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PERFORMANCE OF A DIESEL ENGINE OPERATING ON RAW COAL-DIESEL FUEL AND SOLVENT REFINED COAL-DIESEL FUEL SLURRIES

Final Report

MASTER

By
H. P. Marshall

March 1980

Work Performed Under Contract No. ET-78-S-01-3288

Virginia Polytechnic Institute and State University
Department of Mechanical Engineering
Blacksburg, Virginia

U. S. DEPARTMENT OF ENERGY

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Performance of a Diesel Engine Operating on Raw Coal-Diesel Fuel and Solvent Refined Coal-Diesel Fuel Slurries

(Contract No. ET-78-S-01-3288)

to

U.S. Department of Energy
Technical Information Center,
Office of Procurement Operations, and
Office of University Affairs

by

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March 1980

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ABSTRACT

Performance tests using an 11 kw single cylinder diesel engine were made to determine the effects of three different micronized coal-fuel oil slurries being considered as alternative fuels. Slurries containing 20, 32, and 40 percent by weight micronized raw coal in No. 2 fuel oil were used. Results are presented indicating the changes in the concentrations of SO_X and NO_X in the exhaust, exhaust opacity, power and efficiency, and in wear rates relative to operation on fuel oil No. 2. The engine was operated for 10 hrs. at full load and 1400 rpm. on all fuels except the 40% by weight slurry. This test was discontinued because of extremely poor performance.

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LIST OF SYMBOLS

ATDC	After Top Dead Center
BKw	Brake Kilowatts
Bsec	Brake Specific Energy Consumption
BTDC	Before Top Dead Center
E_{in}	Energy Input
Fkw	Friction Kilowatts
HHV	Higher Heating Value
I.C.	Integrated Circuit
Pot.	Potentiometer
P_{Bkw}	Percent of E_{in} to Bkw
P_{cw}	Percent of E_{in} to Cooling Water
P_{exh}	Percent of E_{in} to Exhaust
P_{Fkw}	Percent of E_{in} to Fkw
P_{unacct}	Percent of E_{in} Unaccounted
Reg.	Regulated
V.D.C.	Volts, Direct Current
Unreg.	Unregulated
NAA	Neutron Activation Analysis

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I

INTRODUCTION

The U.S.A. imports nearly half of the crude oil it uses. To mitigate this condition, and others, much is being done including the development of alternative fuels for internal combustion engines. The work reported on, herein, concerns the performance of an 11 kw, single cylinder, 4-stroke-cycle, diesel engine operating at full load and 1400 rpm on several alternative fuels.

The scope of the work as originally planned is described below in Tasks 1 through 3 along with the expected results.

Task 1 - Power and Efficiency Measurements

The engine will be operated using regular diesel oil and on four different coal-diesel oil slurry fuels. On each fuel the engine will be optimized for best power mixture and run for 10 hours. The slurry fuels will have the following characteristics:

(a) 15 percent by weight raw coal

(b) 25 percent by weight raw coal

(c) 40 percent by weight raw coal and

(d) 40 percent by weight solvent refined coal.

Deliverables

The output from Task 1 will consist of:

1) An energy balance for operation on each of the fuels used during the best power tests.

2) Comparisons of power and efficiency developed when using the different fuels.

Task 2 - Exhaust Emission Studies

For each of the fuels described in Task 1 and for diesel fuel, exhaust emission of SO_x and NO_x will be measured. SO_x will be measured using a Bendix Model 8303 meter. A Bendix Model 8102B will be used to measure NO_x. At each data point the ppm of pollutant per bhp developed will be determined.

In addition to NO_x and SO_x, exhaust smoke capacity will be measured.

Deliverables

The output of Task 2 will consist of:

1) A comparison of the ppm of NO_x and SO_x compounds in the engine exhaust produced during the best power tests using the four different slurry fuels describes in Task 1 and using regular diesel fuel.

2) A determination of the change in SO_x concentration in the exhaust as a result of burning a slurry containing 40 percent solvent refined coal as compared with a slurry containing 40 percent raw coal.

3) A determination of smoke opaqueness as related to percent of coal and type of coal in the coal-diesel oil slurry and a comparison with that occurring with a diesel oil fuel during best power operation.

Task 3 - Wear Measurements

Prior to and following the 40 hours of operation on the slurry fuels the engine cylinder and piston rings will be measured with micrometers to determine accumulated wear.

(During operation on each fuel engine blow-by will be measured.)

1) A determination by direct measurement of total cylinder and ring wear resulting from the combustion of four different slurry fuels (described in Task 1) following 10 hours of operation on each fuel.

2) An inferrence of wear caused by each slurry fuel as indicated by engine blow-by measurements made at the conclusion of 10 hours of operation on each of 4 different slurry fuels.

This report presents the results of the tasks as outlined above according to the extent to which it was possible to carry them out plus additional work not described originally. Task 1 was not completed as described. Slurries containing 20 to 32 percent by weight coal were substituted for the 15 and 25 percent slurries and the 40 percent coal slurry tests were discontinued because of extremely poor performance. In addition to the work described in Task 1-part load operation was attempted. Task 2 was accomplished as described using the substituted slurries. Task 3 was completed as described using the substituted slurries. Additional NAA work which gave increased understanding of the wear phenomenon was completed.

These results are presented in various tables, bar graphs, and curves. Discussion concerning the ways and means of acquiring the results and their significance is also included.

II

LITERATURE REVIEW

Review of Coal Burning Diesel Engines

During the first half of the twentieth century, considerable efforts were made to utilize pulverized coal as a fuel in internal combustion engines. Much of this work was done in Germany.

These German development projects were independently conducted by five industrial companies during the period from 1916 to 1944. Under the various programs, which ran for periods from 8 to 24 years, about 19 coal-dust engines in the power range from 10 to 600 horsepower and at speeds between 160 and 1600 rpm were built and tested (4).

Between 1911 and 1940, most intensive efforts were conducted by Rudolf Pawlikowski, former co-worker of Dr. Diesel (4). He, at his own expense, pioneered the development of a coal burning engine. In 1916 Pawlikowski had achieved the first reliable ignition using coal and in the subsequent years, he brought the engine to a state which was commercially viable (5). He designed and constructed 8 different coal-dust engines ranging from 1 to 3 cylinders.

Pawlikowski solved many of the basic problems concerning feed and control systems, seals and lubrication. Initially, his engines worked with conventional high pressure injection of a coal/air mixture, but later he developed a low pressure fuel injection system using a "by-chamber". This was essentially a pre-combustion chamber in which the coal/air mixture is slowly thermally prepared for combustion.

Other German efforts were inspired by Pawlikowski's work. These efforts achieved, it is claimed, operational reliability, economy and readiness for commercial application.

Just before the second world war, wear tests were conducted at England's fuel research center (6). Coal ash was fed into the intake system of a 293 cc gasoline engine under various speed and load conditions. Similar work on a diesel engine was terminated due to the war.

In 1949, David Hanse at University of North Carolina tested a single cylinder diesel engine on coal-oil slurries of 5, 10, and 20 percent coal by weight (6). The engine ran with a reduced thermal efficiency. Excessive wear on pump plungers and clogged injection nozzles terminated this investigation.

In 1957, at the Southwest Research Institute, a four cylinder spark ignition engine was run on a slurry fuel consisting of 67 percent by weight coal (7). Excessive wear rates ruled out the feasibility of this fuel. Tests were also made on a single cylinder Caterpillar diesel engine using a coal-oil slurry with 30 percent by weight coal. Within a few minutes of starting, tests were stopped because of fuel injection system failures.

In 1959, at Virginia Polytechnic Institute, a single cylinder diesel engine was run on a 50 percent coal-diesel fuel ratio in a test that lasted for 45 hours (8). In this experiment, coal was injected independent of diesel oil through a coal feeder. The arrangement was found unsatisfactory in that the coal delivery rate could not be controlled precisely as engine speed and load varied. A reduction in brake thermal efficiency of about 5 percent was observed. High wear rates with piston, rings and liner were experienced. Lubrication oil contamination by the 150 to 200 μm particle size coal was found to be the chief cause of wear. These factors caused the termination of the experiment.

In 1967, investigation was undertaken at Howard University, Washington, D.C., on a single cylinder diesel engine (6). Modified engine lubrication, exhaust and air intake systems were incorporated. A modified piston using special over-size piston rings was used. Lower compression rings exhibited higher wear, establishing once again, lubricating oil contamination as the major cause of wear. The coals used ranged in size from 610 to 840 μm. During the test which lasted for 100 hours, 2 crankshafts and 4 sets of piston rings and connecting rod bearings were used. A reduction in thermal efficiency and increase in cooling load were observed.

In 1976, work was undertaken in coal-oil slurries at Virginia Polytechnic Institute (9). A single cylinder 1360 cc diesel engine was operated on a slurry of 15 percent by weight solvent refined coal and jet fuel. The coal was pulverized to a nominal size of 2 μm. Initially through nozzle bench tests, it was ascertained that the slurry would flow through the nozzle and form an acceptable spray pattern. An instrumentation system was assembled to monitor and record engine operating conditions, including pressure-time fluctuations in the combustion chamber, fuel consumption and power output. Photomicrographs of the injection nozzle pin and injection pump plunger were presented for wear comparison before and after slurry operation and indicated negligible change. Results indicated that the slurry fuel provided engine power and fuel consumption levels comparable to those of diesel and jet fuels. The main problem encountered during the test was the failure of the fuel injection system to operate for any reasonable period. With 15 percent coal-oil slurry, the operating period was six hours while with 30 percent coal-oil slurry, it was barely three minutes. The problem was attributed to the presence of coal particles wedged in the clearance space of the fuel injection system.

It should be noted at this point that much of the earlier work was made using powdered coal alone. There is some indication that the before mentioned German development programs did use coal-oil slurries: but not to an extent which would give any conclusive results (4).

However, it seems that work on coal-oil slurries will continue because of the availability of finer coal as well as the development of new techniques of refining coal.

Nature of Impurities in Coal

As found in seams, coal is a heterogeneous mixture of organic and inorganic materials. Not only are there large differences in the properties of coal from different seams but also of coal removed from different elevations and different locations in a single seam (10).

Impurities in coal are of two types; inherent and removable. The inherent impurities are inseparably combined with the coal. The others are segregated and can be removed.

Mineral matter is always present in raw coal and forms ash when the coal is burned The ash-forming mineral matter is classified as either inherent or extraneous. Organically combined ash-forming material is called inherent mineral matter and ranges up to 2 percent of the total ash. Extraneous mineral matter also forms ash and is foreign to the parent material from which coal was formed. It usually consists of slate, shale, sandstone, or limestone and includes pieces ranging from microscopic size to thick layers.

Sulfur is always present in raw coal in amounts ranging from traces to as high as 8 percent or even more. This results in the emission of sulfur oxides when coal is burned. Control of air pollution prohibits use of coal with more than a specified amount of sulfur. Three types of sulfur occur in coal: pyritic sulfur, which is sulfur combined with iron; organic sulfur, which is sulfur combined with the coal substance; and sulfate sulfur, in the form of sulfates of calcium and iron.

Methods of Sulfur Removal

Fine crushing and cleaning of the coal removes up to 50 percent of the inorganic sulfur. The froth flotation process can remove up to 90 percent of the pyritic sulfur compounds. However, these methods do not remove sulfur to the extent demanded by air pollution control requirements and hence new methods are being developed.

In the solvent refining process now in operation at the plant at the Bureau of Mines Energy Research Laboratory at Pittsburgh, Pennsylvania coal is crushed to a size less than 0.3 cm. It is then slurried in a coal based solvent. The slurried coal, together with hydrogen, is preheated and fed into a reactor that operates at 6895 kPa and 673K. Under these conditions a large fraction of the total coal is dissolved. The effluent is separated in a high pressure receiver and the liquid slurry is passed to a rotary filter to remove ash and insoluble organic matter. The product "solvent refined coal", is a heavy organic material in the form of small pellets. It contains about 0.1 percent ash and less than 1 percent sulfur. This process removes all inorganic sulfur and up to 70 percent of the organic sulfur.

The Combustion of Powdered Coal

The combustion of a coal particle is characterized by three stages:

1) Time required for the evolution of the volatile contents and their ignition.
2) Time for the combustion of volatile matter.
3) Time for the combustion of remaining matter.

From the estimates of these times, total burning time of the particle is predicted. This time sets an upper limit on the engine speed.

The above burning time parameters depend on the chemical reaction rate of the fuel. In addition, they are also affected by fluid mechanical parameters like heat and mass transfer which in turn are functions of pressure and temperature of the air, and of the relative particle speeds and the turbulence in the engine cylinder. They also depend upon the size of the particles and their internal structure, i.e., their porosity.

In Germany, extensive studies were made by Nusselt and Wentzel on the ignition and combustion speed of coal-dust under simulated engine conditions (4). These tests established that coal is a slow-burning fuel and the maximum speed of a coal-dust engine would be limited to 400 rpm. It was later found that these tests did not truly represent the extremely turbulent conditions in an actual engine cylinder and therefore underestimated the speed that could be attained.

The attainable engine speed is also very much dependent on the size of the coal particle. Based on the experiments conducted by I-G Farben Industry in Germany, the combustion speed increases very rapidly with decreasing particle size (4). This increase slows down considerably for the particles smaller than 25 μm. Recent theoretical studies by Saxton, Creswick and Kircher indicate that a low-speed diesel engine could be operated at 300 rpm on coal particles having sizes no greater than 30 to 40 μm (11). With highly reactive brown coal, the allowable particle size is increased to 70 μm.

Since most modern diesel engines operate in the speed range of 1000 to 3000 rpm, coal particles of much smaller size would be required.

Chemical and Physical Characteristics of Diesel Exhaust

In considering exhaust emission of any internal combustion engine, the constitutents of exhaust are categorized as products of complete combustion, products of incomplete combustion, or products originating from intake air. Carbon dioxide, carbon monoxide and nitric oxide fall in these three categories respectively. If sulfur is present in the fuel, it will produce SO_x compounds.

All of these chemical compounds can be harmful to human beings and control of them is extremely important. In the present investigation measurements are restricted to SO_x and NO_x compounds.

Two oxides of nitrogen are important in the atmosphere; nitric oxide (NO) and nitrogen dioxide (NO_2). Five more oxides of nitrogen are known: NO_3, N_2O, N_2O_3, N_2O_4, and N_2O_5. The oxides NO_3 and N_2O_4 are too unstable to exist at atmospheric conditions; N_2O_3 and N_2O_5 are anhydrides of nitrous and nitric acid respectively and N_2O is a stable compound and can support combustion. The term NO_x is used, generally to represent the gaseous pollutants NO_2 and NO. It is known that NO is oxidized to NO_2 by oxidants including oxygen in the air.

When fossil fuels (gas, fuel oils, and coal) are burned with air, some of the oxygen and nitrogen gas present combine to form NO according to the following reaction:

$$N_2 + O_2 \rightleftarrows 2NO$$

Given time, this reaction continues to an equilibrium level, which depends upon flame temperature, concentration of each gas, and the movement of the gases through zones of different temperatures, pressures and concentrations. Once NO is formed, however, the rate of decomposition is too slow to dissociate into oxygen and nitrogen. As a result, the NO persists, or is "frozen" in the flame products after they leave the high temperature zone. The NO thus formed can react with more oxygen to form NO_2. Thus the main parameters in NO_x formulation are: the flame temperature, the length of time the combustion gases are maintained at that temperature, and the amount of excess air present in the combustion zone.

Hydrocarbon fuels may contain free sulfur, hydrogen sulfide and other sulfur compounds. The sulfur content is determined by measuring the amount of sulfur dioxide formed by combustion and translating this into an equivalent mass of free sulfur (although the sulfur in fuel may be present in a number of different forms). Sulfur and its compounds are objectionable for a number of reasons. Some forms, especially free sulfur and hydrogen sulfide are corrosive and can corrode fuel lines, carburettors and injection pumps. In all forms sulfur will combine with oxygen to form sulfur dioxide which in the presence of water at low temperature will form sulfurous acid. However, exhaust gases leave the engine and the exhaust pipe at a high enough temperature that formation of sulfurous acid is not possible. But the residual gases in the engine and the exhaust pipe after engine shutdown are subjected to favorable conditions for acid formation.

Exhaust smoke density or color is a major problem with diesel engine with regard to its acceptance by the public. The exhaust smoke in diesel is made up of soot particles accumulated together into "clumps" approximately 1 μm or larger in size.

All soot contains about 1 to 3 percent hydrogen by weight. X-ray spectroscopy shows soot to have a graphite structure with hexagonal basic carbon units linked into platelets forming a crystallite about 21 by 13 A and the agglomerates of these can be as large as 30 μm in diameter (12).

Exhaust smoke is currently measured by two different methods. One method consists of drawing a measured volume of exhaust gas through a filter paper which is blackened to various degrees by the amount of particulate filtered from the gas sample. This method, although quick may not always correlate well with visual observations of the same smoke stream. A second method uses an instrument with a photoelectric cell which quantitatively measures the absorption of light passing through a sample stream of exhaust gas. Several instruments of the latter type are currently in use.

III

SLURRY PREPARATION AND PROPERTIES

The twenty, thirty-two, and forty percent by weight raw coal in No. 2 fuel oil slurries used in this investigation were prepared by the Pittsburgh Energy Technology Center operated by the United States Department of Energy. The production of micronized coal in oil (MICO) was accomplished using a batch unit process. Plant grind coal, 70% less than 72 microns, was mixed with diesel oil in a batch attrution mill. After passing through the mill a vibrating screen intercepts and returns oversize particles to the batch unit. Accumulating tanks buffer the continuous units from variations in feed rate. Two continuous units in series progressively reduced the products to the required 3 micron size.

Two methods were used to determine the particle size regime of the dry coal particles. A Scanning Electron Microscope with visual measurement and a Coulter Counter provided particle size measurements in very close agreement. The results of these measurements are shown in Fig. 3-1. The median particle sizes using both methods were determined to be between 2 and 11 microns with the average of all median values lying between 3 and 4 microns.

Two different types of coal were used in preparing the coal-oil slurries. Pittsburgh seam coal was used for the 20% and 40% by weight raw coal - No. 2 fuel oil slurry. Fig. 3-2 illustrates the chemical composition of the coal-oil slurries with these two types of coal. It is important to note that the practical limit of coal concentration in MICO appears to be 50 percent. This is because the viscosity begins to increase sharply beyond this concentration.

The heating values per unit weight and per unit volume are illustrated in Fig. 3-3 and Fig. 3-4. These graphs show the heating value per unit weight is an inverse linear function, the heating value per unit volume is not only nonlinear but has a maximum. This value is approximately 42,488 kJ/l at about 70 percent by weight Pittsburgh seam coal. For lower Freeport coal, it is approximately 44,165 kJ/l at about 90 percent by weight. The volume-based heating value is a direct multiplication product of the density and the mass-based heating value.

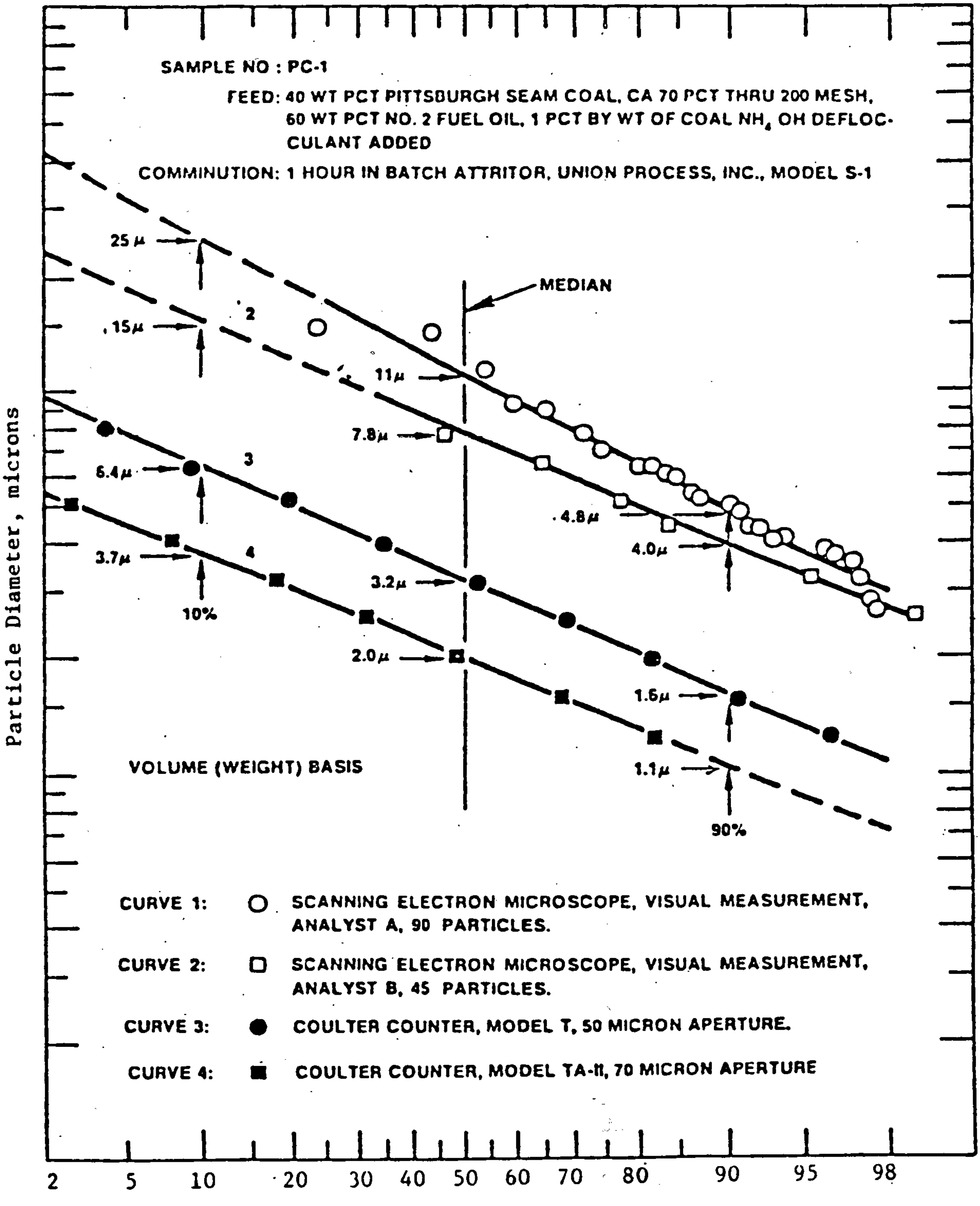


Figure 3-1. Particle Size Distribution of Micronized Coal in Oil (Furnished by Pittsburgh Energy Technology Center)

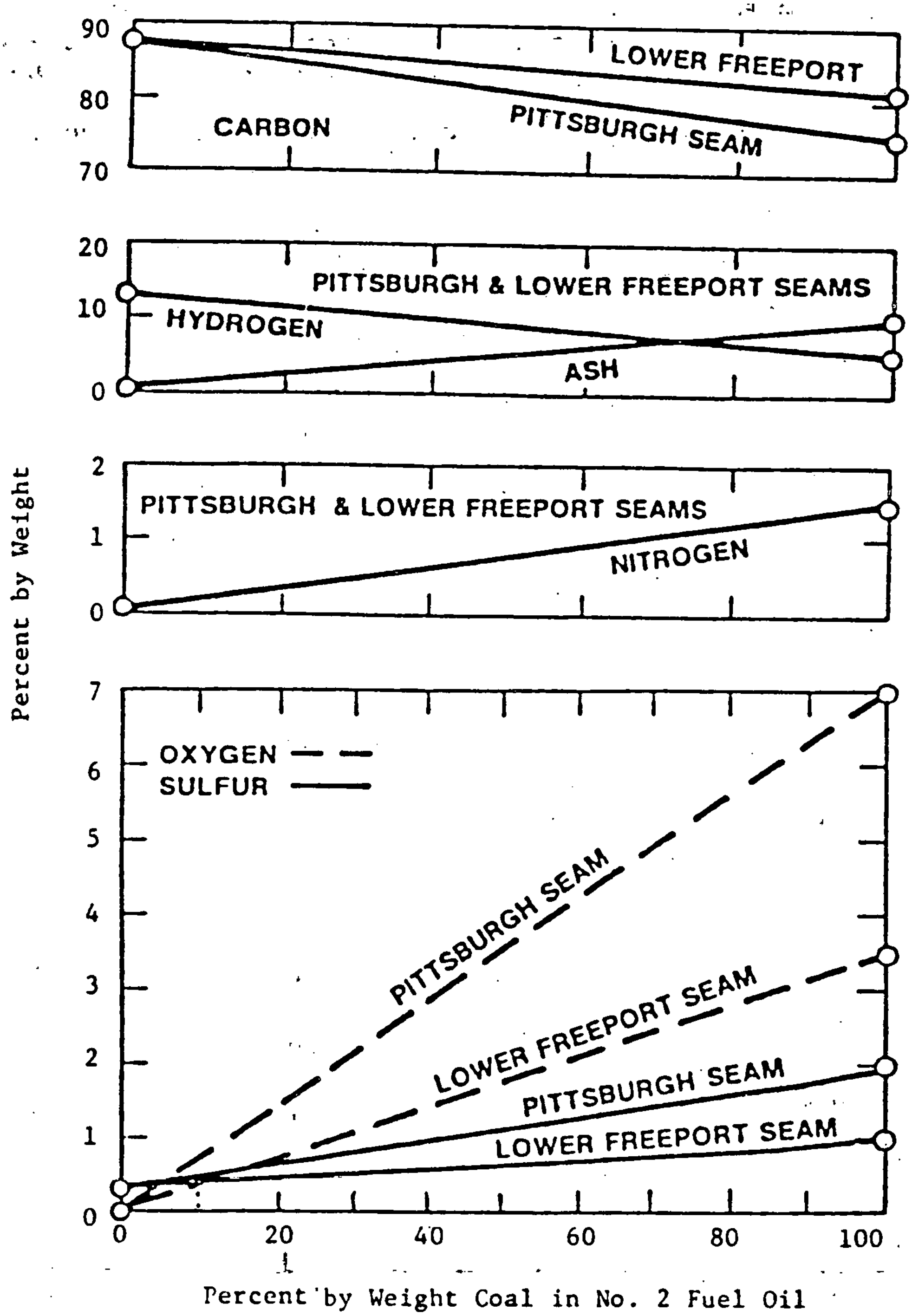


Figure 3-2. Chemical Analysis of Micronized Coal in Oil, Moisture Free Basis (Furnished by Pittsburgh Energy Technology Center)

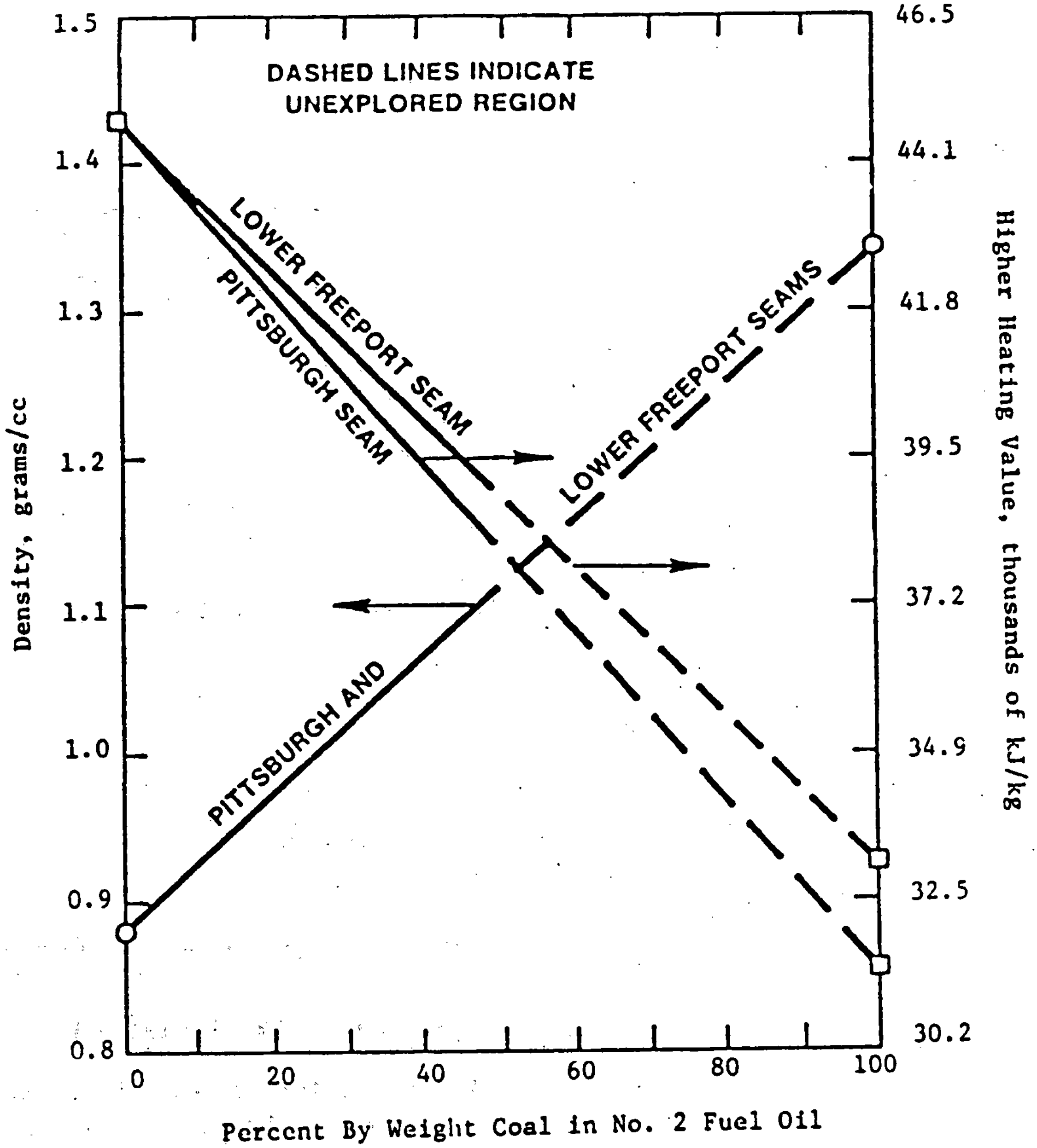


Figure 3-3. Density and Heating Value of Micronized Coal in Oil, Weight Basis (Furnished by Pittsburgh Energy Technology Center)

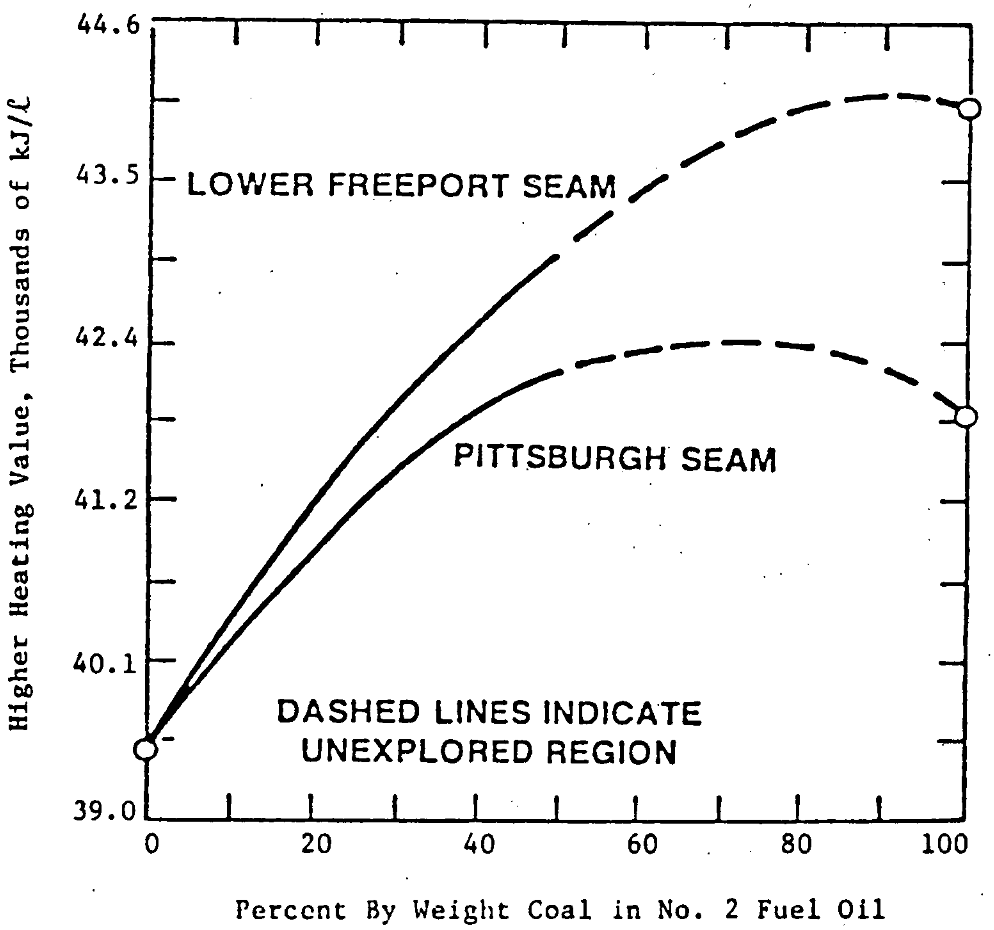


Figure 3-4. Heating Value of Micronized Coal in Oil, Volumetric Basis (Furnished by Pittsburgh Energy Technology Center

IV

EXPERIMENTAL INVESTIGATION

Task 1 - Power and Economy

Description of Equipment and Apparatus

The engine used in this investigation was a single cylinder normally aspirated four-stroke-cycle Nordberg diesel. Complete specifications are given in Table 4-1. The engine is mounted on a steel pedestal and coupled to a D.C. electric dynamometer. Three motor-generator sets supply the dynamometer with excitation voltage, control voltage, and field voltage. This allows the dynamometer to drive the engine for starting or be driven by the engine to determine power output.

Controls allow the dynamometer to maintain a desired speed at various loads. A torque control mode is also available but this was not used in this investigation.

Thermocouples were mounted on the engine to monitor inlet water, outlet water, and exhaust manifold temperatures. Oil pressure was monitored with a bourdon-tube pressure gauge connected by flexible tubing to the engine oil gallery. Fuel consumption was determined using a beam balance scale. A stop watch was used to measure the time to burn a predetermined amount of fuel.

The fuel injection system used is a conventional cam driven fuel injection pump and pintle-type nozzle, illustrated in Fig. 4-1. The injection pump rack control was operated by a hand lever-cable control. The standard fuel transfer pump was used for both diesel oil and coal oil slurry operation.

Table 4-1. Engine Specifications

Manufacturer	Nordberg
Model	4 - FS
Type	Divided-Chamber Diesel
Number of Cylinders	1
Cylinder Bore, cm	11.43
Cylinder Stroke, cm	13.34
Piston Displacement, cc	1360
Maximum Power, kw	11.2
Rated Speed, RPM	1800
Flywheel Mass, kg	226.8

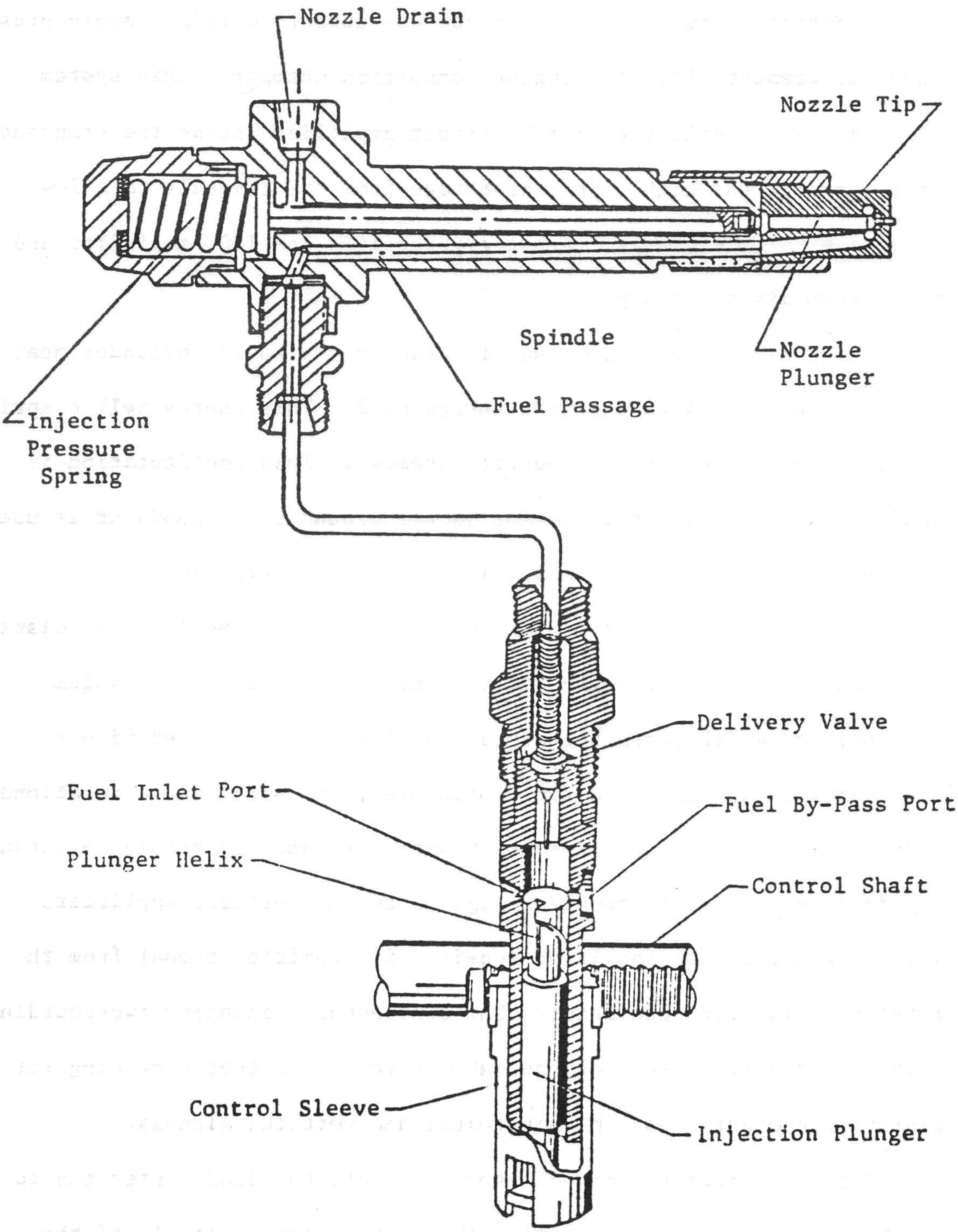


Figure 4-1. Fuel Injection System Details

A Piezotronics quartz transducer was used to obtain dynamic pressure measurements from the engine combustion chamber. This system incorporates a small integrated circuit amplifier inside the transducer. This converts the high impedance charge from the crystals to a low impedance voltage signal. A battery supplies the I.C. amplifier and the output signal with power.

The pressure transducer was mounted in the engine cylinder head through a hole drilled into the energy cell. This energy cell comprises a portion of the divided combustion chamber. This configuration is shown in Fig.4-2. A water cooling jacket around the transducer is used to keep it below its 135°C maximum allowable temperature.

A Tektronix engine analyzer system was used to monitor and display the pressure signal from the Piezotronics transducer. The system incorporated a Tektronix 561 storage oscilloscope equipped with a 3A74 verticle amplifier, a 2B67 horizontal time base, and a rotational function generator. The pressure transducer, and a variable reluctance top dead center sensor provided signals to the vertical amplifiers while the horizontal amplifier received its position signal from the rotational function generator. The continuously changing two-coordinate signals generate a trace on the cathode ray tube, thus providing for continued comparison of the horizontal and vertical signals.

The reluctance sensor was used to locate top dead center and to synchronize the pressure signal with the horizontal signals of the rotational function generator. Top dead center was located on the flywheel and a machine screw attached. The reluctance pickup was mounted to the flywheel housing to pick up the top dead center signal.

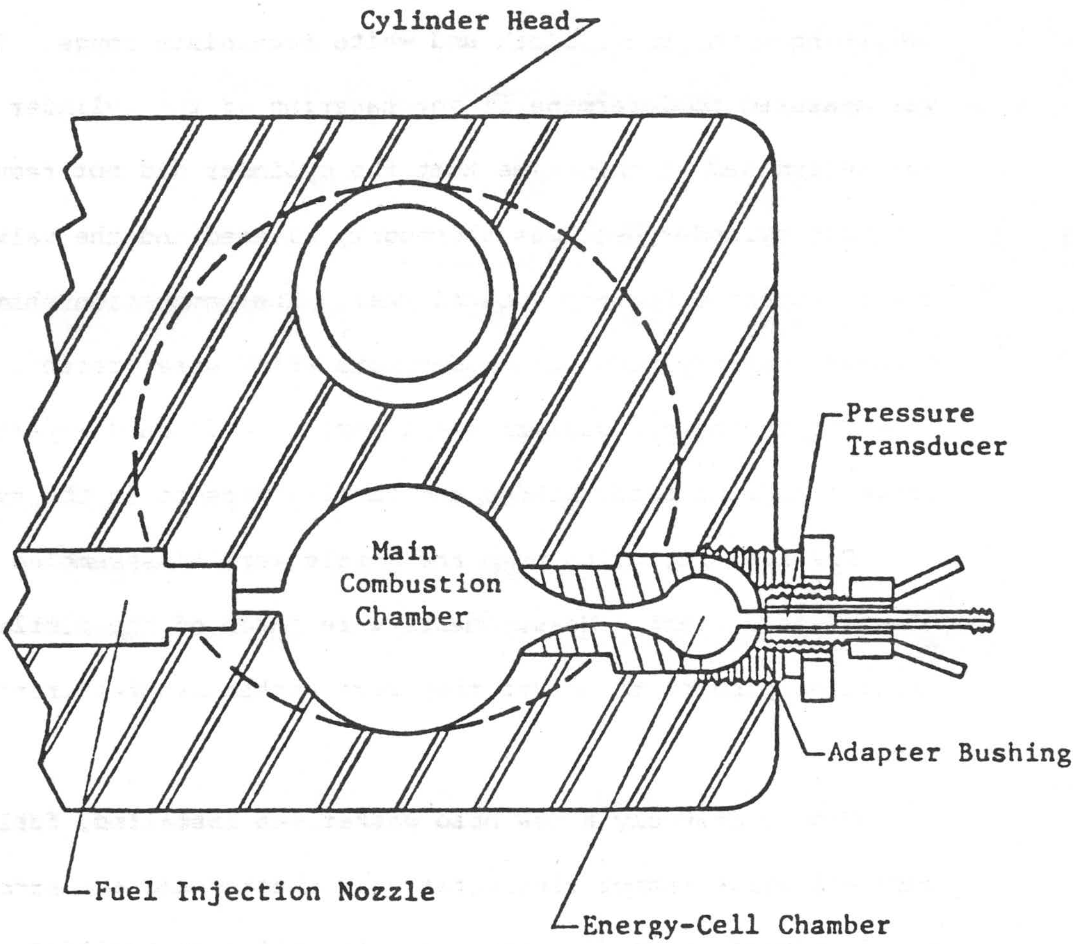


Figure 4-2. Pressure Transducer Details

EXPERIMENTAL PROCEDURE

Engine Preparation

Before any actual testing was begun the Nordberg diesel engine was disassembled and inspected. At this time it was determined that the piston rings and connecting rod bearings should be replaced. A small burr was found on the crank shaft and this was removed by repeated polishing with crocus cloth and white machinists rouge. The cylinder was measured to determine if any tapering of the cylinder existed. It was determined at this time that the cylinder did not require honing.

The cylinder head was thoroughly cleaned and the valves and their seats inspected for any unusual wear. The combustion chamber was also cleaned to remove any carbon deposits which were present.

The engine oil galleries and pump were flushed repeatedly with solvent to remove any sludge and varnish present in the system.

The fuel injection pump and nozzle were disassembled and also cleaned in solvent. Measurements were taken of the pintle nozzle and injection plunger to insure they were within manufacturer's specifications.

Upon reassembly a new head gasket was installed, fuel injection pump and valve tappet clearances were checked and set according to manufacturer's specifications, and the oil sump refilled with 30 weight non-detergent motor oil.

The engine was then started and run-in for twenty hours, varying the speed and load at approximately 30 minute intervals. This was done to insure proper seating of the piston rings and to determine and correct any engine malfunctions that might develop after disassembly and assembly. At this point it was determined that 1400 RPM was the best engine speed to minimize engine vibration.

Data Acquisition

Before testing was started on each fuel the engine was operated on No. 2 fuel oil until the jacket water temperature stabilized at 75°C. At this point the fuel suction line was switched to the fuel to be tested. Fuel injection pump timing was then varied to determine the optimum setting to obtain maximum power at 1400 RPM for each fuel tested. The engine was then operated continuously at 1400 RPM and full load for ten hours on No. 2 fuel oil, to establish baseline data, and then ten hours on each of the slurry fuels. Data were collected at 30 minute intervals.

Fuel consumption was obtained while burning fuel from a 19 liter tank mounted on the scale. A motor driven stirring device was mounted on the fuel tank during slurry operation to insure complete mixing of the coal and No. 2 fuel oil. With the engine running the stop watch was started as the scale beam reached its neutral position. At this point the scale was unbalanced by 500 grams. The stop watch was stopped after the appropriate amount of fuel was burned and the beam rebalanced.

Opacity readings were taken by first opening the exhaust by-pass valve full open to purge the pipe of any soot that might have collected. This valve was then closed to allow only 10 percent of the exhaust to flow through the detector unit. The detector unit was then inserted into the exhaust stream and a reading taken. These readings were repeated at 60 minute intervals.

Combustion pressure-time traces were photographed from the oscilloscope face using the Polaroid camera attachment. Photographs were taken at two hour intervals with the camera aperture set at a 2.8 F-stop and a shutter speed of 0.1 seconds.

The horizontal sweep for all inputs was supplied by the rotational function generator. This generator provides a display of thirty-six 20 degree markers with emphasis at 120 degree intervals and 360 degrees.

To record the oscilloscope displays under operating conditions a C-12 Tektronics camera attachment was used. Polaroid photographs were taken for the various fuels used.

Presentation and Discussion of Results

Three fuels, No. 2 fuel oil, 20% slurry and 32% slurry were each tested for ten hours continuously in the Nordberg diesel engine. The 40% slurry was tested approximately one hour before the test was terminated because of extremely poor performance. Prior to testing each of these fuels the fuel injection timing was varied to obtain maximum power. This had no effect with any of the fuels tested and in each case the injection timing was returned to its original setting.

Engine data and significant test results are listed in Table 4-2. The data taken for No. 2 fuel oil, 20% slurry and 32% slurry showed very little variation over the ten hour test period for each fuel. The values shown for these fuels are the average of the 20 readings taken over these ten hour periods. The values for the 40% slurry are the average of two sets of data taken in a one hour period.

Figures 4-3 and 4-4 show the power output and brake specific energy consumption for the four fuels tested. Power production for the 20% slurry was 88% of the 9.25 kw value for No. 2 fuel oil and 70% of this value for the 32% slurry.

The power production with the 40% slurry was 32% of the power produced with No. 2 fuel oil and less than half that of the power produced with the 32% slurry.

Table 4-2. Test Data From a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 RPM on Raw Coal - No. 2 Fuel Oil Slurries.

Fuel	No. 2 Fuel Oil	20% Slurry	32% Slurry	40% Slurry
Load, newton	110.9	97.6	84.7	35.5
Power, kilowatt	9.25	8.14	7.06	2.96
Inlet Air Temp., C	29	28	26	27
Clg. Water In, C	25	24.5	24.5	17.8
Clg. Water Out, C	79.5	79.5	79.5	79.5
Exhaust Temp., C	471	435	432	482
Atm. Press., kPa	94.5	95.3	94.8	96.0
Bsec, kJ/kw-hr	28,055	32,088	39,831	73,028
Opacity, percent	26	32	41	30

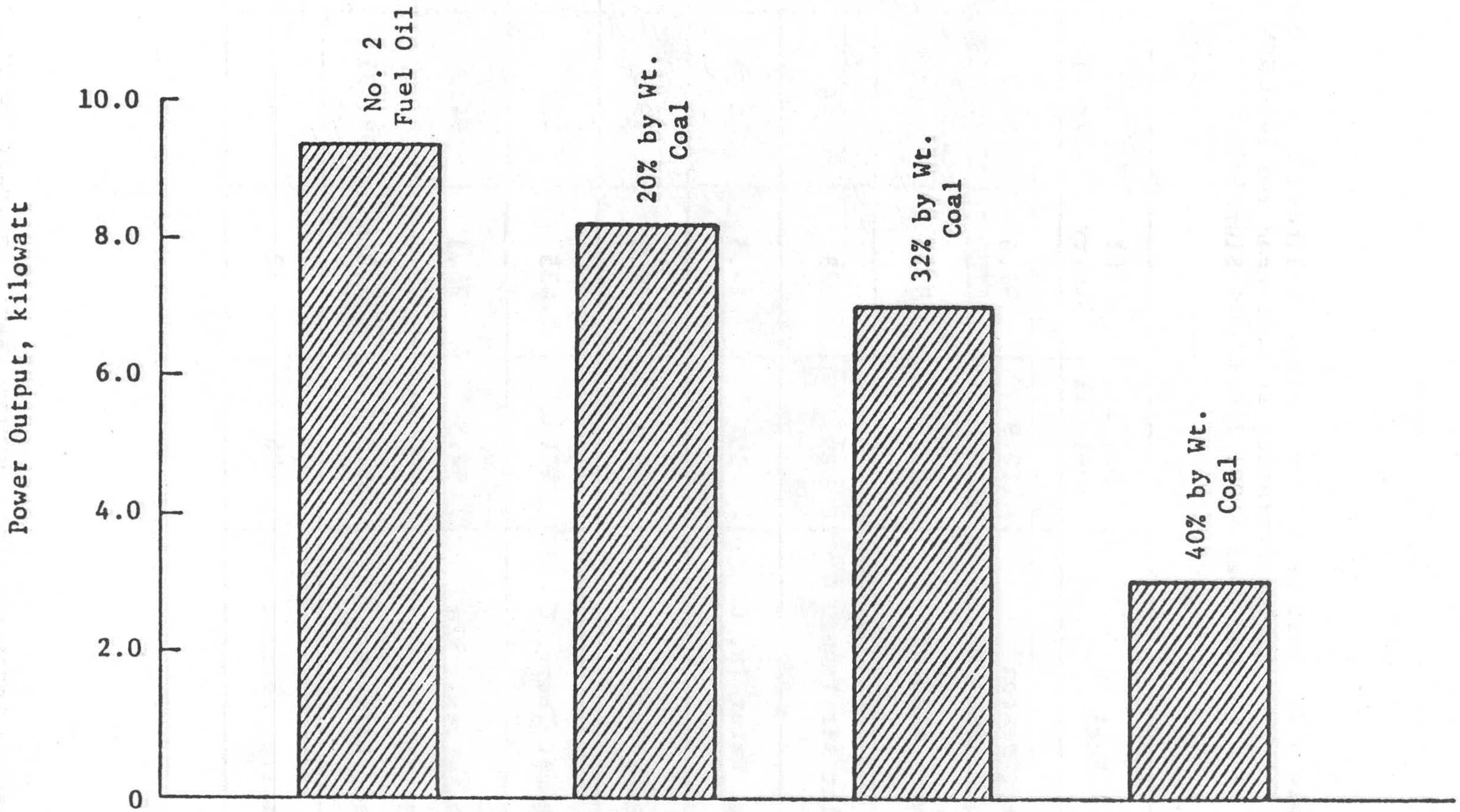


Figure 4-3. Power Production of a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 RPM on Raw Coal - No. 2 Fuel Oil Slurries.

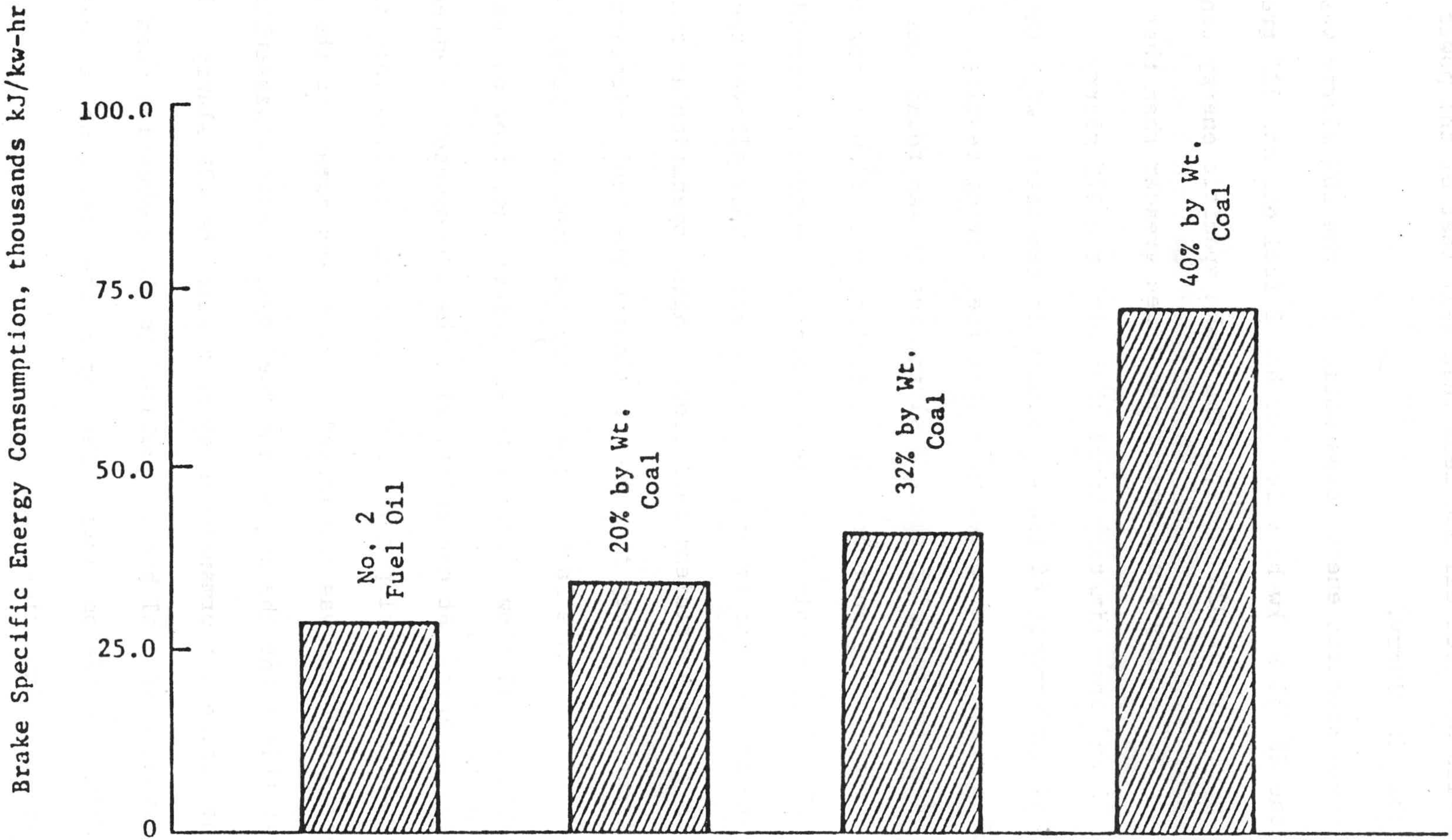


Figure 4-4. Energy Consumption of a Single Cylinder 1360 cc Diesel Engine Operating at a Full Load and 1400 RPM on Raw Coal - No. 2 Fuel Oil Slurries.

The power production with the 40% slurry was 32% of the power produced with No. fuel oil and less than half that of the power produced with the 32% slurry.

Brake specific energy consumption for the 20% slurry was 14% greater than the 28.055 kJ/kw-hr value for No. 2 fuel oil and 32% greater than this value for the 32% slurry. The brake specific energy consumption with the 40% slurry was almost three times greater than that of No. 2 fuel oil and approximately twice that with the 32% slurry.

The performance of the 40% slurry is consistent with the operational problems experienced with this fuel during testing. A ten hour test was attempted with the 40% slurry but it was found that the engine transfer pump would not provide sufficient fuel flow to the injection pump. The fuel supply tank was elevated 1.5 meters to provide a greater pressure head to the transfer pump suction. This allowed the transfer pump to supply sufficient fuel flow. Engine operation at this point was very irregular. Every five to ten minutes the fuel injection pump had to be bled to remove large lumps of agglomerated coal particles in order to reestablish fuel flow. Even with sufficient fuel flow engine performance was very erratic. At one point, with the dynomometer on speed control, no power was being developed while fuel continued to flow into the combustion chamber. The test was terminated to avoid any damage to the engine.

At this point the engine and fuel system were disassembled to determine why the engine performance was so poor with the 40% slurry. It was found that large amounts of coal had accumulated in the combustion chamber and around and behind the piston rings. The top of the piston had a coating of coal approximately 3mm thick.

Because of the heavy coal deposits in the engine it is felt that the poor engine performance was due to the fuel injection systems inability to properly spray the 40% slurry into the combustion chamber. This improper fuel spray pattern apparently disturbs ignition and combustion so badly that coal accumulated in the engine.

Calculations were made to determine the energy distribution to the power developed, engine friction, cooling water, exhaust, and energy unaccountable for the four fuels tested. These results are listed in Table 4-3 and illustrated in Fig.4-5. Values for the 20% slurry and 32% slurry were within 90% and 40% of the values obtained with No. 2 fuel oil respectively. The 40% slurry with its low performance had a very low percentage of input energy to power produced and a much higher percentage to cooling water and exhaust.

In general for all four fuels the percentage of energy to the exhaust is lower than what would normally be the case. This was due to the location of the exhaust temperature thermocouple. Because of the exhaust piping configuration, this thermocouple was mounted 1.0 meters from the exhaust manifold of the engine. Forced convection by an electric cooling fan, used to keep the exhaust and instrumentation piping temperatures within acceptable limits, increased the heat carried away from the exhaust before its temperature was measured.

Pressure-time traces for the four fuels tested are presented on Figs.4-6 and 4-7. Each trace represents 720 degrees of crankshaft rotation or in other words the four-stroke-cycle. After testing the No. 2 fuel oil and 20% and 32% slurries it was found that the pressure transducer was defective. This is evident by the pressure trace that drops well below the horizontal atmospheric line at the start of the compression process on these traces. A new transducer was installed prior to

Table 4-3. Energy Data from a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 RPM on Raw Coal No. 2 - Fuel Oil Slurries.

Fuel	No. 2 Fuel Oil	20% Slurry	32% Slurry	40% Slurry
HHV of Fuel, kJ/kg	44,724	42,053	40,775	39,032
Energy Input, kw	72.06	72.54	77.81	59.85
Pct. E_{in} to Bkw	12.84	11.22	9.08	4.95
Pct. E_{in} to Clg. Wtr.	6.48	6.43	5.76	9.95
Pct. E_{in} to Exh.	10.26	9.55	8.99	12.92
Pct. E_{in} to Fkw	7.20	7.15	6.67	8.67
Pct. E_{in} Unacct.	63.22	65.65	69.50	63.51

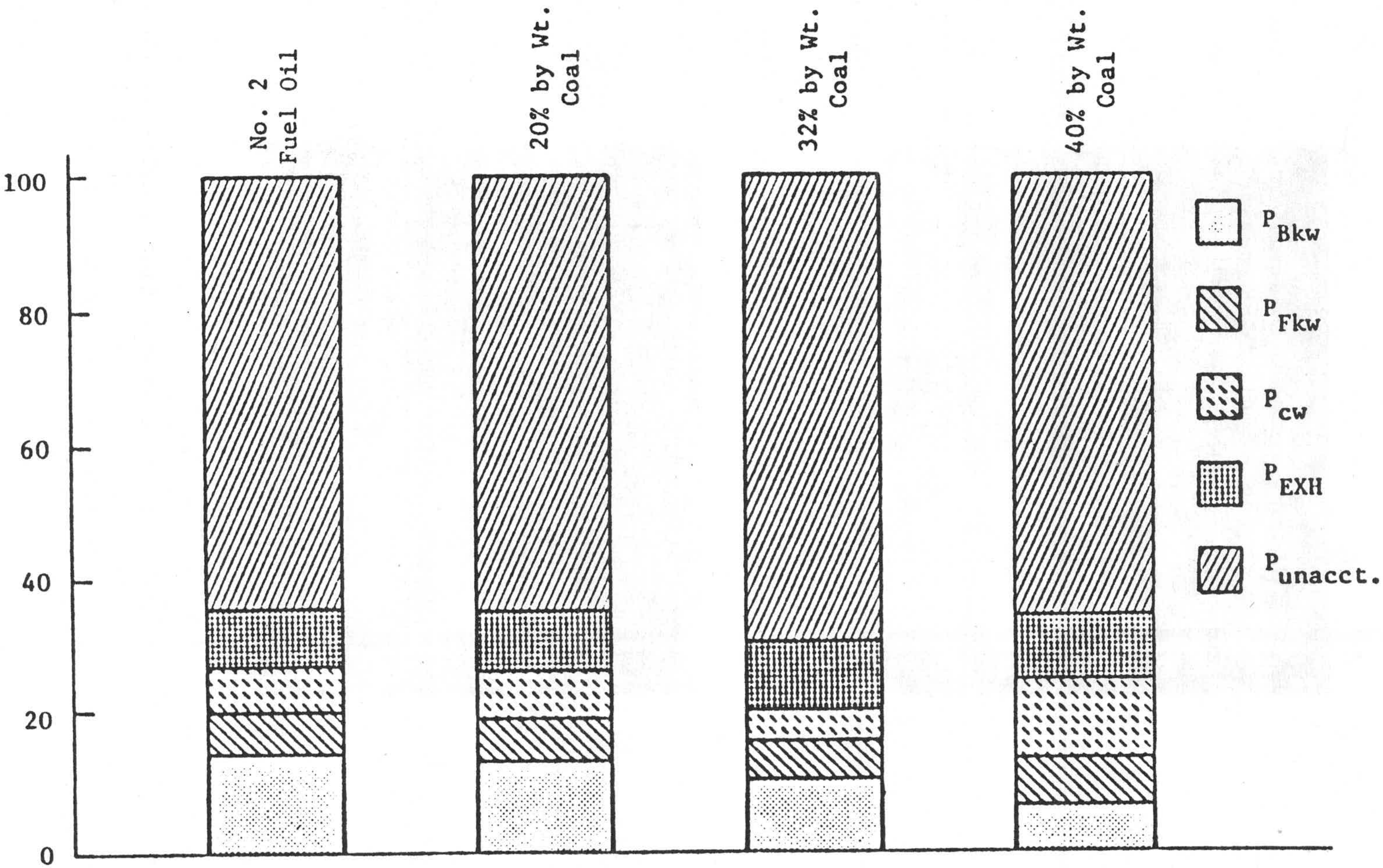
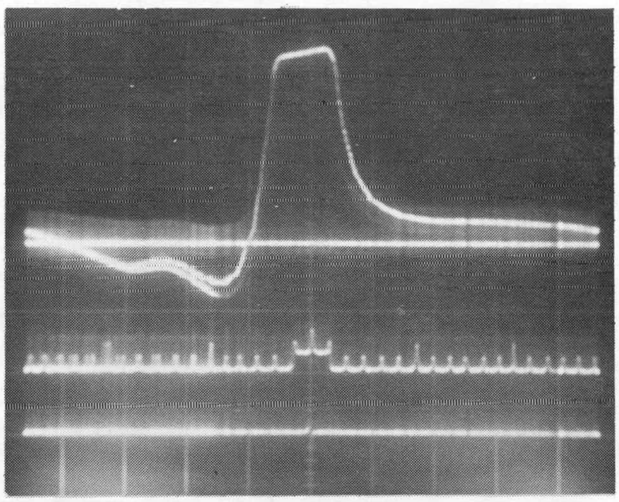
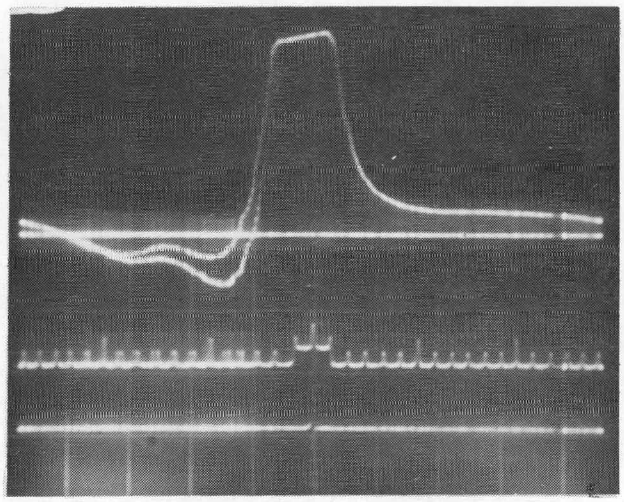


Figure 4-5. Energy Distribution of a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 RPM on Raw Coal - No. 2 Fuel Oil Slurries.

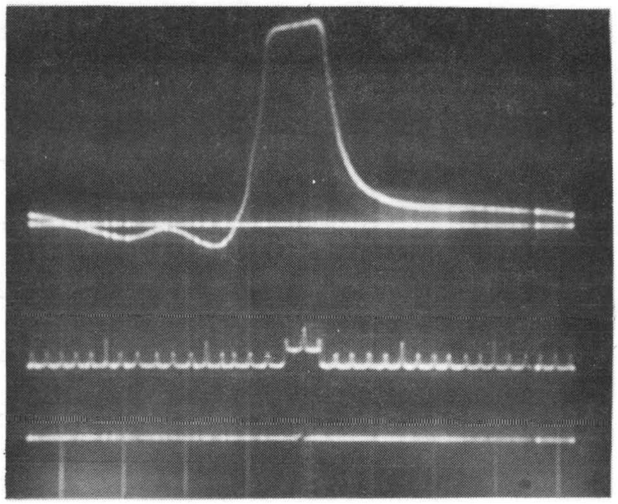


No. 2 Fuel Oil

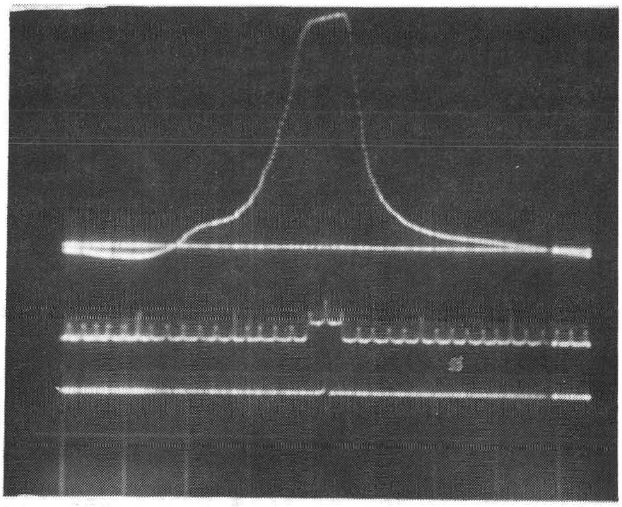


20% by Wt. Coal

Figure 4-6. Pressure-Time Traces for a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 RPM on No. 2 Fuel Oil and 20% by Weight Raw Coal - No. 2 Fuel Oil Slurry.



32% by Wt. Coal



40% by Wt. Coal

Figure 4-7. Pressure-Time Traces for a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 RPM on 32% and 40% Raw Coal - No. 2 Fuel Oil Slurries.

testing the 40% slurry. The pressure time trace for this fuel is correct as compression begins as it should at approximately 180 degrees BTDC.

The flat portion at the top of all four traces illustrates the combustion process and its length represents the time in which combustion takes place. On all four traces this representation in accurate and a good basis for comparing the four fuels tested.

For the No. 2 fuel oil, 20% slurry and 32% slurry the start of combustion occurred at approximately 40 degrees BTDC. The length of combustion for these three fules is approximately 60 degrees of crankshaft rotation. The trace for the 40% slurry shows combustion beginning at 25 degrees BTDC and lasting 40 degrees of crankshaft rotation.

These differences for the 40% slurry explain the low power produced and high brake specific energy consumption values obtained using this fuel. The 15 degree difference in the start of combustion was probably due to the fuel injection system's inability to properly spray the 40% slurry into the combustion chamber with consequent delay of ignition and poor combustion.

Upon completion of full load testing of the four fuels testing was attempted to evaluate the port load performance of the engine at 1400 RPM using these slurry fuels. This was first attempted using the 20% slurry. Engine operation at this point was satisfactory. The engine load was then reduced. At approximately half load engine operation become erratic before it lost all power.

The engine was shut down and the fuel injector disassembled. It was found that the nozzle plunger was siezed with-in the nozzle tip. After applying heat the nozzle plunger was withdrawn. Once apart it was noted that a slag type substance had coated both ports.

A new injection nozzle and plunger were installed and the port load testing resumed in the same manner except with the 32% slurry as a fuel. Again at half load the same malfunction occured. Injector disassembly revealed the same result as before. At this point part load testing was terminated.

A probable explanation of this problem follows. During normal operation minute amounts of fuel enter the clearance between the nozzle plunger and the nozzle tip. With No. 2 fuel oil operation this leakage serves as a lubricant for the plunger. In the case of slurry fuels containing ash, a molten ash is created. As engine load decreases from full load, and temperatures decrease, this molten ash solidifies seizing the plunger in the nozzle tip.

V

EXPERIMENTAL INVESTIGATION

Task 2. Exhaust SO_x and NO_x Content and Capacity

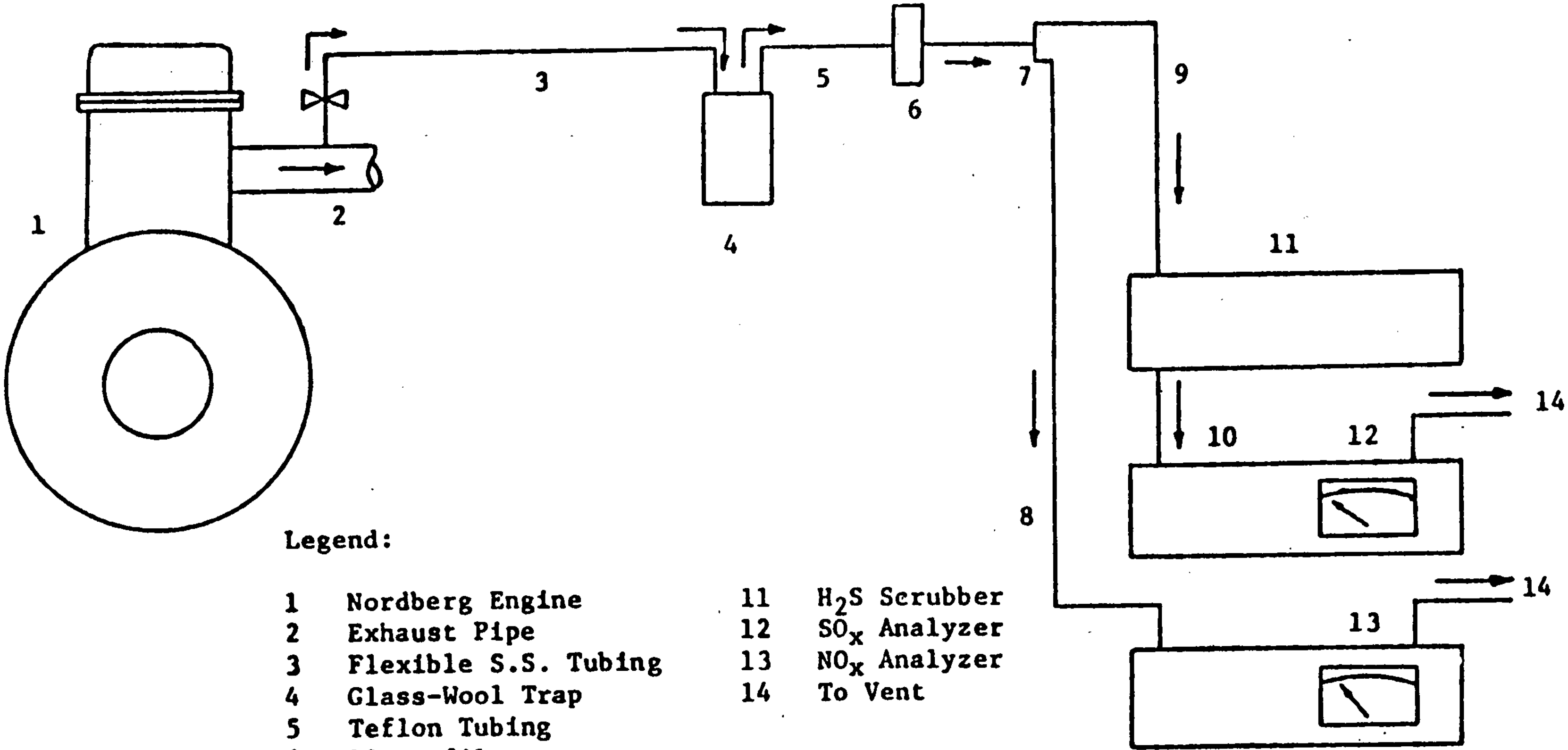
Description of Apparatus

Details of the piping used to carry the exhaust sample to the SO_x and NO_x analyzers are given in Fig. 5.1. The exhaust manifold was tapped at a distance of 0.25 m from the engine cylinder for extracting the exhaust sample. A glass-wool trap was included in the line to trap heavy particulate content of the exhaust. A 10μm filter was placed downstream of the glass-wool trap to prevent any particles larger than 10μm in size from going into the analyzers. This is necessary to prevent clogging the fine capillaries in these instruments.

A Bendix Model 8303 total sulfur monitor was used to monitor the SO_x content of the exhaust gas. Full scale ranges of 0.5 and 1.0 ppm are available on the instrument to read the amount of SO_x. This analyzer was used in conjunction with a Bendix Model 8845 H_2S scrubber in order to remove hydrogen sulfide (H_2S) from the incoming exhaust sample and thus enabling measurement of SO_x alone.

For the measurement of oxides of nitrogen, a Bendix Model 8102 NO_x analyzer was used. This analyzer uses the principle of photometric detection of the chemiluminescence resulting from the flameless gas phase reaction of nitric oxide (NO) and ozone. 100, 200, 500, 1000, 2000, and 5000 ppm ranges are available for measurement.

Opacity of the exhaust gas was measured using a modified version of a device developed by Dr. T. F. Parkinson of VPI & SU staff for the Florida Research Corporation. This device is designed to measure the light-absorption of an exhaust gas stream.



Legend:

1	Nordberg Engine	11	H_2S Scrubber
2	Exhaust Pipe	12	SO_x Analyzer
3	Flexible S.S. Tubing	13	NO_x Analyzer
4	Glass-Wool Trap	14	To Vent
5	Teflon Tubing		
6	10 µm filter		
7	T Connection		
8,9,10	Teflon Tubing		

Figure 5-1. Schematic of Piping for Exhaust Sample

The instrument uses a simple Wheatstone bridge circuit. Two collimated beams of light pass through the exhaust gas stream and strike two photocells. These two photocells form two sides of a Wheatstone bridge circuit as shown in Fig. 5-2. The two photocells respond to the light intensities of a reference beam and a sample beam. When no smoke is present the voltage drop across these cells are equal and the meter reads zero. When smoke is present, the light-intensity of the sample beam is reduced and a positive reading is obtained. This meter deflection is proportional to smoke opaqueness.

The detector unit of the opacity meter is constructed of 64 mm diameter aluminum pipe. Solid quartz tubes carry a light beam from an incandescent lamp source in a parabolic reflector to the exhaust stream. Another set of similar quartz tubes carry the collimated light to the photocells. The sample beam quartz tubes have a sampling gap of 50 mm. The reference beam has a gap of only 2.5 mm. This beam compensates for the soot that collects on the tube faces by appropriately deflecting the meter negatively as the soot collects. The reference tubes have the same sooting characteristics as the sample tubes but the small gap does not allow them the adequate spacing necessary to sample the exhaust gas stream. An illustration of the unit is shown in Fig. 5-3.

The detector unit was mounted in the exhaust gas stream by slipping the unit into a modified pipe cross fitting. Valves were arranged to allow 10 percent of the exhaust gas flow to pass through the detector.

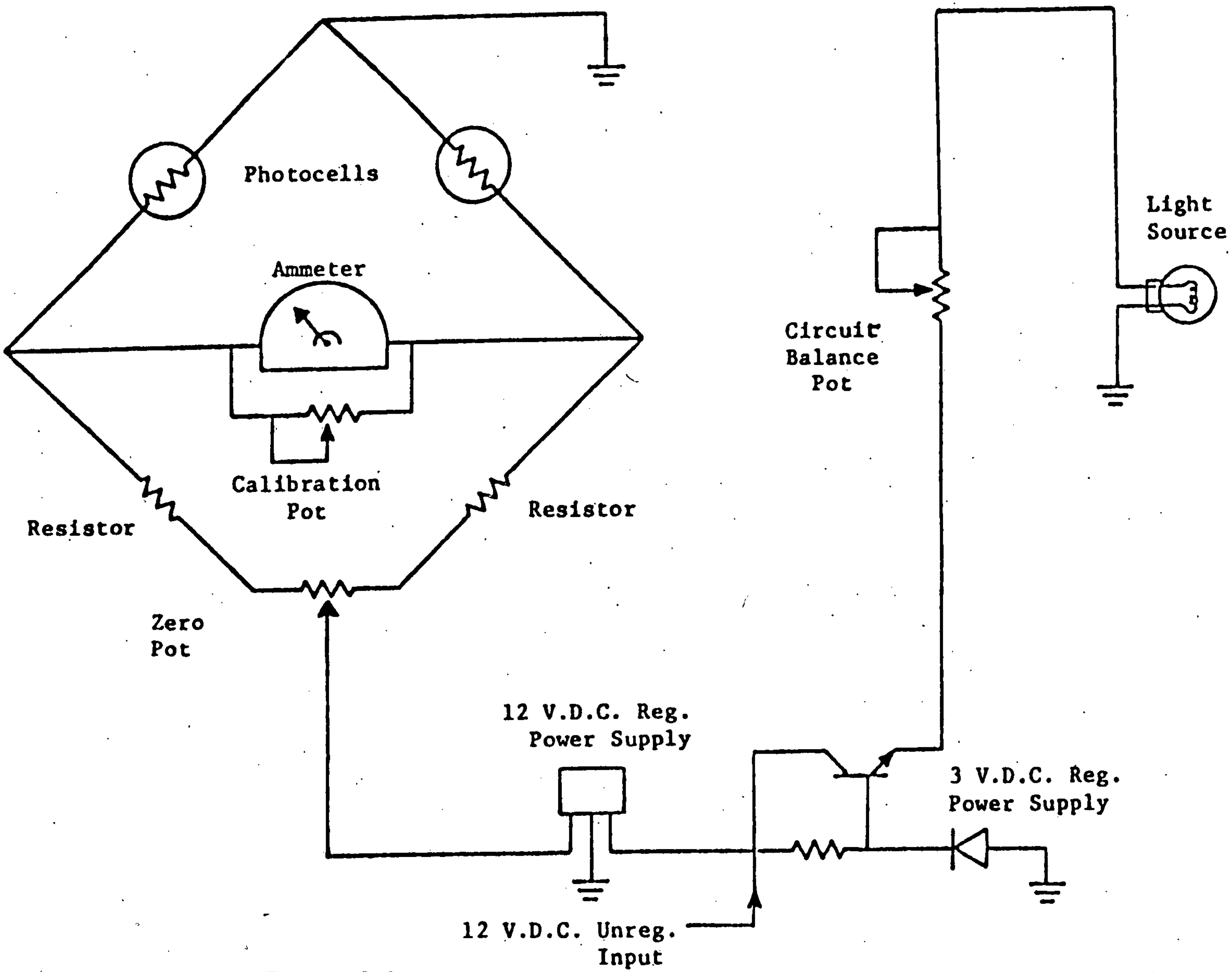


Figure 5-2. Opacity Meter Electrical Schematic

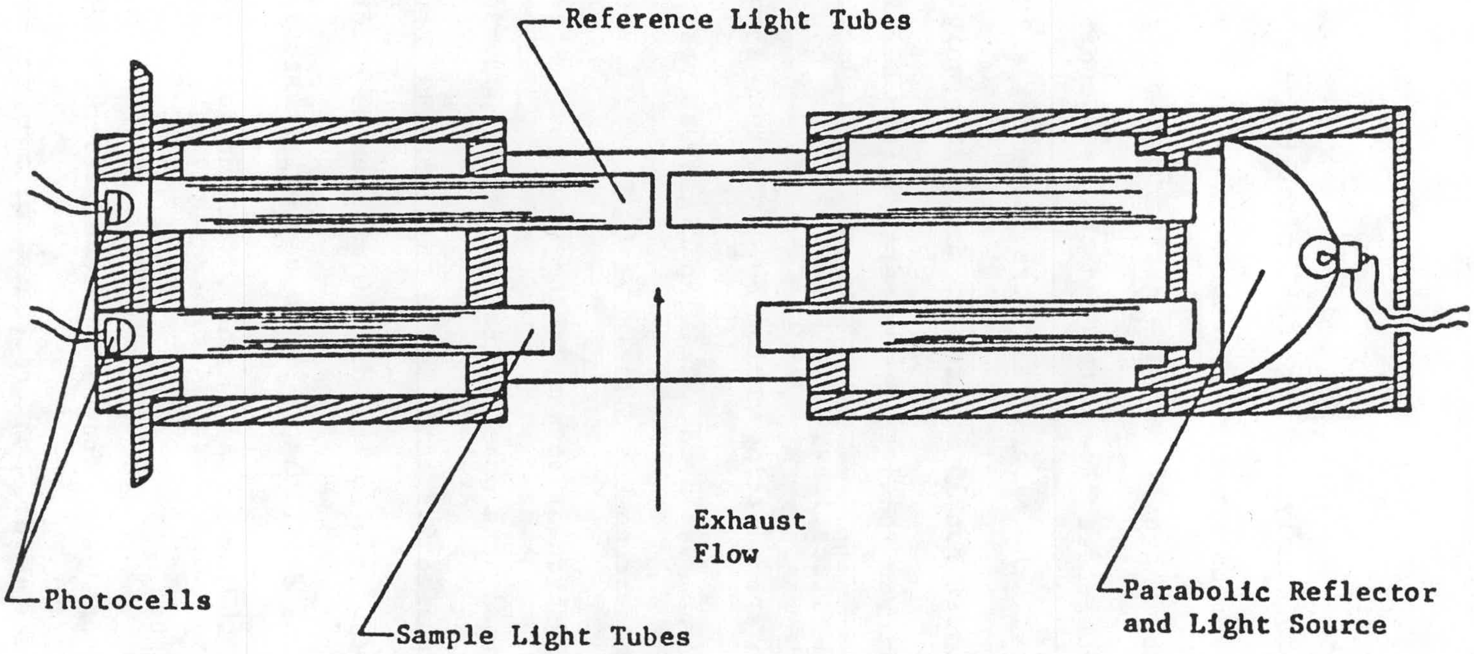


Figure 5-3. Opacity Detector Details

reassembly. At this point it was found that the engine developed rated power at 1400 rpm.

Calibration of the Instruments

The SO_x and NO_x analyzers were calibrated using special span and zero gases. For both analyzers, the zero gas was pure dry air, which is industrially available. The dry air was passed through each instrument at recommended flow rates and the zero controls on the meters adjusted till the meters read zero. The dry air was passed through each analyzer for 30 minutes to check if prohibitive zero drift existed. It was found that the zero drift was well within manufacturer's specifications.

To determine span setting on the SO_x analyzer, a span gas concentration of 0.7 ppm was used. This span gas was passed through the analyzer at the recommended flow rate. Sufficient time was allowed for the instrument to sample the span gas. After a stable reading was obtained, the span control for the 1 ppm range was adjusted so that the meter read 0.7 ppm. Using this setting the analyzer was operated on the span gas for another 30 minutes to check if any span drift existed. The drift was found to be well within manufacturer's specifications. During actual testing, the analyzer was operated on 1 ppm range setting.

For the NO_x analyzer, span gas concentrations of 200 ppm and 515 ppm (NO in N_2) were used. The procedure followed in this case is similar to one used in calibrating the SO_x analyzer. After calibrating the NO_x analyzer, it was ascertained that the meter read correctly on all ranges.

Before each test run, the adjustments and calibrations were repeated to ensure accuracy of measurements.

The opacity meter was calibrated using neutral density filters of known light absorption. A plot was made of neutral density filter absorption versus meter reading. Exhaust smoke density was obtained from these readings.

Experimental Procedure

Before a test was started on any fuel, the engine was operated on No. 2 fuel oil until the jacket water temperature stabilized at 348K. At this point the fuel suction line was switched to the fuel to be tested. Fuel injection timing was then varied to determine the optimum setting to obtain maximum power at 1400 rpm for each of the fuels. The engine was then operated continuously at 1400 rpm and full load for 10 hours on No. 2 fuel oil, to establish baseline data, and on 32 percent and 20 percent by weight coal-oil slurries. When 40 percent slurry was used, the engine developed problems and the run was terminated after 1 hour. Data were collected at 30 minute intervals.

Fuel consumption was obtained while burning fuel from a 5 gallon tank mounted on the scale. A motor driven stirring device was employed during slurry operation to ensure uniform mixing of the coal and oil. With the engine running the time to burn 0.5 kg of the fuel was determined with a digital stopwatch.

Opacity readings were taken by first opening the exhaust by-pass valve full open to purge the pipe of any soot that might have collected. Then this valve was partially closed to allow only 10 percent of the exhaust flow. The detector unit was then inserted into the exhaust stream and a reading taken.

The SO_x and NO_x readings in ppm were read off the meter. It was found necessary to purge the sample line portion from the engine to the glass wool filter every hour to remove the soot that collected. It was also found necessary to change the element in the 10 μm filter as and when it got dirty with soot. The filter element required a replacement every one and half hour, and the necessity of replacement was determined through visual inspection of the element.

Presentation and Discussion of Results

Three fuels, No. 2 fuel oil, 20% slurry and 32% slurry were each tested for ten hours continuously in the engine. As mentioned previously, the test on the 40% slurry lasted for approximately only one hour because of extremely poor performance.

Relevant engine data and significant test results are given in Table 5-1. The data taken for No. 2 fuel oil and 20% slurry did not show much variation over the ten hour test period. There was a certain amount of scatter in the data for SO_x and NO_x compounds for the 32% slurry. However, opacity data for this fuel did not show much variation. The values shown for these fuels are the average of the 20 readings taken over the ten hour test periods. The values for the 40% slurry are the average of two sets of data taken in a one hour period.

Although a comparison of ppm levels of pollutants when the engine is run on different fuels is of primary interest, several indexes were calculated. These include: concentration of pollutant in a unit volume of exhaust gas; amount of pollutant produced in a unit time; ppm pollutant produced per unit power; and, amount of pollutant per unit amount of fuel. These values are tabulated in Table 5-2. The values, are of course, the average of twenty calculations because of the steady state nature of the tests. Corresponding bar graphs are presented in Figs. 5-5 through 5-14. A comparison of opacity of the exhaust streams is shown in Fig. 5-4.

Table 5-1. Test Data from a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 rpm on Raw Coal-No. 2 Fuel Oil Slurries.

Fuel	No. 2 Fuel Oil	20%* Slurry	32%** Slurry	40%* Slurry
Load, N	110.90	97.60	84.70	35.50
Power, kW	9.25	8.14	7.06	2.96
Inlet Air Temp., K	302	301	299	300
Exhaust Temp., K	744	708	705	755
Atm. Pressure, kPa	94.5	95.3	94.8	96.0
SO_x, ppm	0.084	0.301	0.140	0.350
NO_x, ppm	8.5	176.2	45.7	272.5
Opacity, percent	26	32	41	30

* - Pittsburgh Seam Coal
** - Lower Freeport Seam Coal

Table 5-2. Comparison of Pollutants on Various Basis

Fuel		No. 2 Fuel Oil	20%* Slurry	32% ** Slurry	40%* Slurry
Concentration, $\mu g/m^3$	SO_x	233	788	367	916
	NO_x	1.6×10^4	33.2×10^4	8.6×10^4	51.3×10^4
Amount, g/hour	SO_x	1.33×10^{-2}	4.50×10^{-2}	2.09×10^{-2}	5.23×10^{-2}
	NO_x	0.91	18.90	4.70	29.30
ppm/kW	SO_x	0.92×10^{-2}	3.70×10^{-2}	2.00×10^{-2}	11.80×10^{-2}
	NO_x	0.94	21.70	6.50	92.00
Amount g/kg of Fuel	SO_x	2.3×10^{-3}	7.3×10^{-3}	2.9×10^{-3}	10.1×10^{-3}
	NO_x	1.57×10^{-1}	30.70×10^{-1}	5.60×10^{-1}	56.60×10^{-1}

* - Pittsburgh Seam Coal
** - Lower Freeport Seam Coal

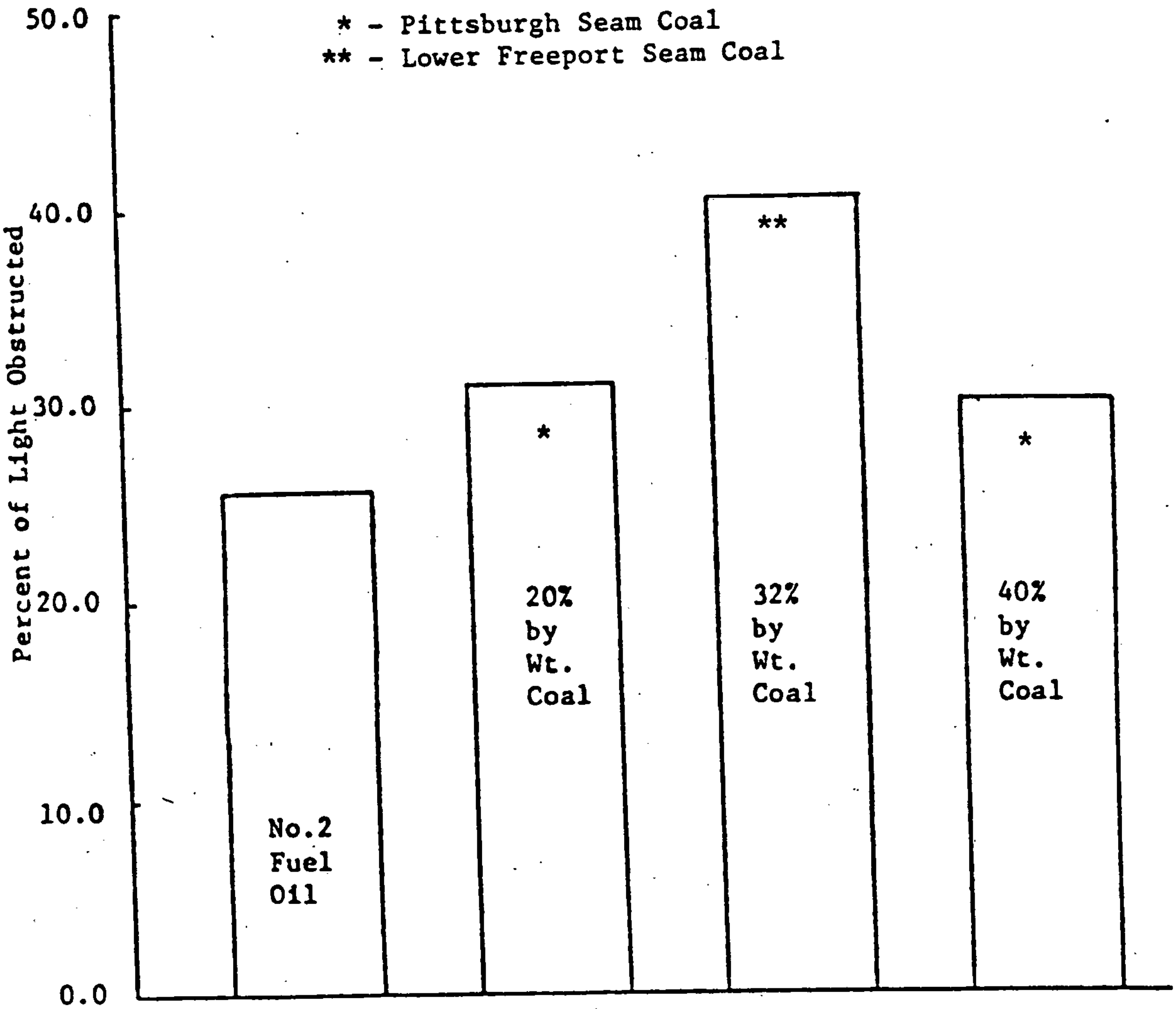


Figure 5-4. Exhaust Opacity of a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 rpm on Raw Coal-No. 2 Fuel Oil Slurries.

* - Pittsburgh Seam Coal
** - Lower Freeport Seam Coal

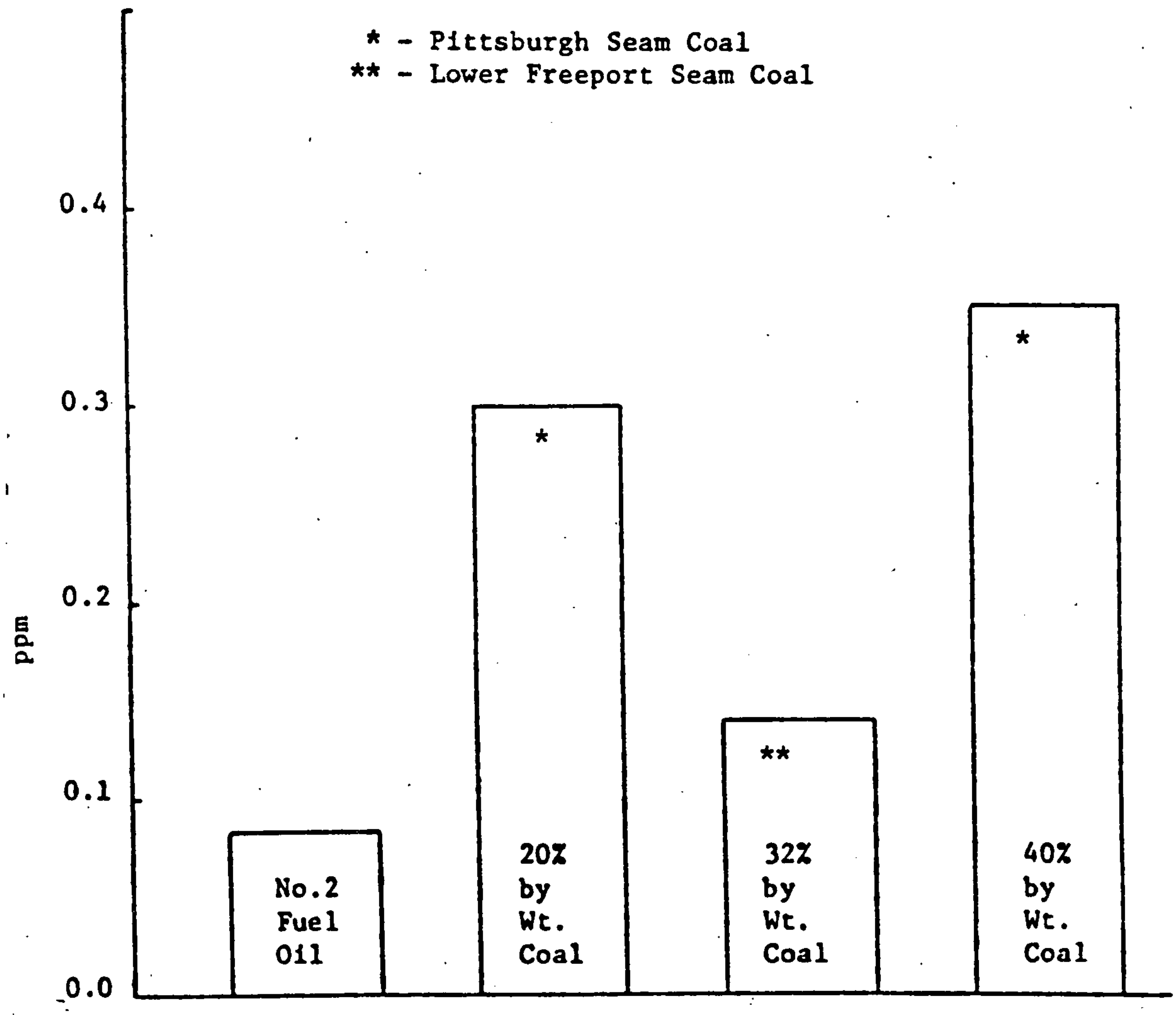


Figure 5-5. Comparison of ppm Level of SO_x Compounds in Exhaust of a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 rpm on Raw Coal-No. 2 Fuel Oil Slurries.

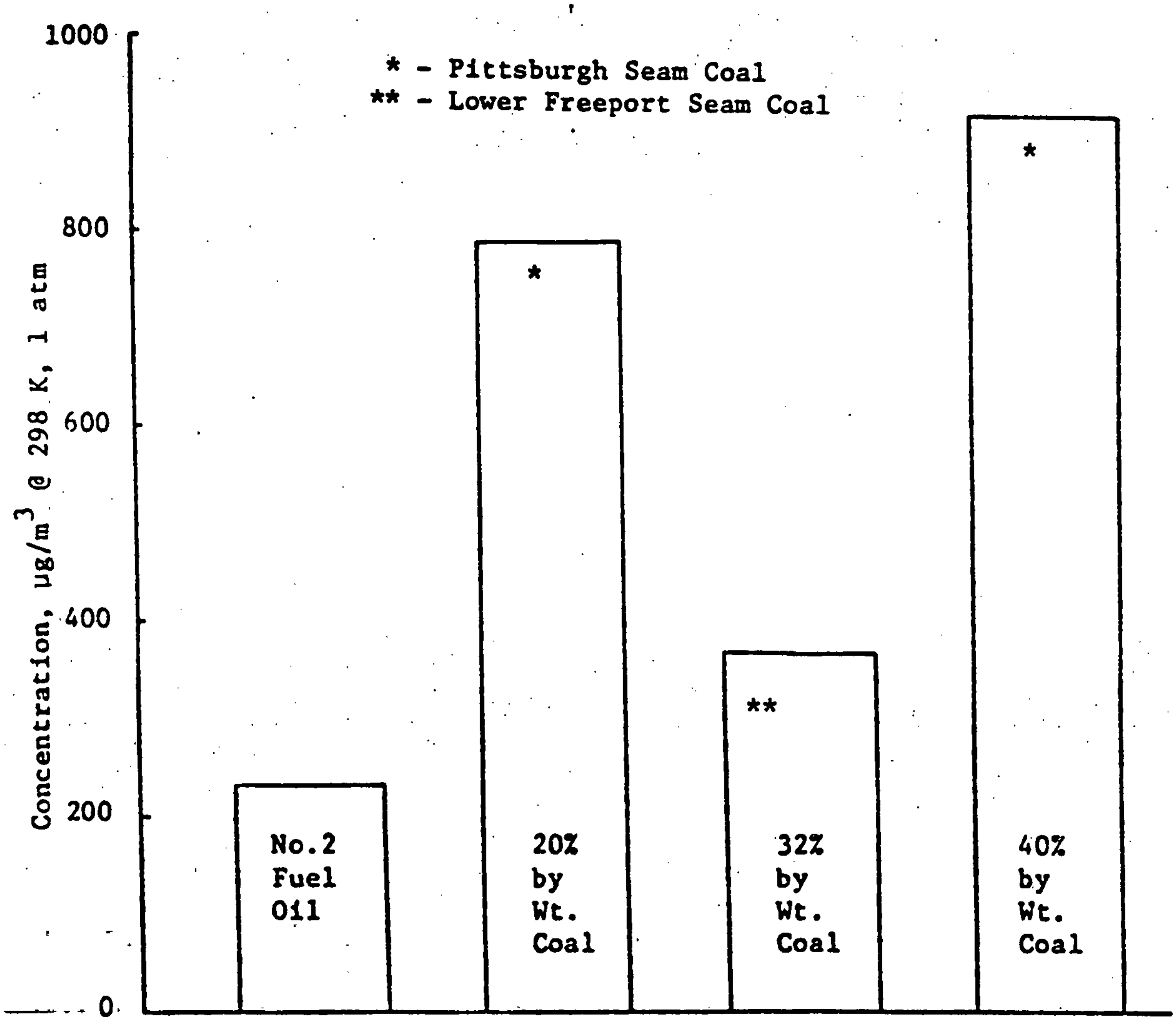


Figure 5-6. Comparison of Amount of SO_x Compounds in 1 m^3 of Exhaust of a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 rpm on Raw Coal-No. 2 Fuel Oil Slurries.

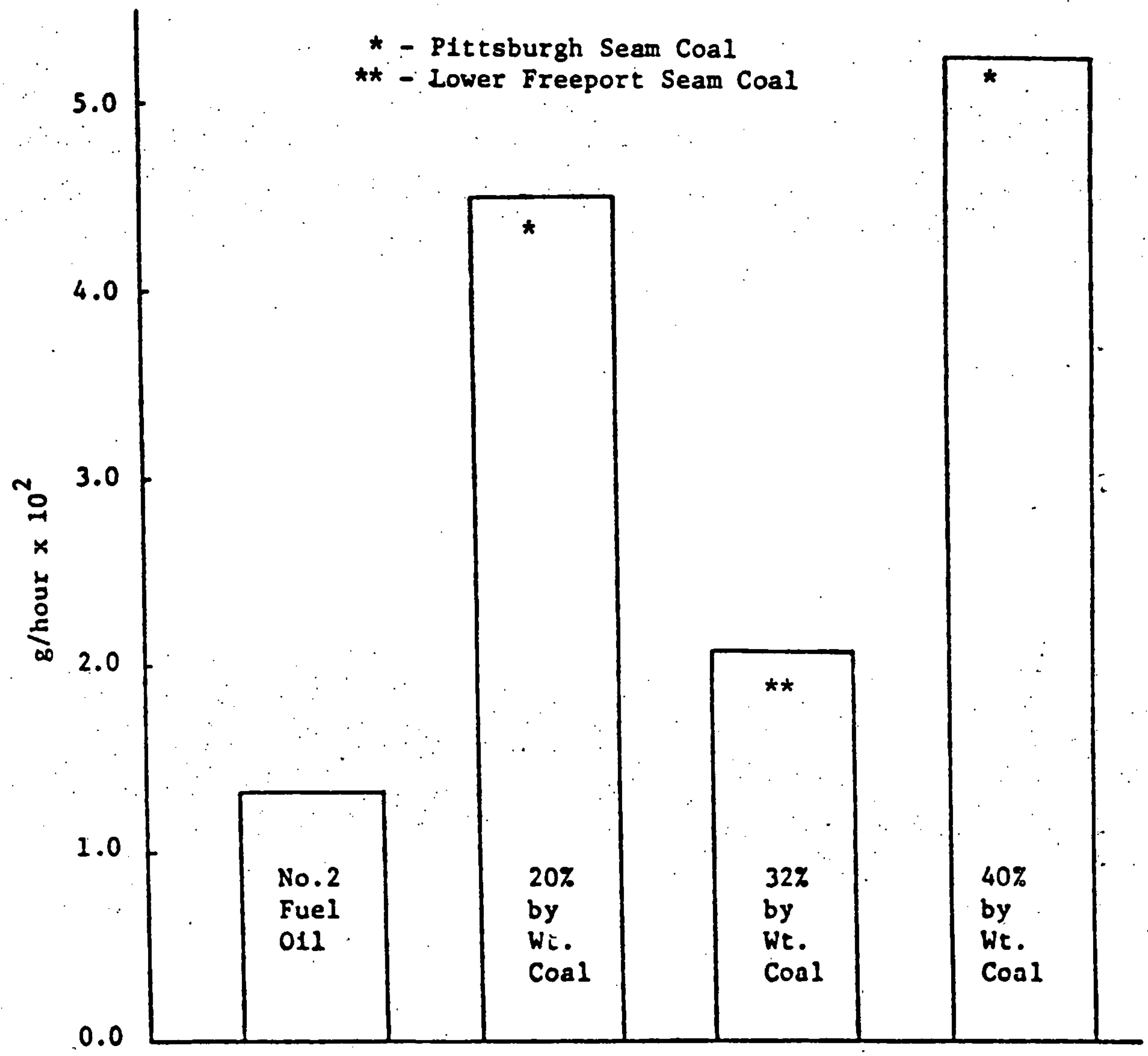


Figure 5-7. Comparison on Time Basis of Amount of SO_x Compounds in Exhaust of a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 rpm on Raw Coal-No. 2 Fuel Oil Slurries.

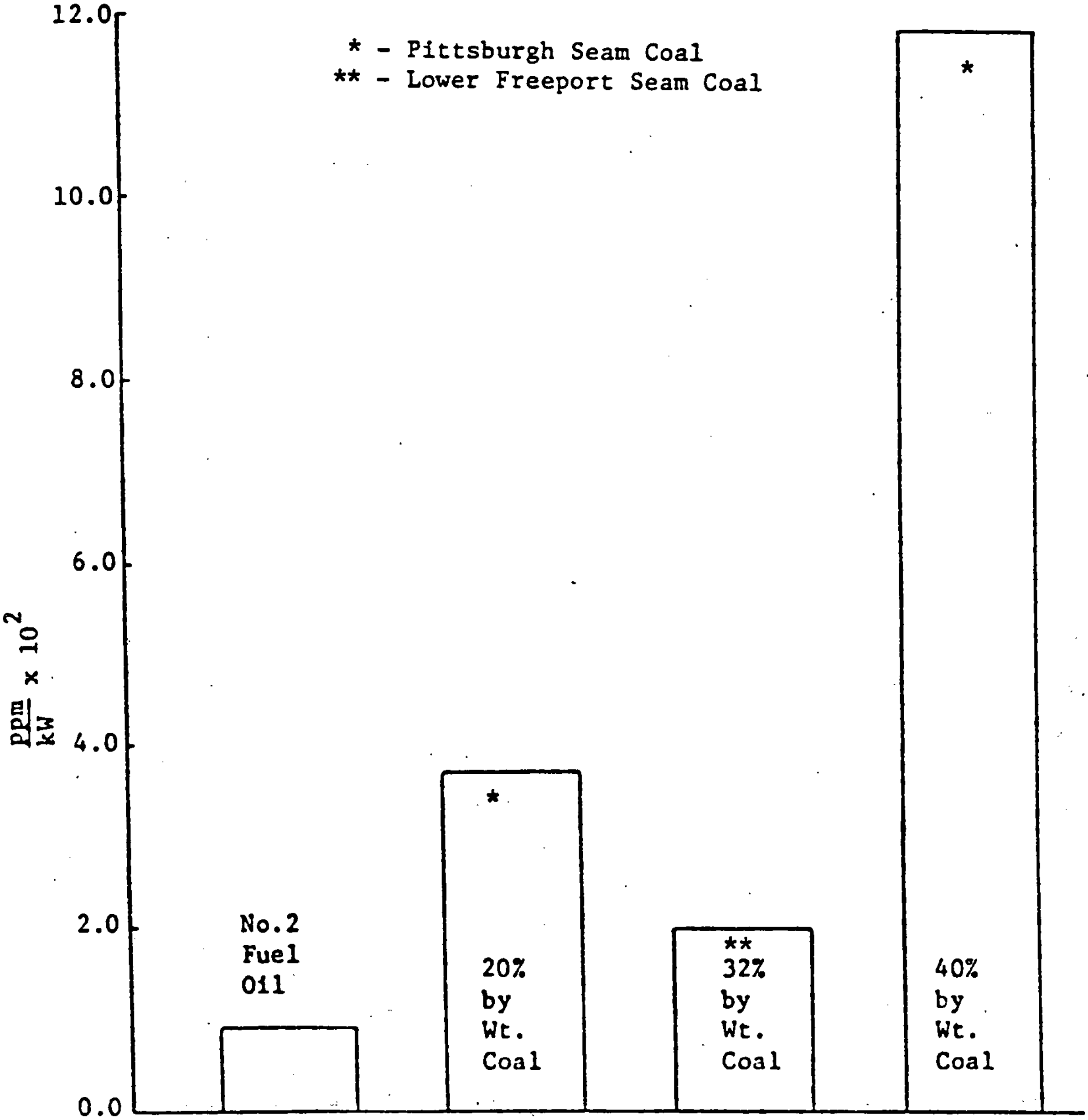


Figure 5-8. Comparison on Power Basis of Amount of SO_x Compounds in Exhaust of a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 rpm on Raw Coal-No. 2 Fuel Oil Slurries.

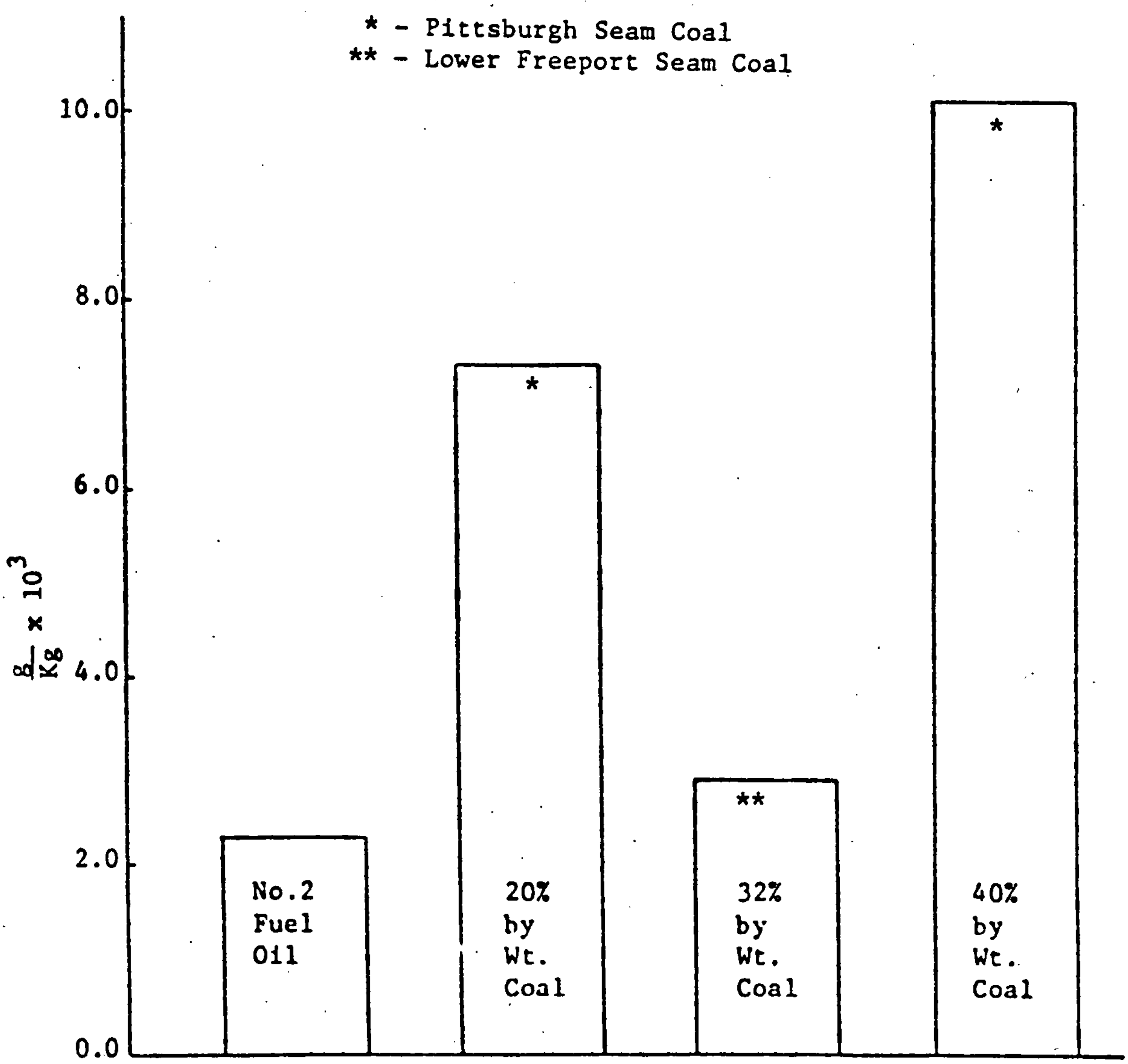


Figure 5-9. Comparison of Amount of SO_x Produced per kg of Fuel by a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 rpm on Raw Coal-No. 2 Fuel Oil Slurries.

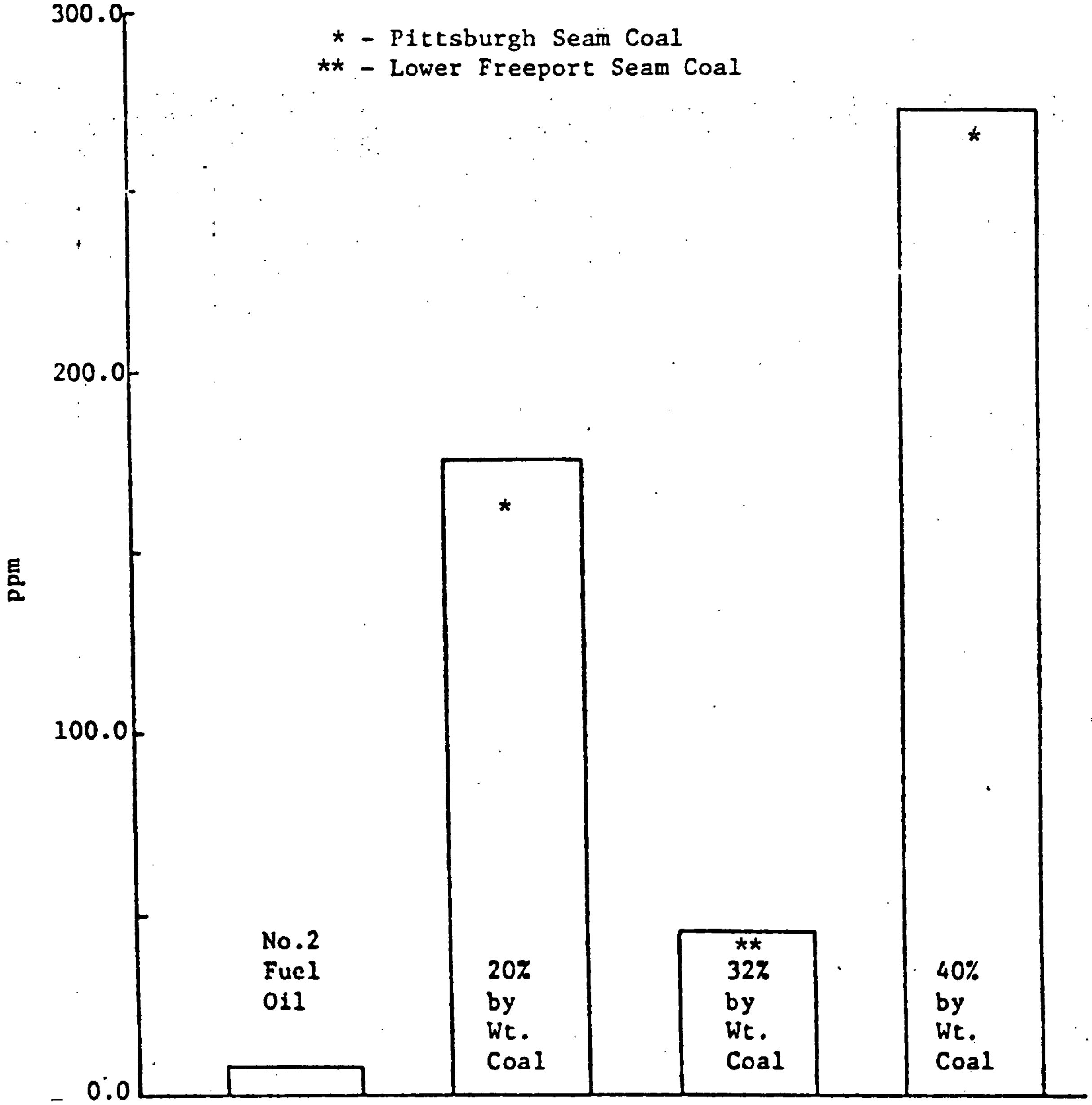


Figure 5-10. Comparison of ppm Level of NO_x Compounds in Exhaust of a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 rpm on Raw Coal-No. 2 Fuel Oil Slurries.

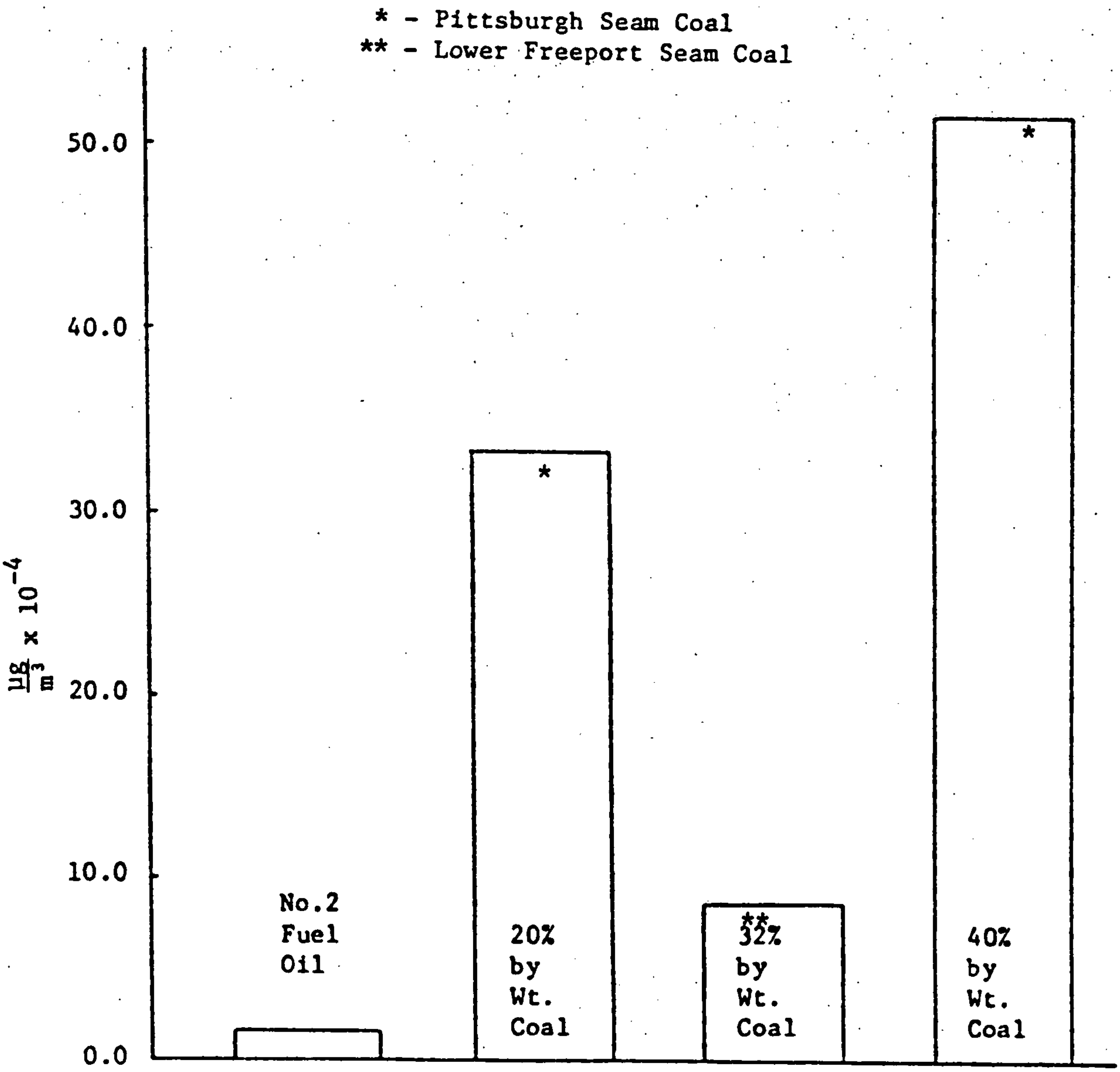


Figure 5-11 Comparison of Amount of NO_x Compounds in 1 m^3 of Exhaust of a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 rpm on Raw Coal-No. 2 Fuel Oil Slurries.

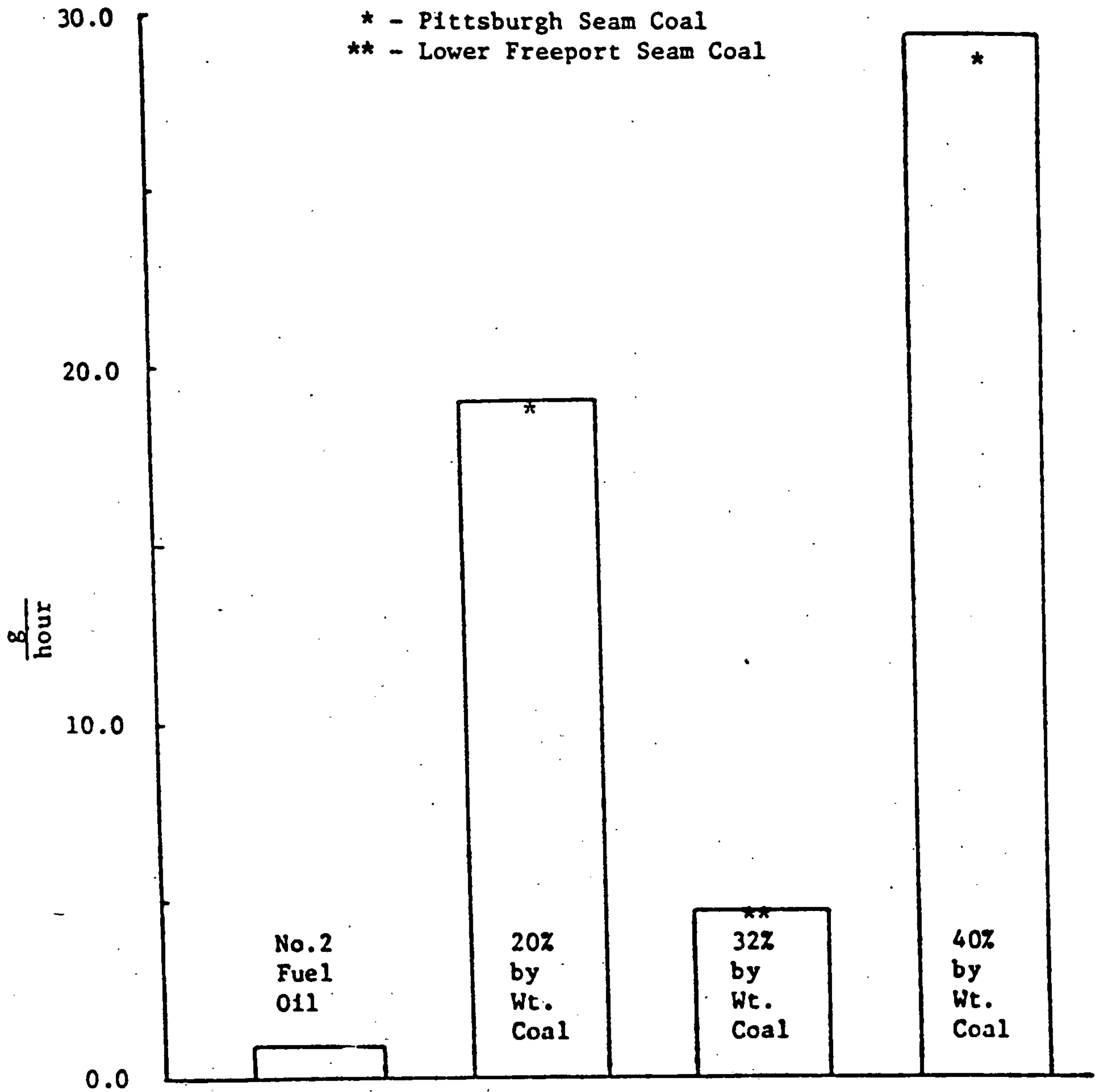


Figure 5-12. Comparison on Time Basis of Amount of NO_x Compounds in Exhaust of a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 rpm on Raw Coal-No. 2 Fuel Oil Slurries.

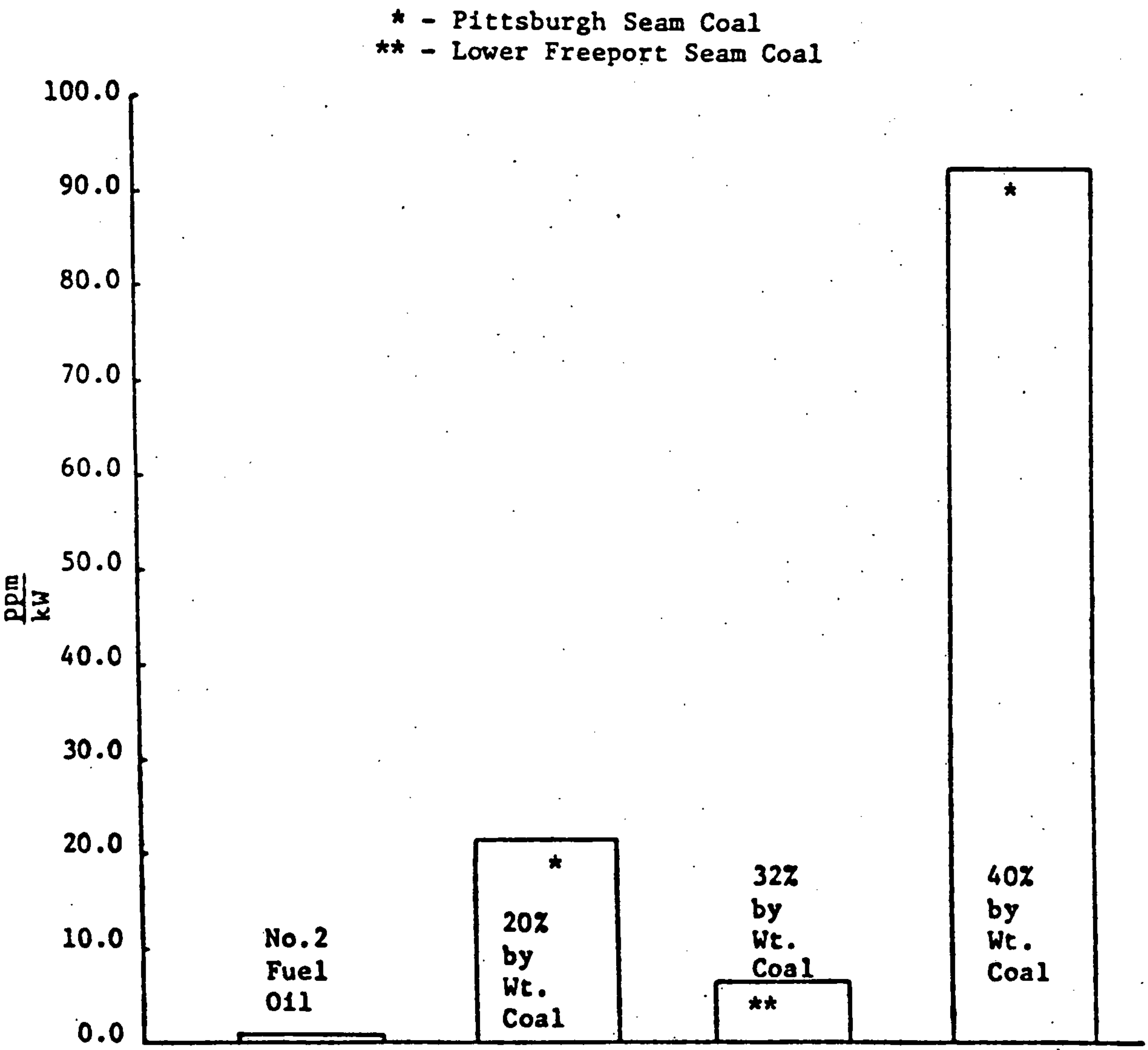


Figure 5-13. Comparison on Power Basis of Amount of NO_x Compounds in Exhaust of a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 rpm on Raw Coal-No. 2 Fuel Oil Slurries.

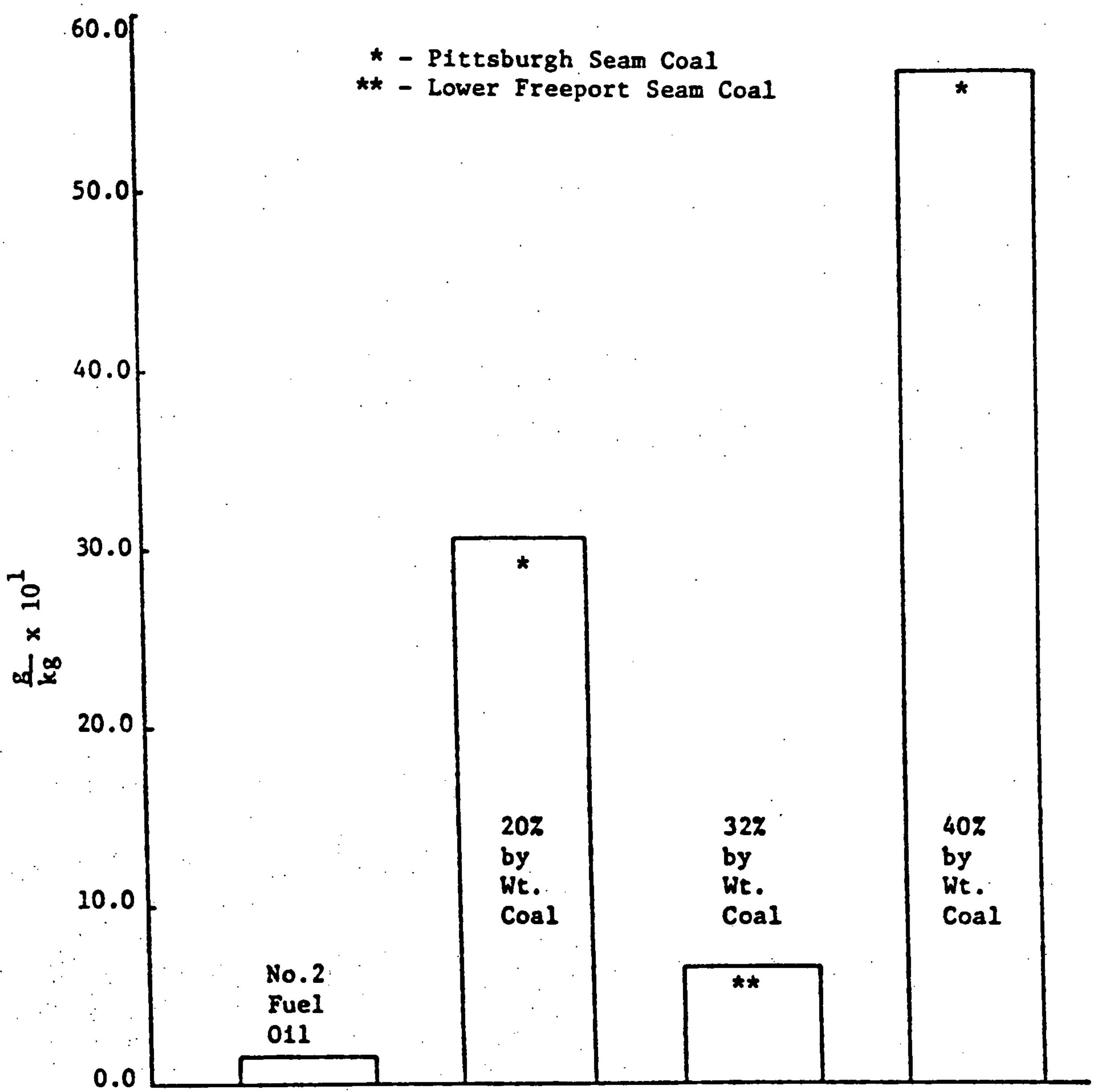


Figure 5-14 Comparison of Amount of NO_x Produced per kg of Fuel by a Single Cylinder 1360 cc Diesel Engine Operating at Full Load and 1400 rpm on Raw Coal-No. 2 Fuel Oil Slurries.

As expected, No. 2 fuel oil gave smallest SO_x concentration in ppm. The 20% slurry, although it contained less coal by weight compared to the 32% slurry, yielded higher number of SO_x in ppm. This is easily explained by referring to the chemical analysis of the two MICO fuels (Figure 3-2). The 20% slurry contains Pittsburgh seam coal, which is much higher in sulfur content compared to the Lower Freeport Seam coal in the 32% slurry. The 40% slurry would be expected to give about double the amount of SO_x when compared to the 20% slurry, since both contain Pittsburgh seam coal. Failure to do this has to do with the incomplete combustion of fuel when the engine was operated on the 40% slurry. As was found later, most of the coal in the 40% slurry did not burn.

For oxides of nitrogen, the No. 2 fuel oil gave the lowest reading of 8.5 ppm. 20% slurry, 32% slurry, and the 40% slurry gave readings which were 21, 5.4, and 32 times respectively. Since several parameters including intake air temperature, overall air/fuel ratio, oxygen availability, combustion temperature, humidity, and nature of fuel can affect the NO_x production, an attempt was not made to explain the variation in the NO_x production.

Opacity test results are illustrated in Fig.5-4. As expected, the lowest reading, 26% light obstructed, was obtained during the operation on No. 2 fuel oil. The increased opacity during operation on the 20% and 32% slurries, 32% and 40% light obstructed respectively, is due to the increased ash content of these fuels. The ash content is 1.0% by weight for the 20% slurry and 2.5% by weight for the 32%

slurry. In comparison, No. 2 fuel oil has an ash content of only 0.25% by weight. Another possible reason for increased opacity when operating on these slurry fuels is that combustion of these slurries is not as complete as with No. 2 fuel oil.

The 40% slurry gave lower opacity results than expected. This is reasonable since most of the coal in the slurry did not burn. For this reason, the opacity reading, 30% light obstructed for this fuel was approximately that for the No. 2 fuel oil.

VI

EXPERIMENTAL INVESTIGATION

Task 3 - Measurement of Engine Wear

Description of NAA Facility

The facility used for the NAA performed on the engine oil samples is the Virginia Polytechnic Institute and State University Nuclear Research Laboratory. The Laboratory (19) is a research organization established in 1970 for the use of the the Univeristy, other public institutions, state agencies, and industrial users of the resources of the V.P.I. & S.U. Research Reactor and auxillary facilities. Services presently available are neutron activation analysis, radioisotope production, X-ray fluorescence analysis, and sample irradiation. On interest here is the NAA which offers elemental analysis of almost any sample. The sample can be analyzed for 68 elements with limits of sensitivity, for most elements of less than one microgram and, for some of less than one nanogram. Table 6-1 is a list of the 68 elements and their maximum detection sensitivities under a standard irradiation program. The sensitivities are given for the most sensitive gamma of the most sensitive isotope for each element. It is assumed that there are no interferences from other elements other than the one under consideration.

The V.P.I. & S.U. Research Reactor provides numerous internal and external irradiation facilities (20). Samples for NAA are usually given three irradiations and three gamma spectra are obtained to optimize the analysis. A typical set of irradiation times, fluxes, wait times, and

Table 6-1. NAA Detectable Elements and Their Sensitivities

Element	Energy MeV	Micrograms	Element	Energy MeV	Micrograms
Ag	0.633	0.038	Na	1.369	0.0016
Al	1.779	0.036	Nb	0.871	19.0
Ar	1.293	0.0048	Nd	0.270	0.084
As	0.559	0.00063	Ne	0.439	6.3
Au	0.411	0.000089	Ni	1.482	1.3
Ba	0.166	0.014	O	0.200	11100.0
Br	0.776	0.0033	Os	0.460	0.19
Ca	3.084	5.8	Pd	0.188	0.042
Cd	0.336	0.12	Pr	1.576	0.016
Ce	0.293	0.065	Pt	0.475	0.20
Cl	2.168	0.038	Rb	0.898	1.1
Co	1.173	0.14	Re	0.155	0.0002
Cr	0.320	0.34	Rh	0.051	0.003
Cs	0.127	0.0045	Ru	0.724	0.15
Cu	1.039	0.11	S	3.103	245.0
Dy	0.546	0.00050	Sb	0.564	0.0016
Er	0.308	0.0023	Sc	0.889	0.006
Eu	0.963	0.000018	Se	0.136	0.26
F	1.626	6.1	Sm	0.105	0.00014
Fe	1.101	45.0	Sn	0.332	0.50
Ga	0.834	0.00093	Sr	0.388	0.028
Gd	0.365	0.048	Ta	0.185	0.088
Ge	0.416	0.31	Tb	0.879	0.037
Hf	0.133	0.13	Te	0.852	3.5
Hg	0.077	0.0038	Th	0.312	0.036
I	0.443	0.0026	Ti	0.320	0.21
In	0.417	0.00004	Tm	0.084	0.027
Ir	0.328	0.00041	U	0.106	0.0065
K	1.525	0.057	V	1.434	0.0017
La	1.597	0.0016	W	0.685	0.0016
Lu	0.208	0.00022	Y	0.202	0.84
Mg	1.014	1.3	Yb	0.396	0.012
Mn	1.811	0.002	Zn	0.439	0.046
Mo	0.140	0.073	Zr	0.744	0.49

counting times is given in Table 6-2. Neutron exposures of megarads are possible within the reactor. Neutron-free gamma irradiations of kilo-rads are also possible.

The NAA Laboratory has two major gamma counting systems utilizing high resolution germanium-lithium, Ge(Li), detectors: a Nuclear Data 812 minicomputer interfaced to a Nuclear Data 4420 system with two 100 MHz analog-to-digital converters, an internal 24,000 word computer CPU and also a computer standard tape unit, permitting on-line data analysis. Gamma spectra are processed with the VAT-69 code (21).

Experimental Procedure (11)

Before any actual testing was begun the Nordberg diesel engine was disassembled and inspected. At this time it was determined that the piston rings and connecting rod bearings should be replaced. A small burr was found on the crankshaft and this was removed by repeated polishing with crocus cloth and white machinists rouge. The cylinder was measured to determine if any tapering of the cylinder existed. It was determined at this time that the cylinder did not require boring or honing.

The cylinder head was thoroughly cleaned and the valves and their seats inspected for any unusual wear. The combustion chamber was also cleaned to remove any carbon deposits which were present.

The engine oil galleries and pump were flushed repeatedly with solvent to remove any sludge and varnish present in the system.

The fuel injection pump and nozzle were disassembled and also cleaned in solvent. Measurements were taken of the pintle nozzle and

Table 6-2. Typical Schedule for Irradiations and Count Times

Reactor Location	Flux	Irradiation Time	Wait Time	Count Time
Central Stringer Rabbit	1.2×10^{12}	9 sec.-10 min.	1 min.	8 min.
Central Stringer	1.3×10^{12}	6-7 hr.	1-3 days	1 hr.
Central Stringer	1.3×10^{12}	6-7 hr.	10 days	1 hr.

injection plunger to insure they were within manufacturer's specifications.

Initial samples for NAA were taken at this time. The coal-fuel oil slurries were thoroughly mixed and samples taken. Filings from the piston rings, piston, and cylinder liner were used as the samples for the engine parts.

Upon reassembly, a new head gasket was installed, fuel injection pump and valve tappet clearances were checked and set according to manufacturer's specifications, and the oil sump refilled with S.A.E. 30 weight non-detergent motor oil.

The engine was then started and run-in for twenty hours, varying the speed and load at approximately 30 minute intervals. This was done to insure proper seating of the piston rings and to determine and correct any engine malfunctions that might develop after disassembly and assembly. At this point it was determined that 1400 RPM was the best engine speed to minimize engine vibration. No oil filter was used after engine run-in to avoid trapping of the wear debris being analyzed by NAA.

Before testing was started on each fuel, the oil was changed and the engine was operated on No. 2 fuel oil until the jacket water temperature stabilized at 75°C. At this point the fuel suction line was switched to the fuel to be tested. A motor driven stirring device was mounted on the fuel tank during slurry operation to insure complete mixing of the coal and No. 2 fuel oil. Fuel injection pump timing was then varied to determine the optimum setting to obtain maximum power at 1400 RPM for each fuel tested. The engine was then operated continuously at 1400 RPM and full load for ten hours on No. 2 fuel oil to establish baseline data; and on each of the slurry fuels.

Eight oil samples were taken at various times during the testing of each fuel.

After all engine operation testing was completed, the engine was again disassembled and inspected.

Presentation and Discussion of Results

Three fuels, No. 2 fuel oil, 32% slurry and 20% slurry were each tested, in that order, for ten hours continuously in the Nordberg engine. The 40% slurry was tested approximately one hour before the test was terminated due to very poor and erratic performance. Prior to testing each of these fuels, the fuel injection timing was varied to obtain maximum power. This had no effect with any of the fuels and in each case the injection timing was returned to its original setting.

Various measurements were taken of the engine components that are usually subjected to the severest wear. The parts measured were the piston rings, piston, cylinder liner and injector pintle and nozzle. The measurements were taken before the testing began and after the testing was completed.

The ring measurements are presented in Table 6-3. The rings were weighed on a Mettler balance. The ring end gap was measured, with the ring in the cylinder liner, with a feeler gauge or vernier calipers appropriately according to relative size. The top compression, middle compression, bottom compression and top oil control rings experienced a 56, 8.5, 38 and 14 percent weight loss respectively. The ring end gaps were severely enlarged, the worst case being the top compression ring going from 0.081 cm to 1.626 cm. One reason the middle compression ring held up better than the bottom compression ring is that it was a chrome ring as opposed to a cast iron ring. The top compression ring was also a cast iron ring. It was expected that the top compression ring would wear the most since it is exposed to the worst conditions in temperature,

Table 6-3. Ring Measurements Before and After Testing

Ring	Weight* gm		End Gap** cm	
	Before	After	Before	After
Top Compression	21.470	9.455	0.081	1.626
Middle Compression	21.260	19.445	0.061	0.208 1.148
Bottom Compression	21.671	13.512	0.076	1.148
Top Oil Control	48.169	41.473	0.175	0.666

* ± 0.0005 gm

** ± 0.0025 cm

pressure and lubrication. A visual observation made is that the compression rings wore on both diametral sides, that exposed to the cylinder liner and that exposed to the piston, since neither was of a constant radius. The oil control ring's severe wear indicates a large amount of oil contamination. For this extreme, after 31 hours of testing, wear can be likened to the wear experienced in a diesel-fueled engine in 1,000,000 miles of road service (22). This amount of wear is not feasible for any engine.

The piston measurements are presented in Table 6-4. The measurements were taken with a micrometer. Positions 1, 3, and 4 were taken perpendicular to, as positions 2 and 5 were parallel to, the piston-connecting rod pin. Piston wear was small, typically 0.002 cm which may be measurement error, for the 31 hours of testing.

The cylinger liner measurements are presented in Table 6-5. The top of the cylinder liner wore evenly, a 0.017 cm increase in diameter. The bottom of the cylinder liner also wore evenly with a 0.003 cm increase in diameter. The increases correspond to a cylinder diameter wear rate of 129 microns per hour which is unacceptably high.

The fuel injection pintle and nozzle measurements are not given here since they were changed during the testing. Reasons for the changes will be discussed when part load tests are discussed later. However, it was visually observed that wear at the pintle tip had occurred as it was virtually gone.

The journal bearing between the crankshaft and connecting rod was new when the testing was started. It was visually inspected after testing. The babbit material was found to be extremely worn and scrat-

Table 6-4. Piston Measurements Before and After Testing

Position*	Diameter**, cm Before	After
1	11.364	11.361
2	11.364	11.364
3	11.422	11.420
4	11.420	11.417
5	11.422	11.422
On Middle Ring Land:		
1	11.405	11.407
2	11.422	11.405

* 1, 3, 4 Perpendicular to piston-connecting rod pin
2, 5 Parallel to piston-connecting rod pin
** ± 0.0025 cm

Table 6-5. Cylinder Liner Measurements Before and After Testing

Position*	Diameter**, cm Before	After
2.54 cm From Top:		
1	11.436	11.453
2	11.433	11.450
Bottom:		
1	11.432	11.435
2	11.427	11.430

* 1 Perpendicular to crankshaft
  2 Parallel to crankshaft
** ± 0.0025 cm

ched, indicating high oil contamination. High amounts of bearing wear are also unacceptable.

Blowby pressure was used as an inference of wear. Figure 6-1 is a plot of blowby pressure versus time for each of the fuels tested. The curve for each separate fuel is erratic. The trend for No. 2 fuel oil is neither increasing nor decreasing, but relatively constant. The trends for the 32% and 20% slurries are increasing, indicating continual wear. The blowby pressure for the 20% slurry is higher than that for the 32% slurry at any given time from the starting time on that fuel. This is another indication of continual wear. It is noted that after the 32% and 20% slurries were run, the blowby pressure would decrease when briefly run on No. 2 fuel oil to clean the fuel lines at the end of each test. The blowby pressure was abnormally high, 35.6 cm H_2O; for the 40% slurry tested and it did not drop back when run on No. 2 fuel oil at the termination of the test. By not dropping back, the blowby pressure indicated that packing of the rings with coal particles may have occurred, as was confirmed upon disassembly of the engine. Since the blowby pressure dropped when run on No. 2 fuel oil after the 32% and 20% slurries it is deduced that some minor packing of the rings with coal particles was taking place under use of these fuels. The increasing trend of the blowby pressure indicated that wear was taking place.

The NAA gave a good indication of the wear that took place and where it occurred. No NAA results are reported for the 40% coal fuel oil slurry due to the short duration of the test using this slurry. The results of the NAA may contain a statistical counting error of plus or

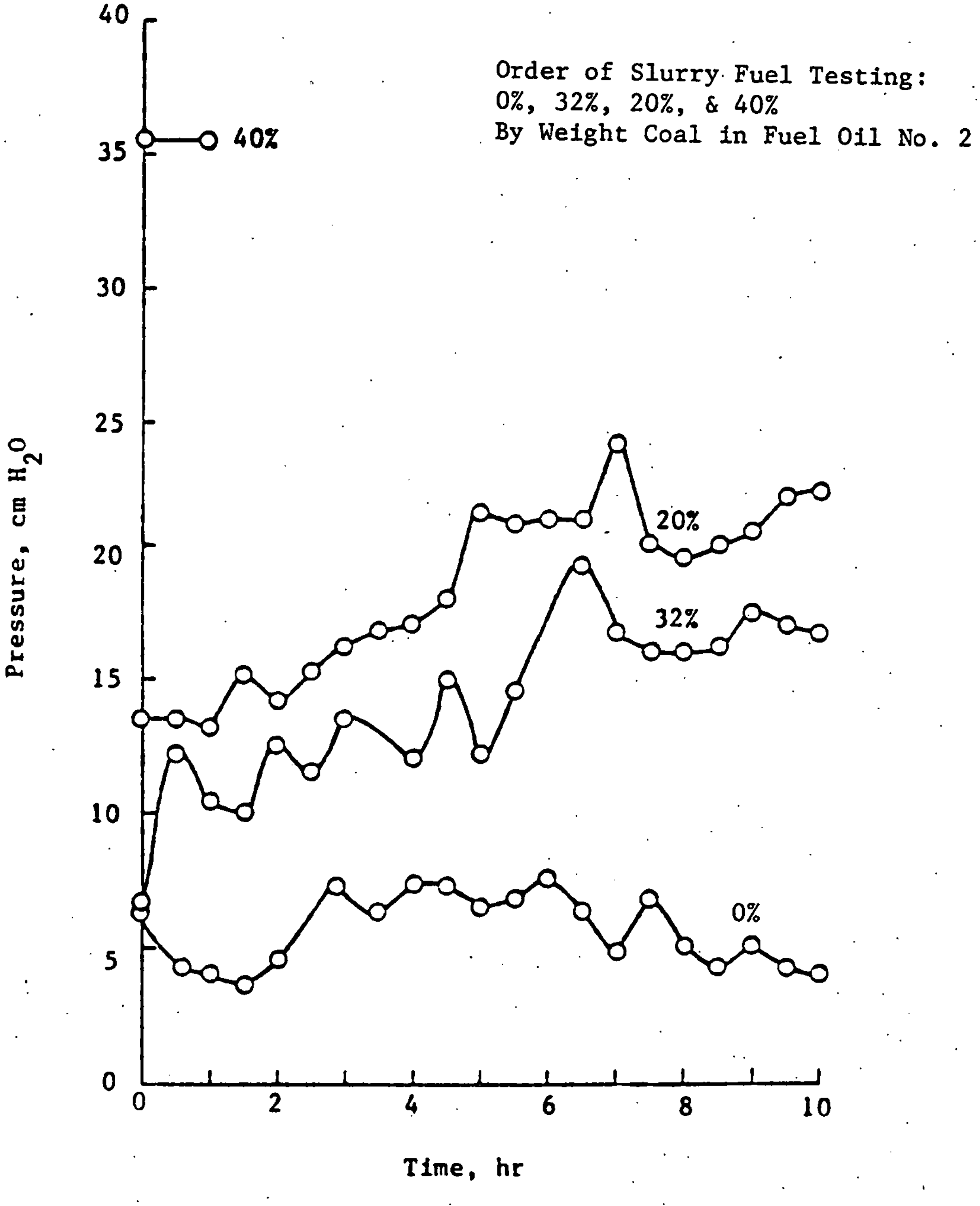


Figure 6-1. Effect of Slurry Fuels on the Crankcase Pressure of a 1.36 l Single Cylinder Diesel Engine at 1400 RPM and Full Load

minus one standard deviation and a systematic error of at least 10%.

Tables 6-6 through 6-9 give the composition of the coal-fuel oil slurries and engine parts. Table 6-6 confirms that the coal used in the two coal-fuel oil slurries came from two different coal seams since few of the elements exhibited near a 60% increase as coal content increases from 20% to 32% in the slurries. By comparing Table 6-6 to Tables (6-7)-(6-10) to find elements where at least one order of magnitude difference between the fuel and each engine part existed, tracer elements were found to indicate the wear that occurred, the place where the wear occurred, and the fuel that leaked past the piston rings into the oil. The order-of-magnitude criterion was used to minimize the effect of fuel leakage on the wear results of the engine parts and vice versa.

Several tracer elements were found. Arsenic, cobalt, chromium, iron, manganese, and vanadium were the tracer elements common to the piston rings, piston, and cylinder liner. Being common to all of the engine parts, the above tracer elements can be used as a general indictator of the engine wear. Tables (6-10)-(6-12) present the data obtained using the above common tracer elements. Selenium and tantalum were found to be tracer elements for the top and third compression rings; the cast iron rings. Using selenium and tantalum, the wear of the first (top) and third compression rings could be determined separately from the rest of the engine parts. These data are presented in Table 6-13. In the same manner mercury is used to indicate oil control ring wear, tin and titanium the piston wear, and nickel the cylinder liner wear. All these data are shown in Tables (6-14)-(6-16). The second, or chrome, compression ring did not contain any distinguishing tracer elements. Potas-

Table 6-6. Composition of Various Percent by Weight Raw Coal-No. 2 Fuel Oil Slurries as Determined by NAA

Element	20% Concentration ppm	Error ppm	32% Concentration ppm	Error ppm
Ag	1.72E 00	3.28E-01	<7.25E-01	
Al	2.07E 03	3.94E 01	3.16E 03	6.03E 01
As	2.05E 00	4.13E-02	4.34E 00	4.57E-02
Au	<1.36E-03		<1.38E-03	
Ba	<6.26E 01		<6.55E 01	
Br	2.71E 00	4.10E-02	1.25E 01	1.08E-01
Ca	<3.38E 02		<5.09E 02	
Cd	<7.05E-01		<7.23E-01	
Ce	3.23E 00	3.66E-01	3.87E 00	3.02E-01
Cl	2.25E 02	2.89E 01	4.33E 02	3.42E 01
Co	1.78E 00	1.01E-01	2.18E 00	1.02E-01
Cr	5.61E 01	1.39E 00	1.91E 01	6.02E-01
Cs	<1.57E-01		<1.55E-01	
Cu	<2.74E 01		<3.15E 01	
Dy	3.12E-01	5.21E-02	6.79E-01	8.37E-02
Eu	4.50E-02	8.77E-04	7.36E-02	1.95E-03
Fe	5.01E 03	1.04E 02	2.76E 03	8.71E 01
Hf	<9.66E-02		<9.44E-02	
Hg	<6.43E-02		<6.25E-02	
I	<2.46E 00		<2.51E 00	
K	3.59E 02	4.51E 00	6.56E 02	8.97E 00
La	2.03E 00	1.92E-02	1.77E 00	1.80E-02
Lu	<1.25E-02		<1.09E-02	
Mg	<8.08E 02		<8.72E 02	
Mn	2.56E 01	9.00E-01	1.98E 01	8.53E-01
Mo	1.44E 00	1.36E-01	1.46E 00	1.23E-01
Na	6.24E 01	5.51E-01	5.05E 01	3.61E-01
Ni	<6.62E 01		<6.37E 01	
Rb	<3.33E 00		<3.09E 00	
Sb	2.09E-01	1.03E-02	3.80E-01	1.15E-02
Sc	4.70E-01	1.05E-02	6.43E-01	1.23E-02
Se	<6.31E-01		<5.66E-01	
Sm	1.26E 00	2.23E-02	1.74E 00	2.91E-02
Sn	<4.63E 01		<5.03E 01	
Sr	<1.77E 02		<1.79E 02	
Ta	<8.10E-02		2.22E-01	4.14E-02
Te	<1.67E 02		<1.74E 02	
Th	<3.05E-01		1.60E 00	1.04E-01
Ti	1.32E 02	1.76E 01	1.05E 02	1.86E 01
U	<5.99E-02		2.09E-01	2.52E-02
V	6.67E 00	2.56E-01	8.37E 00	3.32E-01
W	1.06E 00	1.80E-02	3.12E-01	1.92E-02
Yb	<8.83E-02		2.04E-01	2.68E-02
Zn	<6.53E 00		1.66E 01	3.07E 00
Zr	<5.44E 01		<5.19E 01	

Systematic Error of at Least 10% Not Included in Quoted Error

Table 6-7. Composition of the Compression Rings as Determined by NAA

Element	First (Top) and Third Ring Concentration ppm	Error ppm	Middle Ring Concentration ppm	Error ppm
Ag	<3.98E 00		<4.11E 00	
Al	2.35E 02	1.40E 01	6.24E 02	2.40E 01
As	1.18E 02	2.95E 00	1.20E 02	4.77E 00
Au	9.50E-02	3.54E-03	4.24E-02	3.35E-03
Ba	<4.30E 02		<4.63E 02	
Br	<5.89E-01		<6.50E-01	
Ca	<4.50E 02		<1.13E 03	
Cd	<5.66E 00		<5.90E 00	
Ce	<3.07E 00		<3.26E 00	
Cl	<4.28E 02		<4.72E 02	
Co	3.94E 01	5.06E-01	4.80E 01	5.70E-01
Cr	1.61E 03	2.45E 01	2.78E 03	4.49E 01
Cs	<1.15E 00		<1.19E 00	
Cu	1.69E 00	7.57E 01	1.87E 03	9.08E 01
Dy	<7.05E-01		<7.45E-01	
Eu	<2.48E-02		<2.62E-02	
Fe	9.80E 05	7.74E 03	1.00E 06	8.19E 03
Hf	<5.06E-01		<5.22E-01	
Hg	<3.68E-01		<3.94E-01	
I	<1.75E 01		<1.92E 01	
K	<2.47E 01		1.07E 02	1.34E 01
La	4.66E 00	7.15E-02	7.03E 00	1.38E-01
Lu	<6.31E-02		<6.74E-02	
Mg	<3.54E 03		<3.94E 03	
Mn	8.09E 03	1.21E 02	8.63E 03	1.34E 02
Mo	5.18E 01	1.27E 00	<2.65E 00	
Na	9.10E 01	1.62E 00	2.60E 02	1.44E 00
Ni	<5.27E 02		<5.40E 02	
Rb	<3.05E 01		<3.09E 01	
Sb	<1.39E-01		<1.54E-01	
Sc	<6.58E-02		<6.73E-02	
Se	6.88E 00	1.48E 00	<2.69E 00	
Sm	4.82E-01	2.94E-02	<4.95E-02	
Sn	<3.26E 02		<3.52E 02	
Sr	<1.24E 03		<1.34E 03	
Ta	3.49E 00	1.64E-01	<4.01E-01	
Te	<1.22E 03		<1.33E 03	
Th	<1.25E 00		<1.31E 00	
Ti	<2.79E 02		<3.08E 02	
U	<3.76E-01		<3.97E-01	
V	1.54E 02	4.05E 00	2.26E 02	4.19E 00
W	6.27E 01	1.26E 00	1.96E 00	6.46E-01
Yb	<5.15E-01		<5.45E-01	
Zn	7.90E 01	1.70E 01	1.03E 03	2.66E 01
Zr	<3.96E 02		<4.05E 02	

Systematic Error of at Least 10% Not Included in Quoted Error

Table 6-8 Composition of the Oil Control Rings and the Piston as Determined by NAA

Element	Oil Control Rings Concentration ppm	Oil Control Rings Error ppm	Piston Concentration ppm	Piston Error ppm
Ag	<4.37E 00		1.43E 01	1.37E 00
Al	2.54E 02	2.18E 01	2.65E 02	1.53E 01
As	4.05E 01	6.23E-01	7.91E 01	1.67E 00
Au	2.93E-02	1.74E-03	3.10E-02	1.70E-03
Ba	<6.49E 02		<3.06E 02	
Br	<3.86E-01		6.63E-01	1.07E-01
Ca	<1.27E 03		<6.51E 02	
Cd	<2.94E 00			
Ce	<2.88E 00		<2.39E 00	
Cl	<6.88E 02		<2.97E 02	
Co	3.24E 01	4.95E-01	5.28E 01	4.88E-01
Cr	1.06E 03	1.46E01	2.16E 03	1.82E 01
Cs	<1.25E 00		<8.82E-01	
Cu	<2.18E 02		3.36E 03	1.15E 02
Dy	<1.18E 00		<1.53E 00	
Eu	<1.77E-02		<6.52E-02	
Fe	9.88E 05	6.78E 03	8.50E 05	3.50E 03
Hf	<5.65E-01		<4.11E-01	
Hg	1.56E 00	8.78E-02	<1.79E-01	
I	<2.76E 01		<1.21E 01	
K	8.85E 01	7.20E 00		
La	2.75E-01	2.06E-02	1.11E-01	1.48E-02
Lu	<3.34E-02		<2.68E-02	
Mg	<5.87E 03		<2.90E 03	
Mn	1.12E 04	9.95E 01	6.39E 03	1.00E 02
Mo	<1.13E 00		2.37E 02	2.93E 01
Na	6.82E 01	9.53E-01	1.02E 01	2.32E-01
Ni	<5.71E 02		<4.33E 02	
Rb	<3.26E 01		<2.87E 01	
Sb	2.01E 00	4.12E-02	2.64E 01	4.35E-01
Sc	<7.04E-02		<5.23E-02	
Se	<2.76E 00		<2.02E 00	
Sm	6.41E-02	9.71E-03	2.62E-01	1.26E-02
Sn	<5.13E 02		3.76E 04	9.51E 02
Sr	<1.91E 03		<7.98E 02	
Ta	<4.07E-01			
Te	<1.90E 03		<8.33E 02	
Th	<1.36E 00		<1.08E 00	
Ti	<4.46E 02		5.27E 03	1.60E 02
U	6.07E-01	9.61E-02	<1.84E-01	
V	3.34E 02	3.52E 00	9.51E 01	2.51E 00
W	8.60E 00	1.38E-01	3.87E 01	2.94E-01
Yb	<2.68E-01			
Zn	7.69E 01	1.92E 01	1.16E 02	1.62E 01
Zr	<4.31E 02		<3.21E 02	

Systematic Error of at Least 10% Not Included in Quoted Error

Table 6-9 Composition of the Cylinder Liner as Determined by NAA

Element	Cylinder Liner Concentration ppm	Error ppm
Ag	5.38E 00	1.27E 00
Al	2.10E 03	3.86E 01
As	1.08E 02	1.61E 00
Au	2.51E-02	1.95E-03
Ba	<4.61E 02	
Br	1.73E 00	3.46E-01
Ca	<1.04E 03	
Cd	5.99E 00	1.09E 00
Ce	<2.63E 00	
Cl	<5.22E 02	
Co	6.50E 01	5.57E-01
Cr	4.01E 03	3.28E 01
Cs	<9.14E-01	
Cu	2.10E 03	8.85E 01
Dy	<8.21E-01	
Eu	<9.25E-02	
Fe	8.78E 05	3.12E 03
Hf	<4.29E-01	
Hg	<2.01E-01	
I	<1.92E 01	
K	<4.41E 01	
La	2.10E-01	1.91E-02
Lu	<3.03E-02	
Mg	<4.14E 03	
Mn	9.36E 03	1.20E 02
Mo	2.41E 03	6.26E 01
Na	1.34E 01	2.65E-01
Ni	3.51E 03	2.10E 02
Rb	<3.00E 01	
Sb	1.98E 01	7.69E-02
Sc	<5.48E-02	
Se	<2.13E 00	
Sm	2.43E-01	1.40E-02
Sn	<3.61E 02	
Sr	<1.36E 03	
Ta	3.32E-01	
Te	<1.32E 03	
Th	<1.14E 00	
Ti	<3.14E 02	
U	<1.91E-01	
V	1.65E 02	3.41E 00
W	3.22E 01	2.33E-01
Yb	<2.21E-01	
Zn	6.03E 01	1.33E 01
Zr	<3.35E 02	

Systematic Error of at Least 10% Not Included in Quoted Error

Table 6-10. Concentrations of Tracer Elements Arsenic and Cobalt in the Lubricating Oil

	Arsenic		Cobalt	
Time hr	Concentration ppm	Error ppm	Concentration ppm	Error ppm
		No. 2 Fuel Oil		
0.0	1.00E 00	1.72E-02	2.96E-01	6.69E-02
1.5	9.28E-01	2.06E-02	2.81E-01	4.31E-02
2.5	9.88E-01	2.27E-02	3.46E-01	4.80E-02
4.0	1.02E 00	2.66E-02	4.51E-01	5.10E-02
6.0	9.43E-01	2.68E-02	2.70E-01	4.61E-02
7.5	9.25E-01	2.48E-02	3.72E-01	5.34E-02
9.0	9.18E-01	2.36E-02	3.76E-01	4.70E-02
10.0	9.31E-01	2.25E-02	2.29E-01	4.65E-02
		32% Coal Slurry		
0.0	9.80E-01	2.81E-02	3.75E-01	4.76E-02
1.0	1.60E 00	2.10E-02	7.73E-01	7.02E-02
3.0	1.67E 00	2.06E-02	8.92E-01	7.34E-02
4.5	3.83E 00	5.34E-02	1.17E 00	8.84E-02
6.5	6.08E 00	2.64E-01	1.49E 00	1.07E-01
7.5	6.44E 00	2.55E-01	2.27E 00	1.26E-01
9.0	6.62E 00	5.85E-01	2.16E 00	1.27E-01
10.0	7.27E 00	3.81E-01	1.54E 00	1.13E-01
		20% Coal Slurry		
0.0	3.75E 00	1.58E-01	1.30E 00	9.40E-02
1.5	1.46E 00	2.01E-02	7.18E-01	7.07E-02
3.0	1.61E 00	2.06E-02	7.66E-01	7.36E-02
4.5	2.34E 00	4.01E-02	1.14E 00	8.31E-02
6.0	2.59E 00	3.36E-02	1.60E 00	9.72E-02
7.5	2.62E 00	5.98E-02	1.40E 00	9.07E-02
9.0	2.81E 00	5.33E-02	1.50E 00	9.64E-02
10.0	2.74E 00	4.13E-02	1.37E 00	8.47E-02

Systematic Error of at Least 10% Not Included in Quoted Error.

Table 6-11 Concentrations of Tracer Elements Chromium and Iron in the Lubricating Oil

Time hr	Chromium Concentration ppm	Error ppm	Iron Concentration ppm	Error ppm
		No. 2 Fuel Oil		
0.0	<7.47E-01		<6.57E 01	
1.5	<7.57E-01			
2.5	<7.26E-01		<5.52E 01	
4.0	<1.04E 00	2.92E-01	<5.39E 01	
6.0	<7.03E-01		<5.91E 01	
7.5	<7.33E-01		<6.20E 01	
9.0	<5.96E-01		<5.56E 01	
10.0	<7.46E-01		<5.83E 01	
		32% Coal Slurry		
0.0	<7.39E-01			
1.0	6.41E 00	4.87E-01	9.74E 02	4.76E 01
3.0	1.17E 01	6.63E-01	1.85E 03	7.10E 01
4.5	1.91E 01	8.37E-01	3.13E 03	8.65E 01
6.5	2.65E 01	9.56E-01	3.92E 03	1.01E 02
7.5	3.56E 01	1.09E 00	5.09E 03	1.09E 02
9.0	3.97E 01	1.13E 00	5.83E 03	1.19E 02
10.0	2.33E 01	9.75E-01	3.23E 03	1.01E 02
		20% Coal Slurry		
0.0	2.34E 02	9.26E 00	1.17E 04	3.87E 02
1.5	1.68E 02	1.22E 01	8.42E 03	3.12E 02
3.0	1.70E 02	8.04E 00	6.90E 03	2.82E 02
4.5	4.45E 02	1.57E 01	1.57E 04	4.35E 02
6.0	7.34E 02	3.70E 01	1.98E 04	4.44E 02
7.5	6.62E 02	1.69E 01	2.27E 04	4.95E 02
9.0	6.89E 02	1.86E 01	2.31E 04	5.03E 02
10.0	6.79E 02	3.10E 01	1.86E 04	4.30E 02

Systematic Error of at Least 10% Not Included in Quoted Error

Table 6-12 Concentrations of Tracer Elements Manganese and Vanadium in the Lubricating Oil

Time hr	Manganese Concentration ppm	Manganese Error ppm	Vanadium Concentration ppm	Vanadium Error ppm
		No. 2 Fuel Oil		
0.0	1.22E 00	3.03E-02	1.24E-02	2.73E-03
1.5	4.17E-01	2.16E-02	2.44E-02	2.95E-03
2.5	5.69E-01	2.32E-02	1.35E-02	2.58E-03
4.0	4.87E-01	2.19E-02	1.78E-02	2.23E-03
6.0	4.80E-01	1.73E-02	1.74E-02	2.29E-03
7.5	4.60E-01	2.06E-02	1.40E-02	2.60E-03
9.0	5.79E-01	2.08E-02	1.88E-02	2.43E-03
10.0	5.89E-01	3.44E-02	2.85E-02	4.29E-03
		32% Coal Slurry		
0.0	7.83E-01	3.37E-02	4.95E-02	4.25E-03
1.0	8.72E 00	2.55E-01	9.64E-01	3.97E-02
3.0	1.48E 01	5.27E-01	2.03E 00	7.29E-02
4.5	2.39E 01	7.43E-01	3.61E 00	1.41E-01
6.5	2.91E 01	9.78E-01	5.08E 00	2.22E-01
7.5	3.96E 01	1.42E 00	6.70E 00	2.13E-01
9.0	4.12E 01	1.44E 00	7.41E 00	2.58E-01
10.0	4.77E 01	1.17E 00	8.18E 00	3.07E-01
		20% Coal Slurry		
0.0	2.53E 01	8.79E-01	4.67E 00	1.80E-01
1.5	1.43E 01	4.03E-01	2.58E 00	1.02E-01
3.0	1.93E 01	8.35E-01	3.33E 00	1.51E-01
4.5	2.18E 01	6.81E-01	3.80E 00	1.75E-01
6.0	3.06E 01	1.02E 00	5.54E 00	2.41E-01
7.5	3.48E 01	1.18E 00	6.42E 00	3.13E-01
9.0	3.42E 01	1.42E 00	6.05E 00	3.23E-01
10.0	4.01E 01	1.50E 00	6.71E 00	3.32E-01

Systematic Error of at Least 10% Not Included in Quoted Error

Table 6-13 Concentrations of Tracer Elements Selenium and Tantalum in the Lubricating Oil

Time hr	Selenium Concentration ppm	Selenium Error ppm	Tantalum Concentration ppm	Tantalum Error ppm
		No. 2 Fuel Oil		
0.0	<5.12E-01		<5.88E-02	
1.5	<5.19E-01		<5.46E-02	
2.5	<5.31E-01		<4.84E-02	
4.0	<4.85E-01		<5.28E-02	
6.0	<4.89E-01		<5.47E-02	
7.5	<5.16E-01		<5.08E-02	
9.0	8.27E-01	1.31E-01	<4.99E-02	
10.0	<5.25E-01		<5.31E-02	
		32% Coal Slurry		
0.0	<5.17E-01		<4.88E-02	
1.0	<5.57E-01		<6.05E-02	
3.0	<6.11E-01		<7.31E-02	
4.5	<7.60E-01		<9.16E-02	
6.5	<8.81E-01		<1.12E-01	
7.5	<9.22E-01		<1.15E-01	
9.0	<9.37E-01		<1.19E-01	
10.0	<8.19E-01		<9.93E-02	
		20% Coal Slurry		
0.0	<1.34E 00		<1.72E-01	
1.5	<1.14E 00		<1.37E-01	
3.0	<9.80E-01		<1.19E-01	
4.5	<1.08E 00		<1.32E-01	
6.0	<1.11E 00		5.86E-01	5.78E-02
7.5	<1.16E 00		<1.48E-01	
9.0	<1.16E 00		<1.39E-01	
10.0	<1.08E 00		<1.29E-01	

Systematic Error of at Least 10% Not Included in Quoted Error

Table 6-14 Concentrations of Tracer Element Mercury in the Lubricating Oil

Time hr	Mercury Concentration ppm	Error ppm
	No. 2 Fuel Oil	
0.0	7.93E-01	2.11E-02
1.5	2.59E-01	1.28E-02
2.5	1.84E-01	1.21E-02
4.0	8.49E-02	1.13E-02
6.0	6.56E-02	1.10E-02
7.5	7.75E-02	1.19E-02
9.0	7.54E-02	1.11E-02
10.0	1.07E-01	1.20E-02
	32% Coal Slurry	
0.0	1.41E-01	1.15E-02
1.0	1.95E-01	1.52E-02
3.0	6.77E-02	2.02E-02
4.5	<6.19E-02	
6.5	2.68E-01	4.18E-02
7.5	<9.67E-02	
9.0	<1.08E-01	
10.0	<1.10E-01	
	20% Coal Slurry	
0.0	<7.88E-02	
1.5	1.00E-01	1.78E-02
3.0	<4.84E-02	
4.5	<5.82E-02	
6.0	<6.54E-02	
7.5	<6.77E-02	
9.0	<7.28E-02	
10.0	<6.97E-02	

Systematic Error of at Least 10% Not Included in Quoted Error

Table 6-15 Concentrations of Tracer Elements Tin and Titanium in the Lubricating Oil

Time hr	Tin Concentration ppm	Tin Error ppm	Titanium Concentration ppm	Titanium Error ppm
		No. 2 Fuel Oil		
0.0	1.87E 00	4.00E-01	<9.38E-01	
1.5	<7.88E-01		4.82E 00	3.95E-01
2.5	<7.41E-01		<7.28E-01	
4.0	<7.49E-01		<7.57E-01	
6.0	<8.02E-01		<7.64E-01	
7.5	2.50E 00	4.10E-01	<8.44E-01	
9.0	1.59E 00	3.41E-01	2.38E 00	3.83E-01
10.0	<9.94E-01		7.47E 00	5.39E-01
		32% Coal Slurry		
0.0	<9.39E-01		<9.45E-01	
1.0	1.62E 01	1.91E 00	2.20E 00	1.77E 00
3.0	5.00E 01	3.16E 00	3.05E 01	5.23E 00
4.5	6.19E 01	5.65E 00	3.78E 01	5.58E 00
6.5	6.43E 01	1.51E 01	7.32E 01	9.32E 00
7.5	9.75E 01	1.50E 01	9.07E 01	1.30E 01
9.0	1.18E 02	1.25E 01	9.49E 01	1.17E 01
10.0	1.27E 02	1.10E 01	1.24E 02	1.11E 01
		20% Coal Slurry		
0.0	9.78E 01	1.04E 01	7.39E 01	8.72E 00
1.5	3.41E 01	7.09E 00	3.62E 01	6.01E 00
3.0	1.78E 01		8.52E 01	8.00E 00
4.5	<1.92E 01		3.80E 01	8.18E 00
6.0	<2.44E 01		<2.42E 01	
7.5	<3.69E 01		<3.34E 01	
9.0	<5.48E 01		1.91E 02	2.05E 01
10.0	1.23E 02	2.70E 01	1.14E 02	2.36E 01

Systematic Error of at Least 10% Not Included in Quoted Error

Table 6-16 Concentrations of Tracer Element Nickel in the Lubricating Oil

Time hr	Nickel Concentration ppm	Error ppm
	No. 2 Fuel Oil	
0.0	<5.55E 01	
1.5	<5.29E 01	
2.5	<5.72E 01	
4.0	<4.92E 01	
6.0	<5.41E 01	
7.5	<5.48E 01	
9.0	<4.44E 01	
10.0	<5.98E 01	
	32% Coal Slurry	
0.0	<5.23E 01	
1.0	<6.17E 01	
3.0	<6.27E 01	
4.5	<7.51E 01	
6.5	<7.85E 01	
7.5	<8.62E 01	
9.0	<8.86E 01	
10.0	<6.90E 01	
	20% Coal Slurry	
0.0	<1.86E 02	
1.5	<1.67E 02	
3.0	<1.35E 02	
4.5	<1.74E 02	
6.0	<1.79E 02	
7.5	<1.97E 02	
9.0	<1.85E 02	
10.0	<1.60E 02	

Systematic Error of at Least 10% Not Included in Quoted Error

sium was used as the tracer element for fuel leakage past the piston rings. The potassium data are presented in Table XVIII.

Figures (6-2)-(6-14) one plots of the tracer element concentrations versus time for each of the fuels tested. Figures (6-2)-(6-7) are the plots of As, Co, Cr, Fe, Mn, and V respectively, indicating total engine wear. Figures (6-8)-(6-13) are plots indicating wear rates of the engine parts as represented by their tracer elements Se, Ta, Hg, Sn, Ti, and Ni, as identified above. Figure 6-14 plot the tracer element K used to indicate fuel leakage past the piston rings.

Interpreting the NAA results requires that the following be remembered. First, the order in which the fuels were tested is: No. 2 fuel oil, 32% coal-fuel oil slurry, and 20% coal-fuel oil slurry, in that order. Second, the relative, not absolute, wear rates are evaluated. The time rate of change of the tracer element concentration, or the slope of the different plots, can be interpreted as an indication of the wear rate. Note also that when the No. 2 fuel oil data were plotted as the absicissa of the figures, they were indistinguishable from the axis, as in Figures 6-4, 6-5, and 6-7.

Several general observations can be made when examining Figures (6-2) to 6-14. The wear rates for the two slurry fuels are always higher than the wear rate for No. 2 fuel oil. The first two data points for the 20% coal-fuel oil slurry form a "dip" in the plot of the tracer element concentrations. This is caused by insufficient flushing of the lubrication system after the 32% coal slurry test. The same procedure was followed, after each fuel was tested, to flush the oiling system. The reason for the lack of a "dip" at the beginning of the 32% coal slurry is the low

Table 6-17. Concentrations of Tracer Element Potassium in the Lubricating Oil

Time hr	Potassium Concentration ppm	Error ppm
	No. 2 Fuel Oil	
0.0	2.84E 00	4.80E-01
1.5	3.76E 00	5.82E-01
2.5	<8.69E-01	
4.0	<9.29E-01	
6.0	1.95E 00	4.31E-01
7.5	2.82E 00	4.68E-01
9.0	2.10E 00	5.40E-01
10.0	<1.25E 00	
	32% Coal Slurry	
0.0	4.96E 00	6.32E-01
1.0	8.07E 01	2.05E 00
3.0	1.20E 02	2.86E 00
4.5	2.96E 02	4.92E 00
6.5	5.10E 02	8.57E 00
7.5	6.11E 02	8.58E 00
9.0	7.37E 02	1.25E 01
10.0	7.50E 02	1.12E 01
	20% Coal Slurry	
0.0	2.99E 02	4.95E 00
1.5	9.26E 01	1.75E 00
3.0	1.20E 02	2.46E 00
4.5	2.24E 02	4.57E 00
6.0	2.88E 02	4.50E 00
7.5	3.11E 02	4.14E 00
9.0	3.64E 02	5.83E 00
10.0	3.49E 02	6.05E 00

Systematic Error of at Least 10% Not Included in Quoted Error

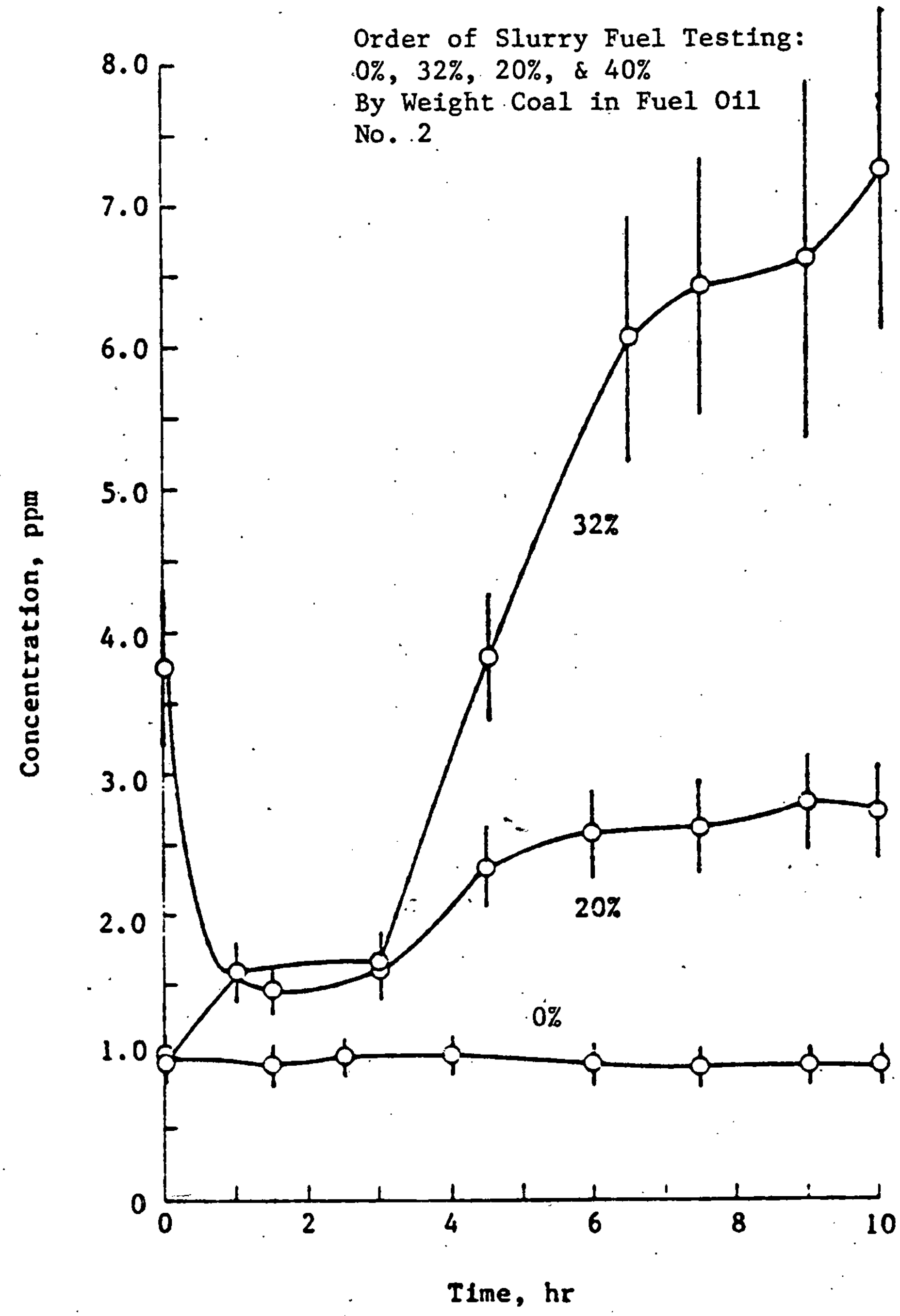


Figure 6-2. Effect of Slurry Fuels on Combined Wear of Rings, Piston, and Cylinder Liner of a 1.36 l Single Cylinder Diesel Engine at 1400 RPM and Full Load Using Arsenic as the Tracer Element

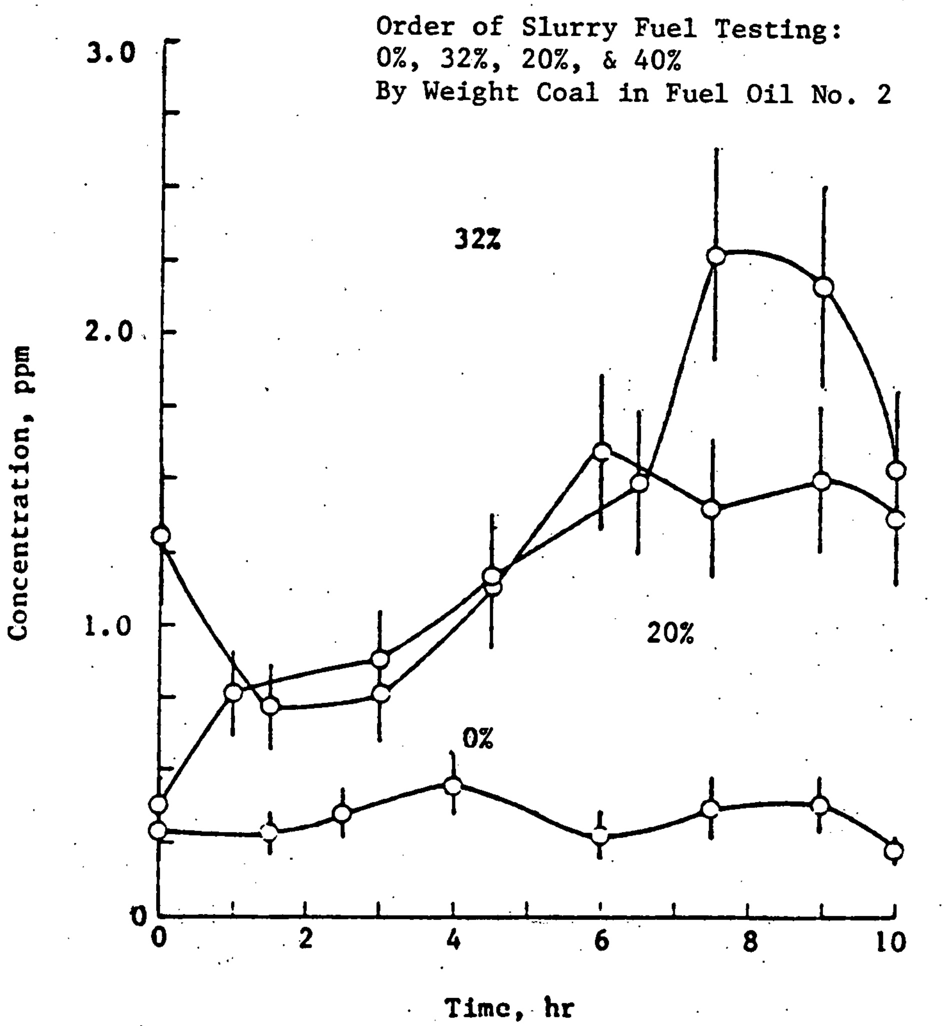


Figure 6-3. Effect of Slurry Fuels on Combined Wear of Rings, Piston, and Cylinder Liner of a 1.36 l Single Cylinder Diesel Engine at 1400 RPM and Full Load Using Cobalt as the Tracer Element

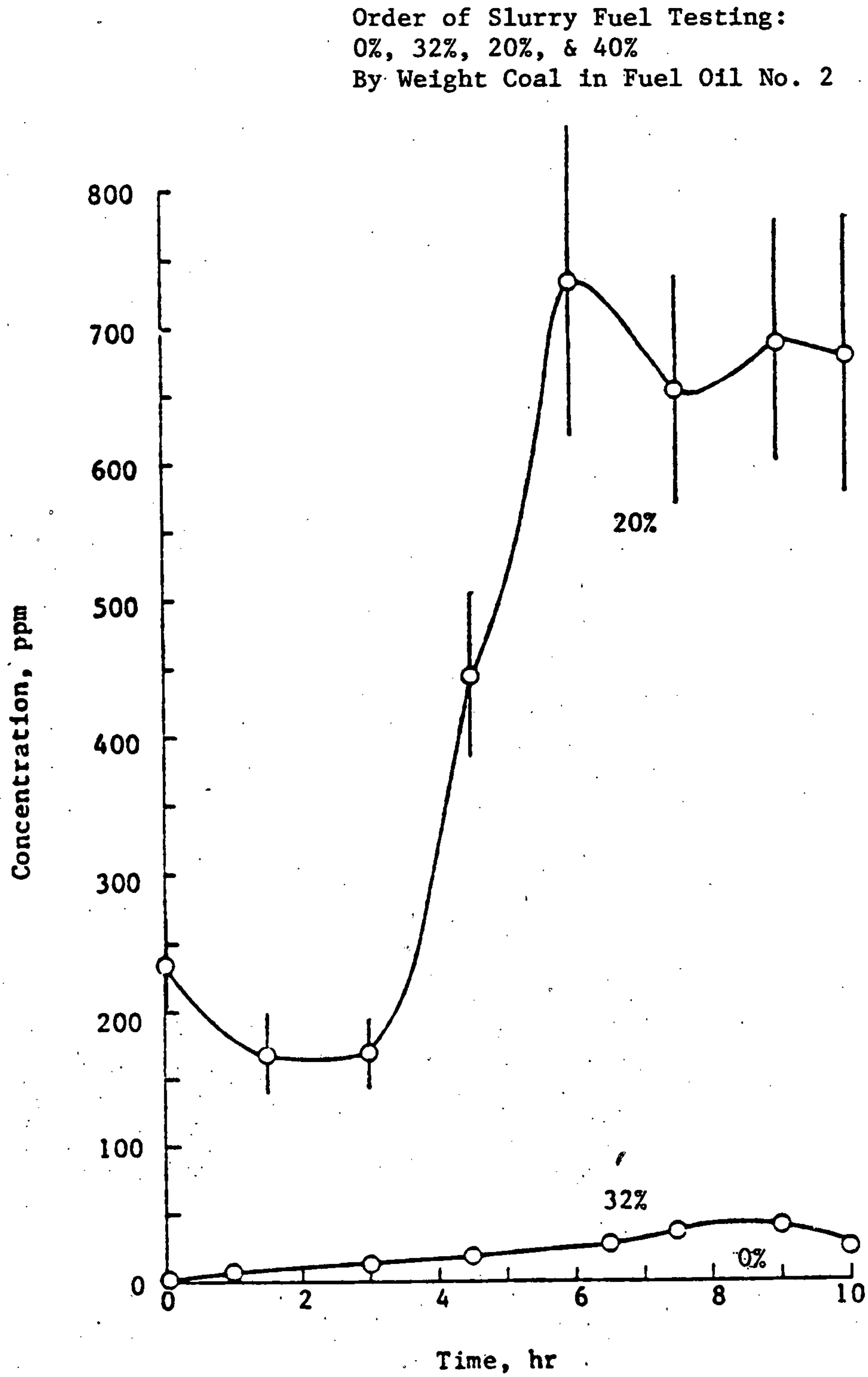


Figure 6-4. Effect of Slurry Fuels on Combined Wear of Rings, Piston, and Cylinder Liner of a 1.36 l Single Cylinder Diesel Engine at 1400 Rpm and Full Load Using Chromium as the Tracer Element

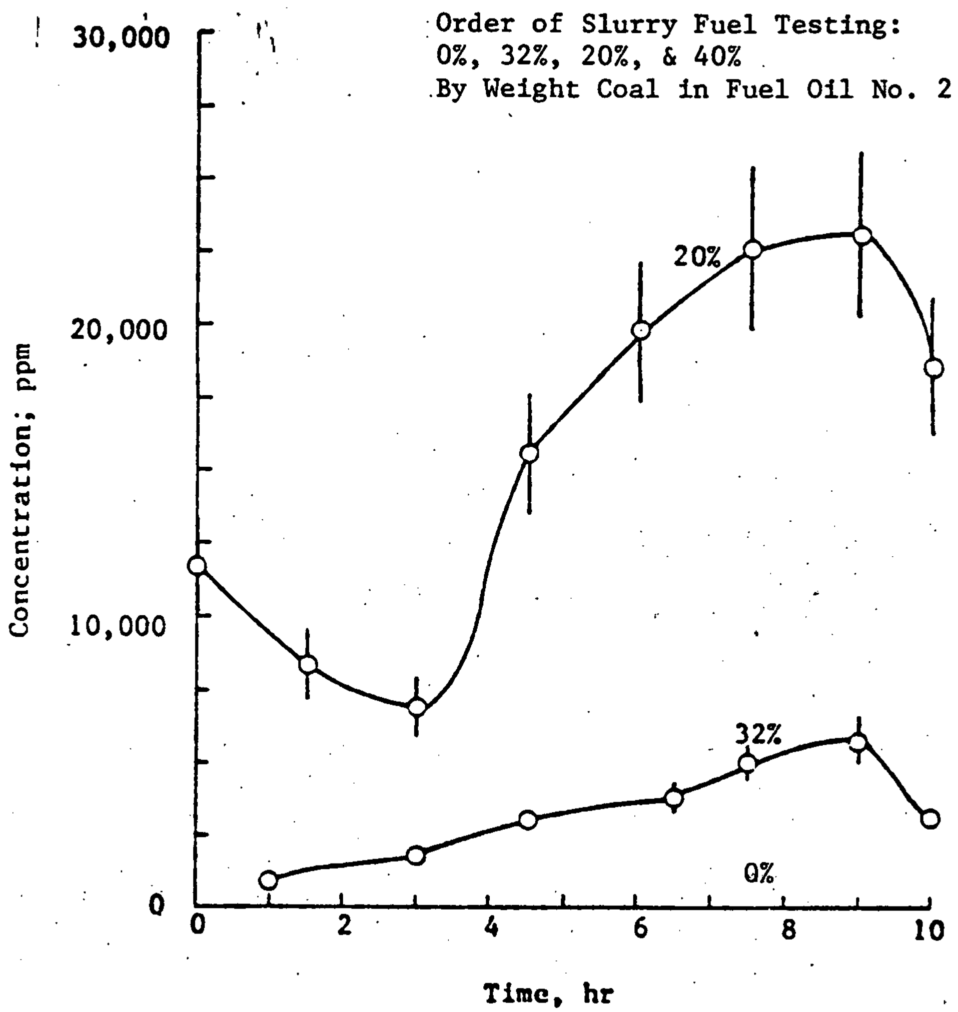


Figure 6-5. Effect of Slurry Fuels on Combined Wear of Rings, Piston, and Cylinder Liner of a 1.36 l Single Cylinder Diesel Engine at 1400 RPM and Full Load Using Iron as the Tracer Element

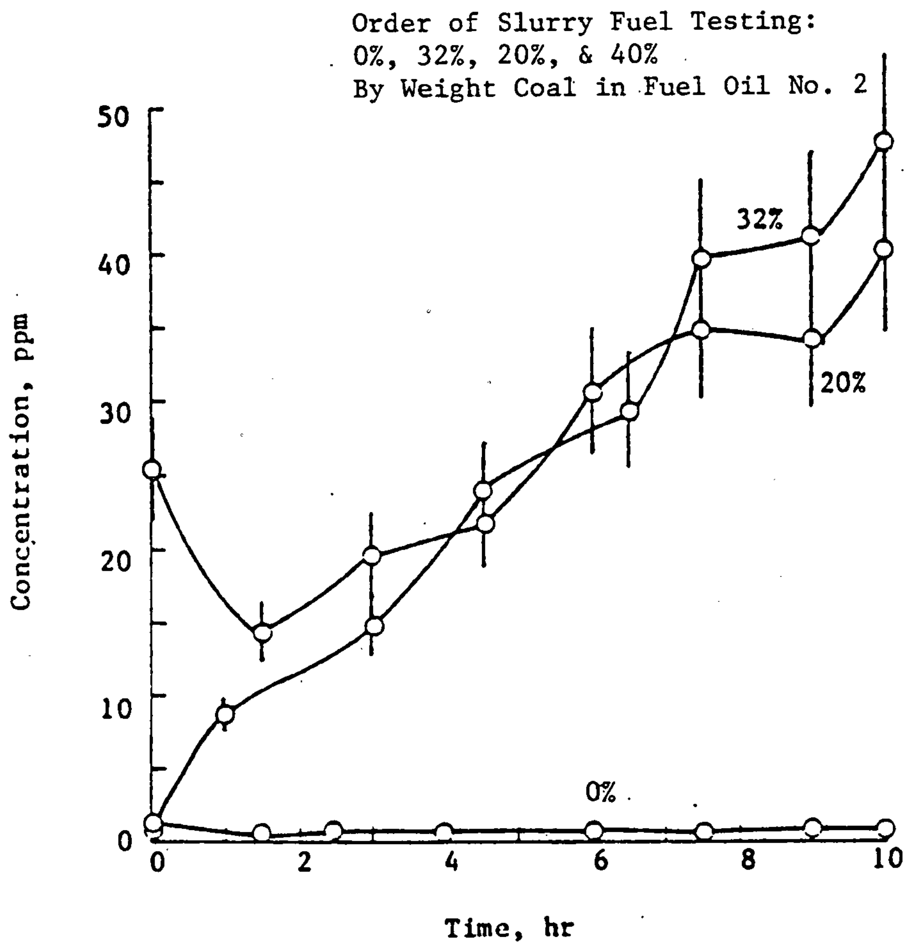


Figure 6-6. Effect of Slurry Fuels on Combined Wear of Rings, Piston, and Cylinder Liner of a 1.36 l Single Cylinder Diesel Engine at 1400 RPM and Full Load Using Manganese as the Tracer Element

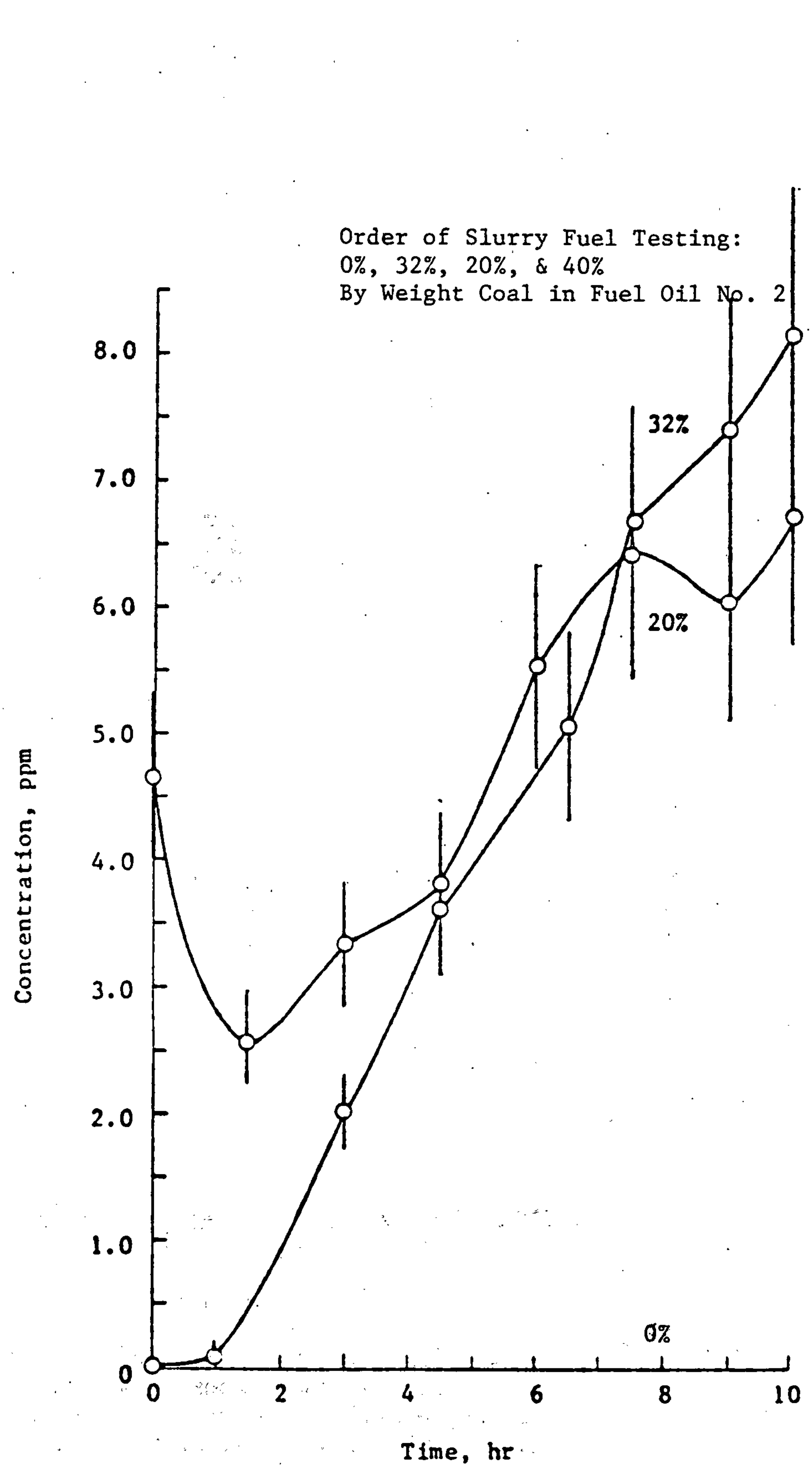


Figure 6-7. Effect of Slurry Fuels on Combined Wear of Rings, Piston, and Cylinder Liner of a 1.36 l Single Cylinder Diesel Engine at 1400 RPM and Full Load Using Vanadium as the Tracer Element

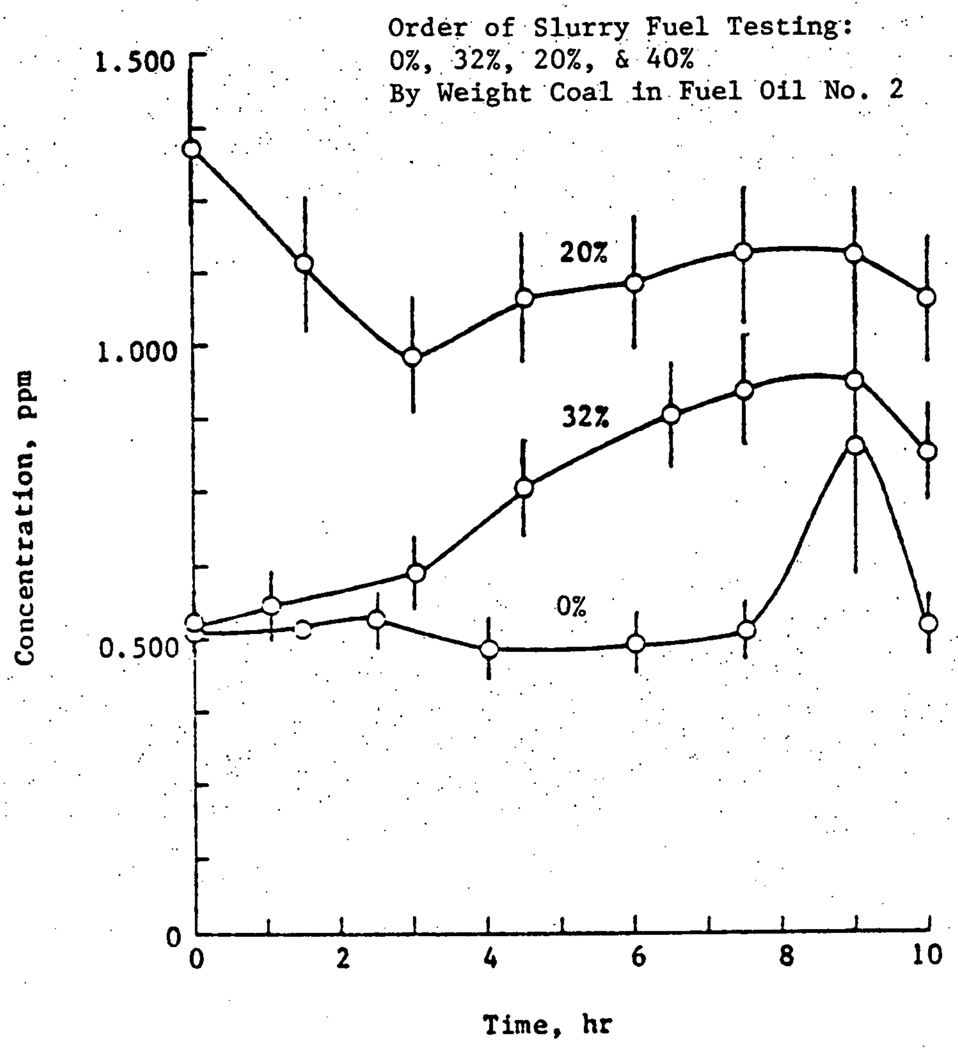


Figure 6-8. Effect of Slurry Fuels on the Wear of the Top and Third Compression Rings of a 1.36 l Single Cylinder Diesel Engine at 1400 RPM and Full Load Using Selenium as the Tracer Element

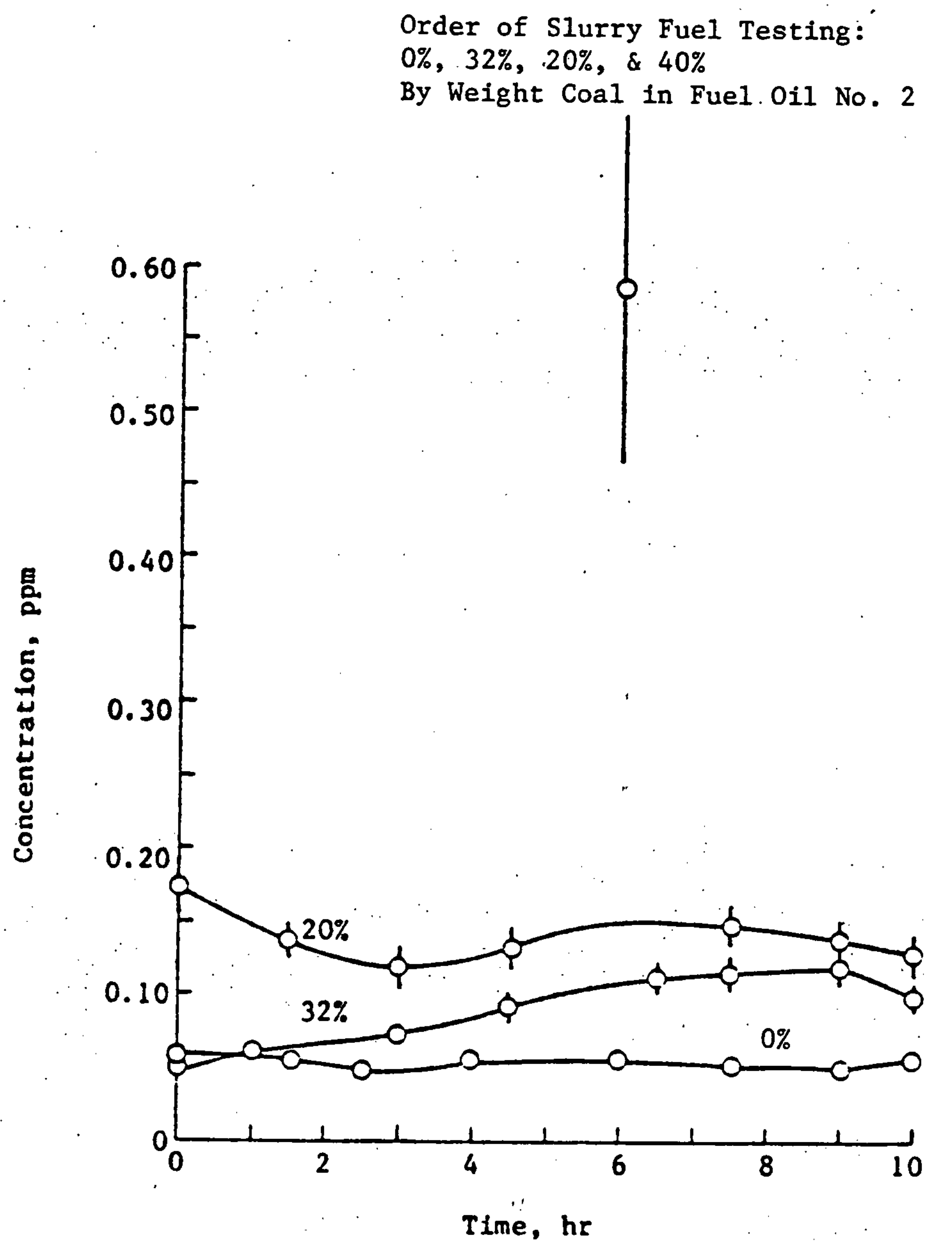


Figure 6-9. Effect of Slurry Fuels on the Wear of the Top and Third Compression Rings of a 1.36 l Single Cylinder Diesel Engine at 1400 RPM and Full Load Using Tantalum as the Tracer Element

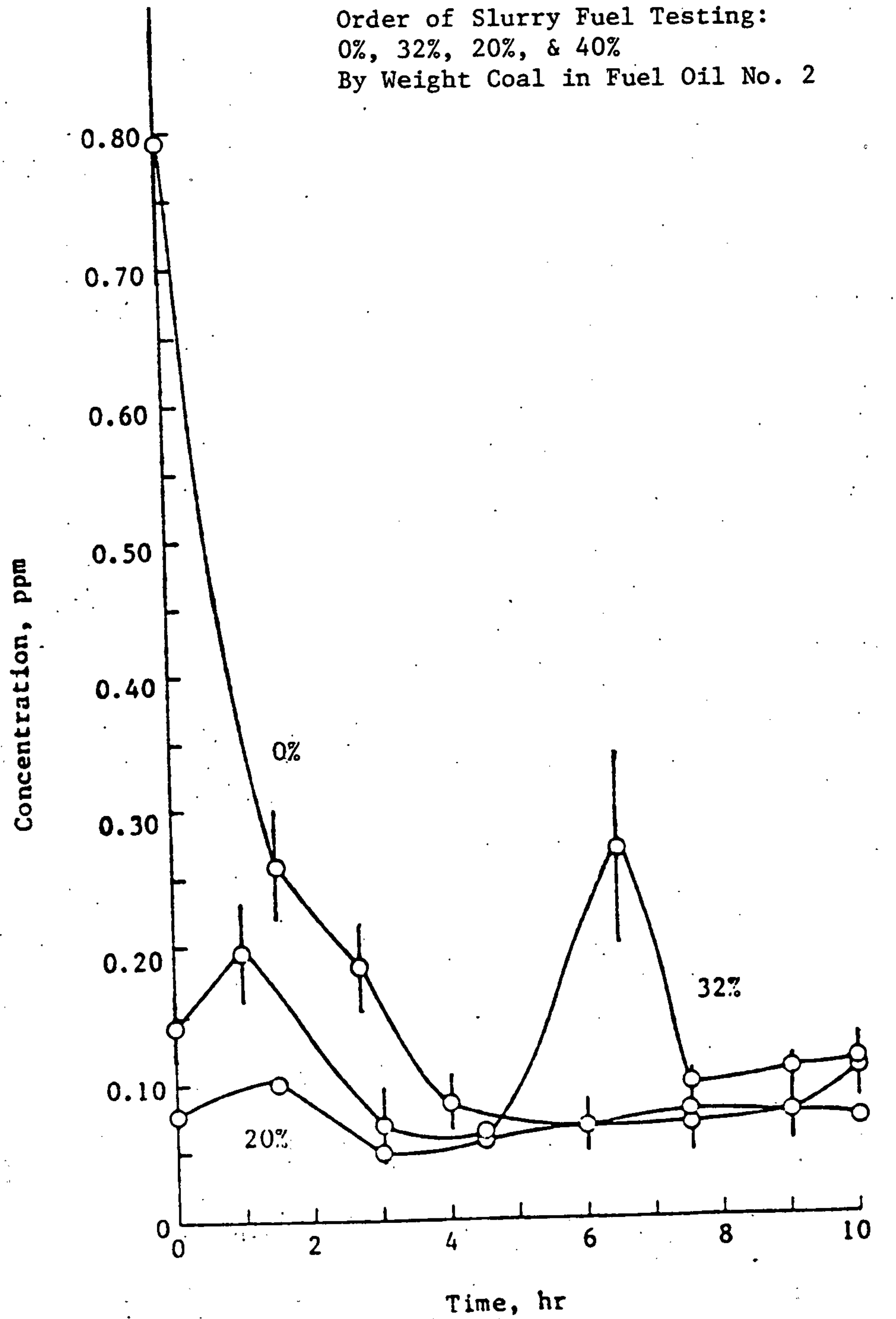


Figure 6-10. Effect of Slurry Fuels on the Wear of the Oil Control Rings of a 1.36 l Single Cylinder Diesel Engine at 1400 RPM and Full Load Using Mercury as the Tracer Element

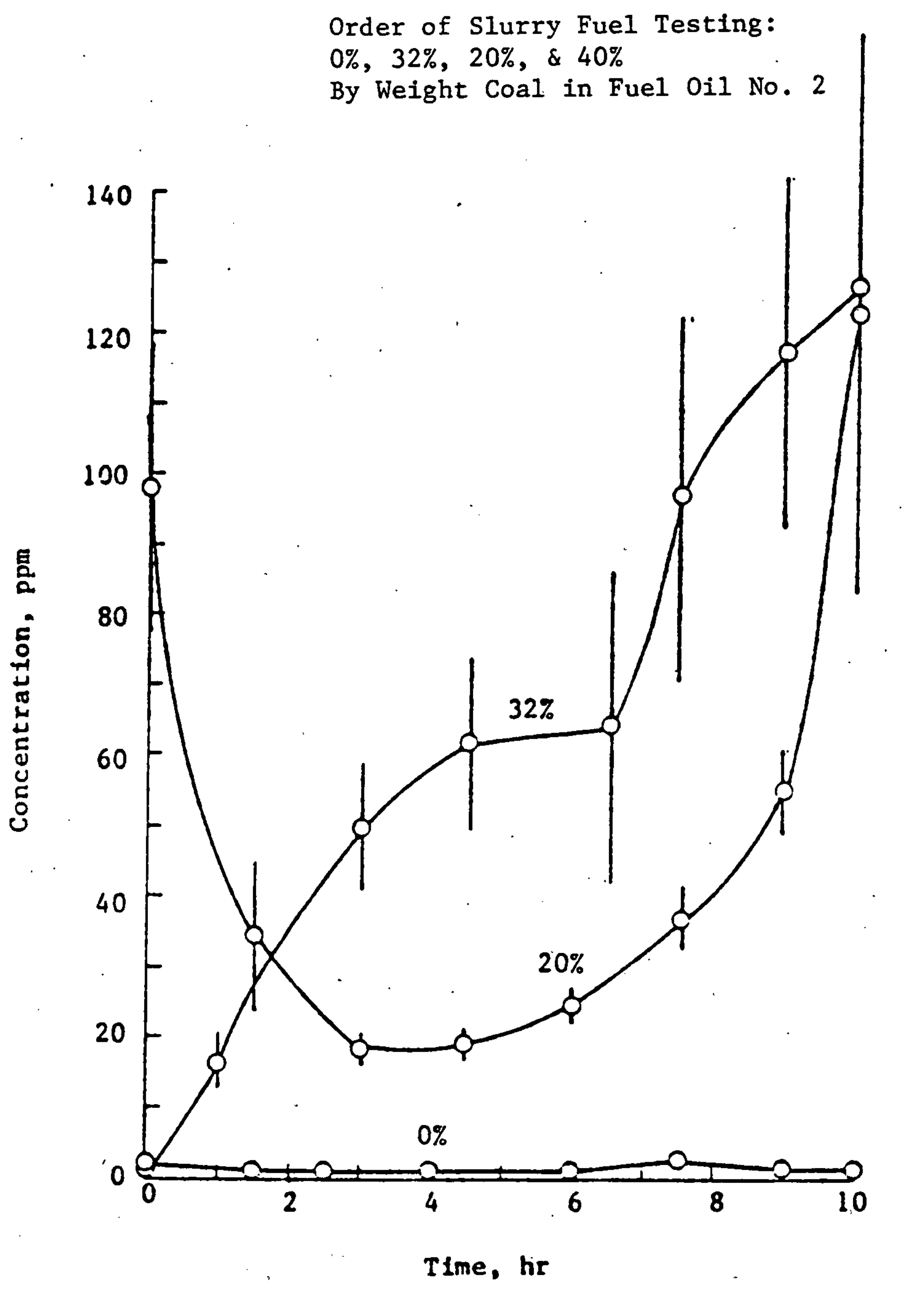


Figure 6-11. Effect of Slurry Fuels on the Wear of the Piston of a 1.36 l Single Cylinder Diesel Engine at 1400 RPM and Full Load Using Tin as the Tracer Element

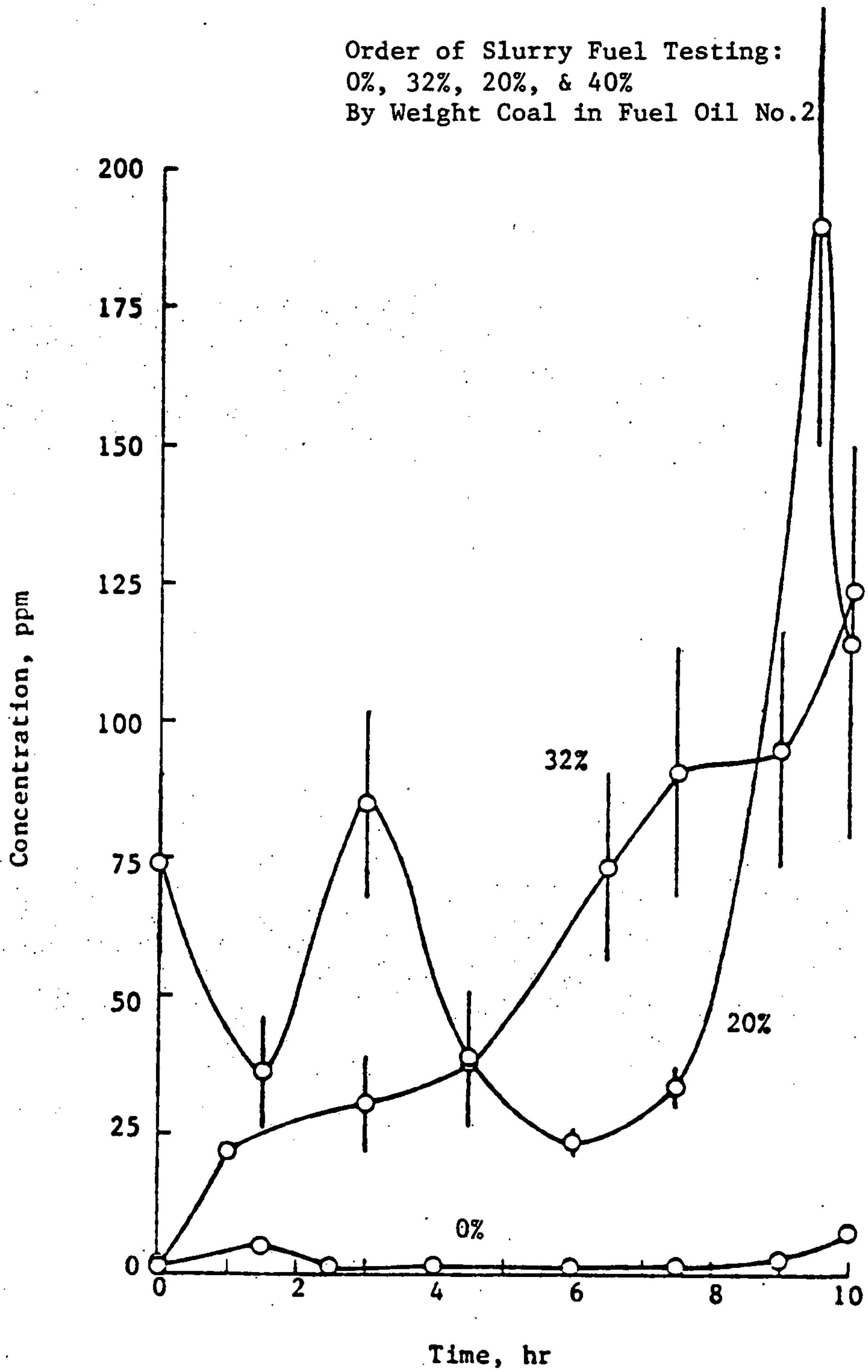


Figure 6-12. Effect of Slurry Fuels on the Wear of the Piston of a 1.36 l Single Cylinder Diesel Engine at 1400 RPM and Full Load Using Titanium as the Tracer Element

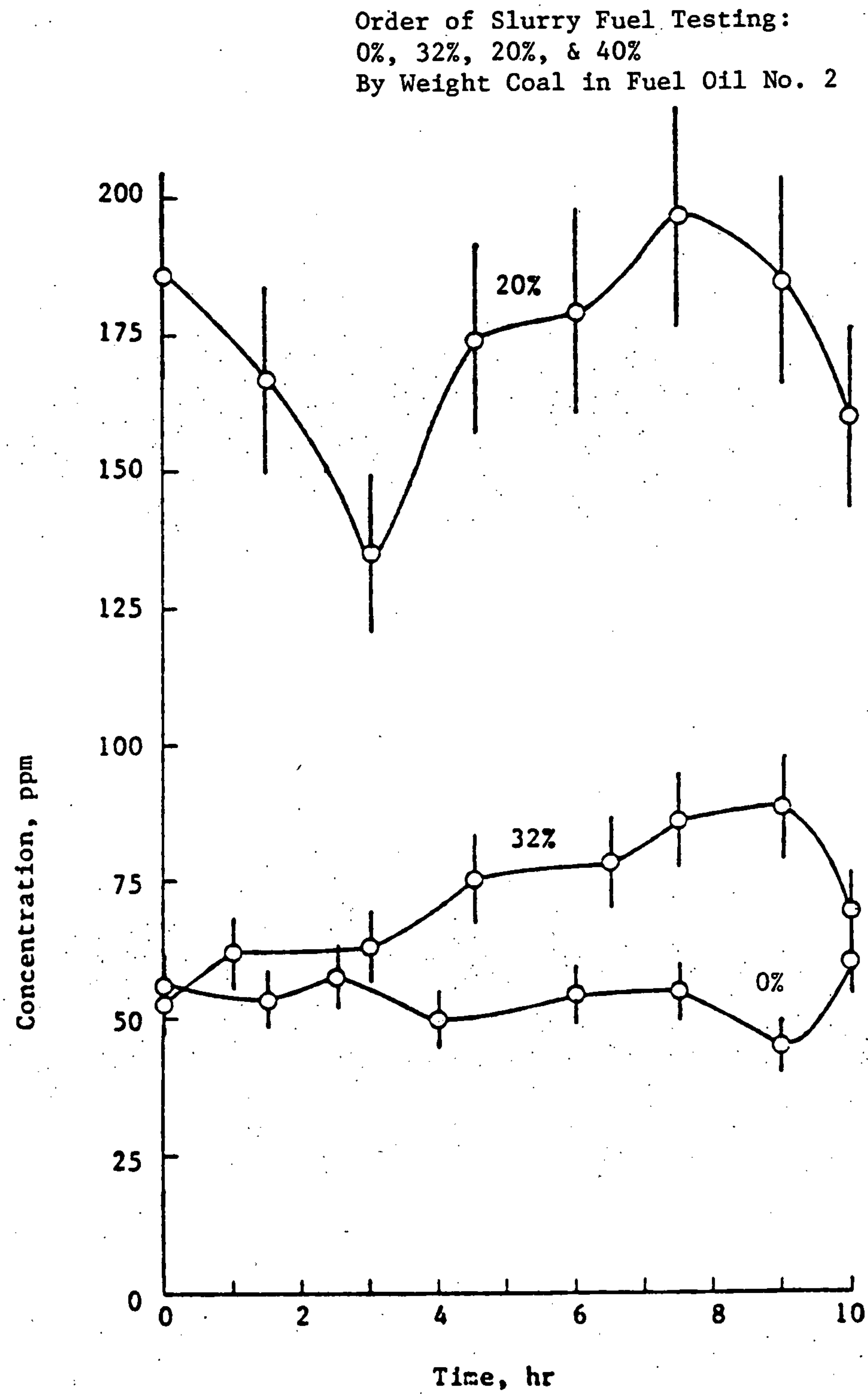


Figure 6-13. Effect of Slurry Fuels on the Wear of the Cylinder Liner of a 1.36 l Single Cylinder Diesel Engine at 1400RPM and Full Load Using Nickel as the Tracer Element

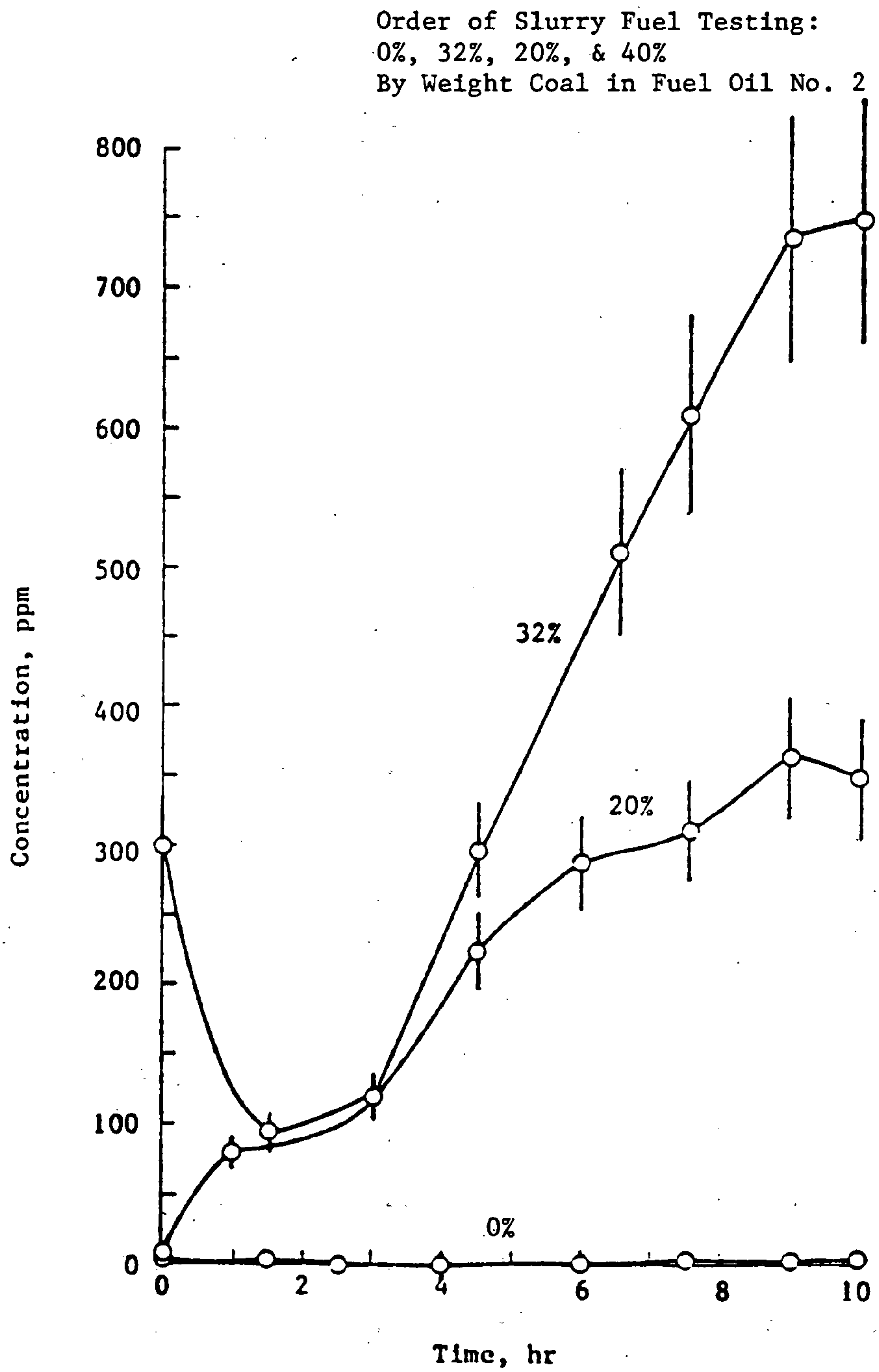


Figure 6-14. Effect of Slurry Fuels on the Leakage of Fuel Past the Piston Rings of a 1.36 1 Single Cylinder Diesel Engine at 1400 RPM and Full Load Using Potassium as the Tracer Element

amount of wear that took place in the previous test, that of the No. 2 fuel oil. The curves do not always indicate a smooth, constantly increasing elemental concentration. This indication of increasing and decreasing wear rates can be attributed to incomplete mixing of the wear particles into the lubricating oil throughout the lubrication system or to errors in the NAA data. The wear that takes place when No. 2 fuel oil is used is negligible compared to that of the slurry fuels, as indicated by the flat curves for the No. 2 fuel oil, except for the case of mercury. The curve for mercury concentration using No. 2 fuel oil starts out very high, 0.80 ppm, and continually decreases for the first five hours of the test at which point it begins to increase slightly to a final concentration of 0.11 ppm at the end of the ten hours of testing. No reasonable explanation for this behavior can be offered at this time.

Examination of the general engine wear curves as depicted by the elements, As, Co, Cr, Fe, Mn, and V, common to all the engine parts analyzed generate confidence in the interpretations being made. The general wear rate caused by the 32% coal slurry was greater than or equal to the wear rate for the 20% coal slurry except as indicated by Cr and Fe. The higher wear rate for the 20% coal slurry as indicated by Cr can be explained by the wearing away of the top compression ring, cast iron type, during the 32% coal slurry test exposing the second compression ring, chrome type, to be abrasive action of the ash and coke particles formed during combustion of the coal. A similar explanation can be offered for the case of Fe, as more and more areas are being exposed to the abrasive particles. The Mn and V curves showed similar wear rates for the two slurry fuels. The 32% coal slurry fuel would have normally been expected to have a higher wear rate due to its higher ash content.

Since the engine in general has been shown to have worn badly under the use of the coal-fuel oil slurries, it would be helpful if it could be determined where the wear occurred. The NAA results show that all of the engine parts analyzed wore badly when the coal slurry fuels were used.

Figures 6-8 and 6-9 show the top and third compression ring wear using selenium and tantalum as tracers. Very little wear occurred using No. 2 fuel oil. The ring wear rate as indicated by each tracer was worse for the 32% coal slurry. Both elements indicate a small wear rate for the 20% coal slurry which is greater than that for the No. 2 fuel oil case. The similarity of the two plots strongly supports the interpretations being made, enough so that the six hour data point for the 20% coal slurry is considered to be a bad data point for the tracer element tantalum.

Figure 6-10 shows wear rates of the oil control rings using mercury as a tracer. Results on No. 2 fuel oil again show a low wear rate, although an unexplainable rapid decreasing rate exists at the beginning. The 32% coal slurry results gave very erratic indications of the highest wear rate. The 20% coal slurry results are somewhat smoother and indicated a wear rate comparable to that of the No. 2 fuel oil case.

Figures 6-11 and 6-12 show piston wear using tin and titanium as tracers. Minimal wear occurred with the use of No. 2 fuel oil. If the first two data points for the 20% coal slurry are attributed to incomplete flushing of the oiling system after the 32% coal slurry, the wear rate is seen to be continually increasing to catastrophic proportions as indicated by tin and supported by the titanium results. The wear rate for the 32% coal slurry is high and relatively steady for both tracer elements. Titanium showed erratic results for the use of the 20% coal slurry, but again supported the ever increasing wear rate seen with tin. The catastrophic wear of the piston towards the end of the 20% coal slurry testing indicates that the piston is making more contact with the cylinder liner than is normal; possibly caused by the packing of coal behind the rings causing the rings to interfere with the normal motion of the piston.

Figure 6-13 shows cylinder liner wear using nickel as a tracer. Again, wear using No. 2 fuel oil was minimal. The 32% coal slurry had a lower wear rate than the 20% coal slurry, which would be expected as more contact was being made between the cylinder liner and the piston by this point.

Fuel leakage past the piston rings into the lubricating oil was indicated by the tracer element potassium. Figure 6.14 shows there was minimal fuel leakage using the No. 2 fuel oil. The rate of fuel leakage was highest for the 32% coal slurry, as well as being very steady. The 20% coal slurry results show an unexpected smaller fuel leakage rate than the 32% coal slurry results. This is unexpected since during the 20% coal slurry testing the piston rings were thought to be worn to the point of being ineffective. Since the fuel leakage was smaller, evidently the piston rings were still sealing effectively. The 32% coal slurry would expectedly have more fuel leakage since there were more coal particles to lodge between the rings and the cylinder liner to cause a loss of sealing.

As was mentioned previously, testing of the 40% coal-fuel oil slurry was terminated after one hour of operation after the three other fuels had been run. Prior to the testing of the 40% coal slurry, attempts were made to run the engine at part throttle loads. None of these attempts were successful due to the seizure of the pintle in the fuel injector. The original pintle was destroyed beyond possible use in an attempt to free it from the injector body. It was for this reason that the fuel injector pintle and nozzle measurements were not given, as the pintle was destroyed before a final measurement was made.

Following the 40% coal slurry test the engine was disassembled. Coal was found packed between and behind the piston rings in the ring grooves. The packing of coal around the rings is physical evidence of the ring failure and fuel leakage.

Wear has been determined to have occurred extensively throughout the engine. The reasons for the wear of the engine on the coal slurry fuels lie with the coal, and not the fuel oil as indicated by the NAA results. The excessive wear of the engine components is due to the abrasive action of ashes and unburnt coke particles formed during the combustion of the coal. Raw coal was used in the slurries tested. Figure 3.2 indicates the ash present in this coal. If Solvent Refined Coal (SRC) had been used, minimal amounts of ash would have been present thus producing a lower wear rate. Unburnt coke particles could have caused a problem even though three micron pulverized coal particles were used in the slurries to enhance complete burning of the particles. In order to determine if three micron particles are small enough to avoid the unburnt coke particles, and the resultant wear, ash would have to be eliminated from the coal and thus tested. SRC eliminates all but 1% of the ash in coal. Thus, an SRC slurry if available would seem to be the next fuel to be tested.

VII

CONCLUSIONS & RECOMMENDATIONS

The power, economy, exhaust opacity, and exhaust emission tests yielded expected results. The maximum power produced was 9.25, 8.14, 7.06, and 2.96 kW for No. 2 fuel oil, 20% coal slurry, 32% coal slurry, and 40% coal slurry, respectively. Brake specific energy consumption for the 20% coal slurry was 14% greater than the 28,100 kJ/kW-hr value for No. 2 fuel oil and 32% greater than this value for the 32% coal slurry under full load testing. The brake specific energy consumption for the 40% coal slurry was approximately three times greater than that for the No. 2 fuel oil. Exhaust opacity for the 20% slurry was 23% higher than the 26% light obstructed value for No. 2 fuel oil and 58% higher than this value for the 32% coal slurry. Exhaust opacity for the 40% coal slurry was equal to that for No. 2 fuel oil due to its incomplete combustion. SO_x exhaust emissions were directly proportional to the sulfur content of the slurry used. NO_x exhaust emissions were lowest for the No. 2 fuel oil and 21, 5.4, and 32 times greater for the 20%, 32%, and 40% slurries, respectively.

Engine wear using No. 2 fuel oil was found through the NAA results to be minimal. Wear rates using coal-oil slurries were found to be unacceptably high. The 32% coal slurry was found to have a higher resultant wear rate than the 20% coal slurry which was higher than that of the No. 2 fuel oil case. The 40% coal slurry was not tested long enough to determine the resultant wear rate.

Although it is possible to operate a small diesel engine on slurry fuels several problems exist. In an unstable suspension coal particles aglomergate and plug the small passages unless great care to exercised.

Exhaust pollutants increase and engine wear is extremely great. It is recommended that in any further work in this area that solvent refined coal in a stable suspension in amounts of 15 percent be used. Exhaust emissions and wear rates should be reduced considerably by the reduced sulfur and ash contents in SRC as opposed to raw coal.

VIII

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IX

APPENDIX-A

Shown below are various methods of calculating significant test results from data obtained from the Nordberg 1360 cc diesel engine operating at full load and 1400 RPM. Sample calculations shown are from test results using 20% by weight raw coal - No. 2 fuel oil slurry, with a higher heating value of 42,053 kJ/kg, as a fuel in the engine.

1) Engine Power Output, Bkw (kw).

$$Bkw = \frac{2\pi\ F\ L\ N}{60,000}$$

where: F = dynamometer scale reading, newton

L = length of dynamometer arm, meter

N = engine speed, RPM

A sample calculation is shown below. The arm length was 0.569 meters and the scale reading was 97.6 newtons.

$$Bkw = \frac{2\pi\ (97.60)(0.569)\ (1400)}{60,000} = 8.14\ kw$$

2) Brake Specific Energy Consumption, Bsec (kJ/kw - hr).

$$Bsec = \frac{3600\ m_f}{Bkw\ (t)}\ (HHV)$$

where: m_f = mass of fuel, kilogram

t = time to burn sample mass of fuel, second

HHV = higher heating value of fuel, kJ/kg

A sample calculation is shown below, where 0.50kg of fuel was burned in 289.80 seconds.

$$\text{Bsec} = \frac{3600\ (0.50)}{8.14\ (289.80)}\ (42{,}053) = 32{,}100\ \text{kJ/kw-hr}$$

3) <u>Energy Input to the Engine, E_{in} (kw).</u>

$$E_{in} = \frac{\dot{m}_f\ (HHV)}{3600}$$

where: $\dot{m}_f$ = mass of fuel flow, kg/hr

A sample calculation is shown below where the mass of fuel flow was 6.21 kg/hr.

$$E_{in} = \frac{6.21\ (42{,}053)}{3600} = 72.54\ \text{kw}$$

4) <u>Percent of Energy to Brake Kilowatt, P_{Bkw}.</u>

$$P_{Bkw} = \frac{Bkw}{E_{in}}\ (100)$$

A sample calculation is shown below.

$$P_{Bkw} = \frac{8.14}{72.54} = 11.22\%$$

5) <u>Percent of Energy to Friction Kilowatt, P_{Fkw}.</u>

$$P_{Fkw} = \frac{Fkw}{E_{in}}\ (100)$$

where: Fkw = Friction kilowatt, kw

A sample calculation is shown below where the engine friction kilowatt was 5.19 kw.

$$P_{Fkw} = \frac{5.19}{72.54}(100) = 7.15\%$$

6) <u>Percent of Energy to Cooling Water, P_{cw}.</u>

$$P_{cw} = \frac{\dfrac{\dot{m}_{cw}(h_{in} - h_{out})}{3600} - Fkw}{E_{in}}(100)$$

where: $\dot{m}_{cw}$ = mass of Clg. Wtr. Flow, kg/hr

h_{in} = Enthalpy of Clg. Wtr. In, kJ/kg

h_{out} = Enthalpy of Clg. Wtr. Out, kJ/kg

A sample calculation is shown below where the cooling water flow was 154.20kg/hr and the inlet and outlet cooling water enthalpies were 104.89 kJ/kg and 334.91 kJ/kg respectively.

$$P_{cw} = \frac{\dfrac{154.20(334.91 - 104.89)}{3600} - 5.19}{72.54}(100) = 6.43\%$$

7) <u>Percent of Energy to Exhaust, P_{exh}.</u>

$$P_{exh} = \frac{\dot{m}_{exh} C_p (T_{exh} - T_{atm})}{E_{in}(3600)}(100)$$

$$\dot{m}_{exh} = \dot{m}_f + \dot{m}_{air}$$

$$\dot{m}_{air} = \frac{P_{atm} \dot{V}_D}{R\ T_{atm}} (N_V)$$

$$\dot{V}_D = \frac{Disp.\ N\ (600{,}000)}{2}$$

where: $\dot{m}_{exh}$ = mass of Exhaust Flow, kg/hr

C_p = Const. Press. Specific Heat of Air, 1.004 kJ/kg-K

T_{exh} = Temperature of Exhaust, °K

T_{atm} = Temperature of Ambient Air, °K

$\dot{m}_{air}$ = Mass of Air Flow, kg/hr

N_V = Volumetric Efficiency, 0.87

P_{atm} = Atmospheric Pressure, N/m^2

$\dot{V}_D$ = Rate of Volume Displaced, m^3/hr

Disp. = Engine Displacement, 1360 cc

R = Air Gas Constant, 287.00 N-m/kg-K

A sample calculation is shown below where the ambient air and exhaust temperature were 301°K and 708°K respectively and the atmospheric pressure was 95,300 N/m^2

$$\dot{V}_D = \frac{1360\ (1400)}{2} \frac{(60)}{1{,}000{,}000} = 57.12\ m^3/hr$$

$$\dot{m}_{air} = \frac{95{,}300\ (57.12)}{287.00\ (301)} (.87) = 54.82\ kg/hr$$

$$\dot{m}_{exh} = 54.82 + 6.21 = 61.03\ kg/hr$$

$$P_{exh} = \frac{61.03\ (1.004)\ (708 - 301)}{72.54\ (3600)} (100) = 9.55\%$$

8) <u>Percent of Energy Unaccounted, P_{unacct}.</u>

$$P_{unacct} = 100 - (P_{Bkw} + P_{Fkw} + P_{cw} + P_{exh})$$

A sample calculation is shown below.

$$P_{unacct} = 100 - (11.22 + 7.15 + 6.43 + 9.55) = 65.65\%$$

APPENDIX-B

Methods of calculating significant test results from data obtained from the Nordberg 1360 cc diesel engine operating at full load and 1400 rpm are shown below. Sample calculations shown are from test results using 20% by weight raw coal-No. 2 fuel oil slurry.

1) Engine Power Output

$$\text{Power Output} = \frac{2\pi FLN}{60{,}000}$$

where: F = dynamometer scale reading, N
L = length of dynamometer arm, m
N = engine speed, rpm

A sample calculation is shown below. The arm length was 0.569 m and the scale reading 97.6 N.

$$\text{Power Output} = \frac{2\pi(97.60)(0.569)(1400)}{60{,}000}$$

$$= 8.14 \text{ kW}$$

2) Concentration of Pollutant in 1 m^3 of Exhaust Gas

Following formula was derived to convert ppm into $\mu g/m^3$.

Consider ideal gas relation,

$$m = \frac{PVM}{\overline{R}T}$$

where: P = pressure of the mixture of gases
V = volume of the gas under consideration, as given by volumetric analysis of the mixture of gases.
M = molecular wt. of the gas under considerations
$\overline{R}$ = universal gas constant
T = temperature of the mixture of gases.

3) Amount of Pollutant Produced per Hour

Rate of exhaust gas displaced by the engine when running at 1400 rpm is given by

$$V = \frac{(Vs)(N)(10^{-6})(60)}{2} \quad \frac{m^3}{hour}$$

where: Vs = engine swept volume, cc
N = engine speed, rpm

Then, $$V = \frac{(1360)(1400)(10^{-6})(60)}{2} \quad \frac{m^3}{hour}$$

$$= 57.12 \quad \frac{m^3}{hour}$$

Then amount of pollutant produced per hour

$$= (57.12)\ (\text{concentration})$$

For a sample calculation, consider the concentration of SO_x, 523.5 $\frac{\mu g}{m^3}$.

$\therefore$ Amount of SO_x per hour

$$= (57.12)(523.5)(10^{-6})\ \frac{g}{hour}$$

$$= 2.99 \times 10^{-2}\ \frac{g}{hour}$$

4) ppm/kW

$$\frac{\text{Number of ppm at a data point}}{\text{Power developed by the engine at the data point.}}$$

A sample calculation is shown below. The SO_x ppm level was 0.2 and the power developed by the engine was 8.14 kW.

$$\frac{ppm}{kW} = \frac{0.2}{8.14} = 2.46 \times 10^{-2}$$

3) <u>Amount of Pollutant Produced per Hour</u>

Rate of exhaust gas displaced by the engine when running at 1400 rpm is given by

$$V = \frac{(Vs)(N)(10^{-6})(60)}{2} \quad \frac{m^3}{hour}$$

where: Vs = engine swept volume, cc
N = engine speed, rpm

Then, $$V = \frac{(1360)(1400)(10^{-6})(60)}{2} \quad \frac{m^3}{hour}$$

$$= 57.12 \quad \frac{m^3}{hour}$$

Then amount of pollutant produced per hour

$$= (57.12)\ (\text{concentration})$$

For a sample calculation, consider the concentration of SO_x, 523.5 $\frac{\mu g}{m^3}$.

$\therefore$ Amount of SO_x per hour

$$= (57.12)(523.5)(10^{-6}) \ \frac{g}{hour}$$

$$= 2.99 \times 10^{-2} \ \frac{g}{hour}$$

4) ppm/kW

$$\frac{\text{Number of ppm at a data point}}{\text{Power developed by the engine at the data point.}}$$

A sample calculation is shown below. The SO_x ppm level was 0.2 and the power developed by the engine was 8.14 kW.

$$\frac{ppm}{kW} = \frac{0.2}{8.14} = 2.46 \times 10^{-2}$$

5) Amount of Pollutant per Unit Amount of Fuel

$$\frac{\text{Amount of pollutant produced per hour}}{\text{Amount of fuel consumed per hour.}}$$

A sample calculation is shown below. The amount of SO_x produced in one hour was 2.99×10^{-2} g and fuel was consumed at the rate of 6 kg per hour. Then, amount of pollutant produced per kg of fuel is

$$\frac{2.99 \times 10^{-2}}{6} = 4.98 \times 10^{-3} \frac{g}{kg} .$$