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# Combustion Characteristics of Dry Coal-Powder-Fueled Adiabatic Diesel Engine

**Final Report**

**R.M. Kakwani**
**R. Kamo**

January 1989

Work Performed Under Contract No.: DE-AC21-86MC23258

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Adiabatics, Inc.
Columbus, Indiana

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Morgantown Energy Technology Center
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January 1989

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## EXECUTIVE SUMMARY

This report describes the progress and findings of a research program aimed at investigating the combustion characteristics of dry coal powder fueled diesel engine. This work was performed under the U.S. Department of Energy, Morgantown Energy Technology Center (DOE-METC) contract number DE-AC21-86MC23258. During this program, significant achievements were made in overcoming many problems facing the coal-powder-fueled engine. The Thermal Ignition Combustion System (TICS) concept was used to enhance the combustion of coal powder fuel.

The major coal-fueled engine test results and accomplishments are as follows:

- Design, fabrication and engine testing of improved coal feed system for fumigation of coal powder to the intake air. This system has very few moving parts and results in consistent fuel delivery and metering for the coal-fueled engine operation.
- Design, fabrication and engine testing of the TICS chamber made from a superalloy material (Hastelloy X). Also, a TICS chamber made from silicon nitride ceramic was designed and fabricated.
- Design, fabrication and engine testing of wear resistant chrome oxide ceramic coated piston rings and cylinder liner.
- Lubrication system was improved to separate coal particles from the contaminated lubricating oil. Thus, the coal-fueled engine test could be performed for a longer period of time.
- Control of the ignition timing of fumigated coal powder fuel by utilizing exhaust gas recirculation (EGR) and variable TICS chamber temperature. EGR also lowered the peak cylinder pressure, rate of pressure rise and NOx emissions.
- Coal-fueled engine testing was conducted in two configurations: Dual fuel (with diesel pilot) and 100% coal-fueled engine without diesel pilot or heated intake air. These engine tests show fast burning, high cylinder pressures and high heat release rates for the combustion of coal powder fuel.
- Cold starting of the 100% coal-powder-fueled engine with a glow plug.
- Coal-fueled-engine was operated with three types of coals: 1. Micronized Bituminous coal, 7 microns mean size, 2. Nonbeneficiated 1.6% ash content Bituminous coal, 21.3 microns mean size, and 3. 7.1% ash content North Dakota Lignite coal, 29 microns mean size.
- Coal-fueled-engine was operated from 800 to 1800 rpm speed and idle to full load engine conditions.

This research investigation on fumigated coal fueled engine with TICS has revealed several interesting points. The most interesting was the effect of exhaust gas recirculation as a timing control device. Significant reduction in peak cylinder pressure and NOx emissions were also observed with the use of exhaust gas recirculation. Another important point is the high speed capability of the coal-powder-fueled engine. The high level of ignition energy in the TICS chamber also enabled the combustion of large particle size coal fuel. In summary, the development of a simple, low cost coal-powder-fueled engine appears possible.

COMBUSTION CHARACTERISTICS OF DRY COAL-POWDER-FUELED ADIABATIC DIESEL ENGINE

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# 1.0 INTRODUCTION

This report entitled "Extending and Enhancing the Scientific Base for Advanced Coal-Fueled Power Systems Utilizing Heat Engines" is submitted to the U.S. Department of Energy, Morgantown Energy Technology Center (DOE-METC) for the contract number DE-AC21-86MC23258. It describes the results and findings of a research program aimed at investigating the combustion characteristics of the dry coal-powder-fueled adiabatic diesel engine.

During the past several years, the U.S. Department of Energy, Morgantown Energy Technology Center, has sponsored many research programs for the development of coal-fueled diesel engines [1-4]*. Most of these programs have used coal-water slurry (CWS) as fuel for the engine. The recent coal-fueled engine development being conducted by General Electric Company [5-6] and A-D Little/Cooper Bessemer [7-8] rely on high pressure injection of CWS into a direct injection diesel engine. These CWS-fueled engines require ignition assist devices such as the injection of diesel fuel pilot or a natural gas torch. Heating of the intake air has been required in some instances to improve the combustion of CWS or to allow engine operation with 100% CWS fuel. The major problem encountered with these engines has been accelerated wear of fuel injection nozzle spray holes, cylinder liners and piston rings. An additional complication of using CWS fuel is that the 50% water content cuts the fuel heating value in half and requires the injection capacity to be twice as compared to diesel fuel no. 2 and heavy distillate fuels.

The use of dry micronized coal powder as fuel for the coal-fueled diesel engine is an alternative to the CWS fueled engine. As discussed in this report a dry coal powder fueled engine can be operated on 100% coal fuel without any external ignition assist sources. The coal powder fueled engine does not need a separate high pressure diesel fuel injection system for the pilot fuel. Also, the coal powder fueled engine can burn different types of coal having a wide range of particle sizes and ash content.

---

* Numbers in parentheses designate references at end of the report.

The feasibility of the coal powder fueled engine was demonstrated by Adiabatics, Inc. under a contract from the DOE-METC [9]. The Thermal Ignition Combustion System (TICS) concept for ignition of the fumigated coal powder fuel was discovered during this program. This system utilizes a hot auxiliary combustion chamber for ignition of the coal powder. These findings have been reported in earlier publications by Kamo et al. [10-11] and Kakwani et al. [12-13].

This report has been organized into five sections. Section 1 contains a general introduction to the research program, background on prior coal powder fueled work, and program objectives. Section 2 describes the technical program approach, test engine and facilities, fuels and lubricants, and coal powder feed system. The coal-fueled engine test results and discussion are presented in Section 3. The summary and conclusions are contained in Section 4, and the recommendations for further work on coal-fueled diesel engines in Section 5.

## 1.1 BACKGROUND ON PRIOR COAL-POWDER-FUELED WORK

Adiabatics, Inc. conducted a research program during 1985 under DOE-METC contract number DE-AC21-84MC21099 on the "Combustion Characteristics of Coal Fuels in Adiabatic Diesel Engines" [9]. The objective of this program was to study the benefits of a high temperature adiabatic diesel engine on the combustion of dry coal powder fuel. The fumigation of fine coal powder to the intake air manifold was conducted in an indirect injection, Caterpillar 1Y73 single-cylinder test engine. The engine was modified into an uncooled configuration by coating the combustion chamber components with thermal barrier (insulating) and/or wear resistant ceramic materials and removing the water cooling system.

Excellent combustion characteristics of coal powder fuel were observed from the engine test results. The initial test plan included running in a dual-fuel mode with injection of diesel fuel into the precombustion chamber and fumigation of coal powder into the intake air. The plan called for operation with up to 50% coal powder. However, the ignition and fast burn rate of the coal powder was better than expected, making it possible to conduct engine tests with 100% coal fuel without any external ignition assist. Earlier work, by other investigators, on coal-fueled diesel engine [5,7] has relied on external ignition sources (i.e. diesel pilot and/or glow plug). With the higher temperatures brought about by the adiabatic engine configuration, it was possible to achieve reliable and fast burning of the coal fuel with consequent improvements in the thermal efficiency. This approach to igniting and burning coal in heat engines is referred to as the "Thermal Ignition Combustion System" (TICS) concept (U.S. Patent No. 4,738,227, dated April 19, 1988).

Heat release analysis indicated very rapid heat release rates and short combustion duration for the coal powder. For example, the combustion duration with coal powder fuel was one third that of diesel fuel. For a typical coal-fueled engine test the peak apparent heat release rate was 0.31 kJ/degree (compared to 0.09 kJ/degree for diesel fuel). The pressure-volume diagram showed the combustion to be taking place at virtually constant volume. The indicated thermal efficiency (computed from the cylinder pressure data) showed higher efficiency for the coal fueled-engine than for the diesel-fueled engine [9].

The test results from this early investigation were very encouraging and the following observations and conclusions were made:

- The coal powder exhibited excellent combustion characteristics in the TICS engine. The burning was very fast with high heat release rates and short combustion duration. Indicated thermal efficiency for the 100% coal-fueled engine was higher than for the diesel-fueled engine.

- Thermal ignition of the powdered coal fuel was achieved in an uncooled insulated engine without external ignition aids.

- Coal powder combustion in the TICS configuration is not limited to medium speed engine operation. It appeared that engine speeds in the 2000 rpm range may be possible with coal-fueled engines utilizing the TICS concept.

- Cold starting was achieved with 100% coal powder fuel when a glow plug was utilized to preheat the TICS chamber.

- Fumigation of coal powder into the intake air caused piston ring sealing problems which resulted in high blow-by and lubricating oil contamination. A centrifugal by-pass filter was successfully used to remove coal particles from the oil as small as 0.1 micron diameter. This minimized the problem and increased the maintenance interval on the oil filters.

- High wear rates of conventional chrome plated piston rings were observed. The wear of the chrome oxide ceramic coated cylinder liner was negligible during the short period of testing with the coal fuel.

The following problems and limitations were encountered during this investigation:

- Difficulty in controlling ignition timing with the coal fuel.

- Non-uniform coal feed rate to the engine caused fluctuations in the engine speed/load.

- Difficulty with the conventional prechamber, which was not able to operate at very high temperatures (>870 C or 1600 F).

As described in this report the current research investigation has made significant progress in reducing or overcoming the above problems.

## 1.2 PROGRAM OBJECTIVES

The objectives of this research program were to improve the combustion efficiency of coal powder fuel in a diesel engine, thereby increasing the coal-fueled engine's thermal efficiency. In particular, the goal of the program was to find solutions to the problems encountered in the earlier program (mentioned in Section 1.1) and achieve consistent operation of the coal powder fueled engine with the TICS concept. The challenging problems and limitations of controlling ignition timing of fumigated coal powder in the TICS engine, consistent and reliable operation of the coal powder feed system, a high temperature TICS chamber, and wear of piston rings were to be overcome in the present research investigation.

# 2.0 PROJECT DESCRIPTION

Section 2.1 describes the technical approach. The details of experimental work conducted with the test engine and facilities including engine description, TICS chamber, adiabatic engine components, lubrication system, and instrumentation are given in Section 2.2. The specifications of fuels and lubricants are described in Section 2.3 and the description of coal powder feed system is presented in Section 2.4.

## 2.1 TECHNICAL APPROACH

The technical approach to this program was to evaluate and enhance the combustion of coal powder fuel in a single cylinder diesel engine with modified fumigation into the intake manifold. The TICS concept was utilized to achieve rapid and controlled burning of coal fuel. This research program was divided into seven tasks:

Task

1 - Detailed Test Plan
2 - Coal Fuel Specifications and Preparation
3 - Coal Feed and Metering System Preparation
4 - Combustion Chamber - Design and Fabrication
5 - Test Engine Preparation
6 - Engine Combustion Tests
7 - Data Analysis

## 2.2 TEST ENGINE AND FACILITIES

### 2.2.1 Engine Description

The specifications of the Caterpillar 1Y73 single-cylinder engine used for this test program are as follows:

| | |
|---|---|
| Type: | Caterpillar 1Y73 |
| Number of Cylinders: | 1 |
| Combustion Chamber: | Prechamber |
| Cycle: | 4 Stroke |
| Bore x Stroke: | 130 x 165 mm (5.125 x 6.5 inches) |
| Engine Speed: | Up to 1800 rpm |
| Compression Ratio: | 16.5:1 |
| Air Aspiration: | Naturally Aspirated |
| Piston: | Aluminum Alloy |
| Cylinder Head and Block: | Cast Iron |

Figures 2-1 to 2-3 show a schematic and photographs of the test engine and test cell used for the coal-fueled engine tests. A schematic of the Caterpillar 1Y73 single cylinder test engine set up in Figure 2-4 shows thermal barrier and wear-resistant ceramic coated engine components, TICS chamber with temperature controller, and exhaust gas recirculation (EGR). The exhaust gases were recirculated to the intake air manifold via a flexible steel pipe through which cooling water was passed in helical copper tubes. This allowed cooling of the exhaust gases before admission to the test engine cylinder. The amount of EGR was remotely controlled by a combination of butterfly and gate valves.

### 2.2.2 TICS Chamber

In order to avoid the difficulties encountered at high temperatures with the standard Caterpillar precombustion chamber (PCC), a new TICS chamber was designed and fabricated from Hastelloy X, a superalloy material capable of continuously withstanding 1000 C (1832 F) temperature. The geometry and volume ratio of the TICS chamber were kept similar to the standard Caterpillar precombustion chamber. TICS chamber wall temperature was controlled by monitoring the outside wall temperature with a thermocouple and temperature controller set up and modulating the cooling water sprayed on its exterior. This system was found to control the TICS chamber temperature quite well and allowed its temperature to be changed and controlled in a matter of seconds. As discussed later in Section 3.2.2, the control of TICS

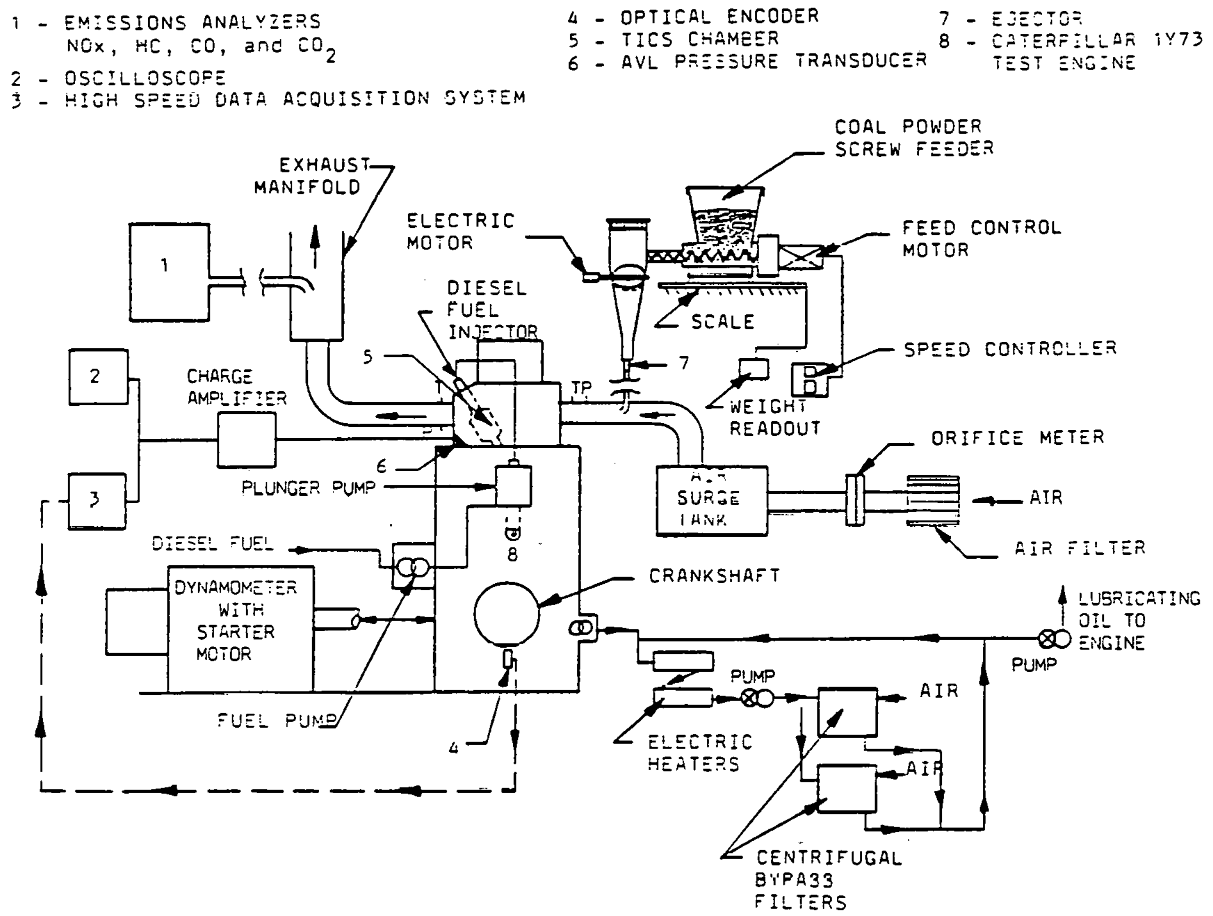


Figure 2-1. Schematic of Test Engine Set-up.

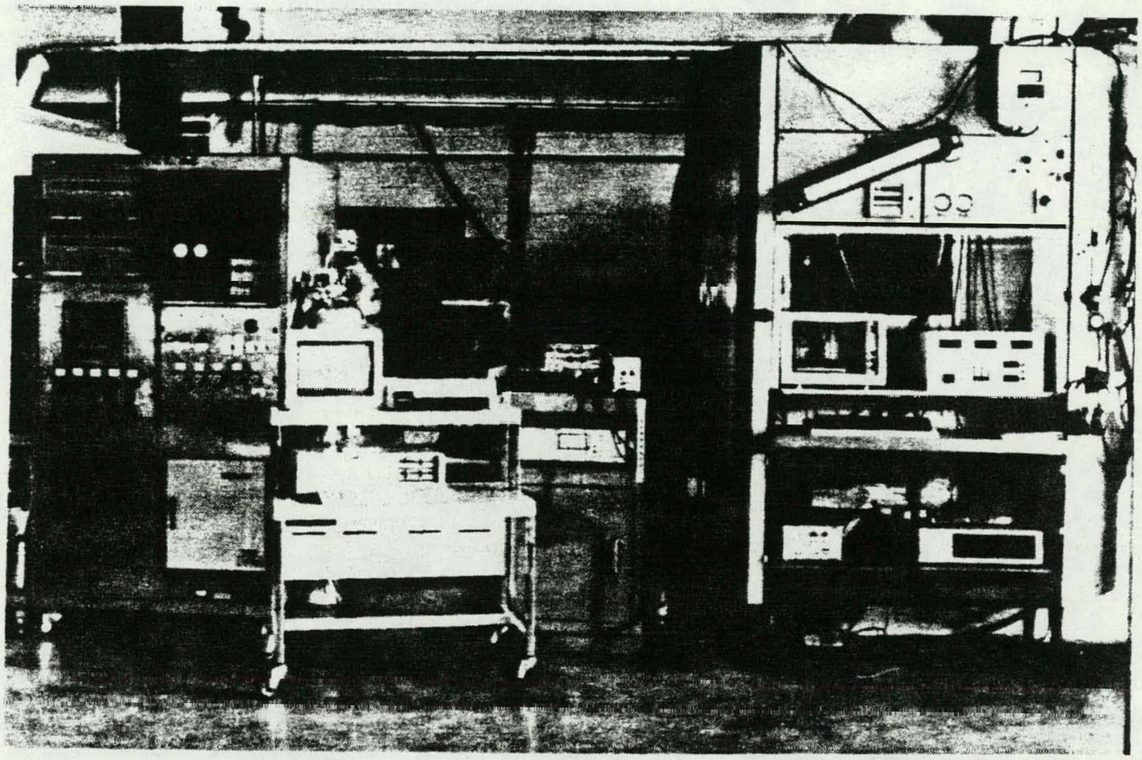

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Figure 2-2. Photograph of Test Cell for the Coal Powder Fueled Engine Tests.

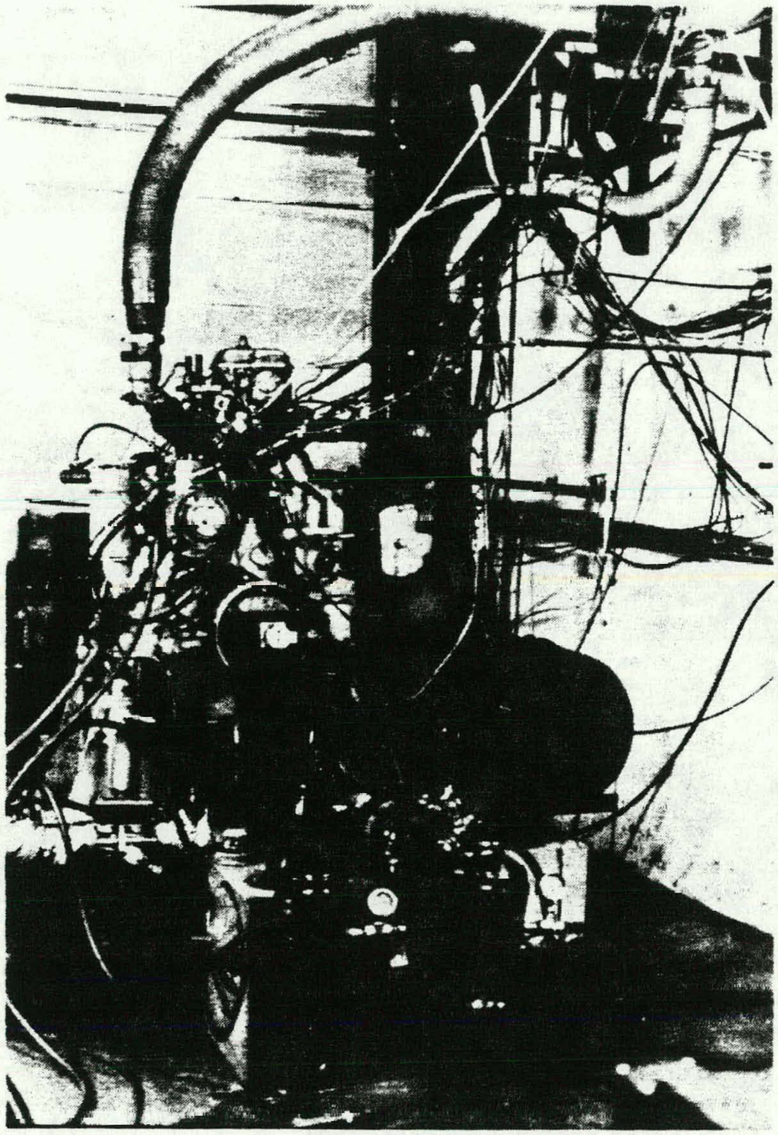

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Figure 2-3. Photograph of Caterpillar 1Y73 Single Cylinder Test Enginc.

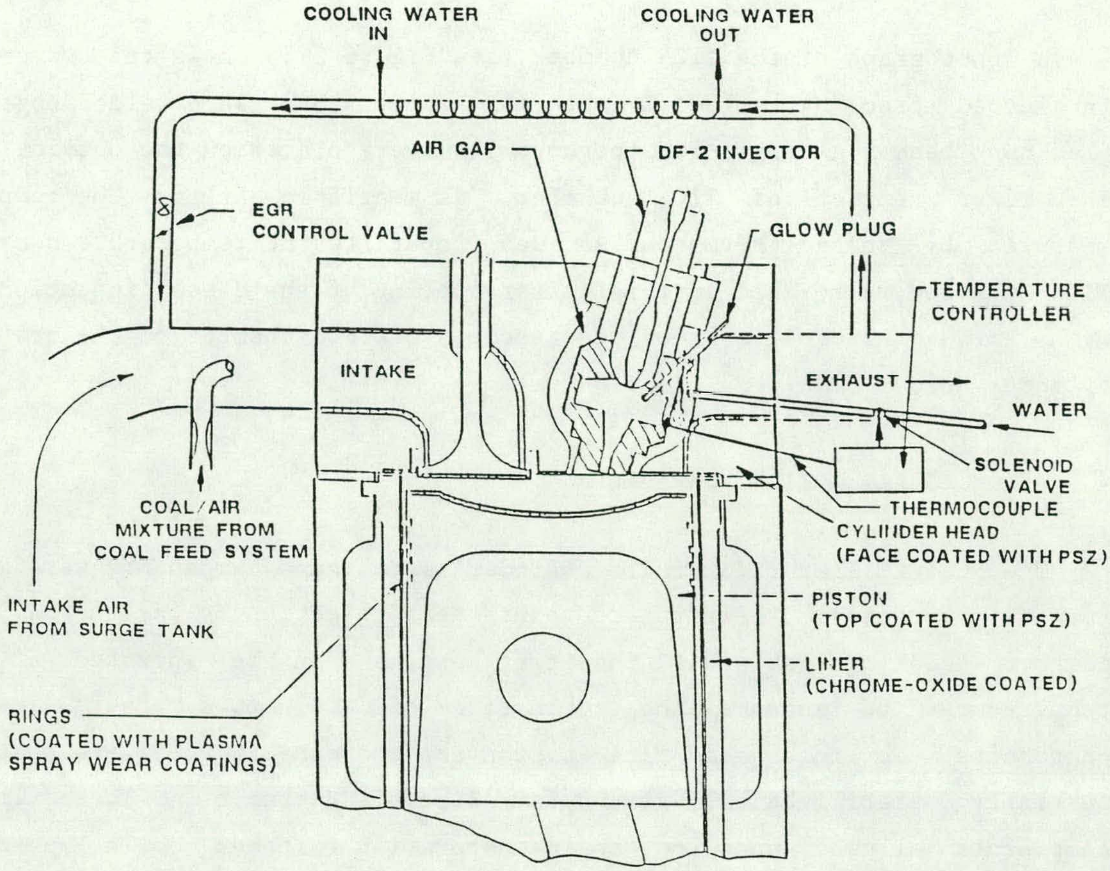


Figure 2-4. Schematic of the Caterpillar 1Y73 Single-Cylinder Test Engine with Coated Components, Controlled TICS Temperature and Exhaust Gas Recirculation Set-up.

chamber wall temperature was necessary to control the ignition of fumigated coal powder fuel in the engine.

A photograph of the TICS chamber (see Figure 2-5) shows the two sections, fabricated from Hastelloy X material after they were welded together by electron beam welding. Two thermocouples were placed on the outside wall of the lower section of TICS chamber. As mentioned earlier, the temperature measured by these thermocouples was input to the temperature controller. TICS chamber also had provision for cooling of the diesel injection nozzle with air. Figure 2-6 shows the assembly of TICS chamber on the test engine cylinder head.

### 2.2.3 Adiabatic Engine Components

The Caterpillar 1Y73 single cylinder test engine components were modified for two purposes. First, to reduce heat rejection by the thermal barrier ceramic coatings so that the test engine can be operated at higher temperatures to enhance the combustion of coal powder fuel. The engine components - cylinder head face, piston top and exhaust port were coated with partially stabilized plasma spray Zirconia ceramic. These insulated components allowed uncooled engine operation (without cooling water in the cylinder head and block). Second, to reduce wear of piston rings and cylinder liner by the abrasive coal powder and ash which was fumigated in the intake air manifold. The cylinder liner surface was modified with a thin coating of wear-resistant chrome oxide. Also, the top ring design incorporated step gap sealing for reducing blow-by and plasma spray chrome oxide coating for the wear resistance.

Figure 2-7 shows a photograph of the test engine components with insulation and/or wear resistant coatings. These coated components are described in Table 2-1. A photograph of the piston rings used for the coal-fueled engine testing is shown in Figure 2-8.

### 2.2.4 Lubrication System

The test engine lubrication system was improved in this program to enable

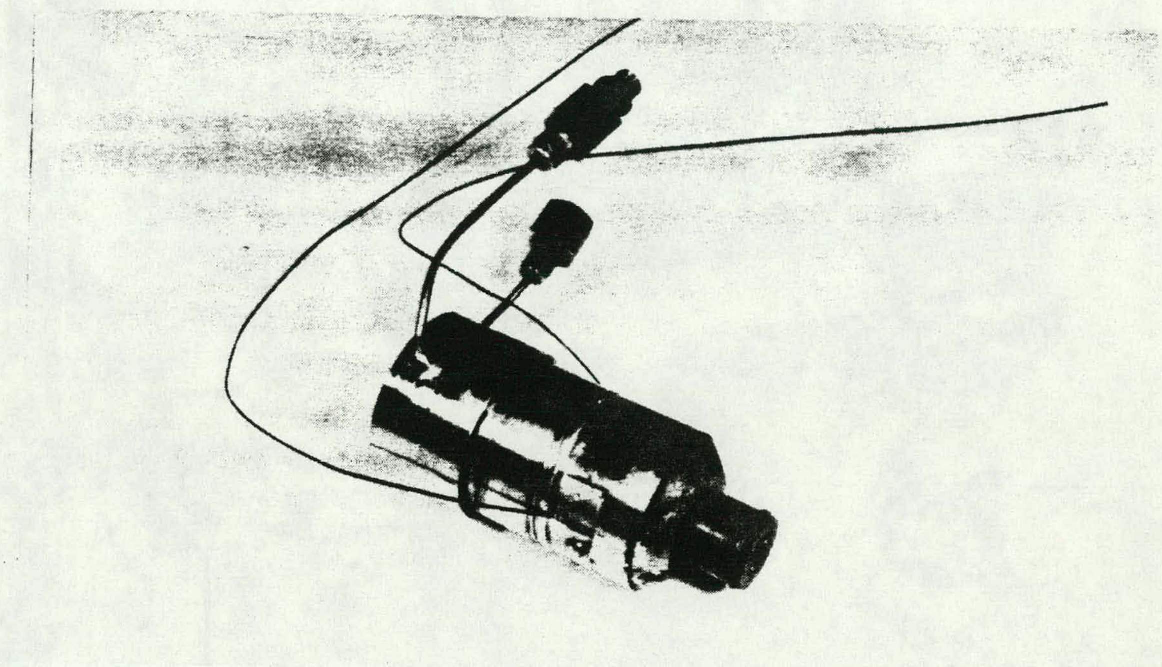

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Figure 2-5. Photograph of TICS Chamber for the Coal Powder Fueled Engine Tests.

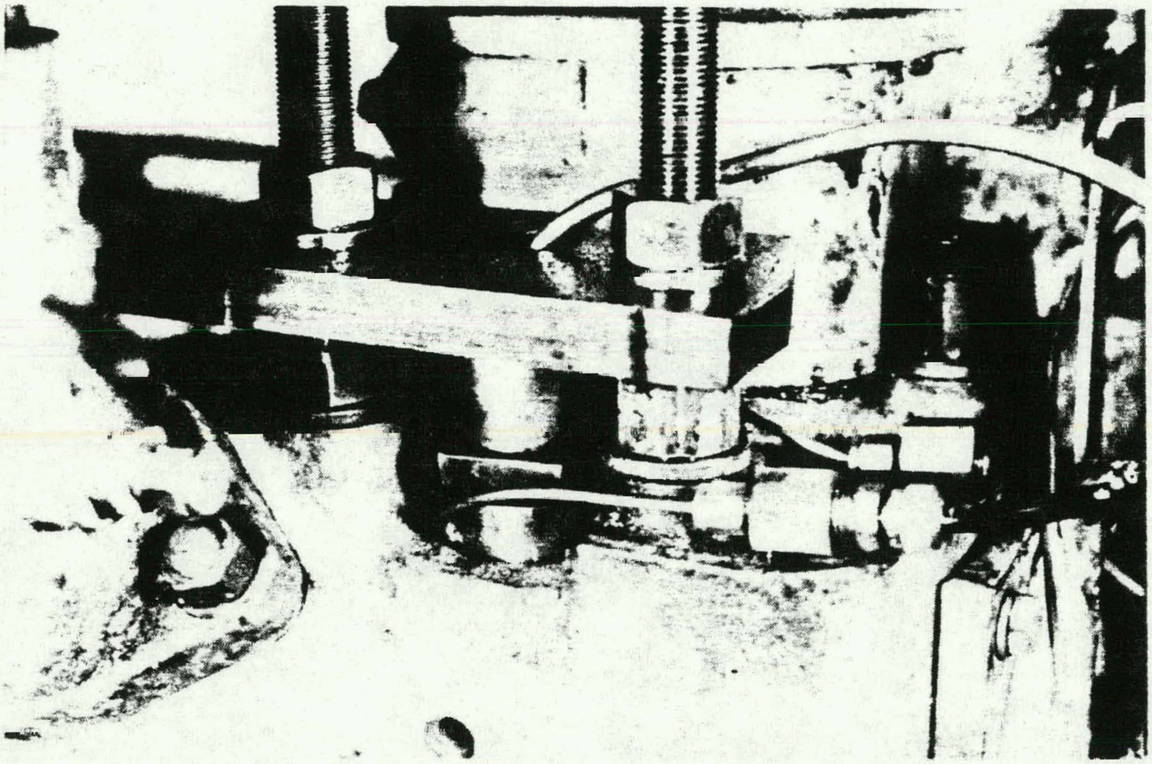

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Figure 2-6. Photograph of Test Engine Cylinder Head Showing Assembly of the TICS Chamber.

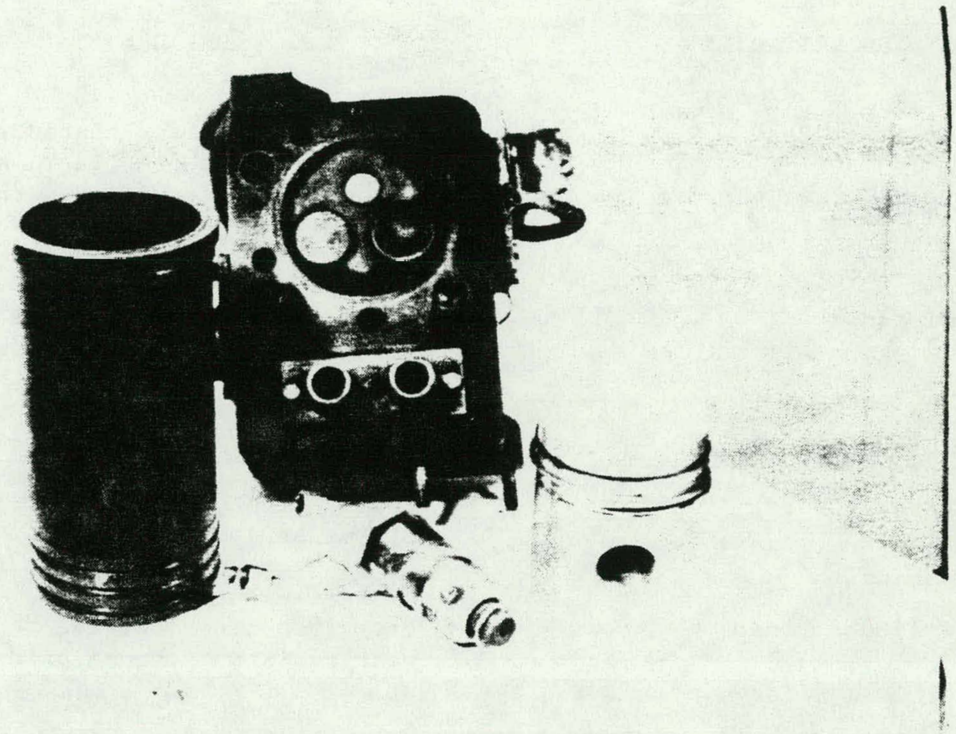

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Figure 2-7. Photograph of Test Engine Components - Cylinder Liner, Cylinder Head, Piston and TICS Chamber.

Table 2-1

Description of Coated Test Engine Components

| Engine Component | Coatings | |
|---|---|---|
| Cylinder Head | Cast iron headface coated with 0.9 mm (0.035 inch) thick plasma sprayed Zirconia and densified with TC5 coating.* | |
| Piston | Aluminum piston top coated with 0.9 mm (0.035 inch) thick plasma sprayed Zirconia and densified with TC5 coating.* | |
| Exhaust port | Coated with 0.76 mm (0.03 inch) thick plasma sprayed Zirconia. | |
| Cylinder liner | Cast iron liner surface coated with wear-resistant chrome oxide coating. | |
| Rings | Top - | step gap ring with plasma spray chrome oxide coating. |
| | Intermediate - | Standard Caterpillar rings (chrome plated). |
| | Oil - | Standard Caterpillar ring (chrome plated). |

* Proprietary coating developed at Adiabatics, Inc., Columbus, Indiana.

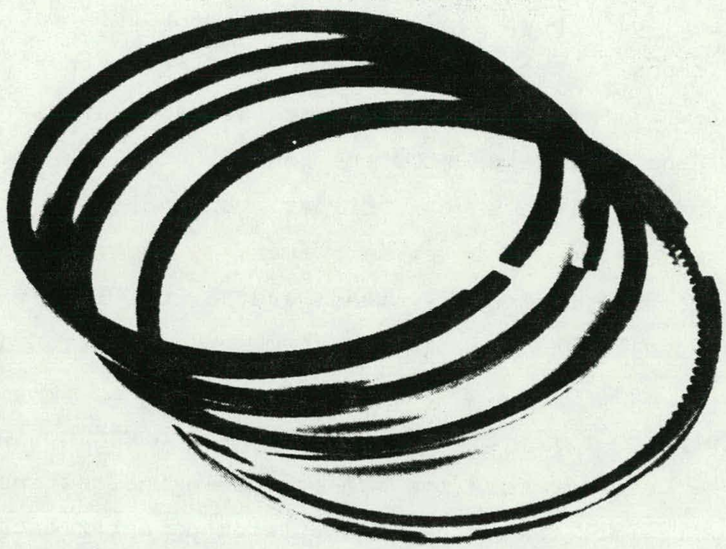

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Figure 2-8. Photograph of Piston Rings Used for the Coal-Fueled Engine Testing.

coal-fueled engine testing for longer period of time. The improvements in the lubrication system were necessary because of the lubricating oil contamination with fine coal powder and ash. This improvement resulted in longer coal-fueled engine test durations.

An improved lubrication system was developed that included centrifugal by-pass filters capable of separating the fine coal particles down to 0.1 micron size. The standard engine lubrication system consisted of an engine driven lubricating oil pump and a paper element type full flow oil filter (rated at 40 microns particle size). Since 50% of the particles in the coal powder were below 7 microns, the paper element filter was not able to separate these fine particles from the contaminated lubricating oil. Also, the full flow paper element oil filter would clog up in short period of engine testing with the coal powder fuel. The lubrication system was improved to overcome these drawbacks and allow longer engine testing periods. As shown in Figure 2-9, this system consists of:

- A metal-wire-mesh full flow oil filter which was not prone to clogging and could be reused for the subsequent engine testing. The old paper element full flow oil filter needed replacement after each test.

- An auxiliary lubricating oil pump driven by an electric motor.

- Two Spinner II model 60 centrifugal by-pass oil filters in parallel to separate the fine coal and ash particles from the contaminated lubricating oil. The filter bowls containing coal filter cake were cleaned after each test.

- Electric oil heaters to heat the lubricating oil to 82 C (180 F) before the engine test. This also increased the filtration performance of the centrifugal oil filters.

This improved lubrication system proved to be very effective in the filtration of contaminated lubricating oil, and allowed the coal powder fueled engine operation for more than one hour duration (depending upon engine load and performance). Also, the engine oil pressure was stable

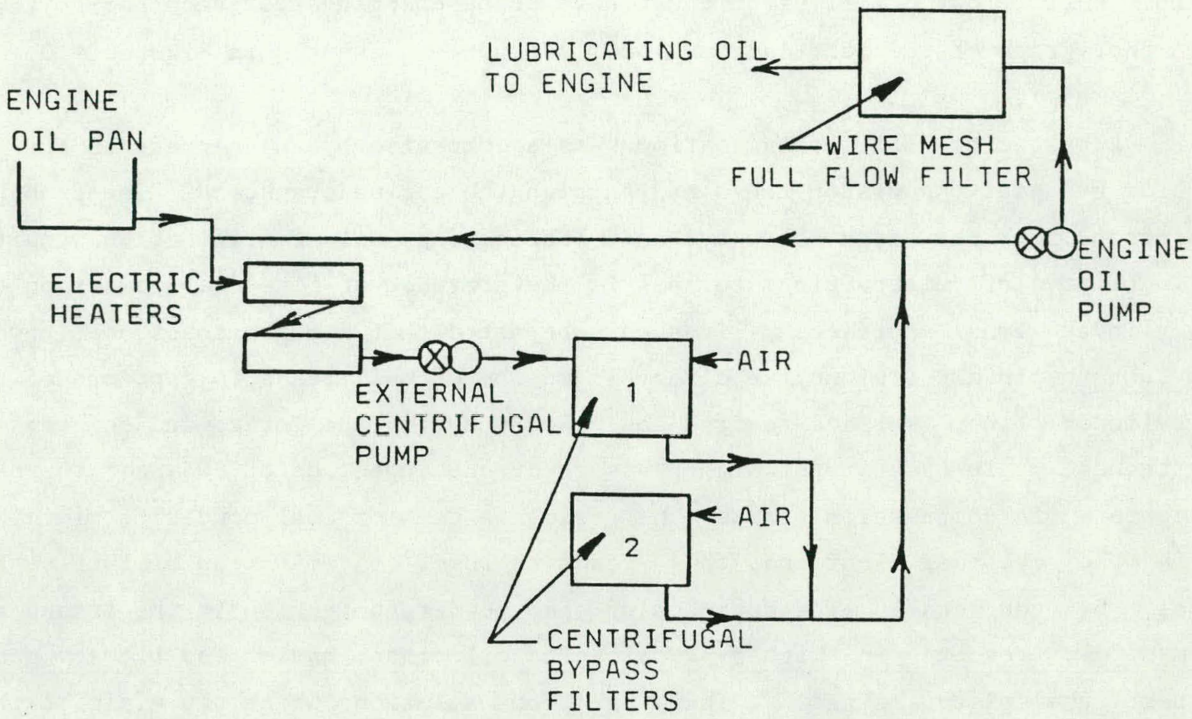


Figure 2-9. Schematic of the Improved Lubrication System for the Coal-Fueled Engine Testing.

during the coal-fueled engine testing. One of the other benefits was that the full flow oil filter did not have to be changed after each engine test. A photograph of the lubrication system set-up is presented in Figure 2-10.

Lubricating oil contamination was accompanied by an increase in the gas blow-by past the piston rings and through the engine crankcase. The probable reason for the high blow-by and lubricating oil contamination were the inability of piston rings to seal in the presence of fine coal powder on the cylinder liner surface. It should be noted that fumigation of coal powder with the intake air, unlike direct injection of CWS, leads to exposure of the cylinder liner surface to fine coal powder during the intake and compression strokes. In case of the high pressure direct injection of CWS near top dead center of compression stroke, the residence time of coal powder is minimized in the cylinder liner and, thus, leads to lower contamination of lubricating oil by the coal. The approach of coal powder fumigation in the intake air manifold results in higher lubricating oil contamination and blow-by gases past the piston rings. There are some solutions which can minimize this problem, such as - design of better sealing piston rings, changes in the coal powder feed system, and modifications in the air motion inside the cylinder to prevent deposition of coal powder on the cylinder liner surface.

### 2.2.5 Instrumentation

The test engine was equipped with instrumentation for collecting the following performance data during the coal-fueled engine testing:

- Engine speed and load
- Flow rates - coal, air
- Pressures - intake, exhaust, blow-by and oil
- Temperatures - intake, exhaust, lubricating oil, wall temperatures of TICS chamber and cylinder head.

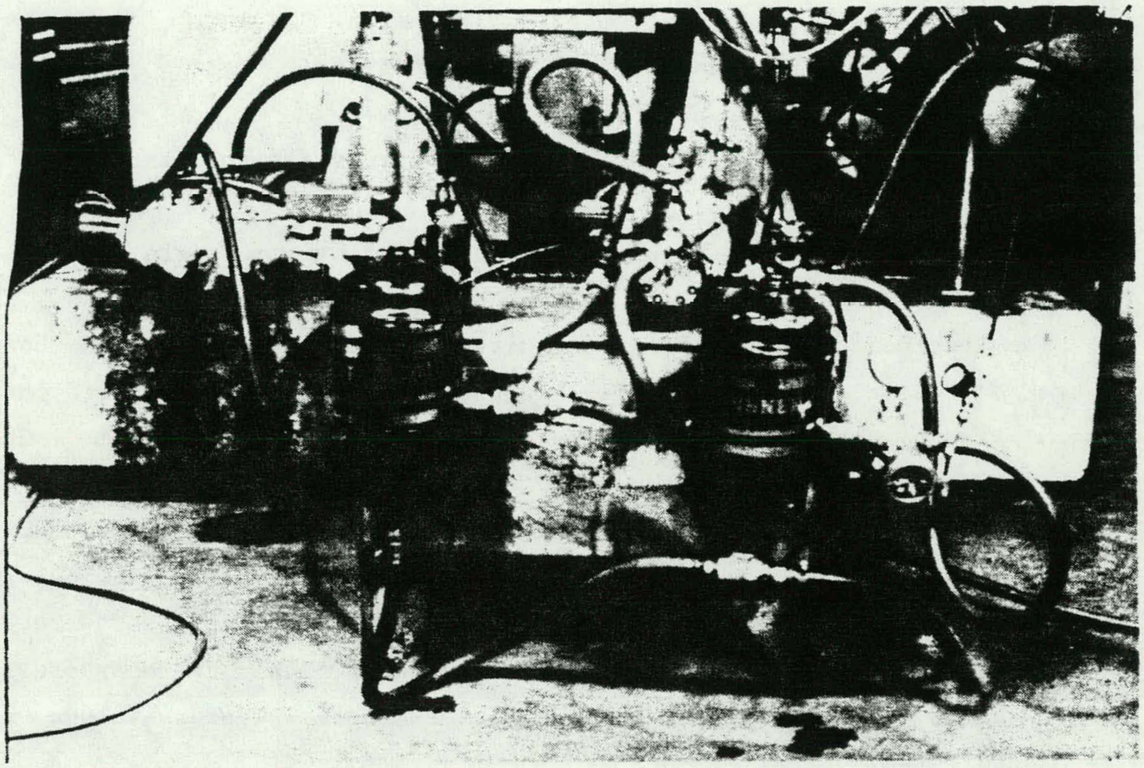

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Figure 2-10. Photograph of Lubrication System for the Coal Powder Fueled Engine Tests.

- Cylinder pressure - AVL 8QP500CA pressure transducer and BEI optical encoder.

- Emissions -

| | |
|---|---|
| CO: | Beckman model 870 NDIR analyzer |
| $CO_2$: | Beckman model 870 NDIR analyzer |
| HC: | Beckman model 400A FID analyzer |
| NOx: | Beckman model 955 Chemiluminescent analyzer |

A photograph of the emissions cart is shown in Figure 2-11.

The engine test data was acquired by two separate data acquisition systems. First, a micro-computer based slow speed system acquired the engine speed, load, flow rates and temperatures at 20 second intervals. Second, a high speed (100 kHz) system was used to acquire and analyze the cylinder pressure data. This data acquisition system consisted of an 80286 processor based microcomputer, Data Translation 2828 board (4 channels simultaneously at 100 kHz total rate), BEI optical encoder and a computer software program. An average of 100 engine cycles was computed to obtain cylinder pressure vs. crank angle, rate of pressure rise vs. crank angle, pressure-volume, and heat release diagrams.

## 2.3 FUELS AND LUBRICANTS

Stauffer SDL-1, a 30 weight polyolester based synthetic lubricant, was used as lubricating oil for the coal-fueled engine testing. Table 2-2 presents properties of the SDL-1 lubricating oil. The outstanding thermal stability and oxidation resistance of SDL-1 lubricant makes it an ideal choice for the high temperature adiabatic engine configuration.

The specifications of the diesel fuel No. 2 (DF-2) are presented in Table 2-3. DF-2 was used for the baseline tests in the Caterpillar 1Y73 test engine.

Three coal powder fuels were tested on the engine. These fuels are

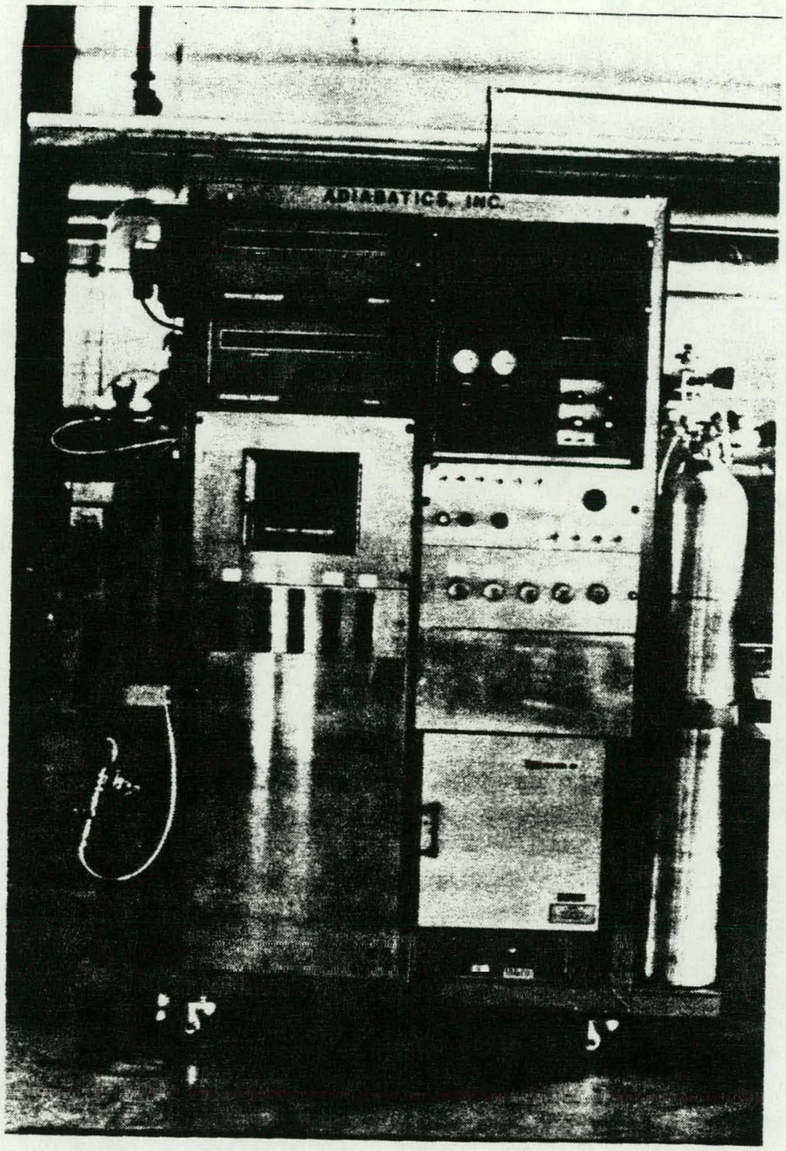


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Figure 2-11. Photograph of Emissions Set-up.

TABLE 2-2

PROPERTIES OF STAUFFER SDL-1 LUBRICATING OIL

| | |
|---|---|
| Viscosities (cs) at 98.9 C (210 F) | 10.1 |
| 37.8 C (100 F) | 69.5 |
| -17.8 C (0 F) | 3100 |
| Cold Cranking Simulator (cp) at -17.8 C | 3000 |
| Viscosity Index | 140 |
| Pour Point, C ( F) | -40 (-40) |
| Total Acid Number | 1.54 mg KOH/g |
| Flash Point, C ( F) | 246 (475) |
| Specific Gravity at 25 C (77 F) | 0.935 |
| Density, $kg/m^3$ (lb/gallon) | 934.5 (7.8) |
| Sulfated Ash | 1.0% |
| Total Base Number | 8.2 mg KOH/g |

## TABLE 2-3

## SPECIFICATIONS OF DIESEL FUEL No. 2 (DF-2)

| | |
|---|---|
| Distillation: | |
| Initial | 177 C (350 F) |
| 10% Recovery | 200 C (392 F) |
| 50% Recovery | 250 C (483 F) |
| 90% Recovery | 302 C (575 F) |
| Maximum | 327 C (620 F) |
| Gravity, API | 40.5 |
| Color, ASTM | Red |
| Viscosity, at 37.8 C, SSU | 34.4 |
| Viscosity, at 37.8 C, Kinematic | 2.5 |
| Flash (Tag Closed Cup) | 62.8 C (145 F) |
| Sulfur, % | 0.17 |
| Pour Point | -23.3 C (-10 F) |
| Cetane Number | 50 |

referred in this report as coal #1, coal #2, and coal #3. The type and specifications of coal fuels are : coal #1 - Micronized Bituminous coal from the Kentucky Blue Gem Seam, 0.9% ash content, 7 microns mean size and 20 microns top size; coal #2 - Non-beneficiated Bituminous coal from the Kentucky Blue Gem Seam, 1.6% ash content, 21.3 microns mean size and 75 microns top size; coal #3 - North Dakota Lignite coal, 7.1% ash content, 29.2 microns mean size and 200 microns top size. The coal analysis results are presented in Table 2-4. The coal #1 and #2 were from the same mine and procured from Otisca Industries, Inc. However, coal #2 was not beneficiated and ground by the dry grinding process to coarse particle size. North Dakota Lignite coal #3 was procured from Energy and Minerals Research Center, University Station, North Dakota. The coal #3 had the highest ash content since it was a non-beneficiated low rank coal.

## 2.4 COAL POWDER FEED SYSTEM

An improved coal powder feed system to fumigate coal fuel in the intake air was successfully designed and tested on the engine. This system overcame the difficulties encountered with the coal feed system used in the earlier research program.

The performance and reliability of the coal feed system was very important for the coal-fueled engine tests. The coal feed system, used in the previous program, provided a non-uniform coal feed rate which caused fluctuations in the engine speed/load. The improved coal feed system resulted in uniform coal feed rate to the engine with a minimal number of parts. Several different concepts were investigated in coming up with this system. In selecting the optimal coal feed system design, the important parameters considered were:

- Reliability of feed system.
- Uniformity of coal feed rate from cycle to cycle.
- Metering of coal fuel to the engine.

TABLE 2-4

ANALYSIS OF COAL POWDER FUELS

| | COAL # 1* | COAL #2** | COAL #3*** |
|---|---|---|---|
| TYPE | BITUMINOUS (BLUE GEM SEAM) | BITUMINOUS (BLUE GEM SEAM) | NORTH DAKOTA LIGNITE |
| BENEFICIATED | YES | NO | NO |
| MOISTURE, % | 5.1 | 3.5 | 5.1 |
| VOLATILE, % | 38.1 | 37.3 | 44.0 |
| ASH, % | 0.9 | 1.6 | 7.1 |
| FIXED CARBON, % | 55.9 | 57.7 | 43.9 |
| CALORIFIC VALUE, MJ/kg (Btu/lb) | 31.72 (13,637) | 32.95 (14,169) | 25.35 (10,897) |
| PARTICLE SIZE IN MICRONS | | | |
| MEAN SIZE | 7.0 | 21.3 | 29.2 |
| 10 % UNDERSIZE | 1.8 | 4.6 | 8.4 |
| 50 % UNDERSIZE | 5.5 | 17.4 | 21.8 |
| 90 % UNDERSIZE | 15.7 | 43.8 | 63.9 |
| TOP SIZE | 20.0 | 75.0 | 200.0 |

---

* PROCURED FROM OTISCA INDUSTRIES.

** COARSE UNCLEANED COAL PROCURED FROM OTISCA INDUSTRIES AND THEN GROUND BY THE DRY GRINDING PROCESS.

*** PROCURED FROM ENERGY & MINERAL RESEARCH CENTER, UNIVERSITY STATION, NORTH DAKOTA. THIS COAL WAS DRYED AND HAD FINAL MOISTURE CONTENT OF 5.1%.

- Control of the coal feed rate.

- Minimization of the explosion hazard of fine coal powder.

A coal feed system based on an ejector was designed and fabricated. Figure 2-12 shows a schematic of this system consisting of an Acrisson model 105 volumetric screw feeder, weighing scale, and an ejector. The selected ejector is unconventional in that the compressed air is admitted in an annular gap and that the direction of coal flow is uni-directional (conventional ejectors would have turned the coal flow path 90 degrees). A fine dispersion of coal powder in air was created downstream of the ejector which was conveyed to the engine intake manifold.

The coal feed rate was varied by changing the speed of the screw feeder. The coal feed rate to the engine was measured by monitoring the weight of the screw feeder and coal powder hopper as a function of time. The coal feed system described herein has proved to be reliable with no maintenance or clogging problems. Figures 2-13 and 2-14 show the photographs of the coal powder feed system.

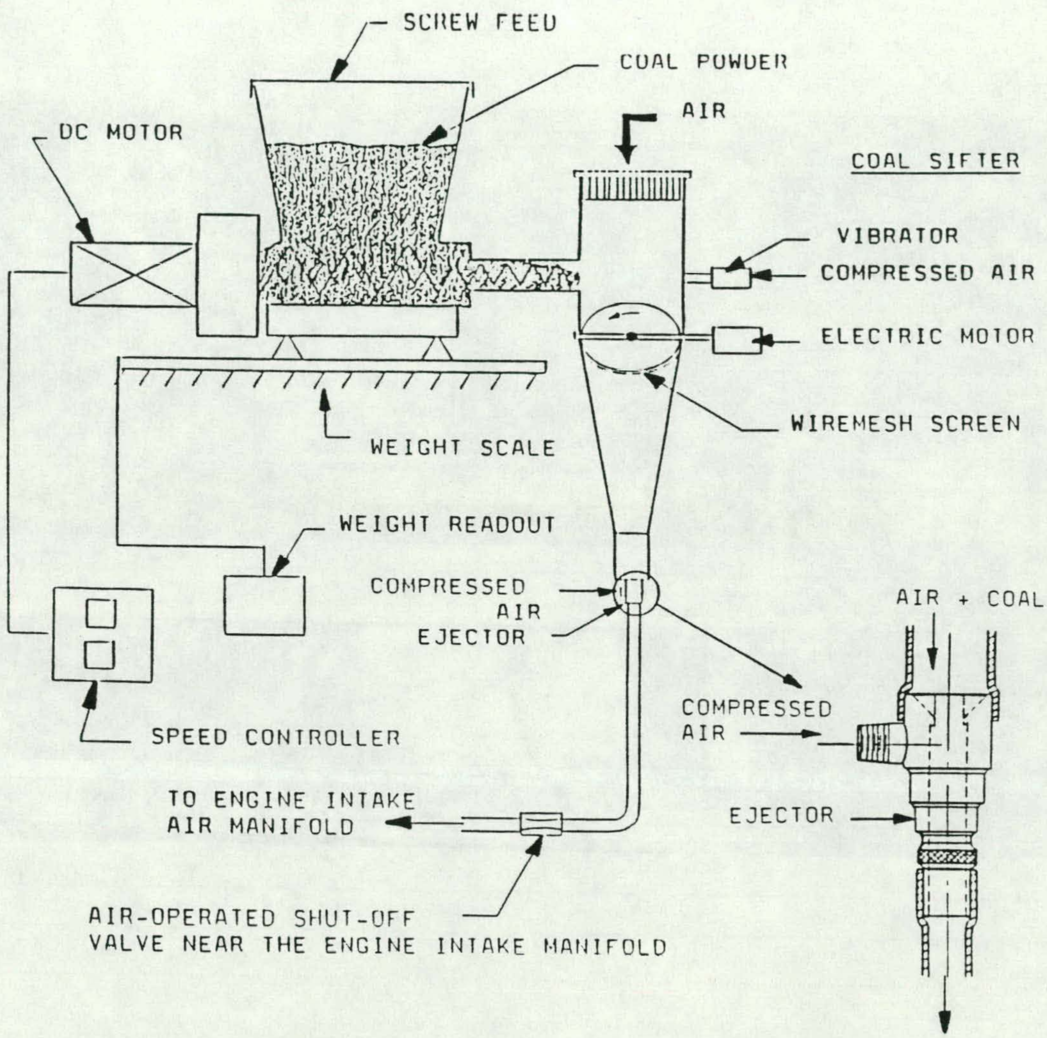


Figure 2-12. Schematic of the Coal Powder Feed System.

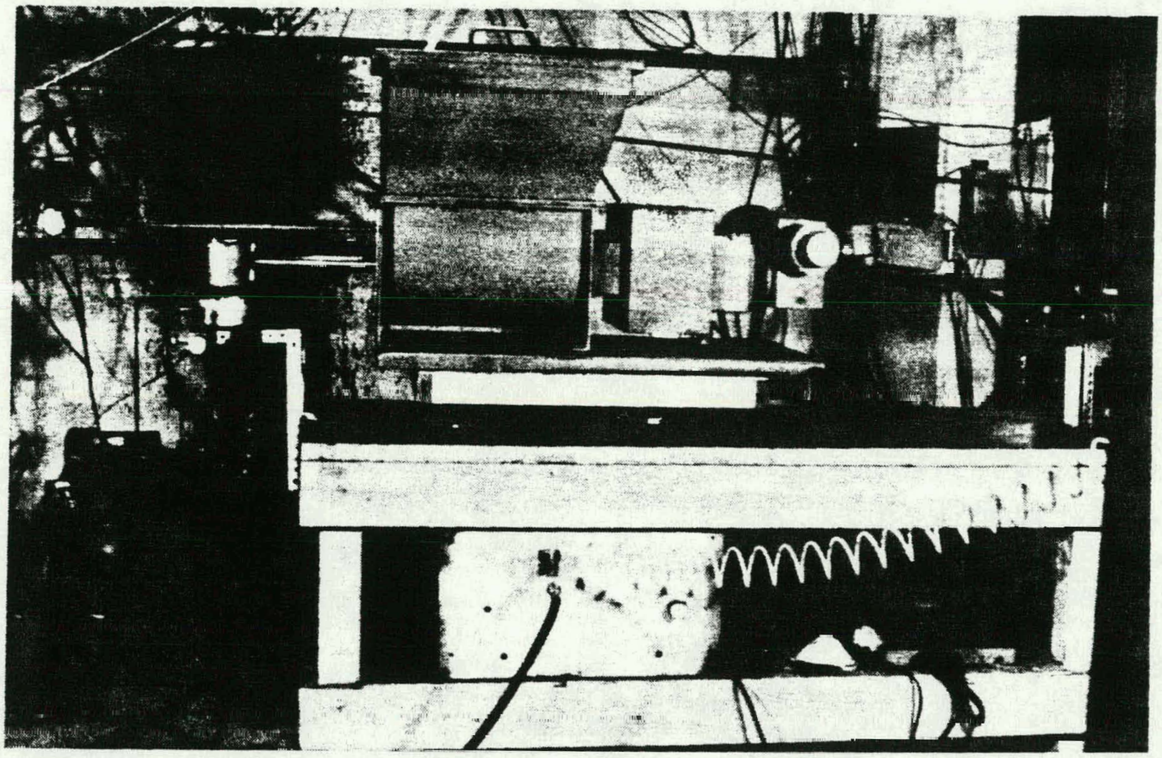

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Figure 2-13. Photograph of Coal Powder Feed System.

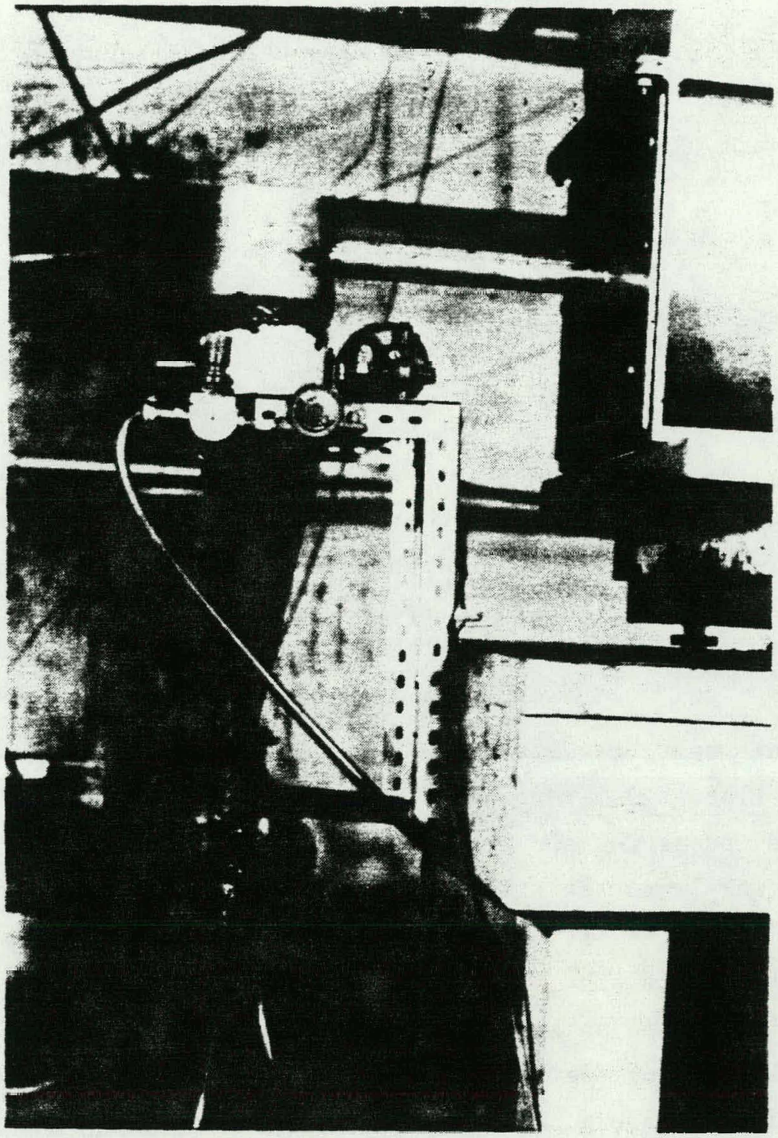

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Figure 2-14. Photograph of Coal Powder Feed System.

# 3.0 RESULTS AND DISCUSSION

This Section presents the program results and discussion for the baseline engine tests with DF-2 and the coal-fueled engine tests. This work was conducted during Task 6 - Engine Combustion Tests, and Task 7 - Data Analysis.

## 3.1 BASELINE ENGINE TESTS WITH DF-2

The baseline engine tests were conducted with diesel fuel No. 2 (DF-2) in the Hastelloy X TICS chamber at controlled outside wall temperature of 649 C. For these tests, the standard Caterpillar fuel injection system and nozzle were used without exhaust gas recirculation. However, the nozzle was cooled on the outside with air to prevent its failure in the high temperature chamber.

The engine test results at 1000, 1200, 1400 rpm engine speeds are presented in Tables 3.1-1 to 3.1-3 and Figure 3.1-1. These results show low peak cylinder pressure and rate of pressure rise with DF-2. The DF-2 injection timing was set at 8 degrees before top dead center and no attempt was made to optimize it, since our emphasis was on the coal-fueled engine tests. These results show a decrease in peak cylinder pressure and peak rate of pressure rise with an increase in the engine speed from 1000 to 1400 rpm. The coal-fueled engine test results, presented next in Section 3.2, show much higher cylinder pressure and rate of pressure rise, even at 1400 rpm engine speed. It should be noted that cylinder pressure and rate of pressure rise values mentioned in this report refer to the main chamber. No cylinder pressure data could be taken in the TICS chamber.

## 3.2 COAL-FUELED ENGINE TESTS

### 3.2.1 Technical Problems and Progress

TABLE 3.1-1

BASELINE ENGINE TEST RESULTS WITH DF-2 AT 1000 RPM

| | | | | |
|---|---|---|---|---|
| ENGINE SPEED, rpm | 1000 | 1000 | 1000 | 1000 |
| TEST NUMBER | 0902ADF | 0902BDF | 0902CDF | 0902DDF |
| TORQUE, N.m | 30.4 | 56.3 | 73.2 | 81.4 |
| BRAKE POWER, kW | 3.2 | 5.9 | 7.7 | 8.5 |
| INDICATED POWER, kW | 6.3 | 9.0 | 10.4 | 11.3 |
| IMEP, kPa | 345 | 489 | 569 | 618 |
| PEAK CYLINDER PRESSURE, MPa | 4.27 | 4.29 | 4.38 | 4.44 |
| (at deg. ATDC) | (13) | (12) | (12) | (11) |
| PEAK RATE OF PRESSURE RISE, MPa/deg | 0.091 | 0.064 | 0.069 | 0.074 |
| (at deg. ATDC) | (10) | (9) | (9) | (9) |
| EMISSIONS | | | | |
| CO, g/bhp-hr | 2.7 | 1.3 | 1.1 | 1.1 |
| (lb/MMBtu) | (0.59) | (0.35) | (0.28) | (0.30) |
| $CO_2$, % | 3.1 | 5.0 | 6.3 | 7.3 |
| HC, g/bhp-hr | 0.4 | 0.2 | 0.2 | 0.2 |
| (lb/MMBtu) | (0.08) | (0.05) | (0.04) | (0.04) |
| NOx, g/bhp-hr | 5.1 | 4.3 | 3.7 | 3.2 |
| (lb/MMBtu) | (1.11) | (1.15) | (0.96) | (0.83) |

TABLE 3.1-2

BASELINE ENGINE TEST RESULTS WITH DF-2 AT 1200 RPM

| | | | | |
|---|---|---|---|---|
| ENGINE SPEED, rpm | 1200 | 1200 | 1200 | 1200 |
| TEST NUMBER | 0902UDF | 0902VDF | 0902KDF | 0902IDF |
| TORQUE, N.m | 28.1 | 57.0 | 68.9 | 84.1 |
| BRAKE POWER, kW | 3.5 | 7.2 | 8.7 | 10.6 |
| INDICATED POWER, kW | 7.1 | 10.9 | 12.6 | 14.2 |
| IMEP, kPa | 325 | 494 | 574 | 646 |
| PEAK CYLINDER PRESSURE, MPa | 4.00 | 4.20 | 4.30 | 4.40 |
| (at deg. ATDC) | (15) | (15) | (14) | (13) |
| PEAK RATE OF PRESSURE RISE, MPa/deg | 0.046 | 0.045 | 0.044 | 0.033 |
| (at deg. ATDC) | (13) | (12) | (11) | (11) |
| <u>EMISSIONS</u> | | | | |
| CO, g/bhp-hr | 4.4 | 1.6 | 1.5 | 1.6 |
| (lb/MMBtu) | (0.78) | (0.38) | (0.37) | (0.42) |
| $CO_2$, % | 3.0 | 5.1 | 6.4 | 7.7 |
| HC, g/bhp-hr | 0.4 | 0.2 | 0.2 | 0.2 |
| (lb/MMBtu) | (0.08) | (0.05) | (0.05) | (0.05) |
| NOx, g/bhp-hr | 5.6 | 5.0 | 4.2 | 3.0 |
| (lb/MMBtu) | (1.00) | (1.19) | (1.08) | (0.79) |

TABLE 3.1-3

BASELINE ENGINE TEST RESULTS WITH DF-2 AT 1400 RPM

| | | | |
|---|---|---|---|
| ENGINE SPEED, rpm | 1400 | 1400 | 1400 |
| TEST NUMBER | 0902MDF | 0902NDF | 0902LDF |
| TORQUE, N.m | 28.6 | 57.0 | 68.3 |
| BRAKE POWER, kW | 4.2 | 8.3 | 10.0 |
| INDICATED POWER, kW | 9.1 | 13.2 | 14.9 |
| IMEP, kPa | 354 | 515 | 581 |
| PEAK CYLINDER PRESSURE, MPa | 3.90 | 4.10 | 4.20 |
| (at deg. ATDC) | (16) | (16) | (14) |
| PEAK RATE OF PRESSURE RISE, MPa/deg | 0.031 | 0.030 | 0.019 |
| (at deg. ATDC) | (14) | (14) | (12) |
| EMISSIONS | | | |
| CO, g/bhp-hr | 3.5 | 2.0 | 1.6 |
| (lb/MMBtu) | (0.61) | (0.48) | (0.39) |
| $CO_2$, % | 3.6 | 5.6 | 6.7 |
| HC, g/bhp-hr | 0.4 | 0.3 | 0.2 |
| (lb/MMBtu) | (0.08) | (0.06) | (0.05) |
| NOx, g/bhp-hr | 5.2 | 4.7 | 4.3 |
| (lb/MMBtu) | (0.91) | (1.13) | (1.04) |

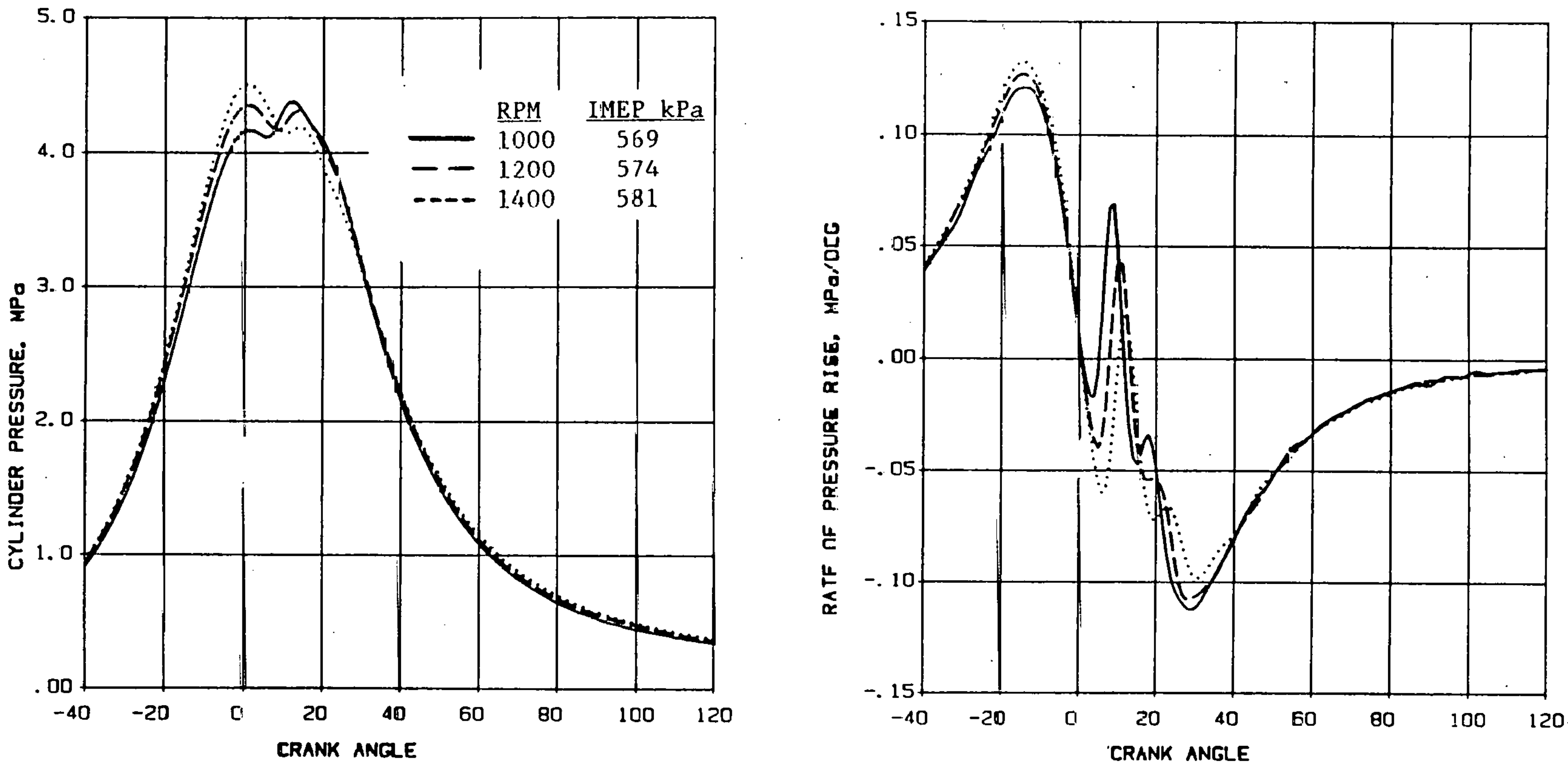


Figure 3.1-1. Cylinder Pressure and Rate of Pressure Rise Diagrams for the Baseline Engine Tests with DF-2 at 1000, 1200 and 1400 rpm Engine Speeds.

At the beginning of this research program, there were many initial problems encountered with the coal powder fueled engine. These major problems and the actions taken are summarized as follows:

- Difficulty in controlling ignition timing of the fumigated coal powder in the test engine with the TICS concept. Due to absence of any ignition timing mechanism like a spark plug or diesel pilot injection, the ignition of coal powder was erratic and dependant on several variables (such as engine load and speed, TICS chamber temperature, and air to fuel ratio). The monitoring of cylinder pressure data and other key engine variables during the engine testing showed inconsistent engine operation on the coal powder fuel. The cylinder pressure data showed preignition of coal fuel in the cylinder before top dead center and led to very high cylinder pressure and high rate of pressure rise. Because of the preignition of coal powder, the engine performance deteriorated due to the negative work done on the piston during the compression stroke of the cycle. In a diesel engine cycle, the control of fuel ignition and heat release rates is achieved by the diesel fuel injection timing and rate. On the other hand, the spark plug timing controls the ignition and combustion of premixed air-fuel mixture in a spark ignition engine. It is essential to obtain ignition and heat release of coal powder fuel at the correct crank angle timing in the engine cylinder to obtain optimum performance from the coal fueled engine. Control of timing means that the exhaust gas emissions can be minimized with an improvement in the engine performance and efficiency.

- Non-uniform coal feed rate to the engine caused fluctuations in the engine speed/load. Also, the earlier coal feed system was not reliable and was prone to mechanical clogging and failure. As discussed earlier in Section 2.4, an improved coal powder feed system was successfully designed and fabricated during Task 3 of this program. This feed system, based on an ejector, was used to fumigate coal powder fuel to the intake air manifold during the entire coal-fueled engine tests conducted in this program.

- Difficulty was encountered with the conventional precombustion chamber.

It was not able to operate at high temperatures required for the TICS concept. A new TICS chamber was designed and fabricated from Hastelloy X, a superalloy material capable of continuously withstanding 1000 C temperature under extreme conditions. The details of this TICS chamber were presented in Section 2.2.2. This Hastelloy X TICS chamber was used during most of the coal-fueled engine tests.

- High wear rates of standard chrome plated piston rings were encountered. A new top ring was fabricated during this program which incorporated the step gap sealing to reduce blow-by and plasma spray chrome oxide ceramic coating for wear resistance.

- High blow-by and lubricating oil contamination were experienced with the coal powder fuel. The wear resistant surfaces on the cylinder liner and piston ring, and step gap sealing of top piston ring were expected to reduce the blow-by and lead to lower lubricating oil contamination. The lubricating oil contamination was still a problem at the end of this program.

Many techniques were tried to find a means to control the coal powder fuel ignition timing and optimize the coal-fueled engine performance. During the initial phase of the coal-fueled engine testing in this program, valuable experience was learned from observations and results of the testing. The cylinder pressure data was a valuable real-time online tool in analyzing the combustion characteristics of coal powder. Preignition of coal fuel was clearly evident from the cylinder pressure versus crank angle signals observed on the oscilloscope. A later analysis of the 100 cycle averaged cylinder pressure data was conducted to yield peak cylinder pressure, rate of pressure rise, pressure-volume diagram, IMEP and indicated power output of the cycle. Also, the peak cylinder pressure (and its crank angle location) of the individual cycles were plotted to observe the consistency of the coal fueled engine operation. The initial attempts to control the combustion of fumigated coal powder included lowering of compression ratio from 16.5 to 14.5, water-cooling the TICS chamber and using diesel pilot for ignition, and using the standard Caterpillar TICS chamber. However, these parameters showed inadequate control of the coal-fueled engine and lower brake thermal efficiency due to decrease in the compression ratio and TICS chamber temperature.

Further improvements in the combustion characteristics of the coal powder fueled engine were carried by two techniques- 1) controlled TICS chamber temperature, and 2) exhaust gas recirculation (EGR). These two methods were discovered in this program after extensive observation of the coal powder combustion in the test engine. The engine test results have shown that both parameters, TICS temperature and EGR, have an effect on the coal combustion in the engine.

### 3.2.2 Coal-Fueled Engine Results and Discussion

The coal-fueled engine test data was tabulated and reduced for analysis. The exhaust emissions of CO, unburned HC, and NOx were converted from ppm (parts per million) to g/bhp-hr (grams per brake horse power per hour) and lb/MMBtu (pounds per million Btu). As mentioned earlier, the cylinder pressure and rate of pressure rise values refer to the main combustion chamber. The cylinder pressure data could not be taken in the TICS chamber.

Because of the loss of unburned coal powder fuel to the lubricating oil in the test engine crankcase, there were difficulties in measuring the brake specific fuel consumption. From the coal-fueled engine test results, upto 20 to 40% of coal fumigated to the intake air was lost to the lubricating oil, depending upon many factors like engine operation on coal powder fuel, engine speed and load, TICS chamber temperature etc. The fumigation of coal powder to the intake air manifold resulted in longer residence time in the engine cylinder - including the intake and compression strokes also. Since the objective of this program was to investigate the combustion characteristics of coal powder-fueled engine, the problem of lubricating oil contamination with unburned coal fuel could not be pursued in this program. However, attempts were made to minimize this problem by the use of wear-resistant piston rings and liner, and an improved lubrication system for separating the fine coal powder (described in Section 2.2.4). It is anticipated that this problem can be overcome with a better understanding of coal powder and air motion in the cylinder, novel piston ring designs, a low pressure coal powder feed system which introduces coal fuel in the cylinder during the compression stroke, or by using other types of engines (for example, a two stroke engine).

The results of the coal-powder-fueled engine performance and durability with three types of coal fuels is presented next.

### 3.2.2.1 Engine Tests with Coal #1 - 7 micron mean size Bituminous coal

Effect of TICS Chamber Temperature The engine test results showed that the TICS chamber of the Caterpillar 1Y73 test engine played a key role in the ignition and combustion of the coal powder fuel. Ignition of the fumigated coal powder in the engine was achieved by the high temperature surface of the TICS chamber. The test engine was operated on 100% coal fuel (without any diesel pilot or other ignition aids) only when the TICS chamber was maintained at high temperatures. At low TICS chamber temperatures and with the water-cooled chamber, a diesel pilot was required to sustain coal powder combustion and engine operation. Thus, the TICS concept was proven to provide reliable and efficient engine operation with 100% coal powder fuel without any external ignition assist sources.

Since a diesel pilot was required at low TICS chamber temperature, and since a too hot TICS chamber caused preignition, controlled cooling of the TICS chamber was used to control ignition timing of the coal powder. Also, at higher engine loads, the engine components - TICS chamber, cylinder head and liner - became hot and controlled cooling lowered the engine component temperatures. Figure 3.2-1 presents a photograph of the test engine cylinder head without the TICS chamber cooling showing a red hot TICS chamber, as seen through two thermocouple holes in the cylinder head. In this test the temperature exceeded 870 C on the outside wall of the Hastelloy X TICS chamber. It should be noted that TICS wall temperature mentioned in this report referred to the temperature measured on the outside surface of the chamber. The inside surface of the TICS chamber, in contact with the

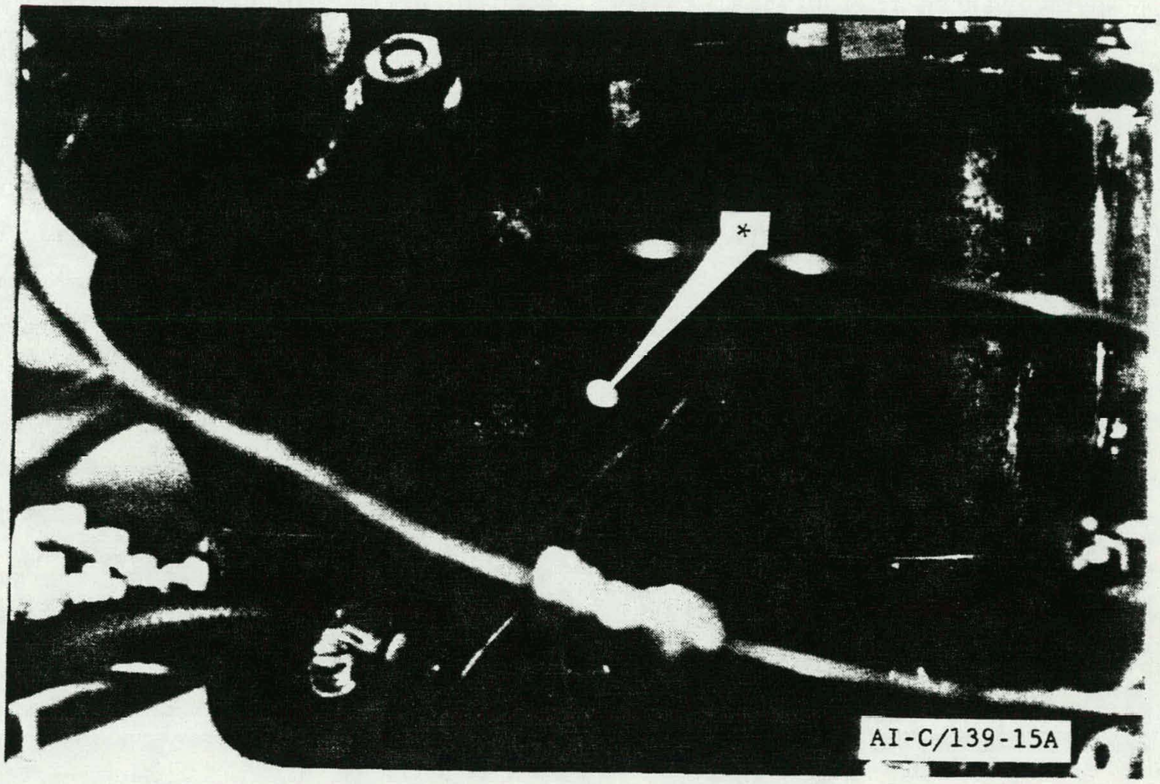


Figure 3.2-1. Photograph of Test Engine Cylinder Head during Coal-Powder-Fueled Engine Testing.
(* Note Red hot TICS Chamber through two holes in the Cylinder Head.)

combustion gases, was at higher temperatures than the measured outside wall temperature.

The higher TICS chamber temperatures resulted in improved engine performance in 100% coal-fueled and dual-fuel engine configurations. For the 100% coal-fueled engine test with the standard Caterpillar TICS chamber, Table 3.2-1 and Figure 3.2-2 show the effect of chamber wall temperature on the engine performance, and cylinder pressure and rate of pressure rise diagrams. For the same coal feed rates, an increase in TICS temperature from 338 to 399 C resulted in an increase in brake power, IMEP, peak cylinder pressure and rate of pressure rise. As seen from these data, an increase in the chamber temperature enhances the coal fuel combustion and leads to an improvement in the engine performance. For the dual-fuel engine (coal powder and DF-2), a similar behavior can be seen in Table 3.2-2. In this case, the TICS chamber temperature was increased from 132 to 260 C by removing water-cooling of the TICS chamber. An increase in the brake power, IMEP, peak cylinder pressure and rate of pressure rise is observed here at the elevated chamber temperature. The cylinder pressure and rate of pressure rise diagrams show a reduction in ignition delay with increasing the TICS chamber temperature.

Additional coal-fueled engine test data with Hastelloy X TICS chamber showed that higher chamber temperatures further improve the combustion of coal powder fuel. However, an optimum chamber temperature was required to prevent preignition of coal powder during the compression stroke. The effect of TICS chamber temperature on the 100% coal-fueled engine test with Hastelloy X chamber is presented in Table 3.2-3 and Figure 3.2-3. EGR was not used during this test to observe only the effect of chamber temperature on the coal combustion. An increase in the chamber temperature was seen to increase the peak cylinder pressure and rate of pressure rise. Also, this led to preignition of the coal fuel in the cylinder. Because of the negative work conducted during the compression stroke of the cycle, the engine performance deteriorated, as observed from a decrease in the indicated power. In order to control the ignition timing of coal fuel at elevated TICS chamber temperature, EGR was used to optimize the engine operation. Due to simultaneous effects of TICS chamber temperature and EGR, a combination of

TABLE 3.2-1

EFFECT OF TICS CHAMBER TEMPERATURE ON
100% COAL-FUELED ENGINE PERFORMANCE (COAL #1)
(STANDARD CATERPILLAR CHAMBER)

| | | | |
|---|---|---|---|
| TICS Chamber Temp., C (F) | 338 (640) | 360 (680) | 399 (750) |
| Test Number | 0426GCL | 0426HCL | 0426ICL |
| Engine Speed, rpm | 1000 | 1000 | 1000 |
| Brake Power, kW | 4.9 | 5.8 | 6.5 |
| Indicated power, kW | 9.8 | 10.0 | 10.3 |
| IMEP, kPa | 537 | 544 | 561 |
| Peak Cylinder Pressure, MPa (at deg. ATDC) | 5.72 (10) | 5.88 (10) | 6.29 (9) |
| Peak Rate of Pressure Rise, MPa/deg (at deg. ATDC) | 0.346 (4) | 0.359 (4) | 0.402 (3) |

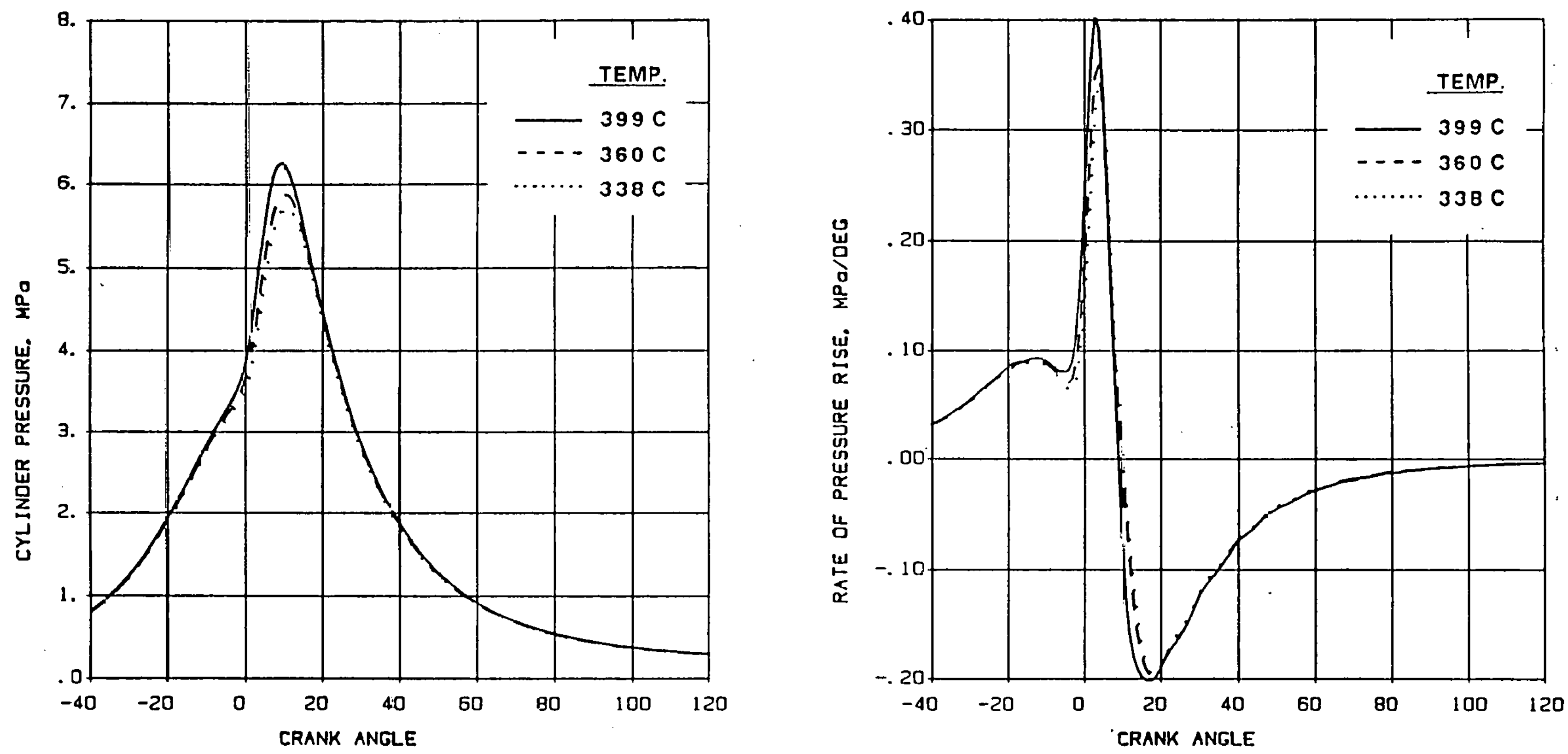


Figure 3.2-2 Effect of Standard TICS Chamber Temperature on Cylinder Pressure and Rate of Pressure Rise Diagrams for the 100% Coal-Fueled Engine Tests (Coal #1, 1000 rpm, no EGR).

TABLE 3.2-2

EFFECT OF TICS CHAMBER TEMPERATURE ON DUAL-FUELED ENGINE PERFORMANCE (COAL #1) (STANDARD CATERPILLAR CHAMBER)

| | | |
|---|---|---|
| TICS CHAMBER TEMP., C (F) | 132 (270) | 260 (500) |
| TEST NUMBER | 0426BDC | 0426CDC |
| ENGINE SPEED, RPM | 1000 | 1000 |
| BRAKE POWER, kW | 3.6 | 5.3 |
| INDICATED POWER, kW | 7.6 | 9.8 |
| IMEP, kPa | 417 | 535 |
| PEAK CYLINDER PRESSURE, MPa (at deg. ATDC) | 3.28 (19) | 4.14 (16) |
| PEAK RATE OF PRESSURE RISE, MPa/deg. (at deg. ATDC) | 0.113 (15) | 0.185 (10) |

TABLE 3.2-3

EFFECT OF HASTELLOY X TICS CHAMBER TEMPERATURE AND EGR ON THE 100% COAL-FUELED ENGINE PERFORMANCE (COAL #1)

| | | | | | |
|---|---|---|---|---|---|
| TICS C<br>CHAMBER TEMP (F) | 299<br>(570) | 538<br>(1000) | 649<br>(1200) | 348<br>(659) | 649<br>(1200) |
| % EGR | 0 | 0 | 0 | 4.8 | 31.3 |
| TEST NUMBER | 0722ICL | 0722JCL | 0722KCL | 0722HCL | 0722MCL |
| ENGINE SPEED, rpm | 1000 | 1000 | 1000 | 1000 | 1000 |
| INDICATED POWER, kW | 9.6 | 9.0 | 8.4 | 9.1 | 8.8 |
| IMEP, kPa | 527 | 492 | 459 | 495 | 478 |
| PEAK CYLINDER PRESSURE, MPa<br>(at deg. ATDC) | 7.33<br>(6) | 7.50<br>(5) | 7.67<br>(2) | 6.40<br>(8) | 6.64<br>(7) |
| PEAK RATE OF PRESSURE RISE, MPa/deg<br>(at deg. ATDC) | 0.50<br>(0) | 0.56<br>(0) | 0.66<br>(-3) | 0.34<br>(3) | 0.37<br>(3) |

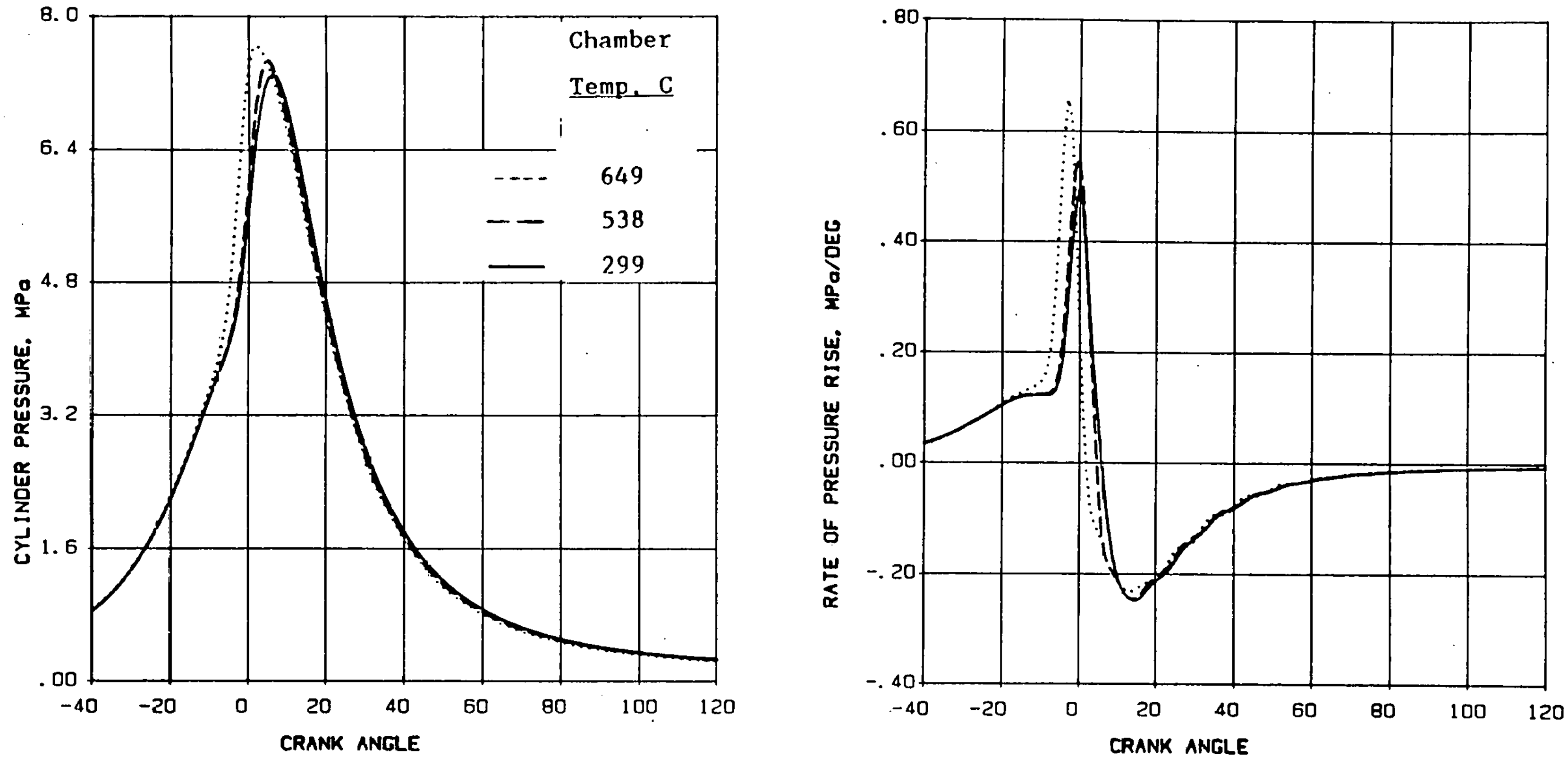


Figure 3.2-3. Effect of Hastelloy X TICS Chamber Temperature on Cylinder Pressure and Rate of Pressure Rise Diagrams for the 100% Coal-Fueled Engine Tests (Coal #1, 1000 rpm, No EGR).

these parameters was found necessary to optimize the coal powder combustion in the engine. A photograph of the Hastelloy X TICS chamber after the coal-fueled engine testing is shown in Figure 3.2-4.

Effect of Exhaust Gas Recirculation (EGR) EGR was successfully used to control ignition timing of fumigated coal powder fuel in dual-fuel and 100% coal-fueled engine configurations. The preignition of coal powder fuel was controlled by the application of EGR during the coal-fueled engine testing. EGR increased the ignition delay and lowered the peak cylinder pressure, rate of pressure rise and NOx emissions. This effect can be seen in Table 3.2-4 and Figure 3.2-5 for the 100% coal-fueled engine tests. The engine performance was considerably improved by EGR as seen by an increase in brake power output and IMEP. It should be noted that these tests were recorded during the same engine test and similar coal powder feed rates to the engine. The engine operation without EGR resulted in preignition of coal fuel before top dead center (BTDC) which increased peak cylinder pressure and rate of pressure rise. In this case, the peak cylinder pressure and peak rate of pressure rise occur at TDC and 13 degree BTDC, respectively, and thus, lead to lower engine power and much higher NOx emissions. By using 17.6% EGR, the preignition of coal fuel was reduced. A further increase in EGR to 26% delayed the coal combustion and reduced the peak cylinder pressure and rate of pressure rise which resulted in lower power output and IMEP.

An optimum amount of EGR and TICS chamber temperature was required to control the ignition timing and optimize the coal-fueled engine operation. With an increase in the TICS chamber temperature, a higher amount of EGR was required to control the ignition timing of coal powder. These results are presented in Table 3.2-3 and Figure 3.2-6. For this engine test 4.8% EGR was used at 348 C chamber temperature while 31.3% EGR was required at 649 C. For a commercial multi-cylinder coal-fueled engine, the EGR control valve can be microprocessor controlled with input from various sensors on the engine. This type of engine control can easily be accomplished as evident from the presently used microprocessor computer control for the passenger car gasoline engines.

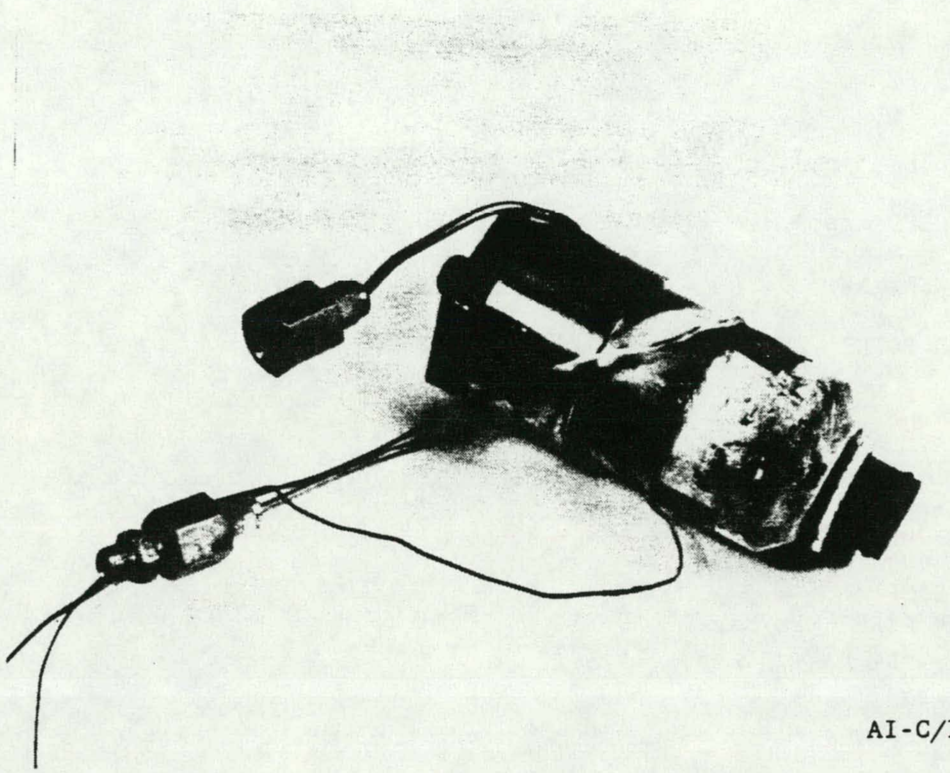

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Figure 3.2-4. Photograph of TICS Chamber after Coal-Powder-Fueled Engine Testing.

TABLE 3.2-4

EFFECT OF EGR ON 100% COAL-FUELED ENGINE PERFORMANCE (COAL #1)

| % EGR | 0 | 17.6 | 26.0 |
|---|---|---|---|
| TEST NUMBER | 0819PCL | 0819UCL | 0819KCL |
| ENGINE SPEED, rpm | 1000 | 1000 | 1000 |
| BRAKE POWER, kW | 6.3 | 8.0 | 7.5 |
| INDICATED POWER, kW | 12.0 | 12.3 | 11.7 |
| IMEP, kPa | 655 | 669 | 640 |
| PEAK CYLINDER PRESSURE, MPa | 9.64 | 8.29 | 7.12 |
| (at deg.ATDC) | (0) | (4) | (8) |
| PEAK RATE OF PRESSURE RISE, MPa/deg | 0.75 | 0.67 | 0.48 |
| (at deg. ATDC) | (-13) | (-1) | (4) |
| EMISSIONS | | | |
| CO, g/bhp-hr | 17.7 | 13.4 | NR |
| (lb/MMBtu) | (1.90) | (1.83) | |
| $CO_2$, % | 14.3 | 15.7 | 17.0 |
| HC, g/bhp-hr | 0.9 | 0.9 | 2.0 |
| (lb/MMBtu) | (0.10) | (0.12) | (0.26) |
| NOx, g/bhp-hr | 62.7 | 16.0 | 5.0 |
| (lb/MMBtu) | (6.75) | (2.20) | (0.65) |

NR Not recorded

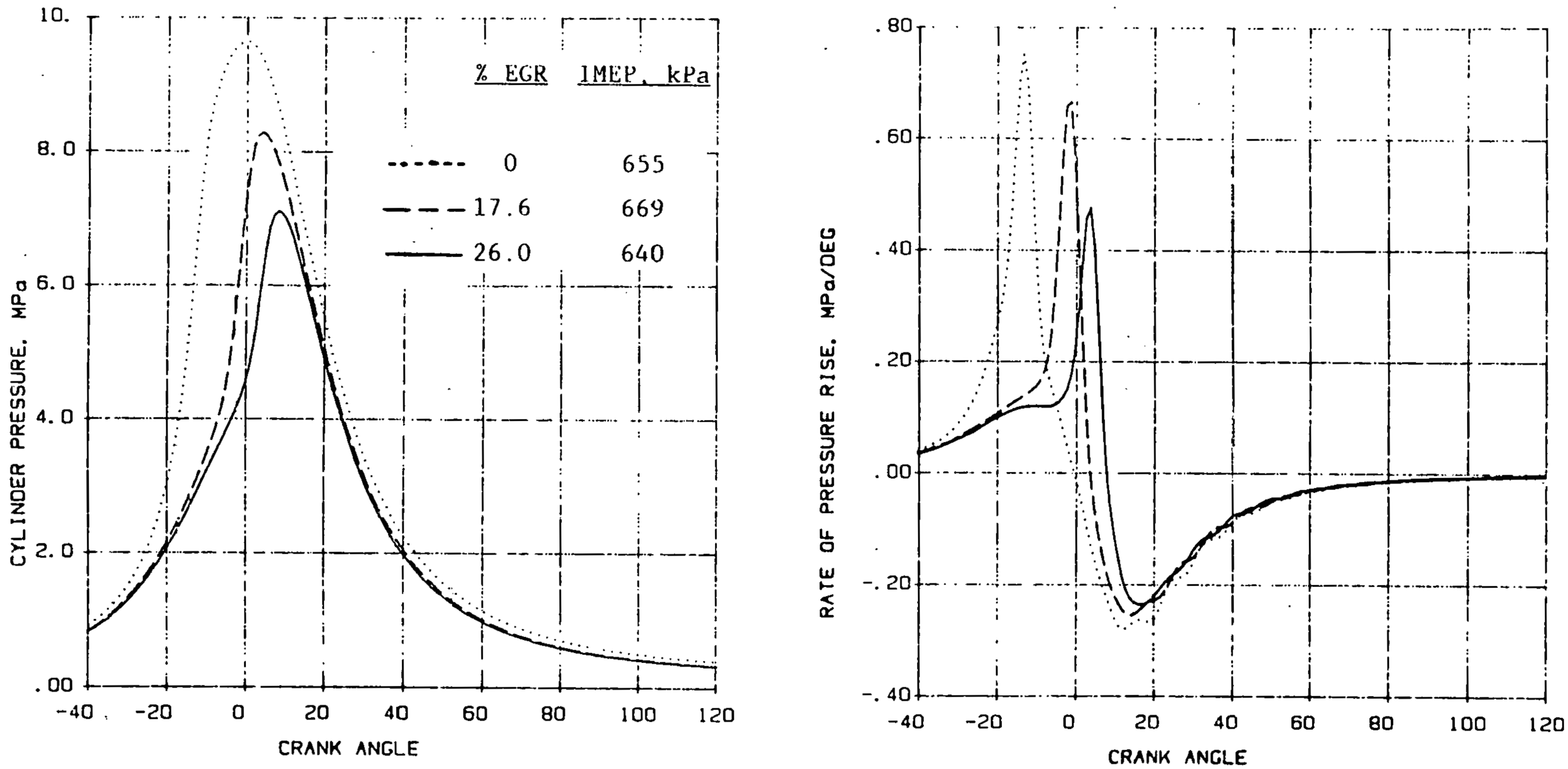



Figure 3.2-5. Effect of EGR on Cylinder Pressure and Rate of Pressure Rise Diagrams for the 100% Coal-Fueled Engine Tests (Coal #1, 1000 rpm).

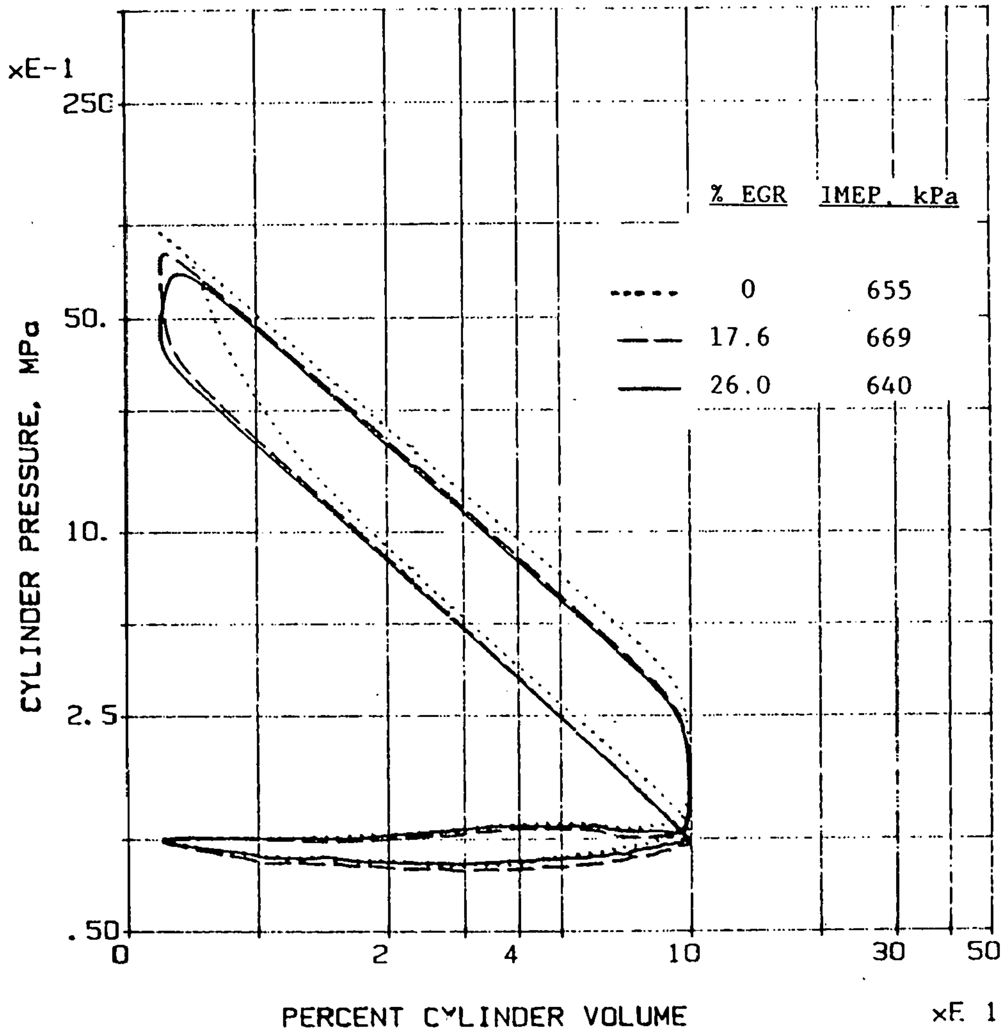



Figure 3.2-5. Effect of EGR on Pressure-Volume Diagrams for the 100%
(continued) Coal-Fueled Engine Tests (Coal #1).

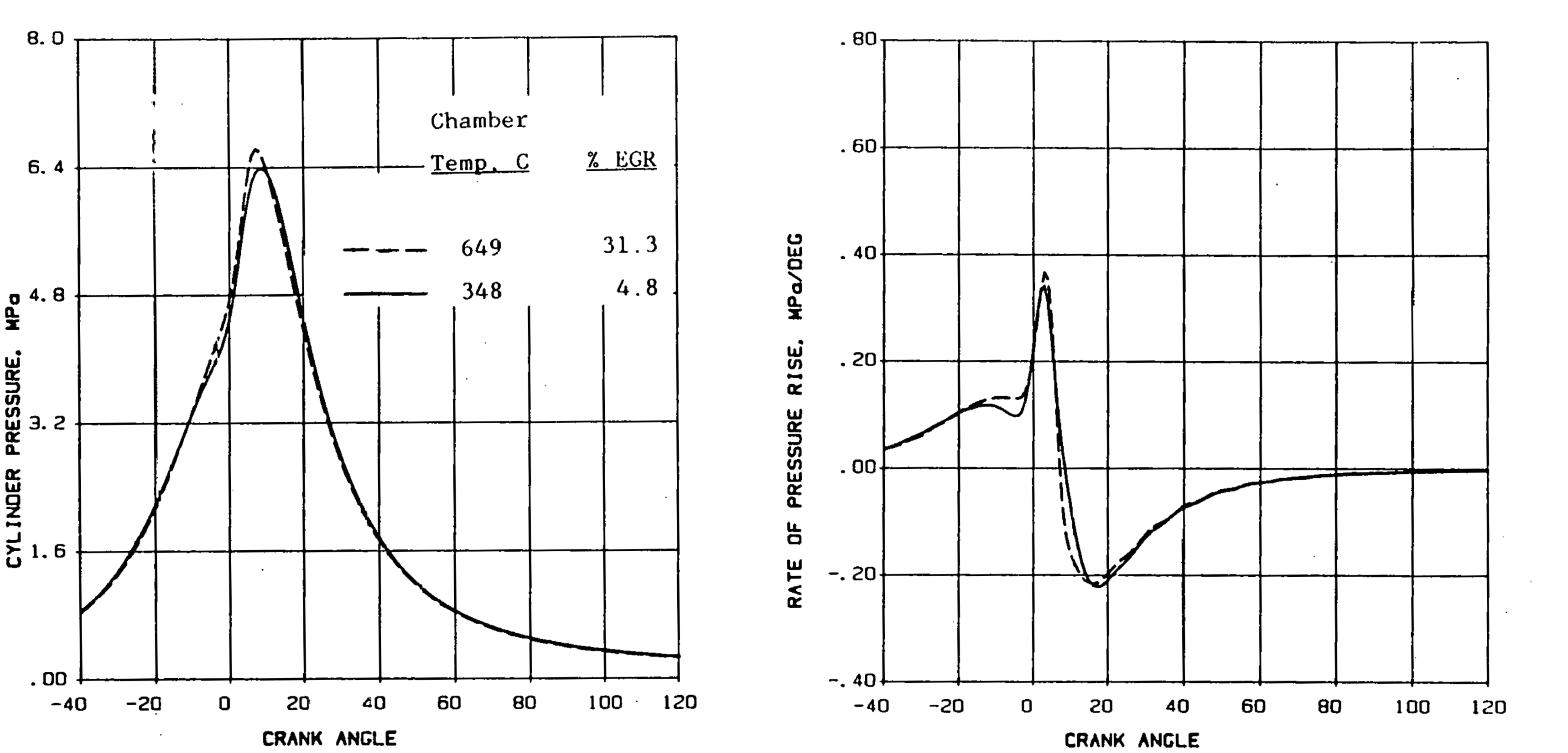



Figure 3.2-6 . Effect of Hastelloy X TICS Chamber Temperature and EGR on Cylinder Pressure and Rate of Pressure Rise Diagrams for the 100% Coal-Fueled Engine Tests (Coal #1, 1000 rpm).

<u>Effect of Engine Speed</u> The 100% coal-fueled engine was operated with coal #1 from 800 to 1800 rpm engine speed range. Table 3.2-5 and Figure 3.2-7 show the effect of engine speed on the engine performance. Due to the preignition of coal at lower engine speeds of 800 and 1000 rpm, higher peak cylinder pressure and rate of pressure rise were observed. For this engine test, the optimum engine speed was seen to be 1200 to 1400 rpm. However, the coal-fueled test engine can be optimized at other engine speeds by proper control of EGR and precombustion chamber temperature. The cylinder pressure and rate of pressure rise diagrams do not show preignition of coal powder at 1200 and 1400 rpm engine speeds. This was due to shorter residence time of coal powder in the engine cylinder at higher speeds. At 1600 rpm engine speed, a further delay in the coal powder ignition leads to lower peak cylinder pressure and rate of pressure rise. However, the coal-fueled engine operation can be optimized for the entire 800 to 1800 rpm speed range by proper control of EGR and TICS chamber temperature. As stated earlier, a microprocessor based controller would be necessary to insure optimum engine operation at each load/speed combination.

### 3.2.2.2 Engine Tests with Coal #2 - 21.3 Micron Mean Size Bituminous Coal

In view of the faster combustion of 7 micron mean size Bituminous coal #1 in the test engine, the coal from the same mine was procured and ground to 21.3 micron mean size. This coal #2 was a non-beneficiated coal from the Kentucky Blue Gem Seam and had larger particle size and ash content as compared to the coal #1 (mean size - 21.3 vs. 7 microns, top size - 75 vs. 20 microns, and ash content - 1.6 vs. 0.9%). The engine tests with coal #2 were carried out to investigate the combustion of coal powder fuel having larger particle size and higher ash content in the TICS engine concept.

The 100% coal-fueled engine test results with coal #2 showed excellent combustion characteristics from 800 to 1800 rpm engine speed range with lower peak cylinder pressure and slower rate of pressure rise as compared to the coal #1. This was anticipated due to longer burning time required for the larger coal particle sizes. Also, much less preignition of coal fuel in the engine was observed which is preferred for the test engine operation and

TABLE 3.2-5

EFFECT OF ENGINE SPEED ON 100% COAL-FUELED ENGINE PERFORMANCE (COAL #1)

| | | | | | |
|---|---|---|---|---|---|
| ENGINE SPEED, rpm | 800 | 1000 | 1200 | 1400 | 1600 |
| TEST NUMBER | 0819GCL | 0819UCL | 0819LCL | 0819NCL | 0812RCL |
| % EGR | 4.4 | 17.6 | 20.9 | 24.1 | 0 |
| BRAKE POWER, kW | 6.7 | 8.0 | 8.7 | 8.3 | 4.8 |
| INDICATED POWER, kW | 9.9 | 12.3 | 14.1 | 14.7 | 13.4 |
| IMEP, kPa | 677 | 669 | 640 | 571 | 457 |
| PEAK CYLINDER PRESSURE, MPa | 9.57 | 8.29 | 8.20 | 7.90 | 6.59 |
| (at deg. ATDC) | (0) | (4) | (4) | (5) | (7) |
| PEAK RATE OF PRESSURE RISE, MPa/deg | 0.96 | 0.67 | 0.65 | 0.49 | 0.36 |
| (at deg. ATDC) | (-12) | (-1) | (-1) | (0) | (2) |
| EMISSIONS | | | | | |
| CO, g/bhp-hr | 34.2 | 13.4 | 14.4 | 12.4 | NR |
| (lb/MMBtu) | (3.95) | (1.83) | (2.17) | (1.76) | |
| $CO_2$, % | 15.5 | 15.7 | 15.1 | 12.0 | NR |
| HC, g/bhp-hr | 1.6 | 0.9 | 1.3 | 1.1 | NR |
| (lb/MMBtu) | (0.19) | (0.12) | (0.19) | (0.15) | |
| NOx, g/bhp-hr | 28.8 | 16.0 | 11.2 | NR | NR |
| (lb/MMBtu) | (3.32) | (2.20) | (1.69) | | |

NR Not recorded

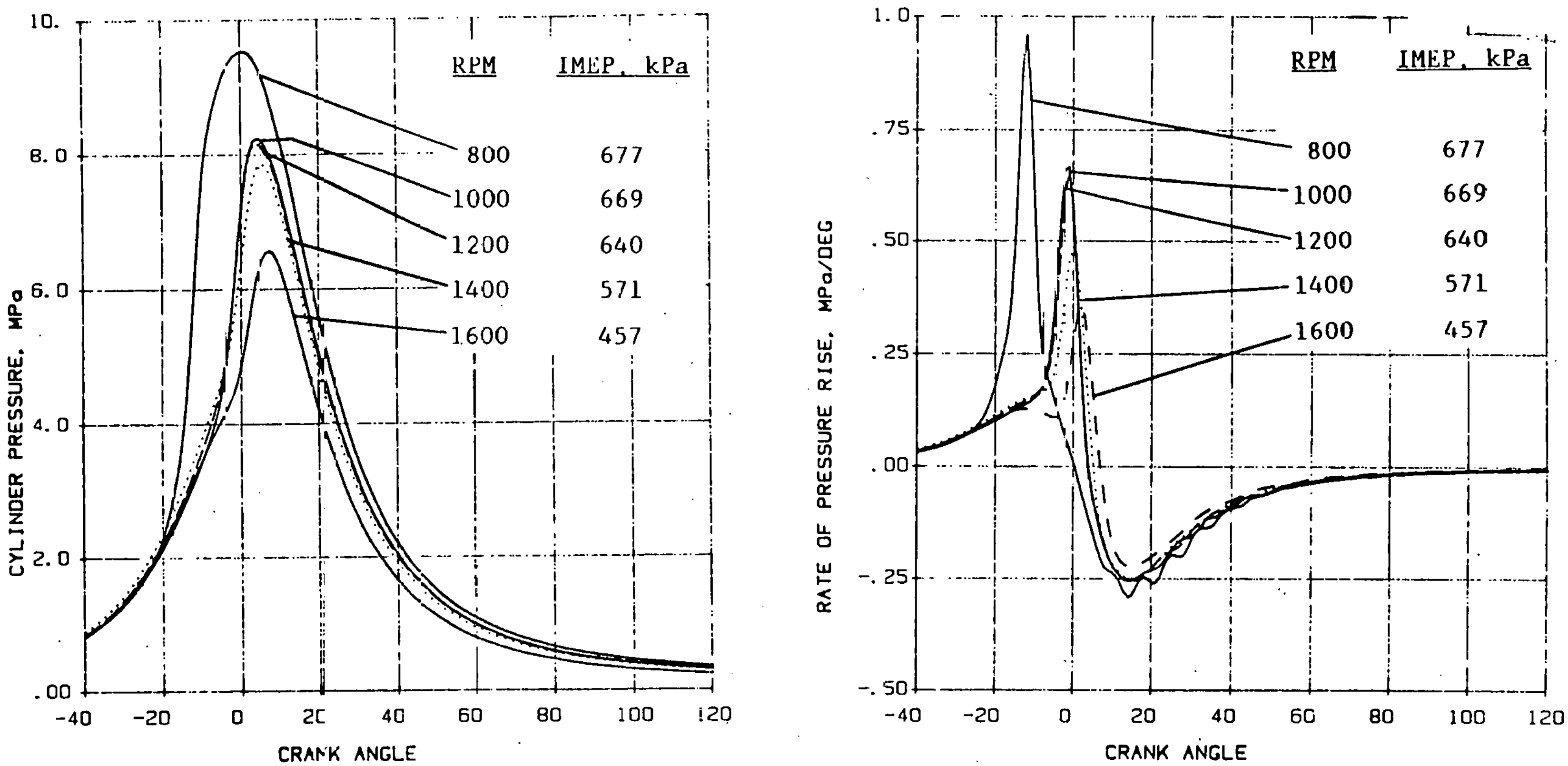



**Figure 3.2-7.** **Effect of Engine Speed on Cylinder Pressure and Rate of Pressure Rise Diagrams for the 100% Coal-Fueled Engine Tests (Coal #1).**

durability. Table 3.2-6 and Figure 3.2-8 present these results which show optimum coal-fueled engine operation for 1200 and 1400 rpm engine speeds. However, the engine performance and emissions could be optimized over the entire speed range by proper control of the EGR and TICS chamber temperature.

EGR was used to control ignition timing of the coal #2 during the 100% coal-fueled engine tests. Table 3.2-7 and Figure 3.2-9 present the effect of EGR on the engine performance and emissions. These engine tests were conducted with the Hastelloy X TICS chamber. A similar effect of EGR is seen here as for the coal #1. In this case, by using 18.7% EGR, the IMEP and power output increased, whereas the peak cylinder pressure, peak rate of pressure rise, and NOx emissions decreased. EGR increases the ignition delay and shifts the cylinder pressure diagram towards after top dead center. The pressure-volume diagram in Figure 3.2-9 clearly indicates improvement in the coal combustion by the constant volume combustion cycle with the use of EGR. Thus, the power output and engine thermal efficiency is maximized for the coal fuel combustion in the engine.

A comparison of 100% coal-fueled engine operation with coal #1 and coal #2 at 1000 rpm is presented in Table 3.2-8 and Figure 3.2-10. The engine power output for both these tests are almost the same (considering the effect of % EGR on the cylinder pressure and power output). The coal #2 was seen to have significantly lower peak cylinder pressure, peak rate of pressure rise and NOx emissions. Also, the CO emissions are slightly lower for the coal #2. From these engine test results, it is obvious that large particle size and higher ash content coal fuel can be efficiently burned in a TICS diesel engine. This presents a major achievement in the development of the coal-fueled engines, since the larger particle size and higher ash content coal fuels have significantly lower cost than the micronized low ash coals.

#### 3.2.2.3 Engine Tests with Coal #3 - North Dakota Lignite Coal

The combustion characteristics of a low rank North Dakota Lignite coal were also investigated in the test engine. This coal fuel, procured from the Energy and Mineral Research Center, University Station, North Dakota, was not

TABLE 3.2-6

EFFECT OF ENGINE SPEED ON 100% COAL-FUELED ENGINE PERFORMANCE (COAL #2)

| | | | | | |
|---|---|---|---|---|---|
| ENGINE SPEED, rpm | 800 | 1000 | 1200 | 1400 | 1800 |
| TEST NUMBER | 0830FCL | 0830GCL | 0830ICL | 0830KCL | 0830MCL |
| % EGR | 22.5 | 18.7 | 13.4 | 22.7 | 31.2 |
| BRAKE POWER, kW | 6.0 | 7.4 | 7.6 | 6.5 | 2.7 |
| INDICATED POWER, kW | 9.5 | 11.7 | 12.8 | 14.4 | 14.1 |
| IMEP, kPa | 646 | 639 | 582 | 562 | 427 |
| PEAK CYLINDER PRESSURE, MPa | 8.65 | 6.78 | 6.86 | 6.74 | 4.90 |
| (at deg. ATDC) | (2) | (9) | (7) | (7) | (10) |
| PEAK RATE OF PRESSURE RISE, MPa/deg | 0.67 | 0.28 | 0.26 | 0.22 | 0.15 |
| (at deg. ATDC) | (-5) | (4) | (2) | (1) | (-12) |
| EMISSIONS | | | | | |
| CO, g/bhp-hr | NR | 11.2 | 11.5 | 19.5 | 45.5 |
| (lb/MMBtu) | | (1.41) | (1.49) | (1.75) | (1.70) |
| $CO_2$, % | 8.0 | 7.9 | 6.1 | 7.3 | 7.6 |
| HC, g/bhp-hr | 3.0 | 1.4 | 1.4 | 2.3 | 5.4 |
| (lb/MMBtu) | (0.31) | (0.17) | (0.18) | (0.20) | (0.20) |
| NOx, g/bhp-hr | 8.8 | 3.0 | 5.1 | 5.9 | 9.6 |
| (lb/MMBtu) | (0.90) | (0.37) | (0.66) | (0.53) | (0.36) |

NR Not recorded

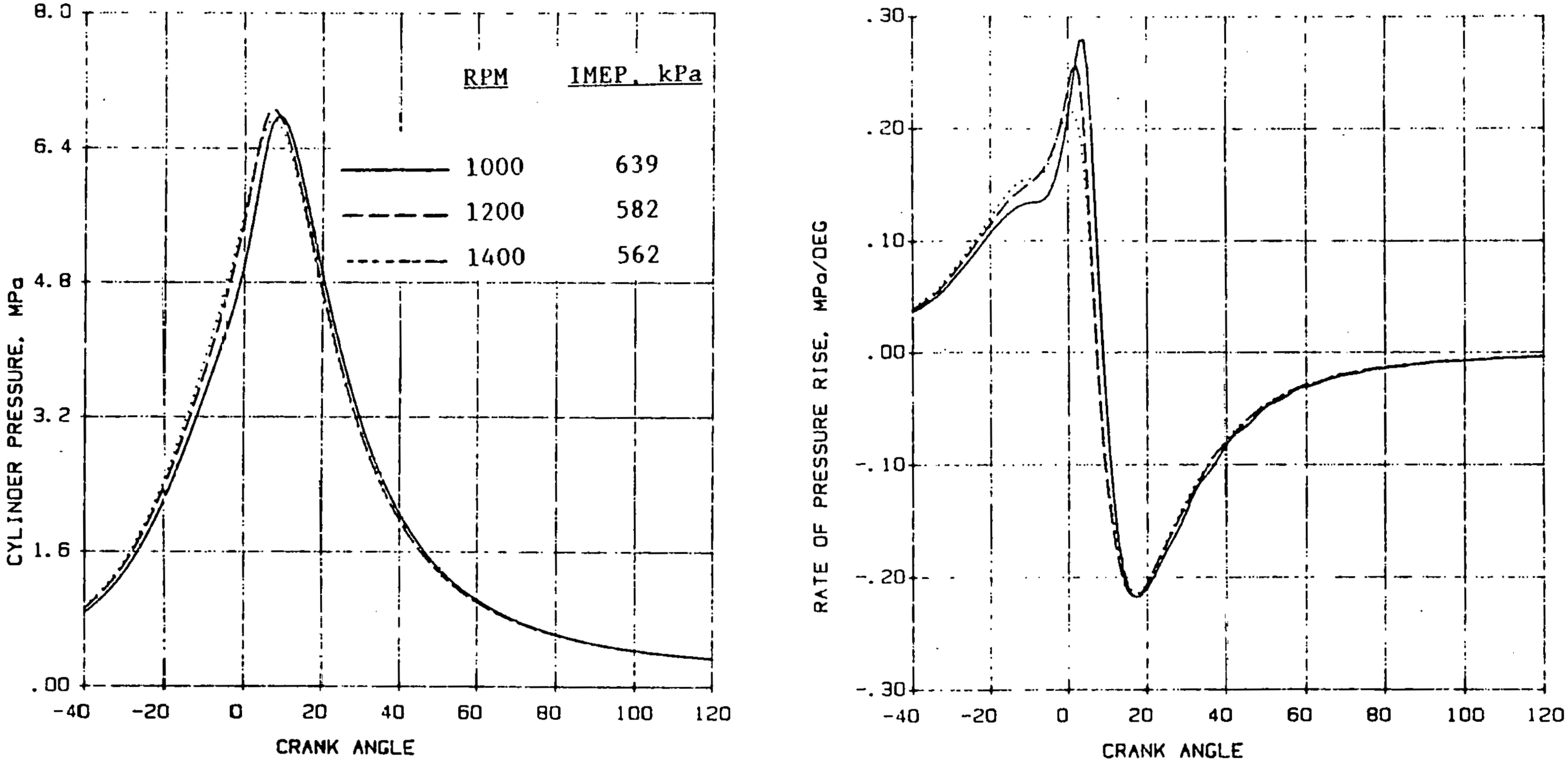



**Figure 3.2-8.** Effect of Engine Speed on Cylinder Pressure and Rate of Pressure Rise Diagrams (Coal #2).

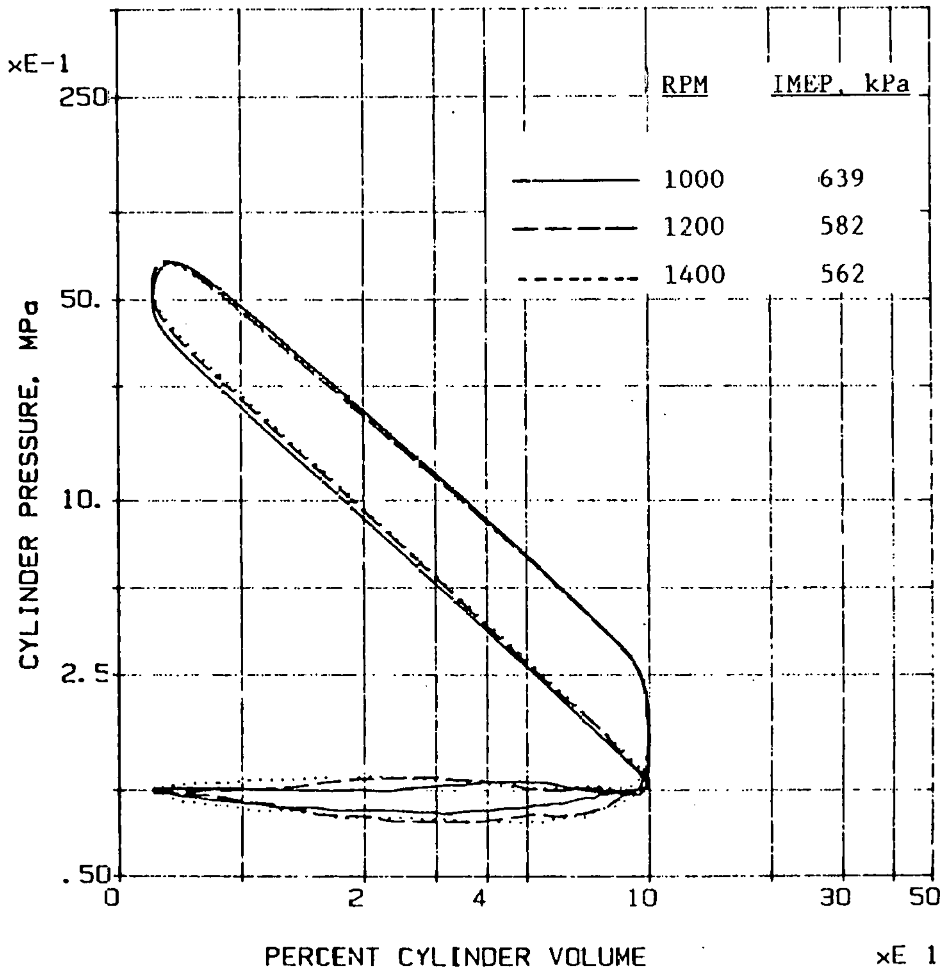



**Figure 3.2-8.** **Effect of Engine Speed on Pressure-Volume Diagrams**
**(continued)** **(Coal #2).**

TABLE 3.2-7

EFFECT OF EGR ON 100% COAL-FUELED ENGINE PERFORMANCE (COAL #2)

| | | |
|---|---|---|
| % EGR | 0 | 18.7 |
| TEST NUMBER | 0830HCL | 0830GCL |
| ENGINE SPEED, RPM | 1000 | 1000 |
| BRAKE POWER, kW | 5.5 | 7.4 |
| INDICATED POWER, kW | 10.8 | 11.7 |
| IMEP, kPa | 591 | 639 |
| PEAK CYLINDER PRESSURE, MPa | 8.2 | 6.8 |
| (at deg. ATDC) | (2) | (9) |
| PEAK RATE OF PRESSURE RISE, MPa/deg | 0.47 | 0.28 |
| (at deg. ATDC) | (-4) | (4) |
| EMISSIONS | | |
| CO, g/bhp-hr | 8.7 | 11.2 |
| (lb/MMBtu) | (0.82) | (1.41) |
| $CO_2$, % | 4.3 | 7.9 |
| HC, g/bhp-hr | 1.2 | 1.4 |
| (lb/MMBtu) | (0.11) | (0.17) |
| NOx, g/bhp-hr | 20.8 | 3.0 |
| (lb/MMBtu) | (1.97) | (0.37) |

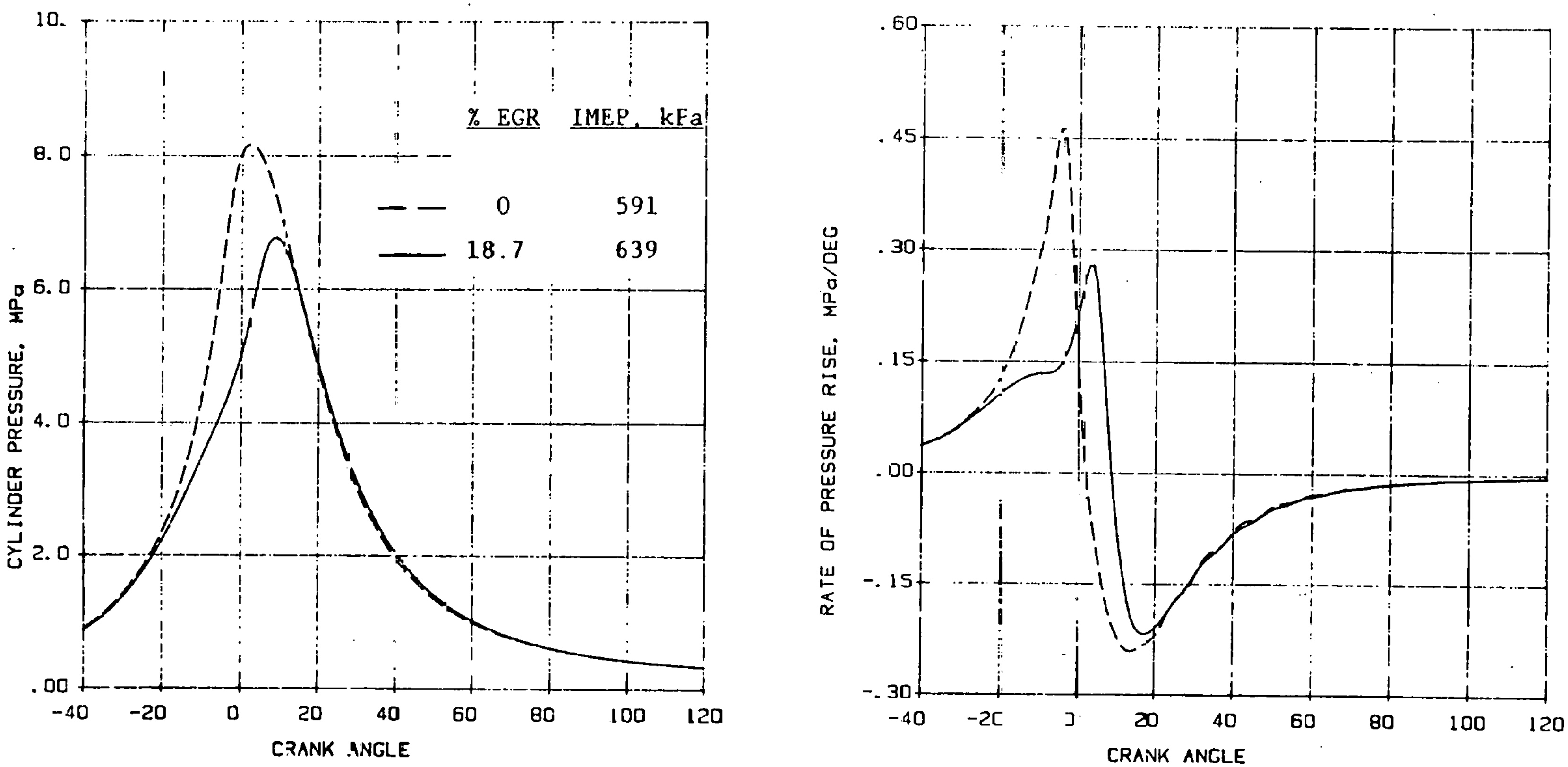



**Figure 3.2-9. Effect of EGR on Cylinder Pressure and Rate of Pressure Rise Diagrams for the 100% Coal-Fueled Engine Tests (Coal #2).**

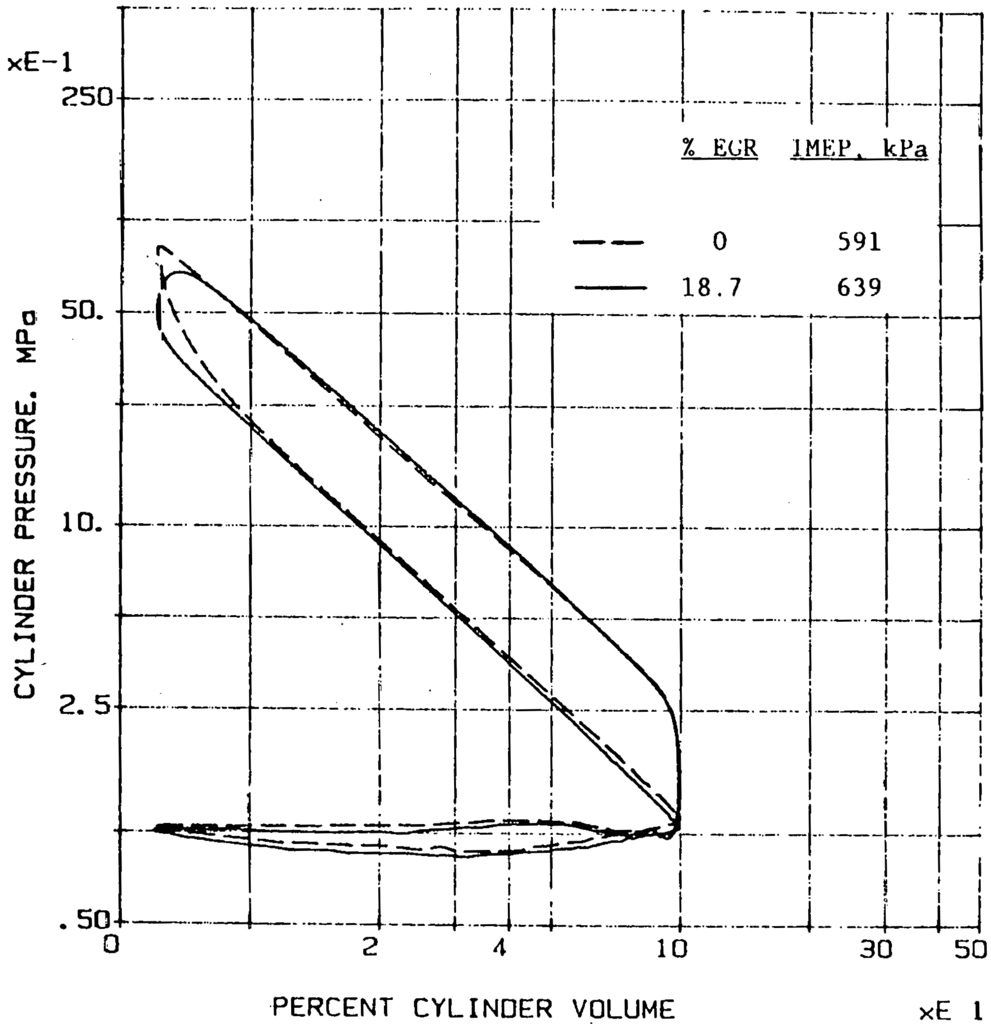
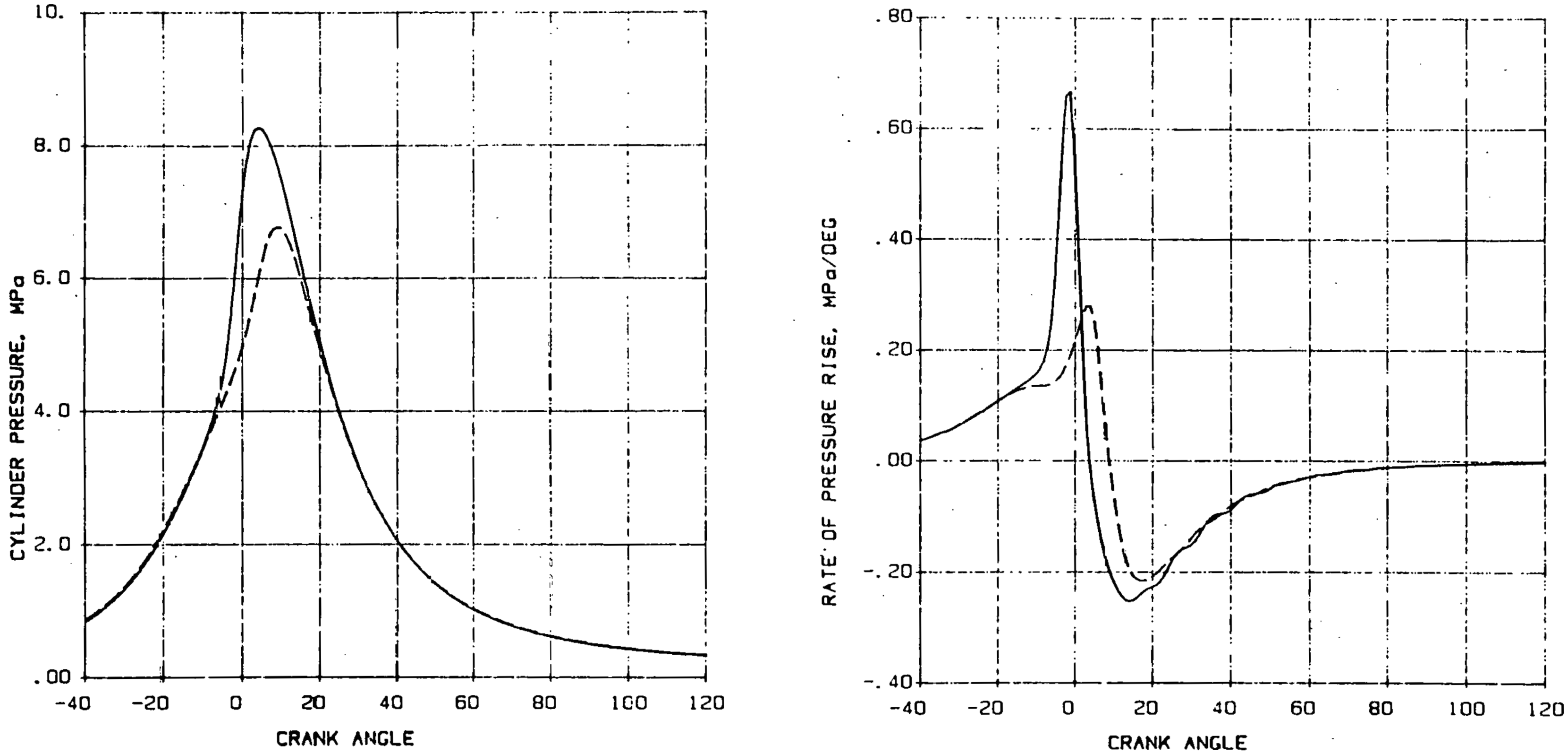



Figure 3.2-9. (continued) Effect of EGR on Pressure-Volume Diagrams for the 100% Coal-Fueled Engine Tests (Coal #2).

TABLE 3.2-8

EFFECT OF COAL PARTICLE SIZE ON 100% COAL-FUELED ENGINE PERFORMANCE

| COAL | COAL #1 | COAL #2 |
|---|---|---|
| TYPE | BLUE GEM SEAM | BLUE GEM SEAM |
| BENEFICIATION | YES | NO |
| MEAN SIZE, MICRONS | 7.0 | 21.3 |
| % ASH | 0.9 | 1.6 |
| TEST NUMBER | 0819UCL | 0830GCL |
| % EGR | 17.6 | 18.7 |
| ENGINE SPEED, rpm | 1000 | 1000 |
| BRAKE POWER, kW | 8.0 | 7.4 |
| INDICATED POWER, kW | 12.3 | 11.7 |
| IMEP, kPa | 669 | 639 |
| PEAK CYLINDER PRESSURE. MPa (at deg. ATDC) | 8.29 (4) | 6.78 (9) |
| PEAK RATE OF PRESSURE RISE, MPa/deg (at deg. ATDC) | 0.67 (-1) | 0.28 (4) |
| EMISSIONS | | |
| CO, g/bhp-hr (lb/MMBtu) | 13.4 (1.83) | 11.2 (1.41) |
| $CO_2$, % | 15.7 | 7.9 |
| HC, g/bhp-hr (lb/MMBtu) | 0.9 (0.12) | 1.4 (0.17) |
| NOx, g/bhp-hr (lb/MMBtu) | 16.0 (2.20) | 3.0 (0.37) |




ure 3.2-10. Comparison of the Cylinder Pressure and Rate of Pressure Rise Diagrams for Coal #1 and #2.

| | | % of EGR | IMEP, kPa |
|---|---|---|---|
| ———— | Coal #1 | 17.6 | 669 |
| ------- | Coal #2 | 18.7 | 639 |

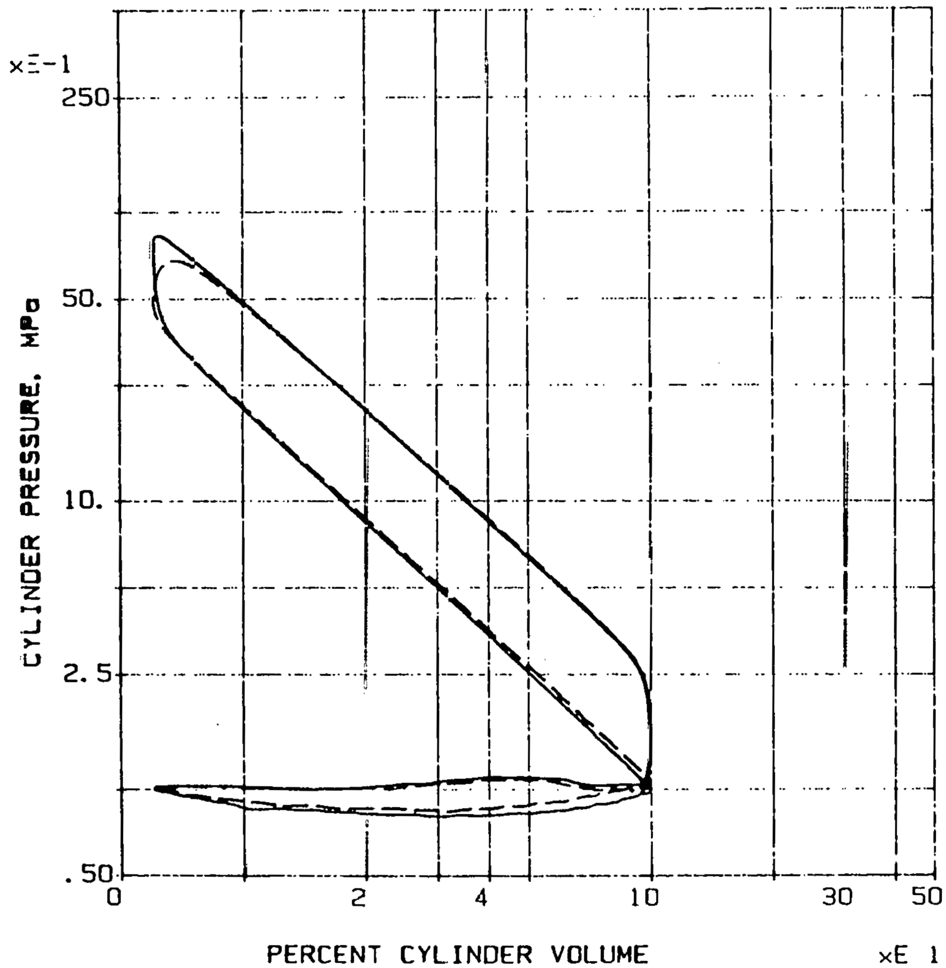



Figure 3.2-10. (continued) Comparison of the Pressure-Volume Diagrams for Coal #1 and #2.

| | | % of EGR | IMEP, kPa |
|---|---|---|---|
| ———— | Coal #1 | 17.6 | 669 |
| - - - - - - - | Coal #2 | 18.7 | 639 |

beneficiated and, thus, contained a very high percent of ash. The analysis of the coal shows 7.1% ash content, 44% volatile matter and 25.35 MJ/kg (10,897 Btu/lb) calorific value. The mean and top sizes were 29.2 and 200 microns, respectively.

The 100% coal-fueled engine test results with the Lignite coal showed very fast burning in the test engine. This was due to high reactivity and volatile content of the lignite coals. At 16.5:1 compression ratio, extreme peak cylinder pressure and rate of pressure rise were observed without EGR. Table 3.2-9 and Figure 3.2-11 present these test data at 1000 rpm with the Hastelloy X TICS chamber. Even at these low loads, preignition of the lignite coal during the compression stroke resulted in peak cylinder pressure of 8.74 MPa at 1 degree BTDC and peak rate of pressure rise at 13 degrees BTDC. This early ignition was observed despite the larger 29 microns mean size for the coal #3. As seen in Figure 3.2-11, the use of EGR reduced the preignition and shifted the cylinder pressure diagram towards ATDC. Thus, the peak cylinder pressure decreased to 6.74 MPa at 7 degree ATDC. The location of the peak rate of pressure rise also shifted to 1 degree ATDC which was much better for the engine operation and durability.

The test engine was operated on coal #3 from 800 to 1400 rpm engine speed range at low loads and 16.5:1 compression ratio. Table 3.2-10 and Figure 3.2-12 show these test results at 1000, 1200 and 1400 rpm engine speed range. In order to control the ignition timing of coal fuel, varying amount of EGR were used to optimize the engine operation. It should be noted that it was possible to control the lignite coal ignition and combustion due to low engine load operation. In view of the extreme rate of pressure rise at higher engine loads, some tests were conducted at a lower compression ratio of 13:1. Figure 3.2-13 shows the cylinder pressure diagrams for this engine test at 800 rpm and full load. The lignite coal did not preignite at this lower compression ratio, even at low engine speed of 800 rpm and full load engine test. These engine test results show that low rank coals can be efficiently burned with the TICS concept.

TABLE 3.2-9

EFFECT OF EGR ON 100% COAL-FUELED ENGINE PERFORMANCE (COAL #3)

| | | |
|---|---|---|
| % EGR | 0 | NR |
| TEST NUMBER | 0921CCL | 0921DCL |
| ENGINE SPEED, RPM | 1000 | 1000 |
| BRAKE POWER, kW | 4.6 | 6.7 |
| INDICATED POWER, kW | 10.0 | 9.8 |
| IMEP, kPa | 544 | 534 |
| PEAK CYLINDER PRESSURE, MPa | 8.7 | 6.7 |
| (at deg. ATDC) | (-1) | (7) |
| PEAK RATE OF PRESSURE RISE, MPa/deg | 0.52 | 0.39 |
| (at deg. ATDC) | (-11) | (1) |

NR Not recorded

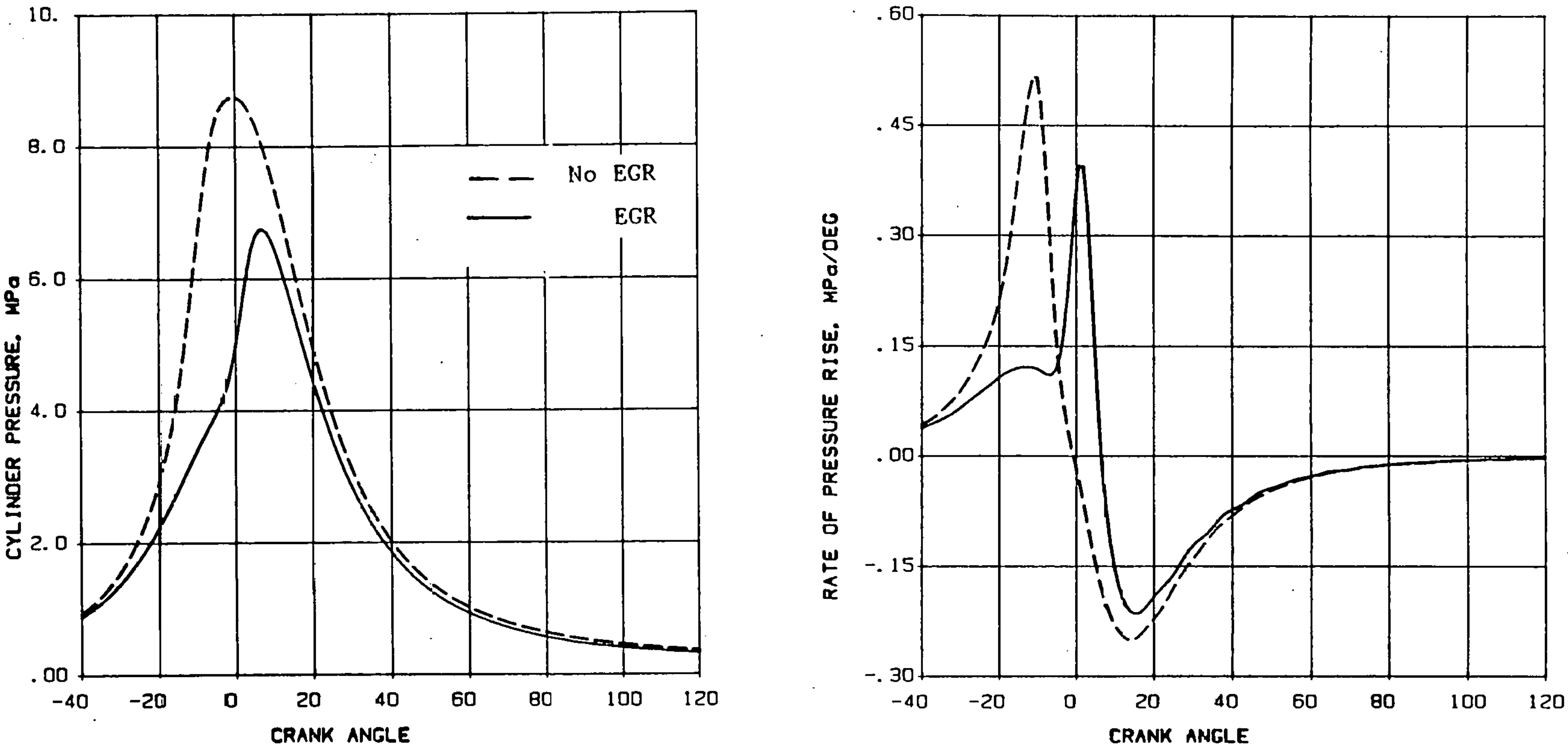



Figure 3.2-11. Effect of EGR on Cylinder Pressure and Rate of Pressure Rise Diagrams for the 100% Coal-Fueled Engine Tests (Coal #3, CR = 16.5:1, 1000 rpm).

TABLE 3.2-10

EFFECT OF ENGINE SPEED ON 100% COAL-FUELED ENGINE PERFORMANCE (COAL #3)

| | | | |
|---|---|---|---|
| ENGINE SPEED, rpm | 1000 | 1200 | 1400 |
| TEST NUMBER | 0920ECL | 0920NCL | 0920GCL |
| % EGR | 0 | 17.6 | 13.8 |
| BRAKE POWER, kW | 4.3 | 4.3 | 4.0 |
| INDICATED POWER, kW | 8.0 | 10.0 | 10.1 |
| IMEP, kPa | 435 | 457 | 393 |
| PEAK CYLINDER PRESSURE, MPa | 6.45 | 6.43 | 6.29 |
| (at deg. ATDC) | (6) | (7) | (6) |
| PEAK RATE OF PRESSURE RISE, MPa/deg | 0.37 | 0.34 | 0.30 |
| (at deg. ATDC) | (1) | (2) | (1) |
| EMISSIONS | | | |
| CO, g/bhp-hr | 22.7 | 20.8 | 37.5 |
| (lb/MMBtu) | (2.17) | (2.0) | (3.30) |
| $CO_2$, % | 5.3 | 6.7 | 4.8 |
| HC, g/bhp-hr | 0.8 | 0.8 | 0.9 |
| (lb/MMBtu) | (0.07) | (0.08) | (0.08) |
| NOx, g/bhp-hr | 6.7 | 7.5 | 5.9 |
| (lb/MMBtu) | (0.64) | (0.72) | (0.52) |

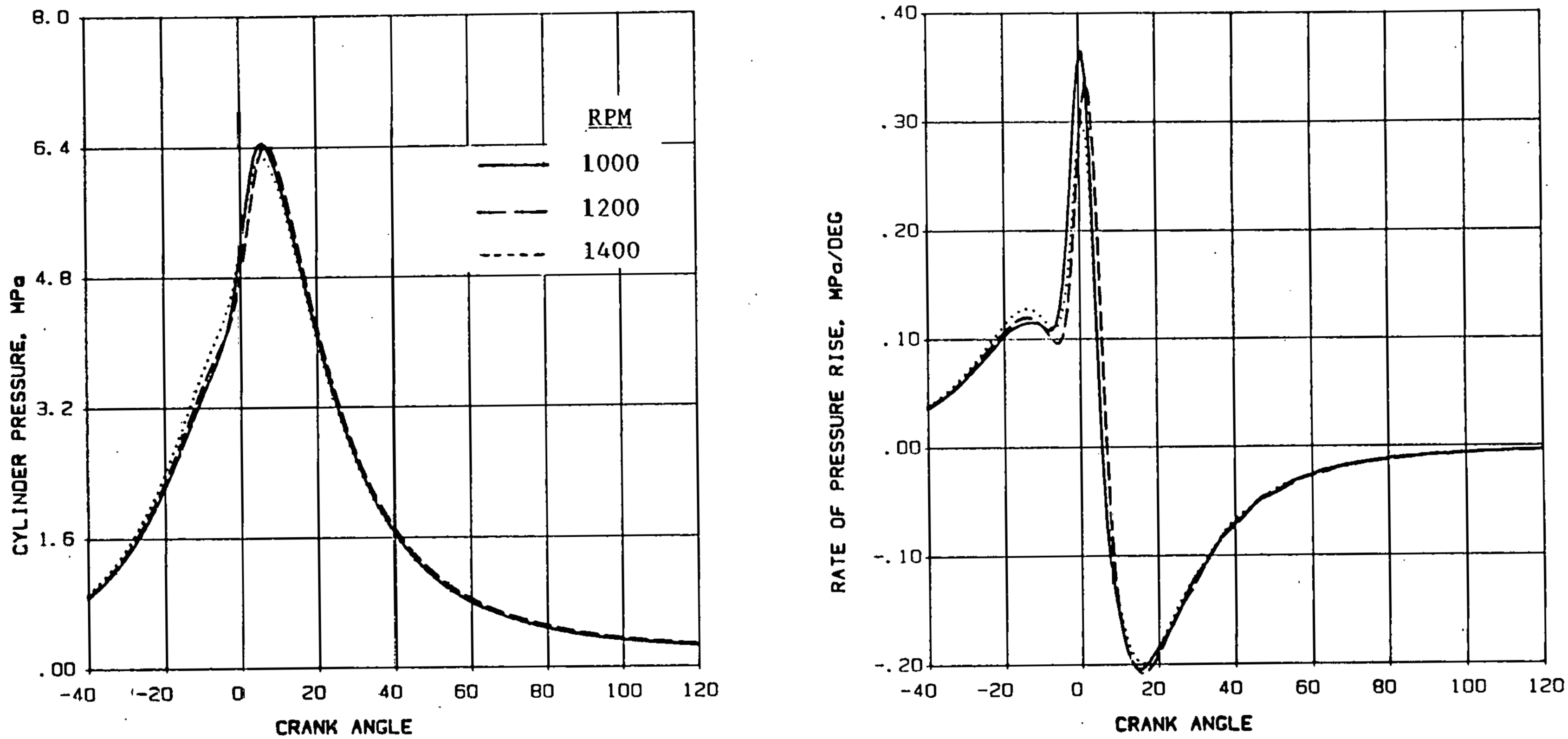
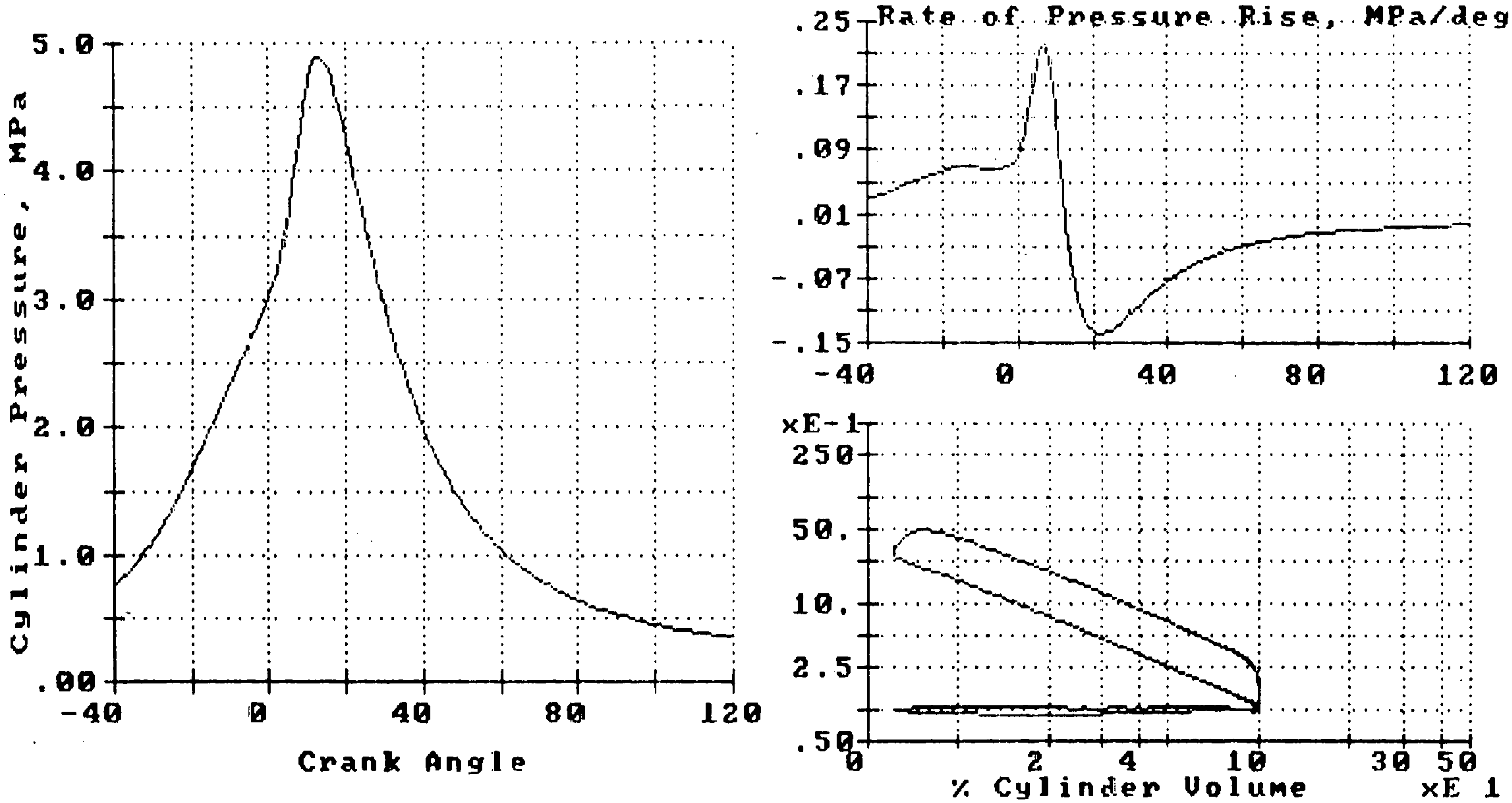



Figure 3.2-12. Effect of Engine Speed on Cylinder Pressure and Rate of Pressure Rise Diagrams for the 100% Coal-Fueled Engine Tests (Coal #3, CR = 16.5:1, Optimum EGR).




d:0928dcl.cyp
Peak Cyl Pres = 4.90 MPa at 13 deg ATDC
Peak dP/dθ = .223 MPa/deg at 7 deg ATDC
Indicated Power = 9.45 kW IMEP = 645.3 kPa PMEP =-8.1 kPa

Figure 3.2-13. Cylinder Pressure Diagrams for the 100% Coal-Fueled Engine Test (Coal #3, 800 rpm).

### 3.2.2.4 Engine Wear Data

For the coal-fueled engine tests in this entire program, cylinder liner and top piston ring used were coated with wear resistant chrome oxide material. As seen in Table 3.2-11, the wear on the cylinder liner bore and the change in the top ring end gap was minimal whereas the standard intermediate piston rings without the chrome oxide coating showed large increase in the end gap. Thus, the coated piston rings and cylinder liner seem to exhibit very low wear rates as compared to conventional materials. A photograph of the test engine piston with rings after the coal-fueled engine testing is shown in Figure 3.2-14. The low wear rates observed during the coal-fueled engine testing are very promising, considering the long residence time of fumigated coal powder fuel in the cylinder during the intake and compression strokes. In comparison, the high pressure injected coal-water slurry stays in the engine cylinder for much shorter time period. Nevertheless, the reported wear rates of the CWS fueled engine have been much greater for the standard cylinder liner and piston rings [8]. The chrome oxide coating should not be considered as the ultimate coating material for the coal-fueled engine, since many potential candidate materials have yet to be tried in the engine environment. Preliminary work on the friction and wear testing of some coating materials was done by Adiabatics, Inc. under a separate METC sponsored program[14].

### 3.2.2.5 Analysis of Exhaust Particulates

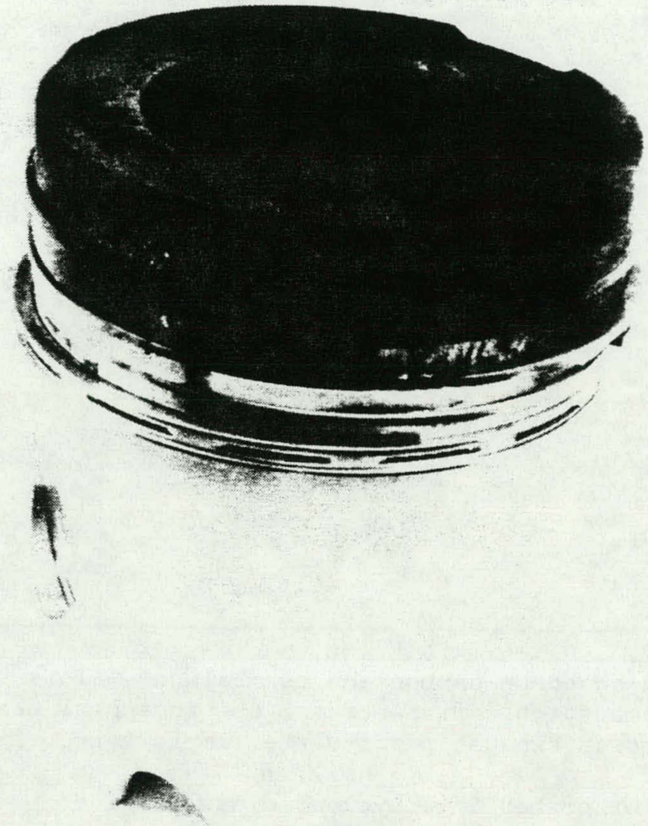
The exhaust particulates collected on the emissions test stand filter were analyzed by quantitative micro-analysis and qualitative scanning electron microscopy. The quantitative micro-analysis of the exhaust particulates was conducted by an analytical laboratory (Galbraith Laboratories, Inc., Knoxville, TN) to give percent carbon, percent hydrogen and percent ash. Table 3.2-12 presents these results for the DF-2, coal #1 and coal #2. The combustion efficiency for the coal-fueled engine testing, calculated on the basis of carbon and ash balance, shows 95.9% for coal #1 and 96.2% for coal #2. It should be noted that these numbers are approximate due to the average exhaust particulate sample collected for the entire engine test and calculations based on carbon and ash content only. Also, the soot

## TABLE 3.2-11

## ENGINE WEAR DATA FOR RINGS AND LINER

ENGINE TESTING: COAL #1 (15 HOURS DURATION)

| RING | COATING (TYPE) | END GAP, mm (INCH) BEFORE | AFTER | CHANGE |
|---|---|---|---|---|
| TOP | $CR_2O_3$ (STEP GAP) | 0.559 (0.022) | 0.559 (0.022) | 0.0 (0.0) |
| 2ND | NONE (STANDARD) | 0.559 (0.022) | 0.864 (0.034) | 0.305 (0.012) |
| 3RD | NONE (STEP GAP) | 0.610 (0.024) | 1.143 (0.045) | 0.533 (0.021) |
| OIL | NONE | 0.686 (0.027) | 1.575 (0.062) | 0.889 (0.035) |
| CYLINDER LINER | $CR_2O_3$ | 130.20 (5.126) | 130.21 (<5.1265) | <0.01 (<0.0005) |



AI-C/155-7A

Figure 3.2-14. Photograph of Piston (with rings) after Coal-Powder-Fueled Engine Testing.

TABLE 3.2-12

ANALYSIS OF EXHAUST PARTICULATES

| | COAL #1 | COAL #2 | DIESEL FUEL No. 2 |
|---|---|---|---|
| % CARBON | 65.8 | 60.2 | 94.7 |
| % ASH | 18.6 | 31.9 | 0.7 |
| % HYDROGEN | 2.2 | 3.6 | 1.1 |
| COMBUSTION EFFICIENCY, % | 95.9* | 96.2* | ** |

* Calculated based on carbon and ash balance. This represents minimum combustion efficiency for the an engine test run. There was not enough exhaust particulate sample for coal #3.

** About 99% or higher in a typical diesel engine.

formed in the test engine was included in the carbon content of the analyzed exhaust particulates. Nevertheless, these results show the coal fuel combustion efficiency of at least 96% in the test engine. The actual combustion efficiency of coal powder in the test engine, however, is expected to be higher than the above reported values.

The exhaust particulate samples were also examined with the scanning electron microscope [15]. In general, the particles were found quite similar to the samples examined from other CWS fueled engines. A common feature of these samples was the presence of a relatively large fraction of soot. The soot consists of chains or clusters of small spherical particles 0.05 to 0.1 microns in diameter and appears to be characteristic of soot material that is normally found in the exhaust of engines operated on DF-2. A photomicrograph of the exhaust particulates collected during DF-2 fueled test confirmed the presence of these small size soot particles (see Figure 3.2-15). For coal fuel operation, the test engine was started on DF-2 before switching over to coal fuel. Sample collection was carried out during both conditions, so the proportion of soot contributed by each fuel is not known.

Photomicrographs of the exhaust particulates for coal #1 and coal #2 are shown in Figure 3.2-15. In addition to the soot, these show the presence of larger particles. Most often these particles were from 1 to 5 microns in diameter. In terms of shape they could be categorized as either blocky, nearly spherical, or irregular with porosity. The blocky particles in many cases were probably unburned coal. This was confirmed by X-ray analysis which indicated that the particles were principally carbon in composition. The spherical particles apparently formed as a result of the solidification of molten droplets and according to x-ray analysis contained elements that are characteristic of mineral matter in coal, namely, Al, Si, Fe, and Ti. The porous particles contained high concentrations of the latter elements as well as carbon, and probably represent partially burned coal particles.

Relatively few particles larger than 10 microns were observed despite the fact that coal #2 had mean size of 21.3 microns. One particle about 20 microns in length was seen for coal #2. Qualitative examination did not reveal marked differences among the samples collected during coal fuel operations. Quantitative measurements of particle size and shape were not carried out.

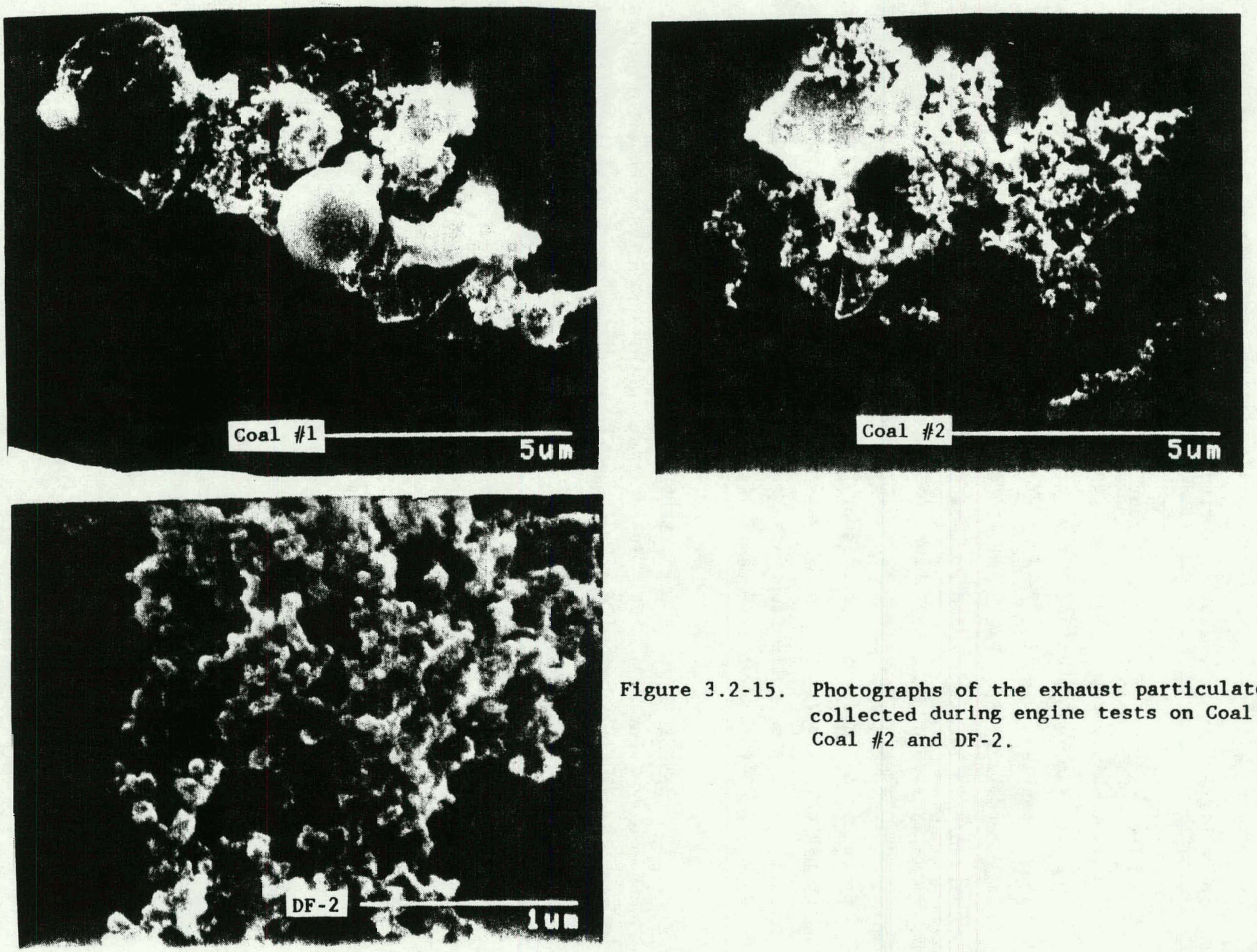



Figure 3.2-15. Photographs of the exhaust particulates collected during engine tests on Coal #1, Coal #2 and DF-2.

# 4.0 SUMMARY AND CONCLUSIONS

This report, entitled "Extending and Enhancing the Scientific Base for Advanced Coal-Fueled Power Systems Utilizing Heat Engines," describes the progress and findings of a research program aimed at investigating the combustion characteristics of dry coal powder fueled diesel engine. This work was performed under the U.S. Department of Energy, Morgantown Energy Technology Center (DOE-METC) contract number DE-AC21-86MC23258. During this program, significant achievements were made in overcoming many problems facing the coal-powder-fueled engine. The Thermal Ignition Combustion System (TICS) concept was used to enhance the combustion of coal powder fuel.

The major coal-fueled engine test results and accomplishments are as follows:

- Design, fabrication and engine testing of improved coal feed system for fumigation of coal powder to the intake air. This system had very few moving parts and resulted in consistent fuel delivery and metering for the coal-fueled engine operation.

- Design, fabrication and engine testing of the TICS chamber made from a superalloy material (Hastelloy X). Also, a TICS chamber made from silicon nitride ceramic was designed and fabricated.

- Design, fabrication and engine testing of wear resistant chrome oxide ceramic coated piston rings and cylinder liner.

- Lubrication system was improved to separate coal particles from the contaminated lubricating oil. Thus, the coal-fueled engine test could be performed for a longer period of time.

- Control of the ignition timing of fumigated coal powder fuel by exhaust gas recirculation (EGR) and controlled TICS chamber temperature. EGR also lowered the peak cylinder pressure, rate of pressure rise and NOx emissions. Also, EGR increased the IMEP and engine efficiency because of the improved engine performance.

- Coal-fueled engine testing was conducted in two configurations: Dual fuel (with diesel pilot) and 100% coal-fueled engine without any diesel pilot or heated intake air. These engine tests show fast burning, high cylinder pressures and high heat release rates for the combustion of coal powder fuel.

- Cold starting of the 100% coal-powder-fueled engine with a glow plug.

- Coal-fueled-engine was operated with three types of coals: 1. Micronized Bituminous coal, 7 microns mean size, 2. Nonbeneficiated 1.6% ash content Bituminous coal, 21.3 microns mean size, and 3. 7.1% ash content North Dakota Lignite coal, 29 microns mean size.

- Coal-fueled-engine was operated from 800 to 1800 rpm speed and idle to full load engine conditions.

This research investigation on fumigated coal fueled engine with TICS has revealed several interesting points. The most interesting was the effect of exhaust gas recirculation as a timing control device. Significant reduction in peak cylinder pressure and NOx emissions were also observed with the use of exhaust gas recirculation. Another important point is the high speed capability of the coal-powder-fueled engine. The high level of ignition energy in the TICS chamber also enabled the combustion of large particle size coal fuel. In summary, the development of a simple, low cost coal-powder-fueled engine appears possible.

## 4.1 CONCLUSIONS

The engine test results obtained during this DOE-METC sponsored research program showed that a coal-powder-fueled engine is feasible and can be operated like a conventional diesel or gasoline fueled engine. The thermal ignition combustion system concept allows engine operation with 100% coal powder fuel without the use of external ignition assist sources. Important features of coal powder fueled engine developed in this program are as follows:

- Simple and low cost coal-fueled engine without expensive high pressure fuel injection systems.

- Ability to burn 100% coal fuel in the engine without external ignition devices such as separate diesel pilot or heated intake air.

- Engine can operate on large particle size, high ash content, and also low rank coal fuels.

- Simple and reliable coal powder feed system.

- High speed engine operation from 800 to 1800 rpm range.

# 5.0 RECOMMENDATIONS FOR FUTURE WORK

Based on the combustion characteristics of dry coal-powder-fueled engine in the present investigation, the following recommendations are suggested for the future work:

- Evaluate combustion characteristics of dry coal fuel in a multi-cylinder engine with the TICS concept. A microprocessor based control system should be used to control the ignition timing of coal powder in the high temperature TICS chamber.
- Turbocharge (or supercharge) the coal-fueled engine. For this purpose, a low pressure (30-50 psi) coal powder feed system will be required.
- A two stroke diesel engine should be considered for the coal powder. This may overcome the lubricating oil contamination problem due to separate lubrication systems in the engine.
- Evaluate the improved piston ring designs for minimizing the blow-by and lubricating oil contamination.
- Evaluate combustion characteristics of dry coal powder-fueled engine to determine the maximum power and speed, minimum NOx emissions etc.

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DOE/MC/23258-2693 COMBUSTION CHARACTERISTICS OF DRY COAL-POWDER-FUELED ADIABATIC DIESEL ENGINE USDOE