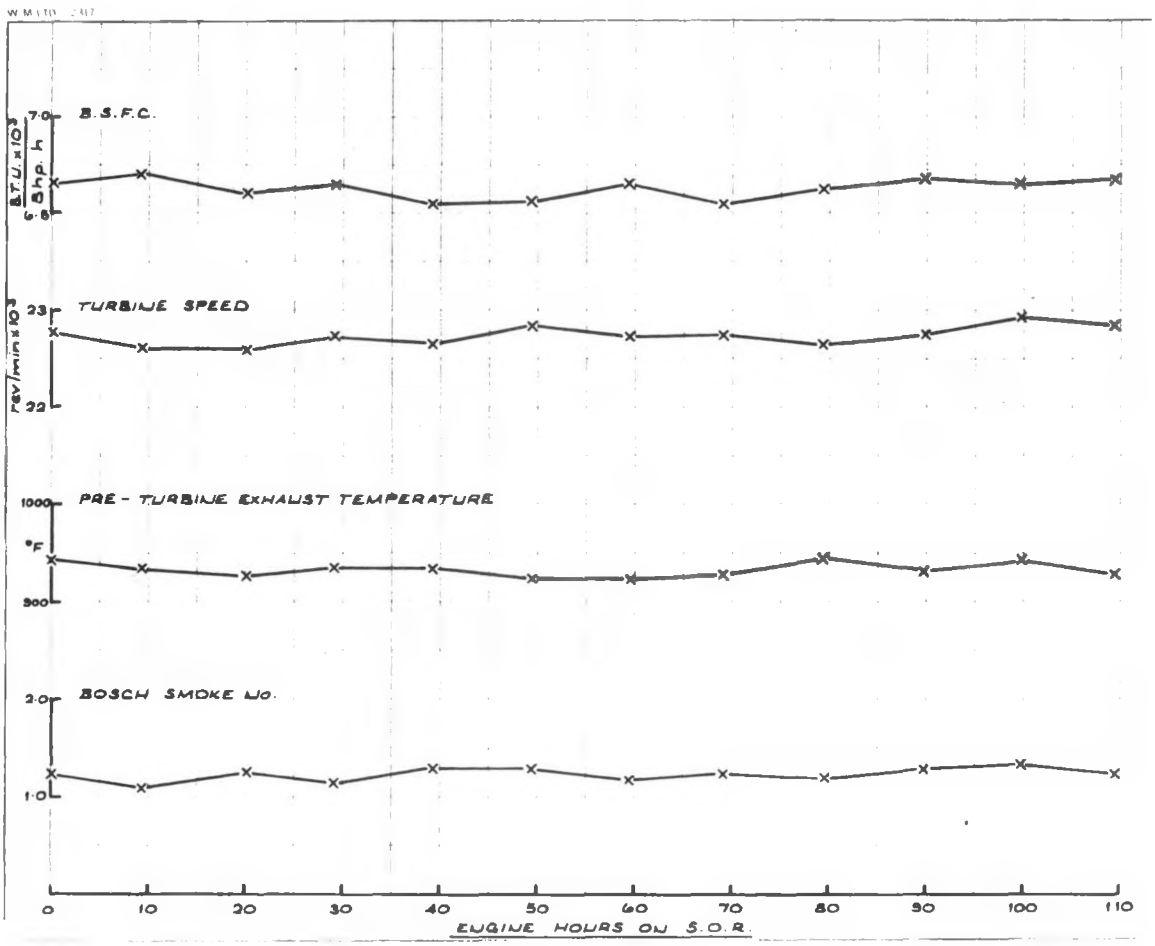


Figure 5-12. Emission Test Results Conducted After Endurance Tests (Unburned Hydrocarbons, NO_x, CO, and Particulates versus BMEP)



Note: <u>Test cycle:</u>

-1.5 hours at 1000 rpm, BMEP = 210 psi
-0.5 hours at 500 rpm, no load
Test points taken at 1000 rpm, BMEP = 210 psi

Figure 5-13. Variation of Performance and Emission Parameters During Endurance Tests

Table 5-1. Analysis of Lubricating Oil Samples Taken During Endurance Test

Endurance Hours	10	40	62	87	114
KV at 100°C	10.90	11.10	11.00	11.30	11.30
Dilution	N	N	N	N	N
Water (%)	0.1	0.1	0.1	0.1	0.1
Insolubles (%)	0.40	0.60	0.70	0.70	0.80
Dispersancy (%)	75.0	73.0	75.0	70.0	74.0
Phosphorus (%)	0.085	0.085	0.086	0.077	0.083
Zinc (%)	0.102	0.103	0.103	0.099	0.100
Calcium (%)	0.408	0.462	0.407	0.437	0.433
Barium (%)	0.002	0.002	0.002	0.002	0.002
Magnesium (ppm)	49	50	46	44	51
Aluminium (ppm)	5	3	4	3	3
Iron (ppm)	18	19	19	19	22
Chromium (ppm)	1	1	1	1	1
Copper (ppm)	5	5	4	4	4
Lead (ppm)	3	2	3	1	1
Tin (ppm)	1	1	1	1	1
Silicon (ppm)	6	5	6	4	6
Sodium (ppm)	94	79	88	83	79
Boron (ppm)	4	4	4	3	4
Vanadium (ppm)	11	10	11	9	10

Oil Type: Shell Rotella TX30

Cylinder heads and pistons were removed from cylinders 5 and 6. Both cylinder heads had been cleaned before starting the endurance test, and both had similar carbon deposits. The head from cylinder No. 6 is shown in figure 5-14. The only significant carbon deposit occurred between the exhaust valves, towards the outside of the combustion chamber.

The valves were removed from both cylinder heads. Photographs of the front inlet and front exhaust valve seats are shown in figure 5-15. Both seats were stained but otherwise in good condition, and this was the case for all the other valve seats examined. A small amount of carbon deposit can be seen just inside the ports, both inlet and exhaust. Again, this was typical of all those examined. The seat faces of all four valves from cylinder No. 6 are shown (after cleaning) in figure 5-16. All seating faces were in good condition, but the exhaust valve seating faces showed black stains.

Figure 5-17 shows part of No. 6 cylinder liner. Slight carbon deposits were present on the liner area above the top piston ring, but these were not abnormally great. Cylinder No. 5 was in a similar condition.

The piston crowns from cylinders 5 and 6 are shown in figure 5-18. Substantial carbon deposits were present around the outer edge of the front of the combustion chamber. These deposits were quite hard and of a white appearance when disturbed. This can be seen around one of the extraction holes on No. 6 piston in figure 5-18. This suggests that these deposits were due at least, in part, to the lubricating oil.

The thrust and nonthrust faces of pistons 5 and 6 can be seen in figure 5-19. These showed no evidence of abnormal wear, deposits, or piston ring leakage. A close-up view of the piston rings and ring grooves

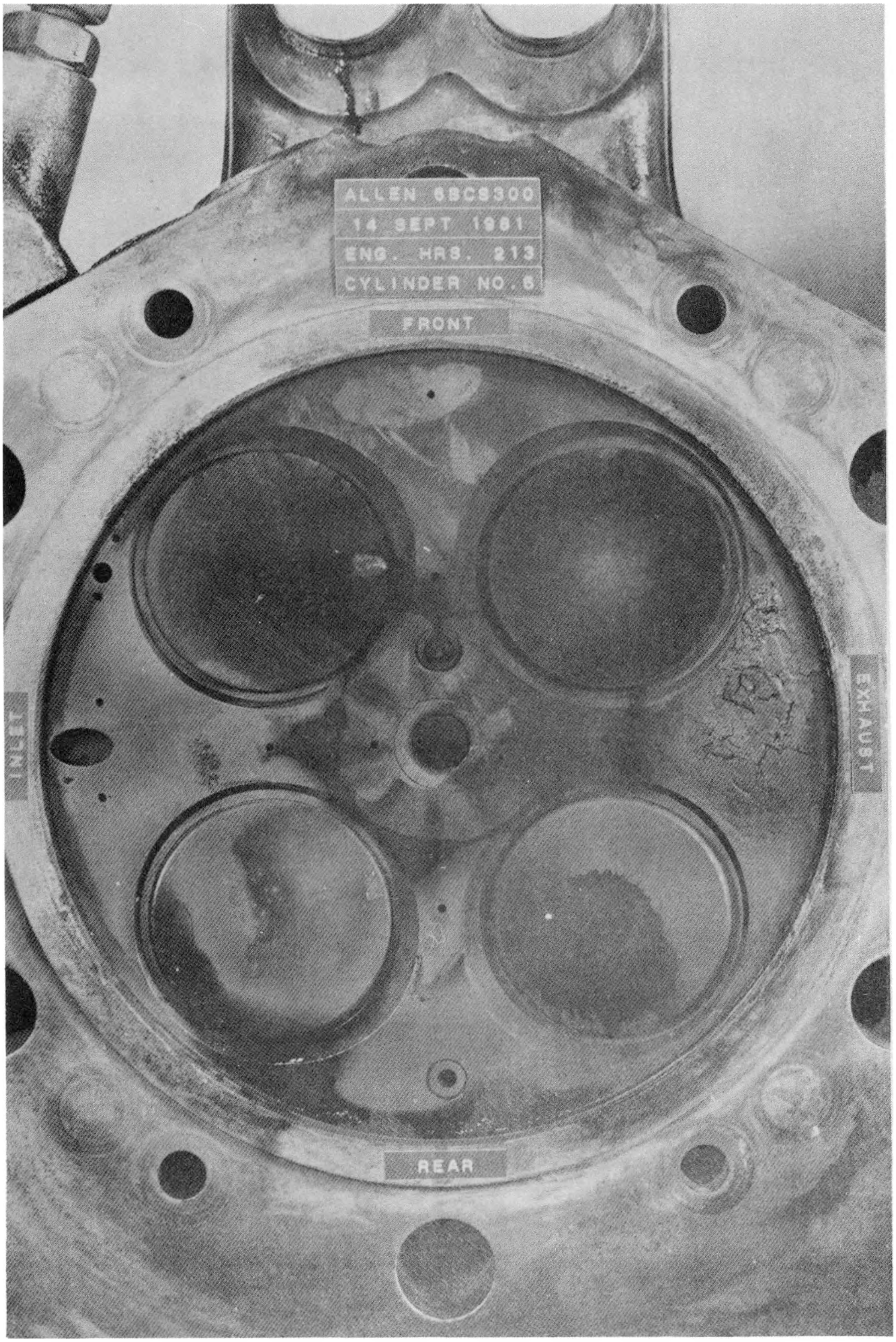
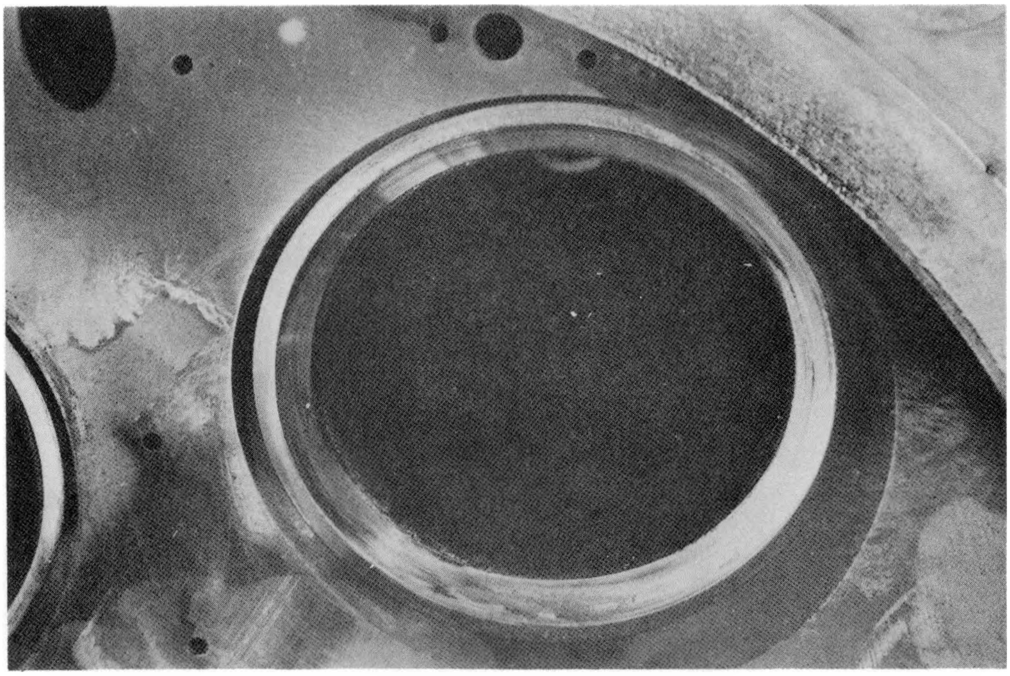
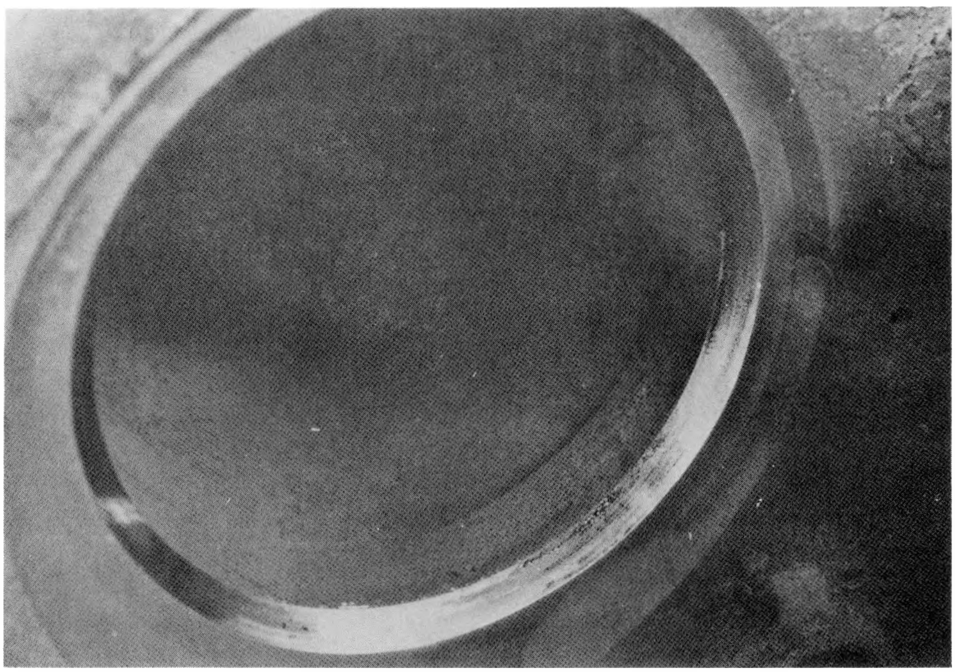


Figure 5-14. Carbon Deposits on Cylinder Head After Endurance Tests



a) Front Inlet Valve Seat



b) Front Exhaust Valve Seat

Figure 5-15. Valve Seat Condition After Endurance Tests

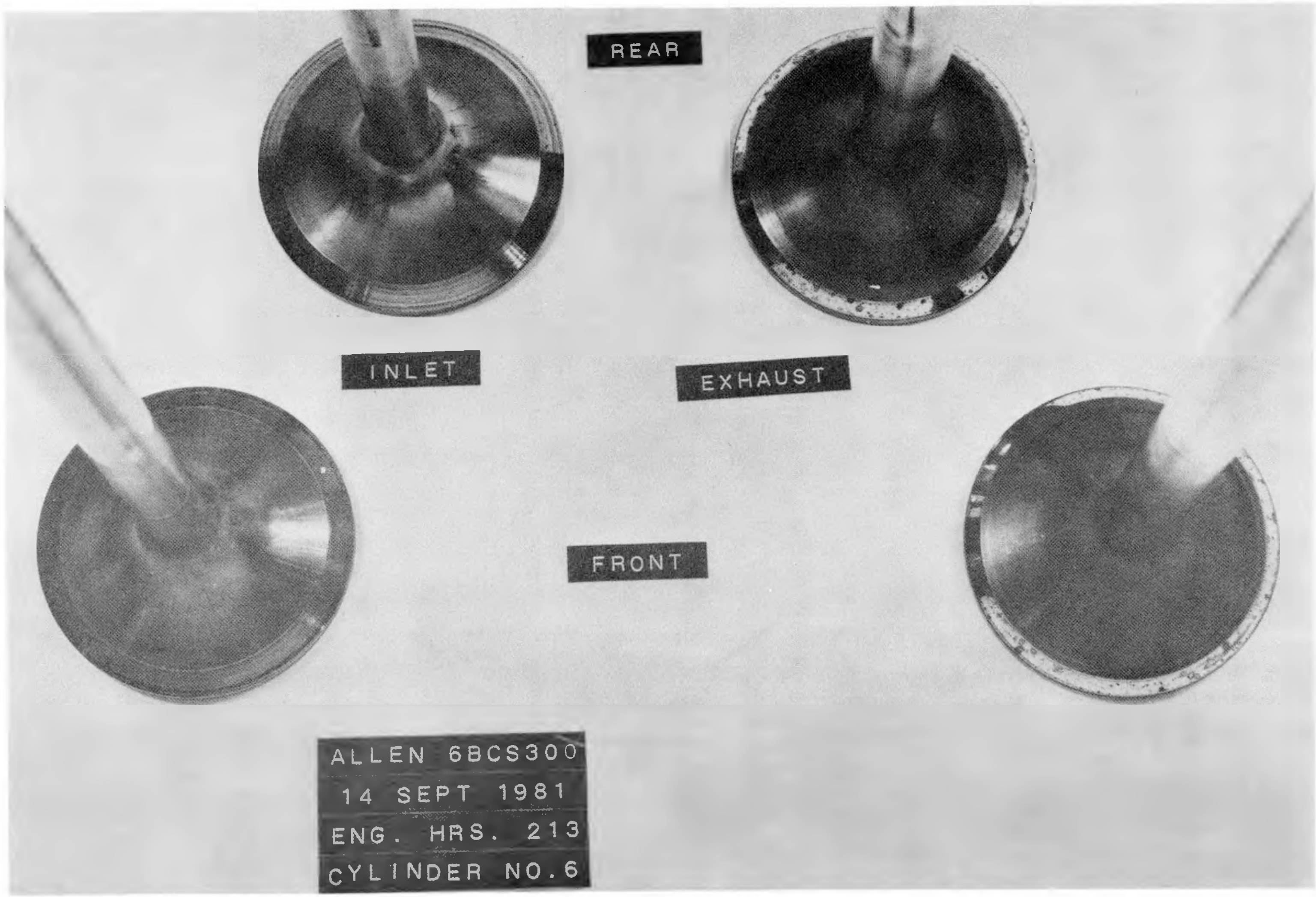


Figure 5-16. Valve Seat Face Conditions After Endurance Tests

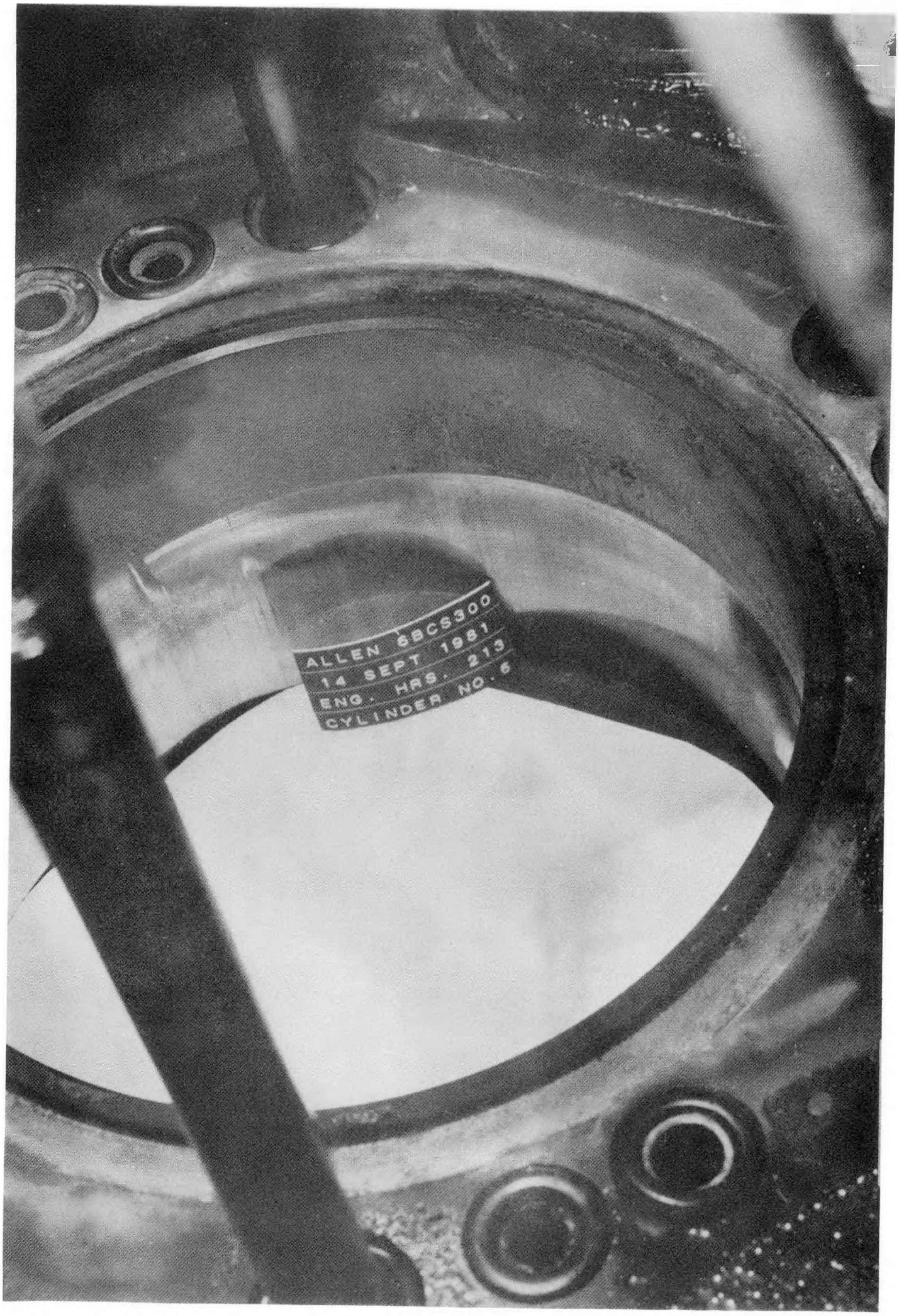


Figure 5-17. Cylinder Liner Condition After Endurance Tests

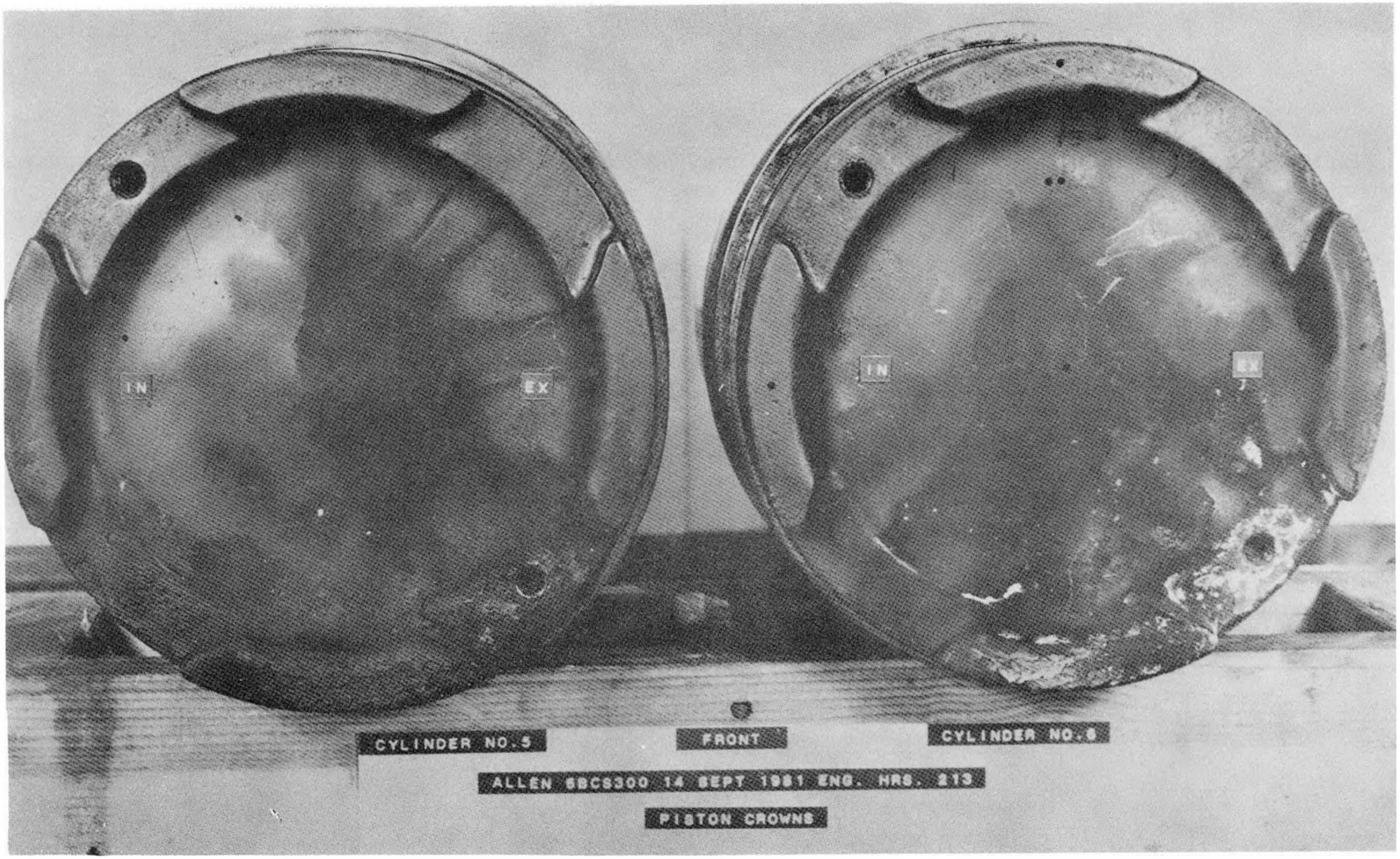
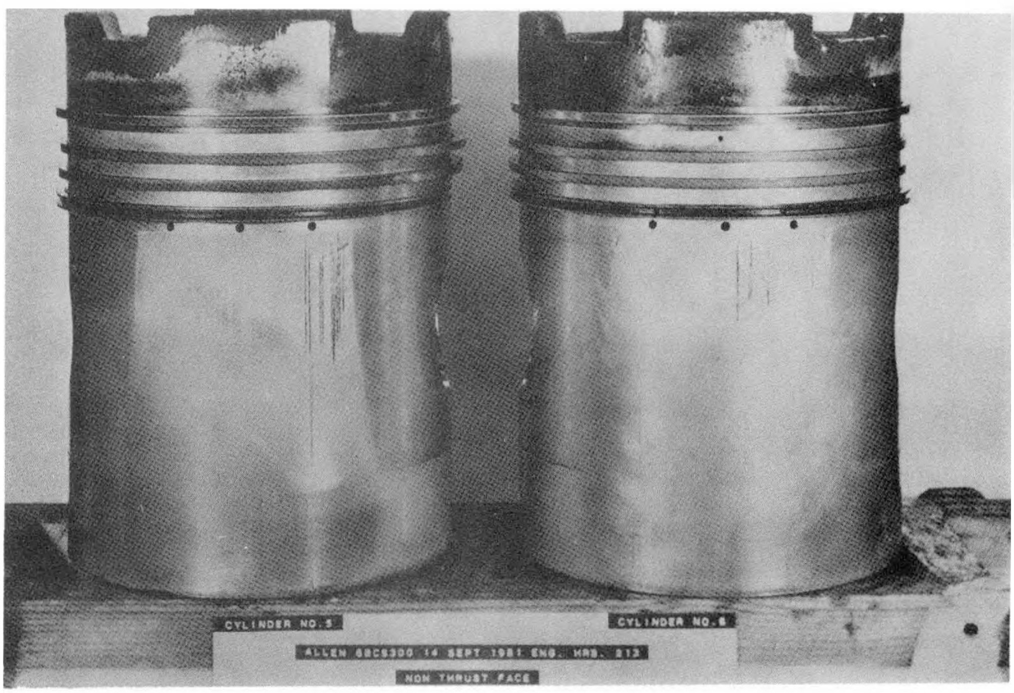


Figure 5-18. Condition of Piston Crowns After Endurance Tests

a) Thrust Face



b) Nonthrust Face

Figure 5-19. Condition of Piston Faces After Endurance Tests of piston No. 6 is shown in figure 5-20. A very light carbon deposit was present behind the top ring but, as ring grooves were not cleaned before the endurance test, this was not considered abnormal.

It should be noted that the small holes visible on No. 6 piston were drilled for Templugs on a previous occasion and are in no way connected with the tests reported here.

Analysis results of samples of lubricating oil taken at intervals during the endurance test are given in table 5-1. No measurable fuel dilution occurred, and there was no significant change in any of the factors covered by the analysis.

While the 115-hour duration of the endurance test was not sufficient to provide accurate data on the long-term effects of using RSO, useful information was nevertheless obtained.

- The filter plugging problem which occurred during the endurance test illustrated the importance of ensuring that fuel temperatures exceeded the wax melting point at all times.
- Carbon deposit build-up on the injector nozzles was not as severe as might have been expected from the deposits found after the go/no-go tests. However, the level of deposits throughout the combustion chamber and in the ports was greater than a standard diesel fuel would cause. This suggests that more frequent overhaul may be required when using RSO.
- There was no indication of deterioration of turbocharger efficiency or any aspect of engine performance at full load during the course of the endurance test. The only significant change revealed by the performance tests conducted before starting the endurance test and at 100 hours was in the

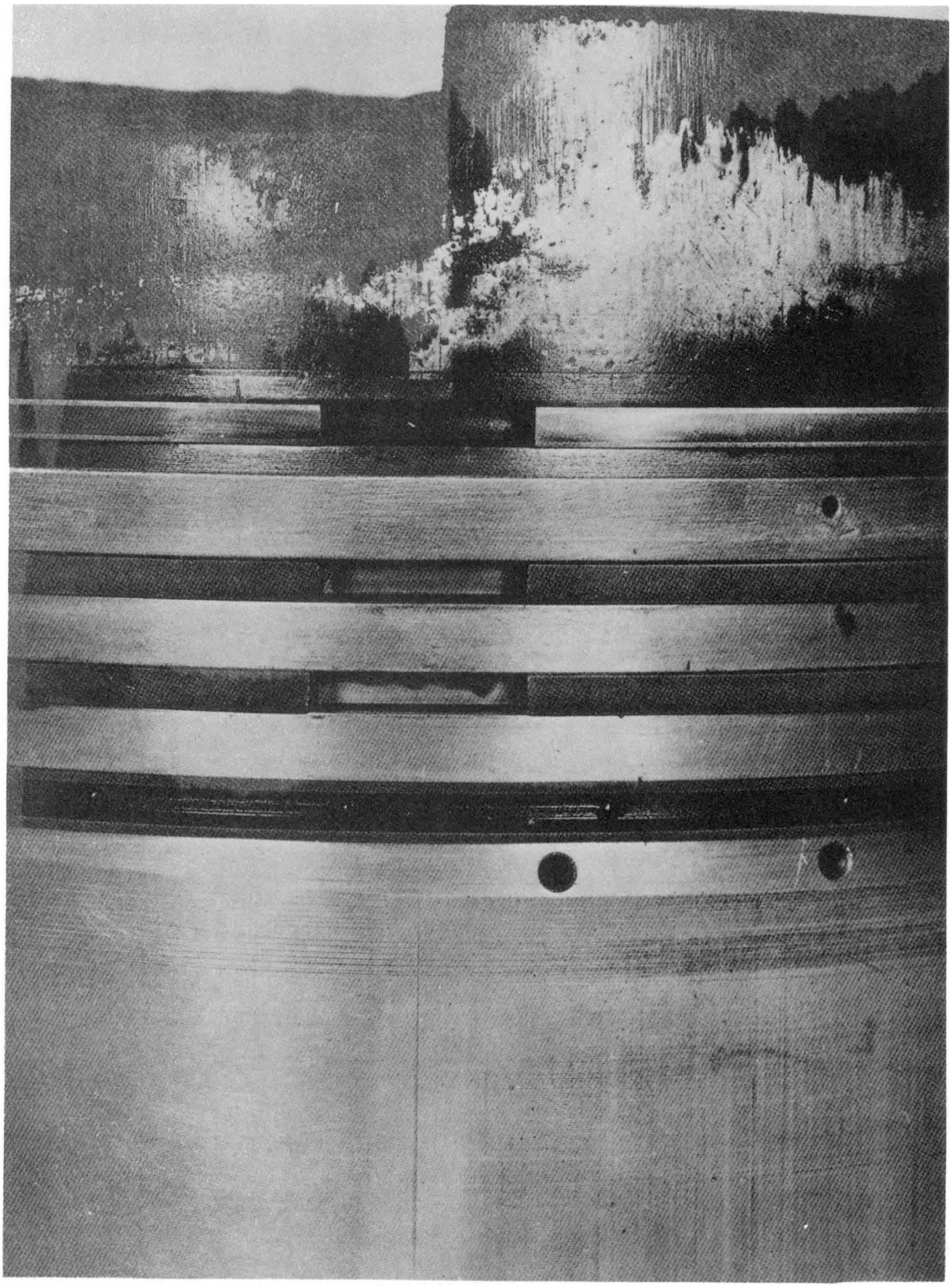


Figure 5-20. Condition of Piston Rings After Endurance Tests (Piston no. 6)

light-load, Bosch smoke number. This showed an increase after 100 hours, but only when RSO was used.

- The high transient smoke levels observed when increasing load from idle are not uncommon on engines of this class. Two possible causes are oil accumulation in the ports during idling and turbocharger lag giving rise to over-rich air/fuel ratios.
- Engines designed or modified for residual fuel operation often have reduced valve overlap to minimize port fouling during light load operation. This also helps to reduce transient smoke levels.

SECTION 6

CONCLUSIONS

As part of a DOE study to determine the effective utilization of alternate fuels in medium-speed diesel engines, an RSO was fired in an APE-Allen, 1,000-rpm, 9.5-in. bore diesel engine. Various fuel injection modes were considered (i.e., direct firing of blends with No. 2 diesel fuel, pilot injection with No. 2 diesel fuel, and dual-rate injection of the RSO). Based on a fuel characterization study and go/no-go tests, it was determined that the direct firing of 100 percent RSO gave performance comparable with that using No. 2 diesel fuel; consequently, performance/endurance tests were performed using 100 percent RSO.

Conclusions of this test program are:

- Laboratory tests showed low levels of corrosion and deposit-causing elements. Therefore, corrosion and wear of engine components, when using RSO, should be no worse than for standard diesel fuel.
- The high wax content of RSO requires heating for supply, handling, and injection systems.
- Laboratory tests showed that the cetane number of RSO was equivalent to No. 2 diesel; hence, no engine modifications should be needed to burn RSO. This was confirmed by the engine tests.
- The engine performance on RSO was essentially similar to standard diesel fuel. The thermal efficiency was slightly lower and Bosch smoke and particulates were slightly higher, especially at low load.
- Soft carbon deposits, formed on injectors when using RSO, did not affect performance.
- The 115-hour endurance test showed no significant performance deterioration. The deposit accumulation in combustion chambers and ports was not severe but was greater than standard diesel fuel would produce. Longer endurance tests are required to fully establish this conclusion.

APPENDIX A

PILOT INJECTOR NOZZLE SELECTION

A range of pilot injector nozzles was specially made with an offset of 16^{0}, this being the angle at which the pilot injector was inclined to the vertical axis of the cylinder. The spray cone angle of the main injector was 150^{0}; this was therefore selected as a suitable cone angle for the pilot injector nozzles. However, as pilot injection would be completed before the piston reached TDC, a smaller cone angle could be used. A study of the piston position during the estimated duration of pilot charge injection showed that a spray cone angle of 120^{0} would provide optimum coverage of the cylinder volume existing at that time. Nozzles were therefore obtained with spray cone angles of both 120^{0} and 150^{0}.

The number and size of holes in the injector nozzles were selected on the basis of spray penetration calculations. The formulas used for these calculations were as follows:

Pressure drop ΔP across nozzle hole:

$$\Delta P = \left(\frac{0.0432 \times V \times N}{A \times n \times d^{2}}\right)^{2} \text{ bar} \qquad (1)$$

Spray penetration L:

$$L = \sqrt{2,676 \times t \times d \times \sqrt{\frac{P}{e}}} \text{ mm} \qquad (2)$$

where ΔP = nozzle pressure drop (bar)

V = fuel volume per injection (mm^3)

N = engine speed (rev/s)

A = injection period (^{o} crank)

n = number of holes

d = hole diameter (mm)

L = spray penetration (in time t) (mm)

t = time for penetration L (ms)

e = charge density (kg/m^3)

Combining (1) and (2):

$$d = \frac{115.6 \times t \times V \times N}{L^2 \times A \times n \times \sqrt{e}} \text{ mm} \qquad (3)$$

or:

$$L = \sqrt{\frac{115.6 \times t \times V \times N}{A \times n \times d \times \sqrt{e}}} \text{ mm} \qquad (4)$$

The values of variables required to determine hole diameter were found to be:

Fuel volume (V) and injection period (A): These two variables combine to give an injection rate (V/A, mm^3/degree) which is a constant determined by the injection pump build. Pilot injection tests required a high injection rate, dual-rate tests a low injection rate. The maximum and minimum rates obtainable with the available pump elements and camshafts were 22.2 mm^3/degree and 11.8 mm^3/degree, respectively.

Engine speed (N): All tests were to be conducted at a speed of 1,000 rev/min (16.67 rev/s).

Spray penetration (L): A study of the combustion chamber geometry showed that a maximum penetration of 110 mm could be sought without risk of fuel impingement on the combustion chamber walls.

Time for Penetration (t): As spray penetration before ignition is being considered, t is equivalent to the ignition delay of the fuel, typically 8 to 10^0 for standard diesel fuel (1.33 to 1.67 ms at 1,000 rev/min). Ignition delay for RSO was unknown, but expected to be on the order of 15 to 18^0 (2.5 to 3.0 ms).

Charge density (e): This was evaluated from the conditions of compression pressure and temperature estimated to exist in the combustion chamber at the point of injection at the specified test speed and load of the engine. A value of 35 kg/m^3 was obtained.

Number of holes (n): The main injector had ten holes; and, therefore, a large number of holes were desirable for the pilot injector. However, the minimum hole diameter which could be produced was 0.25 mm, which, in turn, limited the number of holes that could be used. Three holes were considered an acceptable minimum.

Specimen Calculations

1. Pilot Injection of Standard Diesel Fuel

$V/A = 22.2\ mm^3/degree$ ("pilot" injection)

$N = 16.67$ rev/s

$L = 110$ mm

$t = 1.33$ ms (standard diesel fuel)

$e = 35\ kg/m^3$

$n = 3$

$$d = \frac{115.6 \times 1.33 \times 22.2 \times 16.67}{110^2 \times 3 \times \sqrt{35}}$$

$= 0.265$ mm

2. Dual-Rate Injection of RSO

$V/A = 11.8\ mm^3/degree$ ("dual-rate" injection)

$N = 16.67$ rev/s

$L = 110$ mm

$t = 3.00$ ms (RSO fuel)

$e = 35\ kg/m^3$

$n = 4$

$$d = \frac{115.6 \times 3.00 \times 11.8 \times 16.67}{110^2 \times 3 \times \sqrt{35}}$$

$= 0.238$ mm

Further calculations for the available variations of V/A and expected range of values of t indicated that satisfactory spray penetration could be obtained at all conditions with a range of three nozzle hole number/diameter combinations, as follows:

3 holes: 0.25 mm diameter

3 holes: 0.30 mm diameter

4 holes: 0.25 mm diameter