ENGINE TESTING FOR SYNFUEL OPERATION

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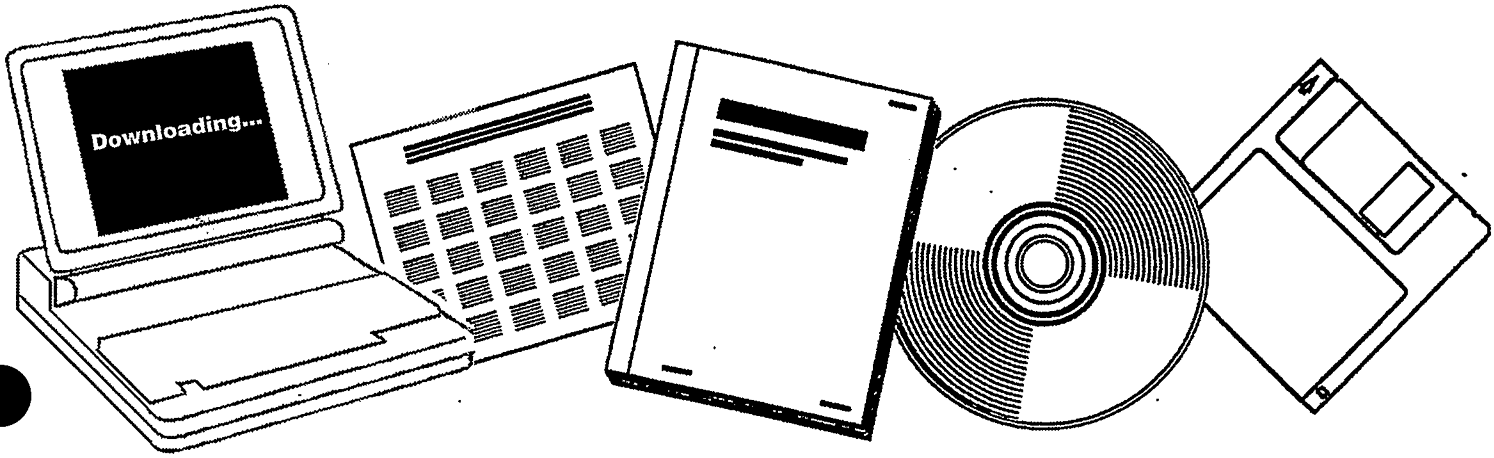

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1. SUMMARY

A heavy duty diesel engine was tested for operation on minimally processed synthetic fuels. Fuels included in this test were a reference No. 2 diesel fuel and liquid products derived from shale, tar sands, and coal. Performance, gaseous and particulate emissions, cold startability and deposit formation with extended idle were tested. Phase I includes baseline testing of a state-of-the-art heavy duty diesel engine meeting current Federal emissions standards. Phase II includes determining practical engine modifications to enhance synfuel operation and a repeat of selected Phase I tests. This report is the result of Phases I and II.

The Phase I engine test procedure was conducted as follows. First, performance data was taken for control diesel fuel, shale fuel, and tar sands fuel. Cold start tests were then conducted on those fuels. Finally, idle deposits tests were run on the fuels. After completion of these tests, the coal liquid blends screening test was run and performance data was taken for this fuel.

A performance analysis of the Phase I data reveals that the three synfuels are a viable alternative to the reference No. 2 diesel fuel in terms of brake thermal efficiency and maximum power output. At engine speeds of 1400 and 2200 rpm, the BSHC, BSCO, and $BSNO_x$ emissions of the three synfuels closely resemble the diesel fuel emissions, especially at high loads. Unfortunately, the smoke and particulate emissions are higher for the tar sands and 57 percent EDS fuels. The shale fuel, however, yields less smoke and particulate emissions compared to the diesel fuel at these two engine speeds.

The greatest variation in the combustion characteristics of these four fuels was due to the increased ignition delay of the 57 percent EDS and tar sands fuels. This increased delay, however, did not result in audible engine knock.

The performance data at engine idle shows that the diesel fuel was the best performer. In general, the gaseous, smoke, and particulate emissions were higher for the synfuels at engine idle.

The cold start test results show that the engine had trouble starting on the tar sands and 57 percent EDS fuels, especially at -20°C. The engine would not start at -20°C with the 57 percent EDS fuel.

The results of the 8-hour idle test show that the three synfuels did not have significant soot deposit problems compared to the control diesel fuel.

The shale fuel's overall performance was as good as the reference diesel fuel's except for a slight reduction in brake thermal efficiency and an increase in gaseous and smoke emissions at idle. The tar sands fuel was consistently the poorest performer in this unmodified engine with the 57 percent EDS fuel's performance only slightly better. The reduction in engine performance when operating on the synfuels may be partially attributed to the fact that the fuel injection timing was optimized for diesel fuel No. 2.

Three engine modifications were made during Phase II. These modifications were:

1. Simulate air-to-air aftercooling.
2. Add a high pressure fuel injection system.
3. Add an ether injection system.

The Phase II test procedure was conducted as follows. Performance data was taken for the control diesel, tar sands, and 57 percent EDS fuels after making engine modification No. 1. These tests were repeated on the engine with modification Nos. 1 and 2. The ether injection system was then added and cold start tests were run at 0°C and -20°C for the 57 percent EDS fuel.

The results of the Phase II tests show that these three engine modifications were successful in solving some of the synfuel operational problems encountered during Phase I. Adding a high pressure fuel injection system reduced the synfuel full load smoke emissions relative to the control diesel fuel. This modification also reduced the smoke and particulate emissions of all three fuels compared to the Phase I results.

Simulating air-to-air aftercooling reduced the brake specific fuel consumption by an average of 3 percent and greatly reduced the low load $BSNO_x$ emissions for all three fuels. Unfortunately, the synfuels low load $BSNO_x$ emissions were consistently higher than these same control diesel fuel emissions.

The combustion analysis results showed that the tar sands and 57 percent EDS fuels still suffer from longer ignition delays compared to the control diesel fuel. This longer delay is due to the synfuels' different chemical composition.

The ether injection system solved the synfuel cold start problems by enabling the engine to start at -20°C on the 57 percent EDS fuel.

In summary, after making the three engine modifications, the tar sands and 57 percent EDS fuels' performance were as good as or better than the control diesel fuels' performance with the following exceptions. The two synfuels had higher low load BSCO emissions, higher full load particulate emissions at 2200 rpm, and higher $BSNO_x$ emissions across the entire load range at 1400 rpm.

2. INTRODUCTION

2.1 BACKGROUND

Development of non-petroleum fuel sources continues to be a goal of this country. This project examines several operational problems of synthetic fuel usage in a heavy duty diesel engine and will further address modifications needed to optimize performance with minimally processed synfuels.

Some specific questions involving synthetic fuel operation in diesels include:

— How do synfuels affect diesel engine cold starting?

— How are particulates affected?

— Will synfuels increase emissions levels of an engine beyond regulated limits?

— Are combustion chamber deposits affected with long-term idle on synfuels?

— Will power or fuel economy be reduced?

— Is engine damage due to knock likely?

— What engine modifications are needed to optimize operation on synfuels?

To adequately address these questions, a representative engine is needed. The engine should be a state-of-the-art, direct injection, multicylinder engine in widespread use. Furthermore, the engine should be turbocharged and aftercooled, and capable of meeting current emissions standards. Deere & Co. provided such an engine, which will be described later in this report, under a no-cost consulting agreement to provide engine hardware and manufacturers recommendation.

Funding for this project was provided by the U.S. Department of Energy, with contract monitoring and administration provided by Martin Marietta Energy Systems under Subcontract No. 11X-28609C.

This project was conducted in two phases. In Phase I, synfuels were tested in a standard configuration engine. During Phase II, the engine was modified to provide better operation on the test fuels.

2.2 OBJECTIVE

The objective of this project was to determine the effects of minimally processed synfuels on heavy duty diesel engine operation. The fuels include a shale-derived product, a tar sands-derived product, and a coal liquid blend. The coal liquid blend is a mixture of coal liquid and petroleum diesel fuel. These fuels will be compared to a reference diesel fuel. Engine performance, gaseous and particulate emissions, combustion characteristics, cold startability, and deposit formation with extended idle will be determined. Results of these tests will be used to determine practical engine modifications for enhanced operation on these synfuels. These modifications will be incorporated in Phase II.

2.3 APPROACH

A heavy duty, direct injection diesel engine was instrumented and installed in a test cell in the Engine Research building at SwRI. One cylinder was instrumented to provide combustion data. The engine exhaust was sampled for gaseous and particulate emissions. Motoring and absorption dynamometers were connected to the engine for performance and cold start testing. The Fuels and Lubricants Division at SwRI provided combustion analysis. The Department of Emissions Research operated the emissions instrumentation and provided emissions analysis.

The Phase I test sequence was as follows:

1. Performance, combustion, and emissions tests were run on the control diesel fuel, shale fuel, and tar sands fuel, respectively.

2. Cold starting tests were run at 0°C and then at -20°C for the three fuels listed above.

3. Idle deposit tests were run on the fuels listed above.

4. Coal liquid blend screening tests were run on fuels composed of 40 percent, 50 percent, and 57 percent (by volume) EDS coal liquid blended into petroleum diesel fuel. These tests included cold starting at 0°C and -20°C.

5. Performance, combustion, and emissions tests were run on the selected blend (57 percent EDS).

6. Idle deposit tests were run on 57 percent EDS.

After completing the Phase I tests, three Phase II engine modifications were made based on the Phase I results. These modifications were:

(1) simulate air-to-air aftercooling
(2) add a high pressure fuel injection system
(3) add an ether injection system

Optimization of the fuel injection timing was also considered as a Phase II engine modification. This engine modification was not implemented due to the amount of time required to adjust the fuel injection timing for each synfuel.

Air-to-air aftercooling was simulated by modulating the flow of laboratory water through the engine's stock air-to-water aftercooler. This modification reduced the intake air temperature to temperatures between 40°C and 70°C (depending upon engine speed and load) which were the lowest temperatures that could be achieved using this setup.

The high pressure fuel injection system was supplied by John Deere and consisted of a high pressure Nippondenso Model RE 26126 fuel injection pump with 12 mm bore x 12 mm stroke plungers. The new fuel pump raised the measured maximum fuel injection pressure from 65 MPa to 90 MPa. These two fuel pressures were measured at an engine speed of 2200 rpm/100 percent load for the old and new fuel pumps, respectively. After installing the new fuel injection system, the fuel injection timing was set at 1400 rpm, 50 percent load so that fuel injection began at 11° BTDC. This 11° BTDC fuel injection timing was identical to the Phase I fuel injection timing at this same engine condition (1400 rpm, 50 percent load), although the dynamic speed-load timing characteristics of the new pump may be different from the Phase I fuel injection pump. A complete set of cylinder and fuel injection pressure diagrams corresponding to the engine test conditions are given in Appendices N through P.

The ether injection system was purchased from John Deere and used an electric solenoid control valve to inject ether into the engine intake manifold.

These three engine modifications were then tested by repeating a modified version of the Phase I test procedure.

The Phase II test sequence was as follows:

1. Performance, combustion, and emissions tests were run on the control diesel, tar sands, and the 57 percent EDS fuels after simulating air-to-air aftercooling.

2. These tests were then repeated on the engine with both modifications (simulated air-to-air aftercooling and the addition of the high pressure fuel injection system).

3. The ether injection system was added to the engine (now with all three engine modifications) and cold start tests were run at 0°C and -20°C for the 57 percent EDS fuel.

3. CONCLUSIONS

The following conclusions are made based on the engine test data collected during Phase I.

A performance analysis of this data reveals that the three synfuels are a viable alternative to the reference No. 2 diesel fuel in terms of brake thermal efficiency (BTE) and maximum power output. In fact, the 57 percent EDS fuel shows a slight increase in BTE at 2200 rpm across the entire load range while the tar sands fuel yields a slightly higher maximum power output compared to the reference diesel fuel. Unfortunately, these same two fuels exhibit higher smoke opacity and particulate emissions. The shale fuel, however, yields less smoke and particulate emissions compared to the diesel fuel.

The measured brake specific emissions (BSHC, BSCO, and $BSNO_x$) of the three synfuels closely resemble the diesel fuel emissions, especially at high loads. The greatest variation occurs at the lowest load condition where it is interesting to note that at 2200 rpm, the $BSNO_x$ emissions from the three synfuels are considerably lower than the baseline diesel fuel.

The high-speed combustion data reveal that the total heat release for the four test fuels is almost identical over the entire load range. This result is expected since the engine BTE and output power are nearly identical for the four fuels at each load setting.

The greatest variation in the combustion characteristics of these four fuels is due to the increased ignition delay of the 57 percent EDS and tar sands fuels. This is the expected result since the cetane number of these two fuels is low compared to the shale and diesel fuels. The increased ignition delays for the tar sands and 57 percent EDS fuels explains why their average and maximum rates of cylinder pressure rise are higher when compared to the diesel and shale fuel values. These greater rates of pressure rise, however, did not result in audible engine knock during the engine tests. The lowest peak cylinder pressure occurred with the 57 percent EDS fuel since it has the longest ignition delay with combustion occurring later during the expansion stroke, as shown in Appendix N.

At 0°C the engine started in less than 5 seconds on the diesel, shale, and tar sands fuels. The 57 percent EDS fuel required more than four times this amount of time, or 20 seconds, to start. At -20°C the engine started on shale and diesel fuel in about 20 seconds. The tar sands fuel required nearly twice this amount of time to start and the engine would not start on the 57 percent EDS fuel. All of these cranking times are acceptable for typical applications of this engine.

The performance data at engine idle shows that the diesel fuel is the best performer. The diesel fuel has the highest BTE, lowest smoke opacity, and lowest gaseous emissions. The tar sands fuel is the poorest performer at idle with the lowest BTE and the highest smoke and particulate emissions. At idle the gaseous, smoke and particulate emissions are higher for the synfuels compared to the diesel fuel. The only exception is that the shale fuel has the lowest particulate emissions at idle.

The high-speed combustion data at engine idle follows the same trend observed at 1400 and 2200 rpm.

The results of the eight-hour idle test show that the three synfuels do not have significant soot deposit problems compared to the diesel fuel. All four fuels cause a light buildup of black soot on the head, valves, pistons, and turbo exhaust. Some of this soot disappears during the two-hour burnoff period. (This period is defined by running the engine at rated speed and load for two hours following the eight-hour idle test.) The only noticeable difference between the synfuels and diesel fuel is that the 57 percent EDS fuel causes a reddish color deposit on the cylinder head that is present before and after the burnoff period.

In summary, the three synfuels compared very well with the reference diesel fuel in terms of BTE, maximum output power, and gaseous emissions in the unmodified engine at 1400 and 2200 rpm. The shale fuel's overall performance was as good as the reference diesel fuel except for a slight reduction in BTE and increase in gaseous and smoke emissions at idle. The tar sands fuel was consistently the poorest overall performer with the 57 percent EDS fuel's performance only slightly better.

The major problems encountered during Phase I tests were an increase in the smoke and particulate emissions for the 57 percent EDS and tar sands fuels at 1400 and 2200 rpm. The three synfuels also suffered from poorer idle performance. The BTE was lower and the gaseous, smoke and particulate emissions were higher during idle for the synfuels compared to the reference diesel fuel. The one exception was the shale fuel which had the lowest particulate emissions at idle. Another major problem was the poor startability of the engine on the tar sands and especially the 57 percent EDS fuel. Surprisingly, engine knock was not a problem during these tests despite the increased ignition delay of the tar sands and 57 percent EDS fuels.

The following conclusions were made based on the engine test data collected during Phase II.

Modifications can be made to a direct injection, heavy duty diesel engine which improve engine performance while operating on minimally processed synfuels. The Phase II modifications selected were able to solve some of the operational problems encountered during Phase I.

Adding a high pressure fuel injection system solved a Phase I operational problem by reducing the tar sands and 57 percent EDS fuels' full load smoke emissions relative to the control diesel fuel. This modification also reduced the smoke and particulate emissions of all three fuels compared to the Phase I results.

Reducing the intake air temperature to 140°F by simulating air-to-air aftercooling reduced the brake specific fuel consumption by an average of 3 percent and greatly reduced the low load $BSNO_x$ emissions for all three fuels.

Unfortunately, the synfuels' low load $BSNO_x$ emissions were consistently higher than these same diesel fuel emissions. Lowering the intake air temperature also increased the three fuels' ignition delay periods which resulted in higher initial heat release rates and higher rates of cylinder pressure rise.

The 57 percent EDS and tar sands fuels still have longer ignition delays compared to the control diesel fuel. Engine modifications did not improve the synfuel combustion characteristics relative to the control diesel fuel since the increase in ignition delay is a function of the differences in the fuels' chemical compositions.

Adding an ether injection system solved the synfuel cold starting problem by enabling the engine to start at -20°C on the 57 percent EDS fuel.

In summary, after making the three engine modifications (simulating air-to-air aftercooling, adding a high pressure fuel injection system, and adding an ether injection system), the tar sands and 57 percent EDS fuels' performance were as good as or better than the control diesel fuel's performance with the following exceptions. The two synfuels had higher low load BSCO emissions. The two synfuels also had higher full load particulate emissions at 2000 rpm and higher $BSNO_x$ emissions across the entire load range at 1400 rpm. The tar sands fuel had higher full load particulate emissions at 1400 rpm and at engine idle.

4. RECOMMENDATIONS

The results of the Phase I and Phase II short-term performance tests indicate that the shale, tar sands, and 57 percent EDS fuels are viable alternatives to the reference No. 2 diesel fuel. SwRI now recommends that these three synfuels be subjected to a transient cycle durability test to determine the long-term effects on engine performance and wear. The results of these durability tests will determine whether the synfuels' longer ignition delays and corresponding higher rates of pressure rise and greater maximum cylinder pressures will lead to premature engine failure. Although audible engine knock was not detected during the steady-state performance tests, damaging knock may occur during extended and repeated transient engine loading. SwRI also recommends that transient emissions tests be conducted with the synfuels to determine the effects on transient exhaust emissions.

Further work is required to optimize the combustion chamber and fuel injection systems for synfuel operation. The high pressure fuel injection system that was added to the engine during Phase II was designed to operate on No. 2 diesel fuel. Changes in the fuel injection nozzle may help to optimize the spray penetration and atomization of the more dense and viscous tar sands and 57 percent EDS fuels. This modification may help to reduce the synfuels' low load BSCO formation by improving fuel/air mixing. Fuel/air mixing can also be improved by modifying the intake port to improve intake air swirl.

SwRI also recommends that performance tests be conducted with variable fuel injection timing since the timing was held constant during Phase I and Phase II testing. The fuel injection timing should be changed to accommodate the tar sands and 57 percent EDS fuels' longer ignition delays. Changes in fuel injection timing may help to reduce the two synfuels' $BSNO_x$ and particulate emissions.

5. TEST SETUP AND PROCEDURES

5.1 TEST MATERIAL

Four fuels were used in this project. Table 5.1 shows the chemical and physical analyses of the test fuels. The control fuel for this program is Phillips D-2 control fuel, Lot G-075. The three synthetic test fuels were supplied to the SwRI Engine and Vehicle Research Division through the SwRI Synthetic Fuel Center.

The tar sands fuel was a result of cooperation between the United States Department of Energy and the Canadian National Research Council, Department of Energy, Mines and Resources. The tar sands fuel was originally anticipated to be a Canadian 1990s diesel fuel. This projection was made during the energy crisis in the late 1970s; however, due to the changing situation with world petroleum supplies, the tar sands fuel will probably not appear in the Canadian marketplace until several years later than was originally anticipated. The fuel contains 78 percent (by volume) of a diesel fuel cut (produced from a 50/50 mixture of conventional western Canadian and tar sands crudes) and 22 percent (by volume) of a hydrogen-treated, cracked stock. By 1990 the tar sands content of the Canadian crude oil pool is predicted to rise from the current 12 percent to 23 percent.

The shale oil-derived fuel originated from Utah shale oil produced by Geokinetics with their in situ retorting process. The crude shale oil was partially hydrogenated by Sun Tech, Inc. in their laboratory at Marcus Hook, Pennsylvania. About 3200 gallons of the upgraded crude were distilled to separate 1700 gallons of diesel fuel. The product is a good quality No. 2-D diesel fuel with the unusual characteristic of high (940 ppm) nitrogen content.

The coal-derived fuel used Exxon Donor Solvent (EDS) middle distillate which was provided to the SwRI Synthetic Fuel Center through the DOE Bartlesville Energy Technology Center. The EDS middle distillate was produced by the demonstration unit operated by Exxon at Baytown, Texas. The EDS process employed two stages of hydrogenation: the first dissolved the coal via noncatalytic digestion, and the second upgraded the coal liquids by conventional fixed-bed hydrotreating. The middle distillate and other products were then separated by fractionation. After the middle distillate was received at SwRI, it was treated with sodium hydroxide to extract phenols and other polar compounds. The coal-derived fuel used in the engine tests was a mixture of EDS and the Phillips D-2 control diesel fuel. These two fuels were mixed due to the poor fuel quality of the EDS. The coal liquid-diesel fuel blend was the poorest quality fuel in the program.

One of the objectives of the tests was to determine the maximum amount of EDS fraction that could be used without encountering operational problems. In Table 5.1, a 57 percent blend is presented.

Table 5.1. Chemical and Physical Analyses of the Test Fuels

Fuel Identification Sample No.	Test Method	Phillips D-2 Control Fuel FL-0420-F	EDS Middle Distillate (1) FL-0765-F	57% EDS 43% D-2 FL-1068-F	Canadian 1990 Diesel Fuel (2) FL-0704-F	Partially Upgraded Fuel FL-0411
Gravity, °API	D-1298	35.1	21.4	26.8	27.5	39.5
Specific Gravity at 60°F		0.8493	0.9254	0.8938	0.8899	0.8275
Distillation, °F	D-86					
IBP/5% Recovered		373/400	412/424	394/419	338/376	356/387
10/20		417/442	431/440	430/443	392/426	404/430
30/40		462/481	449/461	454/466	450/488	448/466
50/60		496/516	473/489	483/501	517/550	484/502
70/80		537/563	509/534	522/550	584/621	522/546
90/95		598/625	573/611	587/624	667/700	579/606
FBP		651	649	656	763	646
Recovery, V%		99.0	98.0	99.0	99.0	99.0
Residue/Loss, V%		1.0/0.0	2.0/0.0	1.0/0.0	1.0/0.0	1.0/0.0
Cetane Number	D-613	46.5	23.5	32.9	34.9	51.1
Cetane Index	D-976	45.4	22.6	31.1	36.0	51.2
Viscosity, cSt at 40°C	D-445	2.50	2.53	2.51	2.91	2.44
Pour Point, °F (°C)		1 (-71)	-54 (-48)	-17 (-27)	-44 (-42)	0 (-18)
Hydrocarbon Type, V%	D-1319					
Saturates		66.2	18.3	35.4	32.7	81.0
Olefins		1.6	6.5	5.2	0.0	1.2
Aromatics		32.2	75.2	59.4	67.3	17.8
Aromatic Carbon, M%	UV					
Monocyclic		—	22.46	—	10.65	4.12
Dicyclic		—	6.36	—	10.18	1.53
Tricyclic		—	1.31	—	3.31	0.21
Elemental Analysis, M%						
Carbon	D-3178	86.50	88.50	87.47	87.04	86.03
Hydrogen	MOD	12.95	10.90	11.67	11.75	13.80
Sulfur	D-2622	0.36	0.01	0.15	0.67	0.04
Oxygen	(3)	—	0.32	—	—	0.050
Nitrogen	(4)	0.012	0.028	—	0.028	0.094
Heat of Combustion	D-240					
Gross, BTU/lb		19477	18788	19040	19006	19744
MJ/kG		45.304	43.701	44.287	44.208	45.996
Net, BTU/lb		18295	17794	17975	17934	18516
MJ/kG		42.556	41.388	41.811	41.715	43.068
Existent Gum, mG/100 mL	D-381					
Unwashed		4.3	14.53	—	300	4.8
Washed		—	—	—	30.1	—
Oxidation Stability, min.	D-525	—	—	—	—	—
Flash Point, °F (°C)		158 (70)	199 (93)	—	144 (62)	157 (69)
Reid Vapor Pressure, PSI	D-323	—	—	—	—	0
Calc. Vapor Pressure, PSI at 500°F	D-2889	—	—	—	—	34
Surface Tension, (Fuel Air is) Dyne/cm	D-971 MOD	—	29.9	—	28.5	26.8

NOTES:
(1) Phenolics removed from EDS by caustic extraction.
(2) Canadian fuel includes components derived from tar sands.
(3) Oxygen content determined by neutron activation.
(4) Nitrogen content determined by visual chemuluminescence.
— Not determined

The engine used for this test was a John Deere model 6466A. This is a six-cylinder, in-line, direct injection, open chamber, medium swirl turbocharged and aftercooled engine. This engine model is common in John Deere applications for agricultural and construction equipment. It is also sold on an OEM basis for various applications, such as generator sets and irrigation pumps. Further engine specifications are shown in Table 5.2.

Table 5.2 Engine Specifications

Model:	**John Deere 6466A**
Type:	**In-line, six-cylinder, two valves per cylinder**
Induction System:	**Turbocharged and aftercooled**
Bore:	**116 mm**
Stroke:	**121 mm**
Displacement:	**7.6 liters**
Compression Ratio:	**17.0:1**
Rated Power:	**150 kW at 2200 rpm**
Peak Torque:	**900 N-M at 1400 rpm**
Injection System:	**Bosch in-line, pump with 11 mm bore x 11 mm stroke plungers**

The oil sump was filled with John Deere Torq Gard 15W-40 lubricant. The coolant was a mixture of 50 percent water and 50 percent antifreeze. Coolant outlet temperature was controlled to 92°C.

5.2 TEST SETUP

Since several types of testing are included in this program, the test installation was planned to minimize changeover efforts between types of tests. The engine is located in a refrigerated test chamber; characteristics of this chamber are listed in Table 5.3; Figure 5.1 shows a schematic of the engine in the test cell.

Table 5.3. Refrigerated Test Chamber Specifications

Minimum Temperature:	**-40°C**
Insulation:	**150 mm urethane**
Length:	**3 meters**
Width:	**3 meters**
Height:	**2.7 meters**
Start System:	**Engine starter or external dynamometer**

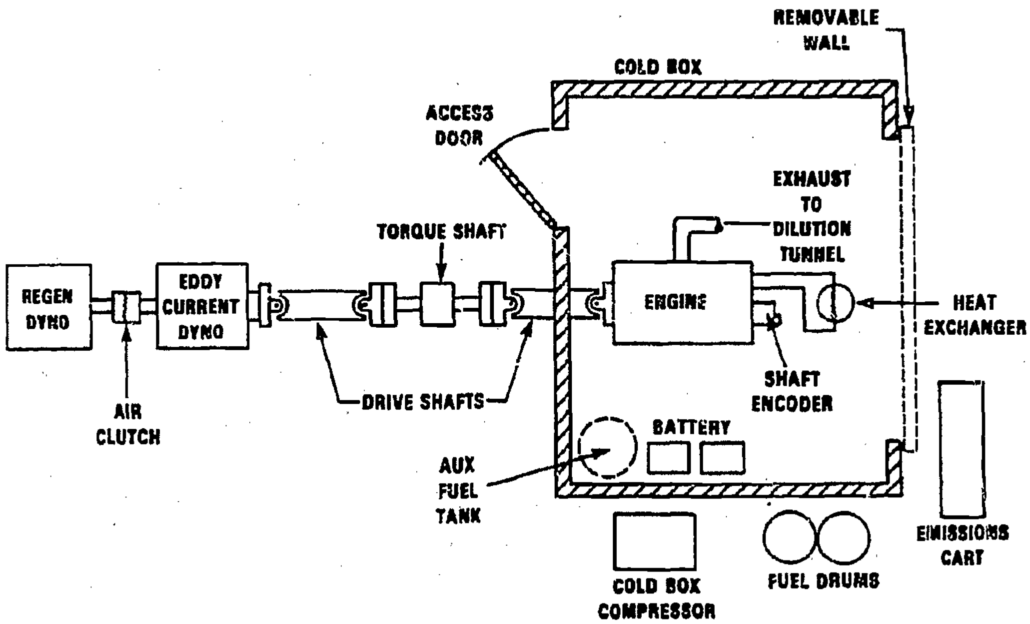


FIGURE 5.1. SCHEMATIC OF THE ENGINE IN THE TEST CELL

A driveshaft runs through the wall of the test chamber and connects to two dynamometers in series. The regenerative dynamometer is used for motoring the engine at a constant speed during cold start testing, whereas the eddy-current dynamometer is used as needed for power absorption in excess of the capabilities of the regenerative dynamometer. An exhaust dilution tunnel and emissions measurement equipment are located outside of the test cell, as well as fuel supply drums and other necessary equipment.

Figure 5.2 is a photograph of the test engine installed in the refrigerated test chamber. Figure 5.3 shows the dynamometer arrangement located outside the refrigerated test chamber.

Since several performance and cold start tests were planned, a cooling system was designed to minimize changeover efforts. A schematic of this cooling system is shown in Figure 5.4. The cooling system has two modes of operation. First, a shell tube heat exchanger was located outside the refrigerated chamber. This heat exchanger was used for performance testing. A small radiator and fan arrangement were located inside the refrigerated test chamber; this arrangement was used between cold start tests. SwRI has found that cold start testing is simplified and accelerated by using an external electric pump to circulate coolant through the engine between cold start attempts. This system was employed to minimize time required between cold start tests.

The engine is fully instrumented with Type T thermocouples for temperature measurement, various pressure transducers, a laminar flow element for measuring air flow, and a "Micro-Motion" mass fuel flow measurement

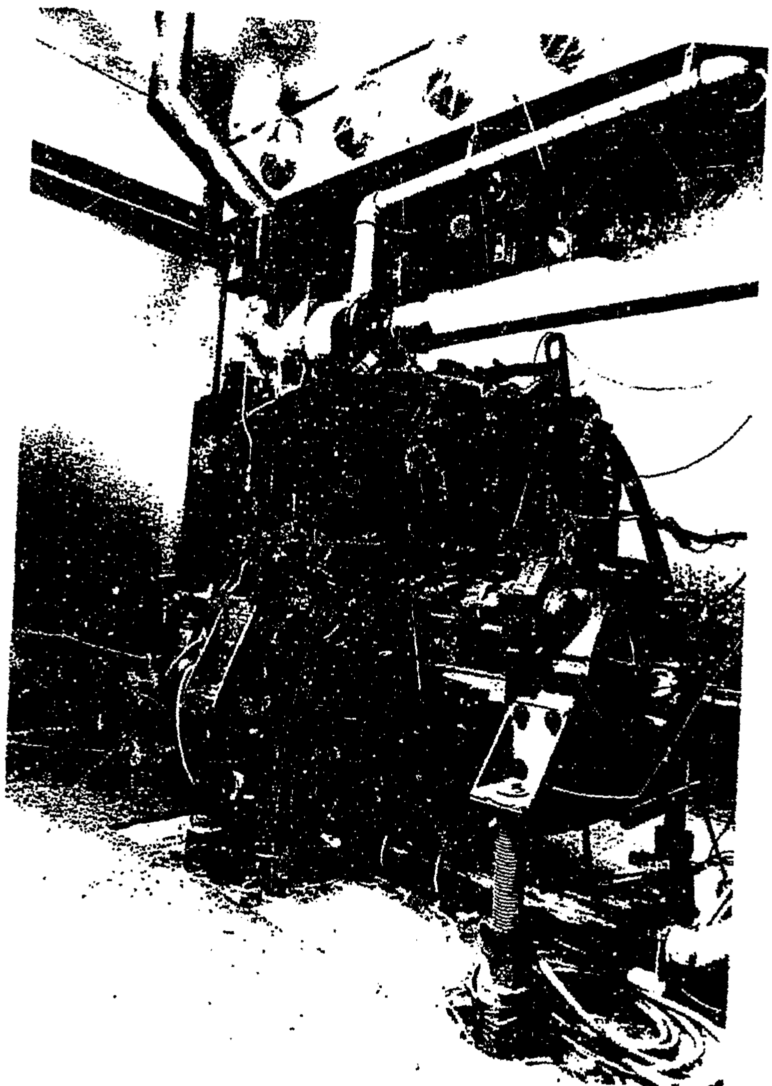


FIGURE 5.2. PHOTOGRAPH OF TEST ENGINE INSTALLED IN THE REFRIGERATED TEST CHAMBER

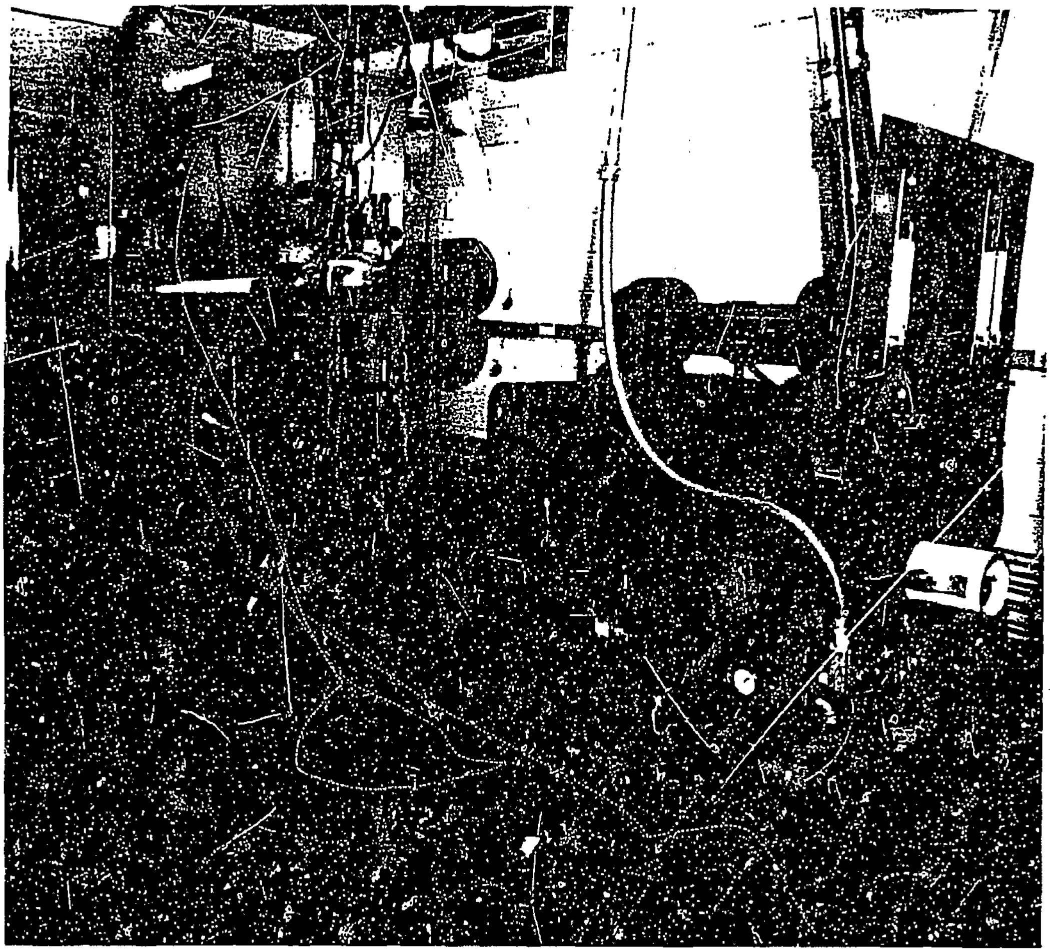


FIGURE 5.3. DYNAMOMETER ARRANGEMENT OUTSIDE REFRIGERATED TEST CELL

meter. Cylinder pressure and fuel injection pressure are monitored with pressure transducers, and injection timing is monitored by a Hall Effect needle lift sensor. A 720 pulse per revolution shaft encoder generates clock pulses for computer acquisition of engine pressure data. Figure 5.5 shows the transducer pressure measurement points. Table 5.4 is a complete instrumentation list.

5.3 PHASE I TEST PROCEDURE

The Phase I test procedure was conducted as follows. First, performance data was taken for the control diesel fuel, shale fuel, and tar sands fuel. Cold start tests were then conducted on those fuels. Finally, idle deposits tests were run on the fuels. After completion of these tests, the coal liquid blends screening test was run and performance data was taken for this fuel.

Figure 5.6 shows the data points used for performance, combustion,

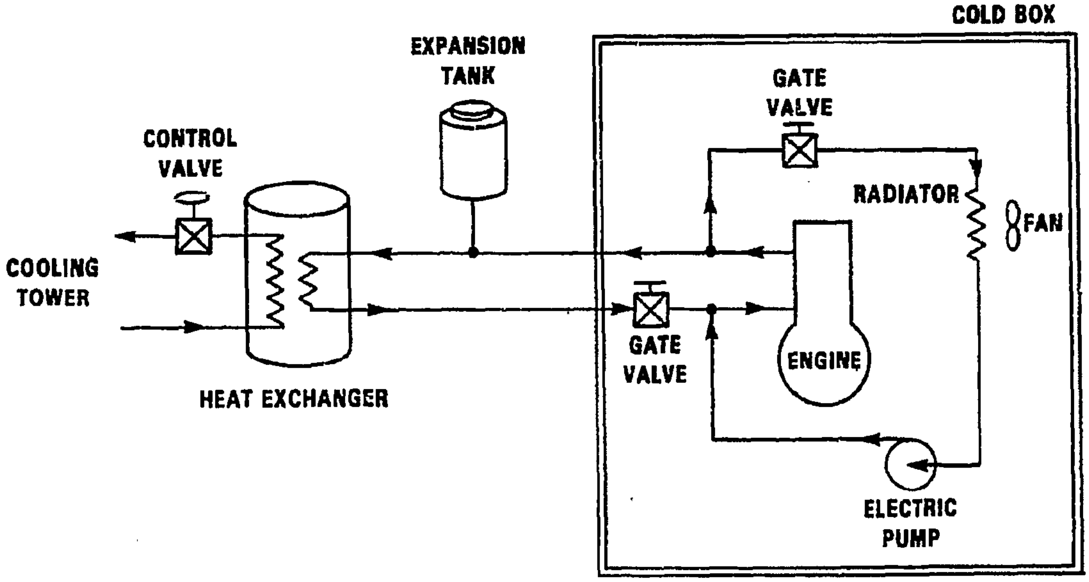


FIGURE 5.4. SCHEMATIC OF THE COOLING SYSTEM

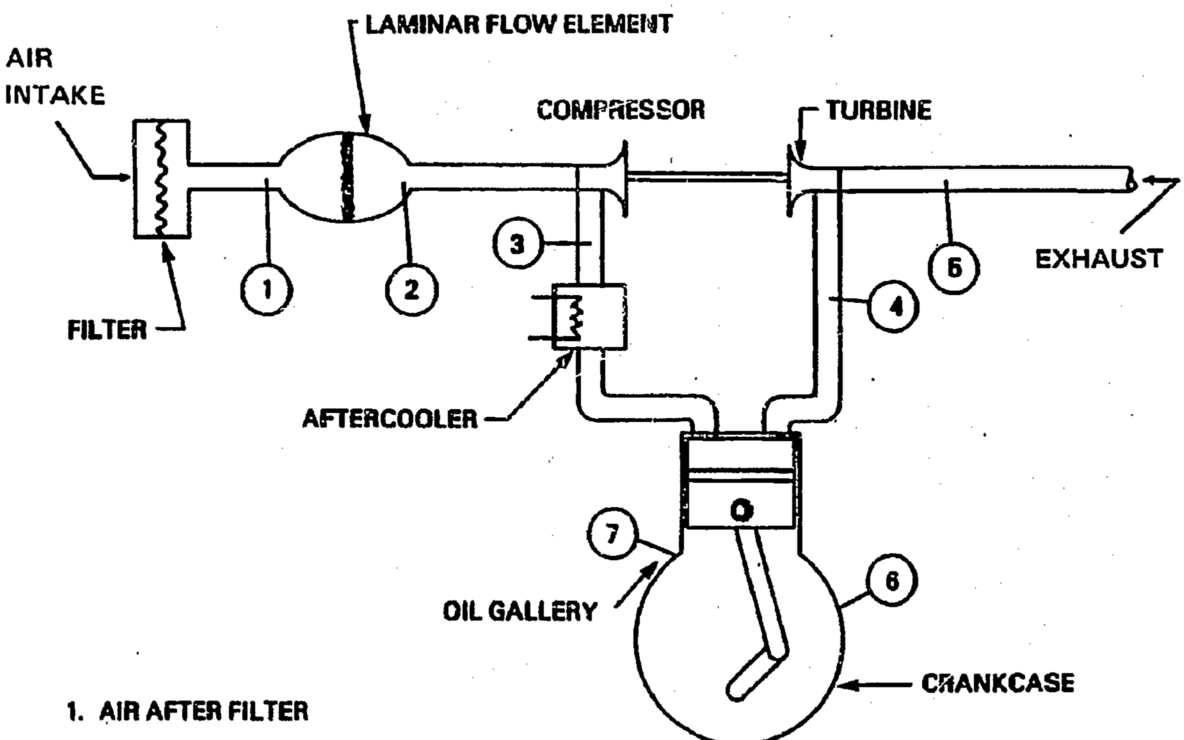
and emissions analysis. These nine points are those suggested by the Engine Manufacturers' Association for alternative fuels testing. The 100 percent power at rated and at torque peak speeds is the maximum attained for each fuel. The 50, 25, and 0 percent outputs were set according to the torque values obtained with the control diesel fuel. In reality, the 0 percent output had to be increased to 7 percent as shown in Figure 5.6. The 7 percent load was the minimum required to ensure stable dynamometer operation.

Temperatures, pressures, speed, load, air flow, fuel flow, and exhaust smoke at each of the test points were recorded by a computer. A high-speed analog-to-digital data acquisition device in conjunction with our computer recorded cylinder pressure, injection pressure, and needle lift for each one-half crank angle degree of operation. These data were used for combustion analyses, including apparent rate of heat release, centroid of heat release, maximum pressure rise, maximum pressure, and ignition delay which will be presented later in this report.

Gaseous emissions measurements were made with a 13-Mode emissions cart. These emissions included hydrocarbons, carbon monoxide, oxides of nitrogen, oxygen, and carbon dioxide. The particulate emissions were measured by the use of an exhaust dilution tunnel.

Two or three repetitions of each data point were run for each of the four fuels tested.

Cold start testing in the laboratory is rather difficult. For this reason, perhaps, there is no standardized test procedure. Some of the synthetic fuels were anticipated to cause cold start problems due to low cetane number. Our test, therefore, was designed to illustrate these problems while maintaining



1. AIR AFTER FILTER
2. AIR AFTER LAMINAR FLOW ELEMENT
3. AIR AFTER TURBO COMPRESSOR
4. EXHAUST BEFORE TURBO
5. EXHAUST AFTER TURBO
6. CRANKCASE
7. OIL GALLERY

FIGURE 5.5. TRANSDUCER PRESSURE MEASUREMENT POINTS

standardized conditions for accurate comparison.

One of the problems of laboratory cold start testing is determining the exact moment the engine begins running under its own power and is no longer being motored by the starter or cranking mechanism. For this test, we chose to use motoring torque as an indication of engine start. This motoring torque was supplied by the dynamometer. The torque was recorded by a strip chart recorder. When the mean motor and torque went from negative (torque applied to the engine) to positive (torque applied to the dynamometer), then the engine was deemed to have started. The time measured to mean positive torque was used to compare cold startability of the test fuels.

Cold start testing was conducted at 0°C and -20°C. Two to three attempts were made on each fuel. The cranking speed was determined by using a set of storage batteries, cold soaked to ambient conditions. The engine was

Table 5.4. Instrumentation List

Item	Range	Sensor	Monitor (Console)	Computer Data Acquisition
Temperatures				
Coolant, Inlet	-10 to 230°F (-22 to 110°C)	T Thermocouple	X (Deric)	X
Coolant, Outlet	-10 to 230°F (-22 to 110°C)	T	X	X
Oil Sump	-10 to 250°F (-22 to 121°C)	T	X	X
Air, Ambient	-10 to 120°F (-22 to 50°C)	T	X	X
Air, Before Turbo	-10 to 120°F (-22 to 50°C)	T	X	X
Air, After Turbo	-10 to 400°F (-22 to 200°C)	T	X	X
Air, Intake Manifold	-10 to 300°F (-22 to 150°C)	T	X	X
Fuel, to Engine	-10 to 120°F (-22 to 50°C)	T	X	X
Engine, Block	-10 to 250°F (-22 to 120°C)	T	X	X
Engine, Head	-10 to 250°F (-22 to 120°C)	T	X	X
Exhaust Ports (8)	-10 to 1400°F (-22 to 760°C)	J	X	X
Exhaust, After Turbo	-10 to 1200°F (-22 to 650°C)	J	X	X
Pressures				
Air, After Filter	0 to 15 psia (0 to 100 kPa)	Transducer		X
Air, After Laminar Flow Element	0 to 15 psia (0 to 100 kPa)	Transducer		X
Air, After Turbo	0 to 100 psia (0 to 700 kPa)	Transducer	X	X
Exhaust, Before Turbo	0 to 100 psig (0 to 700 kPa)	Transducer		X
Exhaust, After Turbo	0 to 25 psia (0 to 170 kPa)	Transducer		X
Crankcase	0 to 25 psia (0 to 170 kPa)	Transducer and manometer	X	X
Oil, Gallery	0 to 100 psig (0 to 700 kPa)	Transducer and gauge	X	X
Fuel, Before Injection Pump	0 to 100 psi (0 to 700 kPa)	Gauge	X	
Fuel, Injection Line No. 1		Kistler 607F122	Oscilloscope	High-speed
Cylinder, Firing Pressure		Kistler 6121A2	Oscilloscope	High-speed
Miscellaneous				
Engine Torque	0 to 3000 rpm	60-tooth gear/ magnetic pickup	X	X
Torque	0 to 700 lb-ft (0 to 950 Nm)	Load cell on eddy-current dynamometer	X	X
		Torque shaft driveline (Eaton-Lebow Model 1106)	X	High-speed
Crankshaft Position	Each 1/2 crank angle degree	Shaft encoder	Oscilloscope	High-speed
Fuel Flow	0 to 90 lb/hr (0 to 40 kg/hr)	Micro-Motion flowmeter	X	X
Air Flow	0 to 1000 CFM (20 to 28 m^3/min)	Laminar Flow Element		X (Press. 1 & 3)
Injector Needle Lift, Cylinder #1		Proximeter	Oscilloscope	High-speed
Smoke Opacity		USPHS meter	X	High-speed
Barometric Pressure		Home Barometer		
Wet Bulb Temperature		Psychrometer		
Dry Bulb Temperature		Psychrometer		

cranked with the on-board starter and these storage batteries, in order to determine a baseline cranking speed. This speed was found to be 182 rpm with the particular military model 6TN 500 cold cranking amp batteries used. The motoring dynamometer was then set to 182 rpm to provide constant cranking speed throughout the test.

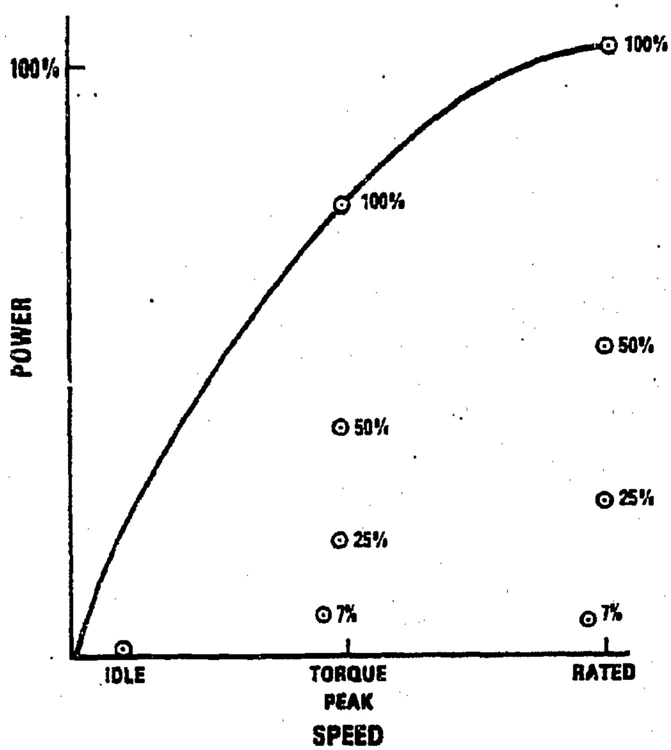


FIGURE 5.6. DATA POINTS USED FOR PERFORMANCE, COMBUSTION, AND EMISSIONS ANALYSES

Continuous idle testing was the final evaluation performed on each fuel. The cylinder head and turbocharger were removed for a pretest inspection. These were cleaned as necessary. Next, the injection system was filled with test fuel and the engine cooled to room temperature. The engine was then started and idled continuously for eight hours. This time period was chosen as the maximum duration normally encountered by an engine of this type and application, such as idling an engine overnight in a truck stop in the northern United States.

Following the eight-hour idle period, the cylinder head and turbocharger were removed and inspected. Deposits were examined, and photographs were taken within 24 hours of shutdown. The engine was then reassembled without cleaning. It was started and operated at rated speed and load for two hours. During this time period, any deposits that could be removed due to burnoff should disappear. The cylinder head and turbocharger were again removed for inspection. The degree to which the deposits were "burned off" was then examined and the deposits remaining were those anticipated to be a problem for the particular test fuel. The engine was then cleaned in preparation for the next idle test. Figure 5.7 shows a schematic of the idle deposit test sequence.

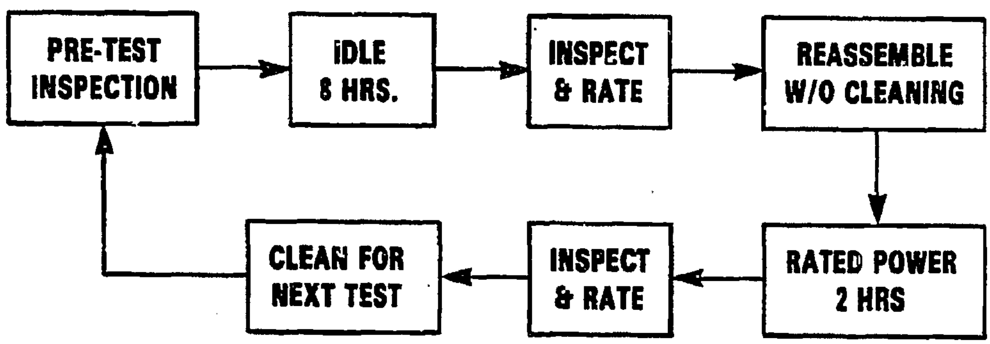


FIGURE 5.7. SCHEMATIC OF THE IDLE DEPOSIT TEST SEQUENCE

Since one of the objectives of this program was to determine the maximum amount of coal liquid that could be substituted for a diesel engine without encountering operational problems, a simple coal liquid blend screening test was devised. Engine performance was evaluated at 100 percent load and speed, 50 percent load at torque peak speed, and at idle. The engine was monitored closely for knocking and smoke emissions. After this short performance test, cold starting attempts were made at 0°C. Figure 5.8 shows a schematic of the coal liquid blend screening test data points.

Three blends of coal liquid/diesel fuel were tested under this screening procedure. These were nominally chosen to be 40, 50 and 60 percent by volume. In actuality, the highest blend was 57 percent. This was the blend chosen for further performance, emissions and combustion analysis testing. This fuel was then subjected to the previously described test procedure.

5.4 PHASE II TEST PROCEDURE

Modifications were made to the Phase I test procedure which were the result of Phase I conclusions. No further tests were conducted with the shale fuel because its performance and emissions are identical to the control diesel fuel performance and emissions. The extended idle deposit tests were not performed during the Phase II tests because the engine did not produce excessive idle deposits when idling on the synfuels compared to the control diesel fuel. Also, cold start tests were only performed on the 57 percent EDS fuel since its cold starting performance was unacceptable during the Phase I tests. The cold start test procedure was identical to Phase I test procedure except ether was injected for one second blasts every five seconds until the engine reached maximum speed.

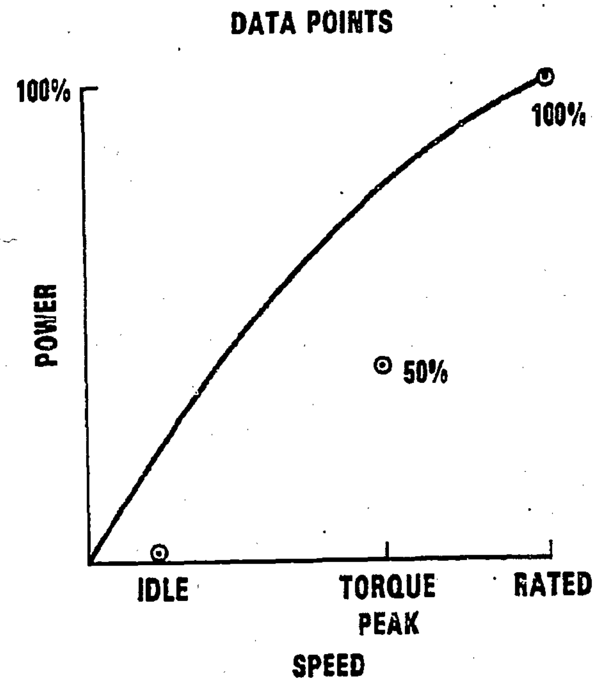


FIGURE 5.8. SCHEMATIC OF THE COAL LIQUID BLEND SCREENING TEST DATA POINTS

Engine performance and emissions tests were conducted after simulating air-to-air aftercooling (modification No. 1) for the control diesel, tar sands, and 57 percent EDS fuels. Air-to-air aftercooling was simulated by circulating laboratory water through the engine's stock air-to-water aftercooler. This modification reduced the intake air temperature to temperatures between 40°C and 70°C (depending upon engine speed and load), which were the lowest temperatures that could be achieved using this setup. The high pressure fuel injection system was then added (modification no. 2) and engine performance and emissions tests were repeated on the engine with both modifications for all three fuels. The test procedure was identical to the Phase I test procedure except repetitions were not performed for each data point. The ether injection system was then installed and the cold start tests were performed at 0 and -20°C with the 57 percent EDS fuel.

6. RESULTS

Presented here are the results from the Phase I standard engine tests. They are presented in the following sequence:

- Performance Testing
- Cold Start Testing
- Idle Deposit Tests

6.1 PERFORMANCE TESTS

Results from the performance tests are presented in two sections. The first section deals with engine performance in terms of power and fuel economy. Emissions analyses results are also included, with gaseous and particulate data presented.

The second section presents combustion analysis data obtained from digitized, high-speed, cylinder pressure data.

6.1.1 Performance and Emissions

Performance testing was conducted at three speeds: rated (2200 rpm), peak torque (1400 rpm), and idle. There are two graphs for each speed. The first of these is titled "Performance" and includes brake thermal efficiency, smoke opacity, and particulates versus brake power. The second graph is titled "Emissions" and includes brake specific hydrocarbons, brake specific carbon monoxide, and brake specific oxides of nitrogen versus brake power. The idle test points are shown as bar graphs.

The data points shown on the graphs represent the numerical average of the two-to-three repetitions of each data point run for a given test fuel. Complete tabular data for each repetition are shown in Appendices A, B, C and D for the control diesel, shale, tar sands, and coal liquid blend fuels, respectively. Appendix E contains tabular data for the coal liquid blend screening test, consisting of 40 percent, 50 percent, and 57 percent EDS by volume. Particulate data represents the average weight increase for two particulate sample filters for each repetition.

Figure 6.1 shows performance results at 2200 rpm. All fuels provided nearly equivalent thermal efficiency and power. The tar sands gave slightly higher peak power, and shale the lowest. Fifty-seven percent EDS produced the highest thermal efficiency across the load range. Smoke opacity was higher with the aromatic containing fuels (tar sands and coal liquid). Full power particulate concentrations also increased dramatically with these two fuels.

Brake specific emissions at 2200 rpm are shown in Figure 6.2. Light load brake specific emissions levels were high for all fuels. High load BSHC and BSCO were nearly equal for all four test fuels. Surprisingly, the control DF-2 fuel produced the highest $BSNO_x$ over most of the load range.

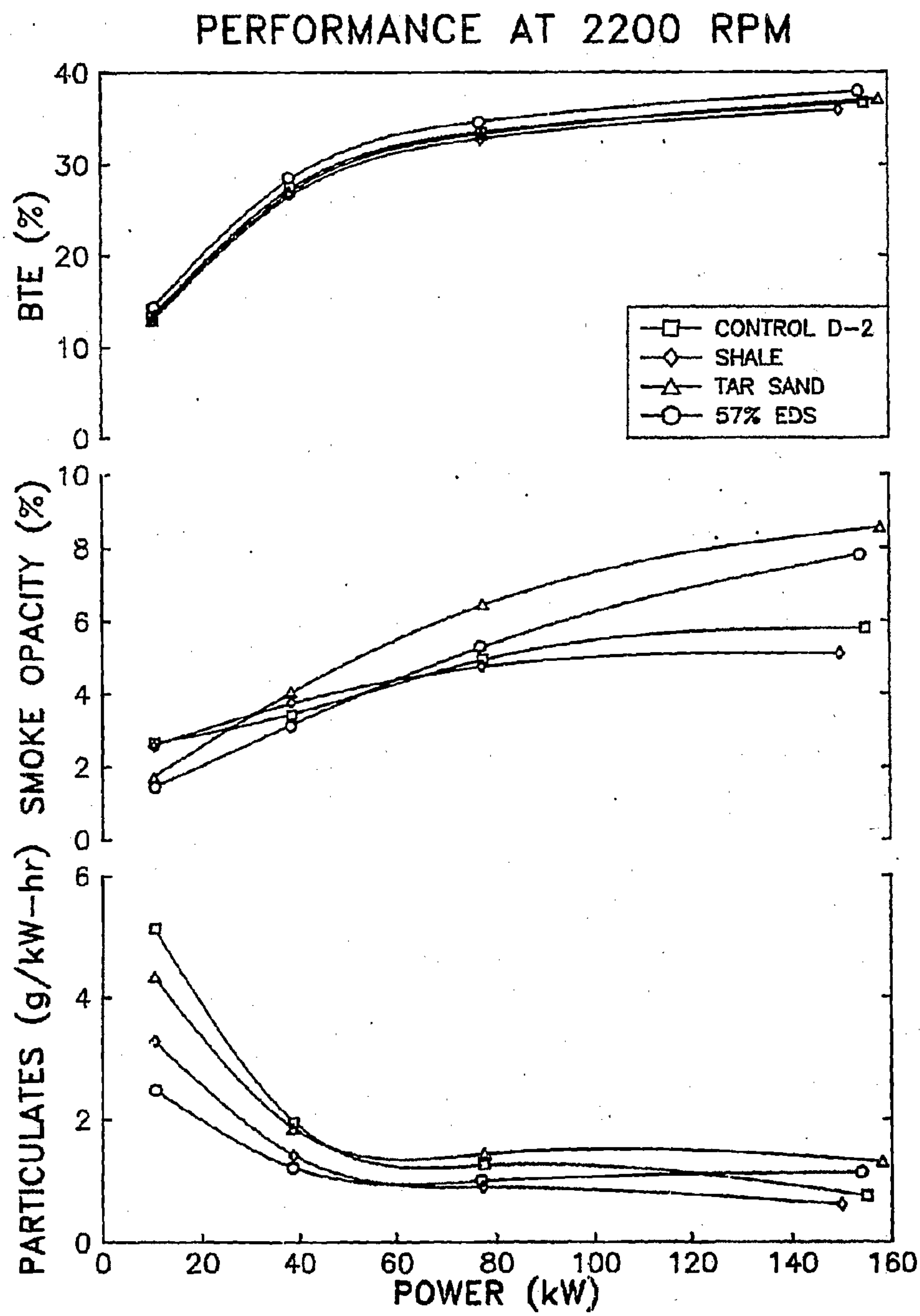


FIGURE 6.1. PERFORMANCE RESULTS AT 2200 RPM

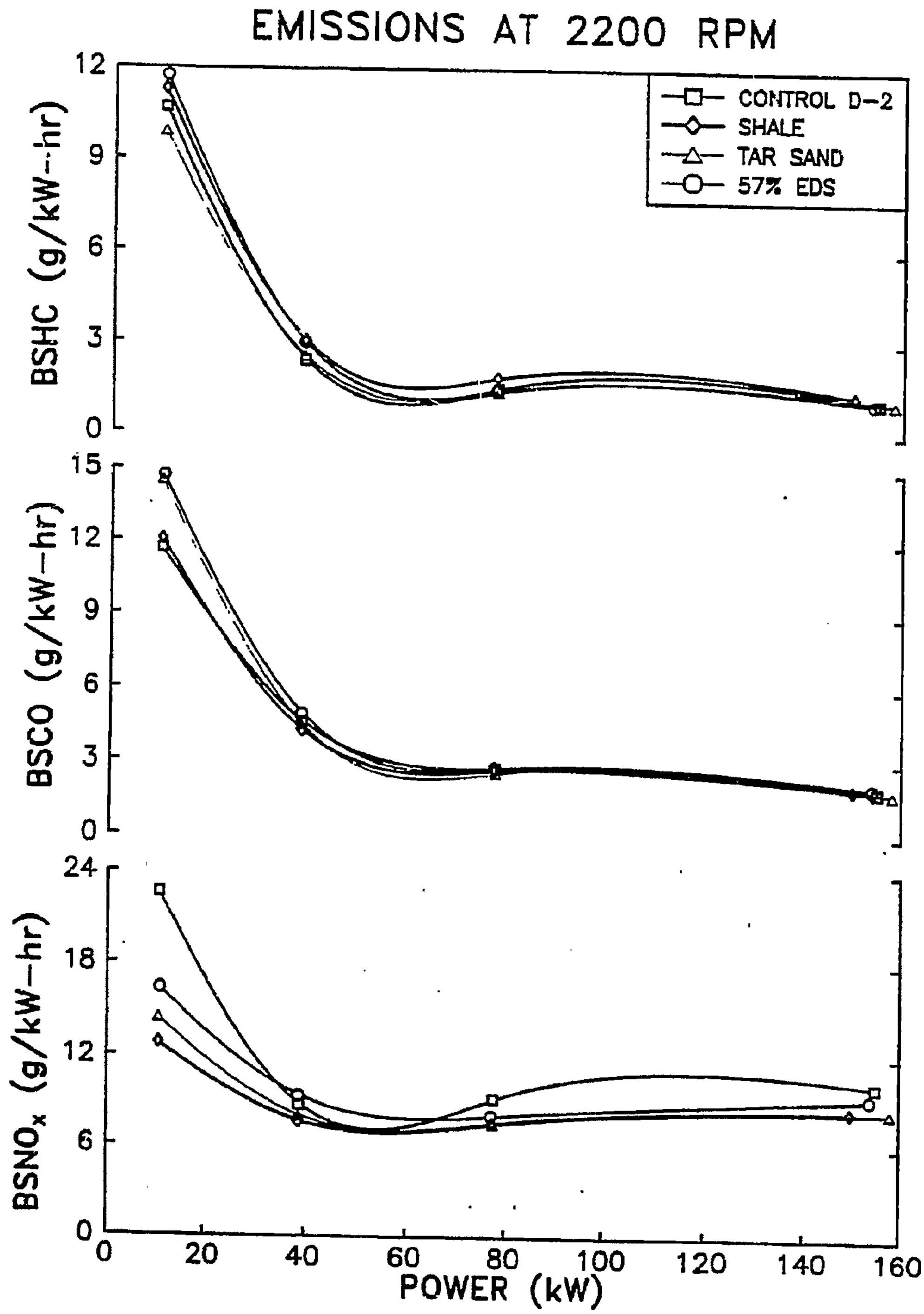


FIGURE 6.2. BRAKE SPECIFIC EMISSIONS AT 2200 RPM

Performance at 1400 rpm, Figure 6.3, closely resembled the 2200 rpm results. Thermal efficiency for all of the synfuels was slightly higher, particularly at the light loads. Smoke opacity increased significantly, as might be expected with this turbocharged engine. Particulate concentrations generally followed smoke opacity, and were high for the tar sands and coal liquid blend fuels. The 57 percent EDS blend particulate data point at 138 kW is in question. Due to laboratory error, only one sample filter was available for weighing at this power level.

In Figure 6.4, BSCO increases for all fuels at the full power point. BSHC and $BSNO_x$ levels are similar to the 2200 rpm results.

Idle tests were conducted at a constant 27 N-M load for consistency in results. Figures 6.5 and 6.6 show performance and emissions, respectively, at the idle condition. The tar sands fuel appeared to be the poorest performer, with low brake thermal efficiency, high smoke and particulates, and high gaseous emissions levels.

6.1.2 Combustion Analysis Results

Combustion in a diesel engine is a complex process involving injection and atomization of the fuel, fuel evaporation, fuel-air mixing, autoignition of premixed fuel, and diffusion burning of the droplet cloud. Changes in fuel properties would be expected to affect all of these processes. Changes in viscosity and specific gravity can lead to changes in the injection and atomization of the fuel. The distillation range would affect fuel evaporation. Differences in atomization and evaporation characteristics can in turn lead to differences in the fuel-air mixing. Changes in the chemical composition of the fuel as well as changes in the fuel-air mixing can affect the ignition and combustion processes. Fuel property changes are, therefore, likely to affect the heat release rate, the thermal efficiency, and the exhaust emission levels.

As previously discussed, the 57 percent EDS fuel, with a relatively low cetane number of 32.9, actually had a higher thermal efficiency than the control D-2 fuel, with a relatively high cetane number of 46.5. This was attributed to a longer ignition delay time resulting in a larger portion of the energy being released during the premixed burning period of combustion. The low cetane number fuel, performed as a closer approximation to constant-volume combustion and, therefore, had a higher thermal efficiency.

Fuel property effects were also observed in the emissions data as presented in the preceding section. In particular the smoke opacity data at high loads correlated well with the aromatic content of the fuel. This correlation has been reported by other researchers.(1) The fuel with the highest aromatic content, the tar sand with 67.3 percent aromatics, had the highest smoke opacity at the high load conditions. The 57 percent EDS fuel had the second highest aromatic content of 59.0 percent and also had the second highest smoke opacity. This trend was similar for the remaining two fuels.

As mentioned the thermal efficiency data and exhaust emissions have been presented in the previous section. In this section the effects of the fuel

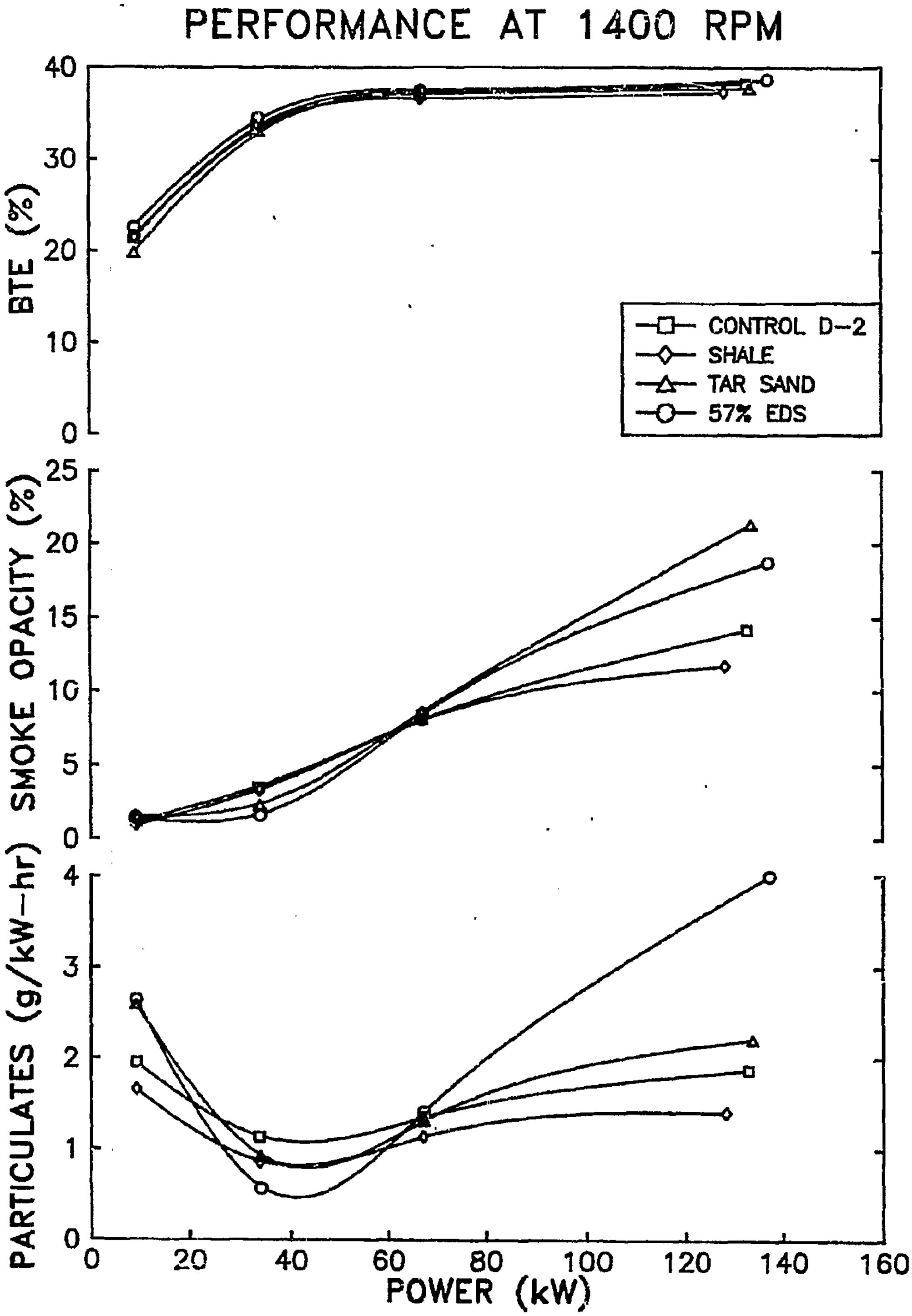


FIGURE 6.3. PERFORMANCE RESULTS AT 1400 RPM

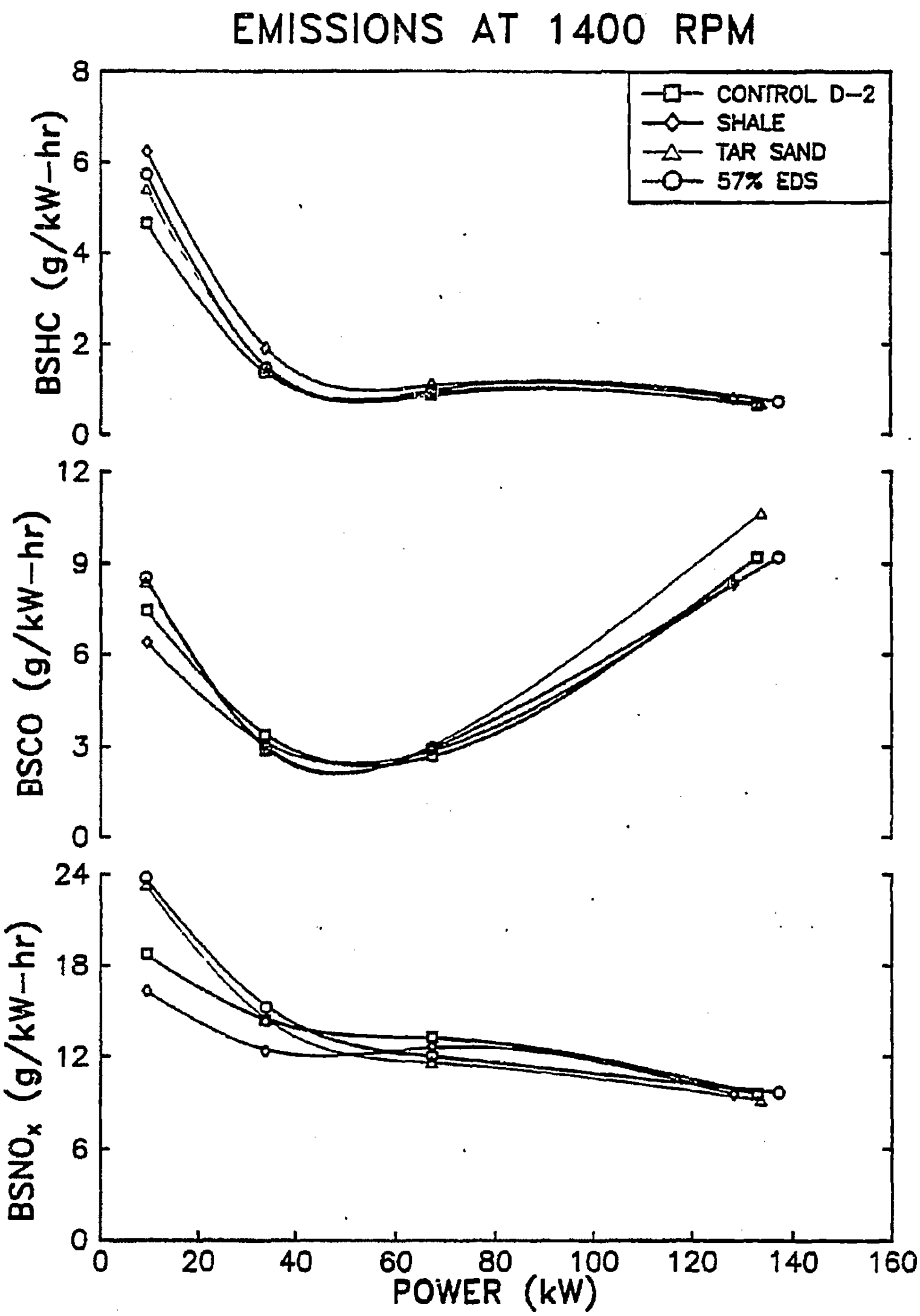


FIGURE 6.4. BRAKE SPECIFIC EMISSIONS AT 1400 RPM

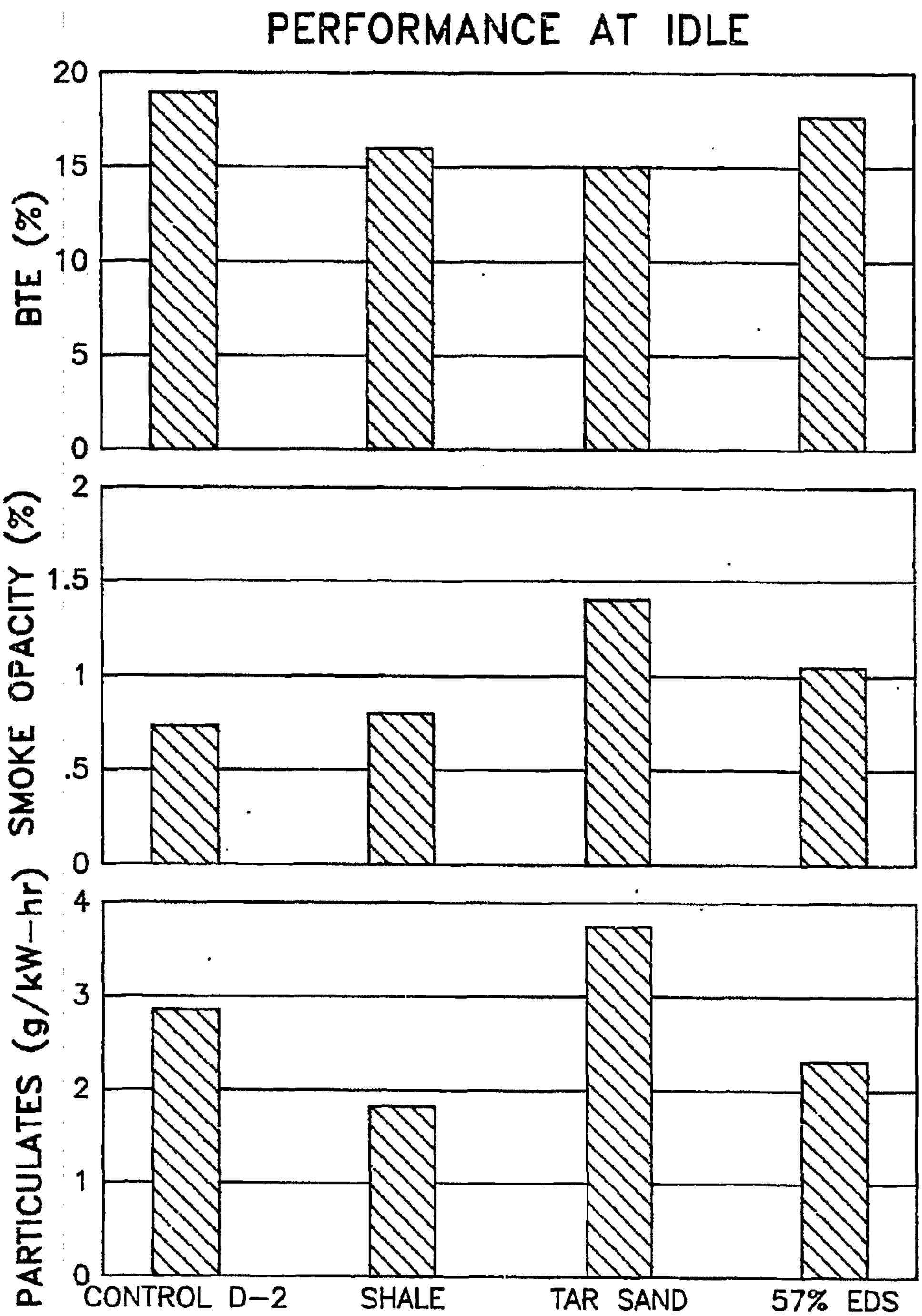


FIGURE 6.5. PERFORMANCE RESULTS AT IDLE

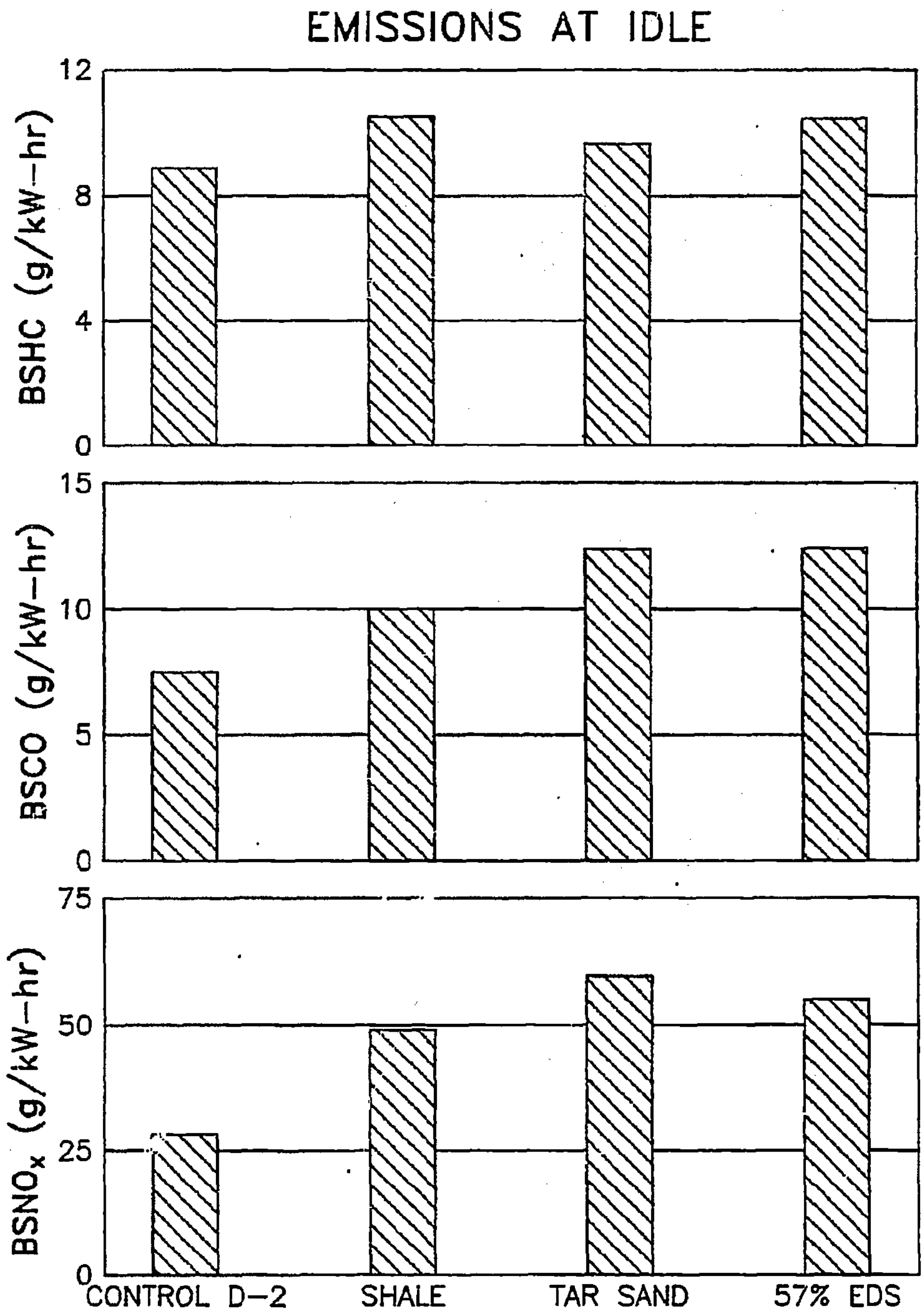


FIGURE 6.6. BRAKE SPECIFIC EMISSIONS AT IDLE

properties on several combustion parameters are examined. These parameters include the heat release rate, ignition delay, peak cylinder pressures, maximum rates of pressure rise and average rates of pressure rise.

Combustion analysis for this program was based upon the acquisition of cylinder pressure data at one-half crank angle degree increments for one hundred engine cycles. These cycles were then averaged to obtain a representative engine cycle for analysis. An average engine cycle was obtained for each test fuel at each of nine different speed-load conditions. The pressure data for the average engine cycle was used as input to a computer program which was used to calculate the apparent rate of heat release, the centroid of the heat release rate diagram, the cumulative heat release, the ignition delay, the maximum cylinder pressure, the maximum rate of pressure rise, and the average rate of pressure rise. The heat release rate diagrams and the cumulative heat release curves are presented in Appendix H for the shale, tar sand, 57 percent EDS fuels, and the baseline control D-2 fuel at each speed-load condition. A summary of these data is provided in Table 6.1 for each fuel at each speed-load condition. A complete set of cylinder pressure and fuel injection pressure diagrams corresponding to the engine test conditions (listed in Table 6.1) are given in Appendix N.

The heat release rate diagrams for the 1400 rpm - 50 percent load test condition are presented in Figures 6.7 through 6.9 for each test fuel as compared to the corresponding baseline fuel result. Figure 6.7 is a plot of heat release rate versus crank angle for the shale and control D-2 fuels. As shown in the figure, the heat release rates were essentially identical for both fuels. Also illustrated in Figure 6.7 are the centroids of the areas under the heat release rate diagrams. The location of the centroid for the control D-2 and shale fuels are indicated by a plus sign and an asterisk, respectively. The centroid of the heat release rate diagram, in particular the crank angle at which the centroid occurs, has been shown to be correlated with indicated power.[2] Trendwise, as the location of the centroid moves toward TDC for a given amount of total heat released, a higher indicated power is produced. This indicates that the most efficient manner of releasing heat and thus producing the most power would be the release of all the energy instantaneously at TDC .

As depicted in Figure 6.7 there is a significant difference in the crank angle at which the centroids are located for the shale and control D-2 fuels. Examination of the heat release rate diagrams indicates that this difference does not appear to be caused by differences in the combustion characteristics but by what appears to be noise or oscillations in the heat release rate curves well before ignition occurs and also after combustion ends.

It is anticipated that the noise problem would affect the validity of the centroid calculation as well as calculation of the cumulative heat release. Therefore, these parameters are presented but are not discussed. It is felt that comparison of the heat release rate diagrams on a relative basis is still valid as well as comparison of ignition delay times, peak cylinder pressures, and rates of pressure rise.

As indicated in Figure 6.7, the rate of heat release for the shale fuel

Table 6.1. Summary of Combustion and Heat Release Data

Test Code No.	Engine Speed (RPM)	Ind. Power (kW)	Max. Press. (MPa)	Max. Press. Rise (kPa/deg)	Avg. Press. Rise (kPa/deg)	Total Heat Release (Joules)	Ig. Delay (deg)	Centroid Xbar (deg ATDC)	Centroid Ybar (J/deg)
111	838.	6.34	5.15	348.85	141.20	462.92	5.80	4.95	10.02
121	825.	5.68	5.23	373.60	144.75	455.24	5.40	6.10	10.45
131	835.	5.92	5.38	488.60	169.15	482.09	7.35	6.40	19.34
161	846.	6.46	5.20	428.00	157.70	499.10	7.50	6.50	15.19
112	1403.	143.46	14.61	555.15	391.90	3774.21	4.90	10.45	40.59
122	1400.	140.91	14.28	528.75	373.05	3671.02	4.75	11.50	40.51
132	1402.	146.52	15.00	660.90	407.00	3800.20	5.50	11.90	43.12
162	1401.	150.21	15.07	635.75	424.55	3902.29	6.00	12.50	45.10
113	1402.	71.04	9.16	613.75	270.75	2043.05	5.45	7.40	25.80
123	1400.	71.76	9.27	589.90	273.15	1930.71	5.30	10.30	27.29
133	1400.	67.44	8.88	826.50	278.15	1870.16	7.20	9.85	31.43
163	1401.	63.88	8.44	893.25	306.00	1920.21	7.40	7.65	33.49
114	1398.	36.13	6.96	688.95	255.20	1080.05	5.60	7.95	26.03
124	1402.	36.99	7.02	676.45	252.95	1068.17	5.70	6.40	25.87
134	1402.	37.46	7.15	890.10	325.90	1129.21	7.70	7.55	39.01
164	1403.	35.45	7.17	1060.00	380.20	1196.38	7.40	10.30	46.89
115	1398.	17.16	5.50	397.55	158.05	619.07	6.80	8.45	15.12
125	1397.	17.94	5.57	386.80	157.40	635.74	6.45	8.75	14.83
135	1404.	12.71	5.40	365.35	165.60	547.04	8.85	9.70	18.70
165	1400.	12.25	5.28	376.70	155.75	550.76	7.75	10.65	16.47
116	2201.	177.84	12.22	331.80	152.75	3393.62	4.50	11.90	31.94
126	2201.	170.88	11.79	326.20	139.15	3203.31	4.80	15.35	30.95
136	2201.	167.79	11.95	349.65	130.45	3191.12	5.95	15.65	31.10
166	2200.	182.43	12.56	326.30	167.45	3259.70	5.40	14.95	38.69
117	2200.	83.37	8.03	232.70	90.83	1759.36	4.50	15.85	17.50
127	2200.	84.18	7.86	229.70	94.94	1694.80	5.60	15.50	18.26
137	2201.	84.99	8.12	359.90	160.85	1793.58	6.75	16.90	20.10
167	2198.	86.94	8.27	430.20	218.00	1860.60	7.20	17.80	25.63
118	2200.	40.88	6.04	183.70	15.97	928.41	5.55	17.05	10.58
128	2202.	41.92	5.99	185.65	20.66	944.90	5.70	16.85	10.31
138	2202.	43.18	6.02	235.00	67.07	1029.03	8.70	15.90	19.32
168	2200.	44.01	5.80	228.45	48.10	1115.22	9.60	21.80	22.35
119	2200.	22.51	5.30	161.95	-16.90	613.11	7.50	14.90	8.86
129	2200.	21.79	5.30	163.75	-22.40	608.35	7.65	16.10	8.73
139	2200.	22.32	5.27	162.65	-32.10	714.93	9.85	16.40	13.18
169	2198.	14.20	5.11	155.20	-62.15	494.48	12.05	16.00	10.80

Second digit of Test Code indicates fuel type:
1 - Diesel fuel
2 - Shale
3 - Tar sands
4 - 57% EDS

was essentially identical to the rate of heat release for the control D-2 fuel. This indicates that the combustion characteristics of these two fuels were similar, as would be expected by examining their cetane numbers. The shale and control D-2 fuels had cetane numbers of 51.1 and 46.5, respectively.

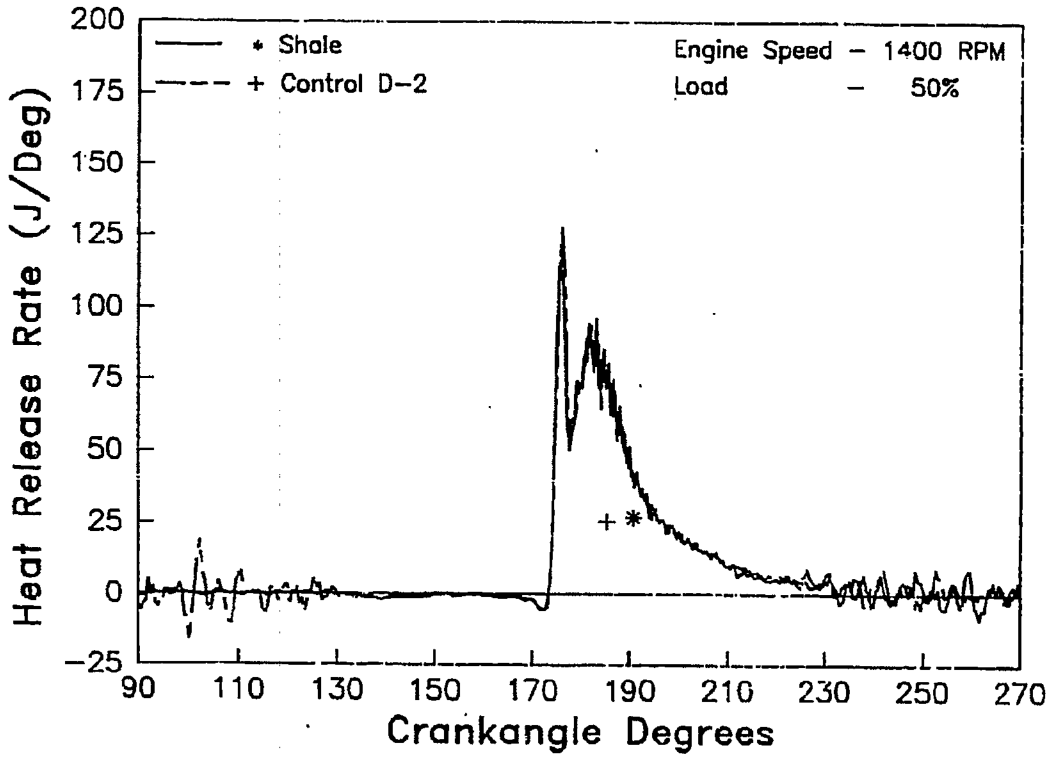


FIGURE 6.7. HEAT RELEASE RATE FOR SHALE AND CONTROL D-2 FUELS AT 1400 RPM, 50 PERCENT LOAD

The heat release rate diagram of the tar sand fuel is compared to the control D-2 fuel in Figure 6.8. As demonstrated in the figure, the ignition delay of the tar sand fuel was 1.7 crank angle degrees longer than the ignition delay of the control D-2 fuel. The longer ignition delay allowed more fuel to evapoarte prior to ignition and resulted in an increased initial rate of heat release for the tar sand fuel. The longer ignition delay of the tar sand fuel would be expected due to its relatively low cetane number of 34.9.

The 57 percent EDS fuel blend also had a relatively low cetane number of 32.9. Thus, when compared with the control D-2 fuel, the 57 percent EDS fuel blend would also be expected to have a longer ignition delay period. This effect is illustrated in Figure 6.9 for the 57 percent EDS and control D-2 fuels. The ignition delay of the 57 percent EDS fuel was 1.9 crank angle degrees longer than the ignition delay of the control D-2 fuel. The longer ignition delay time resulted in more evaporation of the fuel prior to ignition and a correspondingly larger portion of the heat being released during the initial premixed burning phase of combustion.

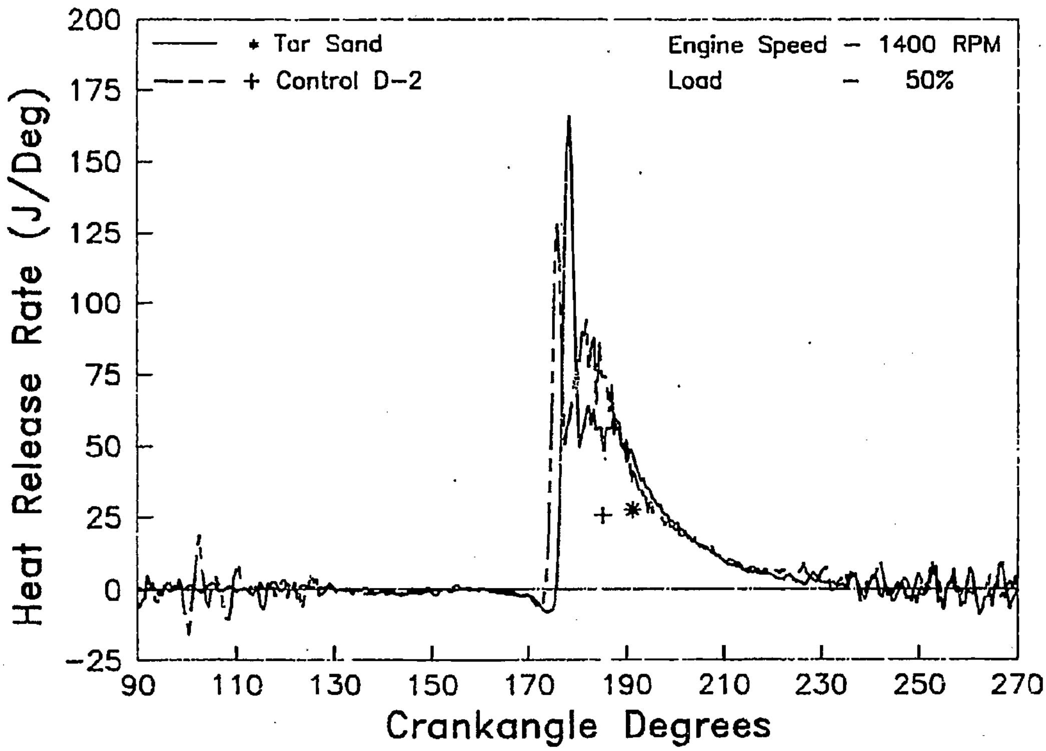


FIGURE 6.8. HEAT RELEASE RATE FOR SHALE AND CONTROL D-2 FUELS AT 1400 RPM, 50 PERCENT LOAD

It would appear that the major difference in the combustion characteristics of these fuels is in the ignition delay period. For these particular fuels the ignition delay trend seems to correlate well with the trend in cetane number. Figure 6.10 is a bar chart showing the ignition delay and total apparent heat release for the four test fuels at the idle condition. The tar sand and 57 percent EDS fuels had longer ignition delay periods than the control D-2 and shale fuels. This trend can be attributed to changes in the cetane number from fuel to fuel. Identical trends can be observed for the ignition delay values at 1400 and 2200 rpm. These data are illustrated in Figures 6.11 and 6.12, respectively. As shown in the figures, the tar sand and 57 percent EDS fuels had longer ignition delay times at all load conditions. The longest delay times for each fuel were observed at the light load condition where boost pressure and cylinder temperature were lowest. At the high load condition, the increased boost pressure and higher cylinder temperatures resulted in shorter delay times for each fuel.

In terms of engine durability, change in peak cylinder pressures and rates of pressure rise due to changes in fuel properties could lead to decreased engine life. Figures 6.13 through 6.15 illustrate the peak cylinder pressure, maximum rate of pressure rise, and average rate of pressure rise for the idle,

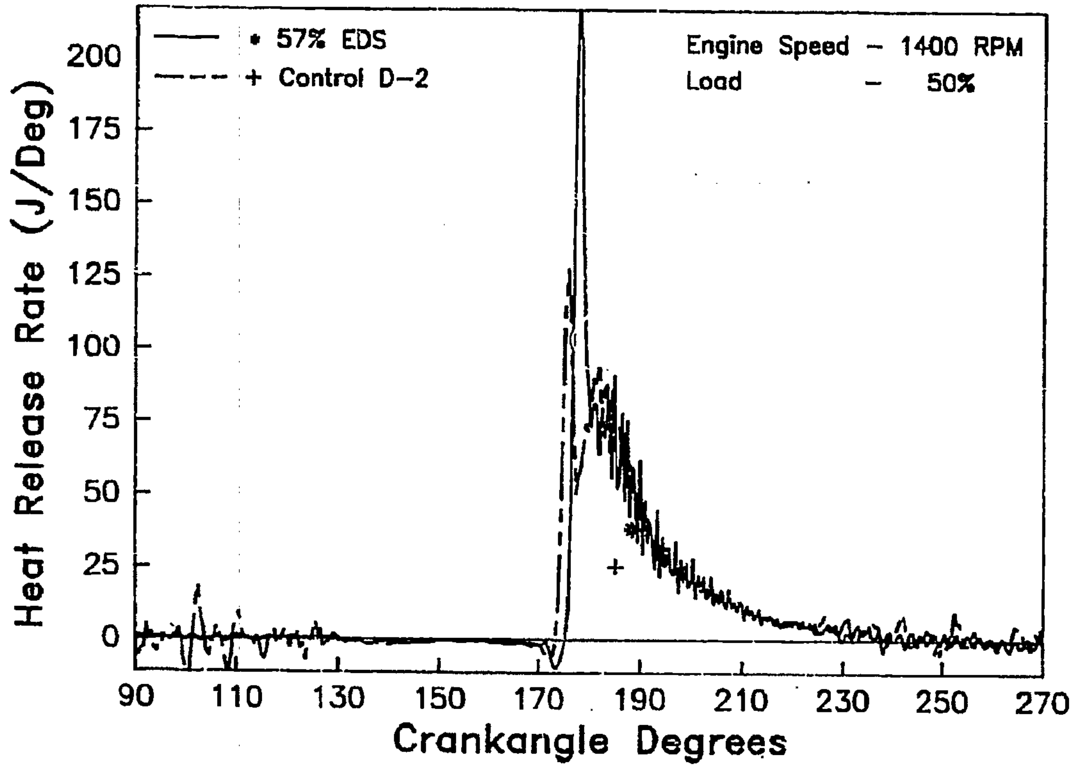


FIGURE 6.9. HEAT RELEASE RATE FOR 57 PERCENT EDS AND CONTROL D-2 FUELS AT 1400 RPM, 50 PERCENT LOAD

1400 rpm, and 2200 rpm conditions, respectively. Figure 6.13 illustrates that the tar sand and 57 percent EDS fuels had higher rates of pressure rise even though peak cylinder pressures were similar. The rates of pressure rise correlated well with the peak heat release rates observed for these fuels and can be attributed to differences in ignition delay.

The peak cylinder pressures and the rates of pressure rise for each fuel are presented in Figure 6.14 for the various load conditions at 1400 rpm. Based on visual observation, the peak cylinder pressures were similar at all loads except the 50 percent power condition. At 50 percent power, the 57 percent EDS and tar sand fuels appeared to have lower peak pressures than the control D-2 fuel. However, these two fuels also had the most variation in the peak pressure measurement at this particular condition. The standard deviation for the peak pressures of the control D-2, shale, tar sand, and 57 percent EDS fuels were 0.01, 0.06, 0.67, and 1.02 MPa, respectively. It was not possible to conclude whether this variation was actual cylinder pressure variation due to heavy knock or variation induced by transducer performance under severe combustion conditions. Within the amount of variation observed there was no significant difference in peak pressures at this condition.

The rate of pressure rise data do indicate differences between the test fuels. The rates of pressure rise are defined in the following manner. The

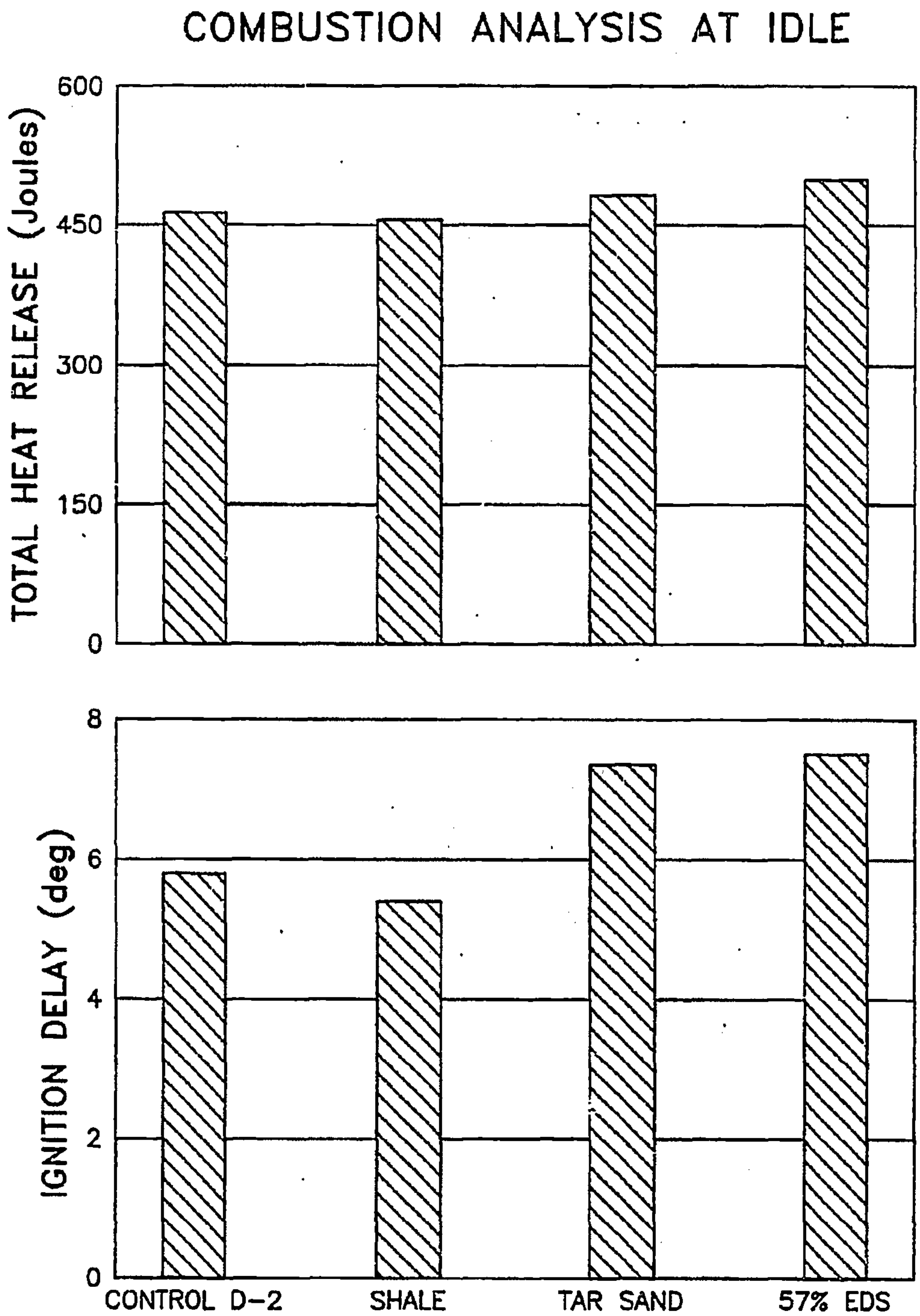


FIGURE 6.10. HEAT RELEASE RATE AND IGNITION DELAY FOR ALL FUELS AT IDLE CONDITION

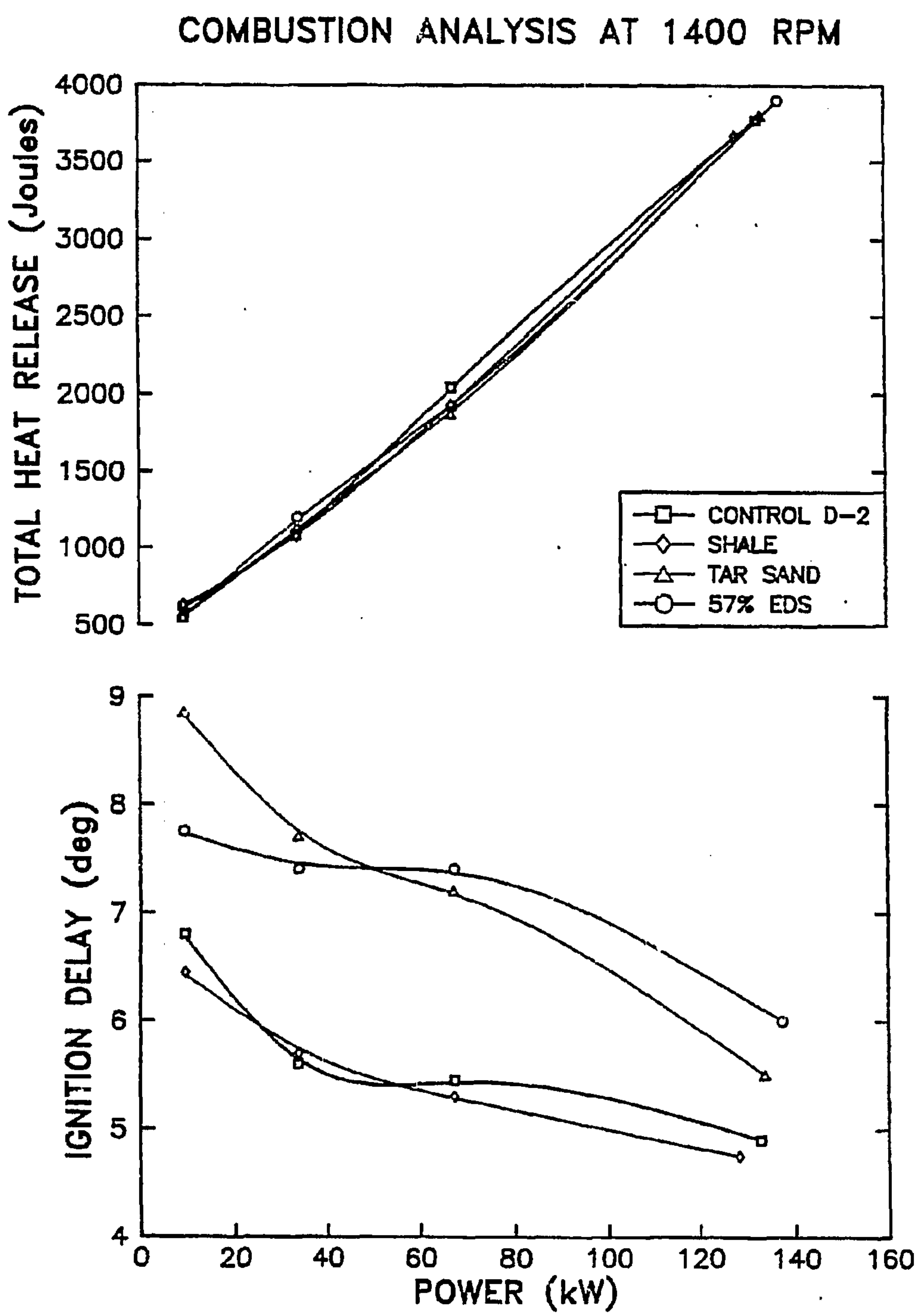


FIGURE 6.11. HEAT RELEASE RATE AND IGNITION DELAY FOR ALL FUELS AT 1400 RPM

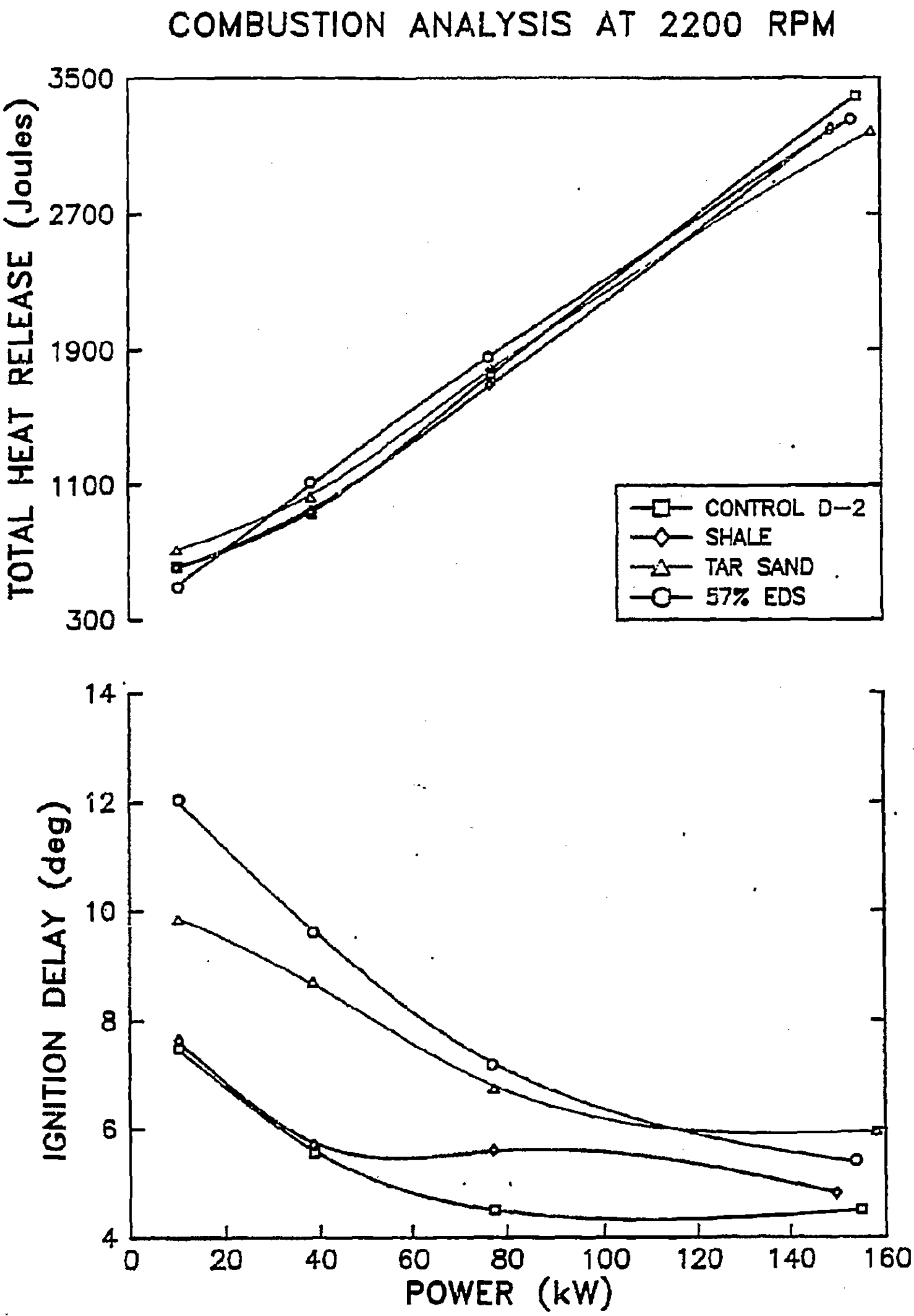


FIGURE 6.12. HEAT RELEASE RATE AND IGNITION DELAY FOR ALL FUELS AT 2200 RPM

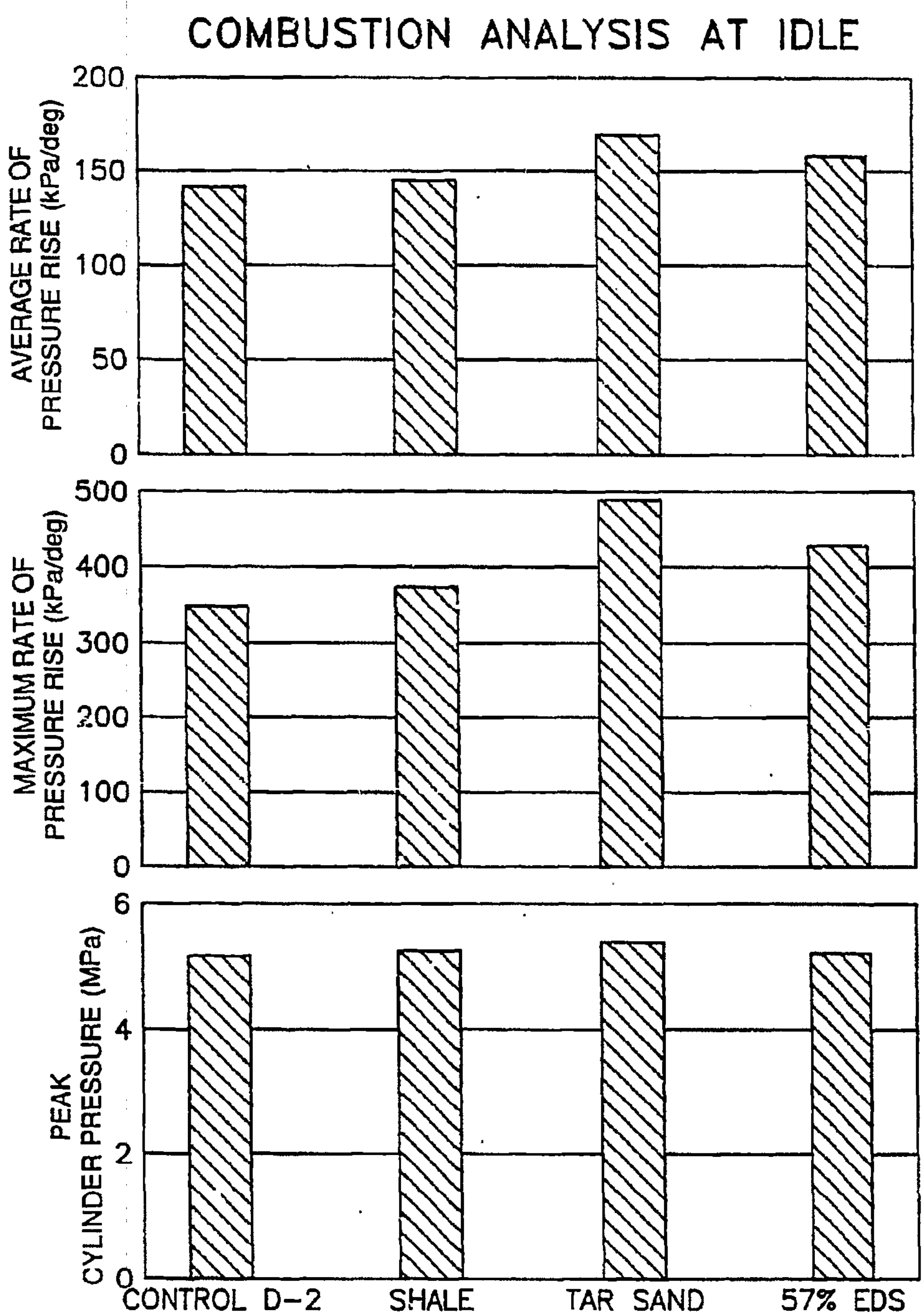


FIGURE 6.13. PEAK CYLINDER PRESSURES AND AND RATES OF PRESSURE RISE FOR EACH FUEL AT IDLE

maximum rate of pressure rise is numerically the largest rate of pressure change during the entire cycle. The average rate of pressure rise is calculated by taking the difference in the pressure at ignition and the peak pressure, divided by the corresponding difference in crank angle.

As indicated in Figure 6.14 the average and maximum rate of pressure rise data follow similar trends. At the light load condition the rates of pressure rise were similar for all fuels. The largest difference between fuels occurred at the 25 percent load condition. At this point the 57 percent EDS fuel had the highest rate of pressure rise, followed by the tar sand fuel. The rates of pressure rise were similar for the shale and control D-2 fuel. This would appear to be in a agreement with the heat release and ignition delay data. The 57 percent EDS and tar sand fuel had longer ignition delays and higher rates of heat release indicating more severe combustion, hence, higher rates of pressure rise. The differences in the maximum rates of pressure rise decreased from fuel to fuel as load was increased to 50 and 100 percent. The average rates of pressure rise appeared to be similar at the 50 and 100 percent load conditions.

The peak cylinder pressures and the rates of pressure rise for each fuel are presented in Figure 6.15 for the 2200 rpm conditions. As shown in the figure there appeared to be little difference in peak pressures between fuels at the part load conditions. The major difference in peak pressures occurred at the full power condition where the 57 percent EDS fuel had higher peak pressures than the base fuel. At this particular load the standard deviations of the peak pressures for the 57 percent EDS and tar sand fuels were again higher than those of the control D-2 fuel. The standard deviations were 0.13, 0.04, 0.45, and 0.40 MPa for the control D-2, shale, tar sand, and 57 percent EDS fuels, respectively. Despite the larger variation in peak pressures for the 57 percent EDS fuel it still appeared to have a significantly higher peak pressure than the control D-2 fuel.

As with the 1400 rpm data, the average and maximum rate of pressure rise data had similar trends, as indicated in Figure 6.15. At the no-load and full-load conditions all fuels had similar rates of pressure rise. The major differences occurred at the 50 percent load condition where the 57 percent EDS and tar sand fuels had much higher rates of pressure rise than the control D-2 and shale fuels.

Since the differences in peak pressures were small, the wide variation in the maximum rate of pressure rise data raises an obvious question. How can there be differences in the maximum rate of pressure rise but no difference in peak pressures? The answer to this question comes from the realization that the maximum rate of pressure rise occurred at a different crank angle, hence different cylinder volume, for each fuel and load.

Figure 6.16 shows the injection timing for each speed-load condition. At idle, the injection timing was 15 crank angle degrees before TDC. As speed increased the injection timing was retarded toward TDC. For the light load-condition the injection timings were 10.8 and 4.3 degrees BTDC for 1400 and 2200 rpm, respectively. As load was increased, the injection timing was advanced. At the maximum power condition this advance was 3.5 degrees for 1400 rpm and 4.7 degrees for 2200 rpm. Thus each speed-load point had a

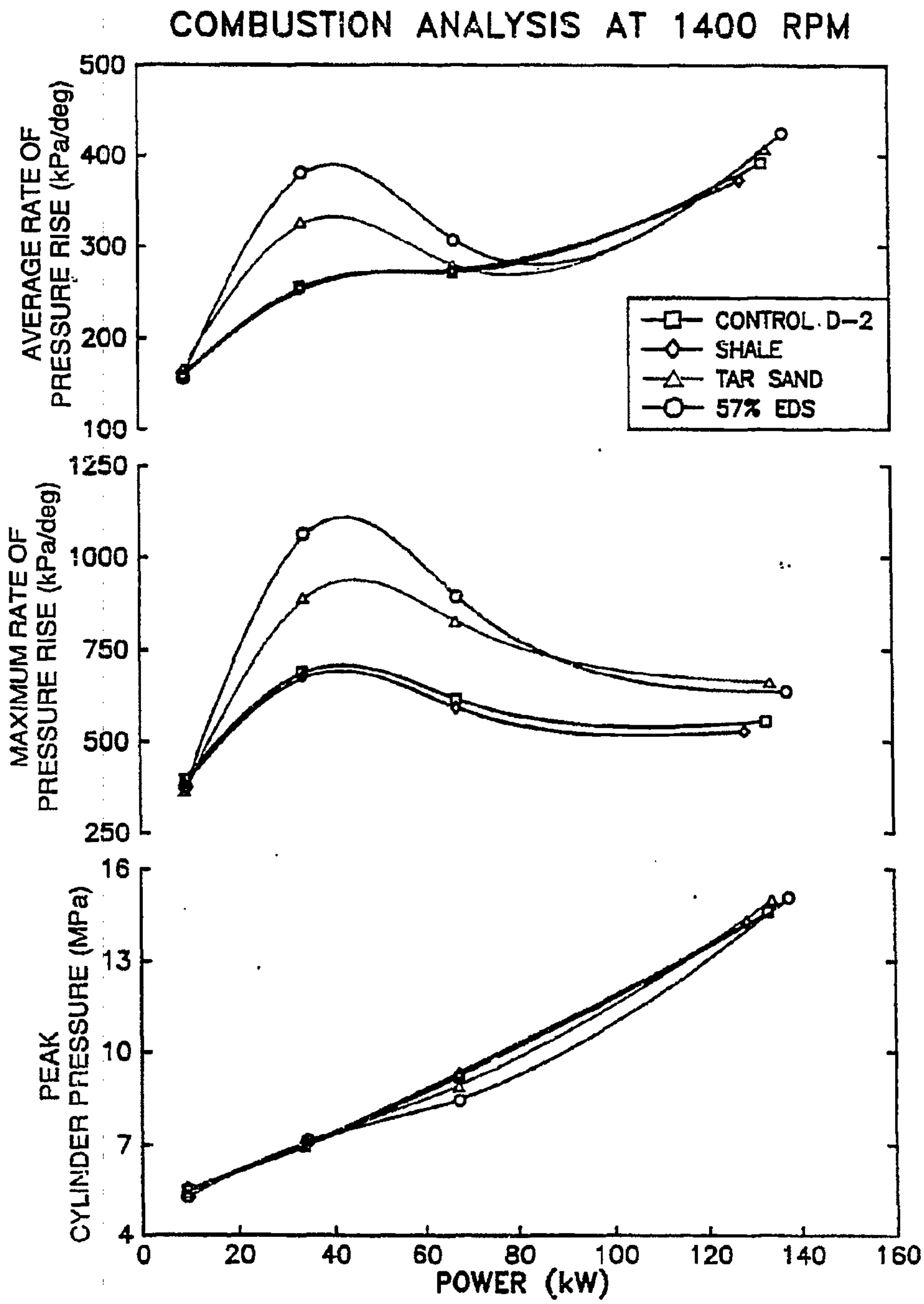


FIGURE 6.14. PEAK CYLINDER PRESSURES AND RATES OF PRESSURE RISE FOR EACH FUEL AT 1400 RPM

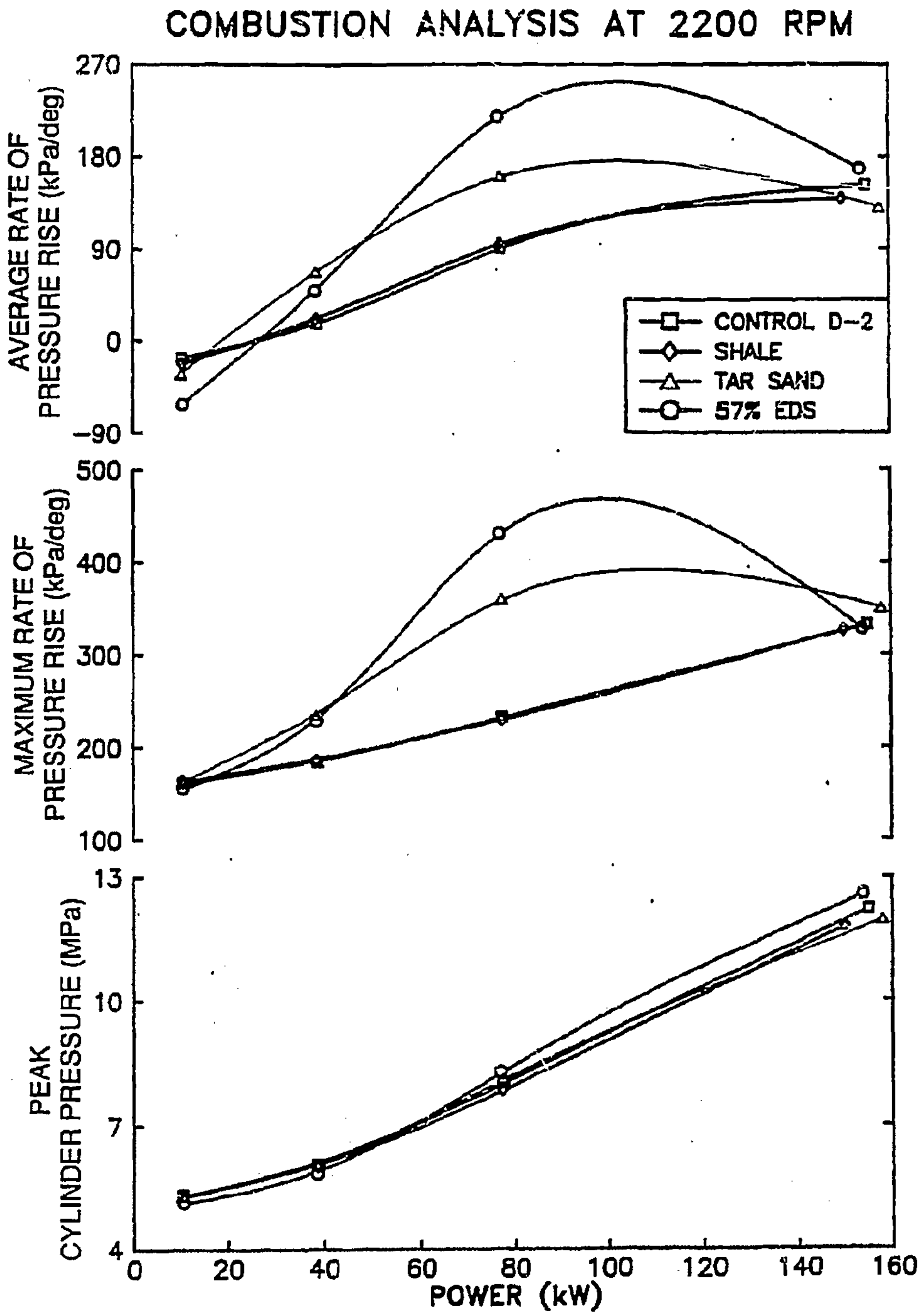


FIGURE 6.15. PEAK CYLINDER PRESSURES AND RATES OF PRESSURE RISE FOR EACH FUEL AT 2200 RPM

different injection timing.

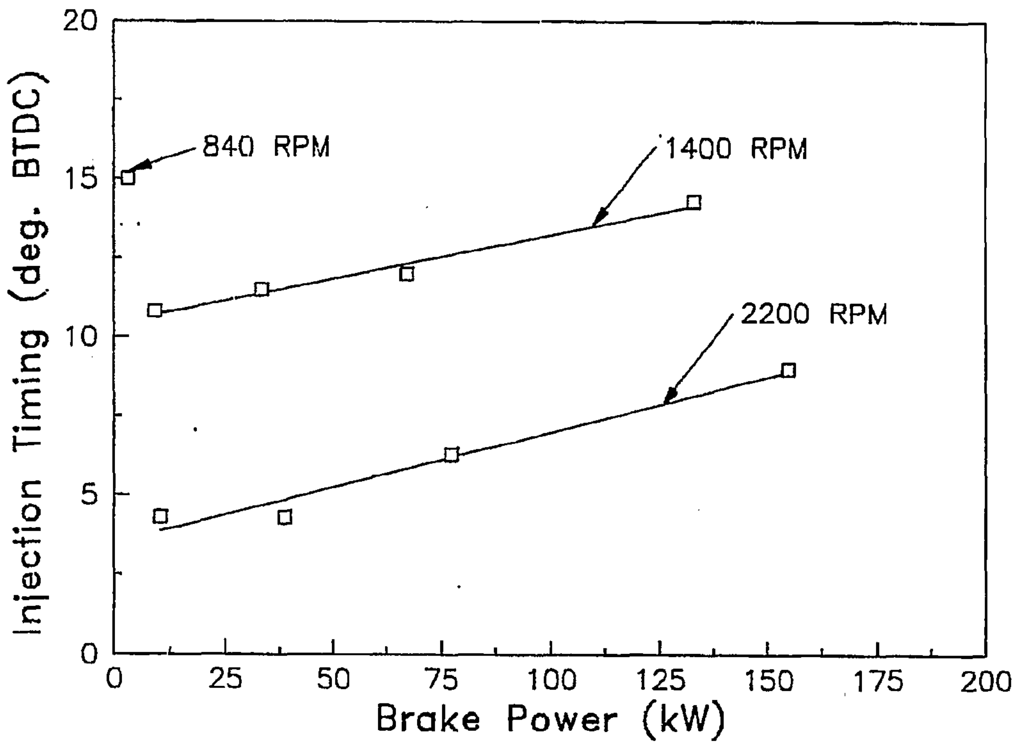


FIGURE 6.16. INJECTION TIMING AND BRAKE POWER AT EACH ENGINE SPEED

Combine this fact with the ignition delay information previously presented and the result is shown in Figure 6.17, which is a plot of the point of ignition versus power for each speed. Examination of Figure 6.17 reveals that the ignition point of all fuels at the part load conditions for the 2200 rpm data occurred after TDC. At this point in the cycle the piston is moving down and cylinder volume is increasing. At the part load conditions the peak heat release rate typically occurred during the premixed combustion phase or within about 10 crank angle degrees following ignition depending on speed and load. It would typically be expected that the maximum rate of pressure rise would occur at the same crank angle as the maximum heat release rate. At the 2200 rpm conditions, ignition and hence the maximum heat release rate occurred well after TDC for the part load conditions. Therefore, any heat released would result in a lower pressure rise as a result of the increasing combustion chamber volume.

Given this situation, it is possible that the maximum pressure due to combustion can be lower than the peak cylinder pressure due to compression. Also, dependent upon the rate of pressure drop due to the increasing volume and upon the energy input, it is also possible that the maximum pressure during combustion can be lower than the cylinder pressure at ignition. This later case would lead to a negative average rate of pressure rise due to combustion, at least based upon the current definition.

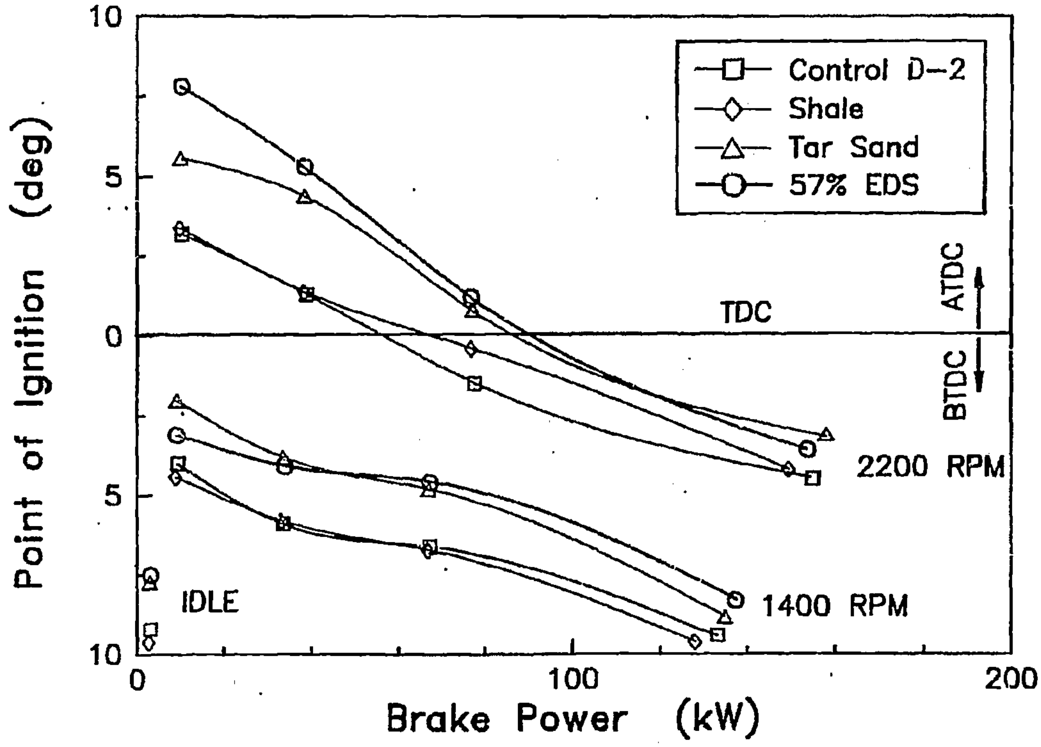


FIGURE 6.17. POINT OF IGNITION AND BRAKE POWER AT EACH ENGINE SPEED

With the previous discussion in mind the following points can be made concerning Figures 6.14 and 6.15. With regard to the 2200 rpm data in Figure 6.15, the late ignition and low energy input at the no-load condition did lead to a negative average rates of pressure rise for all fuels. This means that the maximum pressure during combustion was lower than the pressure at ignition. At the other load conditions the energy input and ignition timing was such that a positive average rate at pressure rise was obtained.

The ignition timing and peak heat release rate would also be expected to affect the maximum rate of pressure rise. At the no-load condition, the ignition occurred so late in the cycle, and the heat release rate was so low, that the maximum rate of pressure rise was due solely to compression. The maximum pressure rise data for the control D-2 and shale fuels increased nearly linearly with power. It might be expected that this increase was due to higher energy input as load increases. This, however, was not the case. The maximum rates of pressure rise for the control D-2 and shale fuels were actually due only to compression and not combustion. For these two fuels, the maximum rate of pressure rise increased with power because of an increase in turbo boost pressure and hence, an effective increase in compression ratio at the higher loads. The high energy input at the full load condition would be expected to be sufficient to result in a significant amount of pressure rise. However, examination of the heat release rate diagrams (Appendix F) indicate that there were relatively low peak heat release rates during the premixed combustion and that a significant amount of the heat was released during diffusion burning late in the cycle. As a result, the maximum rate of pressure rise at the full power condition occurred during compression for all fuels. At the 25 and 50 percent load conditions the peak heat release rate during the premixed phase of combustion for the tar sand and 57 percent EDS fuels were sufficient to result in a rate of pressure rise which was greater than that occurring during compression.

It should be noted that since the combustion occurred mainly after TDC for the 2200 rpm conditions the rates of pressure rise were significantly lower at 2200 rpm than at 1400 rpm. At 1400 rpm ignition occurred before TDC for all load conditions. The peak heat release rates occurred mainly before TDC while the combustion volume was decreasing, thus resulting in high rates of pressure rise. The maximum pressure rise data would therefore be expected to correlate well with the peak heat release rate. Examination of the heat release diagrams indicates that the 57 percent EDS and tar sand fuels had higher heat release rates during the premixed burning and therefore had higher rates of pressure rise. Typically, a longer ignition delay for the 57 percent EDS and tar sand fuels resulted in the peak heat release rate occurring approximately 2 crank angle degrees closer to TDC than the control D-2 and shale fuels. This would also be expected to result in increased rates of pressure rise. The one exception to this was at the no-load condition where the peak heat release rate and maximum rate of pressure rise for the 57 percent EDS and tar sand fuels occurred 2 degrees after TDC while the peak heat release rate and maximum rate of pressure rise for the control D-2 and shale fuels occurred 2 degrees before TDC. This difference was related to the ignition delay times and resulted in similar rates of pressure rise for all fuels at this condition even though the 57 percent EDS and tar sand fuels had higher peak heat release rates.

6.1.3 Conclusions

The results presented have been somewhat affected by the pressure transducer noise problem which was manifested by oscillation in the heat release rate diagram prior to, and following the combustion period. Even though the heat release rate diagrams were somewhat ragged in appearance due to the noise, the overall shape of the diagrams were not believed to have been affected to a great extent. Relative comparisons of the heat release rate diagrams, therefore, appeared to be appropriate.

The effects of the pressure oscillations were most pronounced on the cumulative heat release calculation and calculations of the centroid of area of the heat release rate diagram. Therefore, comparison of these parameters was not considered valid. Parameters which were not expected to be affected, include: the ignition delay, peak cylinder pressure, and the rates of pressure rise. Fuel-to-fuel comparisons were made based on these parameters. Comparisons of the various parameters resulted in the following conclusions:

1. The performance of the shale fuel was essentially identical to that of the control D-2.

2. The ignition delay was longer for the 57 percent EDS and tar sand fuels than for the control D-2 fuel. The longer delay times were due to the poorer ignition quality of the 57 percent EDS and tar sand fuels.

3. The longer ignition delay times for the 57 percent EDS and tar sand fuels resulted in more fuel evaporation before ignition and hence, higher heat release rates than the control D-2 fuel during the premixed combustion phase.

4. The higher peak heat release rates for the 57 percent EDS and tar sand fuels typically resulted in higher rates of pressure rise. This trend was not observed at some conditions due to ignition and combustion occurring late in the cycle.

5. The major difference in performance of the test fuels can be related to the ignition delay times of the various fuels. Injection timing also tends to be an important parameter in accounting for differences in fuel performance.

6.1.4 Recommendations

Recommendations for engine modifications are based upon the assumption that the engine has been optimized for the control D-2 fuel and that it is desirable to match the performance of the test fuels to that of the control D-2 fuel. The ignition delay period was one of the major differences between fuels. The longer ignition delay for the tar sand and 57 percent EDS fuels resulted in higher rates of pressure rise at the intermediate load conditions. The highest rates of pressure rise occurred at the 1400 rpm, intermediate load condition. At these conditions, the ignition delay time can be minimized for the tar sand and 57 percent EDS fuels by optimizing the injection timing and increasing the compression ratio.[4] This should result in lower rates of pressure rise.

Changes in injection timing and compression ratio would also effect the thermal efficiency and exhaust emissions. An increase in compression ratio would likely result in a slight improvement in thermal efficiency. The effect of any changes on the exhaust emissions would be difficult to estimate. At 2200 rpm, the injection timing was already significantly retarded from the idle timing resulting in ignition and combustion late in the cycle. At the 2200 rpm conditions slightly advancing the timing may improve thermal efficiency. This however may increase the NO_x emissions.

6.2 COLD STARTING TESTS

The cold starting tests were performed at ambient temperatures of 0°C and -20°C. The time required for the engine to register a positive torque and reach maximum rpm was recorded two to three times for each fuel and then averaged numerically. Full rack fuel setting was used during the starting tests.

6.2.1 Cold Start Test at 0°C

The results of the cold start tests at 0°C are shown in Figure 6.18. The bottom bar graph shows that the control diesel and shale fuels started in just under 4 seconds while the tar sands fuel started in just under 5 seconds. The 57 percent EDS fuel required 20 seconds to start. This result was expected since the tar sands and 57 percent EDS fuels have poorer ignition quality and thus longer ignition delays compared to the shale and control diesel fuels. The top bar graph in Figure 6.18 shows that the control diesel fuel and shale fuel reached maximum rpm in about the same amount of time. These two fuels reached maximum rpm shortly after starting (approximately 3 seconds) while the tar sands and 57 percent EDS fuels required much more time (approximately 18 and 100 seconds, respectively) to reach maximum rpm. These poor results for the tar sands and 57 percent EDS fuels were probably due to the large amount of fuel that accumulated in the combustion chamber during the no start condition. Subsequent misfiring for these two fuels also helps to explain why they inhibited the engine from reaching maximum rpm shortly after starting.

6.2.2 Cold Start Test at -20°C

The results of the cold start tests at -20°C are shown in Figure 6.19. In general the engine required much more time to start and reach maximum speed at this lower ambient temperature. The engine would not start at -20°C on the 57 percent EDS fuel.

The results of these two cold start tests show that the starting performance of the shale fuel was as good as the diesel fuel. The starting performance of the tar sands and 57 percent EDS fuels, however, was less than desirable.

6.3 IDLE DEPOSIT TESTS

The results of the idle deposit tests are presented in the form of photographs taken of each cylinder head and piston after the 8-hour idle test and two-hour burnoff period. Figures 6.20 through 6.27 are photographs of the number four cylinder (considered to be representative) after the 8-hour idle test and 2-hour burnoff period for the control diesel, shale, tar sands, and 57 percent EDS fuels, respectively.

Figure 6.20 shows that after running the engine for 8 hours on the control diesel fuel there was a light coat of black soot on the head, valves, and piston. The heaviest coat of carbon occurred where the fuel plume came in contact with the piston. A black tarry substance was also formed on the intake valve and piston outer edge. Figure 6.21 shows the combustion chamber after the 2-hour burnoff period. A light coat of carbon was still present on the head, valves, and pistons. This soot was easily wiped off. The black tarry substance was consumed during the burnoff period.

An inspection of Figures 6.22 and 6.23 show that the shale fuel's idle test results are similar to the control diesel fuel results. The shale fuel left a lighter coat of soot in the combustion chamber with more of the tarry substance

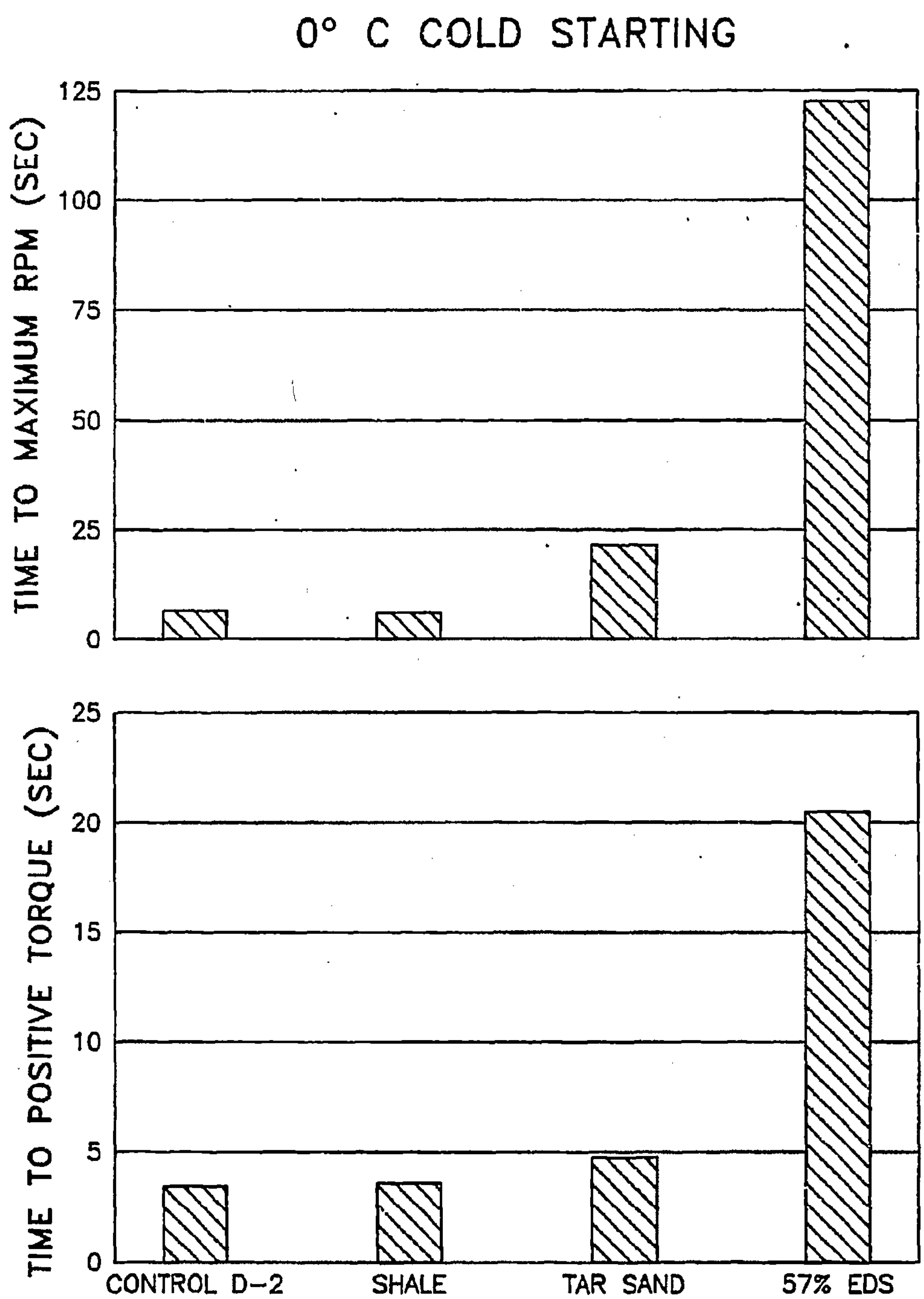


FIGURE 6.18. COLD START DATA AT 0°C

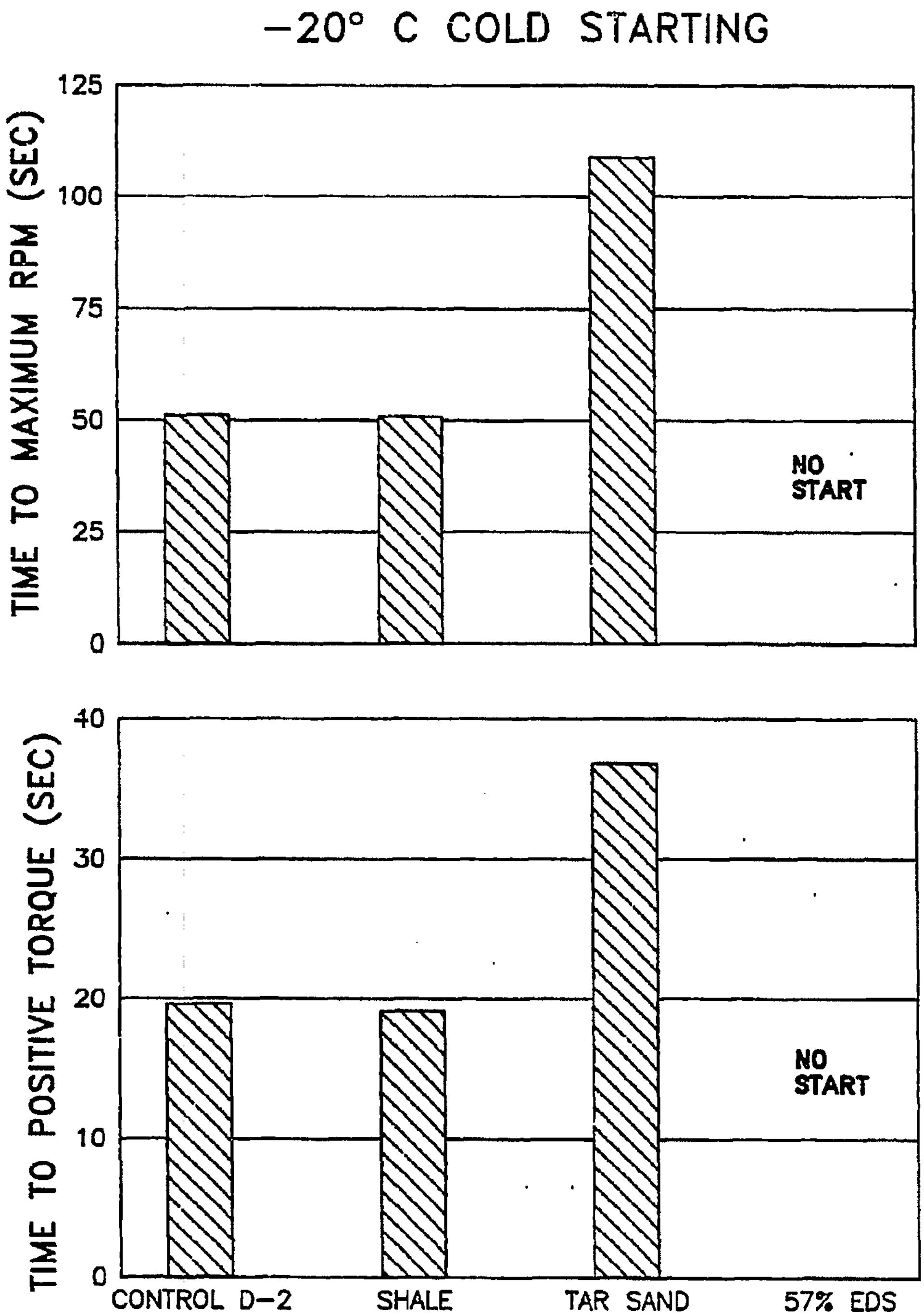


FIGURE 6.19. COLD START DATA AT -20°C

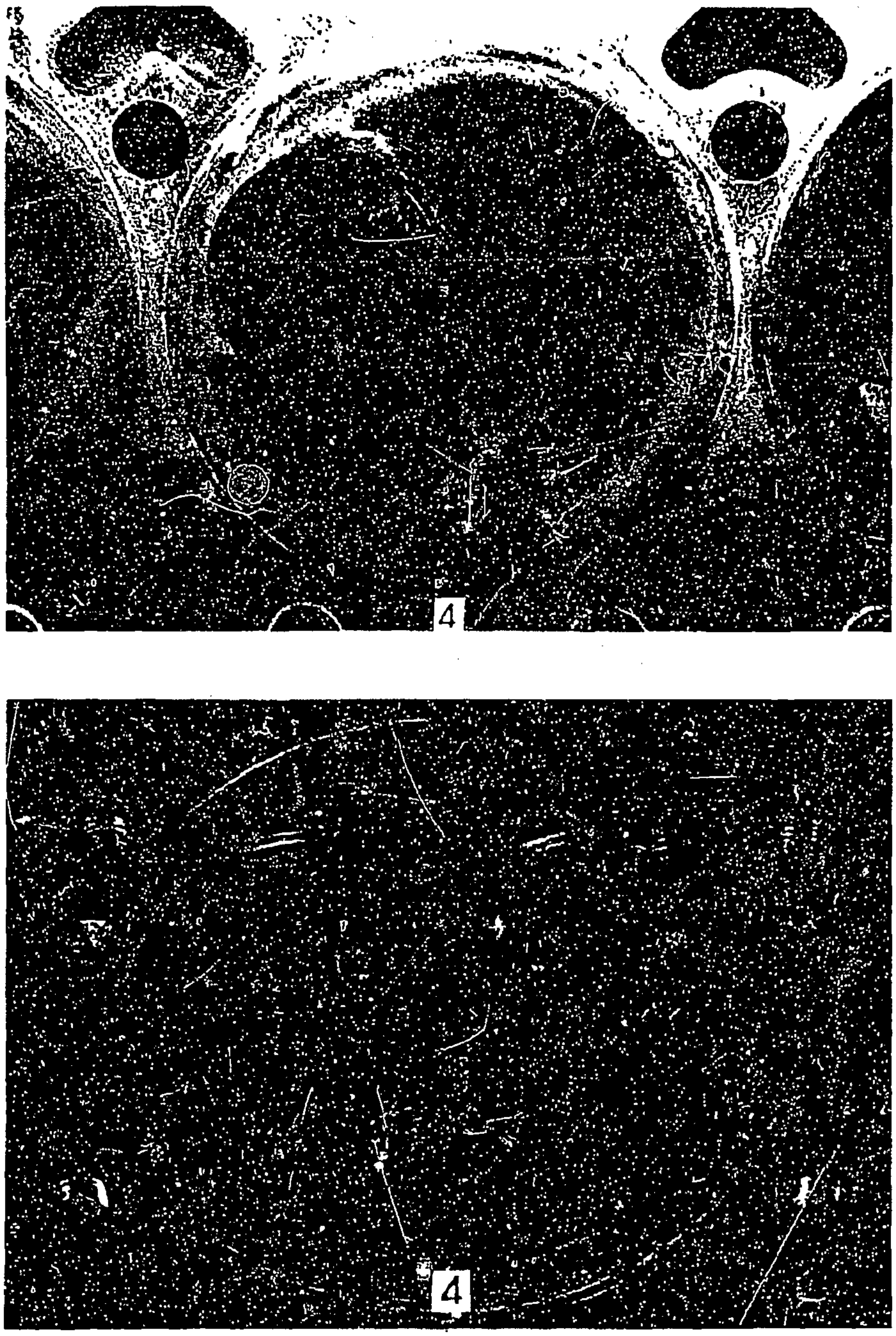


FIGURE 6.20. PISTON AND CYLINDER HEAD DEPOSITS AFTER 8 HOURS CONTINUOUS IDLE, CONTROL D-2 FUEL

FIGURE 6.21. PISTON AND CYLINDER HEAD DEPOSITS AFTER 2 HOURS FULL POWER, CONTROL D-2 FUEL

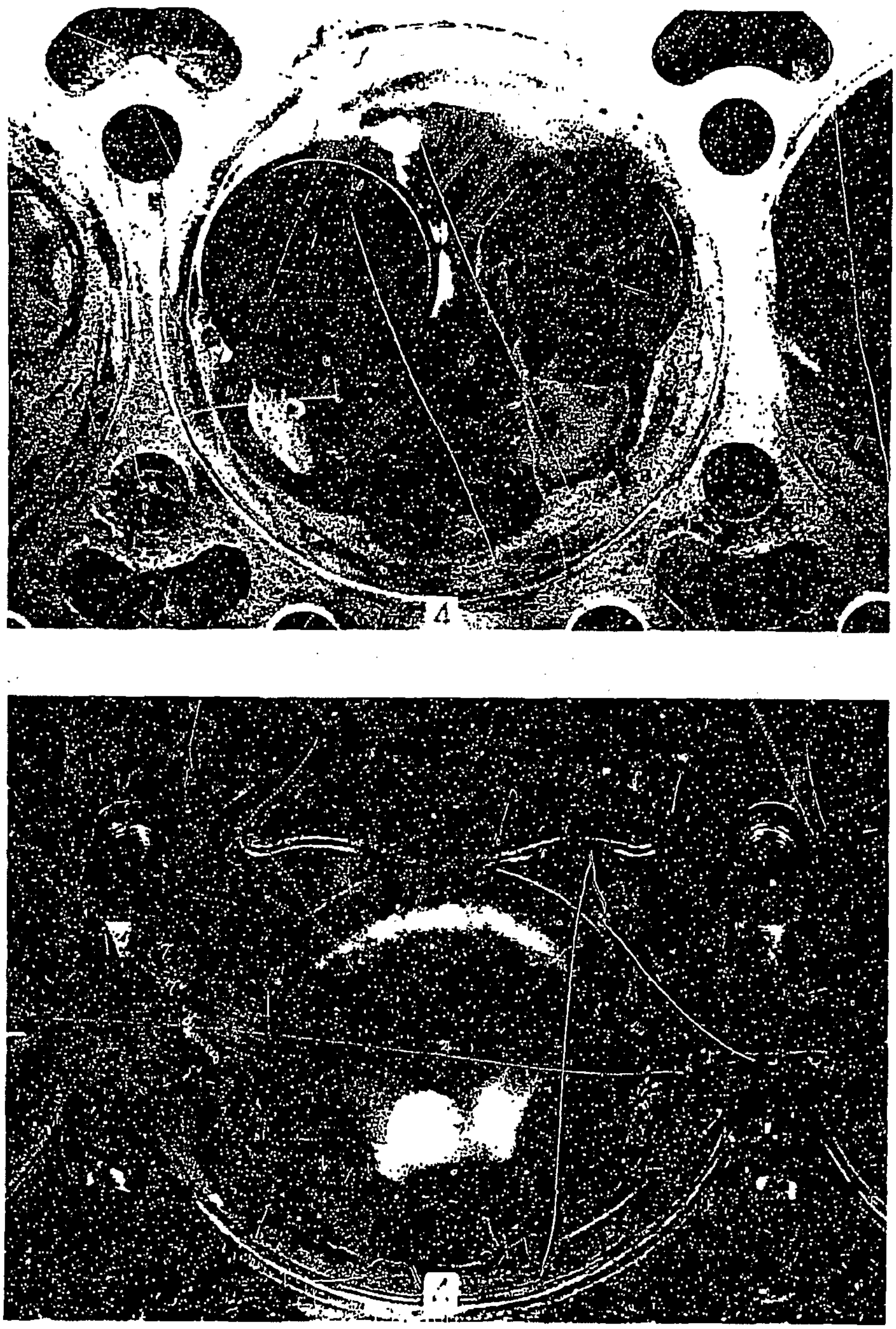


FIGURE 6.22. PISTON AND CYLINDER HEAD DEPOSITS
AFTER 8 HOURS CONTINUOUS IDLE, SHALE FUEL

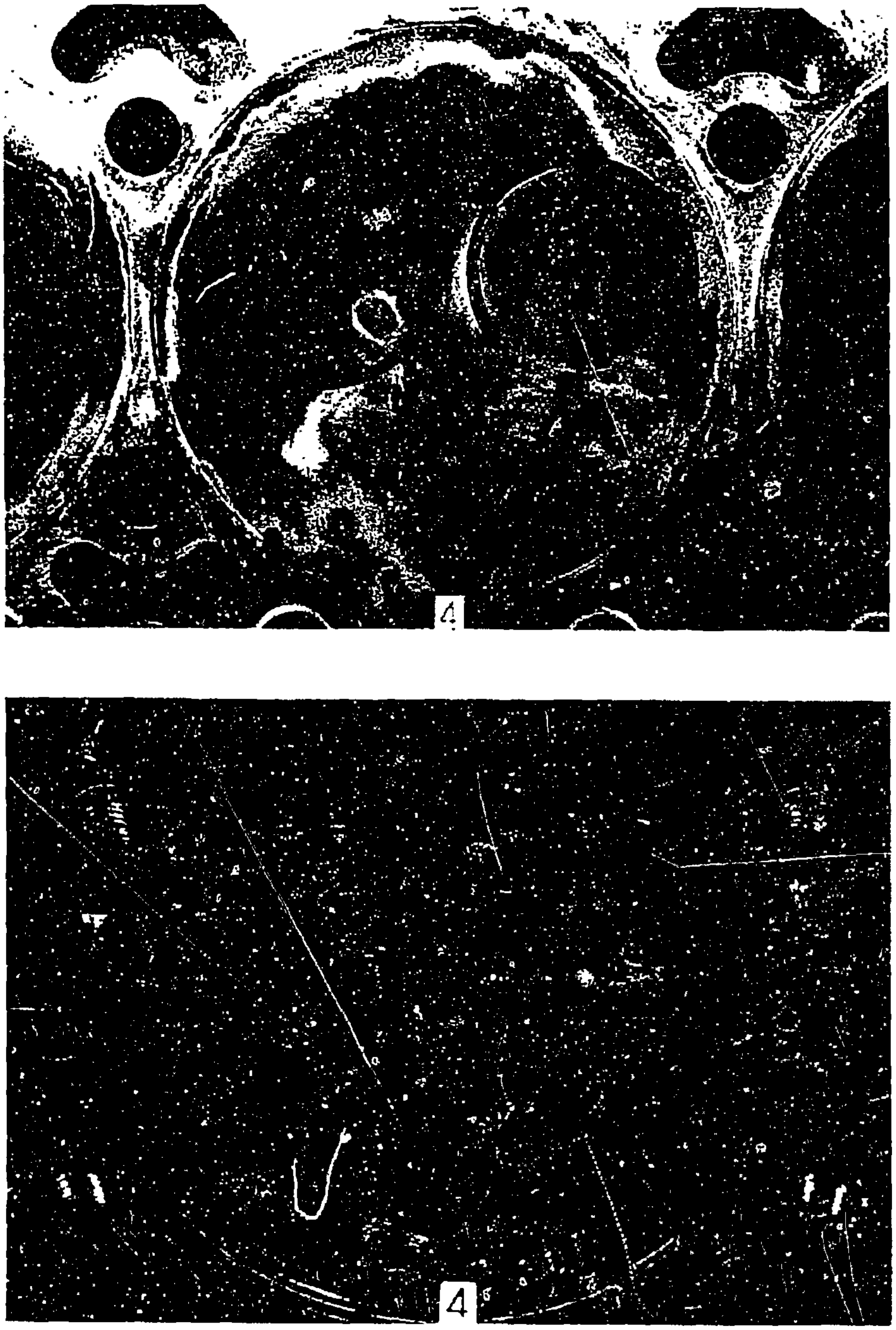


FIGURE 6.23. PISTON AND CYLINDER HEAD DEPOSITS AFTER 2 HOURS FULL POWER, SHALE FUEL

present around the piston edge when compared to the No. 2 diesel fuel results. The piston was only coated with soot where the fuel plume contacted the piston.

Figures 6.24 and 6.25 show that after running the engine for 8 hours on the tar sands fuels there was very little buildup of soot in the combustion chamber. A small amount of tar was present after the 8-hour test but, as was the case with the other fuels, this tar disappeared after the 2-hour burnoff period.

Figures 6.26 and 6.27 show that the 57 percent EDS fuel also left a light coat of soot on the head, valves, and piston. The major difference between this fuel's results when compared to the other fuels is that there was a reddish carbon present on the head before and after the 2-hour burnoff period.

In summary, the engine did not seem to suffer from excessive soot deposits when idling on the synfuels compared to the control diesel fuel. The tar sands fuel appeared to leave the least amount of soot deposits in the combustion chamber.

6.4 PHASE II RESULTS

The Phase II performance results are presented in three sections. The first section covers the performance, emissions and combustion analysis results after making the first engine modification (simulating air-to-air aftercooling). The second section covers these same results after making the first and second engine modifications (simulating air-to-air aftercooling, and adding the high pressure fuel injection system). The third section covers the cold starting results. The results will be discussed by first comparing the synfuels' performance relative to the control diesel fuel's performance with the given engine modification(s). All three fuels' performance will then be compared with the Phase I results.

As in Phase I, performance testing was done at three speeds: rated (2200 rpm), peak torque (1400 rpm), and idle. There are two graphs for each speed. The first of these is titled "Performance" and includes brake thermal efficiency, smoke opacity, and particulates versus brake power. The second graph is titled "Emissions" and includes brake specific hydrocarbons, brake specific carbon monoxide, and brake specific oxides of nitrogen versus brake power. The idle test points are shown as bar graphs. Complete tabular data for the control diesel, tar sands, and 57 percent EDS fuels are given in Appendices I, J, and K, respectively.

6.4.1 Performance and Emissions Results, Simulated Air-to-Air Aftercooling

Figure 6.28 shows the performance results at 2200 rpm after simulating engine air-to-air aftercooling. The tar sands and 57 percent EDS fuels showed a slightly higher brake thermal efficiency compared to the diesel fuel at the 25 percent and 50 percent load conditions. The two synfuels produced more smoke at full load compared to the control diesel fuel. All three fuels have nearly equal full load particulate emissions. Reducing the intake air

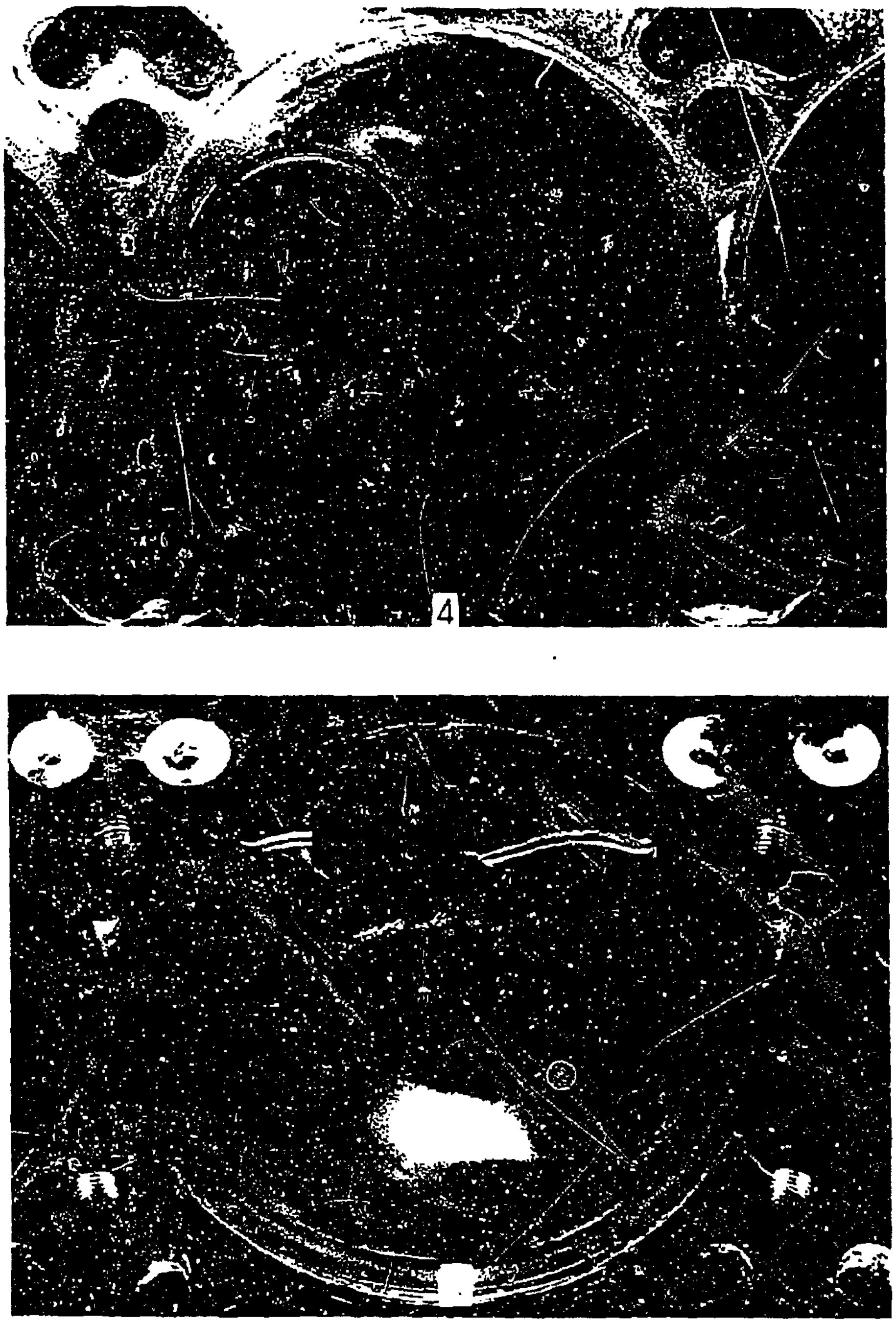


FIGURE 6.24. PISTON AND CYLINDER HEAD DEPOSITS AFTER 8 HOURS CONTINUOUS IDLE, TAR SANDS FUEL

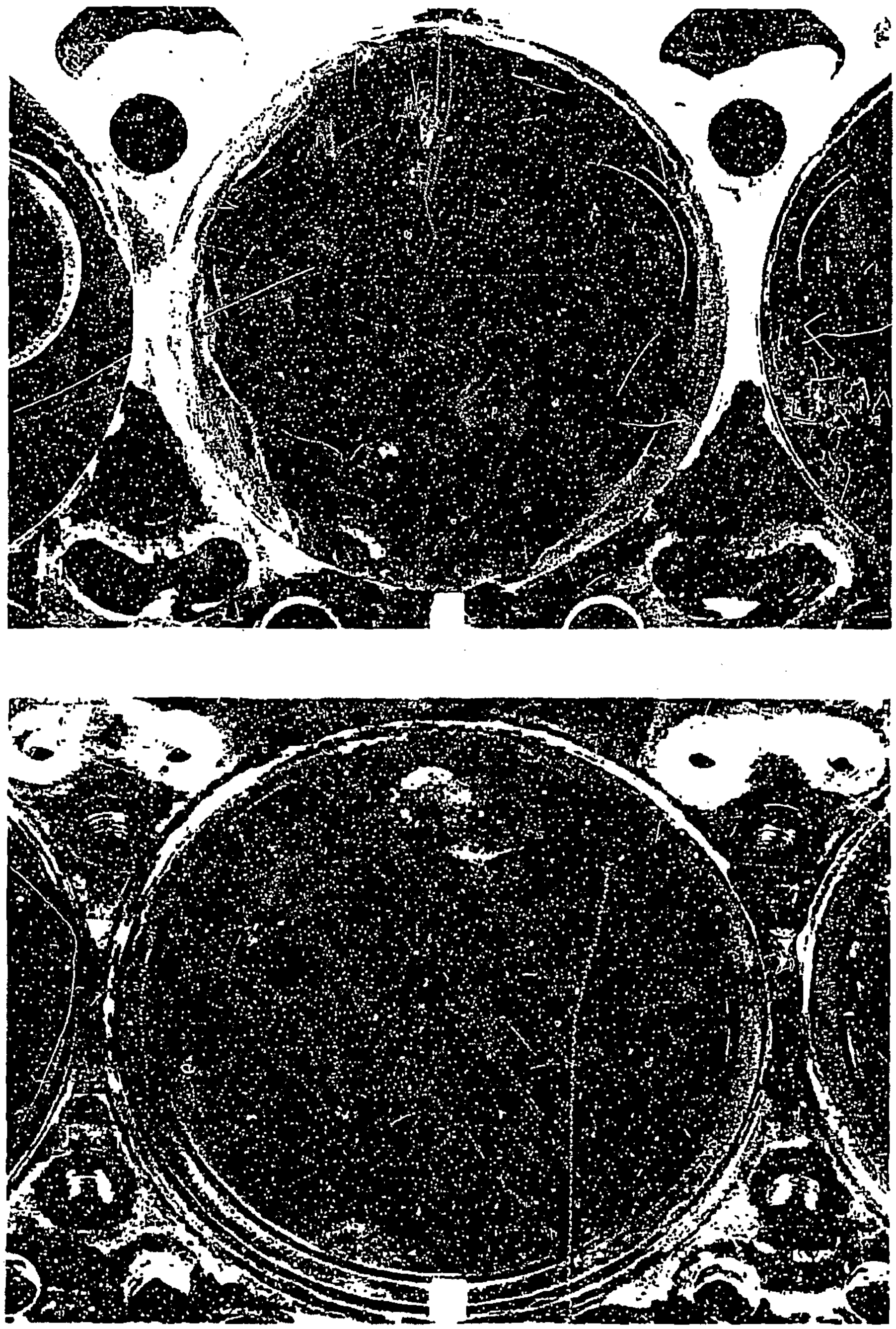


FIGURE 6.25. PISTON AND CYLINDER HEAD DEPOSITS
AFTER 2 HOURS FULL POWER, TAR SANDS FUEL

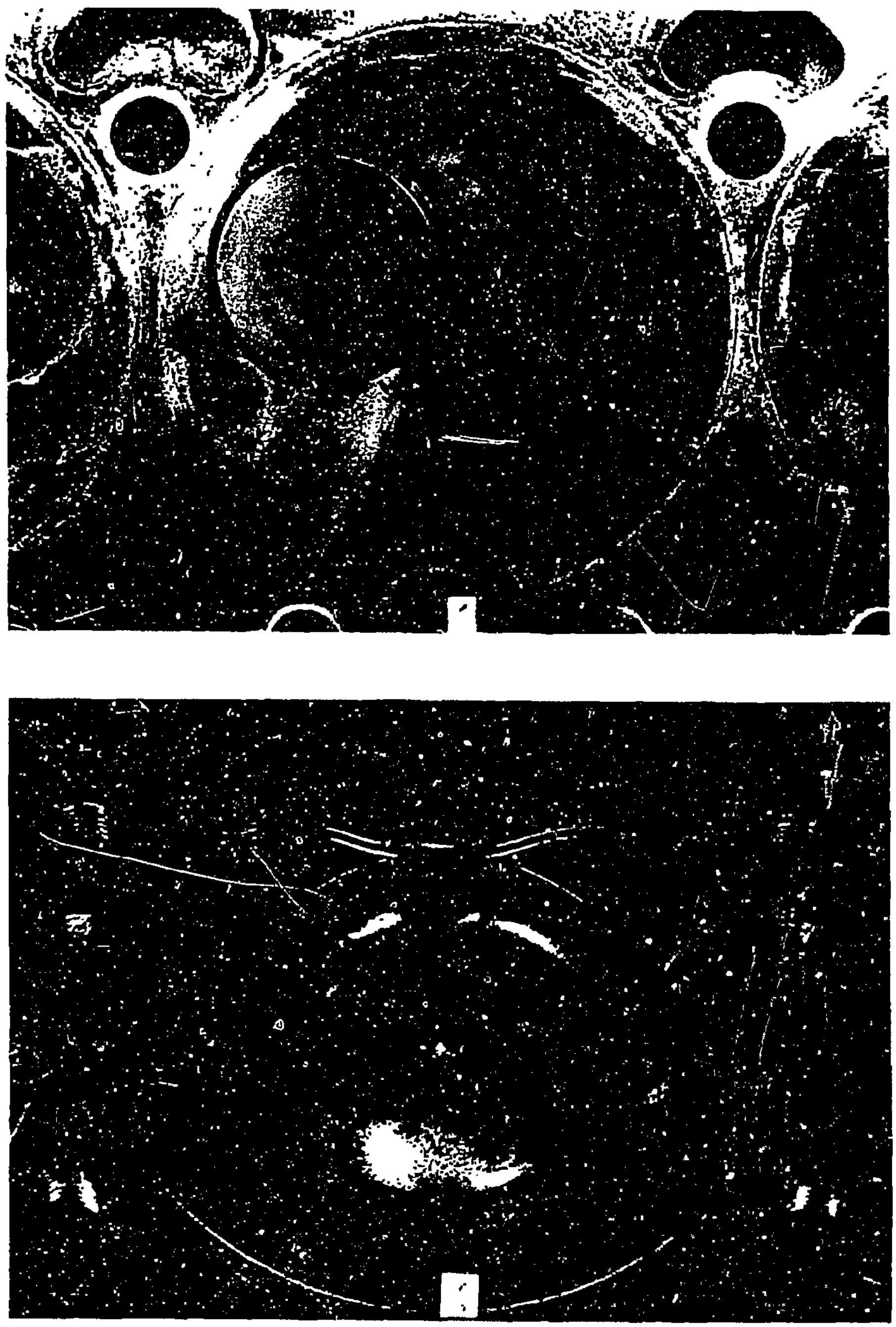


FIGURE 6.26. PISTON AND CYLINDER HEAD DEPOSITS
AFTER 8 HOURS CONTINUOUS IDLE,
57 PERCENT EDS FUEL

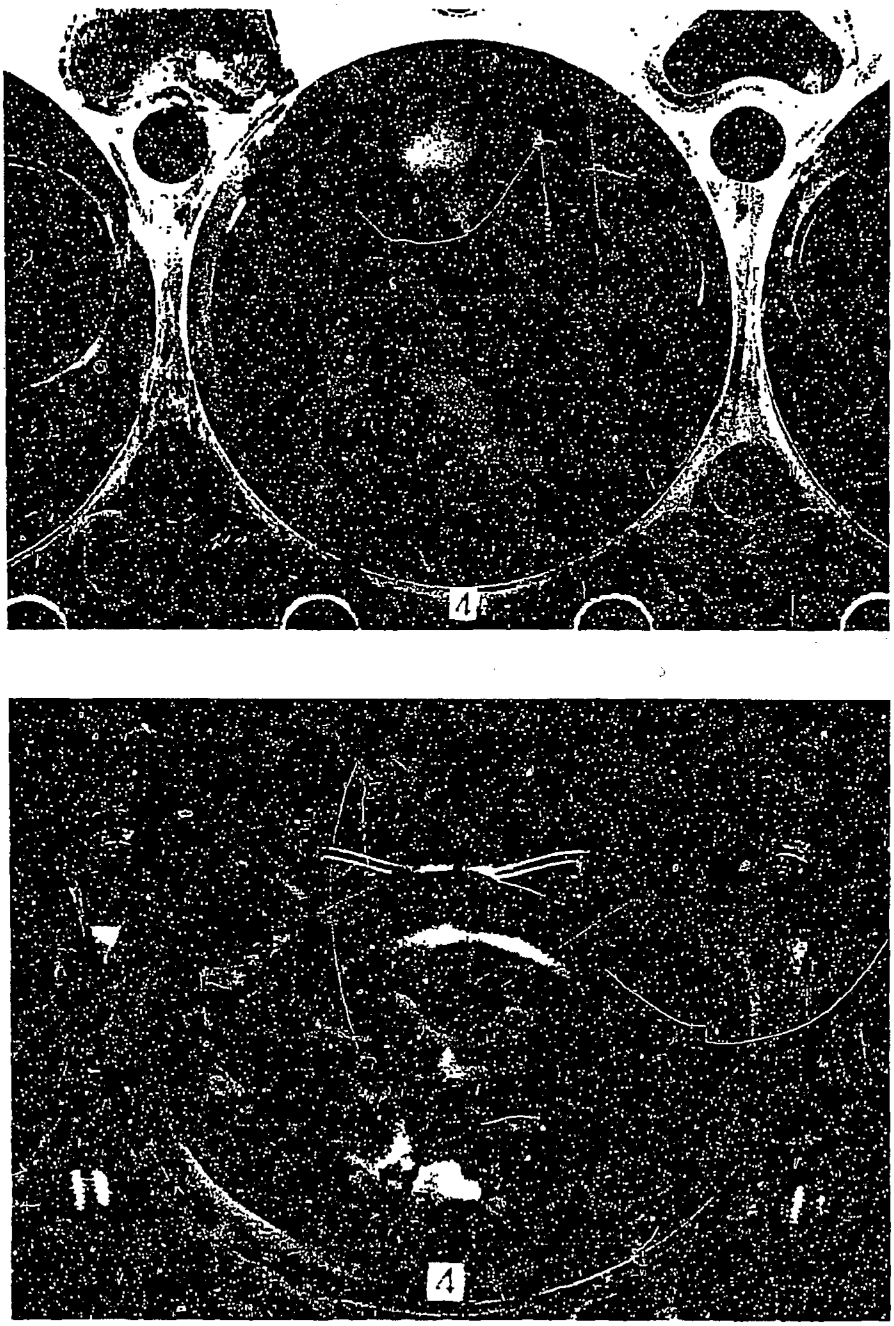


FIGURE 6.27. PISTON AND CYLINDER HEAD DEPOSITS AFTER 2 HOURS FULL POWER, 57 PERCENT EDS FUEL

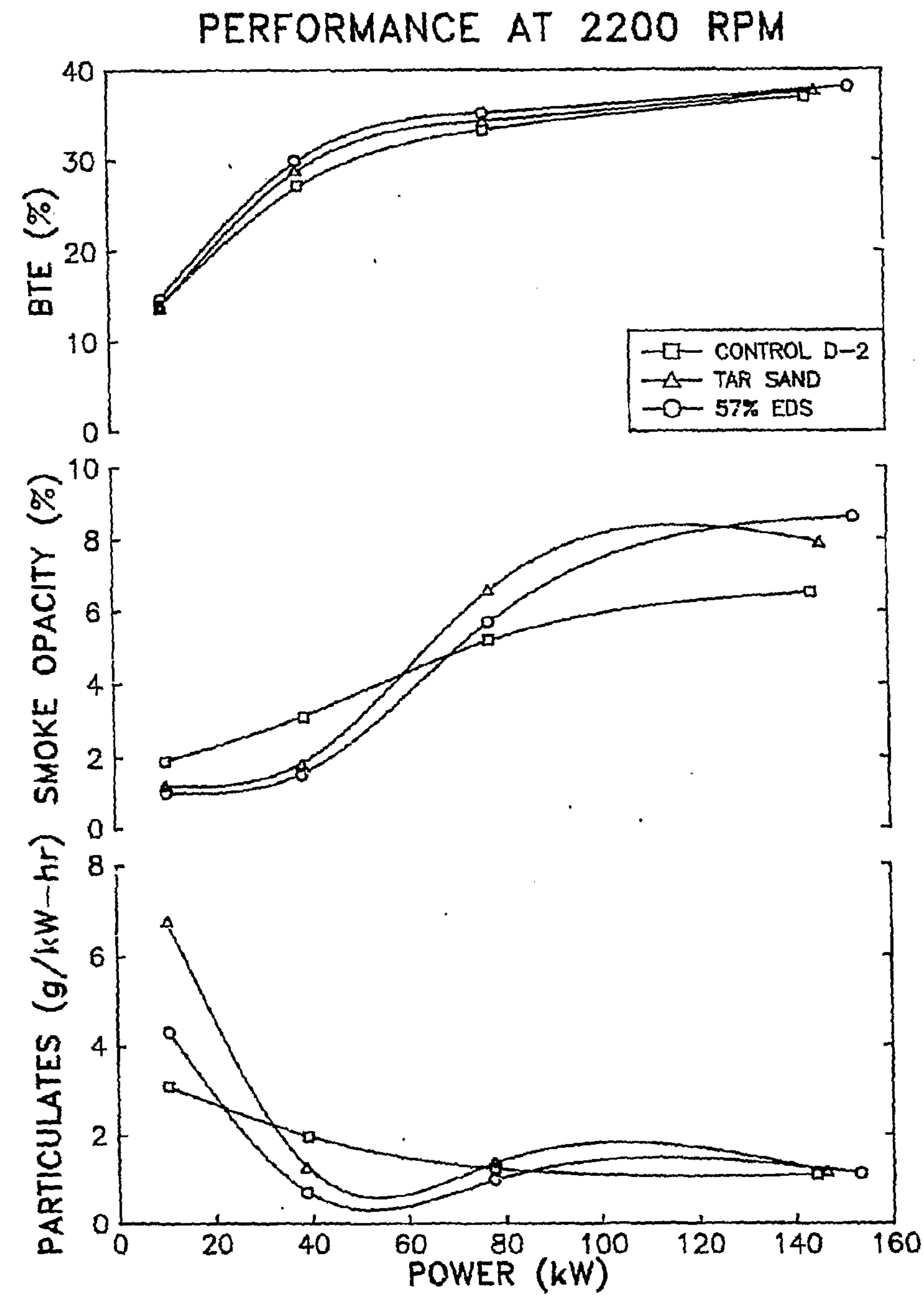


FIGURE 6.28. PERFORMANCE RESULTS AT 2200 RPM, PHASE II SIMULATED AIR-TO-AIR AFTERCOOLER

temperature to 140°F at 2200 rpm reduced the brake specific fuel consumption slightly as compared to the Phase I results.

The brake specific emissions at 2200 rpm are shown in Figure 6.29. The BSHC, BSCO, and $BSNO_x$ emissions were nearly identical for all three fuels at the 50 percent and 100 percent load conditions. The tar sands and 57 percent EDS fuels' BSHC and BSCO emissions increased significantly at the lowest load condition while these same diesel fuel emissions remained equal to the Phase I results. The tar sands and 57 percent EDS fuels' $BSNO_x$ emissions were identical over the entire load range and higher than the diesel fuel emissions. In Phase I the synfuel $BSNO_x$ emissions were lower than the control diesel fuel's over the entire load range. Reducing the intake air temperature to 140°F cut the $BSNO_x$ emissions in half for all three fuels at the lowest load condition compared to the Phase I results. The $BSNO_x$ emissions were not significantly reduced at full load since the reduction in intake air temperature is relatively small compared to the combustion temperatures produced at full load.

Figure 6.30 shows the engine performance results at 1400 rpm for the simulated air-to-air aftercooled engine. All three fuels exhibited identical thermal efficiency curves. The cooler intake air caused a slightly higher brake thermal efficiency across the entire load range compared to the Phase I results. This increase is attributed to the longer ignition delays caused by the lower intake air temperature. The longer ignition delays caused more constant volume combustion and thus higher thermal efficiency. The two synfuels also produced a higher maximum power compared to the control diesel fuel. The tar sands and 57 percent EDS fuels' smoke and particulate emissions were identical to the diesel fuel emissions at low load. The two synfuels caused higher smoke and particulates emissions at full load compared to the diesel fuel which is identical to the Phase I result. Reducing the intake air temperature to 140°F slightly reduced the full load smoke and particulate emissions and brake specific fuel consumption compared to Phase I performance results.

The brake specific emissions at 1400 rpm are shown in Figure 6.31 for the simulated air-to-air aftercooled engine. The BSHC, BSCO, and $BSNO_x$ emissions were identical for all three fuels at the 50 percent and 100 percent load conditions. The tar sands and 57 percent EDS fuels' gaseous emissions were higher than the diesel fuel emissions at the lowest load condition. The BSHC emissions were almost identical to the Phase I results. The BSCO full load emissions were cut in half and the $BSNO_x$ emissions were reduced at light loads compared to the Phase I results.

The engine performance results at idle for the 140°F intake air temperature are shown in Figure 6.32. The tar sands fuel had the highest brake thermal efficiency, smoke, and particulate emissions compared to the 57 percent EDS and control diesel fuels. The two synfuels also had higher brake thermal efficiency, smoke opacity, and particulate emissions compared to the Phase I tests. The control diesel fuel's performance remained about the same.

Figure 6.33 shows the gaseous emissions at idle for the reduced intake air temperature. The two synfuels have slightly higher BSHC, BSCO, and $BSNO_x$ emissions compared to the control diesel fuel. Reducing the intake air

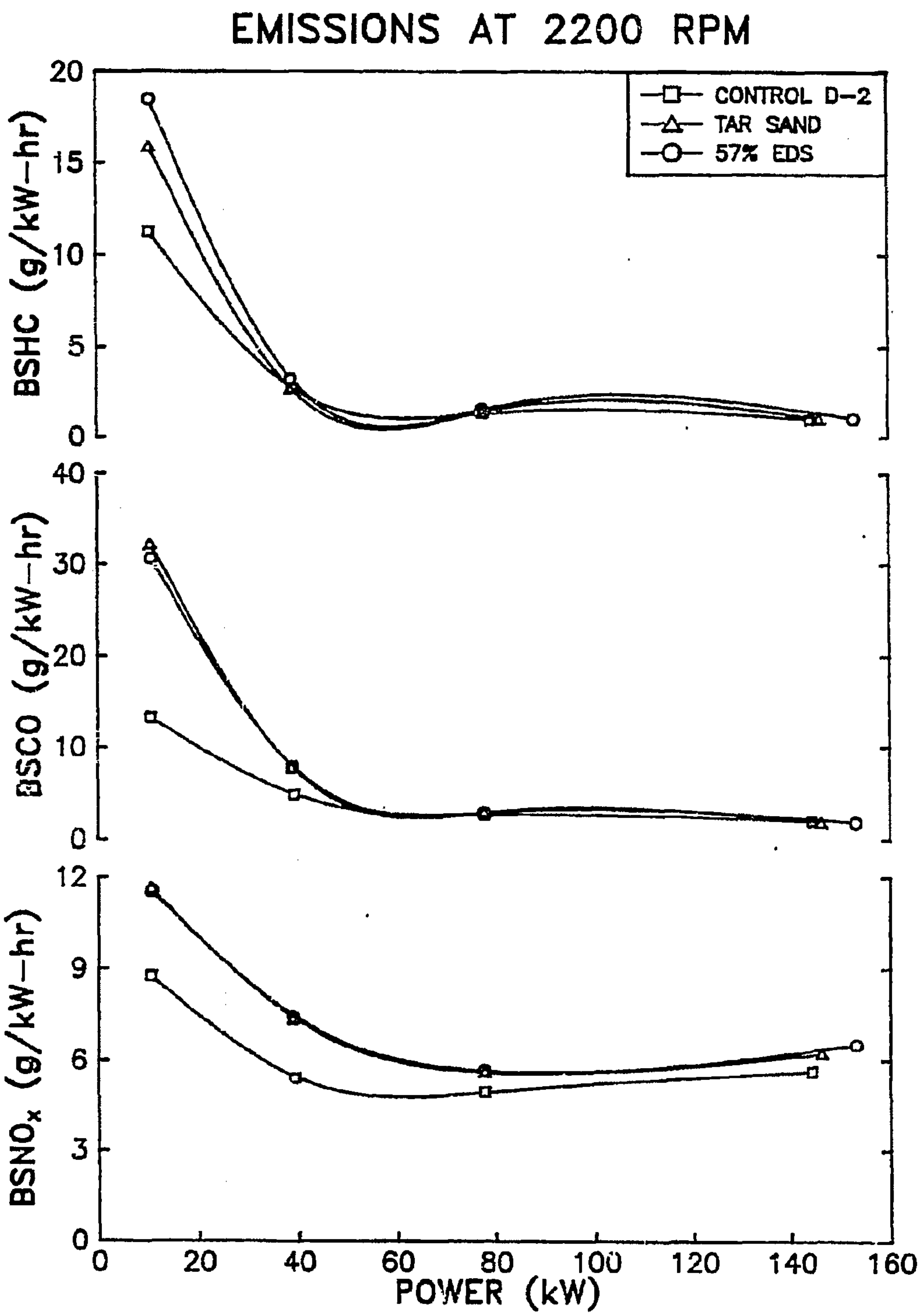


FIGURE 6.29. BRAKE SPECIFIC EMISSIONS AT 2200 RPM, PHASE II SIMULATED AIR-TO-AIR AFTERCOOLER

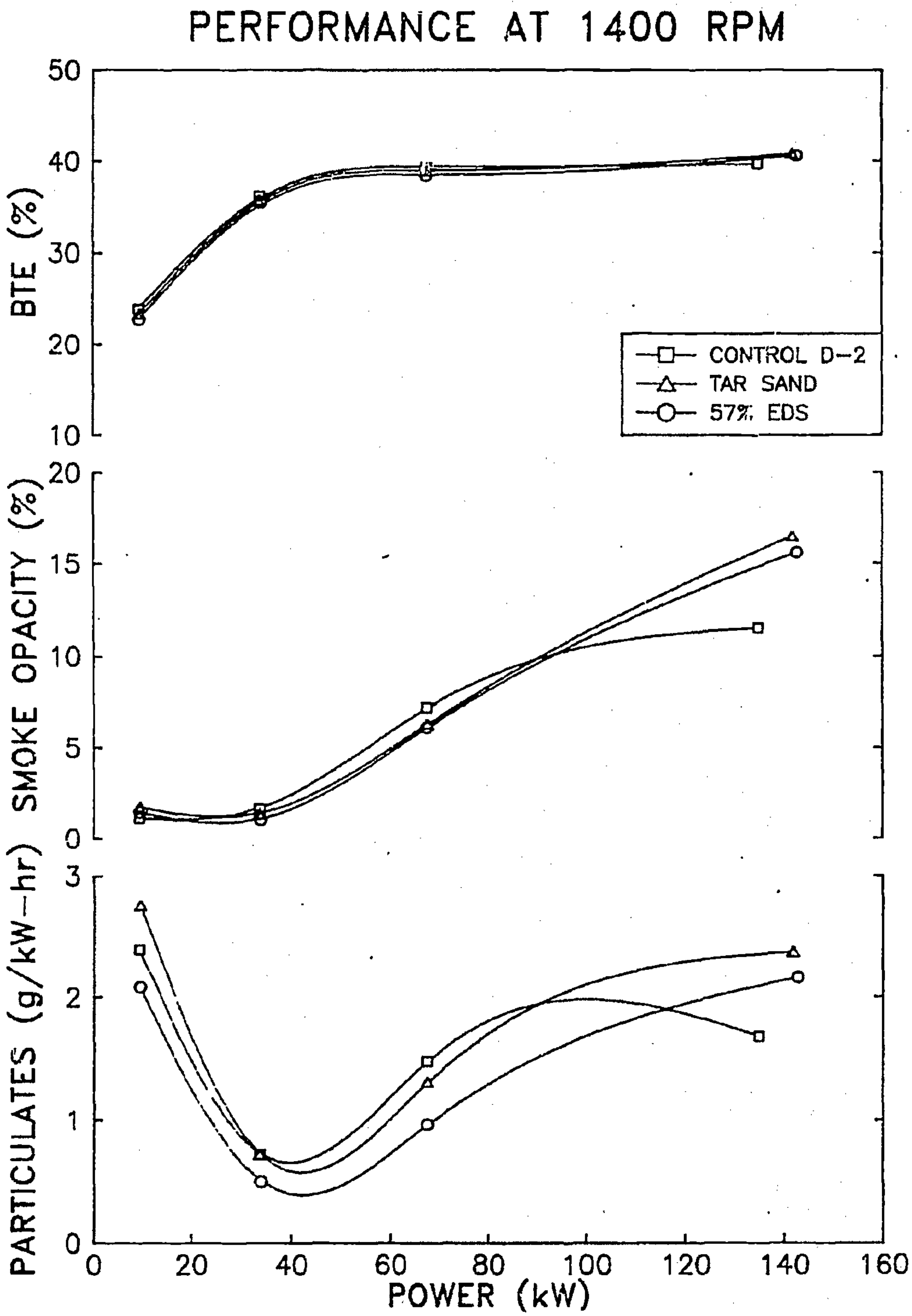


FIGURE 6.30. PERFORMANCE RESULTS AT 1400 RPM, PHASE II SIMULATED AIR-TO-AIR AFTERCOOLER

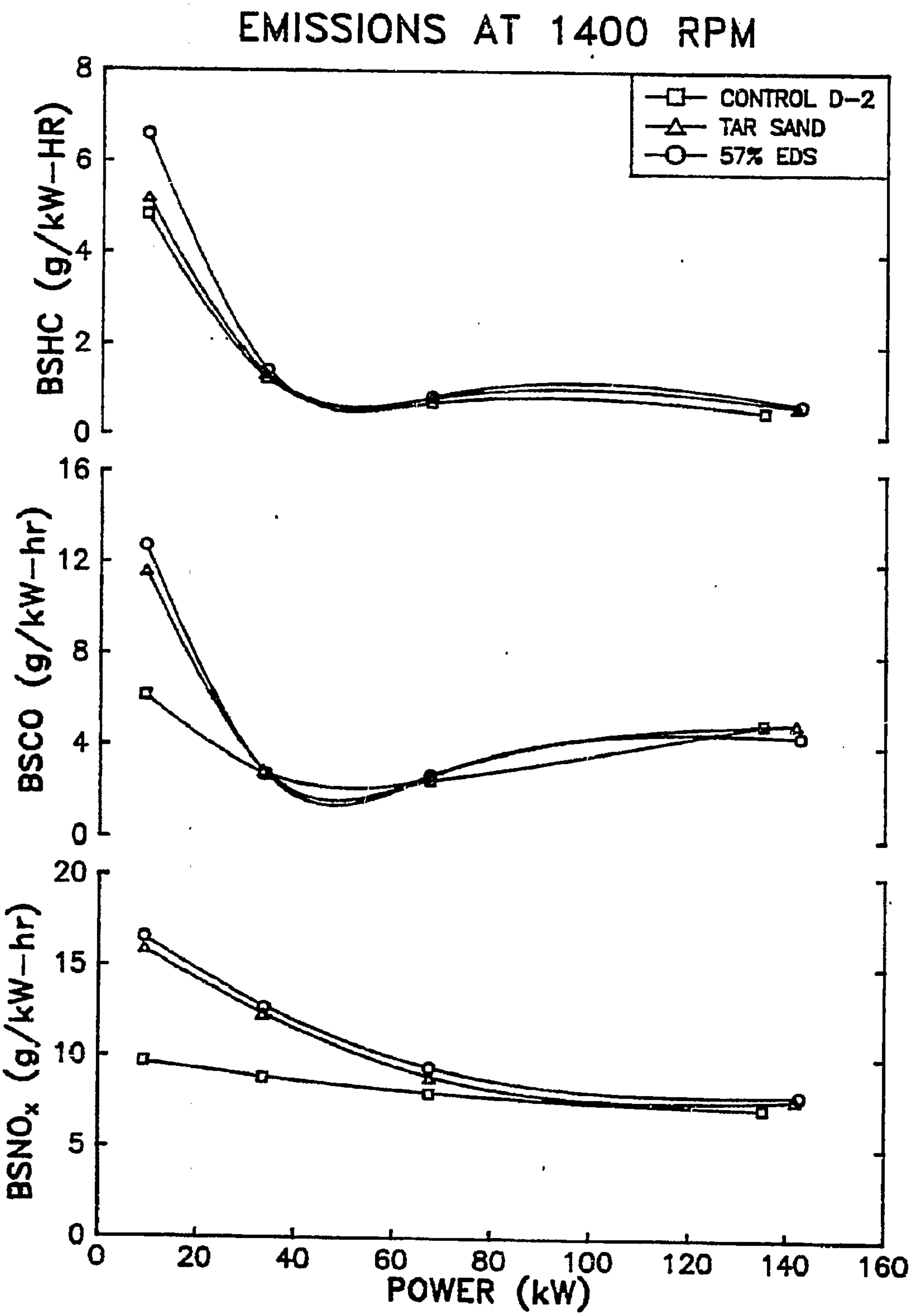


FIGURE 6.31. BRAKE SPECIFIC EMISSIONS AT 1400 RPM, PHASE II SIMULATED AIR-TO-AIR AFTERCOOLER

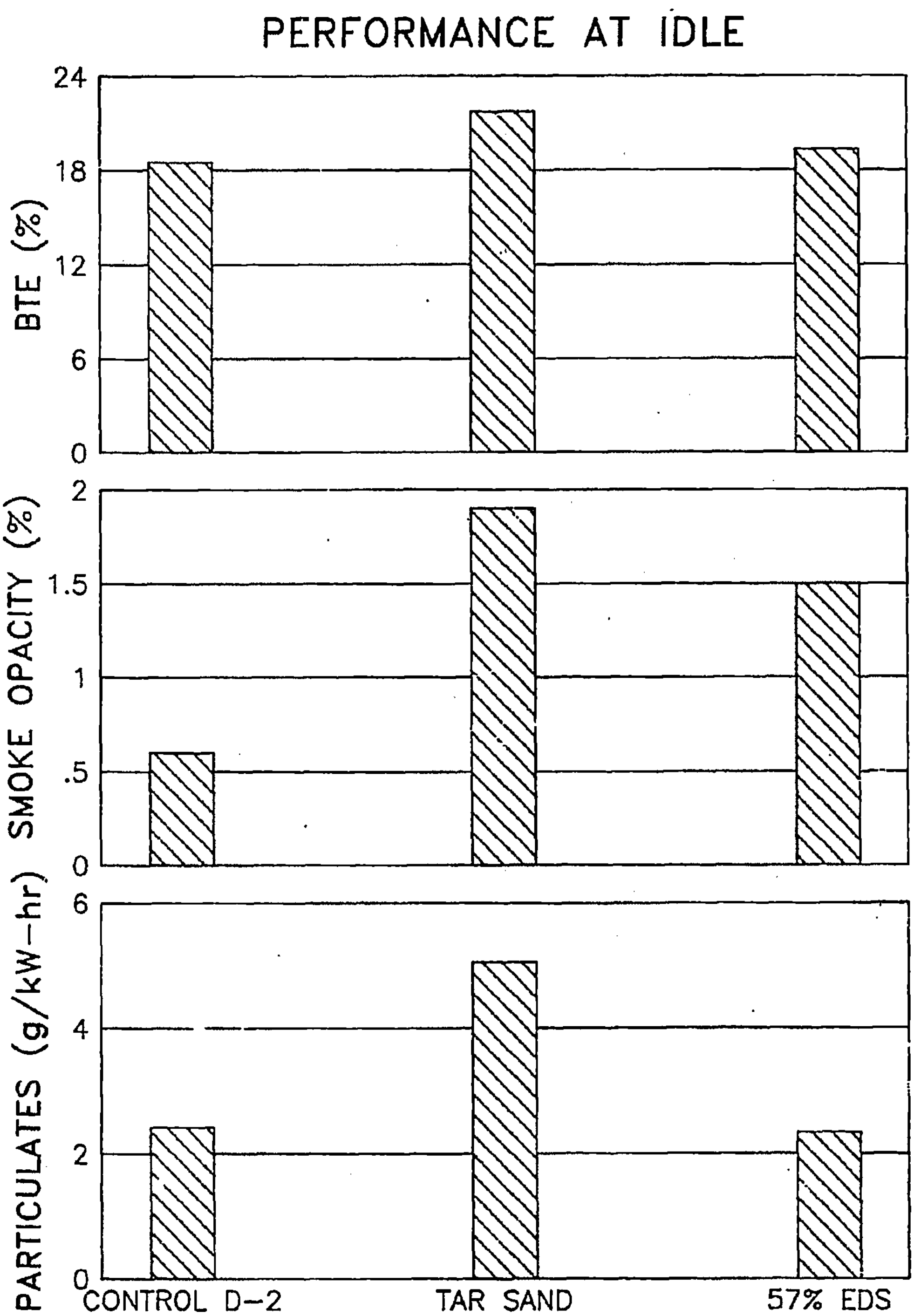


FIGURE 6.32. PERFORMANCE RESULTS AT IDLE, PHASE II SIMULATED AIR-TO-AIR AFTERCOOLER

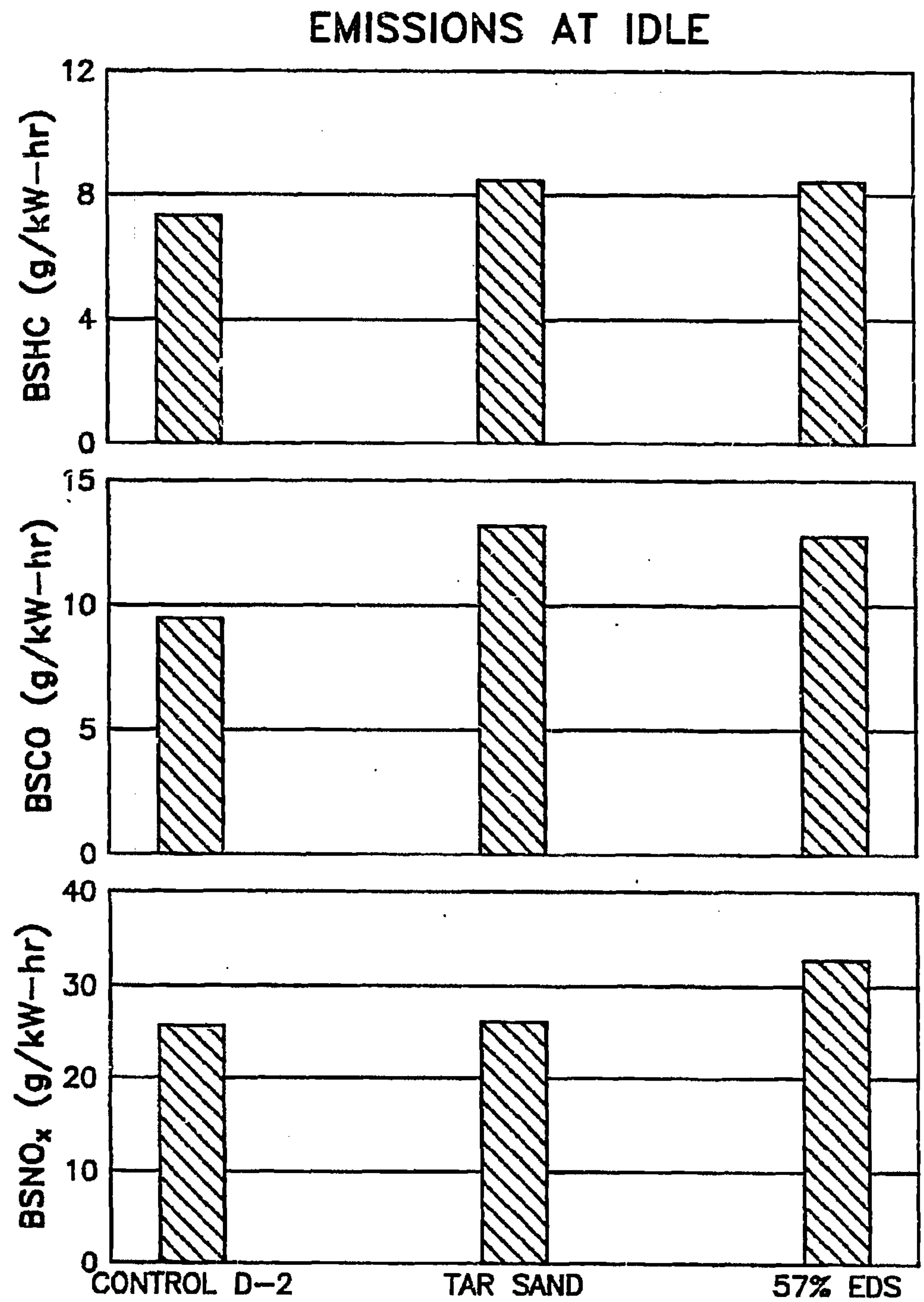


FIGURE 6.33. BRAKE SPECIFIC EMISSIONS AT IDLE, PHASE II SIMULATED AIR-TO-AIR AFTERCOOLER

temperature slightly reduced the BSHC and increased BSCO emissions for all three fuels, while greatly reducing the synfuels' $BSNO_x$ emissions compared to Phase I results.

6.4.2 Combustion Analysis Results, Simulated Air-to-Air Aftercooler

As in Phase I, the effects that the synfuels have on diesel engine combustion were determined by calculating the heat release rate, cumulative heat release, ignition delay, maximum and average rates of pressure rise, and the peak cylinder pressure for each fuel. The combustion analysis data at 1400 rpm, 50 percent load is presented because, based on the Phase I results, this data is a good indicator of the effects that the synfuels have on diesel engine combustion. The combustion and heat release data at 1400 rpm, 50 percent load is presented in Table 6.2 for the engine with simulated air-to-air aftercooling. A complete set of cylinder and fuel injection pressure diagrams corresponding to the simulated air-to-air aftercooled engine are given in Appendix O.

Table 6.2. Summary of Combustion and Heat Release Data at 1400 RPM, 50 Percent Load Simulated Air-to-Air Aftercooler

Fuel Type	Maximum Pressure (MPa)	Maximum Rate of Pressure Rise (kPa/deg)	Average Rate of Pressure Rise (kPa/deg)	Total Heat Release (joules)	Ignition Delay (deg)
DF-2	8.50	833.8	267.8	1840.10	6.0
Tar Sand	8.86	1206.0	377.5	1889.77	7.6
57% EDS	8.93	1180.0	361.7	1896.83	7.3

The heat release rate diagrams for the 1400 rpm, 50 percent load condition are presented in Figures 6.34 and 6.35 for each synfuel compared to the corresponding control diesel fuel result. Figure 6.34 is a plot of heat release rate versus crank angle degrees for the tar sand and control diesel fuels. The figure shows that the peak heat release rate of the tar sand fuel is greater than the diesel fuel. This greater initial heat release rate is due to the longer ignition delay of tar sand fuel. As shown in Figure 6.34 and Table 6.2, the tar sand fuel had an ignition delay 1.6 degrees longer than the control diesel fuel. The longer ignition delay allowed more of the tar sand fuel to evaporate prior to ignition, which resulted in its higher initial heat release rate compared to the control diesel fuel. The longer ignition delay of the tar sand fuel is due to its relatively low cetane number of 34.9 compared to the diesel fuel's cetane number of 51.1. Despite the higher initial heat release rate of the tar sand fuel, the two fuels had similar total heat releases as shown in Table 6.2. The greater initial heat release rate of the tar sand fuel, however, did result in higher maximum and average rates of pressure rise compared to the control diesel fuel. Both fuels produced about the same maximum cylinder pressure.

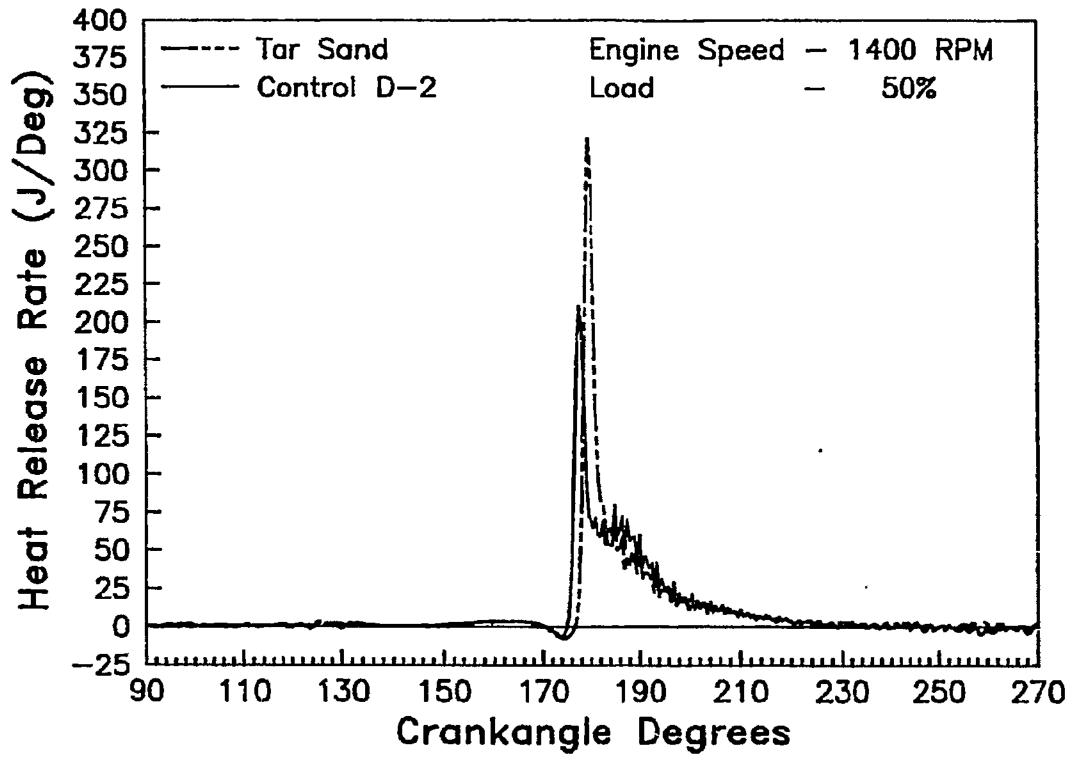


FIGURE 6.34. HEAT RELEASE RATE FOR TAR SAND AND CONTROL D-2 FUELS AT 1400 RPM, 50 PERCENT LOAD, SIMULATED AIR-TO-AIR AFTERCOOLER

The heat release rate of the 57 percent EDS fuel is compared with the control diesel fuel in Figure 6.35. The ignition delay of the 57 percent EDS fuel is 1.3 degrees longer than the control diesel fuel. This increased ignition delay allowed more of the 57 percent EDS fuel to accumulate and vaporize in the combustion chamber before autoignition. The result was a higher initial heat release rate and higher maximum and average rates of pressure rise for the 57 percent EDS fuel compared to the control diesel fuel. The 57 percent EDS fuel's longer ignition delay was due to its low cetane number of 32.9. By comparing these combustion analysis results with the Phase I results, it can be seen that the ignition delay increased slightly for all three fuels by simulating air-to-air aftercooling.

Simulating air-to-air aftercooling on the engine had the effect of increasing the ignition delay and maximum and average rates of pressure rise for all three fuels. The ignition delays increased due to the lower intake air temperature. The total heat release and maximum cylinder pressure for all three fuels remained about the same as the Phase I results.

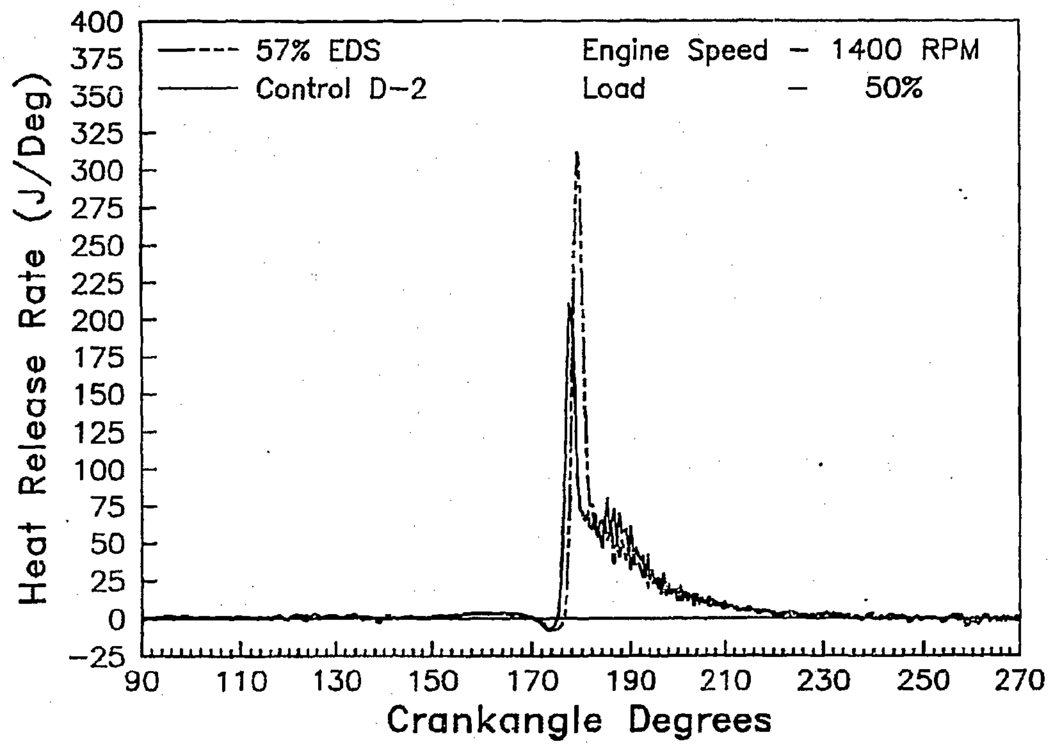


FIGURE 6.35. HEAT RELEASE RATE FOR 57 PERCENT EDS AND CONTROL DF-2 FUELS AT 1400 RPM, 50 PERCENT LOAD SIMULATED AIR-TO-AIR AFTERCOOLER

Thus, the major difference in the combustion characteristics between the two synfuels and the control diesel fuel is attributed to the synfuel's longer ignition delay period. Reducing the intake air temperature to 140°F by simulating air-to-air aftercooling did not improve the synfuel's combustion performance relative to the diesel fuel. In fact, lowering the intake air temperature reduced the combustion performance of all three fuels relative to Phase I results by increasing the maximum and average rates of cylinder pressure rise. Excessive rates of cylinder pressure rise can cause diesel engine knock, although no audible knock was detected during these tests.

6.4.3 Performance and Emissions Results, Simulated Air-to-Air Aftercooler and High Pressure Fuel Injection System

Figures 6.36 through 6.37 correspond to engine performance and emissions plots at 2200, 1400, and idle speed after adding the high pressure fuel injection system to the engine (modification No. 2). These results also include the effects of the simulated air-to-air aftercooler (modification No. 1).

Figure 6.36 shows engine performance results at 2200 rpm. The tar sands and 57 percent EDS fuels' maximum power were about equal and slightly higher than the diesel fuel's maximum power. The two synfuels had higher brake thermal efficiency across the entire load range compared to the diesel fuel with the tar sands fuel yielding the highest brake thermal efficiency. All three fuels showed a slight improvement in brake thermal efficiency which resulted in a significant increase in maximum output power compared to the Phase I results.

All three fuels produced about the same amount of smoke over the entire load range. The smoke produced at full load was about half the amount produced during Phase I.

The two synfuels showed a significant reduction in part load particulate emissions compared to the diesel fuel. However, at full load, the tar sands and 57 percent EDS fuels yielded higher particulate emissions than the diesel fuel. All three fuels showed a reduction in particulate emissions compared with the Phase I results.

The improved performance results at 2200 rpm can be attributed to better fuel/air mixing produced by the high pressure fuel injection system. Increased output power and brake thermal efficiency along with reduced smoke and particulate emissions suggests better air utilization through improved fuel/air mixing.

The gaseous emissions at 2200 rpm for the two engine modifications are shown in Figure 6.37. All three fuels produced the same amount of gaseous emissions over the entire load range. The one exception was the two synfuels which produced higher BSCO at the lowest load condition. Compared to the Phase I results, all three fuels produced the same amount of BSHC, the two synfuels produced more BSCO at the lowest load condition, and all three fuels produced less $BSNO_x$ at the lowest load condition.

The performance results at 1400 rpm after the two engine modifications are shown in Figure 6.38. The two synfuels produced slightly higher maximum power compared to the control diesel fuel. This same result was observed at the 2200 rpm condition. The brake thermal efficiency of the tar sands fuel was higher than the other two fuels at low load conditions. The two synfuels produced less smoke than the control diesel fuel over the load range. The tar sands fuel produced more particulates and the 57 percent EDS fuel produced less particulates than the control diesel fuel. All three fuels showed a great reduction in smoke and particulate emissions compared to the Phase I results.

Figure 6.39 shows the 1400 rpm gaseous emissions results after the two engine modifications. All three fuels produced the same amount of gaseous emissions with the exception of the synfuels which produced slightly higher $BSNO_x$ compared to the diesel fuel. Compared to the Phase I results, all three fuels produced the same amount of BSHC, reduced BSCO at high load, and reduced $BSNO_x$ at the lowest load condition.

The engine performance at idle after the two engine modifications is

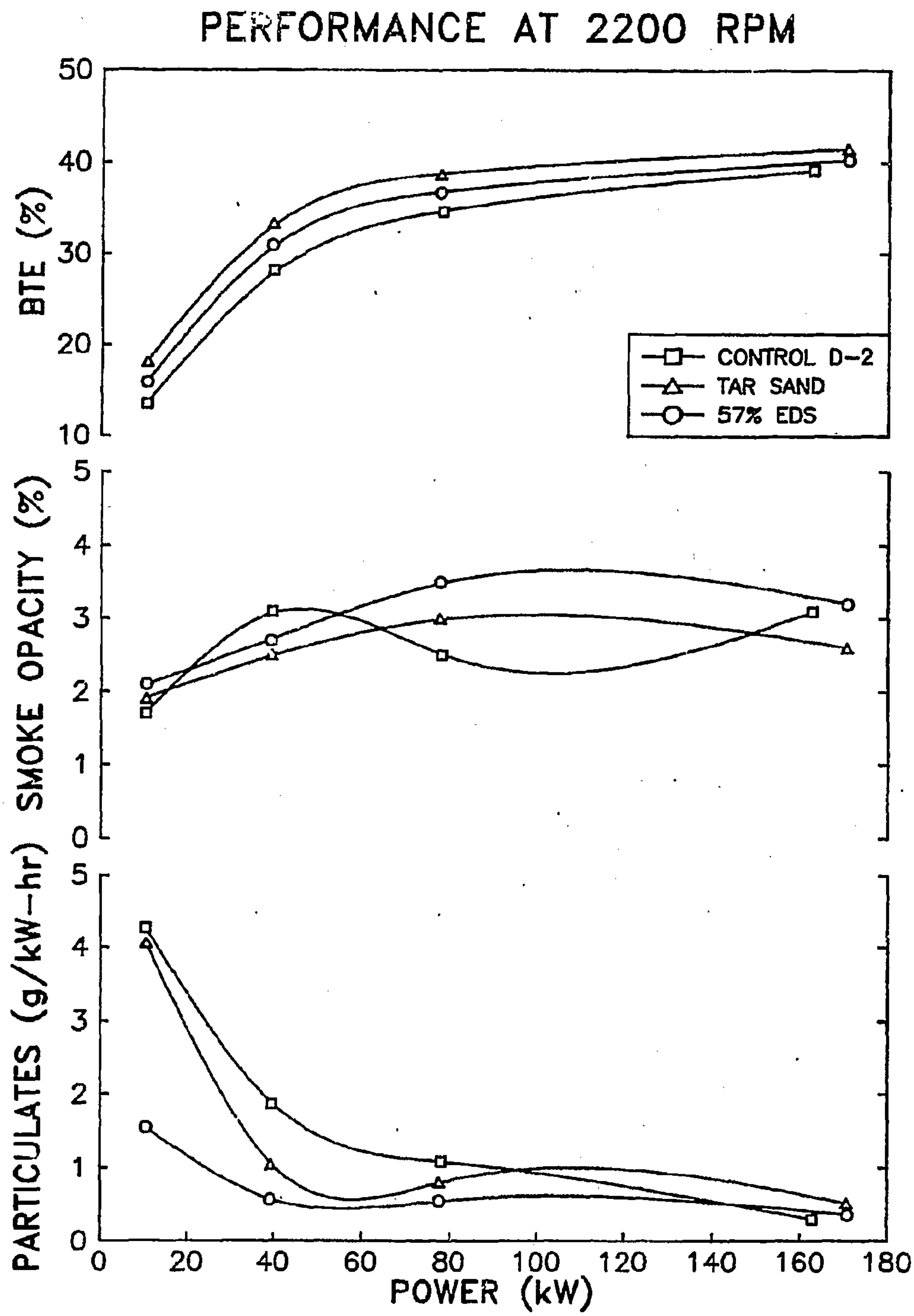


FIGURE 6.36. PERFORMANCE RESULTS AT 2200 RPM, PHASE II SIMULATED AIR-TO-AIR AFTERCOOLER AND HIGH PRESSURE FUEL INJECTION SYSTEM

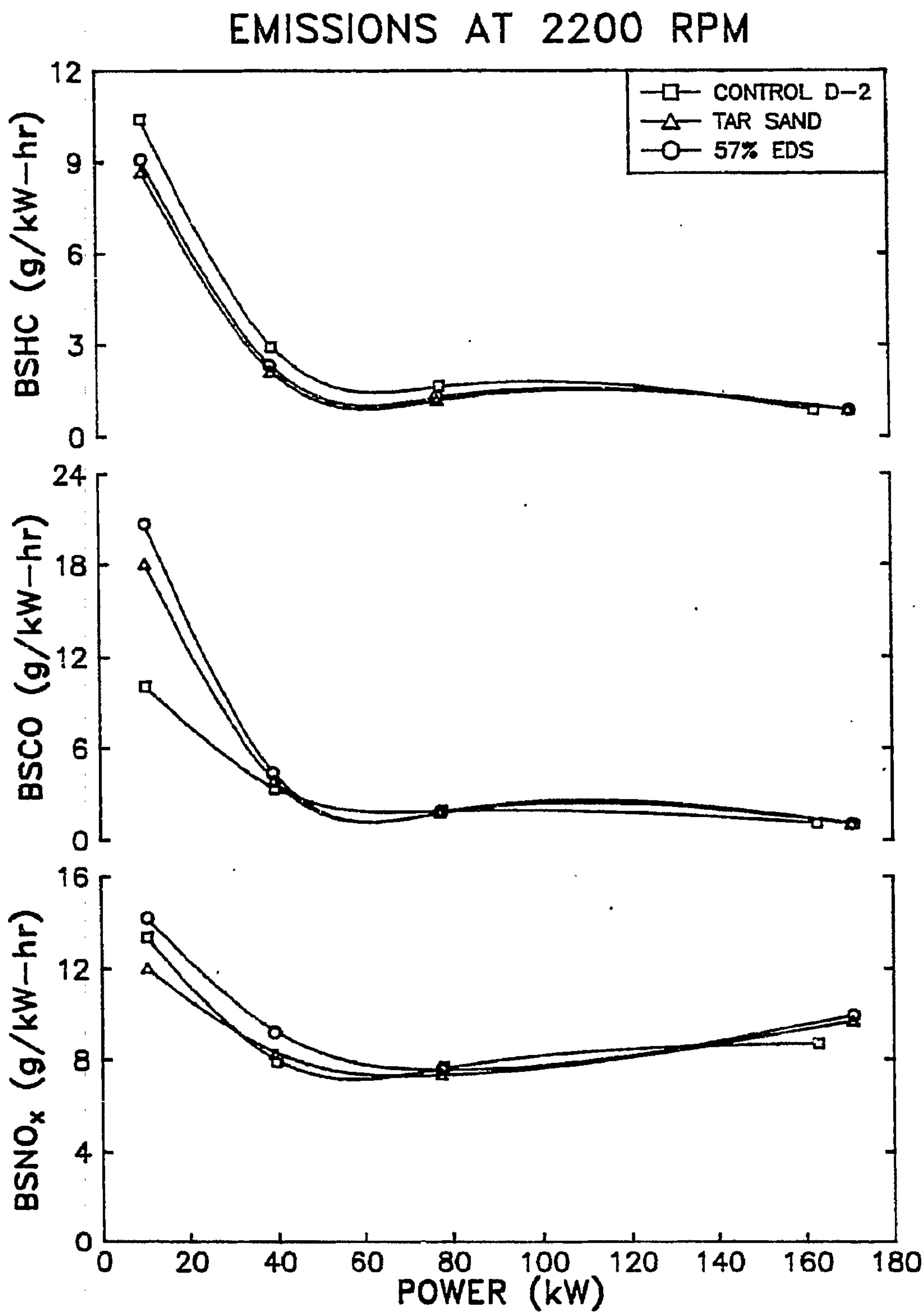


FIGURE 6.37. BRAKE SPECIFIC EMISSIONS AT 2200 RPM, PHASE II SIMULATED AIR-TO-AIR AFTERCOOLER AND HIGH PRESSURE FUEL INJECTION SYSTEM

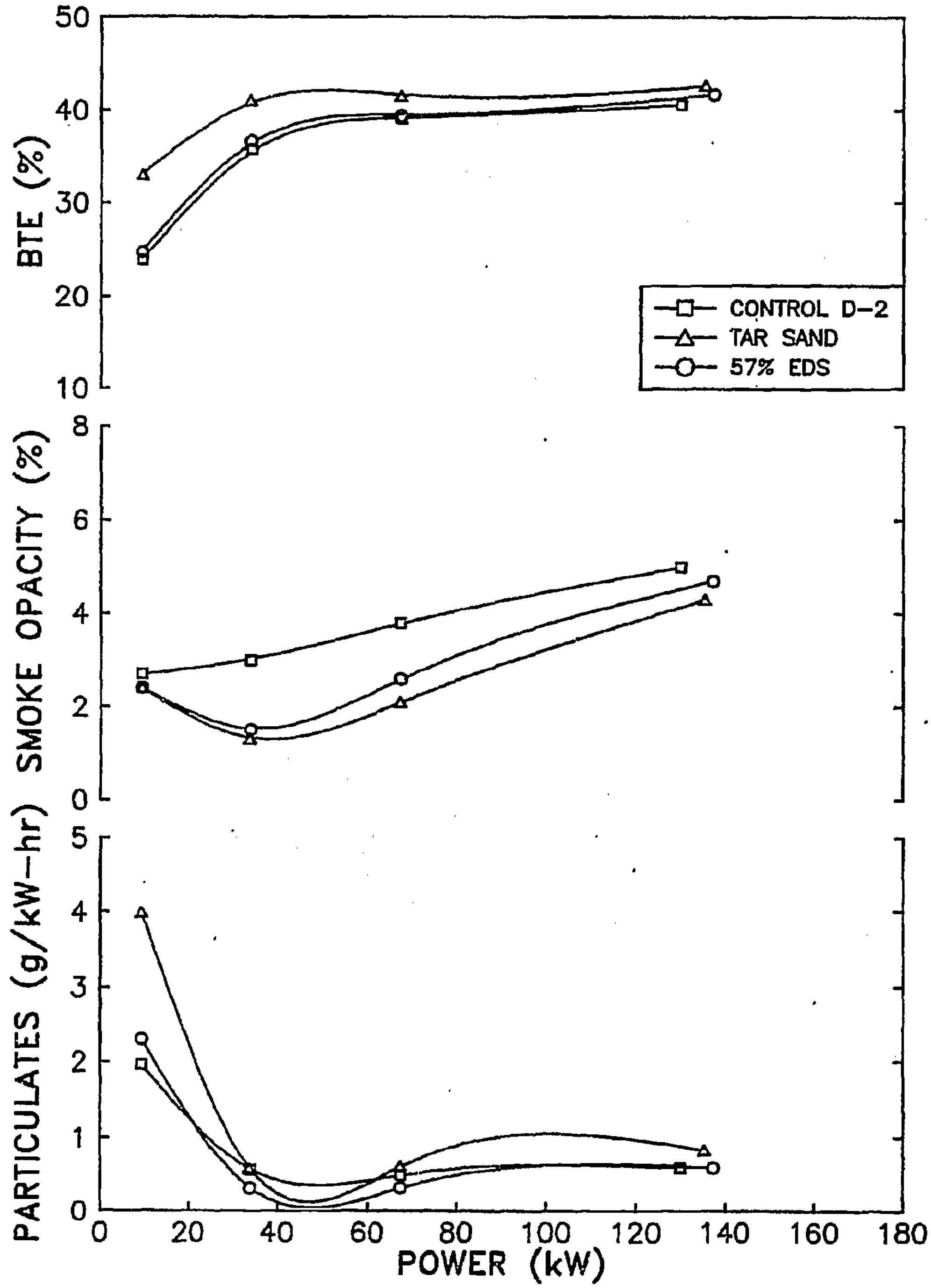


FIGURE 6.38. PERFORMANCE RESULTS AT 1400 RPM, PHASE II SIMULATED AIR-TO-AIR AFTERCOOLER AND HIGH PRESSURE FUEL INJECTION SYSTEM

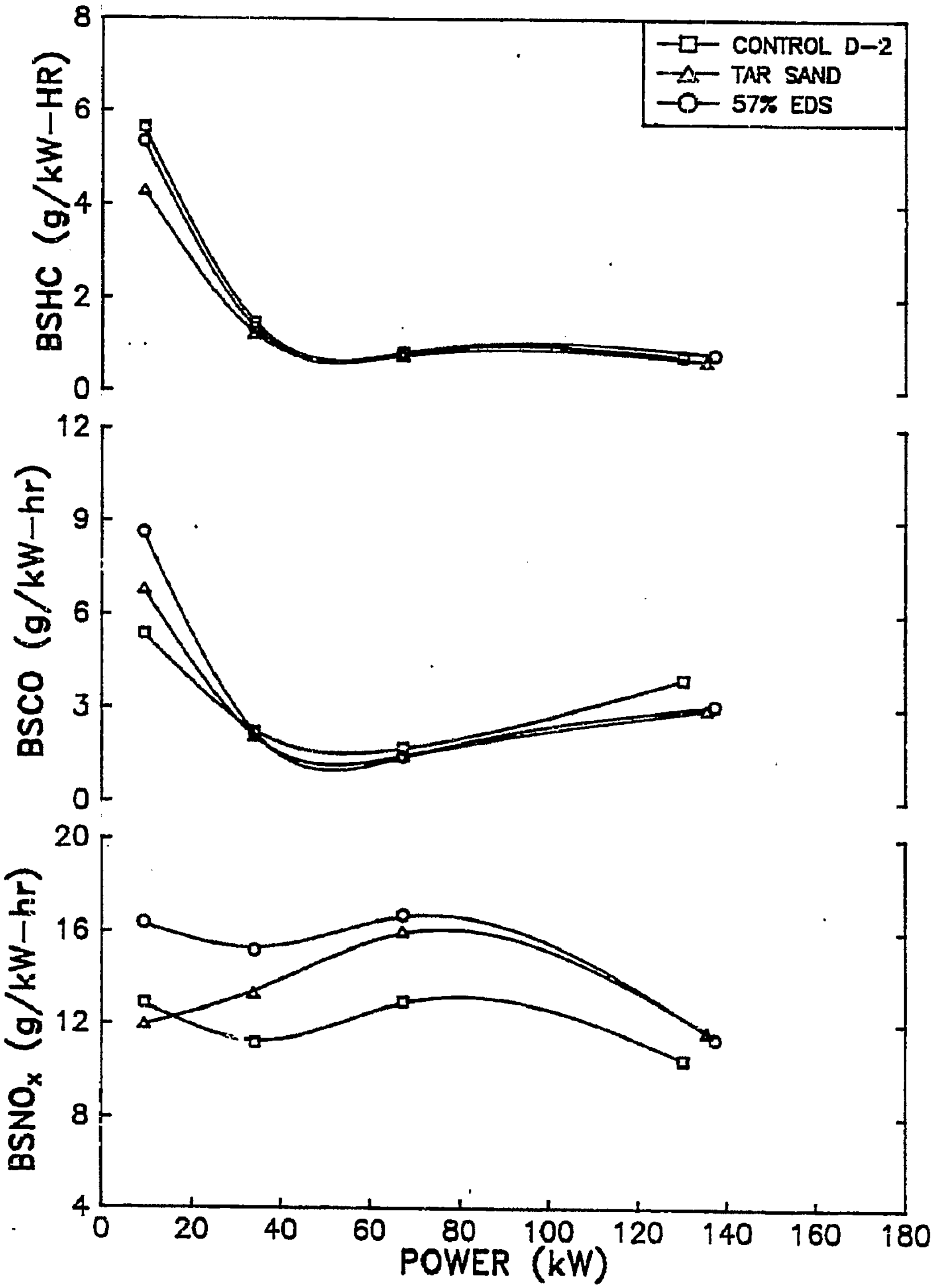


FIGURE 6.39. BRAKE SPECIFIC EMISSIONS AT 1400 RPM, PHASE II SIMULATED AIR-TO-AIR AFTERCOOLER AND HIGH PRESSURE FUEL INJECTION

shown in Figure 6.40. The tar sands fuel has the highest brake thermal efficiency, lowest smoke opacity, and the highest particulate emissions. The 57 percent EDS fuel's performance was equivalent to the control diesel fuel's except for a slight increase in particulate emissions. Compared to Phase I results, the tar sands fuel showed a significant increase in brake thermal efficiency and a reduction in smoke opacity. The control diesel fuel produced more smoke compared to the Phase I result.

Figure 6.41 shows the gaseous emissions results at idle. All three fuels had nearly equivalent gaseous emissions except for the 57 percent EDS fuel which had higher BSCO emissions compared to the other two fuels. The major difference between these results and the Phase I results was a significant reduction in $BSNO_x$ for the two synfuels.

In general, the effect of the two engine modifications can be summarized as follows. Reducing the intake air temperature to 140°F by simulating air-to-air aftercooling had little effect on engine performance but greatly reduced the low load $BSNO_x$ emissions for all three fuels. Adding the high pressure fuel injection system cut the full load smoke and particulate emissions in half while slightly increasing the $BSNO_x$ emissions over the entire load range.

These results suggest that NO_x emissions are more sensitive to intake air temperature while smoke and particulate emissions are a function of fuel/air mixing.

There were two instances where engine modifications were able to improve the synfuel's performance relative to the control diesel fuel's performance. After adding the high pressure fuel injection system at 1400 and 2200 rpm, the two synfuels produced about the same amount of smoke as the control diesel fuel. The tar sands fuel consistently produced the least amount of smoke. This is a great improvement over the Phase I results where these two synfuels produced more smoke than the control diesel fuel. Thus, adding the high pressure fuel system alleviated the Phase I problem of increased synfuel smoke emissions. Adding the high pressure fuel injection system not only improved the performance of the synfuels relative to the diesel fuel, but also greatly reduced the smoke emissions from all three fuels compared to the Phase I results. The second instance also occurred at 1400 and 2200 rpm, where adding the high pressure fuel injection system was successful in reducing the 57 percent EDS fuel's particulate emissions to a point where they were equal to or less than the diesel fuel particulate emissions. The tar sands fuel particulate emissions still remained higher than the diesel fuel particulate emissions.

6.4.4 Combustion Analysis Results, Simulated Air-to-Air Aftercooler and High Pressure Fuel Injection System

The combustion and heat release data at 1400 rpm, 50 percent load is presented in Table 6.3 for the engine with both engine modifications. A complete set of cylinder and fuel injection pressure diagrams corresponding to the simulated air-to-air aftercooled and high pressure fuel-injected engine are given in Appendix P.

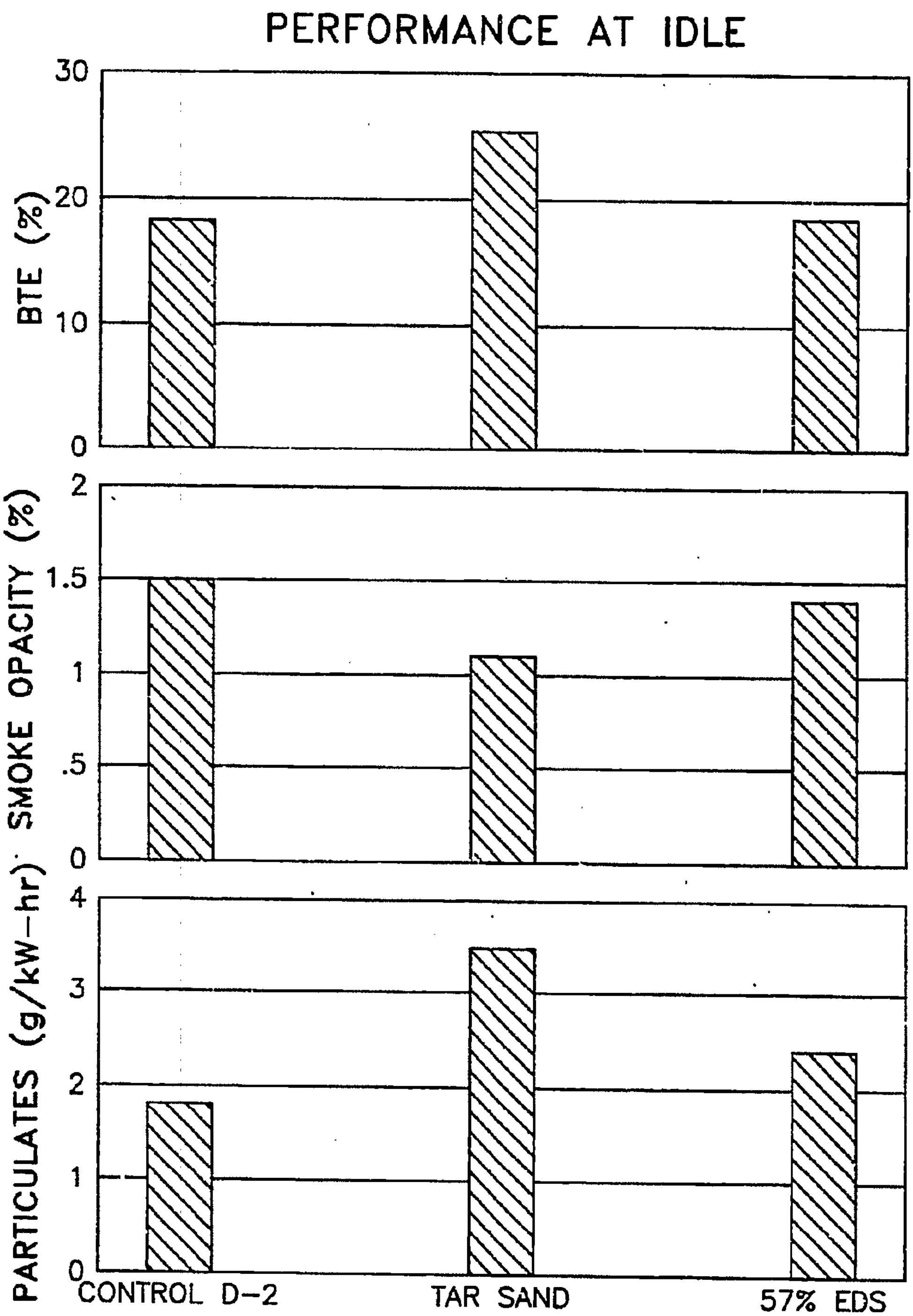


FIGURE 6.40. PERFORMANCE RESULTS AT IDLE PHASE II SIMULATED AIR-TO-AIR AFTERCOOLER AND HIGH PRESSURE FUEL INJECTION SYSTEM

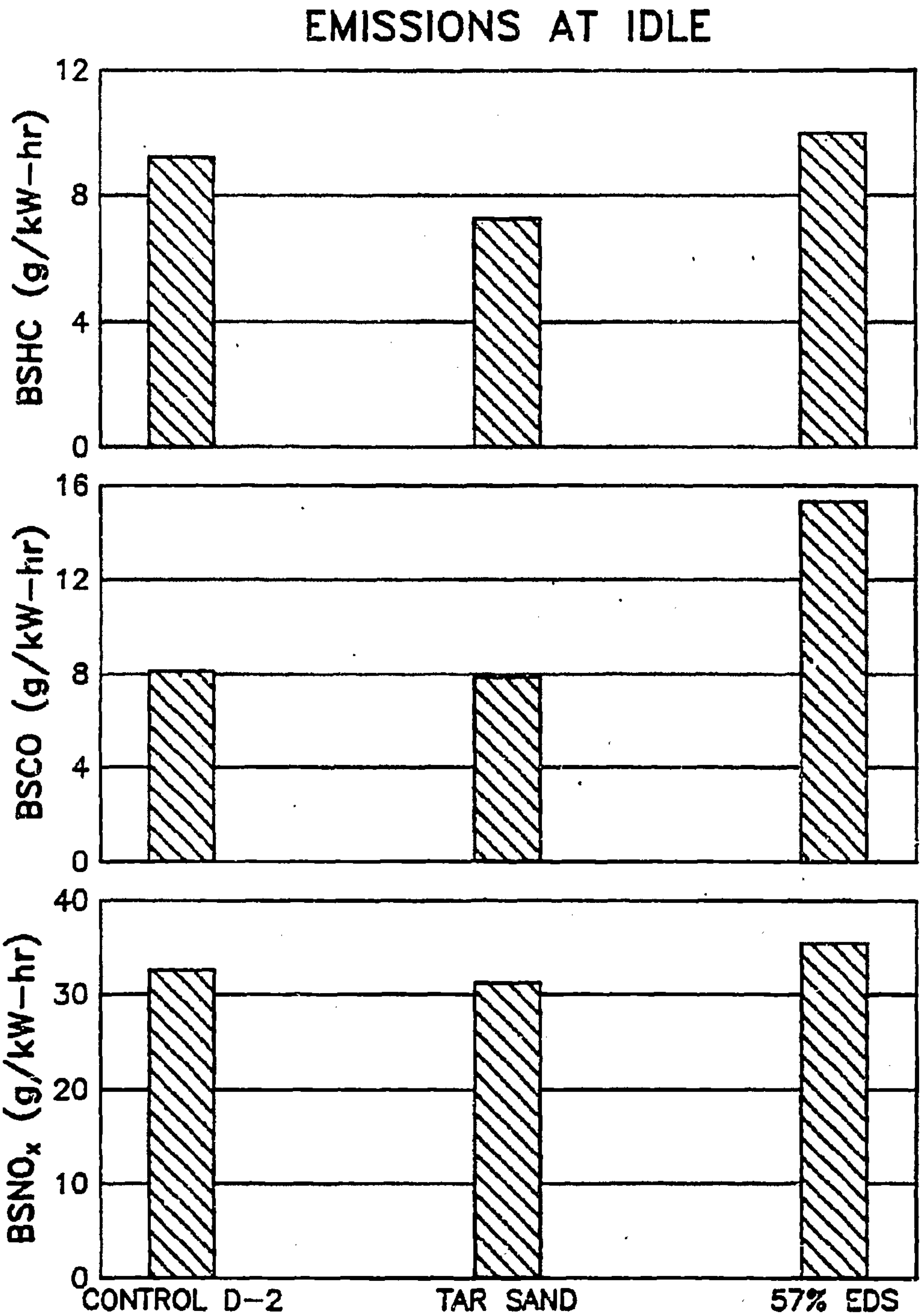


FIGURE 6.41. BRAKE SPECIFIC EMISSIONS AT IDLE, PHASE II SIMULATED AIR-TO-AIR AFTERCOOLER AND HIGH PRESSURE FUEL INJECTION SYSTEM

The heat release rate diagrams are presented in Figures 6.42 and 6.43 for each synfuel compared to the corresponding control diesel fuel result. Figures 6.42, 6.43 and Table 6.3 show that the two synfuels have longer ignition delays and thus higher corresponding heat release rates and maximum and average rates of pressure rise compared to the control diesel fuel. All fuels have similar total heat releases and maximum cylinder pressures. Adding the high pressure fuel injection system slightly improved the synfuel's combustion performance by reducing the tar sands and 57 percent EDS fuel's ignition delays relative to the control diesel fuel's ignition delay. This improvement can be attributed to the high pressure fuel injection system's ability to better atomize the more dense and viscous synfuels. This improved spray atomization increased the rate of fuel-air mixing and reduced the synfuel's physical ignition delay period.

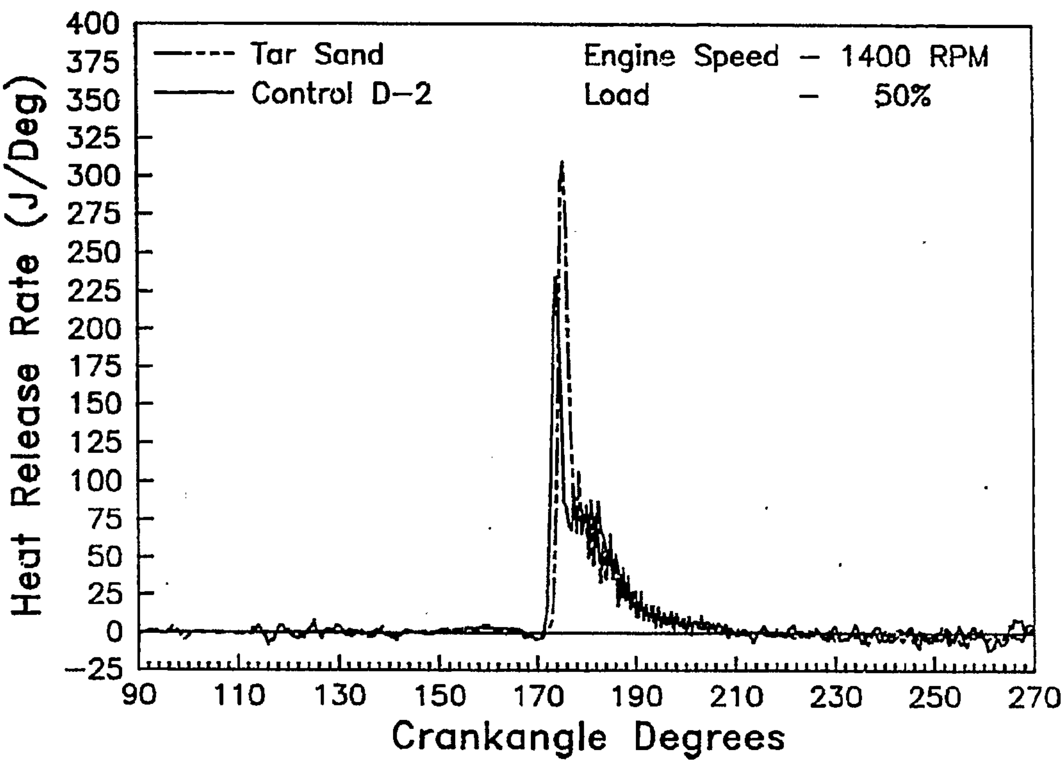


FIGURE 6.42. HEAT RELEASE RATE FOR TAR SANDS AND CONTROL DF-2 FUELS AT 1400 RPM, 50 PERCENT LOAD, SIMULATED AIR-TO-AIR AFTERCOOLER AND HIGH PRESSURE FUEL INJECTION SYSTEM

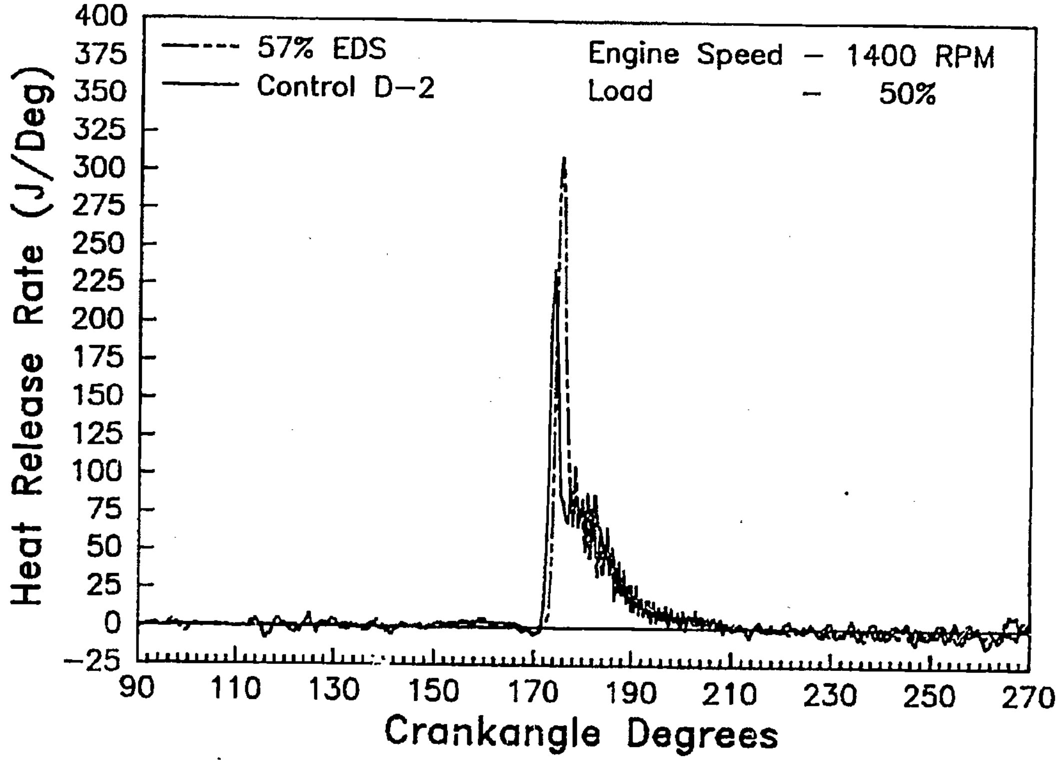


FIGURE 6.43. HEAT RELEASE RATE FOR 57 PERCENT EDS AND CONTROL DF-2 FUELS AT 1400 RPM, 50 PERCENT LOAD, SIMULATED AIR-TO-AIR AFTERCOOLER AND HIGH PRESSURE FUEL INJECTION SYSTEM

Table 6.3. Summary of Combustion and Heat Release Data at 1400 RPM, 50 Percent Load, Simulated Air-to-Air Aftercooler and High Pressure Fuel Injection System

Fuel Type	Maximum Pressure (MPa)	Maximum Rate of Pressure Rise (kPa/deg)	Average Rate of Pressure Rise (kPa/deg)	Total Heat Release (joules)	Ignition Delay (deg)
DF-2	9.63	959.8	340.4	1902	5.2
Tar Sand	9.82	1229.0	395.7	1815	5.6
57% EDS	10.05	1318.0	417.8	1855	6.2

Compared to the Phase I combustion analysis results, the three fuels have slightly lower ignition delay periods and similar total amounts of heat release. However, the maximum cylinder pressure and maximum and average pressure rise rates are higher for the engine with the simulated air-to-air aftercooler and high pressure fuel injection system. It would be expected that the maximum pressure and pressure rise rates would be the same for two operating conditions where the ignition delays and total heat released (quantity of fuel injected) were the same. This can be explained by realizing that the high pressure fuel injection system can inject more fuel into the combustion chamber per crank angle degree. This increased fuel injection rate allows more fuel to accumulate in the combustion chamber prior to autoignition and is responsible for the higher maximum cylinder pressure and higher rates of pressure rise compared to the Phase I results.

The greatest variation in the combustion characteristics between the three fuels is still attributed to the increased ignition delay period of the tar sands and 57 percent EDS fuels relative to the control diesel fuel. Adding the high pressure fuel injection system reduced the synfuel's ignition delay period by reducing the physical delay. Unfortunately, this modification caused the maximum cylinder pressure and pressure rise rates to increase due to the high fuel injection rate which can seriously affect engine durability.

The ignition delay period is primarily governed by the chemical delay period which is a function of the fuel's chemical properties. Engine modifications can be made which will reduce the synfuels' physical delay period. However, it is unlikely that engine modifications can be made which will make the combustion characteristics of the synfuels identical to the control diesel fuel since the combustion of a fuel is more a function of its chemical composition than the particular engine configuration used.

Thus, after adding the two engine modifications (simulating air-to-air aftercooling and high pressure fuel injection system), the tar sands and 57 percent EDS fuels' engine performance were as good as or better than the control diesel fuel's performance with the following exceptions. The two synfuels had higher low load BSCO emissions in all instances except at engine idle where the tar sands fuel had the same BSCO emissions as the control diesel fuel. The two synfuels had higher full load particulate emissions at 2200 rpm and higher $BSNO_x$ emissions across the entire load range at 1400 rpm. The tar sands fuel also had higher full load particulate emissions at 1400 rpm and at engine idle.

6.5 PHASE II COLD START RESULTS AT 0°C AND -20°C

Cold start tests were repeated at 0 and -20°C using an ether injection system and the 57 percent EDS fuel. The cold start data is presented in Appendices L and M. The cold start tests were repeated to reduce this fuel's starting time at 0°C and to verify that the engine would start at -20°C where it failed to start during Phase I tests. Figures 6.44 and 6.45 are plots which show the Phase II results using an ether injection system with the 57 percent EDS fuel. Also shown on these plots for comparison are the 57 percent EDS fuel's Phase I cold starting times. Figure 6.44 shows that at 0°C the engine started in 9.4 seconds and reached maximum speed in 33.2 seconds using the 57 percent EDS

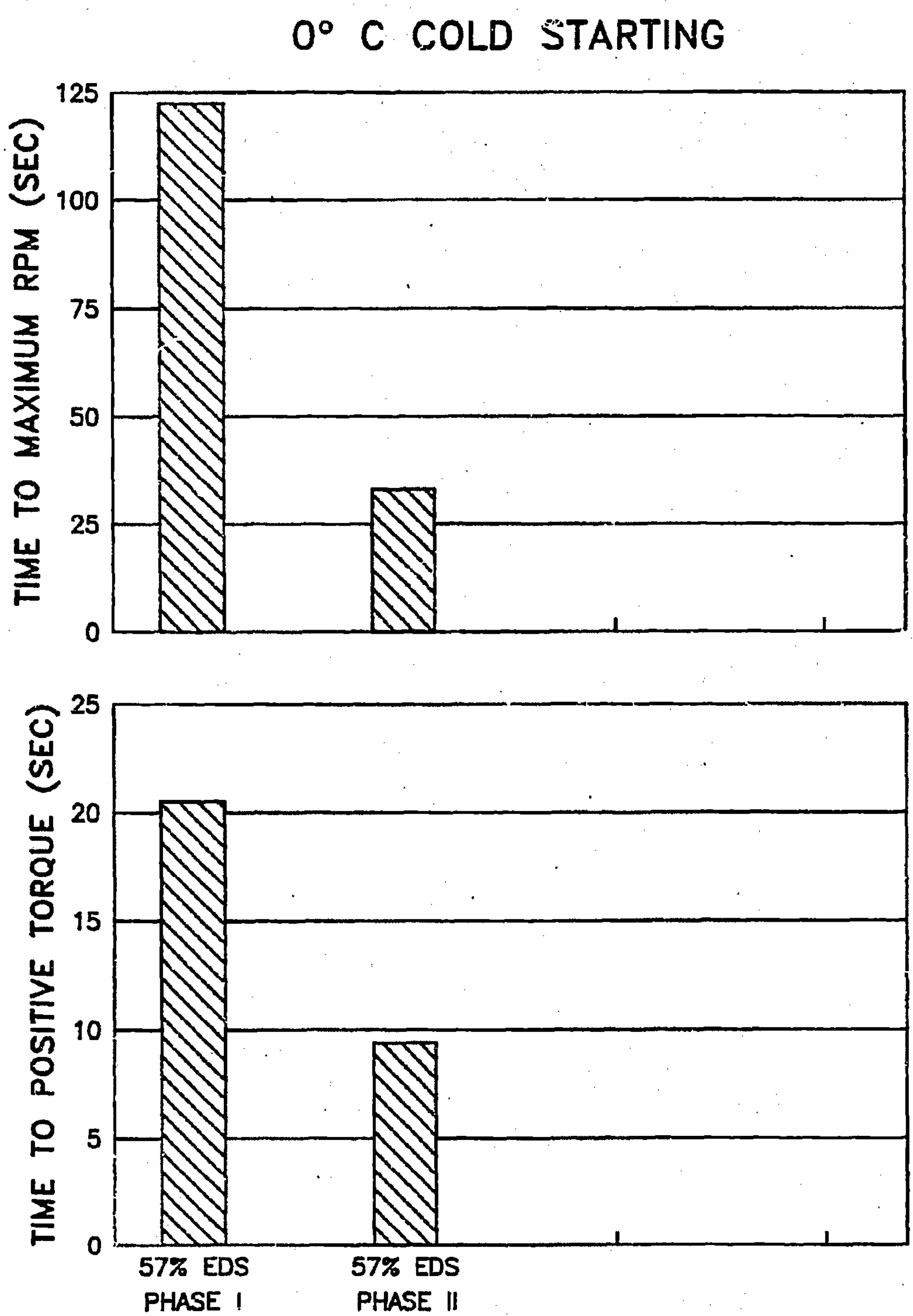


FIGURE 6.44. COLD START DATA AT 0°C, PHASE II WITH ETHER INJECTION COMPARED TO PHASE I

fuel. This is a significant improvement over the Phase I times of 20.5 and 122.5 seconds, respectively.

Figure 6.45 shows that adding the ether injection system enabled the engine to start at -20°C in 25 seconds and reach maximum speed in 67 seconds. Thus adding an ether injection system solved the synfuel cold starting problem encountered during Phase I.

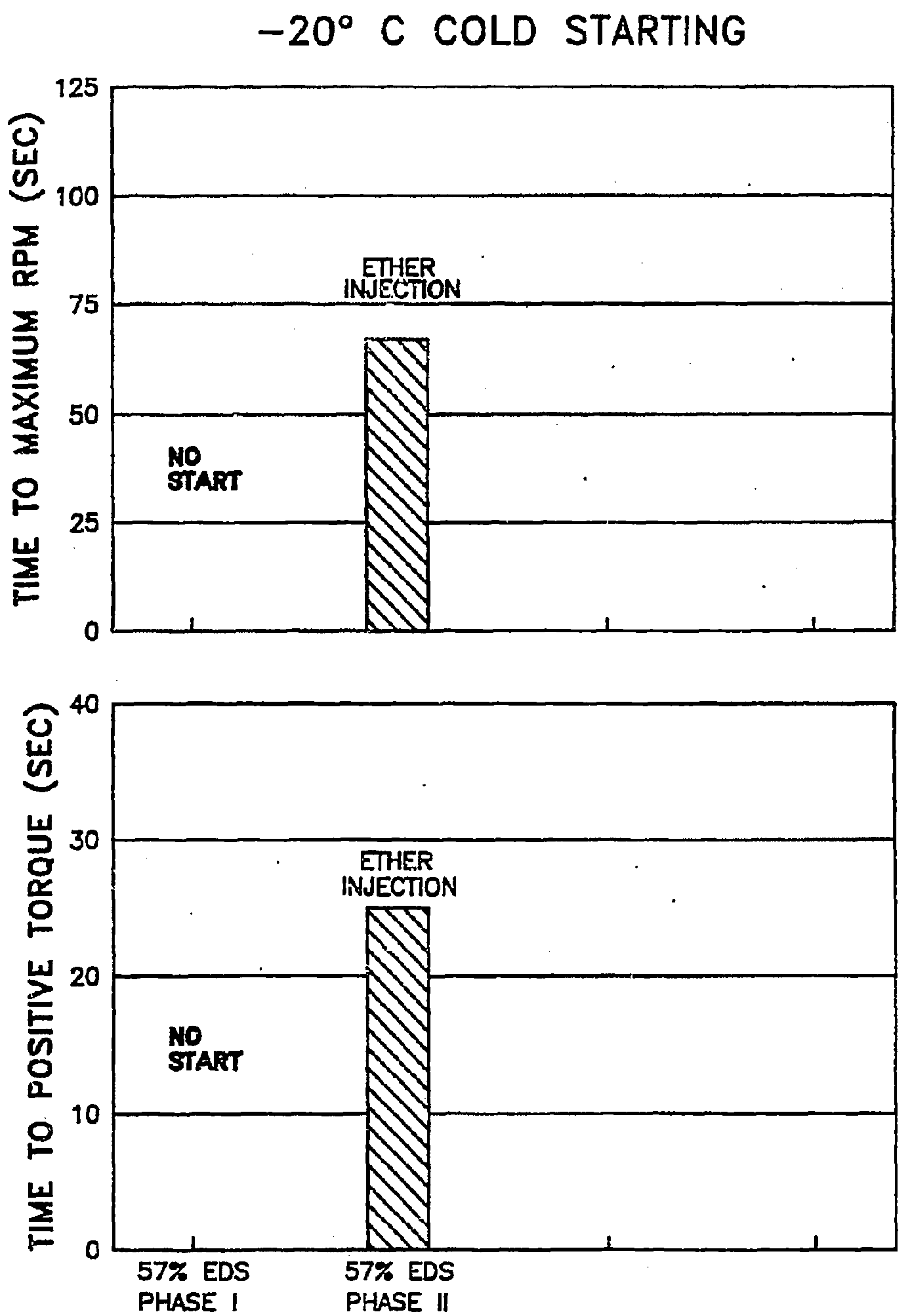


FIGURE 6.45. COLD START DATA AT -20°C, PHASE II WITH EITHER INJECTION COMPARED TO PHASE I

REFERENCES

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4. Callahan, T.J., Ryan, T.W., III, O'Neal, G.B., Waytulonis, R.W., "Control of Diesel Exhaust Emissions in Underground Coal Mines—Single Cylinder Engine Optimization for Water-in-Fuel Microemulsions," SAE Paper 830553.

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APPENDIX A
DIESEL FUEL PERFORMANCE DATA

**** SYNFUEL PROJECT 03-8538 TEST RESULTS ****

BASELINE CONTROL D-2

RUN NUMBER		1	2	3	4	5	6	7	8	9
TEST CODE		11 1 1	11 2 1	11 3 1	11 4 1	11 5 1	11 6.1	11 7 1	11 8 1	11 9 1
DAY	(julian)	5281	5281	5281	5281	5281	5281	5291	5281	5281
TIME	(military)	101528	11 955	131939	143941	15 648	153126	155634	161918	1641 6
PHASE		1	1	1	1	1	1	1	1	1
TYPE FUEL		CONDF2	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2
ENGINE HOURS		46.1	47.1	48.5	49.5	50.0	50.4	50.8	51.2	51.6
ENGINE PARAMETERS										
ENGINE SPEED	(rpm)	835	1398	1397	1402	1397	2197	2195	2196	2200
TORQUE	(N-M)	15.7	854.0	639.8	427.2	214.6	666.5	498.5	332.8	168.0
POWER	(KW)	1.4	125.1	93.6	62.7	31.4	153.3	114.6	76.5	38.7
BSFC	(g/kw-hr)	1278.	237.	227.	235.	266.	231.	239.	258.	316.
BMEP	(bar)	.3	14.0	10.5	7.0	3.5	11.0	8.2	5.5	2.8
BTE	(%)	6.6	35.7	37.2	36.0	31.8	36.6	35.4	32.8	26.8
ENGINE FLOW PARAMETERS										
FUEL FLOW	(kg/hr)	1.8	29.6	21.3	14.8	8.3	35.5	27.4	19.7	12.2
AIR FLOW	(kg/hr)	189.4	574.5	471.2	400.3	348.0	959.5	836.9	712.8	601.4
AIR FUEL RATIO		107.8	19.4	22.1	27.1	41.7	27.1	30.5	36.2	49.2
CHEMICAL AIR FUEL RATIO		119.4	18.7	21.1	26.3	40.8	27.0	30.5	36.1	49.3
SMOKE OPACITY	(%)	.7	15.8	9.4	8.8	3.2	6.2	5.7	5.5	3.9
TEMPERATURE PARAMETERS (deg.c)										
COOLANT IN		84	89	84	87	88	87	91	92	91
COOLANT OUT		86	96	91	91	90	93	94	95	93
OIL SUMP		90	110	107	103	103	112	112	109	107
OIL GALLERY		88	106	103	100	100	108	108	106	104
INTAKE AIR		28	31	32	33	34	35	36	36	35
CELL AMBIENT		45	66	59	54	52	60	58	57	50
BOOST B4 INNER COOLER		46	133	103	80	65	155	129	105	81
BOOST AF INNER COOLER		71	101	91	83	80	112	103	94	87
FUEL IN		33	34	33	34	35	38	39	39	39
EXHAUST #1		138	609	529	443	327	541	504	436	341
EXHAUST #2		114	607	525	428	285	544	483	415	325
EXHAUST #3		139	607	534	453	321	553	486	419	333
EXHAUST #4		141	634	576	490	336	588	530	455	364
EXHAUST #5		147	628	538	451	313	566	510	437	342
EXHAUST #6		150	638	572	446	355	595	518	461	370
EXHAUST STACK		141	607	537	443	319	489	450	400	327
PRESSURE PARAMETERS										
OIL	(kpa)	268.7	306.8	307.7	309.5	309.5	338.9	339.3	340.6	342.1
FUEL	(kpa)	164.4	146.8	153.2	160.4	167.0	112.4	116.0	121.4	127.8
EXHAUST B4 TURBO	(kpa)	******	******	******	******	******	******	******	******	******
FILTER RESTRICTION	(pa)	99.5	373.3	298.6	248.8	224.0	771.4	647.0	522.6	423.0
BOOST AF INNERCOOLER	(kpa)	.9	95.5	55.9	30.3	12.5	118.0	95.0	54.1	27.9
EXHAUST STACK	(kpa)	1.3	4.7	2.0	2.4	2.4	2.7	4.1	4.1	3.7
EMISSION PARAMETERS										
BSHC	(g/kw-hr)	16.201	.4229	.6617	.7329	1.2863	.7996	.9094	1.1821	1.8202
BSCO	(g/kw-hr)	28.790	12.155	4.7144	3.0320	3.7171	1.8686	2.0172	2.6141	4.0530
BSNOx	(g/kw-hr)	84.137	8.9073	10.249	11.252	12.249	8.1383	7.4361	5.3567	5.5295
CO2	(%)	1.7	11.4	10.3	8.2	5.2	8.0	7.0	5.9	4.3
O2	(%)	18.1	4.9	6.8	9.6	13.7	9.9	11.2	12.7	14.8
AMBIENT PARAMETERS										
BARO.PRESSURE	(mm-Hg)	740.4	740.4	740.4	740.4	740.4	740.4	740.4	740.4	740.4
ABSOLUTE HUMIDITY	(gn/lb)	114.7	114.7	112.3	112.3	112.3	112.3	113.5	113.5	113.5
RELATIVE HUMIDITY	(%)	65.7	65.7	54.9	54.9	54.9	54.9	50.4	50.4	50.4
INDICATED PARAMETERS										
IKW		8.2	139.5	108.2	77.6	46.3	185.0	146.2	108.2	70.1
ISFC	(kg/ikw-hr)	214.1	212.3	196.7	190.2	180.4	191.7	187.4	182.2	174.3
IMEP	(bar)	1.5	15.7	12.1	8.7	5.2	13.2	10.4	7.7	5.0
ITE,actual	(%)	39.5	39.8	43.0	44.5	46.9	44.1	45.1	46.4	48.5
ITE,theoretical	(%)	62.9	56.0	56.9	58.2	60.4	58.2	58.9	59.7	61.0
RATIO, actual/theoretical		.628	.711	.755	.764	.776	.758	.767	.777	.795

****** SYNFUEL PROJECT 03-8538 TEST RESULTS ******

BASELINE CONTROL D-2

RUN NUMBER	10	11	12	13	14	15	16	17	18
TEST CODE	11 1 2	11 2 2	11 3 2	11 4 2	11 5 1	11 6 2	11 7 2	11 8 2	11 9 1
DAY (julian)	5303	5303	5303	5303	5303	5304	5304	5305	5305
TIME (military)	103345	1210 4	1420 4	144513	151852	11 9 3	114940	10 330	103331
PHASE	1	1	1	1	1	1	1	1	1
TYPE FUEL	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2
ENGINE HOURS	64.4	65.4	66.5	66.9	67.5	69.2	70.5	72.0	73.3
ENGINE PARAMETERS									
ENGINE SPEED (rpm)	832	1402	1398	1400	1399	2200	2197	2201	2202
TORQUE (N-M)	36.7	916.6	457.2	229.7	64.3	670.7	335.6	168.2	45.5
POWER (KW)	3.2	134.6	66.9	33.7	9.4	154.5	77.2	38.8	10.5
BSFC (g/kw-hr)	258.	217.	228.	253.	407.	231.	256.	306.	637.
BMEP (bar)	.6	15.1	7.5	3.8	1.1	11.0	5.5	2.8	.7
BTE (%)	32.7	39.0	37.1	33.4	20.8	36.6	33.0	27.7	13.3
ENGINE FLOW PARAMETERS									
FUEL FLOW (kg/hr)	.8	29.2	15.3	8.5	3.8	35.7	19.8	11.8	6.7
AIR FLOW (kg/hr)	191.6	609.5	418.4	355.6	330.3	1012.4	745.1	621.5	549.6
AIR FUEL RATIO	231.7	20.9	27.4	41.7	86.2	28.4	37.7	52.5	82.2
CHEMICAL AIR FUEL RATIO	107.3	19.8	26.1	40.1	82.6	28.9	37.6	50.4	78.6
SMOKE OPACITY (%)	.5	14.1	7.9	3.1	.9	5.6	4.8	3.8	3.8
TEMPERATURE PARAMETERS (deg.c)									
COOLANT IN	89	83	87	91	92	88	90	91	92
COOLANT OUT	90	91	91	94	93	93	93	93	94
OIL SUMP	93	109	104	104	100	112	109	106	104
OIL GALLERY	92	104	101	101	98	108	105	105	102
INTAKE AIR	20	22	23	23	24	22	23	20	20
CELL AMBIENT	41	59	52	50	44	59	54	40	41
BOOST B4 INNER COOLER	47	126	76	57	49	146	95	69	57
BOOST AF INNER COOLER	74	97	83	80	78	109	90	83	80
FUEL IN	29	31	31	32	33	34	34	32	33
EXHAUST #1	149	598	462	336	211	538	440	342	246
EXHAUST #2	128	584	441	330	188	525	418	326	232
EXHAUST #3	159	591	450	329	206	532	409	329	249
EXHAUST #4	156	637	482	352	223	571	451	362	274
EXHAUST #5	158	611	468	326	196	548	427	332	244
EXHAUST #6	168	638	464	321	216	590	416	326	280
EXHAUST STACK	175	587	452	326	214	472	386	316	247
PRESSURE PARAMETERS									
OIL (kpa)	264.0	311.4	313.2	313.9	315.4	342.7	345.4	340.7	341.6
FUEL (kpa)	136.9	114.9	123.9	128.7	134.0	75.5	87.1	93.4	97.9
EXHAUST B4 TURBO (kpa)	******	******	******	******	******	******	******	******	******
FILTER RESTRICTION (pa)	124.4	423.0	273.7	224.0	224.0	746.5	572.3	447.9	398.1
BOOST AF INNERCOOLER (kpa)	1.6	102.1	34.2	13.9	5.5	125.1	58.9	30.9	15.7
EXHAUST STACK (kpa)	.7	2.6	1.3	1.3	1.7	4.4	2.7	2.0	1.7
EMISSION PARAMETERS									
BSHC (g/kw-hr)	3.3332	.5848	.7885	1.3252	4.5832	.9507	1.3299	2.4723	8.5192
BSCO (g/kw-hr)	5.9279	9.8713	2.7074	3.4139	8.0320	1.9022	2.8061	4.7408	12.060
BSNOx (g/kw-hr)	19.428	9.4421	13.647	14.665	19.370	10.434	9.2337	8.0178	31.904
CO2 (%)	1.9	10.8	8.2	5.3	2.5	7.4	5.7	4.2	2.6
O2 (%)	19.0	5.3	8.9	13.0	16.9	10.5	13.3	14.7	17.1
AMBIENT PARAMETERS									
BARO.PRESSURE (mm-Hg)	737.9	737.9	736.6	736.6	736.6	735.8	735.8	732.3	732.3
ABSOLUTE HUMIDITY (gn/lb)	59.0	59.0	71.9	71.9	71.9	59.9	59.9	68.5	68.5
RELATIVE HUMIDITY (%)	58.2	58.2	52.0	52.0	52.0	78.0	78.0	66.9	66.9
INDICATED PARAMETERS									
IKW	9.7	149.2	82.1	48.5	23.9	186.5	108.9	70.9	42.5
ISFC (kg/ikw-hr)	85.2	195.5	186.1	175.8	160.6	191.4	181.5	167.2	157.3
IMEP (bar)	1.8	16.7	9.2	5.4	2.6	13.3	7.7	5.0	3.0
ITE,actual (%)	99.2	43.3	45.4	48.1	52.7	44.2	46.6	50.6	53.8
ITE,theoretical (%)	63.7	56.5	58.3	60.4	62.5	58.5	59.9	61.2	62.4
RATIO, actual/theoretical	1.557	.765	.780	.797	.842	.756	.778	.826	.861

**** SYNFUEL PROJECT 03-8538 TEST RESULTS ****

BASELINE CONTROL D-2

RUN NUMBER	19	20	21	22	23	24	25	26	27
TEST CODE	11 1 3	11 2 3	11 3 3	11 4 3	11 5 2	11 6 3	11 7 3	11 8 3	11 9 2
DAY (julian)	5305	5305	5305	5305	5305	5305	5305	5309	5309
TIME (military)	1138 4	123030	13 444	132813	135140	142945	152719	101213	14 256
PHASE	1	1	1	1	1	1	1	1	1
TYPE FUEL	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2	CONDF2
ENGINE HOURS	74.4	75.3	75.8	76.3	76.7	77.3	73.2	80.1	83.1
ENGINE PARAMETERS									
ENGINE SPEED (rpm)	841	1399	1402	1394	1394	2203	2200	2198	2201
TORQUE (N-M)	37.7	896.6	458.7	229.6	64.5	673.7	337.2	168.5	45.3
POWER (KW)	3.3	131.3	67.4	33.5	9.4	155.4	77.7	38.8	10.4
BSFC (g/kw-hr)	480.	225.	226.	249.	388.	229.	250.	311.	632.
BMEP (bar)	.6	14.7	7.5	3.8	1.1	11.1	5.5	2.8	.7
BTE (%)	17.6	37.5	37.5	34.0	21.8	36.9	33.9	27.2	13.4
ENGINE FLOW PARAMETERS									
FUEL FLOW (kg/hr)	1.6	29.6	15.2	8.3	3.7	35.6	19.4	12.0	6.6
AIR FLOW (kg/hr)	192.4	608.3	423.1	355.0	329.2	1020.3	755.4	634.3	559.7
AIR FUEL RATIO	120.8	20.6	27.8	42.6	90.1	28.6	38.9	52.7	84.8
CHEMICAL AIR FUEL RATIO	97.3	19.4	25.9	39.3	80.5	28.4	37.7	51.7	80.2
SMOKE OPACITY (%)	1.0	14.3	8.3	3.9	1.5	6.0	5.1	3.0	2.3
TEMPERATURE PARAMETERS (deg.c)									
COOLANT IN	91	85	87	91	92	88	90	91	92
COOLANT OUT	93	93	91	94	94	93	94	93	93
OIL SUMP	96	110	106	104	99	112	106	106	104
OIL GALLERY	94	105	102	101	98	108	103	103	102
INTAKE AIR	21	22	21	21	21	21	20	21	26
CELL AMBIENT	39	63	53	49	47	55	52	43	51
BOOST B4 INNER COOLER	44	127	75	56	46	146	91	70	62
BOOST AF INNER COOLER	74	98	82	79	77	109	90	84	82
FUEL IN	33	32	33	33	33	35	34	31	34
EXHAUST #1	159	598	463	344	209	534	433	337	251
EXHAUST #2	144	590	450	330	185	528	407	319	221
EXHAUST #3	167	596	451	331	205	530	411	330	243
EXHAUST #4	165	637	484	353	226	569	444	360	283
EXHAUST #5	165	613	465	327	282	550	425	344	248
EXHAUST #6	171	636	464	324	224	597	423	324	278
EXHAUST STACK	164	592	454	328	214	472	379	316	247
PRESSURE PARAMETERS									
OIL (kpa)	254.6	304.7	306.7	307.4	309.1	335.8	340.4	347.4	348.9
FUEL (kpa)	123.6	107.5	126.2	132.3	136.5	80.1	69.9	95.8	100.6
EXHAUST B4 TURBO (kpa)	******	******	******	******	******	******	******	******	******
FILTER RESTRICTION (pa)	124.4	447.9	298.6	248.8	224.0	846.1	597.2	472.8	472.8
BOOST AF INNERCOOLER (kpa)	1.3	101.5	35.4	14.3	5.7	126.4	60.3	32.8	17.3
EXHAUST STACK (kpa)	1.7	2.4	2.0	1.7	1.7	2.7	2.4	2.0	2.4
EMISSION PARAMETERS									
BSHC (g/kw-hr)	7.0823	.7271	1.0561	1.4150	4.7053	1.2534	1.6237	2.2953	13.177
BSCO (g/kw-hr)	9.0189	9.3683	2.6738	3.3345	6.8555	1.9117	2.6833	4.4346	11.279
BSNOx (g/kw-hr)	36.817	9.7078	12.836	14.019	18.111	9.7951	9.1037	9.2868	13.333
CO2 (%)	2.1	11.1	8.3	5.4	2.6	7.5	5.6	4.1	2.6
O2 (%)	17.8	5.6	9.5	13.5	16.9	10.4	12.8	14.8	17.1
AMBIENT PARAMETERS									
BARO.PRESSURE (mm-Hg)	732.8	732.8	732.8	732.8	732.8	732.8	732.8	745.7	745.7
ABSOLUTE HUMIDITY (gn/lb)	74.2	74.2	74.2	74.2	74.2	74.2	74.2	43.3	50.4
RELATIVE HUMIDITY (%)	61.1	61.1	61.1	61.1	61.1	61.1	61.1	31.9	35.9
INDICATED PARAMETERS									
IKW	10.4	146.2	82.1	48.5	23.9	187.2	109.7	70.9	42.5
ISFC (kg/ikw-hr)	152.5	202.4	185.4	171.9	153.0	190.4	176.9	169.9	155.2
IMEP (bar)	1.9	16.4	9.2	5.4	2.7	13.3	7.8	5.0	3.0
ITE,actual (%)	55.4	41.8	45.6	49.2	55.3	44.4	47.8	49.8	54.5
ITE,theoretical (%)	63.1	56.4	58.4	60.5	62.6	58.5	60.1	61.3	62.5
RATIO, actual/theoretical	.879	.741	.782	.814	.882	.759	.796	.813	..872

APPENDIX B
SHALE FUEL PERFORMANCE DATA

**** SYNFUEL PROJECT 03-8538 TEST RESULTS ****

SHALE PERFORMANCE TEST

RUN NUMBER	28	29	30	31	32	33	34	35	36
TEST CODE	12 1 1	12 2 1	12 3 1	12 4 1	12 5 1	12 6 1	12 7 1	12 8 1	12 9 1
DAY (julian)	5310	5310	5310	5310	5310	5310	5310	5310	5310
TIME (military)	94218	103844	11 850	113319	115651	131017	133554	1356 9	142623
PHASE	1	1	1	1	1	1	1	1	1
TYPE FUEL	SHALE	SHALE	SHALE	SHALE	SHALE	SHALE	SHALE	SHALE	SHALE
ENGINE HOURS	85.0	85.9	86.4	86.8	87.2	88.4	88.8	89.2	89.7
ENGINE PARAMETERS									
ENGINE SPEED (rpm)	925	1403	1400	1396	1393	2200	2196	2197	2191
TORQUE (N-M)	37.4	883.3	459.3	230.2	65.4	652.0	335.8	168.4	45.4
POWER (KW)	3.2	129.7	67.3	33.6	9.5	150.2	77.2	38.7	10.4
BSFC (g/kw-hr)	527.	223.	226.	247.	380.	231.	253.	308.	629.
BMEP (bar)	.6	14.5	7.6	3.9	1.1	10.7	5.5	2.9	.7
BTE (%)	15.9	37.5	36.9	33.9	22.0	36.1	33.0	27.1	13.3
ENGINE FLOW PARAMETERS									
FUEL FLOW (kg/hr)	1.7	28.9	15.2	8.3	3.6	34.7	19.6	11.9	6.6
AIR FLOW (kg/hr)	191.0	612.1	424.0	358.3	333.6	996.4	747.3	624.5	552.8
AIR FUEL RATIO	112.4	21.2	27.8	43.1	91.9	28.7	38.2	52.3	94.4
CHEMICAL AIR FUEL RATIO	100.6	20.2	26.5	40.2	82.9	28.8	38.0	50.6	79.8
SMOKE OPACITY (%)	.6	11.1	8.0	3.1	.7	5.1	4.6	3.6	2.2
TEMPERATURE PARAMETERS (deg.c)									
COOLANT IN	91	83	90	91	92	88	90	91	92
COOLANT OUT	92	91	94	94	93	92	93	93	94
OIL SUMP	94	110	106	103	99	112	108	106	104
OIL GALLERY	93	105	103	101	98	108	105	103	102
INTAKE AIR	19	21	22	24	23	30	30	30	30
CELL AMBIENT	43	53	56	51	50	52	49	48	47
BOOST B4 INNER COOLER	48	123	75	58	49	150	100	78	65
BOOST AF INNER COOLER	76	96	83	80	78	110	92	86	83
FUEL IN	29	30	32	32	33	34	35	35	36
EXHAUST #1	163	594	473	345	212	539	442	355	256
EXHAUST #2	152	573	455	333	192	531	424	335	224
EXHAUST #3	168	586	448	332	206	537	414	343	257
EXHAUST #4	170	629	488	354	221	574	459	369	283
EXHAUST #5	162	601	462	329	202	555	431	353	259
EXHAUST #6	160	637	466	335	232	602	435	344	278
EXHAUST STACK	178	584	457	331	216	482	394	329	254
PRESSURE PARAMETERS									
OIL (kpa)	258.7	312.3	314.0	315.3	316.9	342.5	345.0	346.1	347.2
FUEL (kpa)	129.1	113.7	126.4	134.3	143.3	85.3	93.4	98.9	104.5
EXHAUST B4 TURBO (kpa)	******	******	******	******	******	******	******	******	******
FILTER RESTRICTION (pa)	124.4	497.7	348.4	298.6	273.7	1045.1	746.5	597.2	522.6
BOOST AF INNERCOOLER(kpa)	2.6	99.9	36.1	15.1	6.9	119.8	58.7	31.3	16.7
EXHAUST STACK (kpa)	1.0	2.7	2.0	2.0	2.0	4.4	2.7	3.4	3.4
EMISSION PARAMETERS									
BSHC (g/kw-hr)	11.268	.8264	1.1206	1.9319	6.1940	1.3965	1.9107	2.9910	11.283
BSCO (g/kw-hr)	9.8912	8.3406	3.0259	3.0590	6.1434	2.0175	2.7437	4.1636	11.798
BSNOx (g/kw-hr)	52.386	9.3528	12.356	12.024	15.292	8.5719	7.4350	7.0441	11.936
CO2 (%)	2.0	10.6	8.0	5.2	2.5	7.4	5.5	4.1	2.6
O2 (%)	17.4	5.5	8.9	13.3	16.9	9.9	12.3	14.8	16.9
AMBIENT PARAMETERS									
BARO.PRESSURE (mm-Hg)	740.7	740.7	740.7	740.7	740.7	740.7	739.9	739.9	739.9
ABSOLUTE HUMIDITY (gn/lb)	56.1	56.1	56.1	56.1	56.1	56.1	71.4	71.4	71.4
RELATIVE HUMIDITY (%)	68.6	68.6	68.6	68.6	68.6	68.6	47.0	47.0	47.0
INDICATED PARAMETERS									
IKW	9.7	144.7	82.1	48.5	23.9	182.0	108.9	70.1	41.8
ISFC (kg/ikw-hr)	175.3	199.9	185.6	171.3	152.0	190.8	179.6	170.2	156.8
IMEP (bar)	1.8	16.2	9.2	5.4	2.7	13.0	7.7	5.0	3.0
ITE,actual (%)	47.7	41.8	45.0	48.8	55.0	43.8	46.5	49.1	53.3
ITE,theoretical (%)	63.0	56.6	58.4	60.5	62.7	58.5	60.0	61.2	62.5
RATIO, actual/theoretical	.757	.738	.771	.806	.877	.748	.776	.802	.853

**** SYNFUEL PROJECT 03-8538 TEST RESULTS ****

SHALE PERFORMANCE TEST

RUN NUMBER		37	38	39	40	41	42	43	44	45
TEST CODE		12 1 2	12 2 2	12 3 2	12 4 2	12 5 2	12 6 2	12 7 2	12 8 2	12 9 2
DAY	(julian)	5311	5311	5311	5311	5311	5311	5311	5311	5311
TIME	(military)	93840	1045 9	1112 1	1138 9	12 029	124944	1316 4	1342 3	14 546
PHASE		1	1	1	1	1	1	1	1	1
TYPE FUEL		SHALE	SHALE	SHALE	SHALE	SHALE	SHALE	SHALE	SHALE	SHALE
ENGINE HOURS		92.2	93.3	93.8	94.2	94.6	95.4	95.8	96.2	96.6
ENGINE PARAMETERS										
ENGINE SPEED	(rpm)	823	1396	1398	1405	1393	2198	2202	2201	2199
TORQUE	(N-M)	37.4	868.8	458.1	230.2	64.1	649.7	335.6	168.3	45.5
POWER	(KW)	3.2	127.0	67.0	33.9	9.3	149.5	77.4	38.8	10.5
BSFC	(g/kw-hr)	519.	225.	230.	253.	401.	234.	257.	319.	663.
BMEP	(bar)	.6	14.3	7.5	3.8	1.1	10.7	5.5	2.8	.7
BTE	(%)	16.1	37.2	36.3	33.1	20.9	35.8	32.5	26.2	12.6
ENGINE FLOW PARAMETERS										
FUEL FLOW	(kg/hr)	1.7	28.5	15.4	8.6	3.7	34.9	19.9	12.4	7.0
AIR FLOW	(kg/hr)	192.8	600.8	426.7	365.1	337.5	1006.3	758.2	633.1	561.3
AIR FUEL RATIO		115.4	21.1	27.7	42.7	90.1	28.8	38.2	51.2	80.7
CHEMICAL AIR FUEL RATIO		100.3	20.1	26.5	40.6	83.1	29.0	38.0	50.6	79.0
SMOKE OPACITY	(%)	1.0	12.4	8.1	3.5	1.2	5.1	4.9	3.9	2.9
TEMPERATURE PARAMETERS (deg.c)										
COOLANT IN		92	81	89	91	92	97	90	91	92
COOLANT OUT		93	89	92	93	93	92	93	93	93
OIL SUMP		95	109	105	102	99	111	108	106	104
OIL GALLERY		94	104	102	100	97	107	105	103	101
INTAKE AIR		18	23	23	24	23	27	27	27	27
CELL AMBIENT		47	36	33	31	29	38	36	35	33
BOOST B4 INNER COOLER		40	122	75	56	48	146	98	75	62
BOOST AF INNER COOLER		74	95	82	79	77	108	91	85	81
FUEL IN		30	31	31	32	32	35	36	34	34
EXHAUST #1		169	589	466	336	210	530	438	349	259
EXHAUST #2		137	573	448	325	181	525	419	333	226
EXHAUST #3		143	586	450	331	198	529	412	340	255
EXHAUST #4		169	628	486	352	229	567	456	368	280
EXHAUST #5		165	593	463	338	208	548	430	352	266
EXHAUST #6		158	633	455	322	230	596	437	341	275
EXHAUST STACK		159	582	451	323	214	474	390	325	251
PRESSURE PARAMETERS										
OIL	(kpa)	256.1	312.6	314.6	316.4	317.3	342.3	344.6	345.9	347.4
FUEL	(kpa)	130.8	110.8	125.9	135.2	142.3	84.7	92.9	97.8	103.6
EXHAUST B4 TURBO	(kpa)	******	******	******	******	******	******	******	******	******
FILTER RESTRICTION	(pa)	149.3	622.1	447.9	398.1	373.3	1318.9	970.5	796.3	721.6
BOOST AF INNERCOOLER	(kpa)	2.4	96.3	35.9	15.5	6.7	120.2	59.3	31.7	17.1
EXHAUST STACK	(kpa)	1.0	2.4	1.7	1.7	1.7	4.4	3.0	2.7	2.4
EMISSION PARAMETERS										
BSHC	(g/kw-hr)	9.7490	.8846	1.0927	1.8960	6.2877	1.3442	1.7599	3.0676	11.266
BSCO	(g/kw-hr)	10.125	8.3796	2.7671	3.1175	6.6406	1.9832	2.6012	4.2938	12.283
BSNOx	(g/kw-hr)	45.807	9.8267	12.932	12.696	17.333	8.3117	7.6283	8.0434	13.690
CO2	(%)	2.0	10.6	8.0	5.2	2.5	7.4	5.5	4.1	2.6
O2	(%)	16.8	5.4	9.0	13.3	17.0	10.2	12.9	14.8	16.8
AMBIENT PARAMETERS										
BARO.PRESSURE	(mm-Hg)	743.7	743.7	743.7	743.7	746.5	746.5	746.5	746.5	746.5
ABSOLUTE HUMIDITY	(gn/lb)	50.8	50.8	50.8	50.8	53.6	53.6	53.6	53.6	53.6
RELATIVE HUMIDITY	(%)	56.2	56.2	56.2	56.2	40.8	40.8	40.8	40.8	40.8
INDICATED PARAMETERS										
IKW		9.7	141.7	82.1	48.5	23.9	181.3	108.9	70.9	42.5
ISFC	(kg/ikw-hr)	172.3	201.3	187.9	176.4	156.9	192.7	182.4	174.6	163.5
IMEP	(bar)	1.8	15.9	9.2	5.4	2.7	12.9	7.7	5.0	3.0
ITE,actual	(%)	48.5	41.5	44.5	47.4	53.3	43.4	45.8	47.9	51.1
ITE,theoretical	(%)	63.0	56.6	58.3	60.5	62.6	58.6	60.0	61.2	62.4
RATIO, actual/theoretical		.769	.734	.762	.783	.850	.741	.764	.783	.819

APPENDIX C
TAR SANDS PERFORMANCE DATA

**** SYNFUEL PROJECT 03-8538 TEST RESULTS ****

TARSAND PERFORMANCE TEST

RUN NUMBER	46	47	48	49	50	51	52	53	54
TEST CODE	13 3 1	13 2 1	13 3 1	13 4 1	13 5 1	13 6 1	13 7 1	13 8 1	13 9 1
DAY (julian)	5312	5312	5312	5312	5312	5312	5312	5312	5312
TIME (military)	93515	103113	105245	1125 1	12 1 6	125051	1337 1	141534	144150
PHASE	1	1	1	1	1	1	1	1	1
TYPE FUEL	TARSAN	TARSAN	TARSAN	TARSAN	TARSAN	TARSAN	TARSAN	TARSAN	TARSAN
ENGINE HOURS	99.0	99.9	100.3	100.8	101.4	102.2	103.0	103.6	104.0
ENGINE PARAMETERS									
ENGINE SPEED (rpm)	831	1402	1400	1404	1407	2201	2204	2194	2200
TORGUE (N-M)	36.8	921.1	457.2	230.9	45.5	695.3	336.4	167.5	45.7
POWER (kW)	3.2	135.2	67.0	34.0	6.7	160.3	77.6	38.5	10.5
BSFC (g/kw-hr)	557.	227.	232.	260.	520.	231.	261.	319.	660.
BMEP (bar)	.6	15.2	7.5	3.8	.7	11.4	5.5	2.8	.8
BTE (%)	15.5	38.1	37.2	33.2	16.6	37.3	33.1	27.1	13.1
ENGINE FLOW PARAMETERS									
FUEL FLOW (kg/hr)	1.8	30.6	15.6	9.8	3.5	37.1	20.2	12.3	6.9
AIR FLOW (kg/hr)	194.1	616.4	419.9	359.3	335.8	1022.2	763.1	624.3	556.1
AIR FUEL RATIO	108.7	20.1	27.0	40.7	96.4	27.6	37.7	50.9	80.1
CHEMICAL AIR FUEL RATIO	94.6	18.8	25.2	37.5	88.9	27.0	36.7	49.6	78.3
SMOKE OPACITY (%)	1.3	20.9	8.5	2.2	1.4	8.4	6.8	4.1	1.7
TEMPERATURE PARAMETERS (deg.c)									
COOLANT IN	91	86	88	91	90	87	90	92	92
COOLANT OUT	92	93	93	94	92	92	93	94	94
OIL SUMP	96	109	106	103	98	110	108	106	104
OIL GALLERY	94	105	102	101	96	106	105	103	102
INTAKE AIR	21	24	24	24	25	27	28	28	27
CELL AMBIENT	25	38	32	30	29	37	36	33	33
BOOST B4 INNER COOLER	51	129	75	56	48	151	100	74	62
BOOST AF INNER COOLER	75	97	82	78	76	110	92	84	82
FUEL IN	29	32	32	33	33	34	36	35	35
EXHAUST #1	172	616	462	332	194	547	443	342	250
EXHAUST #2	145	589	444	327	179	549	408	325	221
EXHAUST #3	176	607	456	333	185	543	421	347	245
EXHAUST #4	182	651	493	351	215	593	453	360	282
EXHAUST #5	159	627	464	329	177	559	442	349	262
EXHAUST #6	168	646	464	321	199	606	462	349	282
EXHAUST STACK	187	602	452	320	195	486	397	324	248
PRESSURE PARAMETERS									
OIL (kpa)	257.4	311.4	312.7	313.8	315.9	341.0	342.3	343.4	345.3
FUEL (kpa)	169.8	94.3	119.9	130.2	134.1	81.6	92.6	98.7	103.1
EXHAUST B4 TURBO (kpa)	******	******	******	******	******	******	******	******	******
FILTER RESTRICTION (pa)	199.1	821.2	547.4	323.5	423.0	1592.6	1119.8	895.8	796.3
BOOST AF INNERCOOLER (kpa)	2.8	103.7	34.5	14.1	5.8	126.2	60.9	30.7	16.2
EXHAUST STACK (kpa)	1.3	2.7	2.0	2.0	2.0	5.1	3.4	3.4	3.0
EMISSION PARAMETERS									
BSHC (g/kw-hr)	8.9295	.6381	.9289	1.5290	8.5700	1.0730	1.4644	2.7626	10.376
BSCO (g/kw-hr)	11.250	10.508	3.0133	2.9389	11.026	1.8249	2.6102	4.4574	14.209
BSNOx (g/kw-hr)	61.653	9.2246	12.905	14.618	26.599	8.9348	7.5452	9.0674	16.139
CO2 (%)	2.2	11.5	8.6	5.7	2.3	8.1	5.9	4.3	2.7
O2 (%)	17.0	4.9	8.6	12.9	17.2	9.4	12.9	14.9	17.0
AMBIENT PARAMETERS									
BARO.PRESSURE (mm-Hg)	745.0	745.0	745.0	745.0	745.0	745.5	745.5	745.5	745.5
ABSOLUTE HUMIDITY (gn/lb)	74.4	74.4	74.4	74.4	74.4	125.2	125.2	125.2	125.2
RELATIVE HUMIDITY (%)	64.4	64.4	64.4	64.4	64.4	79.4	79.4	79.4	79.4
INDICATED PARAMETERS									
IKW	9.7	149.9	82.1	48.5	21.6	192.5	109.7	70.1	42.5
ISFC (kg/ikw-hr)	184.2	204.4	189.6	182.0	161.0	192.5	184.6	174.9	163.3
IMEP (bar)	1.8	16.8	9.2	5.4	2.4	13.7	7.8	5.0	3.0
ITE,actual (%)	46.9	42.2	45.5	47.4	53.6	44.8	46.8	49.3	52.8
ITE,theoretical (%)	63.0	56.3	58.2	60.3	62.8	58.3	59.9	61.1	62.4
RATIO, actual/theoretical	.744	.750	.782	.787	.854	.769	.780	.807	.847

**** SYNFUEL PROJECT 83-8538 TEST RESULTS ****

TARSAND PERFORMANCE TEST

RUN NUMBER	56	57	58	59	60	61	62	63	64
TEST CODE	13 1 2	13 2 2	13 3 2	13 4 2	13 5 3	13 6 2	13 7 2	13 8 2	13 9 2
DAY (julian)	5315	5315	5315	5315	5315	5315	5315	5315	5315
TIME (military)	13 838	135053	14 916	142648	145224	151431	153440	155353	1615 0
PHASE	1	1	1	1	1	1	1	1	1
TYPE FUEL	TARSAN	TARSAN	TARSAN	TARSAN	TARSAN	TARSAN	TARSAN	TARSAN	TARSAN
ENGINE HOURS	106.4	107.1	107.4	107.8	108.2	108.5	108.9	109.2	109.6
ENGINE PARAMETERS									
ENGINE SPEED (rpm)	837	1396	1397	1403	1393	2195	2194	2203	2196
TORQUE (N-M)	36.8	905.4	460.2	230.0	64.0	678.1	336.3	168.4	44.9
POWER (KW)	3.2	132.3	67.3	33.8	9.3	155.9	77.3	38.8	10.3
BSFC (g/kw-hr)	594.	230.	234.	261.	439.	233.	258.	321.	687.
BMEP (bar)	.6	14.9	7.6	3.8	1.1	11.2	5.5	2.8	.7
BTE (%)	14.5	37.5	36.9	33.0	19.6	37.0	33.4	26.9	12.6
ENGINE FLOW PARAMETERS									
FUEL FLOW (kg/hr)	1.9	30.5	15.7	8.8	4.1	36.4	20.0	12.5	7.1
AIR FLOW (kg/hr)	194.3	600.0	417.4	354.7	329.8	1012.0	749.1	624.9	549.7
AIR FUEL RATIO	101.2	19.7	26.5	40.2	80.4	27.8	37.5	50.1	77.5
CHEMICAL AIR FUEL RATIO	95.4	18.8	25.1	38.4	78.9	27.4	36.8	49.3	77.1
SMOKE OPACITY (%)	1.5	21.8	8.7	2.4	1.5	8.7	6.1	4.0	1.7
TEMPERATURE PARAMETERS (deg.c)									
COOLANT IN	91	86	88	91	92	88	90	92	92
COOLANT OUT	92	93	92	93	93	92	93	94	94
OIL SUMP	94	110	106	103	98	111	108	106	104
OIL GALLERY	93	105	102	100	97	107	105	104	102
INTAKE AIR	24	26	26	25	24	26	25	23	23
CELL AMBIENT	26	37	33	30	27	35	32	32	31
BOOST B4 INNER COOLER	43	129	77	57	47	149	96	71	58
BOOST AF INNER COOLER	73	98	83	78	76	110	90	84	81
FUEL IN	30	32	33	33	33	35	37	36	34
EXHAUST #1	155	618	463	326	214	543	435	346	244
EXHAUST #2	139	599	449	318	192	541	409	331	223
EXHAUST #3	158	613	467	320	197	536	410	341	244
EXHAUST #4	168	651	495	345	215	592	452	356	281
EXHAUST #5	159	626	482	329	208	555	432	341	257
EXHAUST #6	164	625	441	346	216	604	457	355	280
EXHAUST STACK	155	604	457	319	206	483	392	322	247
PRESSURE PARAMETERS									
OIL (kpa)	262.8	313.1	314.8	316.6	317.8	343.2	344.5	346.1	347.4
FUEL (kpa)	167.8	83.1	115.1	126.2	131.9	76.0	86.0	91.8	97.0
EXHAUST B4 TURBO (kpa)	******	******	******	******	******	******	******	******	******
FILTER RESTRICTION (pa)	248.8	895.8	597.2	497.7	472.8	1741.9	1244.2	1045.1	920.7
BOOST AF INNERCOOLER(kpa)	1.0	99.4	33.8	13.0	5.1	124.8	58.9	30.7	15.2
EXHAUST STACK (kpa)	.3	2.0	.7	.7	.3	4.4	2.0	1.3	1.0
EMISSION PARAMETERS									
BSHC (g/kw-hr)	10.344	.7648	.8233	1.4788	5.1910	1.0782	1.2454	2.2384	9.3537
BSCO (g/kw-hr)	13.462	10.834	3.0630	2.8269	8.1531	1.8128	2.4868	4.4412	14.769
BSNOx (g/kw-hr)	57.560	9.1030	10.326	14.131	22.401	7.8636	7.3698	6.7748	12.780
CO2 (%)	2.2	11.5	8.7	5.6	2.7	7.9	5.9	4.3	2.7
O2 (%)	17.7	5.1	9.2	13.0	16.9	10.0	12.8	14.9	16.9
AMBIENT PARAMETERS									
BARO.PRESSURE (mm-Hg)	743.5	743.5	743.5	743.5	743.5	741.9	741.9	741.9	741.9
ABSOLUTE HUMIDITY (gn/lb)	98.7	98.7	98.7	98.7	98.7	93.3	93.3	93.3	93.3
RELATIVE HUMIDITY (%)	74.1	74.1	74.1	74.1	74.1	77.4	77.4	77.4	77.4
INDICATED PARAMETERS									
IKW	10.4	147.0	62.1	48.5	23.9	187.2	108.9	70.9	41.8
ISFC (kg/ikw-hr)	183.7	207.3	191.8	[illegible]	171.8	194.3	183.3	175.8	169.9
IMEP (bar)	1.9	16.5	9.2	[illegible]	2.7	13.4	7.8	5.0	3.0
ITE,actual (%)	47.0	41.6	45.0	47.4	50.2	44.4	47.1	49.1	50.8
ITE,theoretical (%)	62.8	56.1	58.1	60.2	62.4	58.4	59.9	61.1	62.3
RATIO, actual/theoretical	.747	.741	.774	.788	.805	.761	.786	.803	.815

**** SYNFUEL PROJECT 03-8538 TEST RESULTS ****

TARSAND PERFORMANCE TEST

RUN NUMBER		55
TEST CODE		13 5 2
DAY	(julian)	5315
TIME	(military)	123439
PHASE		1
TYPE FUEL		TARSAN
ENGINE HOURS		105.9
ENGINE PARAMETERS		
ENGINE SPEED	(rpm)	1394
TORQUE	(N-M)	64.5
POWER	(KW)	9.4
BSFC	(g/kw-hr)	433.
BMEP	(bar)	1.1
BTE	(%)	19.9
ENGINE FLOW PARAMETERS		
FUEL FLOW	(kg/hr)	4.1
AIR FLOW	(kg/hr)	329.9
AIR FUEL RATIO		80.8
CHEMICAL AIR FUEL RATIO		80.5
SMOKE OPACITY	(%)	1.6
TEMPERATURE PARAMETERS (deg.c)		
COOLANT IN		92
COOLANT OUT		93
OIL SUMP		99
OIL GALLERY		97
INTAKE AIR		25
CELL AMBIENT		32
BOOST B4 INNER COOLER		51
BOOST AF INNER COOLER		78
FUEL IN		32
EXHAUST #1		203
EXHAUST #2		193
EXHAUST #3		206
EXHAUST #4		218
EXHAUST #5		205
EXHAUST #6		215
EXHAUST STACK		214
PRESSURE PARAMETERS		
OIL	(kpa)	317.3
FUEL	(kpa)	130.4
EXHAUST B4 TURBO	(kpa)	******
FILTER RESTRICTION	(pa)	423.0
BOOST AF INNERCOOLER	(kpa)	5.2
EXHAUST STACK	(kpa)	.7
EMISSION PARAMETERS		
BSHC	(g/kw-hr)	5.6265
BSCO	(g/kw-hr)	8.6175
BSNOx	(g/kw-hr)	24.135
CO2	(%)	2.6
O2	(%)	17.1
AMBIENT PARAMETERS		
BARO.PRESSURE	(mm-Hg)	743.5
ABSOLUTE HUMIDITY	(gn/lb)	98.7
RELATIVE HUMIDITY	(%)	74.1
INDICATED PARAMETERS		
IKW		23.9
ISFC	(kg/ikw-hr)	171.9
IMEP	(bar)	2.7
ITE,actual	(%)	50.5
ITE,theoretical	(%)	62.4
RATIO, actual/theoretical		.809

APPENDIX D
COAL LIQUID BLEND PERFORMANCE DATA

**** SYNFUEL PROJECT 03-8538 TEST RESULTS ****

PERFORMANCE TEST 57 % EDS

RUN NUMBER	1224	1225	1226	1227	1228	1229	1230	1231	1232
TEST CODE	16 1 1	16 2 1	16 3 1	16 4 1	16 5 1	16 6 1	16 7 1	16 8 1	16 9 1
DAY (julian)	6030	6030	6030	6030	6030	6030	6030	6030	6030
TIME (military)	112354	121657	125512	141824	15 228	153546	16 514	163259	54711
PHASE	1	1	1	1	1	1	1	1	1
TYPE FUEL	57%EDS	57%EDS	57%EDS	57%EDS	57%EDS	57%EDS	57%EDS	57%EDS	57%EDS
ENGINE HOURS	158.9	159.8	160.5	161.0	162.5	163.1	163.6	164.1	165.2
ENGINE PARAMETERS									
ENGINE SPEED (rpm)	841	1399	1398	1398	1394	2199	2194	2191	2192
TORQUE (N-M)	37.2	934.4	459.0	230.8	63.6	676.6	334.6	167.0	46.6
POWER (KW)	3.3	136.9	67.2	33.9	9.3	155.3	76.9	38.5	10.7
BSFC (g/kw-hr)	510.	222.	231.	248.	378.	227.	249.	303.	590.
BMEP (bar)	.6	15.4	7.5	3.8	1.0	11.1	5.5	2.8	.8
BTE (%)	16.9	38.7	37.3	34.7	22.7	37.9	34.5	28.4	14.6
ENGINE FLOW PARAMETERS									
FUEL FLOW (kg/hr)	1.7	30.4	15.5	8.4	3.5	35.2	19.1	11.6	6.3
AIR FLOW (kg/hr)	192.9	684.3	409.0	347.1	327.9	1000.6	737.9	614.1	540.8
AIR FUEL RATIO	115.3	19.9	26.4	41.4	93.4	28.4	38.6	52.7	86.9
CHEMICAL AIR FUEL RATIO	97.0	19.5	24.8	38.4	83.1	28.8	38.2	50.9	62.2
SMOKE OPACITY (%)	4.1	18.7	8.4	1.4	1.5	7.7	5.2	3.0	1.4
TEMPERATURE PARAMETERS (deg.c)									
COOLANT IN	91	86	89	91	92	88	90	91	92
COOLANT OUT	93	93	93	93	93	93	93	94	93
OIL SUMP	94	109	106	102	98	109	107	105	102
OIL GALLERY	93	104	102	99	97	106	104	102	100
INTAKE AIR	18	21	23	23	24	25	25	25	24
CELL AMBIENT	21	37	31	28	28	35	31	32	28
BOOST B4 INNER COOLER	45	143	83	58	50	152	99	75	60
BOOST AF INNER COOLER	72	99	81	76	75	109	90	83	79
FUEL IN	29	31	32	34	34	34	36	36	37
EXHAUST #1	177	613	453	320	212	532	428	339	248
EXHAUST #2	146	607	447	317	197	519	398	330	238
EXHAUST #3	168	596	452	323	200	516	407	334	229
EXHAUST #4	157	629	482	332	218	566	438	356	283
EXHAUST #5	148	615	458	321	186	535	430	330	247
EXHAUST #6	146	651	457	298	182	576	411	319	213
EXHAUST STACK	153	591	447	305	199	463	379	312	235
PRESSURE PARAMETERS									
OIL (kpa)	257.8	313.3	314.8	316.0	317.2	345.3	346.6	348.1	348.8
FUEL (kpa)	158.4	89.3	100.5	126.4	134.0	77.1	87.4	93.9	99.0
EXHAUST B4 TURBO (kpa)	3.3	55.6	20.8	9.2	6.0	106.8	52.4	31.9	21.8
FILTER RESTRICTION (pa)	99.5	373.3	224.0	199.1	174.2	746.5	497.7	398.1	348.4
BOOST AF INNERCOOLER (kpa)	1.4	107.5	34.2	12.3	5.3	127.5	58.9	30.1	15.5
EXHAUST STACK (kpa)	.3	2.0	1.0	.7	.7	4.1	1.7	1.3	1.0
EMISSION PARAMETERS									
BSHC (g/kw-hr)	11.485	.8008	1.0989	1.7926	5.6519	1.1278	1.4241	2.9288	13.825
BSCO (g/kw-hr)	13.497	9.4148	2.9043	2.9163	8.5789	2.1323	2.7661	4.9179	14.098
BSNOx (g/kw-hr)	62.460	10.118	12.746	16.259	23.382	9.4581	8.2390	9.4283	16.7[illegible]
CO2 (%)	2.1	11.1	8.8	5.6	2.5	7.5	5.6	4.2	2.3
O2 (%)	17.1	5.4	9.3	13.3	16.9	10.7	13.2	15.1	17.4
AMBIENT PARAMETERS									
BARO.PRESSURE (mm-Hg)	748.0	748.0	748.0	748.0	746.5	746.5	746.5	746.5	746.5
ABSOLUTE HUMIDITY (gn/lb)	46.4	46.4	46.4	46.4	77.3	77.3	77.3	77.3	77.3
RELATIVE HUMIDITY (%)	51.7	51.7	51.7	51.7	58.5	58.5	58.5	58.5	58.5
INDICATED PARAMETERS									
IKW	10.4	151.4	82.1	48.5	23.9	187.2	108.2	70.1	42.5
ISFC (kg/ikw-hr)	160.1	200.9	188.8	172.9	147.0	188.0	176.9	166.1	148.5
IMEP (bar)	1.9	17.0	9.2	5.4	2.7	13.4	7.7	5.0	3.0
ITE,actual (%)	53.7	42.8	45.5	49.7	58.5	45.7	48.6	51.8	57.9
ITE,theoretical (%)	63.0	56.2	58.1	60.3	62.7	58.5	60.0	61.3	62.6
RATIO, actual/theoretical	.852	.761	.784	.824	.933	.782	.809	.845	.925

SYNFUEL PROJECT 03-8538 TEST RESULTS

PERFORMANCE TEST 57 % EDS

RUN NUMBER		1233	1234	1235	1236	1237	1238	1239	1240	1241
TEST CODE		16 1 2	16 2 2	16 3 2	16 4 2	16 5 2	16 6 2	16 7 2	16 8 2	16 9 2
DAY	(julian)	6030	6030	6031	6031	6031	6031	6031	6031	6031
TIME	(military)	2141 6	223419	11 227	112852	121648	125049	131514	1336 3	135258
PHASE		1	1	1	1	1	1	1	1	1
TYPE FUEL		57%EDS	57%EDS	57%EDS	57%EDS	57%EDS	57%EDS	57%EDS	57%EDS	57%EDS
ENGINE HOURS		166.6	167.5	167.9	168.4	169.1	169.7	170.1	170.5	170.8
ENGINE PARAMETERS										
ENGINE SPEED	(rpm)	841	1399	1399	1403	1399	2198	2194	2191	2202
TORQUE	(N-M)	37.5	940.0	459.8	232.2	64.1	662.1	335.2	168.9	45.4
POWER	(KW)	3.3	137.7	67.3	34.1	9.4	152.4	77.0	38.7	10.5
BSFC	(g/kw-hr)	464.	222.	228.	250.	385.	226.	248.	301.	612.
BMEP	(bar)	.6	15.5	7.6	3.8	1.1	10.9	5.5	2.8	.7
BTE	(%)	18.5	38.7	37.7	34.4	22.3	38.0	34.7	28.6	14.1
ENGINE FLOW PARAMETERS										
FUEL FLOW	(kg/hr)	1.5	30.5	15.4	8.5	3.6	34.5	19.1	11.7	6.4
AIR FLOW	(kg/hr)	196.1	609.5	410.1	348.9	330.7	995.7	741.0	615.3	553.5
AIR FUEL RATIO		127.8	20.0	26.7	41.0	91.4	28.9	38.8	52.8	86.4
CHEMICAL AIR FUEL RATIO		96.3	19.5	25.3	37.8	79.3	29.2	37.9	50.2	81.1
SMOKE OPACITY	(%)	1.0	18.8	8.5	1.8	1.4	7.9	5.4	3.2	1.5
TEMPERATURE PARAMETERS (deg.c)										
COOLANT IN		86	84	88	90	92	88	90	91	91
COOLANT OUT		87	92	92	93	93	93	93	93	93
OIL SUMP		89	109	105	102	98	110	107	104	103
OIL GALLERY		88	104	101	100	96	106	104	102	100
INTAKE AIR		19	22	23	23	23	25	25	26	26
CELL AMBIENT		22	35	31	26	26	32	33	31	30
BOOST B4 INNER COOLER		41	145	83	62	48	151	100	76	65
BOOST AF INNER COOLER		67	98	81	76	74	109	90	83	80
FUEL IN		31	33	33	32	33	36	37	36	35
EXHAUST #1		168	606	454	329	213	527	424	341	252
EXHAUST #2		133	602	447	310	191	509	401	332	237
EXHAUST #3		156	595	453	327	204	512	404	323	235
EXHAUST #4		157	630	480	346	222	561	446	363	291
EXHAUST #5		144	612	454	324	198	539	430	331	252
EXHAUST #6		148	643	459	303	181	567	411	318	213
EXHAUST STACK		145	587	447	312	196	459	379	312	241
PRESSURE PARAMETERS										
OIL	(kpa)	274.8	313.1	314.7	316.4	317.8	344.6	346.2	347.7	349.7
FUEL	(kpa)	156.7	82.9	112.3	125.9	133.7	77.3	86.7	94.0	99.6
EXHAUST B4 TURBO	(kpa)	2.1	51.3	17.3	8.1	4.7	103.5	51.3	30.5	21.2
FILTER RESTRICTION	(pa)	99.5	348.4	224.0	199.1	199.1	771.4	522.6	423.0	373.3
BOOST AF INNERCOOLER	(kpa)	2.0	109.0	35.1	13.4	6.1	126.3	60.2	30.8	16.8
EXHAUST STACK	(kpa)	.3	2.0	1.3	1.0	1.0	4.4	2.4	1.7	1.7
EMISSION PARAMETERS										
BSHC	(g/kw-hr)	9.4128	.6792	.8778	1.1722	5.8060	.9993	1.3604	2.9890	9.5982
BSCO	(g/kw-hr)	11.289	9.0325	3.0361	2.9912	8.4939	1.9226	2.7698	4.9023	15.264
BSNOx	(g/kw-hr)	47.665	9.2201	11.316	14.189	24.122	9.1593	7.8283	9.1373	16.456
CO2	(%)	2.2	11.1	8.6	5.7	2.6	7.4	5.7	4.2	2.6
O2	(%)	17.7	5.6	9.3	13.2	16.8	10.7	13.2	15.1	17.3
AMBIENT PARAMETERS										
BARO.PRESSURE	(mm-Hg)	744.7	744.7	744.7	744.7	745.0	745.0	745.0	745.0	745.0
ABSOLUTE HUMIDITY	(gn/lb)	70.5	70.5	70.5	70.5	60.0	60.0	60.0	60.0	60.0
RELATIVE HUMIDITY	(%)	75.1	75.1	75.1	75.1	47.0	47.0	47.0	47.0	47.0
INDICATED PARAMETERS										
IKW		10.4	152.2	82.1	49.2	23.9	184.3	108.9	70.1	42.5
ISFC	(kg/ikw-hr)	146.9	200.7	187.1	172.9	151.6	187.1	175.4	166.3	150.7
IMEP	(bar)	1.9	17.0	9.2	5.4	2.6	13.1	7.8	5.0	3.0
ITE,actual	(%)	58.5	42.8	45.9	49.7	56.7	46.0	49.0	51.7	57.1
ITE,theoretical	(%)	63.2	56.2	58.1	60.3	62.7	58.6	60.1	61.3	62.5
RATIO, actual/theoretical		.926	.762	.790	.824	.905	.785	.816	.844	.912

APPENDIX E

COAL LIQUID BLEND SCREENING TEST DATA

**** SYNFUEL PROJECT 03-8538 TEST RESULTS ****

EDS SCREENING TEST

RUN NUMBER		743	744	745	746	747	748	749	750	751
TEST CODE		14 1 1	14 3 1	14 6 1	15 1 1	15 3 1	15 6 1	16 1 1	16 3 1	16 6 1
DAY	(julian)	6017	6017	6017	6017	6017	6017	6021	6021	6021
TIME	(military)	1015 9	105957	11 546	142022	143523	144739	151635	153814	154636
PHASE		1	1	1	1	1	1	1	1	1
TYPE FUEL		40%EDS	40%EDS	40%EDS	50%EDS	50%EDS	50%EDS	57%EDS	57%EDS	57%EDS
ENGINE HOURS		149.0	149.7	149.9	151.4	151.7	151.9	153.8	154.2	154.3
ENGINE PARAMETERS										
ENGINE SPEED	(rpm)	828	1391	2198	833	1391	2199	833	1385	2197
TORQUE	(N-M)	38.0	459.9	673.9	37.2	458.9	672.9	38.7	458.4	679.2
POWER	(KW)	3.3	67.0	155.1	3.2	66.9	154.9	3.4	66.5	156.3
BSFC	(g/kw-hr)	513.	231.	220.	515.	231.	229.	466.	234.	229.
BMEP	(bar)	.6	7.6	11.1	.6	7.5	11.1	.6	7.5	11.2
BTE	(%)	16.7	37.0	39.0	16.6	37.1	37.4	18.4	36.8	37.5
ENGINE FLOW PARAMETERS										
FUEL FLOW	(kg/hr)	1.7	15.5	34.1	1.7	15.5	35.5	1.6	15.5	35.8
AIR FLOW	(kg/hr)	188.7	409.3	1013.5	191.2	409.1	1011.6	188.1	397.5	992.6
AIR FUEL RATIO		111.9	26.4	29.8	114.3	26.5	28.5	119.7	25.6	27.7
CHEMICAL AIR FUEL RATIO		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SMOKE OPACITY	(%)	2.2	10.7	8.0	3.1	10.6	8.2	1.1	9.1	9.1
TEMPERATURE PARAMETERS (deg.c)										
COOLANT IN		92	90	89	91	89	88	91	89	87
COOLANT OUT		93	94	94	93	93	93	92	93	93
OIL SUMP		95	105	110	94	105	111	94	106	110
OIL GALLERY		94	102	106	93	101	107	93	102	106
INTAKE AIR		18	19	19	21	21	23	26	26	27
CELL AMBIENT		22	27	34	24	29	32	30	36	38
BOOST B4 INNER COOLER		51	88	143	51	80	155	61	87	153
BOOST AF INNER COOLER		73	82	109	74	82	111	76	83	112
FUEL IN		30	31	32	31	32	35	31	32	34
EXHAUST #1		172	463	518	166	462	531	161	455	533
EXHAUST #2		142	454	526	147	457	530	134	450	540
EXHAUST #3		172	459	518	164	461	526	163	462	529
EXHAUST #4		166	493	559	168	489	569	172	497	577
EXHAUST #5		155	456	530	159	460	540	167	464	542
EXHAUST #6		175	437	575	167	435	579	179	467	596
EXHAUST STACK		173	454	457	171	453	466	177	460	470
PRESSURE PARAMETERS										
OIL	(kpa)	254.3	312.7	344.1	262.1	313.2	343.3	261.2	313.4	345.0
FUEL	(kpa)	166.0	98.9	81.1	169.0	98.7	81.8	160.6	124.5	82.8
EXHAUST B4 TURBO	(kpa)	3.5	22.9	114.5	3.5	22.5	113.7	3.5	21.9	112.8
FILTER RESTRICTION	(pa)	74.7	199.1	696.8	74.7	174.2	721.6	74.7	199.1	721.6
BOOST AF INNERCOOLER	(kpa)	1.4	36.5	133.0	1.5	35.7	131.8	1.4	34.4	130.3
EXHAUST STACK	(kpa)	0.v	.7	4.4	.3	.7	4.7	.3	1.0	4.4
EMISSION PARAMETERS										
BSHC	(g/kw-hr)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
BSCO	(g/kw-hr)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
BSNOx	(g/kw-hr)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	(%)	.1	.1	.1	.1	.1	.1	.0	.0	.0
O2	(%)	-.0	.2	.1	.1	-.1	.2	-.0	-.0	-.0
AMBIENT PARAMETERS										
BARO.PRESSURE	(mm-Hg)	744.5	744.5	744.5	748.5	748.5	748.5	741.2	741.2	741.2
ABSOLUTE HUMIDITY	(gn/lb)	84.4	84.4	84.4	85.5	65.5	85.5	81.4	81.4	81.4
RELATIVE HUMIDITY	(%)	80.7	80.7	80.7	76.7	76.7	76.7	65.3	65.3	65.3
INDICATED PARAMETERS										
IKW		9.7	81.3	187.2	9.7	81.3	186.5	10.4	81.3	188.0
ISFC	(kg/ikw-hr)	173.9	190.6	181.9	172.5	190.1	190.5	150.5	191.2	190.4
IMEP	(bar)	1.8	9.2	13.4	1.8	9.2	13.3	1.9	9.2	13.4
ITE,actual	(%)	49.2	44.9	47.0	49.7	45.1	45.1	57.1	45.0	45.2
ITE,theoretical	(%)	63.0	58.1	58.7	63.0	58.1	58.5	63.1	57.9	58.3
RATIO, actual/theoretical		.781	.773	.801	.789	.777	.770	.905	.777	.774