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COAL-LIQUID FUEL/DIESEL ENGINE OPERATING COMPATIBILITY

Final Report

By
J. G. Hoffman
F. Martin

September 1983

Work Performed Under Contract No. AC19-79BC10110

General Electric Company
Corporate Research and Development
Schenectady, New York

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COAL-LIQUID FUEL/DIESEL ENGINE OPERATING COMPATIBILITY

FINAL REPORT

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SEPTEMBER 1983

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COAL-LIQUID FUEL/DIESEL OPERATING COMPATIBILITY

J.G. Hoffman and F.W. Martin

INTRODUCTION

This work is intended to assess the possibilities of using coal-derived liquids (CDL) represented by a specific type (SRC II) and shale-derived distillate fuel in blends of petroleum-derived fuels in medium-speed, high-output, heavy-duty diesel engines. The study was conducted jointly by General Electric Corporate Research and Development (CRD) and General Electric Locomotive Engineering Department. The primary thrust of the study was engine tests conducted in the Locomotive Department test laboratories in Erie, Pennsylvania. Additionally, a limited number of bench scale experiments, into the combustion characteristics of CDL fuels, were performed at CRD. Initially this program called for the evaluation of one specific nonpetroleum-derived alternative fuel. This coal-derived liquid is known as solvent-refined coal (SRC II). The project was subsequently modified to include a fully refined shale-derived liquid.

The class of diesel engine to which this work is most specifically aimed can be generally categorized as medium speed (approximately 1200 rpm maximum), medium bore and stroke, and high output. This class of engine is very widely used in the U.S. for a multitude of purposes. These purposes include: locomotive power plants, power generation, inland marine, and ocean-going marine. Over 20,000 engines of this type are in service on the U.S. railroads alone. These engines were generally developed with fuels that can be described as petroleum-derived middle distillate, and meeting the requirements of ASTM specification D975 2D. While this specific fuel specification evolved over the years, the present properties are listed in Table 1. Following the petroleum crisis of 1973, it has become increasingly apparent that alternative fuel sources must be available in the future. In 1979 the transportation sector consumed 55% of U.S. petroleum.⁽¹⁾ The same cited reference indicates that 8½% of the total petroleum consumed by this country is by highway diesels, marine, and railroads. In addition, 6½% of the total oil used by the U.S. is consumed by aviation and an additional 14% by residential and commercial heating. The majority of the petroleum usage cited above represents fuel which either meets the No. 2D distillate fuel specification or comes from the same part of the crude barrel. Studies conducted by various sources, including Shell Oil Company,⁽²⁾ forecast that the demand for products usually filled by No. 2 fuel will increase steadily to 1990 and beyond, while the demand for both aviation gasoline and motor gasoline will steadily decrease. Thus, it is important to search for possible alternative fuels for engines which typically utilize the distillate part of the petroleum barrel (either No. 1 or No. 2).

Neither coal-derived liquid fuels nor shale-derived fuels are widely available in the U.S. Since both type products come from highly capital-intensive processes, it is logical to assume that were they to become commercial realities, they would come on the scene slowly as the supply of petroleum products diminished. Thus, it is appropriate to determine if such materials could be utilized as "fuel extenders" for some large-user industries.

Table 1
ASTM D975 NO. 2D FUEL PROPERTIES

Grade of Diesel Fuel Oil	Flash Point °C (°F)	Water and Sediment Vol %	Carbon Residue On, 10% Residuum %	Ash Weight %	Distillation Temperatures °C(°F) 90% Point		Viscosity				Sulfur Weight %	Copper Strip Corrosion	Cetane Number
							Kinematic, cSt at 40°C		Saybolt, SSU at 100 °F				
	Min	Max	Max	Max	Min	Max	Min	Max	Min	Max	Max	Max	Min
No. 2-D A distillate fuel oil of lower volatility for engines in industrial and heavy mobile service	52 (125)	0.05	0.35	0.01	282 (540)	338 (640)	1.9	4.1	32.6	40.1	0.50	No. 3	40

THE FUELS

There are many processes by which potential liquid fuels may be derived from coal. These processes yield significantly different products. Some of them, in final form, are not recognizably different from fuels derived from petroleum. One such process is the Sasol Synthol. This process⁽³⁾ consists of coal crushing, gasification, gas purification, catalytic reaction, and fractionization. The flow diagram of the Sasol process is shown in Figure 1.

The SRC II process⁽⁴⁾ consists of crushing, solution in appropriate solvents under pressure, hydrocracking, removal of organic sulfur, and fractionization. The flow diagram for this process is shown in Figure 2. This and similar processes, for obvious reasons, are often referred to as direct liquifaction.

Oil shale deposits underlie much of the U.S. The Rocky Mountain section of Colorado, Utah, and Wyoming in its Green River Formation is said to have an estimated 1800 billion barrels of shale oil⁽⁵⁾ which is more than twice the oil reserves of the entire free world. The extraction of oil from oil shale is conceptually straightforward. The shale is heated to a temperature above 900 °F, at which the kerogen decomposes into oil and light hydrocarbon gases. In the above-ground processing method, the shale is mined, brought out to an above-ground facility, crushed, and heated in a kettle or a retort. The temperature depends upon the particular retorting configuration used. This process is shown schematically in Figure 3. Since this process requires very substantial mining and disposal of large quantities of waste in some manner, other processes are being developed which retort the shale underground. Much information is available in the literature which describes the various pretreatment processes to remove impurities and the final refining process as well as estimates of costs. Such investigations were not part of this project. The materials (SRC II and shale fuel) obtained from the Department of Energy for this project differed widely from each other. Table 2 displays major diesel properties of the SRC II middle distillate, typical No. 2D fuel, and No. 2 fuel derived by the Sasol process. Insofar as major diesel properties are concerned, the shale-derived product is indistinguishable from petroleum-derived materials while the coal-derived product differs widely. A more detailed analysis of the SRC II product is provided in a subsequent section.

Figure 1. Flow diagram, South African Sasol Synthol process.

Figure 2. Flow diagram, SRC II process.

Figure 3. Flow diagram, shale oil.

Table 2
PROPERTY COMPARISON OF COAL-DERIVED FUEL WITH ASTM 2D

Property	Typical ASTM 2D	Solvent Refined	Sasol Type
Viscosity at 100 °F SSU	40 max.	37.4	35
Cetane no. (calc.)	40 min.	4.2	48
Sulfur, %	0.5 max.	0.04	0.001
10% B.P. °F	470 typ.	396	385
90% B.P. °F	640 max.	528	581
Distillation recovery %	98 typ.	98	98
High heat value Btu/lb	19,400 typ.	17,360	est. 19,800

TEST PLAN

The objective of the test program was the acquisition and interpretation of engineering data from a current medium-speed diesel engine while burning fuels composed, at least in part, of the SRC II and shale materials. Due to the nearly nonexistent cetane number of the coal-derived product, operation of a compression ignition engine could not be expected to be achieved with 100% SRC II in any conventional manner. On the other hand, the shale product would be expected to be usable "as is." Therefore, it was planned to blend the SRC II product with petroleum-derived diesel fuel. Other investigators chose the route of pilot diesel fuel injection.

The overall test plan is displayed in Figure 4. The first task of this program was to determine if petroleum diesel fuel was compatible with SRC II (middle distillate) and to determine the properties of various blends to select those which might be usable.

Due to the high aromatic content of the SRC II material, one would expect a different reaction on the various gasket materials in the fuel system. In addition, the test fuel could have different injection characteristics or affect the performance of the

- TASK 1 SRC II ASSESSMENT
- TASK 2 SRC II 2-CYLINDER RUNNING
- TASK 3 SRC II 8-CYLINDER RUNNING
- TASK 4 SHALE/NO. 2 DIESEL
 - 4.1 NON-ENGINE WORK
 - 4.2 2-CYLINDER RUNNING
 - 4.3 8-CYLINDER RUNNING
- TASK 5 SHALE AND RESIDUAL PETROLEUM
 - 5.1 NON-ENGINE WORK
 - 5.2 2-CYLINDER RUNNING
 - 5.3 8-CYLINDER RUNNING
- TASK 6 PETROLEUM DISTILLATE AND RESIDUAL
 - 6.1 NON-ENGINE WORK
 - 6.2 2-CYLINDER WORK
 - 6.3 8-CYLINDER WORK

Figure 4. Test plan.

fuel injection system by not providing adequate lubricity. Thus, the second phase of the investigation included both gasket soak tests and bench injection testing. Some of the principal questions an engine designer raises concerning a change in fuel composition involve cylinder pressure, fuel consumption, combustion chamber part temperature, and exhaust gas characteristics. The third phase of this investigation included comparisons of blends of SRC II in diesel fuel and shale-derived fuel as received, blended with diesel fuel, and blends with residual petroleum fuel.

Designers and operators require information about the durability of the diesel engine when a different fuel is considered. This investigation included relatively short (100-200 hours) durability testing in a multicylinder engine. In addition to standard petroleum-derived diesel fuel, the following fuel blends were durability tested: SRC II with petroleum No. 2, shale-derived distillate with petroleum distillate, shale-derived distillate with petroleum residual, and petroleum No. 2 fuel with petroleum residual fuel. Two baseline tests were run. Since the SRC II fuel is potentially more toxic than petroleum-derived products, special handling procedures were developed and monitored during all fuel handling with this product.

ENGINE TESTING

The engine operating characteristics with the test and reference fuels were determined in the engineering laboratory of the Locomotive Engineering Department of the Transportation Systems Business Operation in Erie, Pennsylvania. The Diesel Engineering Laboratory (Figure 5) includes a number of cells in which full size engines can be operated (Figure 6) and 2-cylinder research engines (Figure 7) are available for in-depth tests. The medium-speed engine used in this work is turbocharged, 4-cycle, has a 9-in. bore and 10½-in. stroke, and is aftercooled. In locomotive service the engines are usually operated over a speed range of 450 to 1050 rpm, and are sometimes used at a top engine speed of 1200 rpm. They are manufactured in 8-, 12-, and 16-cylinder versions.

Figure 5. Overall view of Diesel Engineering Development Laboratory.

Figure 6. Typical instrument console: full size engine cell.

Figure 7. Two-cylinder test engines.

The 2-cylinder research engines were used in this investigation to determine basic operating parameters with the experimental fuels. An 8-cylinder engine was chosen for the durability running in order to acquire the maximum number of hours for the total quantity of fuel available. The power assembly (cylinder, piston, head, and rings) is fully interchangeable between the 2-cylinder engines and the commercial 8-, 12-, and 16-cylinder engines. A cross section of the 8-cylinder engine is shown in Figure 8.

The fuel system for this direct-injected engine consists of an individual jerk pump and nozzle for each cylinder. The plunger size of the injection pump (in this investigation) is 17 mm in diameter. An exploded view of the fuel pump is shown in Figure 9 and an exploded view of the nozzle is shown in Figure 10.

INSTRUMENTATION AND MEASUREMENT TECHNIQUE

The principal instrumentation used during this investigation was, of course, the test engines. The 2-cylinder engine is loaded through an electric dynamometer, whereas the 8-cylinder engine is loaded through an alternator whose output is dissipated by resistors. Both of the engine installations are instrumented to yield standard gas and liquid temperature data. The cylinder pressure was taken by an AVL dynamic pressure transducer (Figure 11) flush mounted in the firing chamber, the output of which was amplified, displayed, and photographed from a CRT oscilloscope or amplified and fed into a data acquisition system to be evaluated by a minicomputer.

Piston and valve temperatures were determined by burying thermocouples in specified locations (Figure 12). Signals were transmitted outside the engine via a "grasshopper leg" shown in Figure 13. Exhaust emission data were obtained by using chemiluminescence for oxides of nitrogen, nondispersive infrared for carbon monoxide, and flame ionization detection techniques for unburned hydrocarbons. Figure 14

Figure 8. FDL engine cross section.

Figure 9. Exposed view of fuel pump.

Figure 10. Exposed view of nozzle.

Figure 11. AVL pressure transducer.

Figure 12. Location of thermocouples.

Figure 13. "Grasshopper" method of removing thermocouple signals from moving piston.

Figure 14. Emissions and fuel consumption testing.

is a view of the emissions measurement console. The exact procedure for emissions measurements may be found in an ASME paper, *Four-Cycle Diesel Electric Locomotive Exhaust Emissions: A Field Study*.⁽⁷⁾ The principal smoke measurement device was an AVL instrument (Figure 15) which yields Bosch smoke numbers. This measurement system is a trapped particle procedure and is quantified by using light reflection. In a second smoke measurement device, particulates were quantified by passing a known quantity of exhaust gas through a weighed asbestos filter element and determining the weight gained.

Figure 15. AVL smoke meter.

Fuel consumption was measured by determining the time required to burn a weighed quantity of diesel fuel. The fuel weight scales are equipped with an electronic device which starts and stops the clock when a predetermined weight of fuel has been consumed. One such device is seen in the background of Figure 7.

The effect of the test fuels on engine durability was determined using an 8-cylinder engine. To determine the power assembly wear rates, normal macro measurements of piston ring and gap and cylinder liner internal diameter were made. The cylinder liner measurements were obtained with a dial bore gauge. To obtain more accurate information regarding piston ring wear and cylinder liner wear two other procedures were used: weighed top piston rings and epoxy replicas of the cylinder liner areas normally expected to yield maximum wear. The piston rings were weighed at the start of each fuel test, cleaned, and reweighed at the end of the test. The replica was made by applying a quantity of epoxy material to a previously cut steel bar (Figure 16) which was placed on the wear area of the cylinder liner for 24 hours (or until hard), then removed and evaluated by the use of a profilometer. At the end of the reference fuel runs (approximately 200 hours) and at the end of each test fuel operation (100 to

Figure 16. Epoxy replica.

200 hours) the engine was completely disassembled and all appropriate parts examined. At the beginning of each fuel run, the engine was completely broken-in using standard laboratory schedule. Fuel consumption and exhaust emission determinations were conducted after 10 hours of operation and just prior to completion of the durability test with each fuel. The lubricating oil and lubricating oil filters were changed after each durability run. Lubricating oil samples were withdrawn periodically through the durability run and analyzed for viscosity, total base number, pentane insolubles, and wear metals.

FUEL HANDLING AND SAFETY

Due to the highly aromatic nature of the SRC II fuel compared to petroleum-derived distillate (approximately 60% compared to approximately 30%) and the fact that it is coal derived, toxicity concerns with the CDL product are greater than with petroleum-derived distillate. Some polynuclear aromatic compounds present in coal tar are known to be carcinogens. This investigation did not include health effects, but handling procedures were developed which proved to be quite satisfactory. These procedures are shown in Appendix 1 and include good ventilation, skin protection, and individual breathing masks. All technicians handling the fuel were thoroughly briefed on both risks and proper procedures. Contact with the skin by CDL material should be avoided because it creates a burning irritant. During the fuel blending procedures, air monitoring in the area and on the person handling the fuel was conducted. No unsafe conditions were found. No special precautions were taken while handling the shale fuel blends.

It should be noted that the odor of the CDL is objectionable to many people, even in trace quantities, and that this odor persists for long periods of time. Air monitoring in areas of the laboratory in which the odor persisted at an objectionable level to some personnel, even after washing, showed that the level of benzene soluble fraction of total particulates was well below OSHA-permissible exposure levels.

MATERIAL COMPATIBILITY

Before introducing blends of the CDL fuels into the engine fuel system, compatibility with various gasket materials and filter materials was tested. At the beginning of this work, the fuel pump gaskets and fuel hose linings were of acrylonitrile elastomer. The standard fuel filter used with the engine consists of phenolic resin-coated paper. The compatibility of these materials with SRC II was determined by soaking the gaskets in 100% No. 2 petroleum-derived fuel and 50% blends of No. 2 petroleum fuel and CDL distillate. Thirty days soaking time at room temperature was adequate to define the problem by measuring the percentage volume change of the gaskets. Suitability of using standard fuel filter elements was determined by soaking segments of the filter in 10% CDL and in 100% petroleum fuel for seven days at room temperature. At the end of the soak time, the impact strength of the filter material was determined. Several substitute elastomers were tested in this same manner. These were a cross-linked polyolefin, a nylon polymer, and a fluorinated hydrocarbon. Table 3 displays the comparative volume changes of these different materials. Figure 17 demonstrates the swelling of gasket material and Figure 18 shows the severe swelling of the fuel hose lining after only seven days in 100% SRC II. Only the fluorinated hydrocarbon type materials were resistant to the effects of SRC II to the same degree as the standard materials are to petroleum distillate.

Soaking of the resin-coated filter paper in 100% CDL did not affect its impact strength. A larger amount of material compatibility work with SRC II has been conducted by Gulf Research and Development Company. This information is available on request. The corrosion tests conducted by Gulf include most of the sensitive metals: copper, zinc, aluminum, bronze, lead, brass, and cadmium. The tests were conducted at elevated temperatures (120 °F) for 72 hours by determining weight loss. To overcome the gasket material problems, Viton* gaskets were substituted for the standard ones and Teflon-lined fuel hoses or stainless steel tubing were used.

Table 3
SWELLING OF GASKET AND HOSE MATERIALS

Material	Percent Swell 7 Days in 100% SCR II
Acrylonitrile (std. mtl.)	240
Crosslinked polyolefin	114
Nylon polymer	191
Polyester polymer	149
Fluorinated hydrocarbon	3.4

NOTE: Acrylonitrile in petroleum fuel swells 17% in 7 days.

* Trademark of E.I. Dupont de Nemours and Co., Wilmington, Delaware.

Figure 17. Fuel pump gasket swelling.

Figure 18. Fuel hose and gasket swell.

Before beginning any engine tests, bench performance and durability tests were conducted with the fuel system pump nozzle at the Bendix facility at Sidney, New York. The durability portion of this test consisted of 100 hours of operation on a test stand compared directly to 100-hour test stand operation with standard petroleum fuel. The complete Bendix report is included as Appendix 2. In brief, Bendix testing results are as follows:

1. The SRC II produced slightly shorter injection lags (up to 4° crank angle) than the petroleum fuel.
2. Higher gross line pressures were observed with the CDL.
3. Higher fuel delivery per millimeter of rack setting was observed. The magnitude of this higher delivery is up to 4½% at full load and 33% at low idle.
4. Similar main injection durations were found for the two fuels.
5. Cavitation erosion was no more severe with the SRC II fuel. A black deposit was found on all pump parts. This was especially severe when the system was shut down for a period of four and a half months while Bendix Laboratory ventilation questions were resolved. During durability testing there was evidence that the black deposits had broken off, and thus increased the potential for scored barrels and plungers.
6. No leaking occurred during the testing with the pumps, which had been modified to use fluorinated hydrocarbon seals.

FUEL BLENDS

Before beginning any engine testing, blends of the CDL and petroleum distillate fuel were made in the Chemistry Laboratory. The purpose of this work was to determine if petroleum fuel would blend with the CDL material to produce predictable diesel properties. In addition, fundamental chemical analyses were performed on several blends of the CDL and petroleum fuel. Tables 4, 5, and 6 display the data obtained with 10%, 30%, 50%, and 70% CDL in 90%, 70%, 50%, and 30% petroleum distillate fuel, respectively. The same type of analysis was performed on 100% CDL. One of the principal diesel indicators of these blends is cetane number. Note in Table 4 that the cetane value is "cetane index" derived from the API gravity and 50% distillation point. Table 6 displays the engine-determined cetane number for the 50% blend of CDL and petroleum fuel. The very close correlation (23.5 cetane index and 24.1 cetane number) is important. Most diesel engine manufacturers and petroleum laboratories can determine the cetane index; however, relatively few potential users of CDL have direct access to a cetane engine. This correlation permits prediction of cetane performance.

The determination of pentane insolubles, which is not usually performed on fuel oils, was used to estimate any blending incompatibility of the petroleum fuel and CDL fuel. It is noted that the values for all blends were extremely low and in no case exceeded the insoluble value for the CDL material alone.

Table 7 displays the principal properties determined for blends of shale-derived distillate and petroleum-derived distillate. It should be noted that the petroleum distillate used in these blends was significantly different from the petroleum distillate used with the CDL material. These differences are particularly noted in the properties API gravity, sulfur, and cetane index. The petroleum distillate used with the shale material was very similar to the shale product itself. This difference was not deliberate but simply represents the different petroleum distillate material available in the Erie, Pennsylvania area at the time the two blend studies were made. It is notable that the sulfur content of the petroleum used with shale blends was 0.1%, whereas the sulfur content of the petroleum used with the coal-derived product was 0.54%. Because a considerable

Table 4
ANALYTICAL PROPERTIES OF SRC II AND PETROLEUM DIESEL FUEL

Fuel Blends	100% Pet. No. 2	100% CDL	10% CDL 90% Pet. No. 2	30% CDL 70% Pet. No. 2	50% CDL 50% Pet. No. 2	70% CDL 30% Pet. No. 2
API grav., 60°F	35.9	14.0	33.4	28.8	24.3	19.8
Spec. grav., 60°F	0.8453	0.9725	0.8531	0.8827	0.9082	0.9352
Lb/gal, 60°F	7.038	8.099	7.145	7.350	7.563	7.788
Viscosity, 100°F-SSU	34.81	37.41	34.62	34.97	35.48	36.22
-cST	2.62	3.43	2.56	2.67	2.83	3.06
Pentane insolubles	0	0.04%	0.01%	0.02%	0.03%	0.03%
Flash point, P-M °F	154	138	152	148	146	144
Conradson Carbon-10% Distillation Residue	0.10%	1.74%	0.30%	0.73%	1.04%	1.13%
Heat Value						
Btu/lb	19515	17360	19310	18700	18400	17790
Btu/gal	137350	140600	137970	137440	139160	138550
Sulfur	0.54%	0.22%	0.48%	0.37%	0.26%	0.28%
Distillation, °F						
IBP	374	242	366	358	340	341
5	402	380	396	390	376	384
10	420	396	412	402	396	394
20	444	416	436	428	418	416
30	464	430	456	448	438	432
40	482	446	476	466	448	452
50	502	460	494	482	476	468
60	520	472	512	502	492	482
70	540	490	532	522	510	500
80	564	506	558	544	530	518
90	598	528	590	578	560	544
95	628	548	620	608	590	566
EBP	640	576	646	626	628	608
% Recovery	98.0	98.0	98.0	98.0	99.0	98.0
Barometric press., mm Hg	746.9	752.9	746.9	741.9	741.9	752.9
Calculated Cetane index	49.5	4.2	41.0	32.5	23.5	14.6

Table 5
SPECTROMETRIC ANALYSIS OF SRC II AND PETROLEUM DIESEL FUEL

Fuel Blends	100% Pet. No. 2	100% CDL	10% CDL 90% Pet. No. 2	30% CDL 70% Pet. No. 2	50% CDL 50% Pet. No. 2	70% CDL 30% Pet. No. 2
Results in PPM						
Aluminum	0.25	1.6	0.6	1.1	1.5	1.3
Boron	0.10	1.9	0.4	0.92	1.3	0.61
Barium	0.03	0.07	0	0	0	0
Calcium	0.17	0.5	0.02	0.27	0.25	0.19
Copper	0.22	0.33	0.14	0.14	0.11	0.09
Iron	0.06	4.1	0.3	1.4	3.2	2.4
Sodium	0	0.11	0	0	0	0
Phosphorous	0.45	0.36	0.77	1.1	0.63	0.59
Lead	0.79	0.74	1.1	1.2	0.85	0.91
Silicon	0.27	1.6	0.24	0.67	1.2	0.97
Vanadium	0	0.65	0	0	0.39	0.22
Zinc	0.26	1.3	0.26	0.26	0.16	0.15

Table 6
CHEMICAL ANALYSIS OF BLENDS OF SRC II

Fuel Blends	10% CDL + 90% Pet. No. 2	30% CDL + 70% Pet. No. 2	50% CDL + 50% Pet. No. 2	70% CDL + 30% Pet. No. 2	100% SRC II
Carbon, wt%	86.88	86.78	87.69	85.88	85.48
Hydrogen, wt%	12.46	11.65	11.01	10.00	9.28
Oxygen, wt%	0.50	1.4	2.4	3.1	4.4
Nitrogen, wt%	0.10	0.28	0.43	0.55	0.81
Aromatics, vol%	37	49	60	73.5	90.5
Olefins, vol%	0.5	0.5	0.5	0.5	0.5
Saturates, vol%	62.5	50.5	39.5	26	9
Naphthalenes, wt%	14.1	17.5	21.5	24.4	29
Phenols, wt%	3.24	8.82	14.1	19.3	26.3
Cetane number			24.1		

Table 7
ANALYSIS OF SHALE AND PETROLEUM BLENDS

Fuel Blends	20% Shale	35% Shale	60% Shale	80% Shale	100% Shale	100% Pet. Distill.
API grav., 60°F	40.9	40.6	39.8	39.5	38.1	41.8
Specific grav., 60°F	0.821	0.822	0.826	0.8275	0.8335	0.8165
Btu per pound	19,800	19,840	19,810	19,740	19,600	19,800
Btu per gallon	135,310	135,820	136,250	136,010	136,160	134,600
Sulfur, %	0.1	0.1	0.1	0.1	0.1	0.1
Distillation, °F						
Initial boiling point	396	397	399	403	405	394
10%	440	440	444	448	456	437
20%	463	463	467	470	476	459
30%	480	479	482	485	489	477
40%	496	496	497	498	501	494
50%	514	512	512	511	511	512
Calculated cetane index	61	60.5	59	58	55	62.5

amount of information was available concerning the properties of the shale fuel, it was not deemed necessary to conduct material compatibility or more extensive chemical analysis.

BENCH SCALE COMBUSTION EXPERIMENTS WITH SRC II/DIESEL BLENDS

Prior to the engine tests, a limited set of bench scale tests were conducted with SRC II/diesel blends. However, it became apparent that straight SRC II could be burned readily in a controlled manner, and it was decided to compare SRC II with diesel, burning each separately. These experiments involved steady combustion using an air- or steam-atomized nozzle in a specially constructed ceramic tube. The results of these experiments are detailed in Appendix 6.

The upshot of these experiments was that both smoke and NO levels were higher for SRC II than for straight diesel fuel. There appeared to be no insurmountable barriers to the practical application of SRC II as fuel; however, these tests gave no indication of its auto-ignition characteristics.

TWO-CYLINDER TESTING

The 2-cylinder engine facility is somewhat different from the multicylinder facility. The 2-cylinder engine is loaded through an electric dynamometer; the 8-cylinder engine is loaded through an alternator whose output is dissipated by resistors. In order to compare the different fuels, tests were conducted at three different load conditions: 206 hp/cyl at 1050 rpm, 160 hp/cyl at 879 rpm, and approximately 23 hp/cyl at 535 rpm. Exhaust emissions, specific fuel consumption, valve temperature, piston temperature, and peak cylinder pressure measurements were made on selected blends of the test fuels and petroleum distillate fuel. Numerous tests were conducted with petroleum distillate fuel to establish a baseline. The CDL blends were 10%, 30%, and 35%. The fuel specification for this basic engine specifies a cetane index of a minimum of 37. Reference to Table 4 discloses that a 30% blend of CDL and 70% petroleum No. 2 fuel yields a cetane index of 32.5; thus, the 35% blend limit. This program was not intended to include investigations of such alternative methods as pilot injection, which undoubtedly would permit additional CDL fuel to be used. The characteristics of the shale fuel permitted operation with 100% shale-derived fuel. The blends investigated in the 2-cylinder work were 20%, 30%, 50%, and 100% shale fuel.

In addition to the blends of test fuels with petroleum distillate fuel, the shale fuel was blended with petroleum residual material and performance was compared with petroleum distillate blended with residual. No. 6 petroleum fuel was obtained from a local source. Such fuel has extremely high viscosity and very low cetane number. Rather than blend the No. 6 to an appropriate viscosity for use in these engines without heating by using either 100% No. 2 distillate fuel or 100% shale fuel, the No. 6 product was first reduced in viscosity with a more aromatic light cycle oil. The final blends yielded viscosities of 41 to 42 SSU and a cetane index of 36.5 and 39.5 with the No. 2 diesel fuel blend and the shale blend, respectively. Table 8 displays the principal significant properties of these two test fuels.

Tables 9, 10, 11, and 12 display the exhaust emissions data determined during the 2-cylinder engine investigation. The oxides of nitrogen, carbon monoxide, and unburned hydrocarbon information is displayed as grams per horsepower-hour. The smoke data are reported as Bosch number. One of the most important questions concerning exhaust emissions with regard to the fuels under discussion concerns the oxides of nitrogen from the coal-derived fuels. The middle distillate portion of the SRC II was found to contain 0.8% nitrogen. On the other hand, petroleum-derived distillate fuels contain less than 0.02%. Thus the question, would the use of the CDL material raise the oxides of nitrogen emission as a result of conversion of the fuel-bound nitrogen? The NO_x values displayed in Table 9 certainly do not answer this question. There is evidence that at the lowest load (24 hp/cyl) some of the nitrogen is converted to NO_x . Note that the NO_x values obtained with the 30% and 35% blends of CDL are the highest observed with any of the blended fuel running. In order to better answer this question, a study of fuel-bound nitrogen conversion was partially funded to the University of Wisconsin-Madison. Mr. Chieh-Shen Lin performed this work as part of his Master of Science degree requirements. Portions of the master's

Table 8
ANALYSES OF RESIDUAL BLENDS, TWO-CYLINDER ENGINE TESTS

Fuel Blends	50% Shale and 50% LCO* + No. 6	50% Pet. No. 2 and 50% LCO + No. 6
API grav., 60°F	28.8	27.5
Viscosity, 100°F, SSU	42.1	41.1
Sulfur, %	0.9	1.0
Conradson carbon, %	2.5	2.3
Cetane index	39.5	36.5
Btu/pound	19,060	19,220
Max. distill., °F	632	624
Recovery, %	90	90
Vanadium, PPM	14	31
Aluminum, PPM	2	4
Silicon, PPM	2	4

LCO = Light cycle oil

Table 9
**EXHAUST EMISSION - COAL DERIVED LIQUID,
TWO-CYLINDER ENGINE**

Fuel	hp/cyl	rpm	NO _x g/hp-hr	CO g/hp-hr	HC g/hp-hr	Smoke Bosch No.
Pet. No. 2	206	1050	9.5	3.5	0.8	1.3
10% CDL	206	1050	10.2	4.3	1.5	0.7
30% CDL	206	1050	10.5	5.3	0.6	0.7
35% CDL	206	1050	7.8	4.6	0.6	0.7
Pet. No. 2	100	879	12.6	5.1	1.0	0.8
10% CDL	100	879	11.9	3.6	1.0	0.9
30% CDL	100	879	13.6	4.4	1.0	1.1
35% CDL	100	879	12	5.2	0.8	0.9
Pet. No. 2	24	535	18.9	1.7	1.5	0.4
10% CDL	24	535	17.4	2.1	1.6	0.4
30% CDL	24	535	25.9	2.5	1.5	0.4
35% CDL	24	535	20.9	2.5	1.5	0.7

thesis are reproduced in Appendix 3. In this study, No. 2 diesel fuel blended with SRC II and pyridine-doped diesel fuel were used in a 4-stroke, turbocharged, direct-injection, high speed commercial diesel engine. Mr. Lin found that the SRC II blended fuel produced higher NO_x measurements while the pyridine-doped fuel did not. He concluded that the NO_x emission increase for the blended SRC II resulted from the increased aromatic content of the fuel and not the fuel nitrogen conversion. He notes other studies that have found a strong correlation between NO_x emissions and aromatic content of the fuel. The reason for the correlation is not understood.

Table 10
EXHAUST EMISSIONS - SHALE FUEL, TWO-CYLINDER ENGINE

Fuel	hp/cyl	rpm	NO _x g/hp-hr	CO g/hp-hr	HC g/hp-hr	Smoke Bosch No.
Pet. No. 2*	206	1050	9.2	3.4	1.0	0.9
20% shale	206	1050	8.6	3.7	0.9	1.1
30% shale	206	1050	10.5	3.5**	0.8**	0.8**
50% shale	206	1050	9.9	3.2**	0.8**	0.8**
100% shale	206	1050	9.2	3.5	0.8	0.7
Pet. No. 2*	100	879	12	2.7	1.2	0.6
20% shale	100	879	11.5	3.8	1.1	1.2
30% shale	100	879	13.7	2.6**	0.7**	0.6**
50% shale	100	879	13.9	2.6**	0.7**	0.6**
100% shale	100	879	13.4	4.6	0.9	0.8

* Average three runs.

** Values corrected to baseline run immediately preceding test runs.

Table 11
EXHAUST EMISSIONS - SHALE FUEL, TWO-CYLINDER ENGINE

Fuel	hp/cyl	rpm	NO _x g/hp-hr	CO g/hp-hr	HC g/hp-hr	Smoke Bosch No.
Pet. No. 2*	22	535	15	1.9	2.1	0.4
20% shale	22	535	17.3	2.2	1.5	0.4
30% shale	22	535	12.7	2.5**	1.5**	0.6**
50% shale	20	535	13.6	1.7**	1.5**	0.2**
100% shale	23	535	17.6	1.9	1.2	0.4

* Average three runs.

** Values corrected to baseline run immediately preceding test runs.

Table 12
EXHAUST EMISSIONS - RESIDUAL BLENDS TWO CYLINDER ENGINE

Fuel	hp/cyl	rpm	NO _x g/hp-hr	CO g/hp-hr	HC g/hp-hr	Smoke Bosch No.
Pet. No. 2	206	1050	9.8	1.6	1.7	0.6
Shale and resid.	206	1050	11.3	0.8	1.7	0.2
Pet. No. 2 and resid.	206	1050	11.1	1.5	1.7	0.3
Pet. No. 2	100	875	13.2	1.3	1.8	0.4
Shale and resid.	100	875	15.9	0.9	1.9	0.3
Pet. No. 2 and resid.	100	875	15.1	1	1.7	0.4
Pet. No. 2	22	535	12.8	1.9	3.2	0.6
Shale and resid.	22	535	12.7	3.3	2.4	0.6
Pet. No. 2 and resid.	22	535	14	4.1	3.0	0.6

At the 100 hp/cyl and the 22 hp/cyl load levels, there is a trend for the shale fuel to cause somewhat elevated NO_x emissions. The reason for this is by no means clear. Tables 10 and 11 display these values. The oxides of nitrogen emissions resulting from the residual blended fuel exhibit no evidence of poorer results than with the use of shale-derived liquid blends.

The carbon monoxide emissions are marked by inconsistencies. The diesel fuel baseline tests made during the testing of the experimental fuels are as inconsistent as the difference between the fuels themselves. There is indication that at the lowest horsepower (22 per cylinder), the fuels blended with residual petroleum produce more carbon monoxide than unblended No. 2 fuel. Certainly, there is no evidence that blending the residual fuel with shale fuel causes any more carbon monoxide than blending the residual fuel with petroleum distillate. There is no evidence that the test fuels produce significantly higher values of unburned hydrocarbons than the petroleum fuel used for the baseline for the particular test.

The test fuels were not shown to produce higher smoke levels in the exhaust.

Particulate emissions were determined by utilizing the filter inherent with the exhaust emissions analysis cart. This filter is an asbestos disc. Since the emissions equipment samples a constant portion of the exhaust flow, it is reasoned that if a constant time were chosen for sampling, then the various fuels could be validly compared. The filter discs, of course, were preweighed and maintained in a desiccator. The time dimension for each determination was 15 minutes. The results of eight fuel blends and two petroleum distillate baselines are displayed in Table 13. All of these values are displayed as milligrams per 15 minutes. All of these determinations were made at 206 hp/cyl at 1050 rpm. Also displayed in Table 13 are smoke values determined simultaneously with the particulate emissions. As previously described, the AVL smoke-measuring system is a particle trapping procedure which measures the reflectance under standard lighting conditions. It will be noted that the resulting Bosch smoke values are inconsistent with the particulate weight values obtained from the alternate measurement device. The blend of petroleum distillate and petroleum residual shows significantly higher particulate emissions than any other fuel blend. Petroleum

Table 13
PARTICULATE EMISSIONS AND SMOKE
TWO-CYLINDER ENGINE

Fuel	Particulate MG/15 min	Smoke Bosch No.
Pet. No. 2	0.8	0.6
Pet. No. 2	1.4	0.3
10% CDL 90% No. 2	0.7	0.3
30% CDL 70% No. 2	0.8	0.3
35% CDL 65% No. 2	0.9	0.3
10% shale 90% No. 2	1.1	0.2
30% shale 70% No. 2	0.8	0.4
50% shale 50% No. 2	0.9	0.5
50% shale 50% resid.	1.4	0.2
50% No. 2 50% resid.	2.6	0.3

distillate yielded $1.1 \text{ mg/15 min} \pm 3 \text{ mg/15 min}$, while the petroleum distillate blended with petroleum residual yielded 2.6 mg/15 min . Directionally, increased concentration of CDL in diesel fuel yielded increased particulate concentration; however, the values were not significantly higher than petroleum. The blend of distillate shale and petroleum residual fuel yielded 1.4 mg/15 min which, while higher than blends of shale with petroleum distillate, is not significantly higher than petroleum distillate alone.

Specific fuel consumption was determined by measuring the time required for the engine to consume a predetermined weight of fuel. The heat content of even petroleum distillate fuels varies significantly. The multitude of fuels involved in this test program exhibited gross heat content variability. Tables 4, 7, and 8 exhibit these differences. Convention has established the practice of using high heat values for diesel combustion investigations as opposed to low heat values. Heat values were determined by bomb calorimeter as opposed to estimates from the gravity determination. All specific fuel consumption values were corrected to a constant Btu. In this case, the constant used was 19,350 Btu per pound. In this manner, fuel consumption is compared on the basis of heat input; it is, therefore, a measure of combustion efficiency of the specific fuel involved. Figures 19, 20, and 21 compare CDL blends, shale blends, and residual blends with distillate petroleum fuel. Fuel consumption measurements were made at all three load points (206 hp/cyl at 1050 rpm, 100 hp/cyl at 879 rpm and 20 hp/cyl at 535 rpm). All fuel consumption values are shown as a ratio to the average petroleum distillate baseline in conjunction with the particular series of fuels. In Figure 20, the value for 100% shale fuel at 20 hp/cyl is not shown. The data exhibited a major reduction in specific fuel consumption which was entirely inconsistent with the blends. Since the value is deemed highly questionable, it was decided not to display it.

Figure 19. Coal-derived liquid blends, 2-cylinder SFC.

Figure 20. Shale oil blends, 2-cylinder SFC.

Figure 21. Residual blends, 2-cylinder SFC.

The No. 2 diesel range is displayed on each figure. This represents the repeatability of the fuel consumption measurements taken during each series of tests.

Figures 19, 20, and 21 show that the shale-blended fuel operated with specific fuel consumptions is equivalent to petroleum diesel fuel. The 50% shale blend produced a fuel consumption slightly higher than the range of petroleum fuel at the lowest horsepower setting. The 100% shale fuel value, which is not displayed, exhibited extremely low specific fuel consumption; therefore, there is no directional trend for decreased efficiency with the shale fuel. With the CDL blends there appears to be evidence that fuel efficiency improves at the lower output (100 hp and 20 hp). However, it is obvious that the results have a great deal more scatter. The data for the residual blends (Figure 21) show clearly that the specific fuel consumption with either petroleum distillate or the shale distillate is significantly higher than petroleum distillate alone at the low (20) horsepower. However, there is no evidence that blending the residual with shale distillate is any worse than blending with petroleum distillate. In fact, there is evidence that the use of the shale distillate with the residual material produces better fuel consumption than the blends with petroleum distillate. This undoubtedly results from the improved cetane number of the shale blend (39.5 compared to 36.5). It was previously indicated that the recommended minimum cetane number for this engine is 37.

No attempts were made to optimize the fuel injection timing for the various fuels. All timings during these tests are the same. It should also be pointed out that the fuel system of this engine has a constant start of injection but a variable end of injection. In short, at the time these tests were conducted, the fuel pumps did not have a start of injection helix. It is believed that combustion could be improved at the lower load point with timing adjustment, thus improving fuel efficiency. Table 14 displays the major engine part temperature measurements obtained when operating with the major fuels used in this investigation. All temperature measurements were made at the high horsepower level (206 hp/cyl). Temperature determinations were made using thermocouples as described elsewhere. Three piston temperatures are displayed for both the intake side and the exhaust side of the piston. The thermocouples were located in the crown, above the top ring and below the top ring. Both intake valve and exhaust valve temperatures are displayed. The only significant differences are the elevated valve temperatures with both residual blends. There is no evidence that blending the residual fuel with shale causes increased temperature.

Table 15 is a display of the peak cylinder pressure measurements with the major fuel blends studied in this investigation. The values for all three horsepower levels are included. The data indicates that the 35% CDL blend (questionable cetane number) and the residual blends produced higher peak cylinder pressures at the 206 hp/cyl, 1050 rpm condition. There is also clear evidence that all three CDL blends (10%, 30%, and 35%) and the 100% shale fuel increased cylinder pressure over petroleum No. 2 fuel at the 20 hp/cyl, 535 rpm condition.

Typical two-cylinder engine operating data are included in Appendix 4.

EIGHT-CYLINDER ENGINE DURABILITY TESTING

The durability portion of this investigation was performed on one of the Engine Laboratory 8-cylinder engines in order to reduce the total quantity of fuel consumed; the availability of test fuels was limited. The 8-cylinder engine consumes approximate-

Table 14
PART TEMPERATURES, °F
TWO-CYLINDER ENGINE - 206 HP/CYL

Fuel Blends	Piston Intake			Piston Exhaust			Valve Intake	Valve Exhaust
	Crown	Above Top Ring	Below Top Ring	Crown	Above Top Ring	Below Top Ring		
Pet No. 2 avg. (3)	412	249	231	450	285	245	570	826
10% CDL	408	253	235	427	285	248	575	774
30% CDL	405	255	235	456	288	248	579	776
35% CDL	411	255	237	455	290	249	575	775
30% shale	412	253	237	455	289	250	573	772
50% shale	413	254	237	455	289	251	571	777
100% shale	403	252	234	448	287	248	566	770
50% shale - 50% resid.	413	238	220	444	282	241	598	940
50% Pet. - 50% resid.	407	237	221	445	283	240	603	937

Table 15
PEAK CYLINDER PRESSURE (PSIA)
TWO-CYLINDER ENGINE TESTS

Fuel Blends	hp/Cyl	rpm	Cylinder Pressure	hp/cyl	rpm	Cylinder Pressure	hp/cyl	rpm	Cylinder Pressure
Pet. No. 2 avg. (3)	206	1050	1705	100	879	1143	20	535	738
10% CDL	206	1050	1640	100	879	1120	20	535	800
30% CDL	206	1050	1640	100	879	1140	20	535	780
35% CDL	206	1050	1880	100	879	1160	20	535	780
20% shale	206	1050	1680	100	879	1160	20	535	740
30% shale	206	1050	1770	100	879	1120	20	535	700
50% shale	206	1050	1770	100	879	1130	20	535	710
100% shale	206	1050	1680	100	879	1160	20	535	780
50% shale - 50% resid.	206	1050	1830	100	879	1160	20	535	740
50% Pet. - 50% resid.	206	1050	1810	100	879	1160	20	535	750

ly 100 gallons of fuel per hour of full load operation. Even using the 8-cylinder engine, it only was possible to run between 100 and 200 full-load hours because of fuel availability constraints. One hundred full-load hours of operation is insignificant in the normal life of a heavy-duty diesel engine, which normally operates between 15,000 and 25,000 hours before requiring even piston ring changes. Therefore, the test was expected to yield only directional indications.

In order to develop the maximum amount of wear, the durability tests were run almost entirely at full load. The power output selected for durability running was 250 hp/cyl at 1050 rpm which is equivalent to a popular locomotive rating. During the durability running, the engine was started and operated at all regular throttle settings to ensure that those fuels could be operated under other than full load conditions.

At the start of each test, after engine assembly was complete, the engine was broken-in on standard diesel fuel. The engine was operated on petroleum fuel for approximately 10 hours after break-in before switchover to the test product. Fuel consumption and exhaust emission measurements were performed on the reference fuel and on the test fuel at the beginning of each test. At the end of the test, emission

measurements were again performed to determine if deterioration had occurred. At the end of each test, all power assemblies were removed and appropriate parts were measured. Most parts were reconditioned and reapplied. In some cases, new parts were applied in order to have the most appropriate "clean starting point" available for test fuel operation. For example, new valves were applied in those locations which were used for deposit evaluations. The top piston ring of each assembly was weighed at the beginning of test and end of test. All piston ring gap measurements were determined before and after test. Cylinder liners were measured by dial bore gage at the beginning and end of each test fuel operation. In addition, epoxy replicas were made of the upper and lower wear areas, as described elsewhere in this report.

The sequence of running was as follows: standard diesel fuel, blended coal-derived fuel, 50% shale fuel blended with 50% petroleum diesel fuel, shale distillate blended with petroleum residual, petroleum distillate blended with petroleum residual, and a concluding petroleum distillate fuel. The necessity of two baseline runs was apparent early in the test. Since the cylinder liners were new at the beginning of the program, the wear rate of both cylinder liner and piston rings could be nonrepresentative in such short tests. The baseline fuel tests at the end of the sequence established the true diesel fuel wear rate. Test times were as follows:

Fuel	Hours Operated
Standard diesel fuel	200
Coal-derived liquid	177
Shale + diesel fuel	96
Shale + residual	128
Diesel + residual	133
Diesel fuel	150

Photographs of appropriate engine parts were made at the end of each test fuel run. Appendix 5 contains six important photographs for each engine test. These photographs include fuel pump barrel and plunger, the fuel injector, the turbine wheel, a set of piston rings, a typical piston crown, and a pair of exhaust valves. Figure A-5.7 shows the condition of the fuel pump barrel and plunger from the CDL test and an unused barrel and plunger. This photograph represents the most significant finding in the durability testing. The CDL fuel blend was decidedly corrosive to the fuel pump parts. Beneath the black coating which is obvious in the photograph, severe pitting was observed. The photograph also shows the fuel pump delivery valve. It, too, was corroded. In hindsight, careful reading of the bench test findings with the CDL fuel predicted such results. It is believed that a change in metallurgy of these parts could overcome the problem. However, before SRC II could be used as a fuel extender, this problem would have to be solved.

Figure 22 displays the analysis of all of the fuels used during the durability testing. In blending the fuels, an effort was made to select proportions which would yield fuel meeting the minimum specified for this engine. This includes a minimum cetane index of 37. This criterion was generally met. The sulfur content of the shale blend with petroleum residual is lower than the sulfur content of the petroleum distillate blended with the residual, reflecting the very low sulfur content of the shale material.

The principal lubricating oil deterioration characteristics during each of the tests are shown in Table 16. The lubricating oil was changed after each test. It will be noted that the viscosity increase and the pentane insoluble increase in the test run with shale

Fuels	First Pet. No. 2	CDL + Pet. No. 2	Shale + Pet. No. 2	Shale + Pet. Resid.	Pet. No. 2 + Resid.	Second Pet. No. 2
PROPERTY						
API Gravity @ 60°F	34.1	33.5	35.2	28.6	27.2	34.7
Btu per pound	19,290	18,860	19,430	19,040	18,920	19,380
Viscosity @ 100°F, SSU	34.8	35	34.8	44.9	41.7	34.4
Con. Carbon, %	0.01	0.73	0.01	3.1	2.8	0.02
Distillation, °F						
Initial boiling point	366	336	388	406	388	368
10%	419	342	428	458	432	420
50%	495	451	504	524	520	498
End boiling point	636	602	628	614	628	620
Recovery, %	97.5	98	97	89	90	96.5
Calculated Cetane Index	45	37	49	38	35	47
Spectrometric Analysis, PPM						
Aluminum	0.3	1	0.1	2	4	0
Boron	0.1	0.9	0	—	2	0
Barium	0	0	0	—	0.2	0
Calcium	0.2	0.3	0	9	15	1
Copper	0.2	0.1	0	—	0.6	0
Iron	0.06	1.4	0.3	4	4	0.1
Lead	0.8	1.2	0.7	4	2	14
Nickel	—	—	0	5	8	0.6
Phosphorus	0.5	1.1	0	1	1	0.6
Silicon	0.3	0.7	0	2	4	0.6
Sodium	0	0	0	2	3	0.4
Vanadium	0	0	0.6	14	31	4
Zinc	0.3	0.3	0.1	<1	0.7	5
Sulfur, %	0.2	0.2	0.2	0.8	1.2	0.3
SRC II, vol %	0	30	0	0	0	0
Shale, vol %	0	0	50	50	0	0

Figure 22. Analysis of durability fuels.

blended with petroleum residual is higher than the other fuels. All of the test fuels appeared to reduce the alkalinity of the lubricating oil to a greater extent than either petroleum distillate. This is understandable in the case of the blends with residual fuel since both have relatively higher sulfur content. The reason for the increased loss with the other test fuels is unclear.

The exhaust emissions determinations made during the durability testing are displayed in Table 17. The emissions at the beginning and ending of the test run for each fuel are compared with the range of diesel emissions found during this testing. In general, the gaseous emissions of all test fuels at the beginning of test were found to be within the range of standard diesel fuel. The smoke value for the CDL/diesel mixture and the shale/diesel mixture was found to be slightly lower than the lowest

Table 16
LUBRICATING OIL DETERIORATION

Fuels	First Pet. No. 2	CDL + Pet. No. 2	Shale Pet. No. 2	Shale + Pet. Resid.	Pet. No. 2 + Pet. Resid.	Second Pet. No. 2
<i>Property Change Per 100 Hr.</i>						
Viscosity Increase at 100 °F, SSU	31.5	18.6	28	41	23	25.5
Wt% pentane insol. increase	0.33	0.44	0.2	0.75	0.34	0.19
Total base no. decrease (ASTM 664)	1.3	1.8	2	2.3	2.0	1.1
Iron increase, PPM	1.3	4.4	5	3.3	4.1	2
Copper increase, PPM	1.3	1.6	0	0	0	0
Lead increase, PPM	1.3	0.5	9	0	0	*3.4

* No. 2 fuel for second run contained 14 PPM lead and low flash (gasoline contamination).

Table 17
EXHAUST EMISSIONS
DURABILITY TESTS – 8-CYLINDER ENGINE

Fuels	NO _x (g/hp-hr)		CO(g/hp-hr)		HC(g/hp-hr)		Smoke (Bosch No.)	
Range diesel	+1.5		+1.7		+0.7		+0.5	
	6.8-1		3.8-1.5		0.8-0.3		1.2-0.6	
	Start	End	Start	End	Start	End	Start	End
CDL + diesel	7.6	8.7	2.4	2.2	0.5	0.5	0.5	0.5
Shale + diesel	7.2	7.7	3.6	3.2	1.5	1.6	0.4	0.6
Shale + resid.	6.2	7.5	4.4	4.0	0.6	0.5	1.1	0.9
Diesel + resid.	7.4	8.6	4.6	3.3	0.7	0.8	1.2	0.8

smoke value found with standard diesel fuel. At this level of smoke emissions such a change is insignificant. All test fuels showed a slight increase in NO_x emissions at the end of the durability run. Of the test fuels, the CDL plus diesel exhibited the highest NO_x value but, as stated above, this was still within the range of petroleum distillate fuel. The carbon monoxide and smoke values for both residual blends are higher than the equivalent measurements with the other two test fuels, although still within the range of diesel fuels.

The method of determining specific fuel consumption on the multicylinder engine is the same as used on the 2-cylinder engine which was previously described. Figure 23 compares the specific fuel consumption for each test fuel at the beginning and at the end of the test with standard diesel fuel. There was no significant change in fuel consumption over the course of each of the test fuel runs. The only significant fuel consumption difference with these test fuels is the *reduction* in SFC with the blend of petroleum distillate and petroleum residual. There is directional evidence of an increase in SFC with the blend of shale oil and diesel fuel. A multitude of tests would be required to confirm this slight change.

As discussed earlier, two methods were used to assess the piston ring wear rate. These included measurements of the end gap in a 9-inch diameter standard gage. The gap was determined at the beginning of each test and at the end of each test. Piston

Figure 23. Eight-cylinder endurance SFC.

rings were new at the start of each test. All four piston ring end gap measurements were determined. The second evaluation was the weight loss of the top compression ring. Of the two, the weight loss method is believed to be the most accurate. The gap increase system exposes only the amount of wear which has occurred on the face of the ring, while the weight loss method represents the total ring wear — face and side. Figure 24 displays the weight loss comparison of all six durability runs. The range of wear loss for all eight cylinders and average weight loss of the eight cylinders in milligrams per hundred hours of operation is displayed for each of the six fuels (two runs of petroleum No. 2). The data for each of the cylinders of the 8-cylinder engine are included in a table in Appendix 4. Table 18 exhibits the average gap increase of the top compression ring and the oil ring of each of the tests. This information is reported as thousandths of an inch, per 100 hours of operation. A table in Appendix 4 displays the data for all four rings of each piston of all six engine tests.

As shown in Figure 24, the average top piston ring weight loss for each of the test fuels, except the petroleum No. 2 blended with residual, is within the band of the two petroleum No. 2 tests. The variability of the ring weight loss of the CDL fuel is greater than any of the others. Additional repetitive tests would be required to confirm the indicated increase in wear with the petroleum-residual blends. However, other experience indicates that this is a valid observation. Certainly, there is no evidence that the use of shale fuel blended with either petroleum distillate or petroleum residual produces higher piston ring weight loss than the equivalent fuels of all-petroleum derivations.

The data from this series of short durability tests indicate that the piston ring end gap increase is lower than petroleum fuels for the 30% blend of CDL and the shale plus residual blend. The data also indicate that the ring gap increase for the 50%

Figure 24. Piston ring weight loss.

Table 18
PISTON RING GAP INCREASE
DURABILITY TESTS - 8-CYLINDER ENGINE

Fuels	Ring	End Gap Increase (Inches $\times 10^{-3}/100$ hr)
Pet No. 2 tests	top	1.4 and 2.1
	oil	7.9 and 6.3
30% CDL	top	0.4
	oil	1.3
50% shale 50% pet.	top	5.8
	oil	11.1
Shale plus resid.	top	0.6
	oil	5
Pet. No. 2 plus resid.	top	3.9
	oil	13.6

shale/petroleum distillate and the petroleum No. 2 plus residual are higher than petroleum No. 2 fuel for both top compression ring and oil control rings. If the repeatability of the testing with experimental fuels is the same as the repeatability of the two petroleum No. 2 tests, these indications are true. However, the magnitude of some of the gap increases is so small as to raise serious questions regarding the significance of these differences. It must be recognized that the top compression ring is chromium-plated on the face. The magnitude of the oil control ring wear is such

that the increase in wear rate with the shale blended with petroleum and the petroleum No. 2 blended with residual, and the reduction in wear with the 30% CDL fuel is most likely a valid direction.

Cylinder liner wear rate was also determined by two methods, which are discussed above. Table 19 displays the cylinder liner wear determined by the epoxy method and Table 20 displays this wear as determined by measuring the diameter change with a dial bore gage. The wear rates in Table 19 are radial dimensions; the wear rates in Table 20 are diametrical. Both of these tables display the wear rate at the upper ring reversal position and the lower ring reversal position. These tables display the averages of the eight cylinders. Tables in Appendix 4 exhibit these wear rates for each cylinder. Of these two methods, the epoxy replica is believed to be far more accurate. The very small dimensional changes in the cylinder bore measurements can be greatly influenced by the location of the dial bore gage. The conclusion to be drawn from Tables 19 and 20 appears to be that the cylinder liner wear rate was not shown to be significantly different with any of the fuels tested.

Table 19
CYLINDER LINER WEAR – RADIAL
DURABILITY TESTS – 8-CYLINDER ENGINE

Fuels	Ring	Radial Wear (Inches $\times 10^{-3}$ /100 hr)
Pet. No. 2 tests	top ring reversal	0.1 and 0.76
	lower ring reversal	0.1 and 0.65
30% CDL	top ring reversal	0.08
	lower ring reversal	0.14
50% shale 50% pet.	top ring reversal	0.35
	lower ring reversal	0.41
Shale plus resid.	top ring reversal	0.58
	lower ring reversal	0.5
Pet. No. 2 plus resid.	top ring reversal	0.29
	lower ring reversal	0.28

Table 20
CYLINDER LINER WEAR – DIAMETRICAL
DURABILITY TESTS – 8-CYLINDER ENGINE

Fuels	Location	Diametrical Wear Inlet to Exhaust (Inches $\times 10^{-3}$ /100 hrs)
Pet. No. 2 tests	top ring reversal	0.14 and 0.16
	lower ring reversal	0.29 and 0.21
30% CDL	top ring reversal	0.32
	lower ring reversal	0.4
50% shale 50% pet.	top ring reversal	0.2
	lower ring reversal	0.38
Shale plus resid.	top ring reversal	0.8
	lower ring reversal	0.03
Pet. No. 2 plus resid.	top ring reversal	0.07
	lower ring reversal	0.41

CONCLUSIONS

1. Blends of solvent refined coal and diesel fuel may be handled safely by experienced diesel engine mechanics.
2. A serious corrosion problem was found in the fuel pump parts when operating with solvent refined coal blended with petroleum. It is expected that a metallurgy change can overcome this problem.
3. Proper selection of materials for the fuel system is required to permit handling coal-derived liquid fuels.
4. A medium speed, high horsepower, 4-cycle diesel engine can be operated on blends of solvent refined coal and petroleum without serious consequences save the fuel system corrosion previously mentioned. This is based on a single, short durability test.
5. As represented by the product evaluated, 100% shale-derived distillate fuel may be used in a medium speed, high horsepower, 4-cycle diesel engine without significant consequences.
6. The shale product evaluated may be blended with petroleum distillate or petroleum residual materials and used as a fuel for medium speed, high horsepower, 4-cycle diesel engines.

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Appendix 1

FUEL HANDLING PROCEDURES

Appendix 1

HANDLING PROCEDURES FOR COAL-DERIVED LIQUID FUELS

Introduction

The coal-derived liquid material is combustible, similar in this respect to kerosene or diesel fuel oil. But, because it is derived from coal and coal tar-like material, it is more of a potential health hazard than diesel fuel oil or kerosene, which come from petroleum. The principal area of concern is with skin contact. In addition, combustion products contain toxic fumes and smoke, which are irritating to the eyes and upper respiratory tract if overexposure occurs.

Therefore, the following practices will be observed by all personnel coming in contact with the material. (Note that the coal-derived liquid fuel is not classed as "hazardous," but "possibly hazardous.")

Fire

In case of fire associated with this material, practices for fighting diesel fuel and kerosene fires will prevail. Note that the material floats on and emulsifies with water. Air-supplied rescue equipment must be used in any confined area involving burning coal-derived liquids.

Handling the Material

1. Ventilation must be available. Material must not be handled in a confined area.
2. Workers will wear the following protective clothing when handling coal-derived liquid: neoprene gloves, laboratory smock, neoprene apron when required, shoe covering, and chemical goggles.
3. An individual respirator will be provided and used when handling the material.
4. In the event that spillage or splashing causes the material to come in contact with the skin, the contacted area will be immediately washed with soap and water. In this connection, abrasive soaps are *not* to be used. Nonabrasive liquid hand cleaner of the type intended for use with water is to be used. Waterless cleaners may be used after soap and water wash.
5. Any clothing which has become significantly contaminated with the coal-derived fuel is to be changed immediately.
6. Workers who come in direct contact with the fuel (such as changing fuel lines) will shower at the end of the shift and will use a fresh lab coat daily.
7. It is standard practice to exercise care with high pressure jets of fuel oil (such as those emitted from the nozzle on pop test). The same good work habits are necessary when working with the coal-derived liquids in the fuel injection room.
8. The Plant Industrial Hygiene Department will provide an air sampling device which will be worn by those who could be exposed to the vapors from coal-derived liquids. Instructions for use will be provided by Industrial Hygiene. If this monitoring justifies, the respirator requirement (No. 3) will be modified.

Ventilation and Exhaust Sampling

1. When the 2-cylinder engine is operating on coal-derived liquids, the mandoor between the 2-cylinder cell and the No. 3 engine cell will be open. The cell exhaust fan of the No. 3 engine cell will be on and the intake air vent of the No. 3 cell will be open.
2. To the degree possible, the door of the 2-cylinder engine cell will be closed during operation with coal-derived liquids.
3. The portion of the exhaust stack of the 2-cylinder engine which passes through the main laboratory area is to be free of leaks. Where more probes than usual are inserted into the stack, care must be taken to ensure that there are no leaks around the fittings.

Appendix 2

**BENDIX REPORT –
BENCH PERFORMANCE TESTS,
FUEL SYSTEM**

<h1 style="margin: 0;">ENGINEERING REPORT</h1>		REPORT NO. 4044 DATE 2/17/81 PAGE 1 OF 26																																					
The Bendix Corporation		Electrical Components Division Sidney, New York																																					
TITLE PERFORMANCE TESTS ON #2D FUEL OIL AND SRC #2 OIL WITH THE FUEL INJECTION EQUIPMENT AS APPLIED TO GENERAL ELECTRIC, 9 x 10 $\frac{1}{2}$ " ENGINE		TYPE CUSTOMER EVALUATION CONTRACT NO.: 70729A CLASS NO.: PD-391 EWOM NO.: 588																																					
<div style="display: flex; justify-content: space-between;"> <div> <p><u>DISTRIBUTION:</u> O. Sokol, W. Morton, J. Hoffman-G.E.(2)</p> <p><u>Circulated Copy:</u> D. Baker, H. Dingman</p> </div> <div style="text-align: center;"> <p><u>TABLE OF CONTENTS</u></p> <table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th></th> <th style="text-align: right;"><u>Page No.</u></th> </tr> </thead> <tbody> <tr><td>Index</td><td style="text-align: right;">1</td></tr> <tr><td>Object, Introduction, Conclusions, Discussion</td><td style="text-align: right;">2-6</td></tr> <tr><td>Standard Performance Curve, Both Oils, C-3818</td><td style="text-align: right;">7</td></tr> <tr><td>Notch Performance Curve, Coal Oil, C-3827</td><td style="text-align: right;">8</td></tr> <tr><td>Notch Performance Curve, #2D Oil, C-3819</td><td style="text-align: right;">9</td></tr> <tr><td>Comparison of Pressures by Notch Position, C-3833</td><td style="text-align: right;">10</td></tr> <tr><td>Pressure Transducer Oscilloscope Injection Pressure Characteristics #2D Oil, Photos 1-3</td><td style="text-align: right;">11-13</td></tr> <tr><td>Pressure Transducer Oscilloscope Injection Pressure Characteristics, Coal Oil, Photos 4-6</td><td style="text-align: right;">14-16</td></tr> <tr><td>Effects of the Oils Upon Vital Injection Parameters, Chart 1</td><td style="text-align: right;">17</td></tr> <tr><td>Detailed Examination of Parts From Durability Tests, Chart 2</td><td style="text-align: right;">18</td></tr> <tr><td>Comparison of Oil Viscosities, Chart 3</td><td style="text-align: right;">19</td></tr> <tr><td>Comparison of Various Fuel Properties (From Gulf Oil), Chart 4</td><td style="text-align: right;">20</td></tr> <tr><td>Material Safety Sheets From O.S.H.A. and Gulf Oil, Chart 5,6</td><td style="text-align: right;">21-22</td></tr> <tr><td>Bendix Injection Equipment and Pressure Taps, Chart 7</td><td style="text-align: right;">23</td></tr> <tr><td>Equipment Used in Tests, In Detail, Chart 8</td><td style="text-align: right;">24</td></tr> <tr><td>Detailed Exam of Pressure Pictures, Chart 9</td><td style="text-align: right;">25</td></tr> <tr><td>Test Equipment Arrangement, L-37754</td><td style="text-align: right;">26</td></tr> </tbody> </table> </div> </div>					<u>Page No.</u>	Index	1	Object, Introduction, Conclusions, Discussion	2-6	Standard Performance Curve, Both Oils, C-3818	7	Notch Performance Curve, Coal Oil, C-3827	8	Notch Performance Curve, #2D Oil, C-3819	9	Comparison of Pressures by Notch Position, C-3833	10	Pressure Transducer Oscilloscope Injection Pressure Characteristics #2D Oil, Photos 1-3	11-13	Pressure Transducer Oscilloscope Injection Pressure Characteristics, Coal Oil, Photos 4-6	14-16	Effects of the Oils Upon Vital Injection Parameters, Chart 1	17	Detailed Examination of Parts From Durability Tests, Chart 2	18	Comparison of Oil Viscosities, Chart 3	19	Comparison of Various Fuel Properties (From Gulf Oil), Chart 4	20	Material Safety Sheets From O.S.H.A. and Gulf Oil, Chart 5,6	21-22	Bendix Injection Equipment and Pressure Taps, Chart 7	23	Equipment Used in Tests, In Detail, Chart 8	24	Detailed Exam of Pressure Pictures, Chart 9	25	Test Equipment Arrangement, L-37754	26
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DATE 2/19/81	DATE 2/23/81	DATE 2-27-81	DATE																																				

SC654A

CUSTOMER:

General Electric, Erie, PA
4-cycle locomotive engines, 9 x 10½"

OBJECT:

1. To make performance tests upon one (1) set of their Bendix fuel injection equipment with both #2D diesel oil and SRC #2 middle distillate oil in open air;
2. To check the compatibility of the SRC #2 oil with our equipment and its appendages;
3. To attempt to operate one (1) set said Bendix equipment for 100 hours on durability at the locomotive full load back position.

INTRODUCTION:

There is very little information regarding the SRC #2 oils and their effects upon injection performance or engine operation and compatibility problems. General Electric (Erie, PA) contracted with the Federal Department of Energy to investigate this oil for possible use on locomotive engines.

The method of test was summarized in the letter of 1/18/80 from R. K. Bagnall to Jack Hoffman of General Electric. General Electric's purchase order #462E500330-N of April 11, 1980 launched the project which was planned via Plan Report #4026.

Our August 18, 1980 TWX to Jack Hoffman briefed the customer on our general findings but a re-run of a part of the #2D oil work had to be performed (January 1981) before this report could be issued. The various problems encountered in getting our laboratory facility approved to test the SRC #2 oil unduly prolonged the work.

The injection equipment that was tested has been sold to G.E. since 1969: pump type F3.5E-17, 10-375197-13 and nozzle holder assembly type H3LE337, 10-328312-6. However, by agreement with General Electric, we modified the pump seals with Viton o-rings because prior information from the Gulf Oil Company clearly inferred that Buna N rubber was not compatible to coal oils.

General Electric supplied both barrels of oil to Bendix:

#2D oil - ASTM 975 type RR
SRC #2 coal oil made by Gulf Oil Company (middle distillate type)

CONCLUSIONS:

Notice: The tests were made with both oils at the same rack position and speed settings.

CONCLUSIONS: (con't.)

1. Comparing the SRC #2 middle distillate oil to the #2D oil indicates:
 - a. shorter injection lags by 1.5° to 4° crank which may affect engine timing (Chart #1);
 - b. higher gross-line pressures throughout the notch positions (Curve C-3833);
 - c. more fuel delivery (output), mm^3/st (2.5-4.5% at full load, 33% at low idle) (Chart #1);
 - d. similar duration of main injections (Chart #1) without any hints of secondary injections;
 - e. similar cavitation erosion indication at the entrance to the nozzle holder at the low idle position, Notch #0. This equipment has historically produced slight cavitation with #2D oil after many hours in General Electric service at the cone end of the high pressure line.

This can be seen in graphical form on Curve C-3818 and in detail on the notch performance curves C-3827 (coal oil) and C-3819 (#2D oil). (Note: the General Electric notch positions can be seen in the table on Curve C-3819.)

2. The higher gross-line pressures with SRC #2 oil vary from 500 psi (11%) at Notch #0 up to 1900 psi (21%) with Notch #8. This is detailed on Curve C-3833 by notch position. There is very little difference in residual pressures.

3. The aforementioned similarity of potential cavitation erosion between the two oils is illustrated by:

Photos #1-3 for #2D oil.
Photos #4-6 for coal oil.

These are transducer and oscilloscope checks of the pressures in the various parts of the system (Chart #7). Their principal intent is to measure gross and residual pressures and infer potential cavitation erosion. One can see the high frequency pressure "hash" (in Photos 3,6) at low idle, 5 or 6 rack, 225 rpm wherein the pressure clearly dips below the residual pressure and below atmospheric pressure at the neck of the holder. Chart #9 details the exam of the photos.

4. The modified fuel injection equipment, while in operation, appears compatible with the middle distillate coal oil, SRC #2, for the tests and the 100-hour operation period. No leaks occurred. It is, however, questionable how well the Bendix equipment and/or the fuel filters can "withstand" the coal oil soaking in the static unused state, i.e., shutdown. Black deposits occurred in pump housing fuel chamber which came off and apparently scored the plunger of our master pump. The filters were coated with a black deposit. This situation probably occurred because the entire test apparatus was forced to lay idle (soaking in coal oil) for 4.5 months during the problems involved in getting the laboratory facility approved to test the SRC #2 oil.

CONCLUSIONS: (con't.)

5. The durability test of 100+ hours at General Electric's full load position on the Bendix durability test stand further amplified conclusion #4. Generally, it can be said that all relatively quiescent injection equipment surfaces received a black deposit. This can be tolerated except that it harbors potential scoring problems after many hours of operation. The deposits will become harder and thicker and break off, possibly endangering the integrity of the plunger (of pump) or the needle O.D. Notably, the plunger and needle of the actual equipment assigned for the test (whether for test or for durability work) were in good condition. The detailed exam is described on Chart #2.

6. No external leaks developed from the o ring seals (Viton) of the pump or from the holder assembly. However, future leakage problems may develop on the lapped flat surfaces since black staining occurred on the pump parts involving such surfaces.

7. The following characteristics and/or problems were observed with the coal oil:

- a. It is "slippery" - acts to allow wrenches and other items to easily slip.
- b. Its strong odor is all pervasive (like lysol). Its odor in the lab continues 10 months after its use and all oil, rags, etc. have been removed.
- c. It is a strong solvent of paint on all of our lab equipment painted surfaces.
- d. It is clear one must use seals like Viton or Teflon to withstand the coal oil. Our original Buna N filter gasket and the regular Buna N seal in the quick-connect hose deteriorated within several weeks.
- e. Care must be taken not to expose the eyes or skin to contact with the SRC #2 oil.
- f. It forms deposits on the filter cartridges of both resin coated paper or viscose wound strand. The ratings of the new cartridges were 5-10 microns. This deposit must be inherent to the oil. We did not have "dirt" particles loading up the filters after the initial change of filters after flushing all the equipment.

DISCUSSION:

1. The coal oil's shorter injection lags, higher pressures and larger delivery should be expected since the specific gravity and viscosity are higher than #2D oil. The injection system is "harder":

	Spec. Gravity	Viscosity Saybolt Universal Seconds at 100°F
This coal oil, SRC #2, Middle Distillate	.974	36.3-37.3
#2D Oil	.876	32.6-37.9

2. The deposits upon quiescent surfaces and filters with 100% middle distillate coal oil appear to be the limiting factor. The use of Viton seals abated premature deterioration of low pressure seals. The staining of firmly contacted lapped surfaces was unexpected, and only long durability runs can verify that this is or isn't a real problem.

3. Servicing of the injection equipment after 1-2 years should cost more since service stations must remove the deposits and must relap all sealing surfaces at rebuild time.

HYGIENIC DISCUSSION:

Considerable problems were encountered getting our laboratory facility approved to test the SRC #2 oil. Air monitoring of the fuel injection test stand under actual running conditions by the Industrial Hygiene Department of Bendix (analysis by Kemrow Environmental Services) resulted in benzene soluble fraction of total particulate concentrations given as Polynuclear Aromatic Hydrocarbons (PNA's) in considerable excess of the Occupational Safety and Health Administration (OSHA) permissible exposure limit. As a result, the testing procedures were halted.

Because of the high PNA concentrations reported and in an effort to proceed with the testing of SRC #2 oil, an industrial hygiene reevaluation of the process was conducted by hygienists from Bendix, General Electric, and Gulf Oil. At the time of this testing, our technician was wearing a constant-flow airline respirator as recommended by the Bendix hygienist. The results of this industrial hygiene reevaluation are encompassed in the reports of August 11, 1980 (AD40-20-05, 801TL699) of Mr. Jay G. Holtman. The details and questions of this report can best be handled by contacting Mr. Holtman, Gulf Science and Technology Co., Medical and Health Resources Division, P. O. Box 3240, Pittsburgh, PA, 15230. Both General Electric and Bendix hygienists were given copies of this report, and to date, we have not received any differing opinions. As a result of this reevaluation report, testing was allowed to resume and was completed to our commitment.

Listed from the report are the suggestions made with regard to the SRC #2 test procedures at the Bendix Diesel Injection Laboratory.

- (a) Based on the results obtained through considerable air monitoring, the need for Mr. Elwood to wear a constant-flow airline respirator is not warranted. However, precautionary protection may be indicated due to the mist production and the possibility of SRC #2 fuel splashes. As entirely optional piece of respiratory equipment would be a mist respirator such as the 3M #9910 Dust/Mist Respirator, and this could be used during the data collection at the spray pot. (Note: This respirator is acceptable for cokeoven emission which primarily consists of coal tar pitch volatiles.) An emergency air-supplied respirator should still be provided at the test location, to be used in the event of a catastrophic vapor or mist release.

- (b) To prevent mist contact with the liquid, splash to the face (especially the eyes and breathing zone), closed-cup, chemical splash goggles or, preferably, splash shields should be worn by the operator when performing the fuel injection spray tests. For all other work in the Lab, safety glasses with side shields should be worn.
- (c) During periods of possible SRC #2 fuel handling, neoprene gloves should be worn to afford hand and forearm protection. When maintenance work is in order, cotton lined gloves should be worn to afford some level of protection. Employees at the Gulf Oil P-99 SRC #2 Unit often wear vinyl surgical gloves under the cotton lined monkey gloves when performing maintenance work. This affords them the grip needed and the skin protection that is necessary. Once the cotton lined monkey gloves become soiled with SRC #2 fuel, they should be promptly discarded.
- (d) Elephant trunk ventilation may be warranted at the location where fuel is recycled to the graduated cylinder. This would eliminate vapor production as part of the process.
- (e) In an effort to reduce the poignant SRC #2 odor, any residual fuel on the surface of the engine should be immediately wiped up to reduce the rate of evaporation. Wipe rags should be stored in a covered metal container prior to laundering. All leaks in fuel lines should be immediately repaired to minimize airborne contamination. Any fuel spills should be wiped up immediately with the contaminated rags placed in designated metal storage containers. Any clean-up rags which become saturated with SRC #2 should be discarded in the proper manner.

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100 2100-M DIEYZGEN 1140M HAFIN

CUSTOMER: G.E. LOCOMOTIVE
ENGINE: 9 10 1/2 H
B.P.M. - B.N.P.
1250 CRANK

THE BENDIX CORPORATION
ELECTRICAL COMPONENTS DIVISION

C-3827

TEST CAM: 1-27406 TC
ROLL DIA: 2.75
NOZZLE HOLDER ASSY: 10-328312-6
TYPE: H3LE
LIFT & VEL. CURV: PLUN. VEL. & RPM

MOTION PERFORMANCE PUMP 10-375147-13M
WITH COAL OIL SPEC #2

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

ENGINE FUEL CAM: ROLL DIA: NOZZLE VALVE ASSY: 10-328310
TYPE: 3NM
TIP ORIFICE VEL: DEL. VALVE VEL

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

TEST PUMP: 10-375147-13M
PUMP SPEED: 1775 RPM
PORT CLOSURE: 1.15" TRAVEL @ 286" TRIP
PL & B. ASSY: 10-375417
DIA: 1.7mm
LEAD: 10-375292-2
ORIFICE DRILLING - C.H. - WALL - AREA: 10-246-150" .070 .04 1297

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

DEL. VALVE ASSY: 10-73571-7
TYPE: COMP. DIA: .5"
FUEL LINE: 1.0 O.D. LENGTH: 14"

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

EXTRACTION: 10-73566
DEL. VALVE SPRING: 10-73566
DEL. V. HOLDER: 10-73566

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

INLET SYSTEM: OIL AT 85-90°F @ 35PSI
STANDARD BAYMANN RVTM
3.5" H-3E + BAYM
PUMP HAS VITON O-RINGS

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

BY-PASS AREA: 1.85mm²
DEL. VALVE STOP: 10-73566-11

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

DEL. VALVE SPRING: 10-73566
DEL. V. HOLDER: 10-73566

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
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CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

BY-PASS AREA: 1.85mm²
DEL. VALVE STOP: 10-73566-11

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

DEL. VALVE SPRING: 10-73566
DEL. V. HOLDER: 10-73566

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
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LOG NO. ENG. DATA

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CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

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DEL. V. HOLDER: 10-73566

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

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PUMP HAS VITON O-RINGS

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CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

BY-PASS AREA: 1.85mm²
DEL. VALVE STOP: 10-73566-11

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

DEL. VALVE SPRING: 10-73566
DEL. V. HOLDER: 10-73566

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

INLET SYSTEM: OIL AT 85-90°F @ 35PSI
STANDARD BAYMANN RVTM
3.5" H-3E + BAYM
PUMP HAS VITON O-RINGS

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

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LOG NO. ENG. DATA

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STANDARD BAYMANN RVTM
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PUMP HAS VITON O-RINGS

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CHECKED: 05 8-11-20
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TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

BY-PASS AREA: 1.85mm²
DEL. VALVE STOP: 10-73566-11

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
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TEST NO. 4044
JOB NO. W580
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DEL. VALVE SPRING: 10-73566
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JOB NO. W580
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INLET SYSTEM: OIL AT 85-90°F @ 35PSI
STANDARD BAYMANN RVTM
3.5" H-3E + BAYM
PUMP HAS VITON O-RINGS

TESTED: DRAWN: 05 8-11-20
CHECKED: 05 8-11-20
APPROVED: 05 8-11-20

TEST NO. 4044
JOB NO. W580
LOG NO. ENG. DATA

A-2.8

FUEL DIVISION

NO. 3150 N. DIETZEN DR. E. FAIR
4.11.11.11

Bendix

CUSTOMER
G.E. LOCOMOTIVE

ENGINE - BORE - STROKE - CYCLE - CYLINDER - H.P./CYL - 8 B.S.M. - B.M.E.P.
9 10 1/2 4 8 1/2 16 1050

THE BENDIX CORPORATION
ELECTRICAL COMPONENTS DIVISION

C-3819

TEST CAM
L-27406-TC

ROLL DIA.
2.750

NOZZLE HOLDER ASSY
10-328312-6

TYPE
H3LE

LIFT & VEL. CURVE

PLUN. VEL. # RPM

ENGINE FUEL CAM

ROLL DIA.
2.750

NOZZLE VALVE ASSY
10-328310

TYPE
3NR

TIP ORIFICE VEL.

TEST PUMP SERIAL #79123 98
10-375197-13M / F35F17

NOZZLE O.P.
3900

LIFT
0.25"

DEL. VALVE VEL.

NOTCH REF. OF PUMP 10-375197-13M
WITH #2D OIL

TEST NO.
4044

CON. NO.
14598

LOG. NO.

ENG. DATA

TESTED

DRAWN
F. J. BENDIX
2-20-83

CHECKED

APPROVED
D. J. BENDIX
2-20-83

1-13

PUMP SPEED
157 @ 256 TAP

PORT CLOSURE #

AL & S. ASSY
10-375427

DIA.
17MM

LEAD

DEL. VALVE ASSY
10-73571-7

TYPE
COMP

DIA.
500

RETRACTION
600.00 MM3

BY-PASS AREA
8.5 MM2

DEL. VALVE SPRING
10-73566

DEL. VALVE STOP
10-73808-11

DEL. V. HOLDER

SPRAY TIP NO. OR ORIFICE # TYPE
10-375292-2

ATG FLOW

ORIFICE DRILLING - C.H. - WALL - AREA
10 x .016" .150" .070" .040" 124.2

FUEL LINE I.D. - O.D. - LENGTH
.125" .500" 18"

INLET SYSTEM:-
OIL AT 85-90°F @ 35 PSI
STAND PIPE DAMPING WITH
3FF HOSE + BANJO
PUMP WITH VITON O-RINGS

16TH ENGINE NOTCHES

NOTCH	PUMP RPM	PUMP MAX. JAW	ENGINE OBSERVED, #2D OIL
1	5.25	20-22.5	
2	4.84	18-20	
3	4.37	15.6-17.7	
4	4.37	13.1-14.5	
5	3.47	10.7-11.9	
6	3.53	8.5-9.1	
7	2.47	7.8-8.0	
8	2.85	6.7	
9	2.25	5.8	
10	5.75	5.5-7.0	

SEE C-3833 FOR PRESSURES
C-3827 FOR NOTCH

A-2.9

A-2.10

EUGENE DIETZEN CO.

NO. 3-000 "E" DIETZEN GRAPH - PAUL
M. L. MILLER

Horizontal Time 2 MS/CM = 2 MS/Box = .002 Sec./Box

Needle Lift
.007"/box
and P.C. Pip

Line Pressure
Strain 2000 psi
box

Neck Pressure
Piezo

Nozzle Pressure
Piezo

Pump RPM	439	482	525	525
Pump Rack, MM	16	18	20	22
Appr. Notch Position	6	7	8 low loads	8 high loads

Needle Lift, Injection Pressures at Approximate Notch Positions of the General Electric
9 x 10 $\frac{1}{2}$ Locomotive Fuel Injection System With #2D Fuel Oil (ASTM 975, Type RR)

PHOTO #1

Test #4044
ENP-Bendix
Feb. 1981

A-2.11

Horizontal Time 2 MS/CM = 2 MS/Box = .002 Sec/Box

Needle Lift
.007"/box
and P.C. Pip

Line Pressure
Strain 2000 $\frac{\text{psi}}{\text{box}}$

Neck Pressure
Piezo

Nozzle Pressure
Piezo

Pump RPM	257	353	397	439
Pump Rack, MM	8	9	11	14
Appr. Notch Position	2	3	4	5

Needle Lift, Injection Pressures At Approximate Notch Positions of the
General Electric 9 x 10 $\frac{1}{2}$ Locomotive Fuel Injection System With #2D Fuel Oil
(ASTM 975, Type RR)

PHOTO #2

Test #4044
ENP-Bendix
Feb. 1981

Horizontal Time 2 MS/CM = 2 MS/Box = .002 Sec/Box

Needle Lift
.007"/box
and P.C. Pip

Line Pressure
Strain 2000 psi
box

Neck Pressure
Piezo

Nozzle Pressure
Piezo

Pump RPM	525	225	225	225
Pump Rack, MM	6	5	6	7
Appr. Notch Position	High Idle	#0 Low Idle	(#0 Low Idle)(Idle #1)	Idle #1

Needle Lift, Injection Pressures at Approximate Notch Positions of the General Electric
9 x 10¹/₂ Locomotive Fuel Injection System With #2D Fuel Oil (ASTM 975, Type RR)

PHOTO #3

Test #4044
ENP-Bendix
Feb. 1981

A-2.13

Horizontal Time 2 MS/CM = 2 MS/Box = .002 Sec/Box

Needle Lift
.007"/box
and P.C. Pip

Line Pressure
Strain 2000 psi
box

Neck Pressure
Piezo

Nozzle Pressure
Piezo

Pump RPM	439	482	525	525
Pump Rack, MM	16	18	20	22
Appr. Notch Position	6	7	8 low load	8 high load

Needle Lift, Injection Pressures at Approximate Notch Positions of the General Electric
9 x 10½ Locomotive Fuel Injection System With SRC II Middle Distillate Oil

PHOTO #4

Test #1044
ENP-Berdix
Feb. 1981

A-2.14

A-2.15

Horizontal Time 2 MS/CM = 2 MS/Box = .002 Sec/Box

Needle Lift
.007"/box
and P.C. Pip

Line Pressure
Strain 2000 psi
box

Neck Pressure
Piezo

Nozzle Pressure
Piezo

Pump RPM	267	353	397	439
Pump Rack, MM	8	9	11	14
Appr. Notch Position	2	3	4	5

Needle Lift, Injection pressures at Approximate Notch Positions of the General Electric
9 x 10½ Locomotive Fuel Injection System With SRC II Middle Distillate Oil

PHOTO #5

Test #4044
ENP-Bendix
Feb. 1981

Horizontal Time 2 MS/CM = 2 MS/Box = .002 Sec/Box

A-2.16

Needle Lift
.007"/Box
and P.C. Pip

Line Pressure
Strain 2000 psi
box

Neck Pressure
Piezo

Nozzle Pressure
Piezo

Pump RPM 525
Pump Rack, MM 6
Appr. Notch Position High Idle

225
5
#0 Low Idle

225
6
Low Idle, Idle #1

225
7
Idle #1

Needle Lift, Injection Pressures at Approximate Notch Positions of the General Electric
9 x 10 $\frac{1}{2}$ Locomotive Fuel Injection System With SRC II Middle Distillate Oil

PHOTO #6

Test #4044
ENP-Bendix
Feb. 1981

Notch Position #	Rack MM	Timing Effects or Injection Lag From Port Closure To Begin Injection Crank Degr.		Output of Fuel Delivery					
				Duration Of Main Injection Crank Degr.		MM ³ /St		% Increase With Coal Oil	% Difference Increase By Coal Oil Using Gold Master Set
		Coal Oil	#2D Oil	Coal Oil	#2D Oil	Coal Oil	#2D Oil		
Low Idle 0	5.5	3.0°	5.0°	4.0°	3.0°	120	90	+33.0%	+37 %
Idle 1	7.0	3.0°	6.0°	6.0°	4.0°				
2	8.0	3.0°	7.0°	8.0°	7.0°				
3	9.0	3.0°	5.0°	11.0°	12.0°				
4	11.0	3.0°	5.0°	14.5°	16.0°				
5	14.0	3.5°	5.0°	18.5°	18.0°				
6	16.0	3.5°	5.0°	20.5°	21.0°				
7	18.0	4.0°	6.0°	24.0°	23.0°				
Full Load 8	20.0	4.0°	6.0°	27.0°	27.0°	1400	1340	+ 4.5%	+ 2.5%

Compares Timing, Injection Lag and Delivery

CHART #1

Examination of Bendix injection equipment that had operated at full load for 100+ hours with coal oil SRC II:

Pump Type F3.5E, 10-375197-13, Serial #7912595:

Plunger Assembly. The plunger appeared fine like any plunger run with #2D oil; some scuff marks. The barrel had dark stain deposits on the bottom and top where a pocket exists; similarly on the chamfers to the ports; many vertical axial stain marks on its I.D.; a light brown stain on its O.D.

Delivery Valve Assembly. The top and bottom of the body distinctly stained and some black deposits. The valve is fine except for the black deposit in the sac hole of the delivery valve.

Internal Fuel Chamber of Pump Housing. There was a distinct annulus shaped black deposit on the barrel seat between the barrel and pressure sleeve. However, the rest of the fuel chamber was clean.

Lower Pump Housing Chamber. The bores had a thin blackish coating.

Delivery Valve Holder. Dark stain on its lapped surface.

Delivery Valve Stop. Dark stain.

Delivery Valve Spring. O.K. - as if run with #2D oil.

Plunger Spring. Sooty deposit over the resin coating.

Control Rack. Its numerals (white when new) have been darkened. Some rust near end from atmosphere.

Pressure Sleeve. Stained dark grey on its O.D.

Plunger Cup. Stained vertical axial stripes, but this is also seen with #2D oil.

Control Sleeve and Lower Spring Plate. Rusted on its lower portion, but we blame the atmosphere for this.

Timing Window Gasket. O.K.

Paint on Outside of Pump Housing. Only stained a bit, but we did not have any leaks. The coal oil corrodes all paint surfaces on the lab test stand and devices.

Nozzle Holder Assembly, Type H3LE,337, 10-328312-6:

Nozzle Assembly. Body - there is a black deposit on the top of the body where "stagnant" fuel rests mating with the nozzle holder body; similarly such exists in the top annulus groove and the lower internal groove. Using hard paper, we can wipe it off.

Nozzle Assembly. Needle - is o.k. except for some staining.

Nozzle Spring, Push Rod, and Annular Spacer. Stain deposit all over which can be wiped off.

CHART #2 - Durability Exam

INSPECTIONS OF SOME RAW SRC II PRODUCTS^a
FROM A VARIETY OF COALS AND TWO PETROLEUM FUEL OILS

ENG. REPORT 4044
Page 20

Product:	SRC II		Petroleum Fuels	
	Middle Distillate	Heavy Distillate	No. 2 Grade	No. 5 Grade ^b
<u>Inspections:</u>				
Gravity: °API	13.3	0.4	>30	19
Density (15°C): kg/dm ³	0.974	1.072	<0.376	0.940
Color	dark	dark	light	dark
Viscosity: cSt				
100°F	3.1-3.4	49.6-90.2	2.0-3.6	26-194
210°F	-	4.0-5.1	-	2.9-48 ...
Viscosity: SUS				
100°F	36.3-37.3	231-418	32.6-37.9	124-900
210°F	-	39.8-42.7	-	36-224
Flash Point, P-H: °F	>160	>180	>130	>150
Pour Point: °F	<-45	<+45	<+5	-15 - +80
Carbon Residue, Con.: %W				
10% Bottoms	<1.2	-	<0.35	-
Total Sample	-	<1.5	-	2 - 10
Nitrogen: %W	0.9-1.1	1.2-1.4	<0.02	<0.3
Oxygen: %W	3.6-4.3	1.4-1.0	<0.09	<0.4
Sulfur: %W	<0.2	0.37-0.47	0.04-0.48	0.07-1.9
Carbon: %W	86.0	89.1	87.0	88.3
Hydrogen: %W	9.1	7.5	12.8	10.7
Hydrocarbon Groups (HPLC): %W				
Saturates	35-38	-	>65	-
Aromatics & Polar Compounds	62-65	-	<32	-
Asphaltenes, IP143: %W	<0.1	0.9-2.7	<0.1	<5.0
Phenolics: %W	-	-	0	-
Naphthalenes: %W	14-19	-	<6	-
Smoke Point: mm	5-8	-	>14	-
Ash, D482: %W	<0.001	0.03-0.1	<0.003	<0.05
Nickel: ppm	<0.1	0.3-0.9	<0.1	46 ^c
Vanadium: ppm	<0.1	<0.1-1.1	<0.1	180 ^c
Sodium: ppm	-	2-11	<0.5	2-20
Neut. No (Tan), D664	0.27-0.42	0.25-0.57	<0.30	<0.45
Copper Strip Corrosion, D130	1-3	1	1	1
Heat of Combustion, Gross, D240				
BTU/Lb	16,900	17,000	19,300	19,700
BTU/Gal	137,100	151,800	136,700	146,600
Cetane No., D613	<20		40-55	-
Autoignition Temperature: °F	925	895	595	600-700
Thermal Stability, MBIL (UI661)				
Thimble Rating				
Unwashed	1	1	1	1
Washed	1	1	1	1
Washed and Wiped	1	1	1	1
Rating of Tube	1	1	1	1
Accelerated Stability, D2274				
Deposit Weight, mg/100 ml	<0.8	<3.5	<1.0	-
Stability Test, 64 hr @ 210°F				
Insolubles: mg/100g	<0.3		<0.5	-
Distillation: °F				
Over point	D36	D1160:760mm	D66	
10%	338-396	538-554	369-389	-
50%	386-406	566-584	422-445	-
90%	425-444	640-656	498-516	-
End Point	463-500	785-820	580-593	-
	533-553	920-939	630-640	-

Notes:

- a - Preliminary values based on Pilot Plant production. Values of commercial product may vary. Reprocessing is also capable of altering product properties.
- b - Product is a blend of distillate and residual fuels.
- c - Metals content subject to considerable variation depending on crude source.

11/30/78

CHART #4

U.S. DEPARTMENT OF LABOR
Occupational Safety and Health Administration

MATERIAL SAFETY DATA SHEET

This is from Gulf
 Research, Oct. 9,
 1979 letter of Lar-
 Kerner to Cooper
 Energy.

SRC II MATERIAL

Revised 8/79, Replaces 7/79 CRH

SECTION I	
MANUFACTURER'S NAME The Pittsburg & Midway Coal Mining Co.	EMERGENCY TELEPHONE NO. (713) 226-1011
ADDRESS (NUMBER, STREET, CITY, STATE & ZIP CODE) North Fort Lewis, WA 98433	
CHEMICAL NAME & SYNONYMS NA	TRADE NAMES & SYNONYMS Middle Distillate
CHEMICAL FAMILY Coal derived middle distillate	FORMULA NA
CAS NUMBER ND	TSCA REGISTRY ENTRY ND

SECTION II - HAZARDOUS INGREDIENTS					
MATERIALS	%	TLV (Units)	MATERIALS	%	TLV (Units)
Middle Distillate	99+	*	Benzene	< 1	10 ppm

*The health hazards, particularly skin lesions associated with coal liquefaction processes, are recognized as potential health problems. Therefore, it is strongly recommended that inhalation and skin exposure be kept to a minimum and that all recommended precautions be observed when handling this material. See Section V. and IX.

DOT HAZARD CLASS: Combustible liquid

SECTION III - PHYSICAL DATA			
BOILING POINT °C (°F)	177-288°C (350-550°F)	SPECIFIC GRAVITY (H ₂ O=1) 15.6° / 15.6°C	0.97
VAPOR PRESSURE (mm Hg.)	ND	PERCENT, VOLATILE BY VOLUME (%)	97
VAPOR DENSITY (Air = 1)	ND	EVAPORATION RATE	ND
SOLUBILITY IN WATER	Slightly soluble		
APPEARANCE AND ODOR	Amber to black oil, strong creosotelike odor		

SECTION IV - FIRE AND EXPLOSION HAZARD DATA			
FLASH POINT	> 71°C (160°F) closed cup	FLAMMABLE LIMITS	ND
EXTINGUISHING MEDIA		LEL	UEL
☐ ALCOHOL FOAM ☒ CARBON DIOXIDE ☒ DRY CHEMICAL ☒ FOAM ☒ WATER SPRAY (FOG)			
☐ OTHER			
SPECIAL FIRE FIGHTING PROCEDURES Use water spray to keep fire-exposed containers cool, flush spills away from fire exposures and to disperse vapors. Use air-supplied rescue equipment for enclosed areas. This material floats and emulsifies with water.			
FIRE AND EXPLOSION HAZARDS Combustible. Flammability similar to diesel fuel or kerosene. Either misting of the material through handling or heating to its flash point is likely to give sufficient vapors for ignition upon exposure to flame or incendiary sparks.			
CHART #5			

NA - Not Applicable

ND - No Data Available

SECTION V - HEALTH HAZARD DATA

THRESHOLD LIMIT VALUE Suggested guideline for airborne exposure to coal derived materials:
0.2 mg/m³ as benzene solubles. See Section II.

EFFECTS OF OVEREXPOSURE SEVERELY IRRITATING TO THE EYES; STRONGLY IRRIT. TO THE SKIN. SYSTEMIC TOXICITY, PARTICULARLY CG & RESP. EFFECTS, CAN OCCUR FROM THE POSSIBLE SKIN ABSORP., INHALATION, AND INGEST. OF THIS MATERIAL DUE TO THE PRESENCE OF PHENOLIC COMPOUNDS. PROLONGED & REPEATED EXPOSURES MAY LEAD TO DERMATITIS & POSSIBLY TO SKIN TUMOR FORMATION. CAUTION: HIGH PRESS. SKIN INJECTION MAY OCCUR WHEN WORKING WITH FUEL INJECTORS. INJURY WILL NOT APPEAR SERIOUS AT FIRST; WITHIN A FEW HOURS TISSUE WILL BECOME SWOLLEN, DISCOLORED, AND EXTREMELY PAINFUL.

EMERGENCY AND FIRST AID PROCEDURES - SKIN CONTACT: IMMED. WATER DELUGE SHOWER. FOLLOW BY RINSING WITH CASTOR OR OLIVE OIL FOR LARGE SKIN SURFACE EXPOSURES. EYE CONTACT: FLUSH IMMED. WITH WATER FOR 15 MIN. INHALATION: REMOVE FROM EXPOSURE, GIVE ARTIF. RESP. IF NECESSARY. INGESTION: DO NOT INDUCE VOMITING (ASPIRATION HAZARD). GIVE 1-2 OZ ACT. CHARCOAL FOLLOWED BY 1-2 GLASSES OF MILK OR 2-4 OZ VEG OR OLIVE OIL. OBTAIN IMMED. MED. AID FOR ALL CASES OF CONTACT. HIGH PRESS. SKIN INJECTION: EMERG. MED. TREAT. MUST BE OBTAINED IMMED. AFTER ACCIDENTAL INJECTION. PHYSICIAN MUST BE FAMILIAR WITH LOCAL PROCEDURES FOR TREATMENT OF THIS TYPE OF WOUND (I.E., INCISION, SALINE IRRIGATION, REMOVAL OF NECROTIC TISSUE, & WOUND DRESSING).

SECTION VI - REACTIVITY DATA

STABILITY: UNSTABLE STABLE X CONDITIONS TO AVOID
INCOMPATIBILITY (Materials to avoid) Reacts with strong oxidizing materials.

HAZARDOUS DECOMPOSITION PRODUCTS
When heated to decomposition, it will emit irritating and toxic fumes.

HAZARDOUS POLYMERIZATION: MAY OCCUR WILL NOT OCCUR X CONDITIONS TO AVOID

SECTION VII - SPILL OR LEAK PROCEDURES

☐ EVACUATE AREA	☒ RESPIRATORY PROTECTION (AS PER SECTION VIII)	☐ EVAPORATE SMALL AMOUNTS IN HOOD	☐ NEUTRALIZE AND WASH AWAY WITH WATER
☒ STOP FLOW	☒ SKIN PROTECTION (AS PER SECTION VIII)	☒ INCINERATE UNDER CONTROLLED CONDITIONS	☒ OBSERVE GOVERNMENTAL SPILL & WATER QUALITY REGULATIONS
☒ ELIMINATE ALL SOURCES OF IGNITION, FLAMMABLES	☒ ABSORB OR SCRAPE UP	☐ INCINERATE USING AFTER BURNER & SCRUBBER	☒ REMOVE SOILED CLOTHING
☒ AVOID INHALATION	☒ VACUUM UP	☐ BURY IN REMOTE AREA OR USE AS LANDFILL	☐ OTHER
☒ AVOID DERMAL CONTACT			

SECTION VIII - SPECIAL PROTECTION INFORMATION

	DURING NORMAL USE	FOR GASES, VAPORS, DUSTS, FUMES, MISTS EXCEEDING TLV	SPECIAL (E.G. THERMAL PROCESSING, SPRAY APPLICATIONS)
GENERAL VENTILATION	Yes	Yes	
LOCAL EXHAUST	Yes	Yes	
RESPIRATORY PROTECTION (1-3)		2, if needed	3, for large spills

1. Particle-Removing Air Purifying Air Respirator (Mechanical Filter)

2. Gas and Vapor-Removing Air Purifying Respirator (Canister)

3. Full Face Mask Positive Pressure-Demand Type Supplied Air

EYE PROTECTION	SAFETY GLASSES	X	CHEMICAL GOGGLES	X	FACE SHIELD		(E) EXCELLENT
PROTECTIVE GLOVES	NEOPHENE	G	POLYVINYL ALCOHOL	NR	POLYETHYLENE	NR	(G) GOOD
	NATURAL RUBBER	P	BUTYL RUBBER	NR	POLYVINYL CHLORIDE	NR	(F) FAIR
							(P) POOR
							(NR) NOT RECOMMENDED

OTHER PROTECTIVE EQUIPMENT The application of a skin barrier cream before work and several times during work is recommended.

SECTION IX - SPECIAL PRECAUTIONS

PRECAUTIONS TO BE TAKEN IN HANDLING AND STORING Avoid skin and eye contact. Avoid the inhalation of mists, fumes, or vapors. Maintain good ventilation. Fresh change of work clothes daily. Showering and clothes change recommended at the end of each shift. Combustible hydrocarbons empty drums may contain combustible vapors. Wash out drums with water before discarding.

OTHER PRECAUTION:

Animal data suggest that SRC materials have the potential of producing fetotoxic effects. Therefore, it is prudent to prevent fertile females from receiving significant exposure to this material.

NOTICE

The data and recommendations presented herein are based upon our research and the research of others, and are believed to be accurate. No guarantee of their accuracy is made, however, and the products discussed are distributed without warranty.

CHART #6

FOR TRANSPORTATION SPILLS OR LEAK EMERGENCIES, CALL:
CHEMTREC - 800-424-9300
(CHEMICAL TRANSPORTATION EMERGENCY)

TEST EQUIPMENT:

Arrangement thereof is depicted by Sketch #L-37754 illustrating the Hartridge 1500 test stand set to .256" tappet setting.

Injection Equipment:

Cam L-27406 TC; 2.75 dia. roller;
Fuel supplied @ 35 psi at 85° - 90° F via a Teflon braided hose;
Continuous bleed-out of Bendix injection pump entrance through a .062" d orifice;
Damping via 4-foot stand pipe;
H.P. line .125" ID x .50 OD x 14" with strain gage pickup in the middle of it;
Bendix injection pump: Type F3.5E-17, 10-375197-13M;
(The "M" signifies that we added Viton o-rings to the pump.) The pump was calibrated in Production;
Bendix nozzle holder, Type H3LE 337, 10-328312-6 with spray tip or orifice plate;
Bendix nozzle, Type 3NK, 10-328310;
Bendix tip, TC, 10-375292-2 (10-.016" - 150°) or equivalent flow orifice plate;
Viton o-rings in pump - 10-375845-220 and -229.

Pressures in Injection System:

Strain gage in the middle of the high pressure line; Piezo electric transducers for the holder neck and nozzle pressure; linear transducer for needle lift; the start of the strain line pressure trace is used to measure residual pressure.

Scales: 2 ms/1 horiz. box; 1 volt/vert. box or 2000 psi/box
calibrated; the needle is approximately .007"/vert. box.

Port Closure: Signal is the vertical pip occurring on the needle lift trace just prior to the beginning of the needle lift.

Residual Pressure: It is measured by the strain gage in the high pressure line. It was set always to horizontal grid just below the line pressure trace when at atmospheric pressure.
Residual pressure = difference of trace to grid line.

Fuel Filter:

One quart size Fulflo filter B8 3/4" BD container with element E19 x 8-2 TZV. This is viscose wound strand over mesh for five micron removal and uses Buna N rubber gasket. This was changed to Viton gasket.

Coal Oil Tested:

Supplied by General Electric who obtained it from Gulf. This was one barrel of coal oil SRC #2 middle distillate.

#2D Fuel Oil Tested:

Railroad fuel #2D oil (ASTM 975, Type RR) obtained from General Electric.

Jobs: EWOM W-588.

Equipment Used in Test

CHART #8

Pressure Diagrams in Photos

Notch Position	#2D Oil Photo #1-3	Coal Oil Photos #4-6
Notch #8	No cavitation; At port closure P = 2000 psi line pressure.	No cavitation; At port closure P = 4000 psi line pressure.
Notch #2 is lowest position that full needle lift occurs for both oils.	Needle lift .025"; No erosion.	Needle lift .025"; No erosion
Notch #1 7 rack	Needle lift .017"; Port closure at 1000 psi line pressure; No erosion.	Needle lift .025" with preinjection; Port closure P = 3000 psi line pressure; No erosion.
Notch #1-#0 6 rack	Distinct erosion at the neck and nozzle - slight in line; Has needle lift .007".	No erosion; Low needle lift .007"; This fuel quantity may be for Notch #1 with coal oil.
Notch #0 5 rack	Distinct line and neck erosion	Possible neck and line erosion.

Note: A. The above notch positions represent about 85-90% of total hours of engine operation in a locomotive and that is why Notches #2 to 7 are omitted in analysis.

B. The nozzle transducer was out of calibration and reads too high a pressure, but its qualitative results are accurate.

C. The ripple seen in some photos of the strain line pressure do not affect the qualitative representation. This was found to be caused by lash in the drive coupling of the test stand. We found the vibration inlet hose, at times, causing similar tracing.

Exam of Pressure Trace Photos #1-6 For Erosion Potential

CHART #9

A-2.26

FIND NO.	QTY REQD	CODE IDENT	PART NUMBER	DESCRIPTION	NOTE REF
PARTS LIST					
UNLESS OTHERWISE SPECIFIED LINEAR DIMENSIONS ARE IN INCHES TOLERANCES: .XX - .03, .X - .1, ANGLES - 1° OTHER STANDARDS PER 9380 AND MIL-D-1000. NOTE REF			SIGNATURES: PREPARED CHECKED MATERIAL	DATES: 2-6-81 2/6/81	The Bendix Corporation Electrical Components Division Sidney, New York
MATERIAL SPEC			PROCESS SPEC	APPROVED: [Signature] [Signature]	
TEST 4044			NEXT ASSEMBLY		
TITLE: SCHEMATIC LAB HARTRIDGE #1500 TEST BLOCK			PART CODE IDENT NO C 77820 L-37754		
SCALE			DATE		

THIS DOCUMENT CONTAINS PROPRIETARY INFORMATION AND SUCH INFORMATION MAY NOT BE DISCLOSED TO OTHERS FOR ANY PURPOSE OR USED FOR MANUFACTURING PURPOSES WITHOUT WRITTEN PERMISSION FROM THE BENDIX CORPORATION.

Appendix 3

STUDY OF FUEL BOUND NITROGEN CONVERSION

A STUDY OF THE FUEL NITROGEN CONVERSION AND SOME
PERFORMANCE AND EMISSION CHARACTERISTICS OF BLENDED
SRC-II IN A HIGH SPEED DIESEL ENGINE

BY
CHIEH-SHEN LIN

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
(Mechanical Engineering)

at the

UNIVERSITY OF WISCONSIN-MADISON

1980

Abstract

Blended SRC-II and pyridine doped diesel fuel were compared to regular #2 diesel fuel in a 4-stroke, turbo-charged, direct injection, high speed commercial diesel engine.

The brake specific fuel consumption based on heating value, turbocharging, combustion characteristic and smoke did not change between blended SRC-II and regular #2 diesel fuel. The maximum torque, hydrocarbon and NO_x emissions were higher for blended SRC-II, however there was no difference in the NO_x measurements of the pyridine doped fuel and regular #2 diesel fuel.

The NO_x emission increase for the blended SRC-II is believed to be caused by the increased aromatic content of the blended SRC-II and not the fuel nitrogen conversion.

APPROVED:

David E. Foster

David E. Foster
Assistant Professor of
Mechanical Engineering

Date: June 27, 1980

Chapter 1

Introduction

On the Fuel Nitrogen Conversion

-- Fuel Nitrogen

Performance and emission characteristics of alternative fuels has recently become a topic of great concern. Some of the alternative fuels like shale oil, fuel derived from coal and fuel derived from tar sands usually contain higher concentrations of bound nitrogen. The nitrogen content varies according to the sources and refining processes. The oil shale (kerogen portion) contains from 0.3 to 2% nitrogen (Ref. 1) and the typical average nitrogen content of U.S. coal is from 1.0 to 1.7% (Ref. 2). The available middle distillate product, for example Athabasca tar sands derived diesel fuel, contains 0.022% of nitrogen. Shale derived Marine Diesel Fuel contains 0.24% (Ref. 8), yet the SRC-II (Solvent Refined Coal) contains about 0.9%. Note that usually the normal #2 diesel contains about 0.01 to 0.02% of N.

The impact of the nitrogen content on the emissions depends on the type of power plant. If NO_x is the only nitrogen compound pollutant considered, the lower the original thermal NO_x the higher the impact will be and vice versa.

For example, if a high speed direct injection diesel engine produces 1200 ppm of NO_x at full load ($A/F = 28$), adding 0.1% nitrogen to the fuel will increase the NO_x emission about 70 ppm if all the fuel-N were converted to NO_x , which is about 6% increase (see Fig. 1-1). For burners, less thermal NO_x is produced so the impact is more noticeable.

— Conversion

The N-emissions, attributable to fuel nitrogen is called fuel nitrogen conversion, and a conversion efficiency is defined as the N-emissions contributed by fuel-N divided by the imaginary N-emissions assuming that all the fuel-N is converted. Here the N-emissions include NO_x , NH_3 , HCN etc. (Ref. 1), but for lean combustion NO_x is the only survivor.

— In Low Pressure Burners

A great deal of investigation of the fuel nitrogen conversion in burners has been done both by burning nitrogen doped fuels and real high-N fuel. For doped fuel, it has been shown that there is always nitrogen conversion both in premixed and diffusion flames; the conversion is lower in diffusion flames (Ref. 4). For high-N fuel, Mansour (Ref. 5) found that 20 to 40% conversion was observed when burning SRC-II in a lab burner. The conversion can

Fig. 1-1 Theoretical NO_x concentration attributed by 100% fuel nitrogen conversion for 0.1% N increase by mass in fuel vs. A/F ratio

be reduced by using two-stage burner (Ref. 1) and a commercial two-stage, low NO_x burner is already available (Ref. 6).

-- In Engines

As for the engine, very little research has been done. DeVito & Cernansky showed that by burning pyridine doped gasoline in a CFR engine, indirect fuel injection produced 70 to 100% and direct fuel injection produced 0 to 66% fuel nitrogen conversion. Tuteja & Clark (Ref. 8) also used the pyridine doped fuel but in a high speed, direct injection, two-stroke, naturally aspirated diesel engine, and the results showed no significant difference in NO_x emissions between the doped fuel and base line fuel.

In this research the question of whether or not there is any fuel-N conversion in diesel engine was addressed. Unfortunately, up to now there has not been runable high nitrogen middle distillate fuel available. Consequently in this research both blended middle distillate SRC-II and pyridine doped #2 diesel fuel were used.

On the Comparative Performance and Emission Characteristics of Blended SRC-II

The influences of the fuel on the diesel engine has been studied for as long as the diesel engine has been in

existence, yet there has not been an overall systematic work on the performance and emission of alternative fuels until just recently. An extensive study was performed by Gross and Murphy (Ref. 9). Tuteja & Clark (Ref. 8) compared the oil shale and tar sands derived fuel with regular #2 diesel fuel. The fuel properties vs. particulate relationship was studied by Burley & Rosebrock (Ref. 10), some interesting results relating aromatic content not only to particulates but also NO_x and HC emissions were shown, which is similar to the results of Gross & Murphy.

Although the fuel nitrogen conversion is the primary concern in this study, some performance and emission characteristics were also investigated for the blended SRC-II fuel. Actually, in this experiment the most important variable of diesel fuel, cetane no., was kept constant for both fuels. This was done to facilitate the fuel-N conversion study, yet some interesting phenomena were revealed.

Chapter 5

Conclusion

1. The general performance and emission characteristics of blended SRC-II and #2 diesel fuel are similar. The characteristics measured include: brake specific fuel consumption based on heating value, turbocharging, combustion (ignition delay, maximum cylinder pressure, maximum pressure rise) and smoke.
2. The maximum torque is slightly different for the two fuels due to the small decrease in the heating value per volume of blended SRC-II, (the SRC-II itself is higher in heating value per volume but the other component T-17 is lower).
3. Hydrocarbon emissions were observed to be higher for blended SRC-II, this was attributed to its higher aromatic content.
4. Higher NO_x emissions were also observed for blended SRC-II, but there was no difference between pyridine doped fuel and #2 diesel.
5. It was shown that the NO_x increase corresponds well with Gross and Murphy's empirical relationship between aromatic content and NO_x emission. Aromatic content appears to be the cause for the NO_x increase instead of higher nitrogen content of blended SRC-II.

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Appendix 4

TYPICAL ENGINE TEST LOGS AND WEAR DATA

Table A4-1
CYLINDER LINER WEAR DATA (DIAMETRICAL)
DIAL BORE GAGE – INCHES $\times 10^{-3}$ /100 HOURS

Cyl.	Location	Inlet to Exhaust						Side to Side					
		No. 2 Diesel	30% CDL	50% Shale	Shale and Resid.	Pet. and Resid.	No. 2 Diesel	No. 2 Diesel	30% CDL	50% Shale	Shale and Resid.	Pet and Resid.	No. 2 Diesel
1L	upper	.29	.10	.10	1.24	0	0	.29	.35	0	0	.65	0
	lower	.68	.75	.10	.24	0	0	0	0	3.02	0	.65	.20
2L	upper	.15	.90	0	.65	0	.40	.19	.25	0	0	.84	0
	lower	.05	.45	0	0	.52	.33	0	.50	.73	.35	0	0
3L	upper	.34	.30	0	.29	.52	.07	.92	0	0	.41	0	.20
	lower	.29	.35	.10	0	.32	0	.19	.30	.42	.47	0	0
4L	upper	.29	.25	.31	1.35	0	.07	.83	0	—	0	1.23	.13
	lower	.49	0	1.56	0	.65	.40	.19	.05	1.46	.65	0	.20
1R	upper	.05	0	.31	.88	0	0	.44	.05	0	0	.91	0
	lower	.19	0	.83	0	.84	0	0	.20	1.46	.47	0	.27
2R	upper	0	.30	.63	.59	0	0	.49	.30	0	0	.91	0
	lower	.19	.55	0	0	.26	.27	0	.85	.10	.24	0	.40
3R	upper	0	.30	.21	.47	0	.13	.39	.35	0	0	.39	.13
	lower	.10	.30	.42	0	0	.47	0	1.00	.10	0	0	.80
4R	upper	0	.40	0	.94	0	.60	.53	.20	0	0	1.36	.07
	lower	.34	.80	0	0	.71	.20	0	.65	0	1.00	0	.27

Table A4-2
CYLINDER LINER WEAR DATA (RADIAL)
EPOXY REPICA – INCHES $\times 10^{-3}$ /100 HOURS

Cyl.	Location	Inlet to Exhaust					
		No. 2 Diesel	30% CDL	50% Shale	Shale and Resid.	Pet. and Resid.	No. 2 Diesel
1L	upper	.10	.05	.48	.42	.34	.49
	lower	.10	.15	.38	.22	.25	.27
2L	upper	<.05	<.05	.25	.38	.18	.57
	lower	.10	.12	.44	.48	.31	.63
3L	upper	<.05	<.05	.31	.41	.26	.51
	lower	.15	.17	.31	.31	.23	.51
4L	upper	.15	.07	.21	.48	.14	.83
	lower	.12	.15	.42	.53	.29	.65
1R	upper	.24	.35	.56	.94	.58	1.13
	lower	.10	.17	.42	.35	.32	.60
2R	upper	<.05	<.05	.15	.56	.23	.77
	lower	<.05	.12	.44	.94	.29	1.08
3R	upper	.10	<.05	.18	.76	.18	.95
	lower	.09	.12	.27	.54	.19	.73
4R	upper	.05	<.05	.63	.65	.40	.79
	lower	.08	.10	.58	.59	.38	.73

Table A4-3

PISTON RING WEAR DATA
GAP INCREASE – INCHES/100 HOURS
WEIGHT LOSS – GRAMS/100 HOURS

Cyl. Ring		No. 2 Diesel		30% CDL		50% Shale		50% Residual 50% Shale		50% Residual		No. 2 Diesel	
		Gap	Weight	Gap	Weight	Gap	Weight	Gap	Weight	Gap	Weight	Gap	Weight
1L	1	.001	.1052	.000	—	.006	.1165	.000	.1657	.004	.1892	.001	.1263
	2	.000		.000		.002		.000		.004		.001	
	3	.001		.000		.004		.000		.009		.003	
	4	.007		.003		.011		.002		.012		.005	
2L	1	.001	.1411	.000	.1586	.003	.1795	.001	.1152	.005	.2089	.002	.1072
	2	.001		.000		.002		.000		.005		.001	
	3	.001		.000		.007		.000		.008		.003	
	4	.006		.002		.013		.003		.011		.005	
3L	1	.002	.2024	.002	.2571	.005	—	.000	.1544	.005	.2016	.003	.2011
	2	.000		.000		.000		.000		.003		.001	
	3	.002		.000		.005		.001		.010		.003	
	4	.007		.001		.011		.006		.016		.008	
4L	1	.002	.2238	.000	.1670	.008	.1109	.000	.1155	.003	.1251	.002	.0952
	2	.001		.000		.004		.001		.004		.001	
	3	.001		.000		.007		.001		.009		.003	
	4	.007		.000		.014		.006		.013		.007	

Table A4-4

PISTON RING WEAR DATA
GAP INCREASE – INCHES/100 HOURS
WEIGHT LOSS – GRAMS/100 HOURS

Cyl. Ring		No. 2 Diesel		30% CDL		50% Shale		50% Residual 50% Shale		50% Residual		No. 2 Diesel	
		Gap	Weight	Gap	Weight	Gap	Weight	Gap	Weight	Gap	Weight	Gap	Weight
1R	1	.000	.1275	.001	.1277	.007	.1366	.002	.1046	.003	.1781	.002	.0858
	2	.000		.000		.005		.001		.003		.002	
	3	.002		.000		.009		.001		.007		.003	
	4	.007		.000		.014		.006		.013		.007	
2R	1	.001	.1850	.000	.1164	.007	.0896	.000	.1654	.003	.2306	.003	.1251
	2	.001		.000		.009		.000		.003		.002	
	3	.001		.000		.009		.002		.003		.004	
	4	.008		.000		.013		.008		.017		.007	
3R	1	.002	.1276	.000	.1272	.005	.1141	.001	.1338	.003	.1769	.002	.1071
	2	.001		.000		.005		.001		.003		.002	
	3	.002		.000		.005		.000		.007		.003	
	4	.007		.000		.007		.005		.013		.005	
4R	1	.002	.1755	.000	.1127	.005	.1467	.001	.1723	.005	.1758	.002	.1193
	2	.001		.000		.004		.000		.005		.001	
	3	.002		.000		.007		.001		.008		.005	
	4	.009		.004		.010		.005		.013		.006	

ENGINE TEST STAND LOG 2-CYLINDER

DATE

TEST REQUEST

TEST TITLE

ALTERNATIVE FUELS - D.O.E. PROJECT

ENGINE NO. 2-18

LINE A	TIME	LOAD					WATER		FUEL OIL			LUBE OIL		AIR				EXH.		COUNTERS						
		N	RPM	TORQUE	HP CYL	BMEP	PRESS FLOW		PRESSURE			PRESSURE		FLOW GPM	ORIF PRESS	ORIF DIFF	FLOW #/SEC	AIR MAN		REC. PRESS	TOTAL	RTH N	IDLE	CYCLES		
							HDR.	GPM	HDR.	GEAR	RAIL	F IN	F OUT					HDR	LFT						RT	
1		8	1050	128	206		19.5		48.2			122		49.0			22.5		50.7		14.7					
2		5	879	74	100		23.0		48.3			122		48.8			9.8		12.3		4.6					
3		2	535	25	20		21.3		48.1			122		48.0			-		-		-					
4		8	1050	128	206		22.6		38.9			126		49.1			21.4		50.7		14.7					
5		5	879	74	100		22.0		37.2			124		55.4			10.0		12.3		4.6					
6		2	535	25	20		22.8		49.3			121		44.1			-		-		-					
7		8	1047	128	206		22.7		38.2			124		49.3			21.4		50.7		14.7					
8		5	879	74	100		23.0		37.8			124		49.7			5.7		12.3		4.6					
9		2	535	25	20		22.7		44.1			124		51.5			-		-		-					
10		8	1050	128	206		21.5		47.0			124		49.5			22.4		50.7		14.7					
11		5	879	74	100		21.0		47.7			124		48.8			9.8		12.3		4.6					
12		2	535	25	20		22.3		47.3			122		46.0			-		-		-					
LINE B	TIME	TEMPERATURES OF										CONSUMPTION										TURBINE				TESTERS INITIALS
		WATER		LUBE OIL		FUEL IN	AIR MANIFOLD		HIGH PRESS. AIR	REC.	CYL		FUEL		LUBE		OIL TEMP.	OIL PRESS.	ST. 1,2 AIR IN TEMP.	RPM						
		IN	OUT	IN	OUT		LI	RI			LBS	TIME	SFC	LBS	TIME	SLC										
1		160	166	162	167			178	195	843	877	870	10	4.210												
2		163	168	159	162			158	177	598	858	930	5	4.102												
3		160	163	170	171			147	173	615	610	542	3	9.720												
4		167	173	170	176			180	185	916	876	875	10	4.163												
5		160	166	150	154			162	187	593	860	884	5	4.283												
6		175	177	172	172			75	70	390	574	585	5	16.681												
7		165	170	166	173			190	200	908	892	883	10	4.024												
8		160	165	160	164			160	182	790	873	934	5	3.938												
9		155	157	152	153			115	125	481	594	516	5	15.486												
10		153	160	156	163			178	190	893	890	882	10	3.970												
11		155	160	157	161			163	178	836	865	940	5	3.935												
12		175	180	161	167			85	03	506	581	496	3	9.801												
		SAFETY DEVICES TESTED				ACR	FA	GR	DLP		HWT	LOP		OS	WD											
C PARTS CHANGED OUT OR REPAIRED, OIL ADDED, ETC.										D TIME		TEST POINT COMMENTS														
1																										
2																										
3																										

A-4.3

#2 DIESEL (BASELINE FOR CDL TEST SCALE RUNS)

10% CDL / 90% #2 DIESEL

30% CDL / 70% #2 DIESEL

35% CDL / 65% #2 DIESEL

ENGINE TEST STAND LOG 2-CYLINDER

DATE _____

TEST REQUEST _____

TEST TITLE ALTERNATIVE F.L.S. - D.O.E. PROJECT

ENGINE NO. 2-18

LINE A	TIME	LOAD					WATER		FUEL OIL			LUBE OIL				AIR				EXH.		COUNTERS					
		N	RPM	TORQUE	HP /CYL	BMEP	PRESS FLOW		HDR.	GEAR	RAIL	PRESSURE		F IN	F OUT	HDR	GPM	ORIF PRESS.	ORIF DIFF.	FLOW 1/SEC	AIR MAN		REC. PRESS.	HOURS			
							HDR.	GPM				F	G								LFE	RT		TOTAL	RTN	IDL	CYCLES
1		8	1050	128	206		40.0					122		51.5				16.8			50.7		14.7				
2		5	875	74	100		41.0					122		51.4				6.7			12.3		4.6				
3		2	535	25	20		41.2					122		51.5				—			—		—				
4		8	1050	128	206		41.0					122		51.5				16.5			50.7		14.7				
5		5	875	74	100		41.2					122		50.5				6.6			12.3		4.6				
6		2	535	25	20		41.5					122		51.5				—			—		—				
7		8	1050	128	206		40.5					122		50.0				16.7			50.7		14.7				
8		5	875	74	100		40.5					122		50.5				6.6			12.3		4.6				
9		2	535	25	20		40.6					122		50.0				—			—		—				
10		8	1050	128	206		40.8					122		50.5				16.7			50.7		14.7				
11		5	875	74	100		40.5					122		50.0				6.5			12.3		4.6				
12		2	535	25	20		40.6					122		51.8				—			—		—				
LINE B	TIME	TEMPERATURES OF										CONSUMPTION										TURBINE				TESTERS INITIALS	
		WATER		LUBE OIL		FUEL IN	AIR MANIFOLD		HIGH PRESS. AIR	REC.	CYL		FUEL		LUBE		OIL TEMP.	OIL PRESS.	ST. 1,2 AIR IN TEMP.	RPM							
		IN	OUT	IN	OUT		— I	— R			LBS	TIME	SFC	LBS	TIME	SLC											
1		175	179	174	180			186	190	727	808	744	10	4.473													
2		171	175	172	177			175	180	734	785	815	5	4.615													
3		176	176	173	174			134	156	578	636	410	3	12.505													
4		175	179	173	180			185	195	720	809	754	10	4.463													
5		174	176	173	179			179	179	733	794	813	5	4.621													
6		170	171	171	174			137	160	594	634	420	3	12.362													
7		177	180	175	183			185	194	726	799	740	10	4.453													
8		176	178	175	181			174	176	725	775	800	5	4.523													
9		177	177	175	176			136	158	581	665	390	3	11.736													
10		180	182	176	185			188	199	720	805	774	10	4.414													
11		176	180	176	181			175	179	731	787	820	5	4.513													
12		170	170	170	174			133	155	560	665	382	3	11.423													
		SAFETY DEVICES TESTED				ACR	FA	GR	DLP		HWT	LOP		OS	WD												
PARTS CHANGED OUT OR REPAIRED, OIL ADDED, ETC.										D TIME		TEST POINT COMMENTS															

A-4.4

ENGINE TEST STAND LOG 2-CYLINDER

DATE _____

TEST REQUEST _____

TEST TITLE ALTERNATIVE FUELS - D.I.E. PROJECT

ENGINE NO. 2-18

LINE A	TIME	LOAD					WATER		FUEL OIL			LUBE OIL				AIR				EXH.		COUNTERS				
		N	RPM	TORQUE	HP CYL	BMEP	PRESS FLOW		PRESSURE			PRESSURE		FLOW GPM	ORIF PRESS.	ORIF DIFF.	FLOW #/SEC	AIR MAN		REC. PRESS.		HOURS				
							HDR.	GPM	HDR.	GEAR	RAIL	F IN	F OUT					HDR	LFT			RT	TOTAL	OTH N	IDLE	CYCLES
1		8	1050	128	206		22.5		47.5			122		50.3		23.4			50.7		14.7					
2		5	879	74	100		22.5		47.5			122		51.0		9.9			12.3		4.6					
3		2	535	25	20		22.5		48.4			122		50.0		-		-	-		-					
4		8	1050	128	206		22.4		46.0			124		49.5		23.8			50.7		14.7					
5		5	879	74	100		22.5		48.0			122		49.0		9.8			12.3		4.6					
6		2	535	25	20		23.0		47.0			122		47.5		-		-	-		-					
7		8	1050	128	206		21.0		48.0			122		49.5		23.4			50.7		14.7					
8		5	879	74	100		21.0		48.5			122		48.5		10.0			12.3		4.6					
9		2	535	25	20		21.5		49.0			122		47.0		-		-	-		-					
10		8	1050	128	206		37.5		49.0			120		50.5		16.8			50.7		14.7					
11		5	875	74	100		38.0		50.0			122		52.0		6.6			12.3		4.6					
12		2	535	25	20		38.5		50.8			122		52.0		-		-	-		-					
LINE B	TIME	TEMPERATURES OF										CONSUMPTION										TURBINE				TESTERS INITIALS
		WATER		LUBE OIL		FUEL IN	AIR MANIFOLD		HIGH PRESS. AIR	REC.	CYL		LBS	FUEL TIME	SFC	LUBE		OIL TEMP.	OIL PRESS.	ST. 1/2 AIR IN TEMP.	RPM					
		IN	OUT	IN	OUT		LI	RI			LBS	TIME				SLC	LBS					TIME	SLC			
1		167	172	166	172			185	203	795	883	872	10	4.179												
2		163	167	162	166			167	186	692	892	917	5	4.056												
3		172	172	163	163			131	161	560	648	552	3	9.701												
4		167	172	168	173			184	201	787	885	871	10	4.197												
5		163	168	167	169			174	188	778	873	939	5	4.050												
6		168	170	165	165			130	151	582	612	578	3	9.823												
7		163	168	165	169			182	199	787	889	879	10	4.172												
8		163	168	166	169			173	187	793	876	949	5	4.021												
9		165	166	163	163			132	158	600	652	522	3	10.965												
10		165	175	171	178			185	194	778	833	750	10	4.434												
11		170	174	165	170			166	179	667	780	809	5	4.601												
12		175	175	165	166			128	150	531	644	396	3	12.468												
		SAFETY DEVICES TESTED				ACR	FA	GR	DLP		HWT	LOP		OS	WD											
C	PARTS CHANGED OUT OR REPAIRED, OIL ADDED, ETC.								O TIME		TEST POINT COMMENTS															
1																										
2																										
3																										

A-4.5

#2 DIESEL - (B) SECURE 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00 11.00 12.00 13.00 14.00 15.00 16.00 17.00 18.00 19.00 20.00 21.00 22.00 23.00 24.00 25.00 26.00 27.00 28.00 29.00 30.00 31.00 32.00 33.00 34.00 35.00 36.00 37.00 38.00 39.00 40.00 41.00 42.00 43.00 44.00 45.00 46.00 47.00 48.00 49.00 50.00 51.00 52.00 53.00 54.00 55.00 56.00 57.00 58.00 59.00 60.00 61.00 62.00 63.00 64.00 65.00 66.00 67.00 68.00 69.00 70.00 71.00 72.00 73.00 74.00 75.00 76.00 77.00 78.00 79.00 80.00 81.00 82.00 83.00 84.00 85.00 86.00 87.00 88.00 89.00 90.00 91.00 92.00 93.00 94.00 95.00 96.00 97.00 98.00 99.00 100.00

ENGINE TEST STAND LOG 8-CYLINDER

OPERATIONS (CYCLE, SPECIAL TEST, REPAIR) END FANCE RUNNING

TEST REQUEST # _____

DATE _____

STAND 7-13

Line A	Time	LOAD										PRESSURE - PSI OR AS INDICATED - IN. HG.												COUNTERS						
		Notch	Turbo RPM	Engine RPM	Vclss	Amps	Elec. HP	Aux. HP	Gross HP	L. C. Pos.	Rack MM.	LUBE OIL AT - PSI				FUEL OIL - PSI		AIR MAN. - IN. HG.		FUEL TIME MM.	FUEL WT. LBS	Barom. In. Hg.	AMB. °F	Total Hours	Run N. Hours	Idle Hours	Cycles	Fuel Meter	Lube Oil Added	
												Filter In	Filter Out	HDR	Turbo	HDR		Left	Right											
1		8	1440	1050	628	1929			2007				101.2	86.9	16.8			60.1	60.2	4.276	50	29.41	68							
2		8	14380	1019	628	1920			2004				99.5	86.1	16.5			60.3	55.5	4.113	50	29.73	65							
3		8	19710	1050	628	1927			2004				102.0	88.0	17.0			61.7	61.0	4.143	50	29.42								
4		8	20340	1047	615	1961			2083				105.0	90.0	17.0			62.4	63.0	4.026	50	29.12	72							
5		8	20580	1048	617	1960			2080				102.0	89.0	16.0			61.6	61.0	3.978	50	29.43	55							
6		8	20310	1018	617	1962			2089				105.0	91.4	16.6			61.2	60.8	3.992	50	29.52	59							
7		8	20220	1017	621	1903			1987				101.2	84.2	16.2			59.8	53.7	3.986	50	29.58	78							
8		8	19830	1052	621	1905			1989				97.4	85.7	15.6			53.3	52.2	3.989	50	29.79	78							
9		8	20160	1052	621	1904			1987				100.5	87.1	15.9			56.2	55.4	3.982	50	29.53	78							
10																														

Line B	TEMPERATURES °F														Comp. Disch.			Testers Initials
	Water		Lube Oil		Fuel In	Air Manif		Air In	Stack	Pre-Turbine Temp.								
	In	Out	In	Out		Left	Right			RT	RB	LT	LB					
1	174	175	176	176	33	174	175	20	722	1035	1021	964	976	272	271	# 2 DIESEL (30% COLD BASELINE)		
2	167	172	175	177	29	167	168	21	732	1045	1025	966	984	273	273	30% COLD / 70% # 2 DIESEL (START)		
3	169	175	177	178	43	172	173	29	744	1003	987	1046	1069	287	288	30% COLD / 70% # 2 DIESEL (END)		
4	167	175	176	178	49	169	170	45		1034	1041	1130	1085	320	320	# 2 DIESEL (50% SHALE BASELINE)		
5		176	177	181	60	172	172	66	814	1068	1078	1173	1121	341	341	50% SHALE / 50% # 2 DIESEL (START)		
6		174	175	177	63	168	167	54	809	1045	1048	1147	1102	326	325	50% SHALE / 50% # 2 DIESEL (END)		
7		179	181	187	79	176	175	36	872	1174	1143	1129	1113	348	349	# 2 DIESEL (SHALE/RESIDUAL BASELINE)		
8		179	181	187	79	176	175	85	855	1163	1128	1127	1099	340	340	50% SHALE / 50% RESIDUAL (START)		
9	172	178	180	186	88	177	174	88	838	1092	1129	1126	1149	356	355	50% SHALE / 50% RESIDUAL (END)		
10																		

C	PARTS CHANGED OUT OR REPAIRED										PERFORMANCE NOTES, OIL, WATER TREATMENT									
1																				
2																				
3																				
4																				
5																				
6																				
7																				
8																				

A-4.6

ENGINE TEST STAND LOG 8-CYLINDER

OPERATIONS (CYCLE, SPECIAL TEST, REPAIR) ENDURANCE RUNNING

TEST REQUEST # _____

DATE _____

STAND 7-18

Line A	Time	LOAD										PRESSURE - PSI OR AS INDICATED - IN. HG.												COUNTERS					
		Notch	Turbo RPM	Engine RPM	Volts	Amps	Elec. HP	Aux. HP	Gross HP	L. C. Pos.	Rack MM	LUBE OIL AT - PSI				FUEL OIL - PSI		AIR MAN. -IN.HG.		FUEL TIME MIN.	FUEL WT. LBS.	Barom. In. Hg.	AMB °F	Total Hours	8th N. Hours	Idle Hours	Cycles	Fuel Meter	Lube Oil Added
												Filter In	Filter Out	HDR	Turbo	HDR		Left	Right										
1		8	21030	1052	648	1957			2088				101.0	88.0			62.3	61.5	3.731	50	29.75	74							
2		8	20760	1052	648	1957			2088				104.0	89.0			59.4	59.2	3.721	50	29.48	65							
3		8	20760	1053	648	1957			2088				113.0	90.0	16.0		65.6	65.2	3.744	50	29.76	56							
4																													
5																													
6																													
7																													
8																													
9																													
10																													

Line #	TEMPERATURES °F																Testers Initials
	Water		Lube Oil		Fuel In	Air Manif.		Air In	Stack	Pre-Turbine Temp.				Comp. Disch.			
	In	Out	In	Out		Left	Right			RT	RB	LT	LB	Left	Right		
1	173	181	182	188	80	178	176	89	845	1150	1197	1170	1115	373	373	# 2 DIESEL (50% RESIDUAL BASELINE)	
2	173	178	179	185	78	175	174	77	816	1119	1166	1133	1078	371	371	50% RESIDUAL/50% #2 DIESEL (START)	
3	171	175	177	184	73	173	171	54		1082	1130	1104	1030	339	340	50% RESIDUAL/50% #2 DIESEL (END)	
4																	
5																	
6																	
7																	
8																	
9																	
10																	

C	PARTS CHANGED OUT OR REPAIRED	PERFORMANCE NOTES, OIL, WATER TREATMENT
1		
2		
3		
4		
5		
6		
7		
P		

A-4.7

Appendix 5

DURABILITY TEST PHOTOGRAPHS

Figure A-5.1 Pump barrel and plunger; standard fuel.

Figure A-5.2 Fuel injector; standard fuel.

Figure A-5.3 Turbine wheel; standard fuel.

Figure A-5.4 Piston rings; standard fuel.

Figure A-5.5 Piston crown; standard fuel.

Figure A-5-6 Exhaust valves; standard fuel.

Figure A-5.7 Pump barrel and plunger; CDL fuel (25%).

Figure A-5.8 Fuel nozzle; CDL fuel (25%).

Figure A-5.9 Turbine wheel; CDL fuel (25%).

Figure A-5.10 Piston rings; CDL fuel (25%).

TR 3954

RMVD FROM #7 ENG - 2/21/81

1R POSITION

177 FULL LOAD HOURS ON

TEST FUEL AFTER BREAK-IN

Figure A-5.11 Piston crown; CDL fuel (25%).

TR 3954

EXHAUST VALVES

RMVD FROM #7 ENG - 2/21/81

1L POSITION

177 FULL LOAD HOURS ON

TEST FUEL AFTER BREAK-IN

Figure A-5.12 Exhaust valves; CDL fuel (25%).

Figure A-5.13 Pump barrel and plunger; 50% shale/50% diesel.

Figure A-5.14 Fuel injector; 50% shale/50% diesel.

Figure A-5.15 Turbine wheel; 50% shale/50% diesel.

Figure A-5.16 Piston rings; 50% shale/50% diesel.

Figure A-5.17 Piston crown; 50% shale/50% diesel.

Figure A-5.18 Exhaust valves; 50% shale/50% diesel.

Figure A-5.19 Barrel and plunger; shale and residual.

Figure A-5.20 Fuel injector; shale and residual.

Figure A-5.21 Turbine wheel; shale and residual.

Figure A-5.22 Piston rings; shale and residual.

Figure A-5.23 Piston crown; shale and residual.

Figure A-5.24 Exhaust valves; shale and residual.

Figure A-5.25 Barrel and plunger; diesel and residual.

Figure A-5.26 Fuel injector; diesel and residual.

Figure A-5.27 Turbine wheel; diesel and residual.

Figure A-5.28 Piston rings; diesel and residual.

Figure A-5.29 Piston crown; diesel and residual.

Figure A-5.30 Exhaust valves; diesel and residual.

Appendix 6

**FUEL ASSESSMENT
AND EQUIPMENT PREPARATION**

Appendix 6

FUEL ASSESSMENT AND EQUIPMENT PREPARATION

Bench Scale Combustion Experiments with SRC II/Diesel Blends

The objective of this program was to run SRC II in small scale apparatus prior to use in full scale engine runs. In this way any handling problems could be worked out and potential combustion problems, if any, could be identified. The program was set up to compare combustion and emissions from SRC II directly against those for No. 2D oil burned under identical conditions. The subtask as originally defined called for burning of SRC II/No. 2 oil blends. However, it was quickly determined that straight SRC II could be burned in a controlled fashion and it was decided to compare the two fuels burned separately.

Experimental

The experiments were carried out in a well ventilated, high bay room which was isolated from other parts of the building by heavy doors and reinforced concrete walls.

The fuels were burned as air-atomized liquid sprays at the bottom of a vertical, insulated flame tube, shown schematically in Figure A-6.1. This apparatus was built and used to study burning of No. 2 oil sprays by B.W. Gerhold, C.P. Fenimore and P.K. Dederick.^(A-6.1,2) A more detailed sketch of the burner is shown in Figure A-6.2, and the modified Delavan fuel nozzle is shown in Figure A-6.3. The air and steam supply systems are sketched in Figure A-6.4; the steam as added for the present work. The insulated chimney construction is seen in Figure A-6.5, and the fuel delivery system is shown in Figure A-6.6. There were a few brass fittings but, where possible, everything was stainless steel or Teflon.

At the start of a run, hydrogen gas was introduced through the atomizing air line and burned in the main air at a low, gradually increasing rate over a period of approximately 30 minutes, so that the ceramic warmed up slowly and did not suffer thermal shock. After the inner tube surface was glowing red, the main air was set and liquid fuel was injected into the tube and ignited carefully. The system was allowed to stabilize for 15 minutes or so before gas samples were taken.

Gas samples were taken through a water-cooled stainless probe. They passed through an ice-cooled trap and were pumped through a bellows pump to the analytical instruments. The following measurements were made on the dry samples:

CO₂ - NDIR

CO - NDIR

O₂ - Paramagnetic

NO - NDI

unburned HC - FID

The measured values were corrected back to those for the actual wet gas by using the calculated equilibrium value for H₂O concentration in the flame gases.

Figure A-6.1 Flame tube schematic. The coarse grain ZrO_2 tube (6 cm id, 3 mm wall, 61 cm height) was insulated with a 1.8 cm thick blanket of packed ZrO_2 fiber inside a high temperature alloy tube, which in turn was held within a 15.25 cm od Fiberfrax tube. The air-atomizing fuel nozzle was a Delavan (30609-2) solid core type. The water-cooled sample probe was located about 42 cm above the fuel nozzle. Product gas velocities were 15 m/s so that the sampling time was around 30 ms after fuel injection.

In addition, a smoke sample was removed through a separate hot water heated line about five feet long to a GE Von Brand smoke monitor equipped with a continuous reflectance readout. The technique is used routinely in the development of gas turbine combustors for a relative measure of smoke.

The fuel flow was metered through a constant-displacement gear pump with an arrangement that allowed the flow rate to be checked during a run. The atomizing air flow and the main air flow were metered through calibrated critical flow orifices. The temperature of the main air flow was measured with a recording thermocouple.

The analytical instruments were calibrated during warmup of the burner. Fuel flow and air flows were then set at a given point and the readings allowed to settle to steady values. The same procedure was followed for the next and succeeding points of the run. At the end of the run, the tube was cooled slowly with a stepped-down hydrogen flame. During this period, the calibration of the instruments was rechecked. The data were written on a single strip chart recorded by switching back and forth from one measurement to another.

Figure A-6.2 Oil spray flame apparatus (assembly).

Figure A-6.3 Delavan siphon nozzle 30609-2 with adapter.

A-6.5

Figure A-6.4 Main air, atomizing air, and steam systems.

Insulation

- A ZIRCAR Zirconia Cyl., Type ZYC, 2 7/8 od x 2 3/8 id
- B ZIRCOA CA Stabilized Zirconia, Coarse Grain, Comp. 1651 or 1247
2.60 od centerless ground x 2 1/4 id x ~ 6 1/4 long Cyls.
- C ZIRCAR Zirconia Bulk Fibers, Type ZYBF - 2
- D ZIRCAR Alumina Silica Cyl., 6 od x 4 id x 20 x 1 thick

Figure A-6.5 Oil spray flame apparatus: first stage chimney

Results

The experimental product compositions are plotted along with the calculated adiabatic flame values in Figures A-6.7, 8, 9, and 10. Exact agreement between the two sets of data should not be expected, since the calculated mol-fractions represent equilibrium values in the hot flame zone; during cooling in the sample probe some composition changes can take place. Thus the experimental CO_2 values should be slightly higher than the calculated curve and CO values should be correspondingly lower. Presentation of the data in this way provides a convenient assessment of the quality.

Both the gas compositions and visual flame observations indicated good combustion of all the fuels under the experimental conditions. The major species CO_2 , CO , and O_2 all followed the calculated curves in a regular fashion.

Due to the slowness of formation of NO , the mol-fractions of NO in lean flames fell well below the calculated equilibrium curves, as expected. In rich flames of fuels containing nitrogen, the NO values were higher than the equilibrium value, but lower than that for complete conversion of fuel-N to NO . Again, the kinetics limited the rate at which equilibrium could be obtained. The NO values for all fuels have been replotted together on a larger scale in Figure A-6.11; they will be discussed further below.

Positions of both Valves (4):

← Output of 0.297 cc/rev. pump to experiment.
Output of 0.584 cc/rev. pump returns to beaker.

↓ Output of 0.584 cc/rev. pump to experiment.
Output of 0.297 cc/rev. returns to beaker.

Positions of Valve (5):

← Bypass;
Inputs to each pump connected;
normal running mode.

↑ Calibrate;
Inputs to each pump isolated;
Fuel flows from burette,
thru pump being calibrated,
and on to experiment. Alternate
system recirculates.

- 1 100 ml. Burette
- 2 4 1/4 qt SS Beaker
- 3 1/2" od x .035" wall SS Tubing
- 4 4 Way Valve
Whitey SS 43 Y F2
- 5 On/Off Ball Valve
Whitey SS 43S4
- 6 Zenith Pump
0.584 cc/rev.
- 7 Zenith Pump
0.297 cc/rev.
- 8 Micarta Pump Drive
Pinion on Graham
15:1 Speed Reducer
- 9 1/4" od x .035" wall
SS Tubing
- 10 HOKE Filter, SS,
6320 F 4 Y, 40-55 μ .
- 11 HOKE Filter, SS,
6347 F 8 S, 10-15 μ .
- 12 Pressure Gauge,
0-15 psig
- 13 HOKE Metering Valve
1315 M 4 Y
- Heating Wire, No.
22, Teflon Coated
- Heating Tapes,
Silicone Rubber

Figure A-6-6 Fuel system.

Figure A-6.7 Flame tube combustion data, No. 2D oil.
 No. 2D oil: $(C_{1.0} H_{1.78})_n$; HHV = 19,500 Btu/lb.
 Preheated ISO air, 600 °F (589 K). Air-atomized spray, 1 atm.
 Solid lines represent equilibrium mol-fractions calculated at the adiabatic flame temperature. Experimental probe sample mol-fractions are shown by symbols as follows:

○ CO₂ × O₂
 □ CO △ NO

ISO air is defined as of 60% relative humidity at 58 °F (15 °C) sea level conditions.

Figure A-6.8 Flame tube combustion data, SRC II.
 SRC II: $\text{CH}_{1.250}\text{S}_{0.001}\text{O}_{0.018}\text{N}_{0.008}$; HHV = 17,300 Btu/lb.
 Preheated ISO air, 600 °F (589 K). Air-atomized spray, 1 atm.
 Solid lines represent equilibrium mol-fractions calculated at the adiabatic flame temperature. Experimental probe-sample mol-fractions are shown by symbols as follows:

○ CO_2	x O_2
□ CO	△ NO

The dashed line represents the mol-fraction of NO which would exist if all N in the fuel formed NO and zero NO formed by the thermal process.

Figure A-6.9 Flame tube combustion data, SRC II steam atomization.
 SRC II: $C_{1.0}H_{1.25}O_{0.018}N_{0.008}$. Preheated ISO air, 600 °F (589 K). Steam-atomized spray, 1 atm.
 Solid lines represent equilibrium mol-fractions calculated at the adiabatic flame temperature. Experimental probe sample mol-fractions are shown by symbols as follows:

○ CO_2 △ NO
 □ CO

ISO air is defined as air at 60% relative humidity at 59 °F (15 °C) sea level conditions. The dashed line represents the mol-fraction of NO which would exist if all N in the fuel formed NO and zero NO formed by the thermal process.

Figure A-6.10 Flame tube combustion data, SRC II with 2 wt% of DII-2. SRC II containing 2 wt% of diesel ignition improver. The ignition improver (DII-2) was composed of hexyl nitrates.
 Overall composition of fuel: $\text{CH}_{1.261}\text{O}_{0.023}\text{N}_{0.010}$ Air atomized spray flames. Preheated 150 air, 600 °F (589 K); 1 atm.
 Solid lines represent equilibrium mol-fractions calculated for SRC II at the adiabatic flame temperature. Experimental probe-sample mol-fractions are shown by symbols as follows:

○ CO₂ x O₂
 □ CO Δ NO

The dashed line represents the mol-fraction of NO which would exist if all N in the doped fuel formed NO and zero NO formed by the thermal route.

Figure A-6.11 Summarized NO data; bench scale flame tube. Experimental points represent total NO in gas sample, i.e., thermal NO plus NO from fuel-N.

- △ Baseline No. 2D oil, air atomization.
- SRC II, air-atomization.
- SRC II containing 2 wt% of DII-2, air atomization.
- SRC II, steam-atomization.
- NO from fuel-N if it all formed NO and zero thermal NO was produced. DII-2 in SRC II. (Definition of $[RN]_0$)
- NO from fuel-N if it all formed MO and zero thermal NO was produced. SRC II alone without ignition improver.
- NO from fuel-N if it all formed NO and zero thermal NO was produced. SRC II with steam atomization.

All experimental points in the equivalence ratio range have been plotted.

Figure A-6.12 Smoke comparison, SRC II versus No. 2 oil. Circles represent SRC II, squares represent No. 2 oil, points flagged in the same direction have the same atomizing air flows. See Table A-6.1 for more complete identification. Solid lines represent data from this work; dotted lines represent data from reference A-6.1.

Von Brand smoke numbers have been plotted for No. 2D oil and for SRC II in Figure A-6.12. Unlike NO concentrations, smoke numbers are sensitive to the quantity of atomizing air employed. The data on air flows are summarized in Table A-6.1. In Figure A-6.13, the mass flow of atomizing air has been held constant; the order of increasing smoke is No. 2D oil/air, SRC II/steam, SRC II/air, SRC II with 2% D II-2/air. All experimental measurements of unburned hydrocarbons are given in Figure A-6.14. Again the symbols are defined in Table A-6.1. The measurements were made with an unheated Bendix flame ionization detector. There is considerable scatter in the data; they are the least satisfactory of those reported here. However, steam atomization clearly gave higher levels of unburned HC than did air, at least for levels greater than 20 ppm. Also, for all fuels there was a strong increase of unburned HC with increasing equivalence ratio for $\phi > 1.2$.

Figure A-6.13 Smoke comparison, SRC II with DII-2 and with steam atomization. Mass flow of atomizing gas was 0.555 g/sec in all cases.

- Straight SRC II with air atomization.
- ◐ Straight SRC II with steam atomization.
- △ SRC II with 2 wt% of DII-2 (hexyl nitrates).
- ◻ No. 2D oil with air atomization.

See Table A-6.1 for further information.

Figure A-6.14 Unburned hydrocarbons, all fuels. Symbols are defined in Table A-6.1.

Table A-6.1
RELATIVE SMOKE DATA

The von Brand smoke number ranges from 0 to 100. The limit of 100 represents zero smoke. In stationary gas turbine practice, a number ≥ 95 is considered to be acceptable. Smaller numbers indicate a visible stack plume.

Symbol	Fuel	Atomizing Gas			Total Air g/sec	Source
		Gas	g/sec	T, K		
○	SRC II	air	0.617	422	6.20	this work
○	SRC II	air	0.555	422	6.13	this work
○	SRC II	air	0.487	422	6.07	this work
●	SRC II	air	0.487	298	6.07	this work
△	SRC II + 2 D11-2	air	0.555	422	6.13	this work
○	SRC II	steam	0.555	422	6.13*	this work
□	No. 2D oil	air	0.555	422	6.13	this work
□	No. 2D oil	air	0.356	298	5.58	ref. 2
□	No. 2D oil	air	0.487	298	5.58	ref. 2

*This number includes atomizing steam.

Figure A-6.15 Calculated adiabatic flame temperatures.

- No. 2 oil, air atomization, HHV = 19,500 Btu/lb.
- - - SRC II, air atomization, HHV = 17,300 Btu/lb.
- · - SRC II, steam atomization

In the case of steam atomization, the steam was considered to be part of the air in computing equivalence ratios.

Discussions

There were no difficulties handling SRC II when good laboratory practices were followed. The most objectionable feature was the persistent, creosol-like odor which persisted on clothing long after exposure to the fuel.

All of the fuels burned well under the test conditions. Excessive concentrations of CO or unburned HC were not found in the gas samples.

Only in NO, smoke, and unburned HC are there significant differences. These will be discussed briefly.

Nitric Oxide, NO

In Figure A-6.16, the experimental NO data for No. 2D oil are presented along with the calculated adiabatic equilibrium curve, and with the NO levels calculated for a simple, one-dimensional model assuming the NO formed by the thermal (Zeldovich) mechanism

where the first reaction is rate determining. At a point one tube diameter downstream of the spray injector, it was assumed that the combustion reactions (except for NO formation) were completed and the gas composition across the tube cross section was uniformly that corresponding to the overall equivalence ratio. Thereafter the hot products progressed 40 cm through the ceramic tube without heat loss; the NO formation occurred during this period. The gases were then sampled and quenched in a water-cooled stainless steel probe. The solid line in Figure A-6.16 represents the NO values calculated by this model using accepted values of the specific constants⁽¹⁰⁾ and equilibrium concentration values for O and N₂ (Figure A-6.7).

Except for very rich mixtures ($\phi > 1.3$), the experimental NO values fall well below the dashed equilibrium curve, as expected; the $\text{O} + \text{N}_2$ reaction was too slow to achieve equilibrium in the time available (≈ 25 msec.).

The solid curve for the simple kinetic model (Figure A-6.16) predicts trends correctly, but gives only order of magnitude agreement with the experiment. This is probably all that should be expected from such a simple one-dimensional model. Actually, at a point one diameter downstream, one should not anticipate complete uniformity of temperature and composition over the tube cross section; instead there will be a distribution of concentration and temperature values about the mean value for the overall equivalence ratio. Thus each volume element passing through the cross section will be generating NO in accordance with the Zeldovich mechanism at the local temperature and concentration. When the overall equivalence ratio is unity, some regions will be leaner and some richer than stoichiometric. Then deviation of concentration in either direction from stoichiometric results in a lower local NO production rate; hence, near stoichiometric ($\phi = 1$), NO production at the plane in question is lower than for the one-dimensional model. On the other hand, for overall very lean ($\phi = 0.6$) or for very rich ($\phi = 1.4$) mixtures, deviations of local temperature and composition toward $\phi = 1$ will give a greater *increase* in local NO production rate than the local *decrease* to be expected from a like deviation away from $\phi = 1$. This results from the strong exponential temperature dependence of the NO formation rate. Hence, for a symmetrical pattern of temperature and concentration distributions about the mean for these rich and lean mixtures, the production of NO should be higher than for the uniformly premixed overall equivalence ratio. This reasoning should hold for all combustor tube cross sections further downstream, and the integrated effects will be measured in the probe sample. Of course, the deviations from overall ϕ should decrease along the tube as mixing occurs. This kind of model should bring the calculated curve and experiment into better agreement. The solid line as drawn in Figure A-6.16 should represent the limit for fast mixing. It is conceivable that the extent of deviation in the shape of the experimental curve from the limiting model curve may be used as an indication of the degree of mixing.

Figure A-6.16 NO data, No. 2D oil. Air preheated to 600 °F (589 K).

- △ Experiment atomizing air 0.555 g/sec.
 - △ Experiment, atomizing air 0.411 g/sec.
 - Adiabatic flame equilibrium data.
 - Simple one-dimensional model. Combustion reaction (except for NO formation) completed within one tube diameter. NO formation continued at constant rate to probe.
- The constant rate was calculated by the following equation:

$$\frac{dX_{NO}}{dt} = 1.2 \times 10^{14} e^{-\frac{37,500}{T}} \left(\frac{P}{RT} \right) X_0 X_{N_2}$$

where X = mol fractions
 R = gas constant (cc-atm/mol K)
 P = pressure, atm
 T = K
 X_0 , X_{N_2} and T were the calculated equilibrium values for an adiabatic flame.

Similar curves for SRC II with air atomization and with steam atomization are shown in Figures A-6.17 and 18, respectively. The SRC II contained about 1 wt% of nitrogen chemically combined in it. In lean flame gases, the fuel-N mostly forms NO; in rich flame gases, a smaller fraction forms NO, and the remainder is converted to N_2 , HCN and NH_3 . The elementary reactions involved are partially summarized in Figure A-6.19. The dotted curves in Figures A-6.17 and 18 given the NO concentration if all fuel-N formed NO and none was formed by other routes.

The experimental points and the calculated equilibrium curves (dashed lines) represent total NO concentrations irrespective of the mechanism of formation. The solid curves represent NO formed from N_2 by the thermal (Zeldovich) mechanism for the simple one-dimensional model discussed above. There is no reason to believe that the thermal and fuel-N processes of NO formation occur completely independently of each other and that the resulting NO concentrations are additive, but it is frequently convenient to use this concept as a limiting case. It will be done here.

In Figure A-6.17, the peak of the measured NO is seen to occur around $\phi = 0.95$ at a value of 1750 ppm, whereas the sum of the calculated thermal and fuel-N values is 2320 ppm. Hence NO calculated by one or both of the two possible routes must be too high. Recall that in the case of No. 2 oil where there was zero fuel-N (Figure A-6.16), the peak measured NO was 400 ppm below that calculated by the one-dimensional model and that this was attributed to incomplete mixing. It seems that a similar situation should exist with SRC II as the fuel, and then the calculated thermal NO would be corrected to 800 ppm. This together with a yield of 80% from fuel-N would bring agreement with experiment and seems not unreasonable. Of course, a drop in absolute temperature of 2.5% (50 K) would also bring agreement at the stoichiometric point; it is impossible to say which effect occurred here.

Fenimore^(A-6.4,5) has critically examined his own data and those of others for flames of gaseous fuels; he concluded that the yield of NO from fuel-N could be correlated by Equation 4 of Figure A-6.19 with $\alpha = [OH]$ where [OH] is the equilibrium concentration of the OH radical expressed as (gmol/cm³). This same expression has been used on our present SRC II data and the computed yield has been plotted in Figure A-6.20. (The experimental points were obtained by subtracting the [NO] concentrations for No. 2 oil from those of SRC II.) The correlation appears to hold fairly well for SRC II under the present experimental conditions. When hexyl nitrate was added to SRC II, the correlation held fairly well for $\phi > 1.1$, but around $\phi = 1.0$ experimental values of the NO yield were low by about 15% (see Figure A-6.21). The correlation predicts lower yields than those observed for the steam atomized case.

Experimental yield values are summarized in Figure A-6.22. In the region $1.2 < \phi < 1.4$ they are nearly identical for all the cases studied.

Figure A-6.17 NO data, SRC II with air atomization. Air preheated to 600 °F (589 K).

- Experiment
- Adiabatic flame calculated equilibrium data.
- One-dimensional model calculated thermal NO (as in Figure A-6.16).
- · - · - Calculated NO assuming all fuel-N formed NO and none was produced by the thermal route.

Figure A-6.18 NO data, SRC II with steam atomization. Air preheated to 600 °F (589 K).

- Experiment
- Adiabatic flame calculated equilibrium data.
- One-dimensional model calculated thermal NO.
- .-.- Calculated NO assuming all fuel-N formed NO and none was produced by the thermal route.

Estimated values of the kinetic rate constants, R_i , are:

$$R_1 \approx 10^{12} [\text{HCN}][\text{OH}] \text{ mol cm}^{-3} \text{ sec}^{-1}$$

$$R_2 \approx 5 \times 10^{12} [\text{NO}][\text{NH}_3]$$

$$\frac{R_3}{R_2} \approx 700 \left(\frac{[\text{H}_2\text{O}]}{[\text{NO}]} \right) e^{\frac{-50 \text{ kcal/gmol}}{RT}}$$

Above reactions take place concurrently in fuel-rich hydrocarbon flame gases. NO is produced by (3) and destroyed by (2). After HC consumed, "steady-state" NO decays slowly toward equilibrium value until quenched in sample probe.

$$\text{Yield on NO} \equiv \frac{[\text{NO}]}{[\text{RN}]_0} \approx \frac{1}{1 + \frac{[\text{RN}]_0}{\alpha}} \quad (4)$$

where $\alpha = \frac{R_3[\text{NO}]}{R_2}$ and $[\text{RN}]_0$ is the concentration

of NO in flame gases if all fuel-N formed NO and none formed by thermal route.

The yield of NO may also be estimated by assuming $\alpha = [\text{OH}]_{\text{equil}}$, as has been done here. (see references 5, 6).

Figure A-6.19 NO chemistry in rich flame gases after Fenimore. (A-6.5)

Figure A-6.20 Yield of NO from fuel-N, SRC II/air atomization.

- Calculated $\alpha = [\text{OH}]$.
 X Experiment; (measured $[\text{NO}]$ from SRC II - measured $[\text{NO}]$ from No. 2 oil) / $[\text{RN}]_0$ where $[\text{RN}]_0$ is the concentration of NO from fuel-N if it all formed NO and zero NO formed by the thermal route.

Figure A-6.21 Yield of NO from fuel-N, SRC II + 2% DII-2 (hexyl nitrate)/air atomization.

- Calculated $\alpha = [\text{OH}]$.
 X Experiment; (measured [NO] – measured [NO] from No. 2 oil)/[RN]₀ where [RN]₀ is the concentration of NO from fuel-N if it all formed NO and zero NO formed by the thermal route.

Figure A-6.22 Summarized experimental yields of NO from fuel-N.

- SRC II, air atomization
 □ SRC II with 2% DII-2/air atomization calculated as in Figures A-6.20 and A-6.21.
 X SRC II, steam atomization.
 Zero thermal NO assumed.

Figure A-6.23 Calculated product mean molecular weights. adiabatic flames.

— SRC II, air atomization.
 - - - No. 2 oil, air atomization.
 . . . SRC II, steam atomization.
 The atomizing steam was considered to be a component of the air.

If the near-stoichiometric points for added hexyl nitrate are excluded, it appears that for the present work exhaust NO concentrations can be estimated to within ≈ 200 ppm by:

1. Use of the one-dimensional model with the Zeldovich equation for thermal NO (equilibrium [O] assumed).
2. Use of the fuel-N yield equation from Figure A-6.19 with $\alpha = [\text{OH}]_{\text{equil}}$ for fuel rich flames.
3. In fuel lean mixtures, the yield of [NO] from fuel-N = 0.80
4. Adding the thermal and fuel-N components of NO; thus $a + b$ or $a + c$.

This procedure predicts trends in the data correctly, but further refinement of the model is necessary to permit the precise calculation of NO levels required in present day technology. Furthermore, the success may be limited to rather simple geometries such as that used here.

Smoke

Smoke from SRC II and from No. 2 oil flames are compared in Figure A-6.12 for a number of different atomizing air flows. For both fuels, measured smoke decreased with increasing atomizing air flow. When compared at the same equivalence ratio, and at a fixed atomizing air flow (flags on points in the same direction), SRC II consistently gave more smoke than No. 2 oil. This is not surprising in view of the significantly higher aromatic content of SRC II.

If a smoke number ≥ 95 is taken as the criterion for acceptable combustion, No. 2 oil could be burned up to $\phi = 1.31$ with atomizing air of 0.555 g/sec under the test conditions, but SRC II could not be burned richer than $\phi = 1.20$ under the same conditions.

In Figure A-6.13, smoke numbers are compared at a constant atomizing gas flow; in one case, the atomizing gas was steam. It is seen that addition of 2% D11-2 to SRC II resulted in a small increase in smoke. On the other hand, substitution of steam for atomizing air significantly reduced smoke from SRC II; but even with steam, the smoke level was not reduced to that of No. 2 oil with atomizing air.

The mechanisms by which D11-2 and steam achieve these effects are not understood.

In general, SRC II appears to burn much like No. 2 oil, but it is smokier and produces more NO.

Summary

1. Both SRC II and No. 2D oil have been burned successfully under closely monitored conditions as an air (or steam) atomized spray flame in a bench scale ceramic tube.
2. Exhaust gas compositions CO_2 , CO , NO , O_2 , unburned hydrocarbons, and von Brand smoke numbers were determined as a function of equivalence ratio.
3. Adiabatic flame temperatures and compositions were calculated. The calculations compared with experimental exhaust compositions.
4. The flame appearance and gas compositions for SRC II were quite similar to those for No. 2 oil; they differed primarily in smoke and in NO levels.
5. For fuel rich flames compared at the same equivalence ratio and atomizing air flow, SRC II flames had consistently higher smoke levels. This is attributed to the higher aromatic content of SRC II.
6. SRC II exhaust gases contained higher NO concentrations. In fuel rich flames, the yield of NO decreased with increasing ϕ in accordance with the chemistry proposed by Fenimore^(A-6.5) and Haynes.^(A-6.6)
7. Increasing atomizing air flows reduced smoke numbers but had no effect on NO levels. The effect was greater with No. 2 oil than with SRC II.
8. Steam (rather than air) atomization of SRC II significantly reduced smoke, but not to the level achieved with No. 2 oil/air.
9. Steam atomization of SRC II resulted in much lower exhaust NO levels. This was due mostly to the reduced flame temperature and consequent reduction of thermal NO.
10. Addition of 2% of diesel ignition improver (hexyl nitrates) slightly increased smoke number.
11. Although the hexyl nitrates increased fuel-N by about 24%, the exhaust NO values were almost the same as for SRC II itself, especially close to the stoichiometric fuel/air ratio $\phi = 1.0$.

12. There appear to be no insurmountable barriers to the practical application of SRC II as a fuel. Cleanliness and careful handling are required. The odor is persistent.
13. These tests give no indication of the autoignition characteristics of the fuel which are so critical to compression ignition engines.

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