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# INNOVATIVE COAL-FUELED DIESEL ENGINE INJECTOR

Final Report

By
P. Badgley
D. Doup

May 1991

Work Performed Under Contract No. AC21-88MC25132

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

By
Adiabatics, Inc.
Columbus, Indiana

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**For**
**U.S. Department of Energy**
**Office of Fossil Energy**
**Morgantown Energy Technology Center**
**P.O. Box 880**
**Morgantown, West Virginia 26507-0880**

**By**
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**3385 Commerce Drive**
**Columbus, Indiana 47201**

**May 1991**

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INNOVATIVE COAL-FUELED DIESEL ENGINE INJECTOR

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## EXECUTIVE SUMMARY

This report, entitled "Innovative Coal-Fueled Diesel Engine Injector," describes the progress and findings of a research program aimed at development of the Coal Water Slurry (CWS) injection system in conjunction with the Thermal Ignition Combustion System (TICS) concept to achieve autoignition of CWS at various loads and speed ranges (up to 1,800 rpm) in a single-cylinder diesel engine. This work was performed under the U.S. Department of Energy, Morgantown Energy Technology Center (DOE-METC) contract number DE-AC21-88MC25132 from September 1988 to March 1991.

The test results obtained during this program show the development of an electronically controlled, hydraulically actuated CWS-injection system operating at low injection pressures of 13.8 to 20.7 MPa (2,000 to 3,000 psi) with very low wear of the nozzle spray orifice as compared to the wear data reported for other CWS injectors. Also, the program objectives of 100 percent CWS-fueled engine operation with the TICS concept without the use of external ignition assist sources up to 1,800 rpm were achieved. The high level of ignition energy in the TICS chamber enabled combustion of CWS fuel in the test engine.

High heat release rates and short combustion durations were observed for the Kentucky Blue Gem seam CWS-fueled engine tests with the TICS concept. The heat release analysis shows a significant portion of the CWS fuel burning in the premixed combustion mode. An increase in CWS injection pressure from 13.8 to 20.7 MPa increased the peak heat release rate. Performance data for coal powder, CWS and diesel-fueled engine tests show higher cylinder pressure and heat release rates for coal powder and CWS compared to diesel fuel. In the case of 100 percent CWS-fueled operation, test data up to 1,800 rpm speed range shows a maximum brake thermal efficiency of 33.5 percent at 1,000 rpm in the single cylinder test engine. However, the brake thermal efficiency in the multi-cylinder CWS-fueled engine will be even higher. The test engine operation was optimized during 45 hours and 40 minutes of 100 percent CWS engine testing during Phase II of the program with further study of the effects of different parameters on the CWS injection and combustion. Amongst them are included: Improved performance with the swirl type precombustion chamber (PCC) design and larger (47cc) PCC volume. There exist optimum values of PCC temperature (982$^{o}$C), nozzle orifice size (1mm), injection timing and exhaust gas recirculation (EGR - 10 percent). Further, gaseous emissions, smoke and particulate measurements were made. Based upon the emissions measurements the combustion efficiency (carbon burnout) was of the order of 99 percent.

To date, no emissions standards have been set for stationary coal fueled engines (regarding NOx, HC, CO, etc. except in California). The stringent 1994 Federal heavy duty truck emission limits are 6.7 g/kW.h NOx, 1.74 g/kW.h HC, 20.8 g/kW.h CO, and 0.13 g/kW.h particulates. The measurements under optimum conditions indicate that the present Caterpillar 1Y73 engine running with CWS and using the TICS combustion system has the potential to meet the 1994 emission standards. Further, it is interesting to note that with the TICS, the temperatures in the combustion chamber could be maintained higher at idle and low loads which could help in lowering HC and CO further. Also, with the CWS operation, the NOx decreased as the load increased which is an added advantage over the diesel and other I.C. engines.

## 1.0 INTRODUCTION

This report entitled "Innovative Coal-Fueled Diesel Engine Injector," is submitted to the U.S. Department of Energy, Morgantown Energy Technology Center (DOE-METC) per the requirements of their contract number DE-AC21-88MC25132. This report describes the results and findings of a research program aimed at development of an electronically controlled coal water slurry (CWS) injection system in conjunction with the Thermal Ignition Combustion System (TICS) to achieve autoignition of CWS.

During the past several years, the U.S. Department of Energy, Morgantown Energy Technology Center, has sponsored research programs for the development of coal-fueled diesel engines [1,2]*. Most of these programs have used coal water slurry as fuel for the engine. The major coal-fueled reciprocating engine development programs are being conducted by General Electric Company [3,4] and A-D Little/Cooper Bessemer [4,5] which 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. In some instances, intake air heating was required to improve the combustion of CWS or to allow the engine operation with 100 percent CWS fuel. The major problem encountered with these engines has been the wear of fuel injection nozzle spray holes, cylinder liners and piston rings. An additional complication of using CWS fuel is that the 50 percent water content cuts the effective fuel heating value in half and requires the injection capacity to be twice that required with diesel fuel to maintain the same power level.

## 2.0 PURPOSE

The purpose of this research investigation was to develop an electronic coal water slurry injection system in conjunction with the Thermal Ignition Combustion System (TICS) concept to achieve autoignition of CWS at various engine load and speed conditions without external ignition sources. The combination of the new injection system and the TICS is designed to reduce injector nozzle spray orifice wear by lowering the peak injection pressure requirements.

## 3.0 BACKGROUND REVIEW OF CWS INJECTION SYSTEMS

The development of CWS injection systems has been the focus of recent investigations by many companies e.g. GE, A.D. Little/Cooper Bessemer, and EMD/SwRI. Earlier research and development work by Southwest Research Institute, NIPER, Sulzer, and Energy and Environmental Research Corporation has resulted in considerable progress in fuel injection systems for coal slurries. However, CWS injectors still need R & D work to achieve the durability required for commercial engine applications.

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

3.1 CWS Injection System by GE

During the investigation of CWS fuel using the GE/7FDL research engine, GE has developed three types of CWS injection systems [6,7] as follows:

- System I fuel injection equipment (FIE) consisted of modified standard size diesel fuel injection equipment with a CWS isolation pump placed between the high pressure pump and the injector to prevent plunger sticking. Due to the low volumetric energy density of CWS compared to diesel fuel, the engine was operated at only 1/3 of full load with 40 MPa maximum injection pressure.

- System II FIE was an up-scaled version of System I FIE capable of supplying CWS for the full load engine operation.

- System III FIE consisted of an accumulator based CWS injection system with high injection pressure at the start of the injection cycle and whose operation is fairly independent of engine speed and load. This injection system has been found to improve CWS burnout considerably at both full and part engine loads. In the CWS accumulator injection system, a conventional jerk pump was used to pump diesel oil to a diaphragm pump. The CWS on the opposite side of the diaphragm was thus pressurized and pushed into the accumulator injector. The accumulator volume of this injector is about 325 cc. The system was sized to inject 3 gm of CWS per injection, with the injection pressure falling from 70 to 48 MPa as injection occurred. GE has evaluated a number of different nozzle geometries - 10 to 12 holes and 0.39 to 0.51 mm hole diameters. The CWS fueled engine test results with the accumulator injector have been presented by Flynn and Hsu [8].

3.2 CWS Injection System by A.D. Little/Cooper Bessemer

Two different types of CWS injection systems were designed and operated on the Cooper JS1 engine [9]. The first was a jerk pump based system using a unique AMBAC injector design. The jerk pump, which handles only diesel fuel, provides the fuel metering function and hydraulic pressure required for the injection. The AMBAC injector provides a barrier between diesel fuel and CWS and uses a multi-hole nozzle for atomization. CWS fuel was supplied either from a pressurized tank or from a holding tank using a Moyno pump.

The second system was based on the Cooper-Bessemer common rail fuel system. Pressurized CWS was supplied by an accumulator and fuel metering was handled by Cooper-Bessemer's common rail unit. Initial tests with the jerk pump system were plagued by mechanical jamming of the moving parts in contact with CWS. Systematic design modifications during Phase I JS testing have solved early problems and CWS tests were conducted for as long as two hours continuously. Most of the injection system development and Phase 2 testing have been with the jerk pump system, while the common rail system remains the backup system. The injection system parameters of jerk pump CWS injection system are as follows:

| | | |
|---|---|---|
| • Nozzle hole size | 0.25 - 0.5 | mm |
| • Injection pressure | 48.3 - 103.4 | MPa |
| • Nozzle opening pressure | 13.8 - 34.5 | MPa |

### 3.3 Technical Problems with CWS Injectors

At the present time in the development of CWS injectors, the fuel injection nozzle is the component with the shortest life. In particular, the standard nozzle hole has been found by GE and A.D. Little/Cooper Bessemer, through CWS-fueled engine test results, to have a useful life time of 3 to 5 hours with CWS fuel operation. This short life of the nozzle makes it the most critical component of the CWS-fueled engine. By using wear resistant materials such as silicon carbide, diamond compact and cubic boron nitride, the nozzle life was extended to about 100 hours. To obtain 2,000 hours of nozzle life however, will require extensive R & D on the various aspects of the CWS injection.

A photograph showing the wear of nozzle hole area after 4.5 hours of full load CWS-fueled GE-7FDL engine testing (Figure 3.3-1) shows highest wear at the center and exit of the hole. The original profile of the hole had a single 0.55 mm diameter, as compared to eroded hole diameters of 0.66 mm at the entry and 0.76 mm at the exit. Due to the nozzle hole wear, the injection pressure fell from about 55 to 47 MPa as shown in Figure 3.3-2. This 15 percent reduction in injection pressure caused unacceptable atomization and combustion characteristics of CWS fuel in the engine. According to GE's wear analysis of nozzles, the wear mechanism of the nozzle hole involves erosion, cavitation and corrosion. GE has used various wear resistant materials to solve the wear problem of the nozzle hole. Figure 3.3-3 shows photographs of single hole orifice through which CWS at 27.6 MPa was continuously flowed. The orifice air erosion tests conducted with different materials show low wear with superhard materials like diamond compact and cubic boron nitride.

### 3.4 TICS Concept by Adiabatics, Inc.

The feasibility of the dry micronized coal powder fueled engine was demonstrated by Adiabatics, Inc. under earlier contracts with the DOE/METC [10,11]. The Thermal Ignition Combustion System (TICS) concept for ignition of fumigated coal powder fuel by means of a precombustion chamber operating at high temperatures was discovered during these programs. Single cylinder engine tests achieved operation with 100 percent coal powder fuel without using external ignition sources. Important features of the coal powder fueled engine test results are as follows [12,13]:

- A simple and reliable coal powder feed system was developed.
- Ability to burn 100 percent coal powder fuel in the engine without external ignition devices like pilot diesel fuel injection or heated intake air was demonstrated.
- Control of the ignition timing of the fumigated coal powder fuel was accomplished by using exhaust gas recirculation (EGR) and controlled TICS chamber temperature. EGR also lowered the peak cylinder pressure, rate of pressure rise, and NOx emissions.
- Cold starting of the 100 percent coal powder fueled engine with a glow plug was demonstrated.
- Coal-fueled engine operation from 800 to 1,800 rpm speed and idle to full load with three types of coals was demonstrated:
  1. Micronized bituminous coal, 7 microns mean size;
  2. Nonbeneficiated 1.6 percent ash content bituminous coal, 21.3 microns mean size; and
  3. 7.1 percent ash content North Dakota lignite coal, 29 microns mean size.

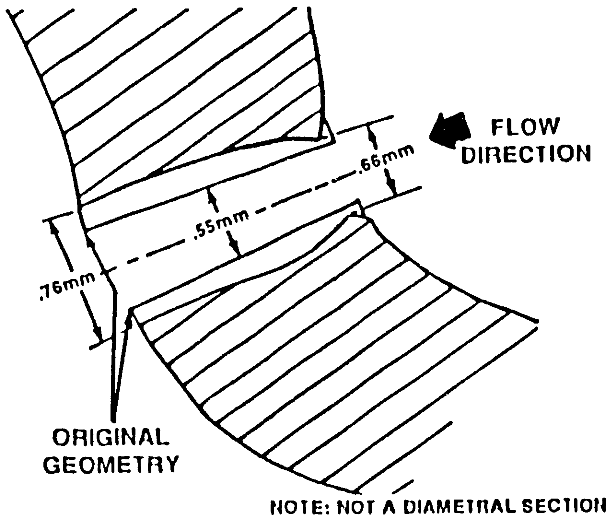


Figure 3.3-1 Cross Section of Steel Nozzle After 4.5 Hours at Full Load on CWS

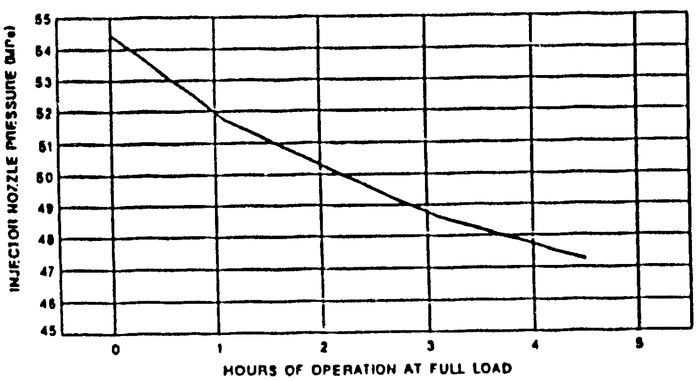


Figure 3.3-2 Reduction in Fuel Injection Nozzle Pressure as a Function of Time on CWS (GE Data)

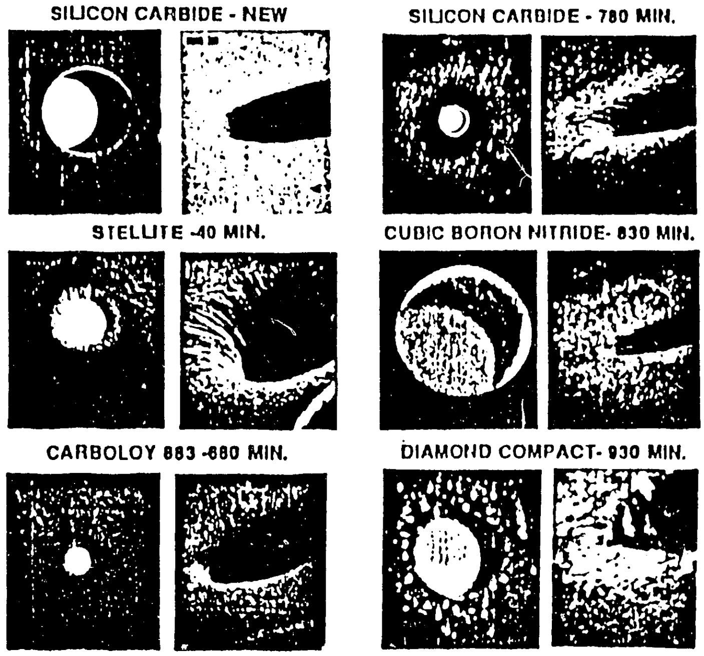


Figure 3.3-3 Erosive Wear of Orifices by Continuous 27.58 MPa (4,000 psi) CWS Flow (GE Data)

This research investigation on fumigated coal-fueled engines revealed that the high amount of ignition energy in the TICS chamber enabled the combustion of even large particle size coal fuel in the test engine. This ignition energy was provided by the uncooled TICS chamber which was operating at high wall temperatures (up to 900°C). Based on these results a research program was initiated by Adiabatics, Inc. to develop an electronically controlled CWS injection system in conjunction with the TICS concept to achieve autoignition of CWS at various engine load and speed conditions without employing diesel pilot ignition assist.

## 4.0 PROJECT METHODOLOGY

This project was intended to develop and demonstrate an Innovative Coal-Fueled Diesel Engine Injector to provide better atomization, less erosion of spray holes, and more durability as compared to the present state-of-the-art CWS injection and the project is described in the following sections. Section 4.1 outlines the project objectives and section 4.2 outlines the technical approach with a brief description of the CWS injector and TICS, the new concept developed by Adiabatics, Inc.

### 4.1 Project Objectives

The project objectives were as follows:

- To develop an electronically controlled hydraulically actuated coal-water slurry (CWS) injection system in conjunction with the thermal ignition combustion system (TICS) to achieve the autoignition of CWS at various engine load and speeds without employing any ignition source such as diesel pilot or natural gas torch.
- To optimize the CWS-fueled injection and combustion systems.
- To monitor the combustion and emissions including the smoke and particulates.
- To obtain some qualitative idea of the wear and durability of the injection system.
- To check the ability of the developed injector to burn 100 percent CWS up to 1,800 rpm.
- To develop an understanding of the problems with the system such as contamination by coal/ash, consistency, and various other maintenance and associated operational problems.

### 4.2 Technical Approach

The technical approach taken to accomplish the project goals was to develop an electronically controlled CWS injection system in conjunction with the TICS concept to achieve auto ignition of CWS without any external ignition sources. The TICS concept developed by Adiabatics, was utilized to achieve the rapid burning of the CWS fuel. This research program has been carried out in two phases each with a series of subtasks as follows:

PHASE I - PRELIMINARY ENGINEERING

- Technology survey and program plan
- Injector design and bench testing
- Preliminary engine tests and analysis
- Topical report

PHASE II - DEVELOPMENT ENGINEERING

- Injector/Engine modifications
- Parametric optimization studies
- Insulated engine testing and analysis
- Emissions, particulate and smoke measurements
- Final report

The key elements of this investigation, namely, the innovative CWS injector and the TICS are described in the following sections:

## 4.3 Innovative CWS Injector

The CWS injection system is an electronically controlled, accumulator system with servo-actuation of the injector valve. A high speed solenoid controlled the CWS injection timing and duration. A schematic of the CWS injection system is shown in Figure 4.3-1. Photographs of the CWS injector with volume type accumulator and its installation on the test engine cylinder head are shown in Figure 4.3-2. Figure 4.3-3 shows photographs of the bladder accumulator used to pressurize CWS up to 20.7 MPa (3,000 psi) pressure and the Micromotion mass flowmeter for measurement of the CWS fuel flow in the engine. The CWS handling system for mixing, storage and filling the bladder accumulator is shown in Figure 4.3-4.

High pressure CWS was provided to the injector at constant pressure from a bladder type accumulator used as a pump. During this test program, CWS pressures ranged from 13.8 to 20.7 MPa (2,000 to 3,000 psi). In order to reduce CWS pressure drop during the injection period, a volume type accumulator was incorporated into the injector body. The accumulator volume for the injector is approximately 180 cc. The CWS injector was sized to inject 0.3 cc of CWS per stroke at the full engine load with the injection pressure falling from 20.7 to 15.5 MPa as injection occurred. Low injection pressures were chosen because CWS was injected directly into the TICS chamber which requires much lower pressure than a direct injection engine and to explore nozzle hole wear at these lower injection pressures.

A standard, water cooled, multi-hole diesel fuel injection nozzle was modified to inject CWS in the test engine, by blocking the existing holes by electron beam welding and then electro-discharge machining (EDM) a single spray hole. Figure 4.3-5 shows a photograph of the modified nozzle and plunger used for the CWS injector. Two different nozzles were made with 0.736 and 0.978 mm diameter spray hole sizes, respectively. Wear resistant materials were not used for the nozzle in the first phase of this program.

The CWS injection was accomplished in the following manner: A magnetic pickup, mounted on the engine camshaft, provided an electronic timing signal to the high speed solenoid valve, which vented the servo-fluid pressure acting on the end of the injector plunger. As a result of the reduced servo-fluid pressure and upward forces acting on the plunger from the high pressure CWS, the nozzle plunger lifts off the seat, thus allowing CWS injection into the test engine combustion chamber. The injection duration was controlled by an electronic driver for the solenoid valve. The CWS injection event was completed by de-activating the solenoid valve, which quickly raised the servo-fluid pressure and forced the plunger back to its seat. A piezoresistive pressure transducer measured the pressure of the CWS being injected upstream of the nozzle hole. Also, a piezoelectric pressure

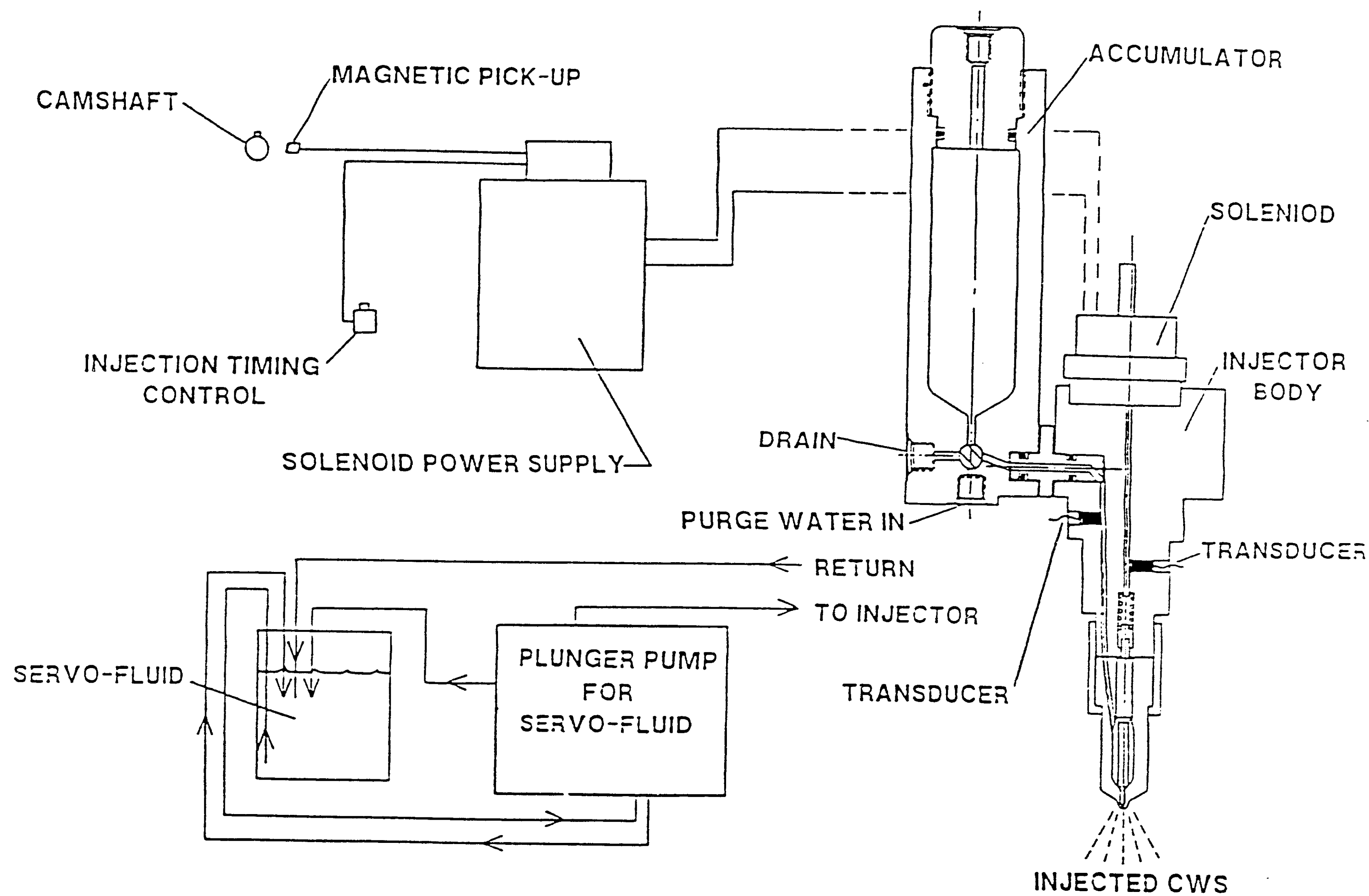


Figure 4.3-1 Schematic of CWS Injection System

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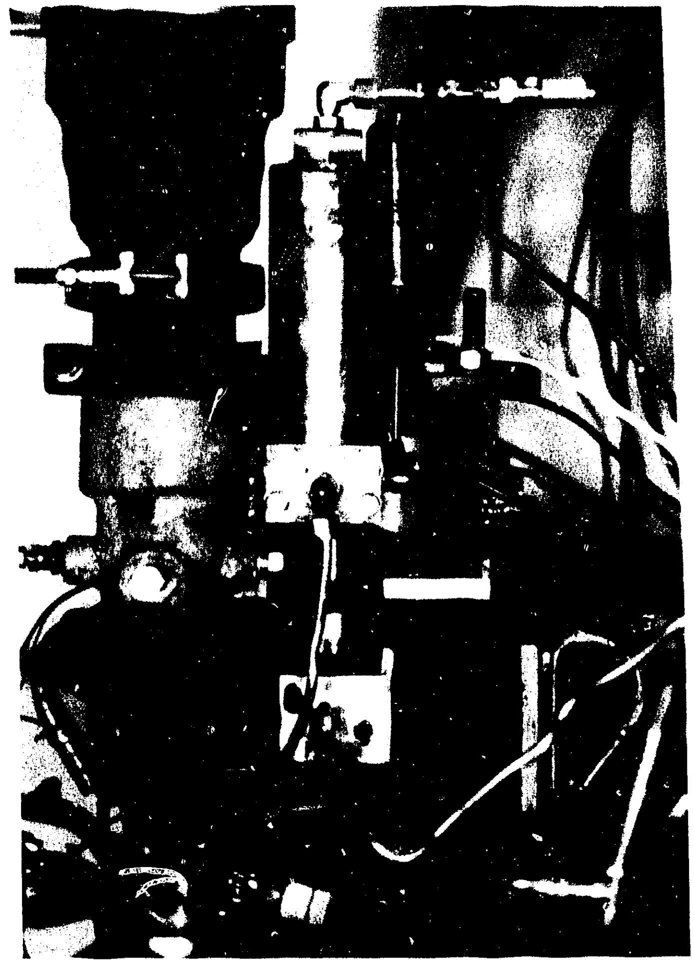

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Figure 4.3-2 Photographs of CWS Injector (with accumulator) and Its Installation on the Test Engine

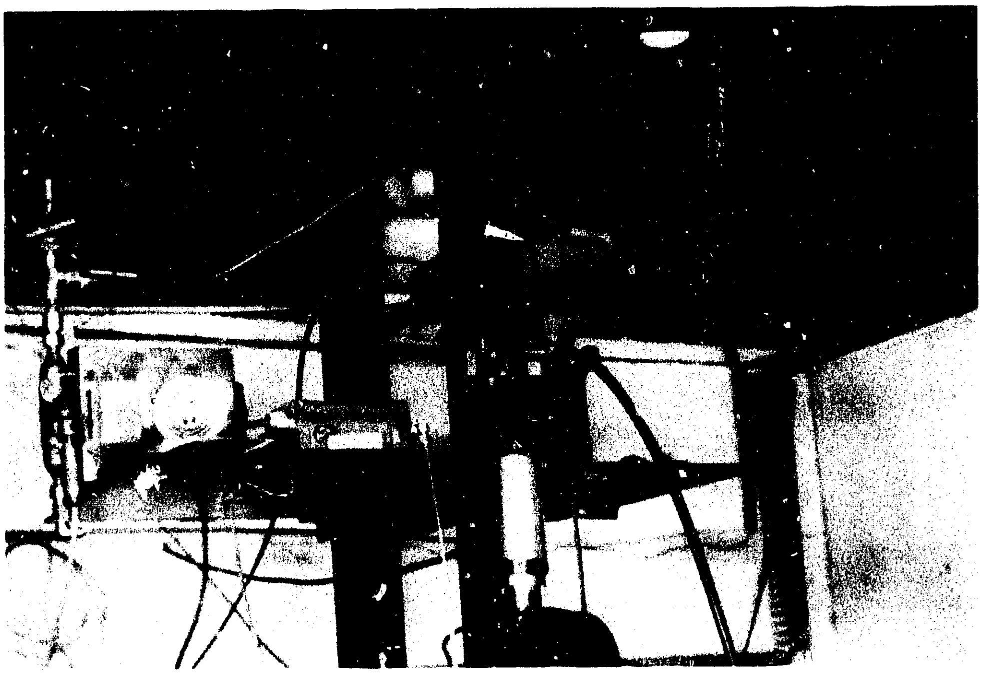

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Figure 4.3-3 Photograph of the Bladder Accumulator and Micromotion Mass Flowmeter Used for the CWS-Injection System

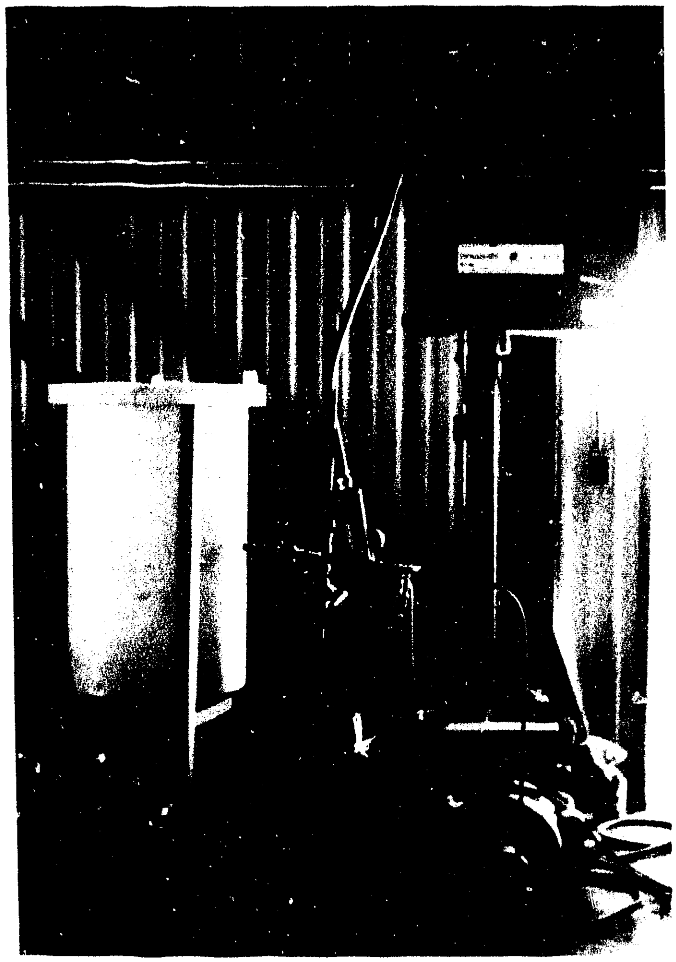

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Figure 4.3-4 Photograph of CWS Handling System Used for the CWS-Injection System

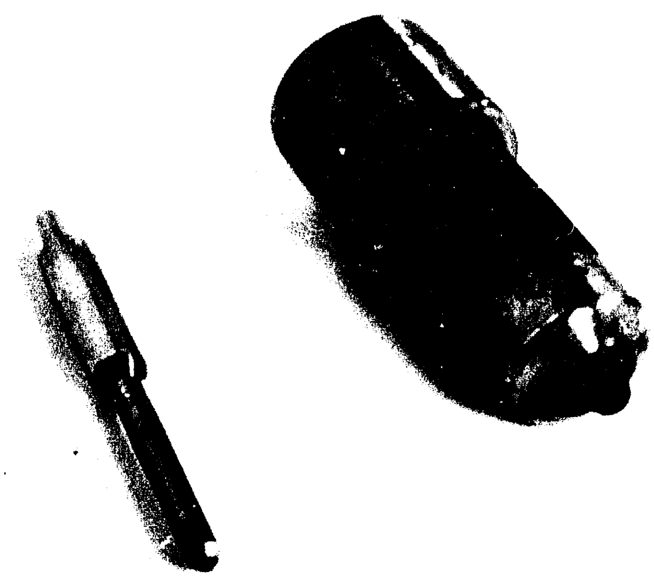

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Figure 4.3-5 Photograph of Modified Fuel Injection Nozzle (with plunger) Used for the CWS Injector transducer was used to measure the servo-fluid pressure. During the engine testing with the CWS injector, these pressures were recorded on a computer for later analysis of the CWS injection timing, pressure and duration as the injection occurred.

A high pressure plunger pump was used for supplying the servo-fluid to the injector body at a constant pressure. The servo-fluid was comprised of water with 1 percent soluble oil additive for rust prevention. Since the solenoid valve was electrically operated, the CWS injector was quite amenable to electronic controls. A magnetic pickup mounted on the engine camshaft provided an electronic timing signal for the start of injection. This signal was then fed to an adjustable electronic timing delay circuit and the modified timing signal then triggered the electronic solenoid driver, thus allowing on-line change in the start of injection timing. The amount of fuel injected per cycle was controlled by electrically varying the injection duration.

## 4.4 Experimental Setup

The experimental set-up consisted of a Caterpillar 1Y73 single-cylinder engine and the newly developed injection system. The performance was determined by measuring various parameters such as load, speed, air and fuel flows, cylinder pressure and various temperatures. In addition, the gaseous emissions were monitored from the exhaust gas, such as, HC, CO, $CO_2$, NOx and smoke and particulates as well. The details on the various systems of the experimental set up are as follows:

### 4.4.1 ENGINE AND EMISSIONS SYSTEMS SETUP

#### Engine Details

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-Hastelloy X |
| Cycle: | 4 Stroke |
| Bore x Stroke: | 130 x 165 mm (5.125 x 6.5 inches) |
| Engine Speed: | 800 to 1,800 rpm |
| Compression Ratio: | 16.5:1 |
| Air Aspiration: | Naturally Aspirated |
| Piston: | Aluminum Alloy with PSZ Thermal Barrier Coating |
| Cylinder Head: | Cast Iron with PSZ Thermal Barrier Coating on Headface. |
| Liner: | Cast Iron with Chrome Oxide Wear-Resistant Coating. |
| Rings: | Top Ring Coated with Chrome Oxide Wear-Resistant Coating. Intermediate and Oil rings were standard. |
| Injector Orifice | M2 Tool Steel |

Figure 4.4.1-1 shows a schematic of the test engine used for the coal-fueled engine tests which shows thermal barrier and wear-resistant

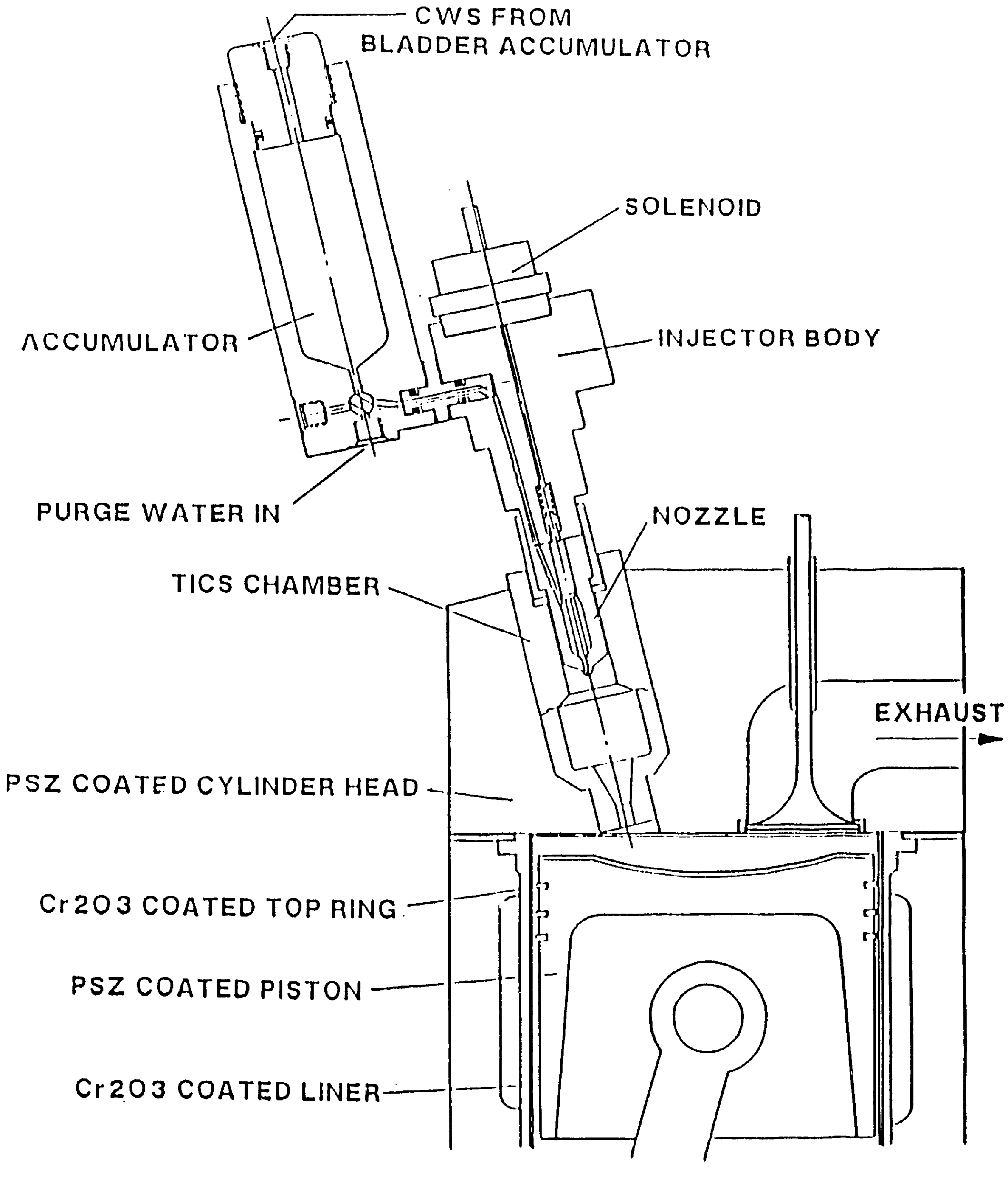



Figure 4.4.1-1 Schematic of Single-Cylinder Test Engine With CWS Injector

ceramic coated engine components, TICS chamber, and CWS injection system. Photographs of the test engine with CWS injector during the CWS-fueled engine tests are presented in Figure 4.4.1-2.

In order to avoid the difficulties encountered at high temperatures with the standard Caterpillar precombustion chamber, a new TICS chamber was designed and fabricated from Hastelloy X, a superalloy material capable of continuously withstanding 1,000°C (1,832°F) temperature. The photograph of the TICS chamber is shown in Figure 4.4.1-3. The geometry of the TICS chamber was kept similar to the standard Caterpillar precombustion chamber. The thermocouples were placed on the outside wall of the lower section of TICS chamber to measure the wall temperature during the coal-fueled engine testing.

The Caterpillar 1Y73 single cylinder test engine components were modified for two purposes. First, the thermal barrier ceramic coatings were used to reduce heat rejection so that the test engine could be operated at higher temperatures to enhance the combustion of CWS fuel. The engine components - cylinder head face and piston top 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, the cylinder liner surface was coated with a thin coating of wear-resistant chrome oxide to reduce wear of piston rings and cylinder liner by the abrasive coal powder and ash. Also, the top ring design incorporated step gap sealing for reducing blow-by and both plasma spray chrome oxide or chrome carbide coatings for the wear resistance.

The test engine lubrication system consists of a metal wire mesh full flow oil filter, an auxiliary lubricating oil pump, centrifugal by-pass oil filters (capable of separating coal particles down to 0.1 micron size), and an electric oil heater (to preheat the lubricating oil to 90°C before the engine tests). This improved lubrication system proved to be very effective during the CWS-fueled engine tests and demonstrated effective filtration of the lubricating oil contaminated with unburned coal powder and ash. Also, the engine oil pressure was more stable during the slurry coal-fueled engine testing than in the past coal powder fumigated engine testing.

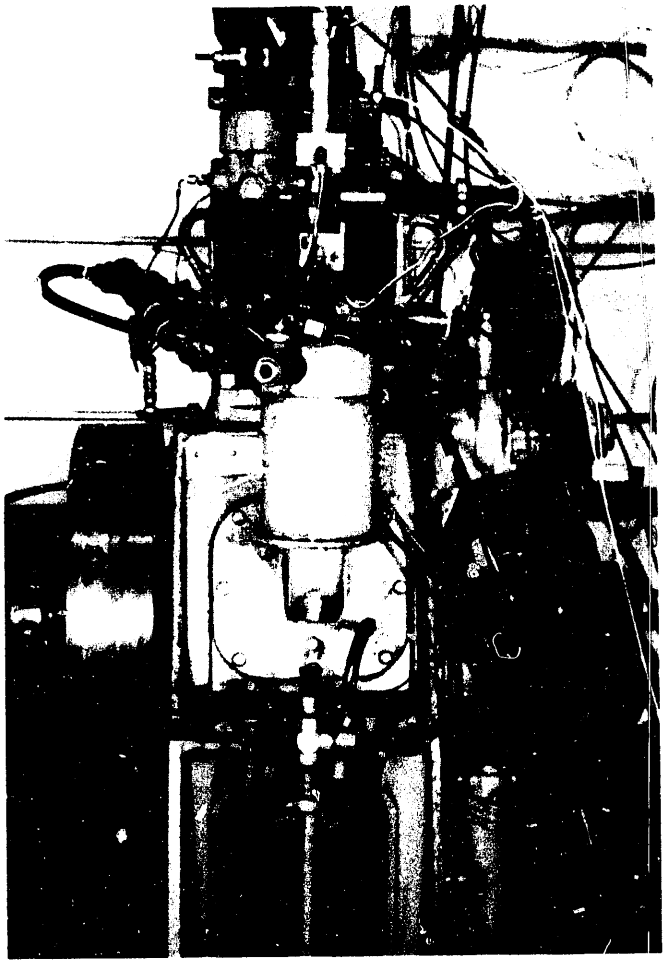
The test engine was equipped with instrumentation for collecting the following performance data during the coal-fueled engine testing:

- Engine speed and load
- Flow rates - CWS (Micromotion Mass Flowmeter, model D25)
  - Air (Orifice meter)
- Pressures - Intake, exhaust, blow-by and oil
- Temperatures - Intake, exhaust, lubricating oil, and wall temperatures of TICS chamber.
- Cylinder pressure - AVL 8QP500CA pressure transducer, BEI optical encoder, and a high speed data acquisition system.

<u>Emissions System</u>

The gaseous emissions were measured using the following analyzers:

CO: Beckman model 870 NDIR analyzer
$CO_2$: Beckman model 8/0 NDIR analyzer



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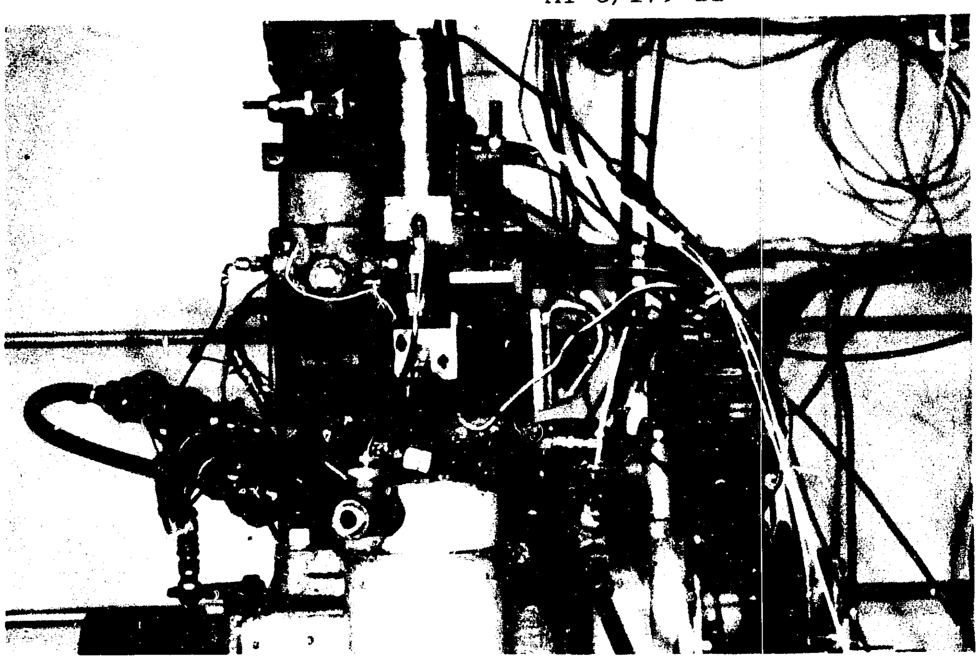

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Figure 4.4.1-2 Photographs of the Single Cylinder Test Engine With the CWS Injector

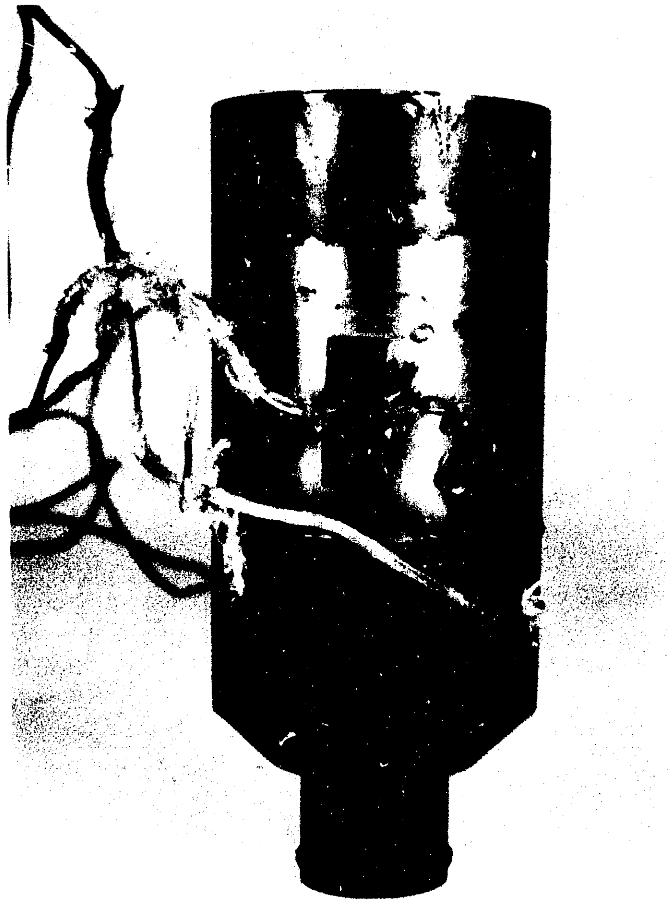

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Figure 4.4.1-3 Photograph of TICS Chamber Made From Hastelloy X

HC: Beckman model 400A FID analyzer
NOx: Beckman model 955 Chemiluminescent analyzer

Further, the smoke was measured with an AVL model 409 smokemeter and particulates were measured at selected times with a full flow ceramic foam filter made up of Lithium and Aluminum Silicate with 2.56 pores per millimeter.

The emission sample tube which transports the exhaust gas from the engine to the emissions analyzers was unheated throughout all engine testing.

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. 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.

### 4.4.2 TYPES OF CWS FUEL

The CWS fuel, procured from Otisca Industries, was prepared from Kentucky Blue Gem seam and Taggert seam bituminous coals. The specifications of these CWS fuels are presented in Table 4.4.2-1. Taggert seam CWS was used for the CWS injector bench testing and the initial engine testing. However, Blue Gem seam CWS was used for all the subsequent engine testing because of its better burning.

## 5.0 RESULTS AND DISCUSSION

The results obtained during Phases I and II of the investigation are presented as follows:

### 5.1 Preliminary Engineering - PHASE I

This section presents the program results and discussion for the bench and preliminary engine testing of the CWS injector. Also, the performance obtained with various other fuels such as dry coal powder [12,13] and diesel fuel (DF #2) using the innovative CWS injector is presented.

### 5.1.1 Bench Testing of CWS Injector

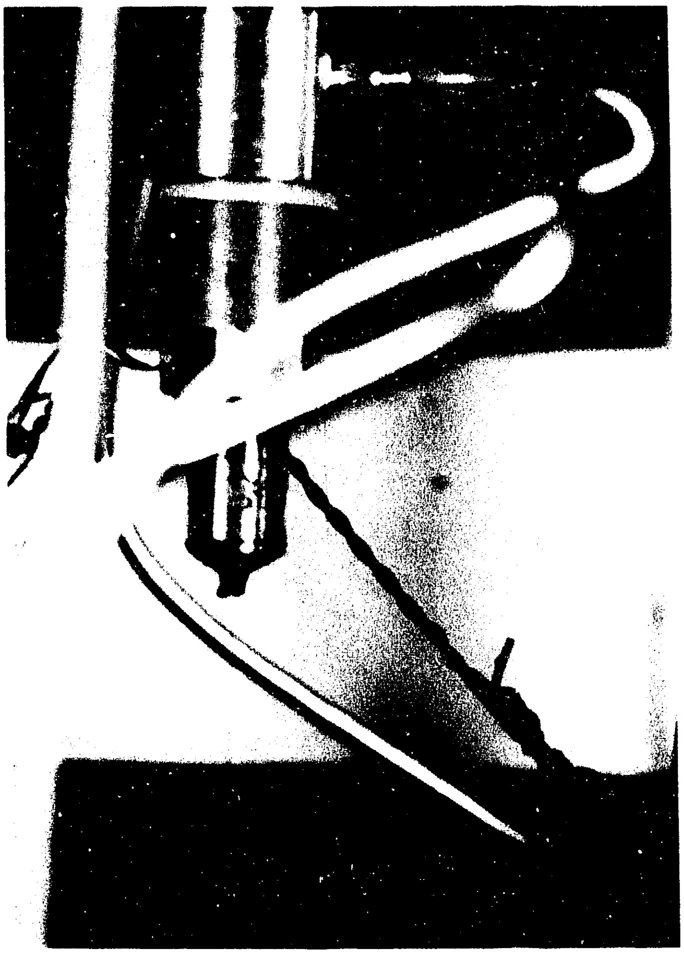
The bench testing of CWS injector with accumulator was conducted with the Taggert seam CWS. The CWS injector was bench tested over an equivalent engine speed range of 440 to 1,800 rpm by injecting CWS outside the engine while the test engine was operating on diesel fuel No. 2. An external trigger from the test engine camshaft provided the timing signals for the injection of CWS. A standard steel fuel injector nozzle with a single 0.97 mm diameter nozzle spray hole was bench tested with CWS from 13.8 to 20.7 MPa pressure (2,000 to 3,000 psi) for a total duration of 4.5 hours. Nozzle hole wear was negligible and could not be measured during this bench testing. Figure 5.1.1-1 shows photographs of the CWS injector on the test bench and an injection event for the CWS at 20.7 MPa (3,000 psi) pressure.

CWS injector bench test results showed excellent operation as per design

Table 4.4.2-1

**ANALYSIS OF CWS FUELS USED**

| | | |
|---|---|---|
| Coal type: | Blue Gem seam | Taggert seam |
| Beneficiated: | Yes | Yes |
| Solids loading: | 49 % | 50% |
| Viscosity: (at 112 per sec.) | 170 cp | 41 cp |
| Lower Heating Value: | 32,797 kJ/kg (14,100 Btu/lb) | 32,564 kJ/kg (14,000 Btu/lb) |
| Particle Size at 50 Mass Percent: | 3.3 microns | 2.9 microns |
| Maximum: | 11.5 microns | 9.5 microns |
| Proximate Analysis: | | |
| Ash % | 0.85 | 0.83 |
| Total Sulfur % | 0.95 | 0.69 |
| Volatile % | 40.11 | 35.58 |
| Fixed Carbon % | 59.04 | 63.59 |



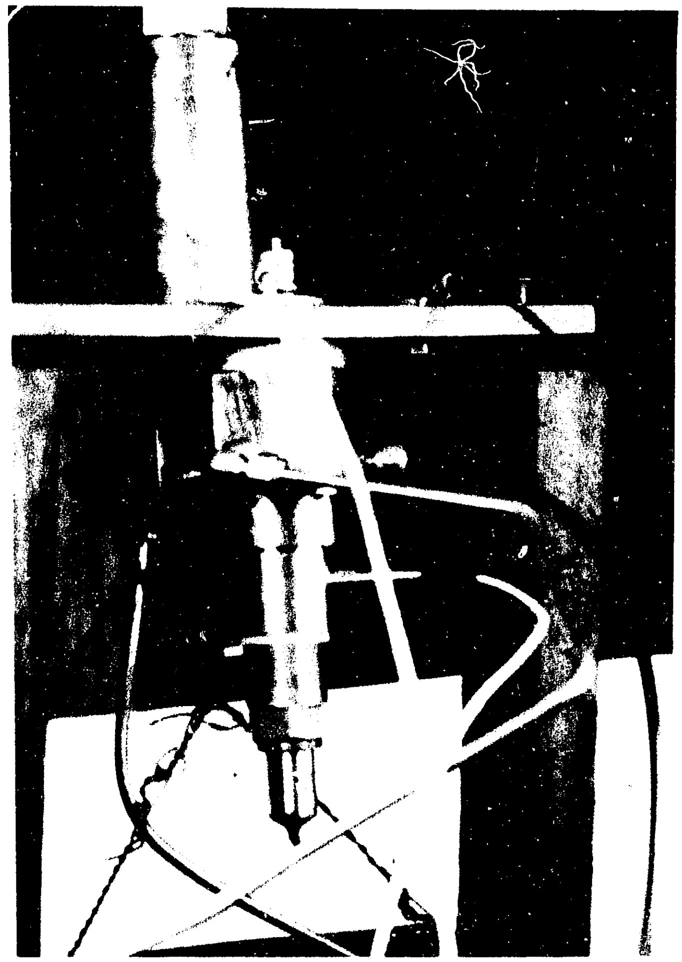


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Figure 5.1.1-1 Photographs of CWS Injector During Bench Testing With the Taggert Seam CWS specifications at various engine speeds. CWS pressure and flow rates were based upon visual observations and CWS injection pressure vs. time during the injection period. The analysis of CWS injection pressure vs. time (crank angle) measurements indicated a maximum of 20 percent drop in the CWS pressure during the injection period at higher CWS flow rates. However, the CWS pressure drop was only 5 to 15 percent at lower CWS flow rates. The CWS injector with 0.97 mm nozzle hole was capable of injecting from 30 to more than 300 $mm^3$ slurry per stroke. Thus, the CWS-fueled engine operation would be possible from idle to full load engine condition at various engine speeds. The slurry injection duration was adjustable from 1.5 ms to about 10 ms (9 to 60 degrees crankangle at 1,000 rpm engine speed). Also, the start of injection timing was varied from 100 degree BTDC to TDC with a resolution of 0.1 degree interval with the electronic timing device. This on line change in the injection timing was found to be useful during the later CWS-fueled engine testing. The CWS fuel injection pressure was varied from 13.8 to 20.7 MPa by applying different air pressure to the bladder accumulator.

The CWS and servo-fluid pressures diagrams recorded during the bench testing with Taggert seam CWS at 20.7 MPa pressure are presented in Figures 5.1.1-2 and 5.1.1-3. These pressure diagrams provide valuable information about the CWS injection pressure vs. timing (crank angle), start and end of injection and injection duration. As shown in Figures 5.1.1-2 and 5.1.1-3, CWS injection durations are 2.52 and 4.52 ms for the two cases, respectively.

### 5.1.2 Engine Test Summary and Wear Results

Table 5.1.2-1 presents a summary of the CWS-fueled engine tests conducted and the nozzle hole wear data. The last line of data presented in the table shows a high wear rate of the injector nozzle hole which was the result of testing at high engine speeds (up to 1,800 rpm). As mentioned before, a standard steel nozzle without wear-resistant materials or coatings was used for the CWS-fueled engine tests. Figure 5.1.2-1 shows scanning electron microscope photomicrographs of the 1 mm nozzle hole after 4.5 hours bench test with Taggert seam CWS, and 9.25 hours engine test with Taggert seam and Blue Gem seam CWS. The nozzle hole appears to have retained its original cylindrical shape and the diameter seems to be uniform along the length of the hole. Figure 5.1.2-2 presents photographs of the CWS injector, and the nozzle seat and plunger after CWS-fueled engine tests. No wear was observed on the nozzle seat or plunger during this program. Leakage of the servo-fluid past the plunger into the CWS probably was beneficial in avoiding the upward flow of CWS in the nozzle. Because of this fact, the CWS did not cause wear of the plunger.

The test engine teardown after the CWS-fueled tests did not reveal any problems or deposits on the engine components. Figures 5.1.2-3 and 5.1.2-4 show photographs of the piston, cylinder liner, cylinder headface, and intake and exhaust valves after CWS-fueled engine testing.

### 5.1.3 Performance with CWS, Dry Coal Powder and Diesel (DF#2) Fuels

The preliminary test results obtained with CWS fuels were compared with the engine test results for combustion of dry coal powder and diesel fuel No. 2 (DF#2) in Table 5.1.3-1 and Figures 5.1.3-1 and 5.1.3-2. The results indicate much higher heat release rates and shorter combustion duration for the coal powder fuel. The coal powder fuel, fumigated with the intake air, was ignited by the TICS chamber and exhaust gas recirculation was used to

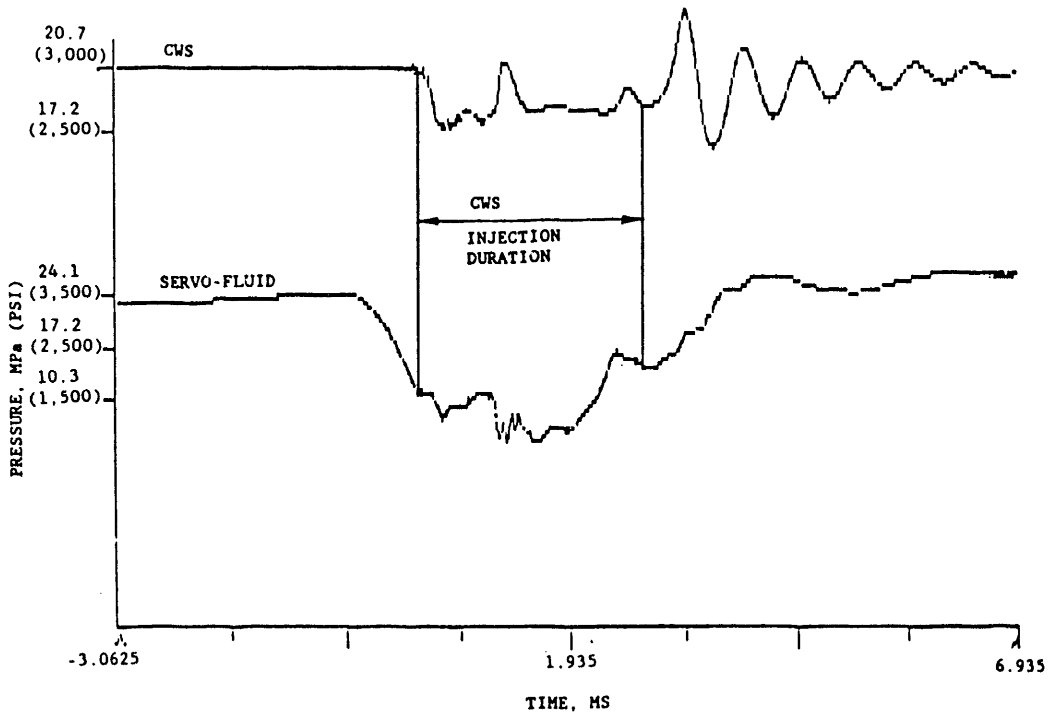


Figure 5.1.1-2 CWS and Servo-fluid pressures vs. Time during the Bench Testing with Taggert Seam CWS
Injections Per Minute = 500
Injection Duration = 2.52 ms
CWS Injected = 196 $mm^3$/stroke

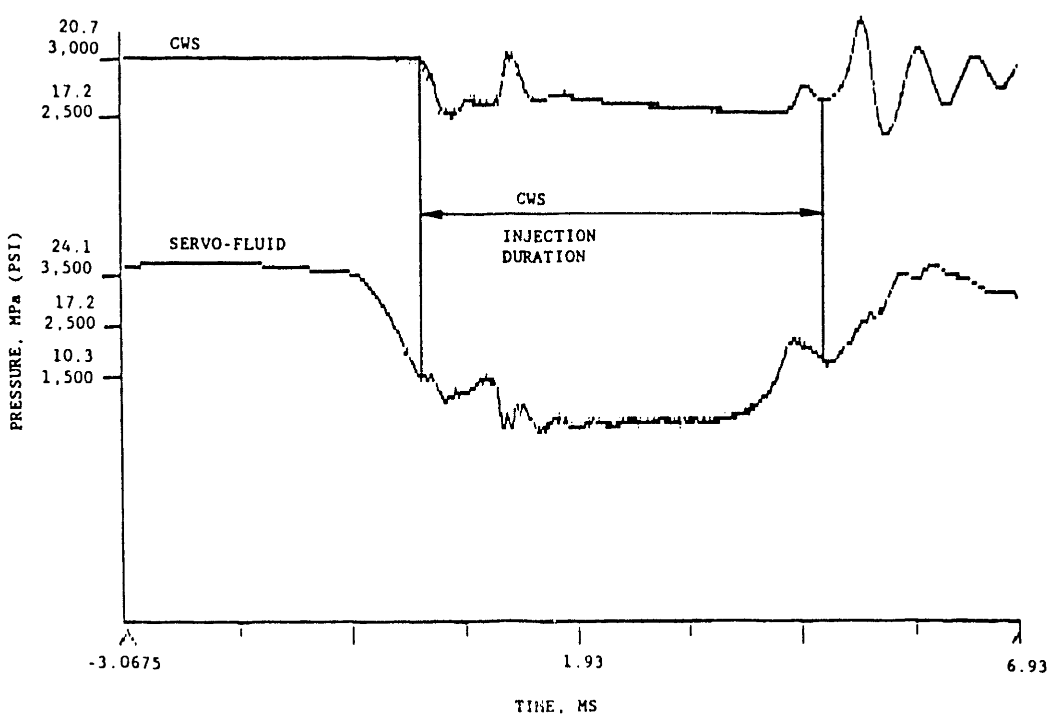


Figure 5.1.1-3 CWS and Servo-fluid pressures vs Time during the Bench Testing with Taggert Seam CWS
Injection Duration = 4.52 ms
CWS Injected = 358 $mm^3$/stroke

Table 5.1.2-1

## SUMMARY OF INITIAL CWS-FUELED ENGINE TESTS AND NOZZLE HOLE WEAR DATA IN PHASE I (STANDARD STEEL NOZZLE WITH SINGLE HOLE SPRAY)

| NOZZLE ID | COAL TYPE | CWS PRESSURE MPa | RUN TIME HR : MIN | NOZZLE HOLE SIZE, MM (INCH) BEGIN | END | FLOW AREA INCREASE, % | WEAR RATE, MM/MIN X $10^{-4}$ (IN/MIN) X $10^{-6}$ |
|---|---|---|---|---|---|---|---|
| A | TAGGERT SEAM | 13.8 | 3 : 38 | 0.9779 (0.0385) | 0.9906 (0.039) | 2.6 | 0.58 (2.3) |
| A | BLUE GEM SEAM | 13.8 TO 20.7 | 5 : 45 | 0.9906 (0.039) | 1.0414 (0.041) | 10.5 | 1.47 (5.8) |
| B | BLUE GEM SEAM | 13.8 TO 20.7 | 4 : 26 | 0.7366 (0.029) | 0.7493 (0.0295) | 3.5 | 0.48 (1.9) |
| B | BLUE GEM SEAM | 20.7 | 2 : 20 | 0.7493 (0.0295) | 0.8382 (0.033) | 25.1 | 6.35 (25.0) |

TOTAL ENGINE TEST DURATION
WITH TAGGERT SEAM AND
BLUE GEM SEAM COALS: 16 : 09

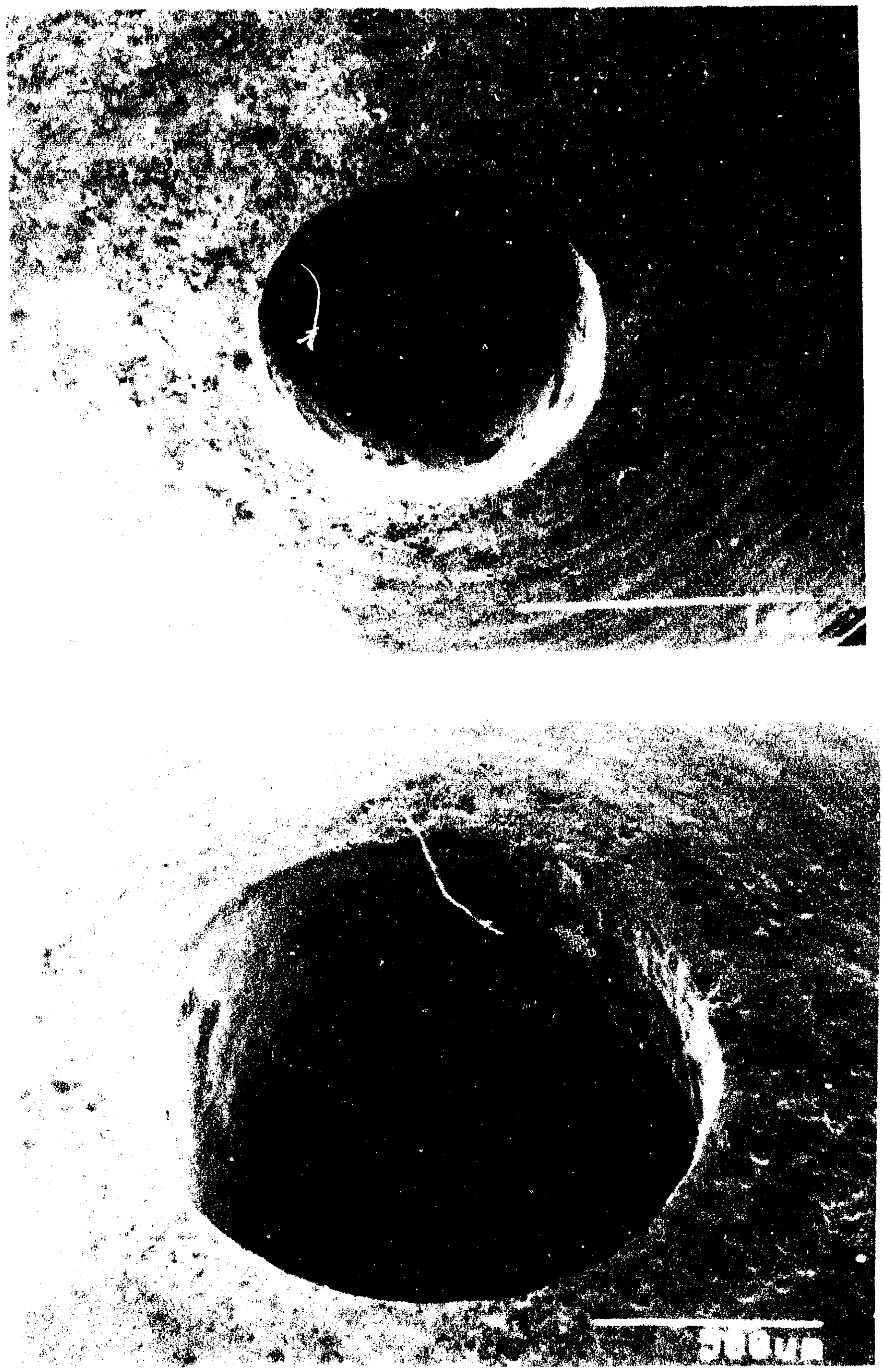

Figure 5.1.2-1 SEM Photomicrographs of Nozzle Hole after CWS-Fueled Bench and Engine Tests (Nozzle ID = A, see Table 5.1.2-1 for data)

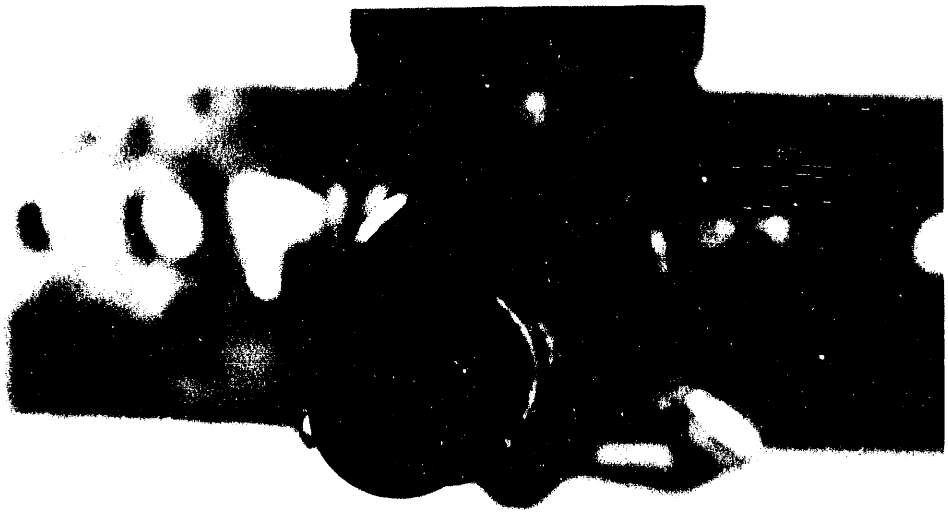

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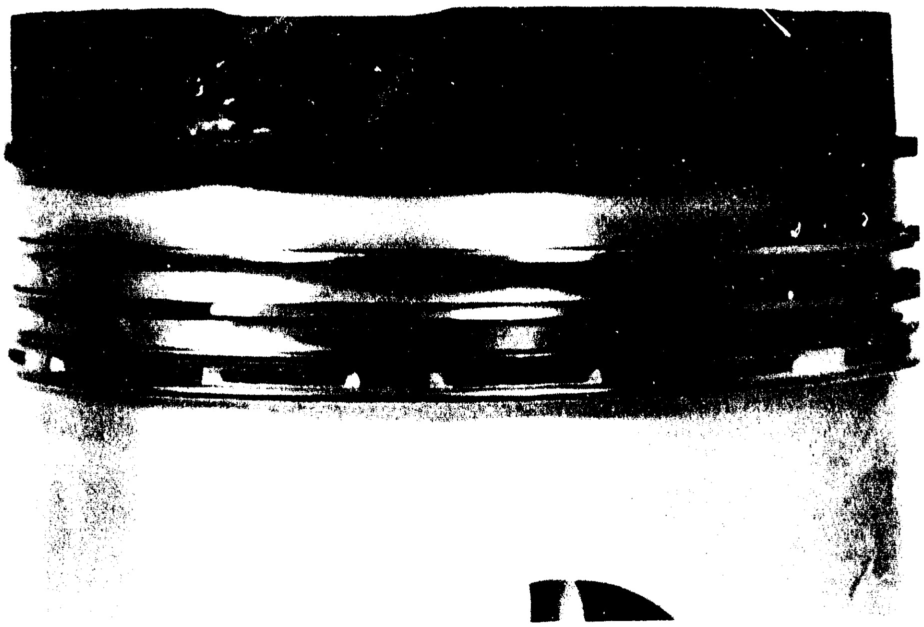
Figure 5.1.2-2 Photographs of CWS Injector, and Nozzle and Plunger After CWS-Fueled Engine Tests



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AI-C/181-14

Figure 5.1.2-3 Photographs of Piston After CWS-Fueled Engine Tests

AI-C/182-24A

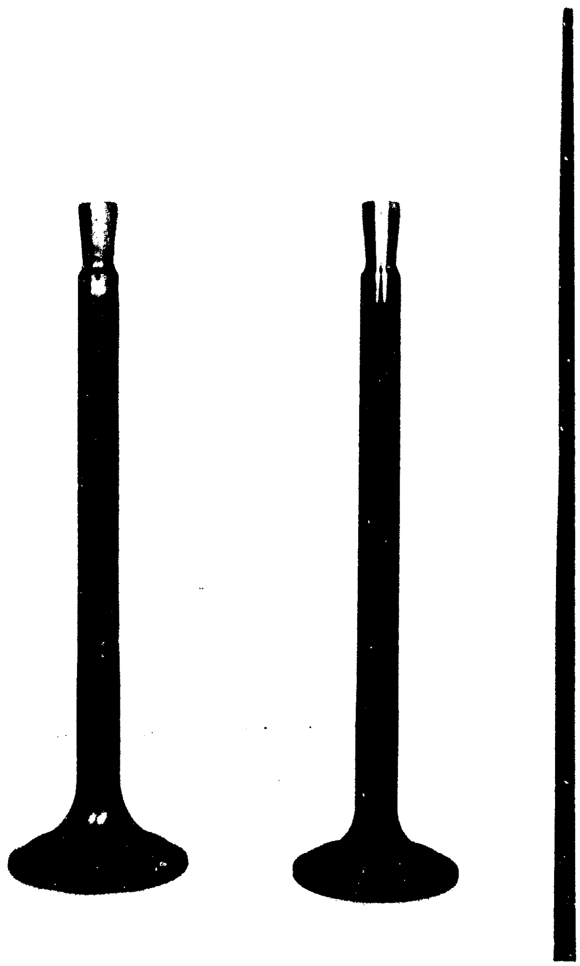

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Figure 5.1.2-4 Photographs of Cylinder Head, and Intake and Exhaust Valves After CWS-Fueled Engine Tests

Table 5.1.3-1

COMPARISON OF CWS, COAL POWDER and DF-2
FUELED ENGINE PERFORMANCE

| FUEL | CWS | COAL POWDER | DF-2 |
|---|---|---|---|
| TEST NUMBER | 0824GCL | 0819KCL | 0902CDF |
| ENGINE SPEED, rpm | 1,000 | 1,000 | 1,000 |
| INJ. TIMING, deg BTDC | 29 | Fumigated | 8 |
| % EGR | 0 | 26.0 | 0 |
| BRAKE POWER, kW | 7.8 | 7.5 | 7.7 |
| INDICATED POWER, kW | 9.2 | 11.7 | 10.4 |
| IMEP, kPa | 500 | 640 | 569 |
| PEAK CYLINDER PRESSURE, MPa (at deg ATDC) | 5.32 (7) | 7.12 (8) | 4.38 (12) |
| PEAK RATE OF PRESSURE RISE, MPa/deg (at deg ATDC) | 0.285 (3) | 0.48 (4) | 0.069 (9) |
| <u>EMISSIONS</u> | | | |
| CO, g/bhp-hr (lb/MMBtu) | 18.1 (4.41) | NM | 1.1 (0.28) |
| $CO_2$, % | 12.4 | 17.0 | 6.3 |
| HC, g/bhp-hr (lb/MMBtu) | 0.3 (0.07) | 2.0 (0.26) | 0.2 (0.04) |
| NOx, g/bhp-hr (lb/MMBtu) | 3.1 (0.76) | 5.0 (0.65) | 3.7 (0.96) |
| SMOKE, Bosch | NM | NM | NM |

NM - Not Measured

Emissions measurement was not certified

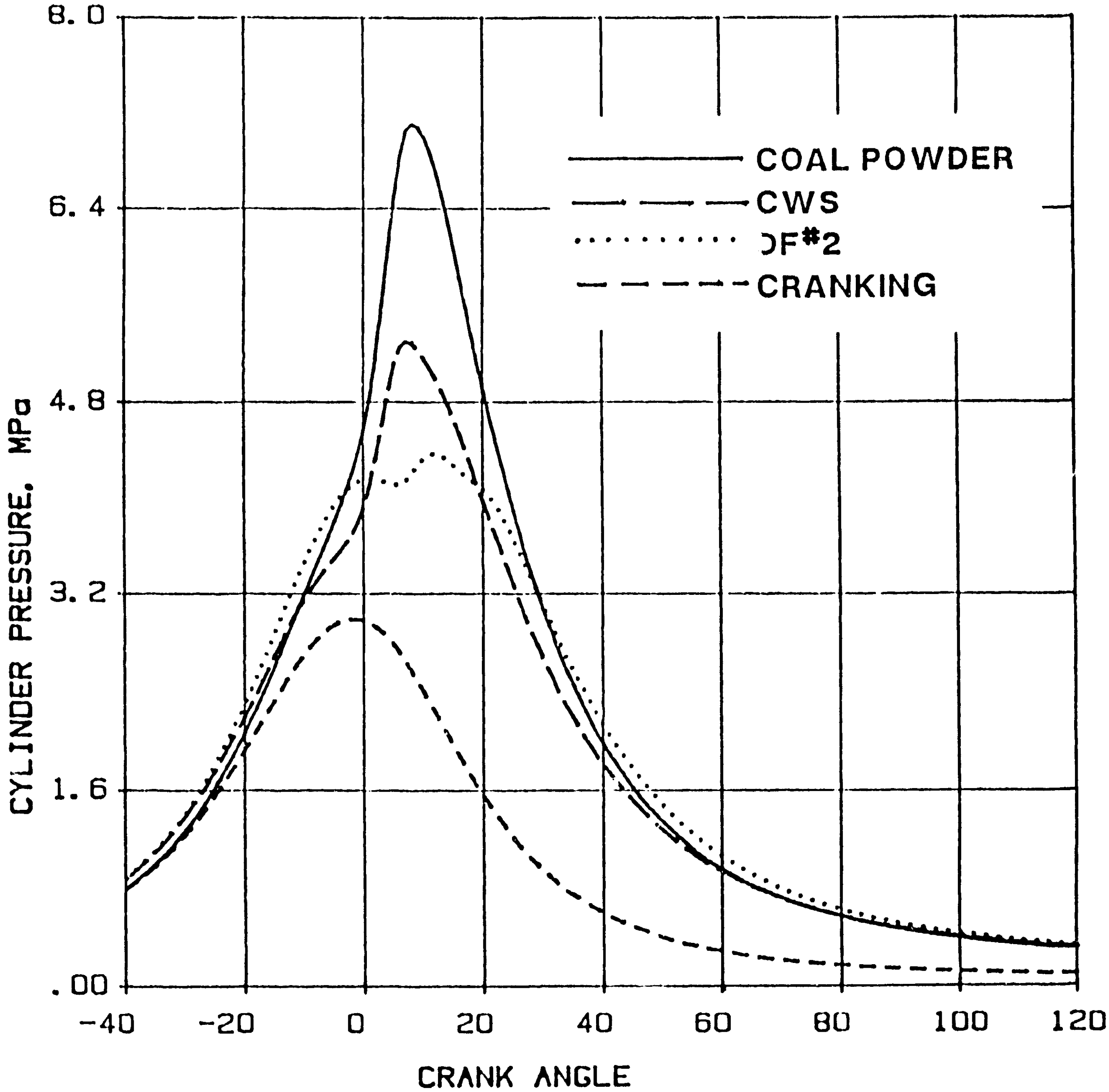


Figure 5.1.3-1 Comparison of Cylinder Pressure Data for Coal Powder, CWS and DF#2 at 1,000 RPM Engine Speed

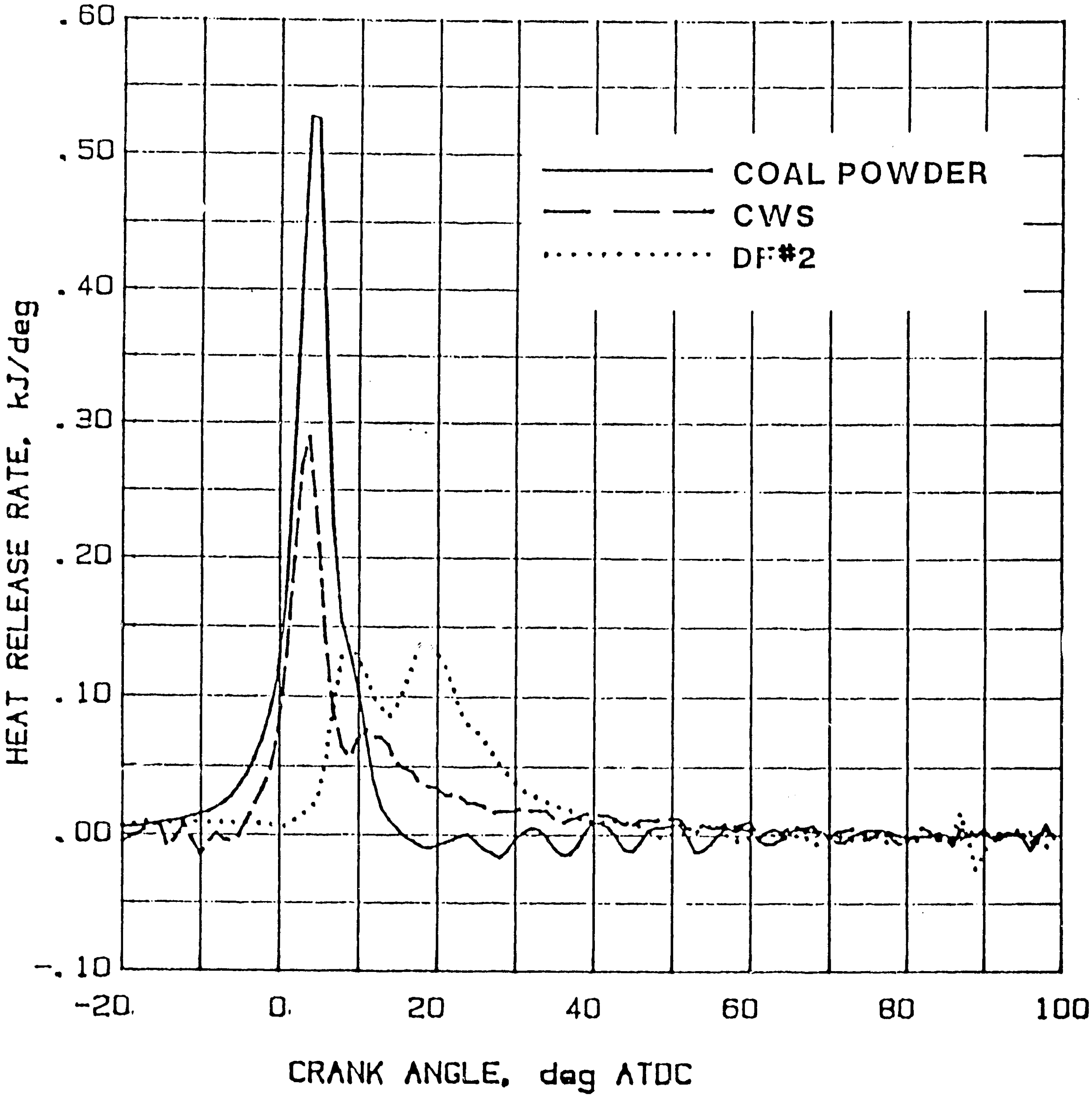


Figure 5.1.3-2 Comparison of Heat Release Data for Coal Powder, CWS and DF#2 at 1,000 RPM Engine Speed

control the ignition timing [13]. The engine testing with DF#2 was carried out using the standard Caterpillar diesel fuel injector [13], while the CWS-fueled engine tests were carried out with the CWS injector developed in this program. The CWS injection pressure and nozzle hole diameter were 20.7 MPa and 1.016 mm, respectively. TICS chamber made from Hastelloy X was used for all three fuels discussed here.

A comparison of the cylinder pressure data shows highest peak cylinder pressure and peak rate of pressure rise for the coal powder combustion. The peak cylinder pressure for coal powder, CWS and DF#2 were 7.12, 5.32 and 4.38 MPa, respectively. Also, the heat release analysis results in Figure 5.1.3-2 show highest peak heat release rate for the coal powder and lowest peak heat release rate for the DF#2. For coal powder and CWS combustion, a major portion of the heat release was seen to be during the premixed combustion mode, whereas DF#2 heat release results show a significant portion of the heat release during the diffusion combustion mode. Also, the shapes of coal powder and CWS heat release rates were more concentrated near TDC.

The NOx level for the CWS was the lowest, followed closely by the DF#2. The peak cylinder temperature, one of the primary causes of thermal generated NOx, was reduced by the additional heat required to vaporize the water in the CWS. Coal powder fuel gave the highest NOx emissions because of higher peak cylinder temperature. However, the CO for the CWS was much higher, which suggests that there was still optimization of the test engine parameters to be carried.

### 5.1.4 Effect of Engine Load

The engine test results for the part to full load 100 percent CWS-fueled engine operation at 1,000 rpm engine speed are presented in Table 5.1.4-1. These engine tests were conducted with Blue Gem seam coal using nozzle B, 0.7366 mm hole diameter, and 20.7 MPa CWS injection pressure. A comparison of the cylinder pressure and heat release data presented in Figures 5.1.4-1 and 5.1.4-2, shows rapid heat release rates and shorter combustion duration at various engine loads.

The cylinder pressure and the rate of pressure rise values refer to the main combustion chamber. The heat release model was used to compute the gross heat release rate (including heat transfer to combustion chamber walls and crevice volume) from the cylinder pressure data. The heat release data for the lower engine loads, 272 and 340 kPa IMEP, show that most of the burning was in the premixed combustion mode, whereas 500 kPa IMEP data show both premixed and diffusion combustion modes. As expected the peak heat release rate increases with the engine load. The pressure-volume diagram shows effectively constant volume combustion for the CWS (see Figure 5.1.4-3).

### 5.1.5 Effect of Engine Speed

Preliminary engine test results from 1,200 to 1,800 rpm speed range are presented in Table 5.1.5-1 and Figures 5.1.5-1 and 5.1.5-2. These 100 percent CWS-fueled engine tests were conducted without external ignition assist with nozzle B (0.7493 mm hole diameter) and 20.7 MPa CWS injection pressure. The data shows maximum brake thermal efficiency of 27.9 percent and maximum peak cylinder pressure of 5.4 MPa (783 psi) at 1,400 rpm engine speed. The test data at 1,600 and 1,800 rpm engine speeds shows lower peak cylinder pressures

TABLE 5.1.4-1

100% CWS-FUELED ENGINE PERFORMANCE AT VARIOUS LOADS

Otisca Blue Gem Coal
Hastelloy X chamber temp = 730 to 760+ C
Intake air temp = 71 C
CWS Injection Pressure (at begin) = 20.7 MPa
Nozzle Hole Diameter = 0.7366 mm (0.029 inch)

| TEST NUMBER | 0824ICL | 0824HCL | 0824GCL |
|---|---|---|---|
| ENGINE SPEED, rpm | 1,000 | 1,000 | 1,000 |
| LOAD, ft.lb | 26.0 | 34.4 | 55.1 |
| (N.m) | (35.3) | (46.6) | (74.7) |
| INJ. TIMING, deg BTDC | 32 | 30 | 29 |
| FUEL FLOW, kg/mm | 0.055 | 0.066 | 0.105 |
| AIR/DRY FUEL RATIO | 33.2 | 27.7 | 17.4 |
| BRAKE POWER, kW | 3.7 | 4.9 | 7.8 |
| BRAKE THERMAL EFF., % | 25.2 | 27.8 | 28.2 |
| INDICATED POWER, kW | 5.0 | 6.2 | 9.2 |
| IMEP, kPa | 272 | 340 | 500 |
| PEAK CYLINDER PRESSURE, MPa | 4.96 | 5.21 | 5.32 |
| (at deg ATDC) | (6) | (8) | (7) |
| PEAK RATE OF PRESSURE RISE, MPa/deg | 0.221 | 0.244 | 0.285 |
| (at deg ATDC) | (2) | (3) | (3) |
| PEAK HEAT RELEASE RATE, kJ/deg | 0.192 | 0.252 | 0.291 |
| (at deg ATDC) | (2) | (4) | (4) |
| <u>EMISSIONS</u> | | | |
| CO, g/bhp-hr | 17.6 | 11.1 | 18.1 |
| (lb/MMBtu) | (3.84) | (2.67) | (4.41) |
| $CO_2$, % | 5.7 | 7.6 | 12.4 |
| HC, g/bhp-hr | 0.4 | 0.2 | 0.3 |
| (lb/MMBtu) | (0.09) | (0.06) | (0.07) |
| NOx, g/bhp-hr | 5.6 | 6.8 | 3.1 |
| (lb/MMBtu) | (1.23) | (1.63) | (0.76) |
| SMOKE, Bosch | NM | NM | NM |

NM = Not Measured

Emissions measurement was not certified

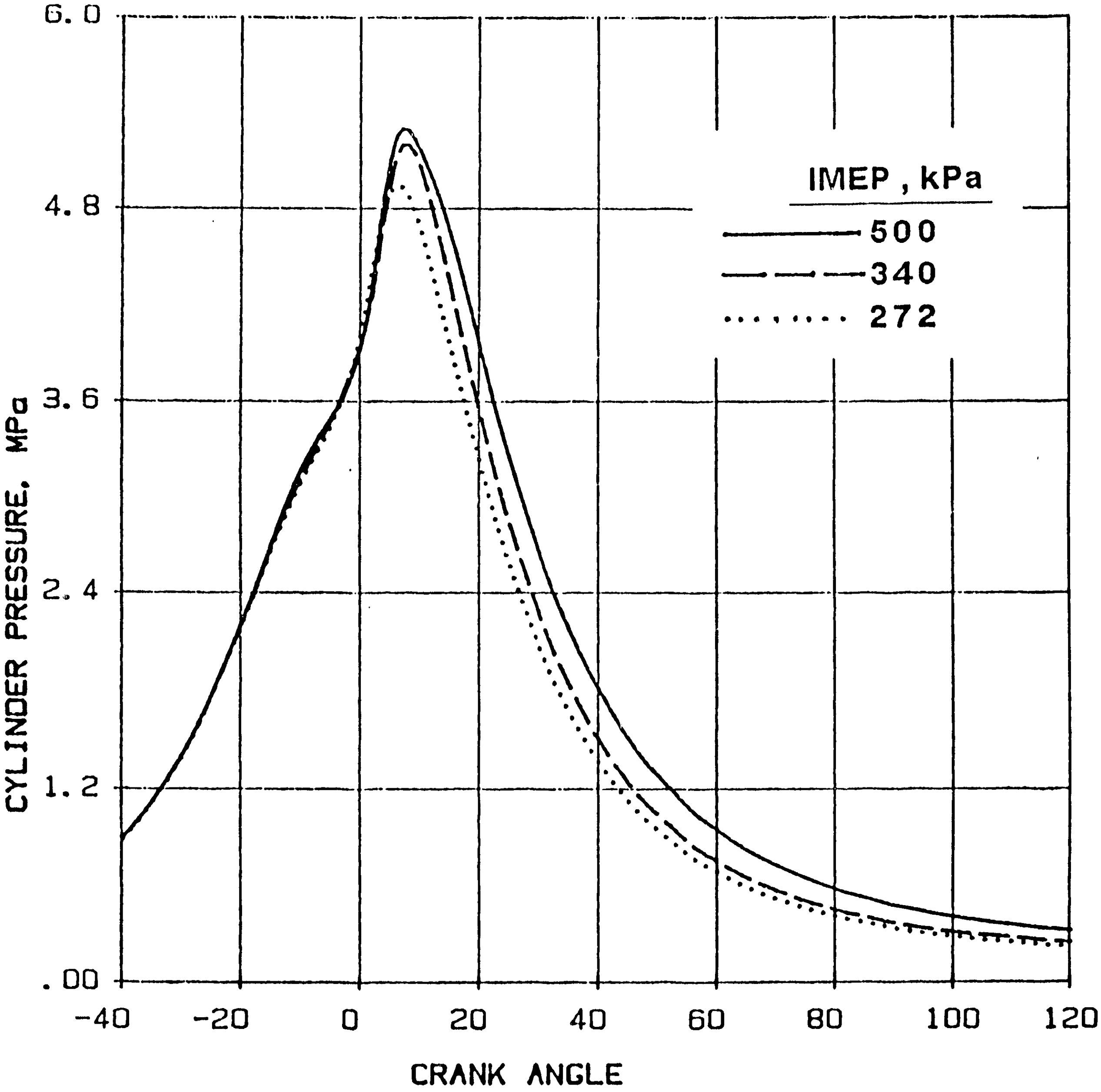


Figure 5.1.4-1 Cylinder Pressure Diagrams for Blue Gem Seam CWS-Fueled Engine Tests at Different-Loads (see Table 5.1.4-1)
Engine Speed - 1,000 RPM

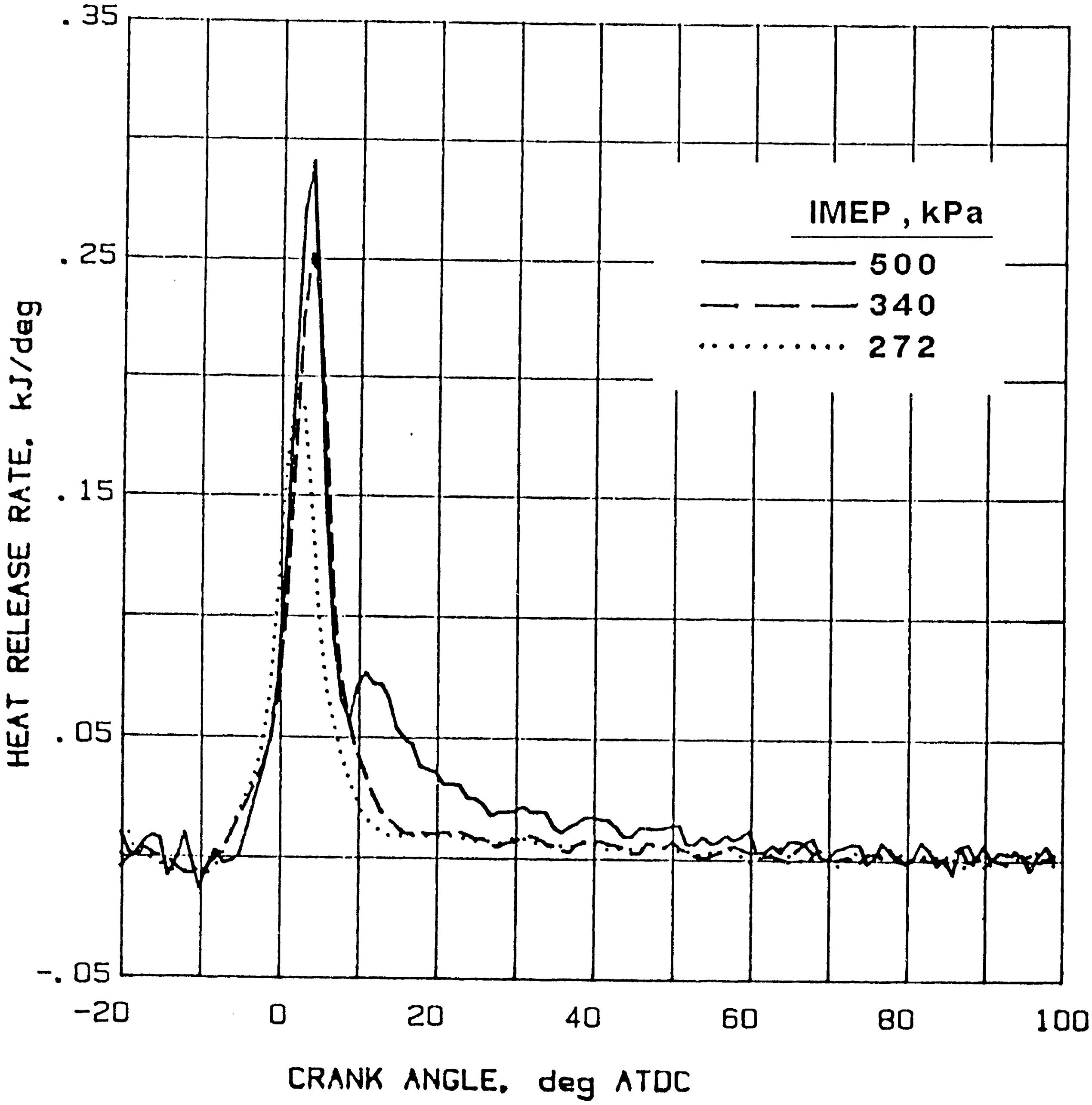


Figure 5.1.4-2 Heat Release Diagrams for Blue Gem Seam CWS-Fueled Engine Tests at Different-Loads (see Table 5.1.4-1) Engine Speed - 1,000 RPM

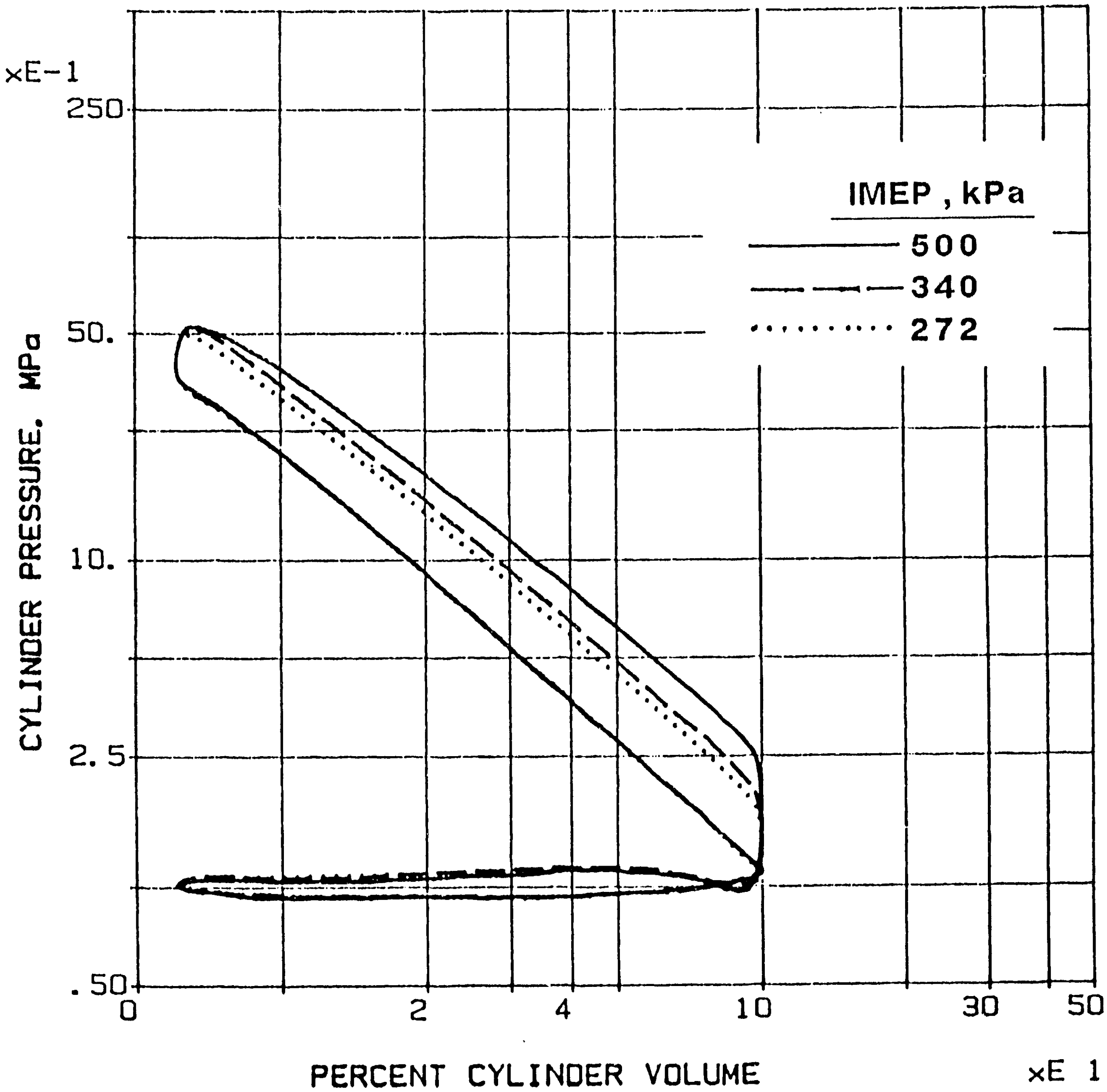


Figure 5.1.4-3 Pressure Volume Diagrams for Blue Gem Seam CWS-Fueled Engine Tests at Different-Loads (see Table 5.1.4-1)
Engine Speed = 1,000 RPM

TABLE 5.1.5-1
100% CWS-FUELED ENGINE PERFORMANCE AT VARIOUS SPEEDS

Otisca Blue Gem Coal
Hastelloy X chamber temp = 752 to 856°C
Intake air temp = 56 to 77°C
CWS Injection Pressure (at begin) = 20.7 MPa
Nozzle Hole Diameter = 0.7493 mm (0.0295 inch)

| TEST NUMBER | 0929FCL | 0929HCL | 0929KCL | 0929ICL |
|---|---|---|---|---|
| ENGINE SPEED, rpm | 1,200 | 1,400 | 1,600 | 1,800 |
| LOAD, ft.lb | 24.1 | 34.9 | 39.0 | 29.1 |
| (N.m) | (32.7) | (47.3) | (52.9) | (39.5) |
| INJ. TIM., deg BTDC | 30 | 30 | 30 | 30 |
| START OF COMBUSTION, deg BTDC | 3 | 5 | 7 | 4 |
| FUEL FLOW, kg/mm | 0.072 | 0.0948 | 0.138 | 0.138 |
| AIR/DRY FUEL RATIO | 30.7 | 28.0 | 22.6 | 25.6 |
| BRAKE POWER, kW | 4.1 | 6.9 | 8.9 | 7.4 |
| BRAKE THER. EFF., % | 21.7 | 27.9 | 24.4 | 20.6 |
| IND. POWER, kW | 6.4 | 9.4 | 12.0 | 12.4 |
| IMEP, kPa | 292 | 368 | 409 | 376 |
| PEAK CYLINDER PRESSURE, MPa (at deg ATDC) | 5.36 (7) | 5.42 (7) | 5.04 (5) | 4.69 (7) |
| PEAK RATE OF PRES. RISE, MPa/deg (at deg ATDC) | 0.281 (3) | 0.241 (3) | 0.10 (1) | 0.078 (2) |
| PEAK HEAT RELEASE RATE, kJ/deg (at deg ATDC) | 0.292 (4) | 0.243 (3) | 0.082 (1) | 0.091 (5) |
| <u>EMISSIONS</u> | | | | |
| CO, g/bhp-hr (lb/MMBtu) | 10.9 (2.06) | 5.4 (1.32) | 10.9 (2.30) | 15.5 (2.78) |
| $CO_2$, % | 6.8 | 7.4 | 8.8 | 9.3 |
| HC, g/bhp-hr (lb,MMBtu) | 0.2 (0.04) | 0.1 (0.03) | 0.3 (0.06) | 0.4 (0.08) |
| NOx, g/bhp-hr (lb/MMBtu) | 10.6 (1.99) | 7.8 (1.88) | 6.1 (1.29) | 9.5 (1.70) |
| SMOKE, Bosch | NM | NM | NM | NM |

NM = Not Measured

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Emissions measurement was not certified

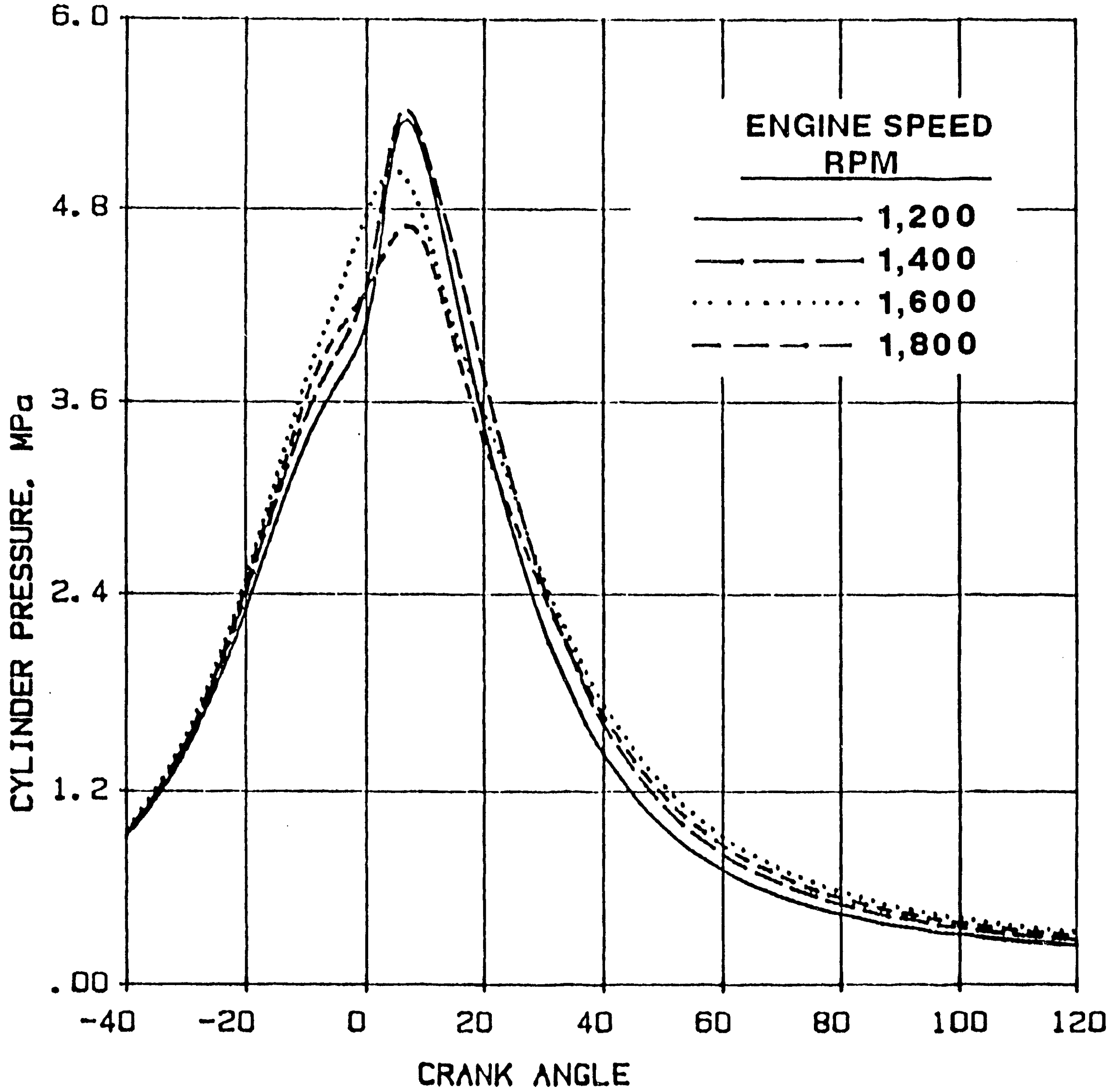


Figure 5.1.5-1 Cylinder Pressure Data for 100% Blue Gem Seam CWS-Fueled Engine Tests at Different Speeds

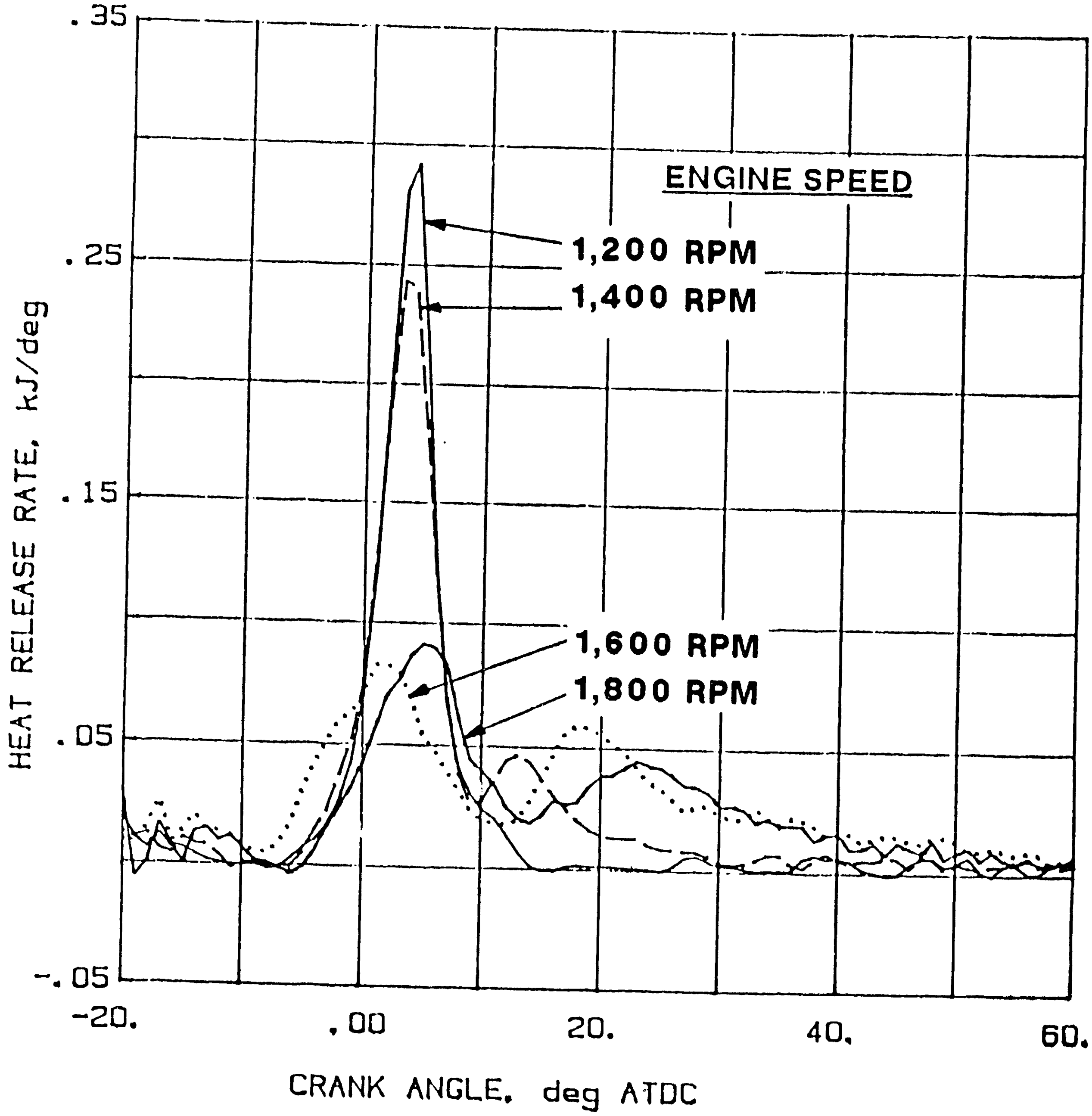


Figure 5.1.5-2 Heat Release Data for 100% Blue Gem Seam CWS-Fueled Engine Tests at Different Speeds

and brake thermal efficiency because of lower intake air temperature and non-optimized CWS injection timing.

These results demonstrate the feasiblity of CWS-fueled engine operation up to 1,800 rpm. This speed range is typical of many current heavy duty diesel engines.

5.1.6 Effect of CWS Injection Pressure

The effect of CWS injection pressure on the cylinder pressure and heat release rate data in Figures 5.1.6-1 and 5.1.6-2 shows an increase in the peak heat release rate with an increase in the injection pressure from 13.8 to 20.7 MPa. This behavior was expected because of better CWS atomization and lower Sauter mean diameter at the higher injection pressures [14]. The lower injection pressures resulted in lower wear of the nozzle hole and a less complicated CWS injection system when compared to data reported for other CWS injectors.

## 5.2 Development Engineering - PHASE II

During Phase II, both the CWS injector and prechamber designs were modified in an attempt to optimize the injector and engine performance.

In order to provide a more durable injector spray hole, and to facilitate measurement of the spray hole wear, the fuel injector has been modified to incorporate a replaceable spray orifice insert (shown in Figure 5.2-1). The orifice insert is a simple flat disk with a hole in its center which is clamped to the injector. Disks were fabricated from tungsten carbide, silicon nitride and M2 tool steel. Of the three disk materials, only the M2 tool steel disk was engine tested.

Engine testing was performed with three different nozzle hole diameters (1, 0.91 and 0.76 mm). The predicted performance of these three nozzle hole diameters are shown in Figure 5.2-2 which plots injection duration at 1,800 rpm versus hole diameter at constant injection pressure for the maximum flowrate required by the engine.

The one piece Hastelloy X prechamber used during Phase I was modified to enable the configuration to be easily changed. First, the prechamber was made into two parts (a top half and a bottom half). The prechamber halves were clamped together and sealed with a gasket. The two piece prechamber greatly reduced machining costs since one top half was used with different bottom halves. The second prechamber modification was a machining change to accommodate the new CWS injector nozzle cap which housed the replaceable spray insert orifice. A photograph of the modified CWS injector and prechamber is shown in Figure 5.2-3.

For each injector and prechamber configuration, engine data was obtained at each of the following test conditions:

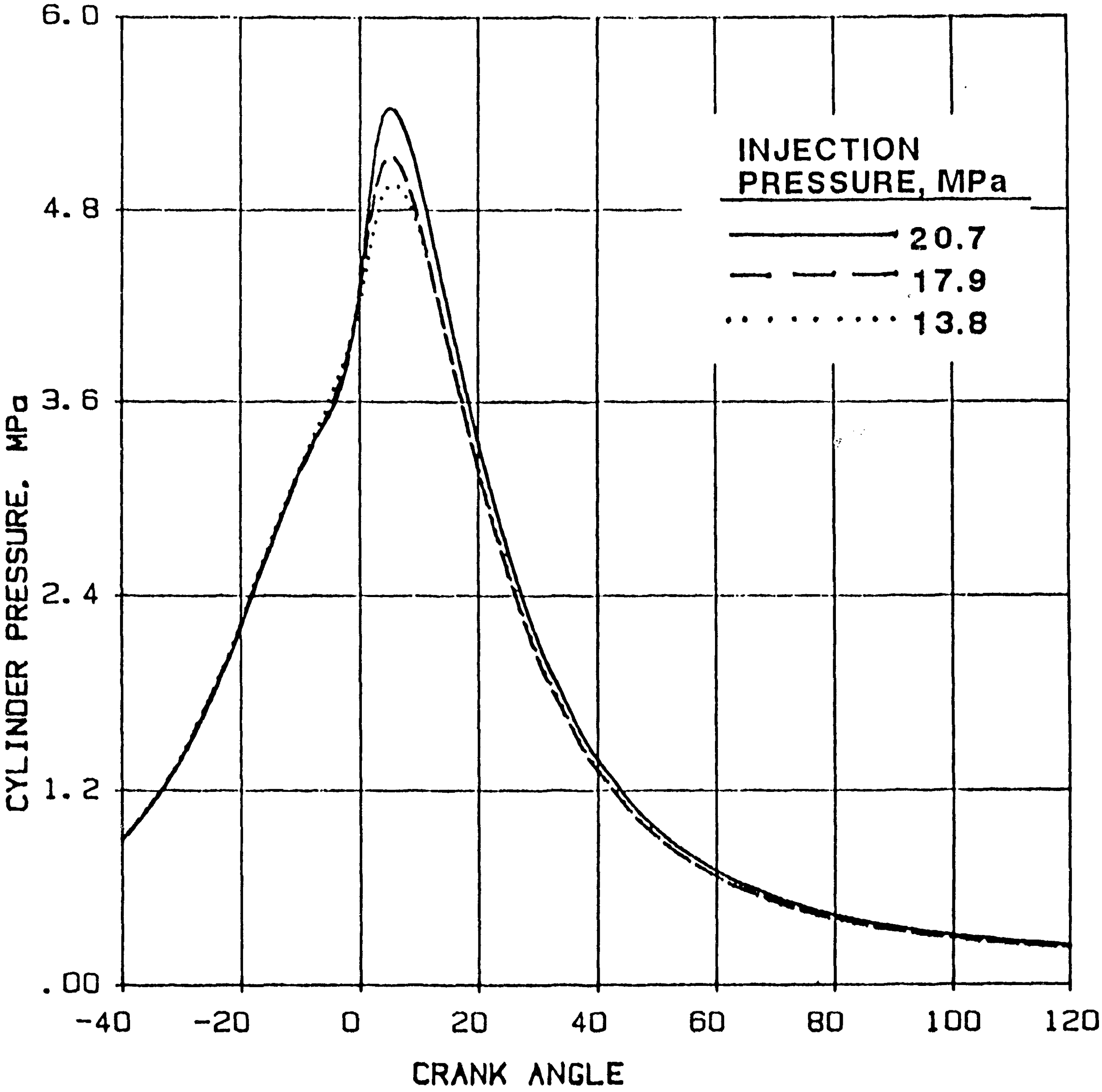


Figure 5.1.6-1 Cylinder Pressure Data for CWS-Fueled Engine Tests From 13.8 to 20.7 MPa CWS Injection Pressures (Engine Speed = 1,000 RPM)

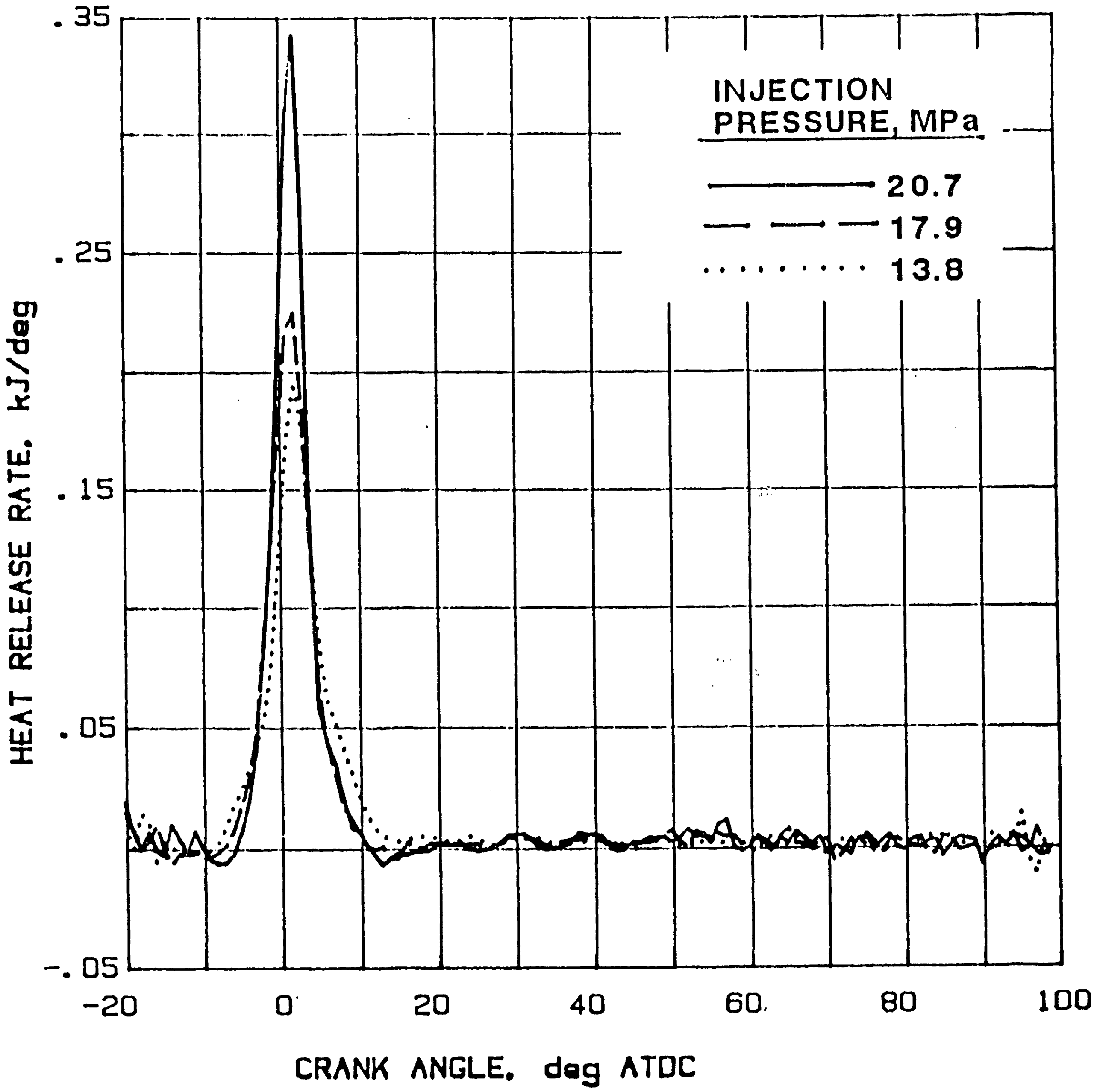


Figure 5.1.6-2 Heat Release Data for CWS-Fueled Engine Tests From 13.8 to 20.7 MPa CWS Injection Pressures (Engine Speed = 1,000 RPM)

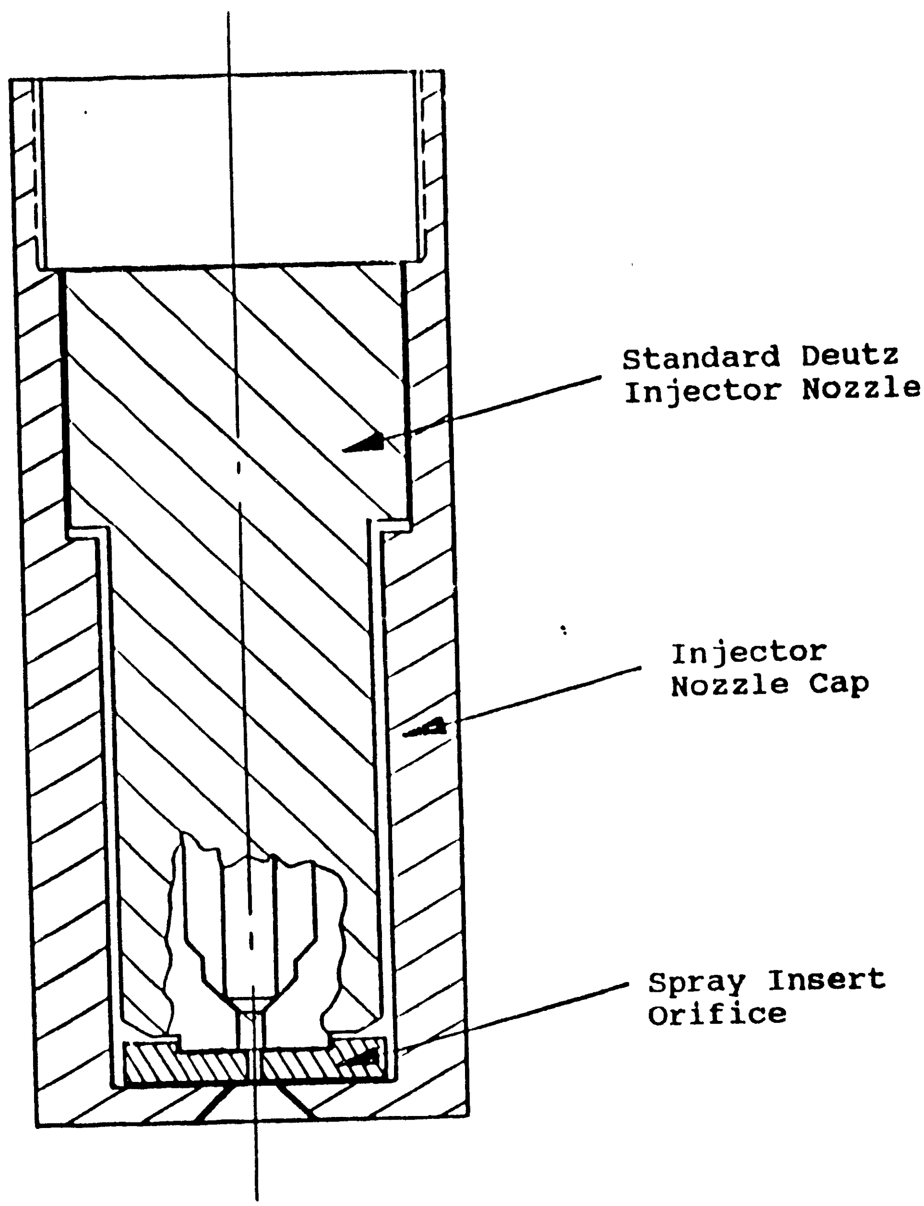


Figure 5.2-1 CWS Injector Nozzle Assembly

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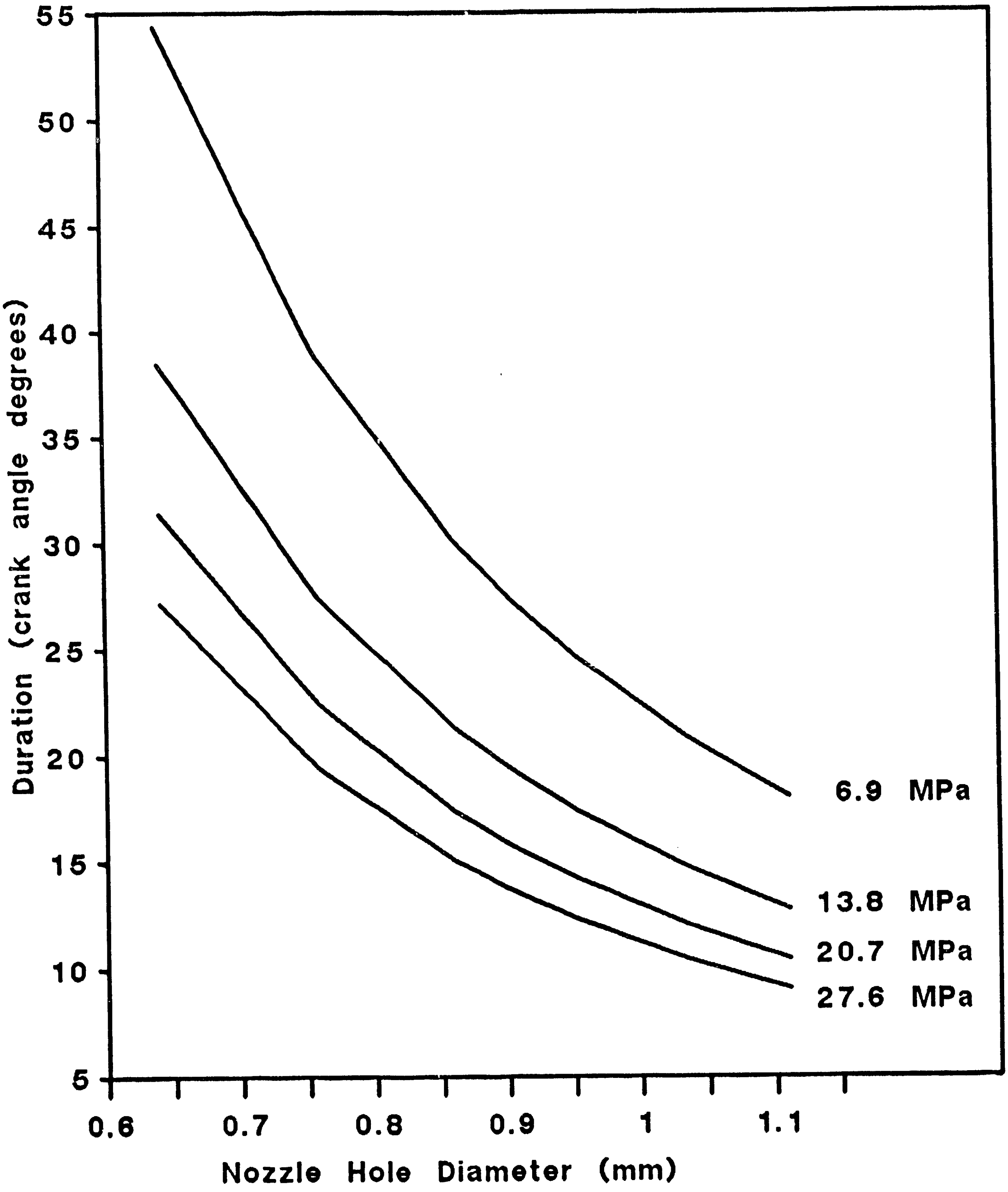
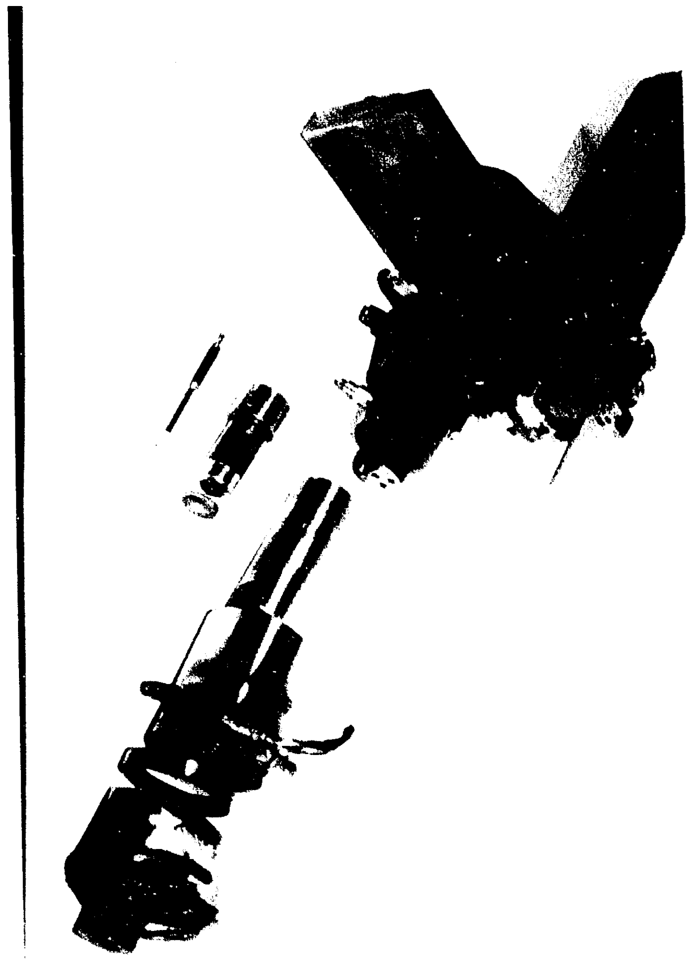



Figure 5.2-2

## INJECTION DURATION vs NOZZLE DIAMETER and MEAN INJECTION PRESSURE



AI-233-9A

Figure 5.2-3 Modified CWS Injector and Prechamber

Engine Test Matrix

| | | Engine Speed, rpm | | |
|---|---|---|---|---|
| | | 1,000 | 1,400 | 1,800 |
| | Idle | X | X | X |
| Load | 50% | X | X | X |
| | Full | X | X | X |

A summary of various optimization studies as well as wear data are presented in the sections that follow. All of the testing during Phase II was carried out with Otisca Blue Gem seam CWS.

### 5.2.1 Precombustion Chamber Design

In order to improve the performance from the baseline (straight round throat) CWS precombustion chamber (PCC) design, two additional throat concepts were explored. The concepts were a multi-hole throat called the "pepper pot" (Figure 5.2.1-1) and a single hole throat machined to induce swirl (Figure 5.2.1-2). Figure 5.2.1.3 is a drawing of the pepper pot design prechamber which shows the cylinder and piston crown (shown with the piston at 30 degrees before top dead center).

While testing the three prechamber design concepts, prechamber volumes were held constant at 47 cc. The 47 cc prechamber volume accounted for 31.4 percent of the total clearance volume and produced a 15.7:1 compression ratio. The injector nozzle hole diameter was about 1 mm. Timing of the CWS injection was optimized for maximum power at each test point.

The comparison of the overall performance with the baseline, swirl and pepper pot prechamber tests are presented in Figures 5.2.1-4 through 5.2.1-6 for a range of loads from 100 to 500 kPa BMEP at 1,000, 1,400 and 1,800 rpm. In all cases, the injection pressure was maintained at 20.7 MPa. Initial running with the pepper pot PCC design showed extremely poor performance and very high precombustion chamber temperatures. The pepper pot chamber was modified to add one additional 5 mm hole along the centerline axis of the chamber. This modification improved the engine performance. All of the test data shown for the pepper pot chamber was taken after this modification. It can be seen that at 1,000 rpm, both the new designs (swirl and pepper pot) have shown improvement as compared to the baseline and the pepper pot gives the highest efficiency. This may be attributed to the better atomization and mixing of the fuel and air. The higher NOx in the case of pepper pot could be attributed to the higher flame temperature presumably due to the better burning achieved with improved mixing.

However, at 1,400 and 1,800 rpm, the swirl chamber has shown the highest thermal efficiency. Further, the performance improvements were reflected in lower BSFC, CO and smoke level in the case of swirl chamber. At 1,400 rpm, the pepper pot temperatures were found to be very high and the power was low. The pepper pot PCC could not be run at 1,800 rpm as the PCC temperatures exceeded the preset limit of 982$^{o}$C (1,800$^{o}$F).

### 5.2.2 Effect of Injection Timing

The effect of CWS injection timing is shown in Figure 5.2.2-1. The data points were taken at 1,400 rpm with a 1 mm injector nozzle hole diameter, the

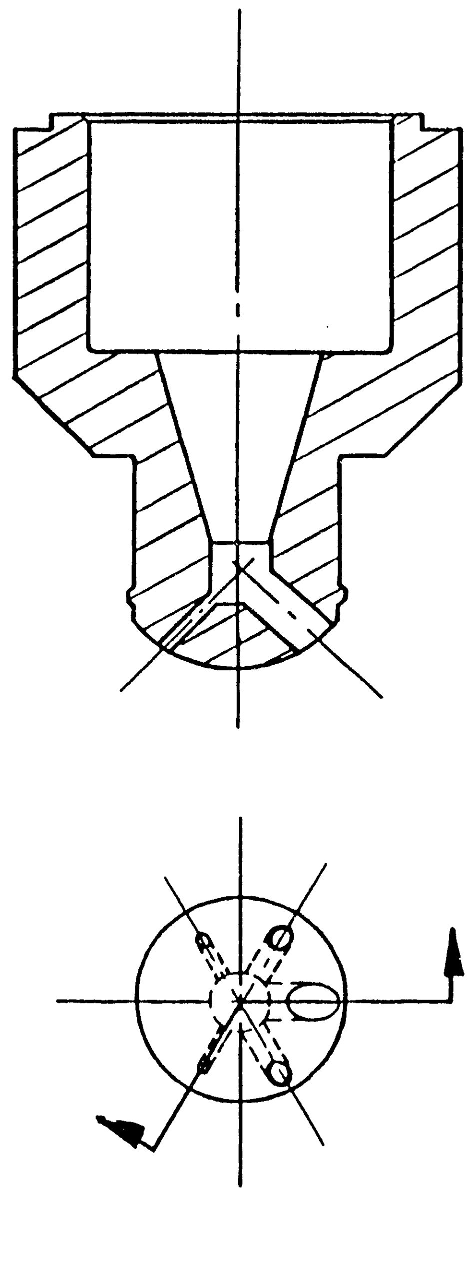


Figure 5.2.1-1 Pepper Pot Prechamber Design Made From Hastelloy X

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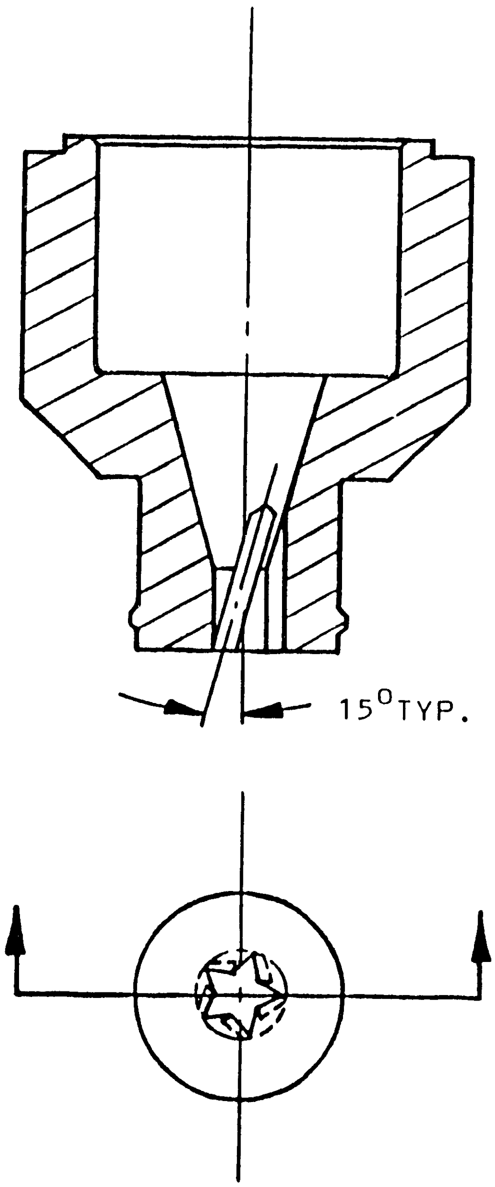


Figure 5.2.1-2 Swirl Prechamber Design Made From Hastelloy X

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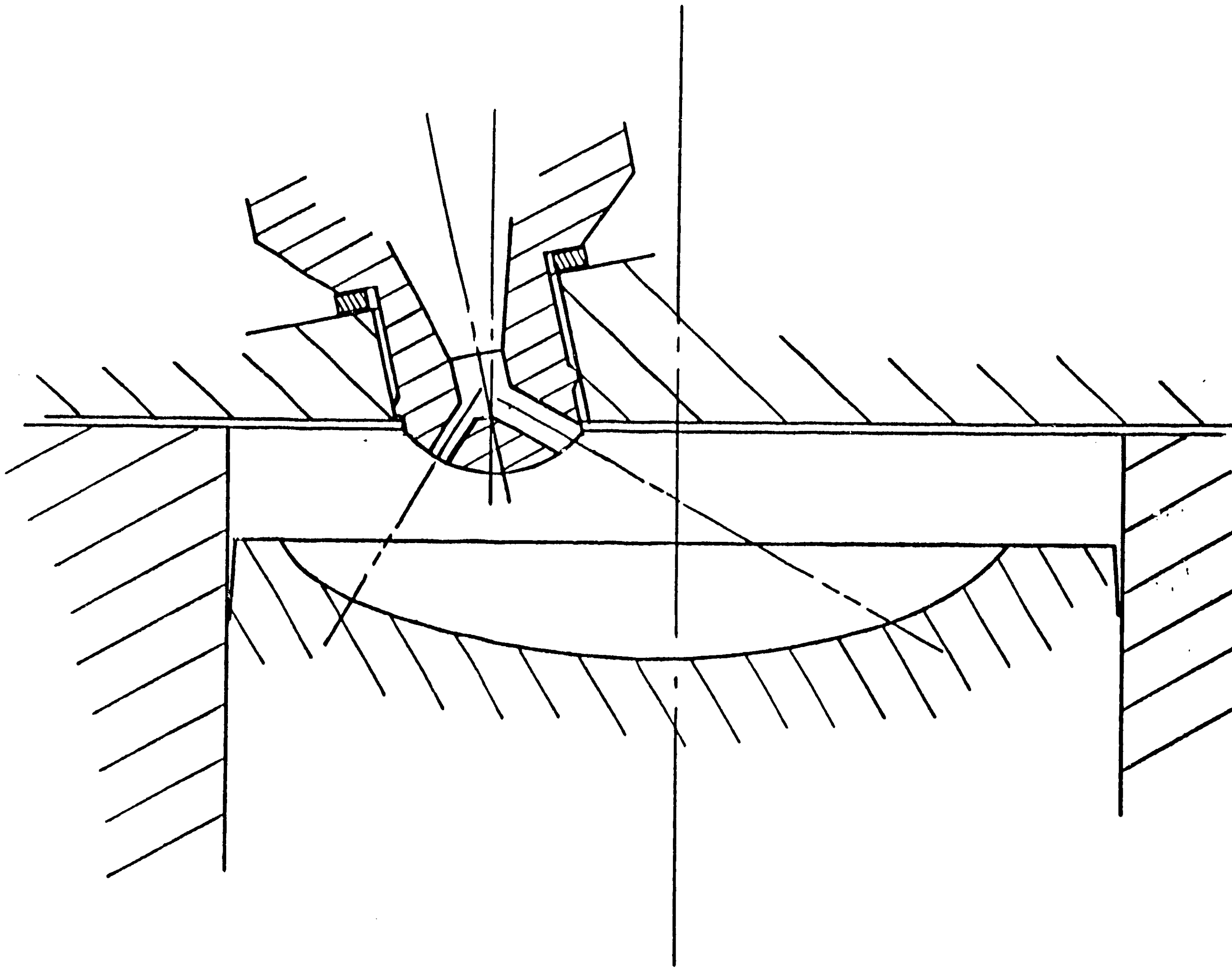


Figure 5.2.1-3 Pepper Pot Prechamber Combustion Gas Flow at $30^{o}$ BTDC

AI - 900137

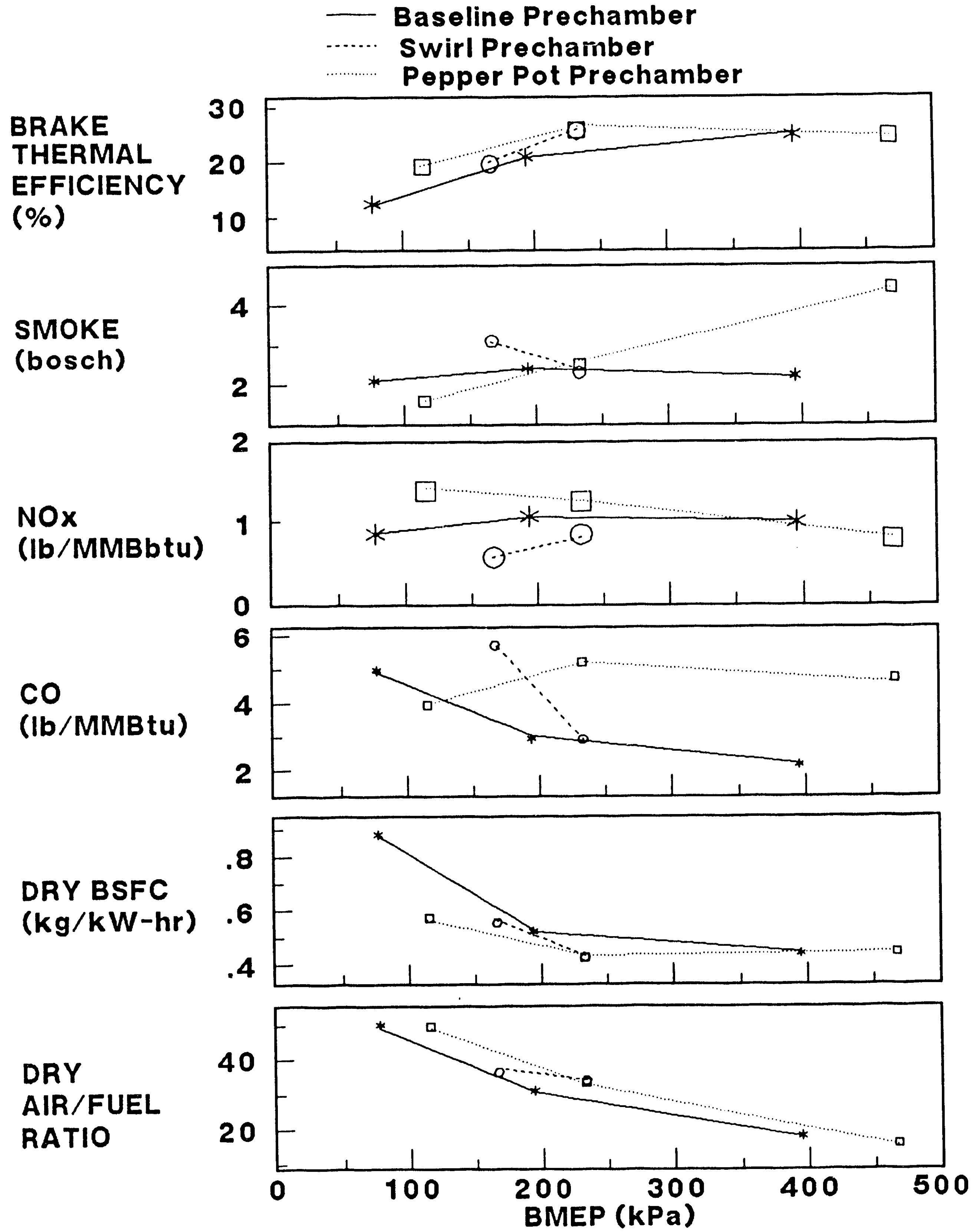



**Figure 5.2.1-4 Innovative Coal-Fueled Diesel Engine at 1,000 RPM and 20.7 MPa Injection Pressure**

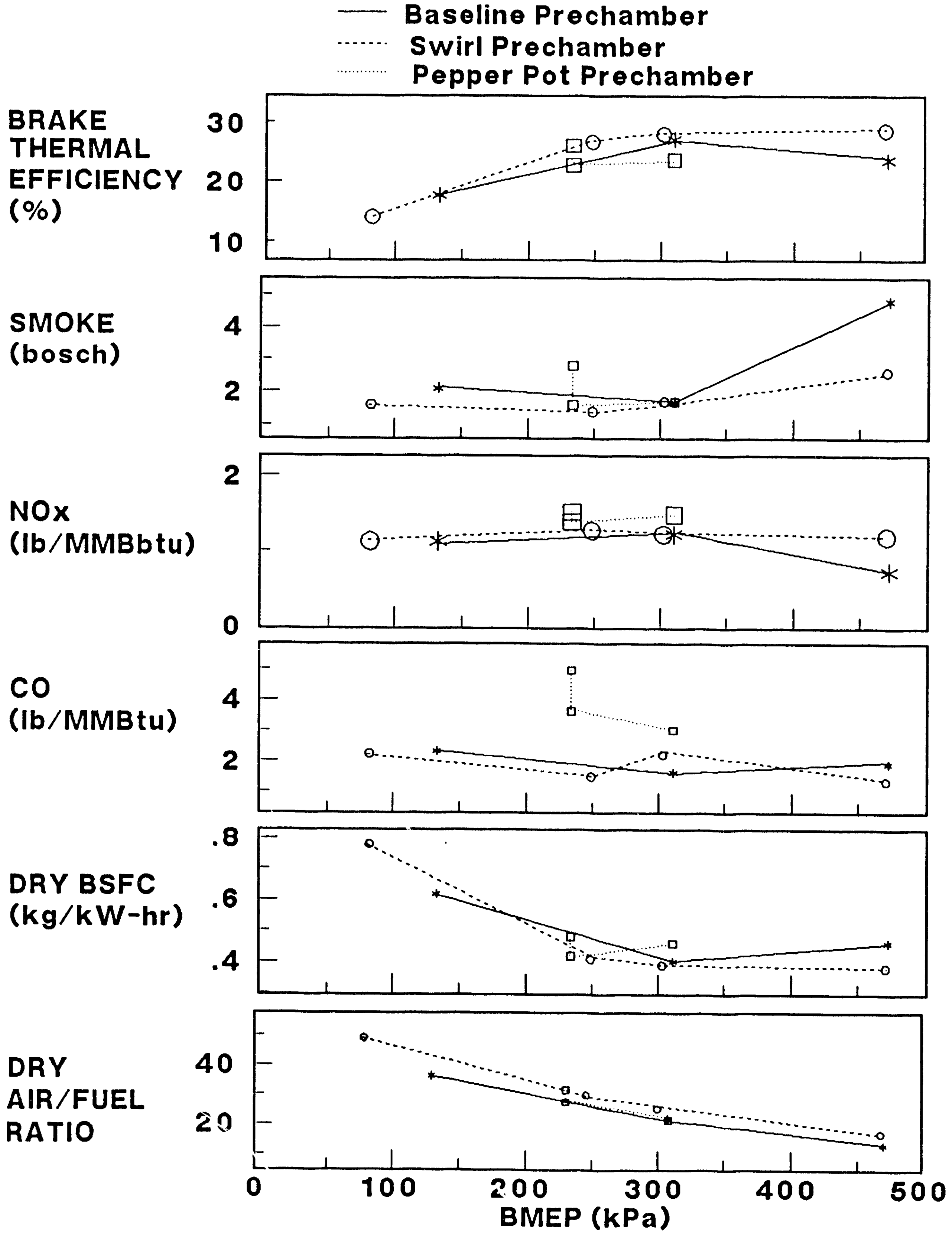



Figure 5.2.1-5 Innovative Coal-Fueled Diesel Engine at 1,400 RPM and 20.7 MPa Injection Pressure

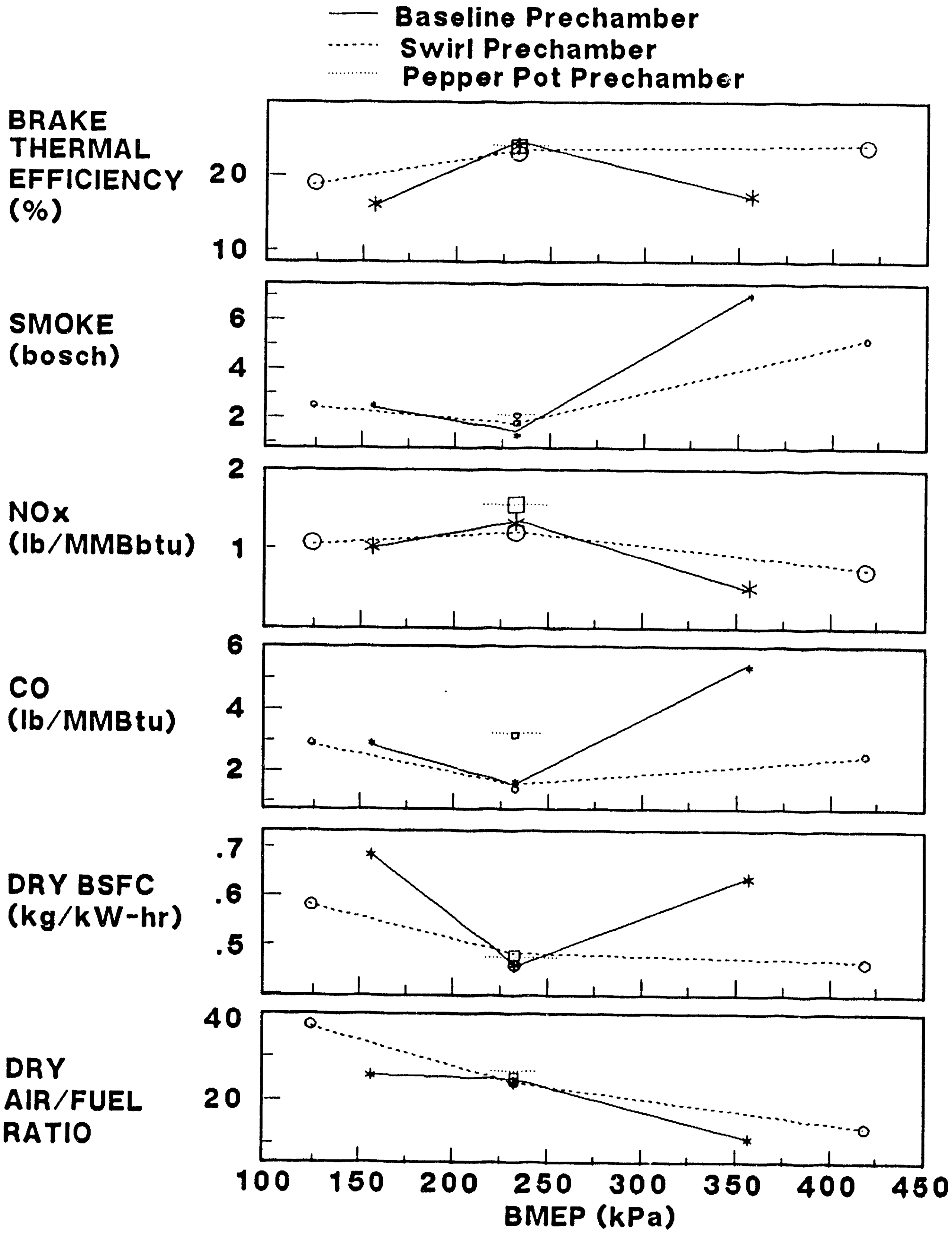



Figure 5.2.1-6 Innovative Coal-Fueled Diesel Engine at 1,800 RPM and 20.7 MPa Injection Pressure

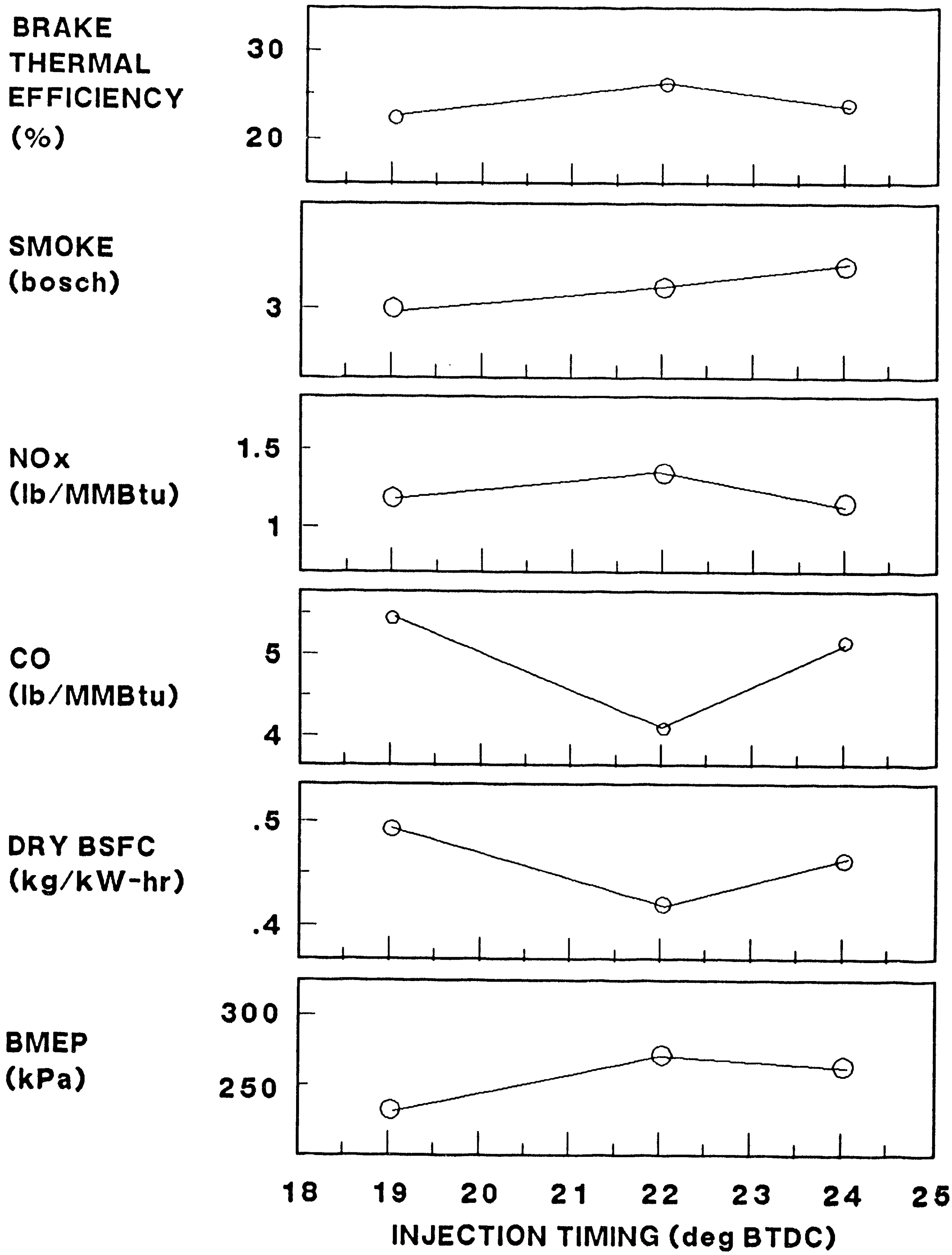



Figure 5.2.2-1 Effect of Injection Timing at 1,400 RPM

swirl prechamber, a 40 cc prechamber volume and a 16.4:1 compression ratio. It can be seen that the effect of injection timing was significant. A variation of three degrees of injection timing significantly degrades engine performance. Figures 5.2.2-2 thru 5.2.2-3 shows injection timing for all of the tests run with each configuration at 1,000 and 1,400 rpm. A nomenclature Table showing the Plot Legend for identifying each individual curve is shown as Table 5.2.2-1. This Table is used for additional plots in the following sections.

5.2.3 Effect of PCC Temperature

The locations where PCC temperatures were measured were shown in Figure 4.4.1-3. Figures 5.2.3-1 thru 5.2.3-3 show plots of lower PCC temperature versus BMEP at each speed and encompassing all engine configurations. As a general rule, the higher the prechamber temperature was, the better the engine performed. It can be seen by examining these curves that lower PCC temperature is affected more by engine design configuration than by load or speed. Upper PCC temperature versus lower PCC temperature at the three speeds and all load points is shown in Figures 5.2.3-4 thru 5.2.3-6. Examination of these plots shows that upper chamber temperature is consistently lower than the lower PCC temperature and that the configuration uniformly affects the magnitude of this difference. The temperature contrast is the result of the upper chamber being in contact with the water cooled CWS injector.

5.2.4 Effect of PCC Volume

The effect of the change in PCC volume on the performance was explored with the swirl type prechamber (since the swirl design performed best). Five variations of prechamber volumes were tried in which sleeves were either inserted inside the prechamber to reduce prechamber volume or a taller intermediate seal was installed to increase prechamber volume. All engine testing was with injection timing set at optimum. Table 5.2.4-1 is a summary of the prechamber volume configurations tested. Note that compression ratio did not remain constant. The compression ratio is increased when the PCC volume is decreased and vice versa. The comparative results are presented in Figure 5.2.4-1. It was interesting to see that the total power output improved with the increase in PCC volume up to the second from the largest prechamber volume. The largest 54 cc prechamber volume produced high power output (though not the highest) with a low 15:1 compression ratio. An investigation into the effect of compression ratio on engine performance was not performed but it is very possible that a higher compression ratio in conjunction with the larger prechamber volume could perform best. The performance improvement with larger volumes was reflected in the emissions, namely, lower HC, CO and smoke. The engine would not run on 100 percent CWS with the 20 cc prechamber volume.

5.2.5 Effect of Injector Orifice Diameter

Three different injector nozzle hole diameters were engine tested in an effort to determine the effect of hole diameter on CWS atomization, injection pressure requirement, ignition delay and CWS combustion. Special effort was made to ensure that the length over diameter (L/D) ratio was the same for all three nozzle hole diameters. For this testing, the swirl type prechamber was used in conjunction with a 47 cc prechamber volume and 15.7:1 compression ratio. Injection timing was optimized for maximum power output. A ceramic

Table 5.2.2-1

# PLOT LEGEND

| | PRECHAMBER THROAT | INJECTOR ORIFICE (mm) | PCC VOLUME (cc) | SYMBOL |
|---|---|---|---|---|
| ———————— | BASELINE | 0.96 | 47 | ✳ |
| ━━━━━━━━ | SWIRL | 1.00 | 47 | ○ |
| - - - - - - - - - - - - | PEPPER POT | 1.00 | 47 | □ |
| ▬ ▬ ▬ ▬ ▬ ▬ | SWIRL | 0.74 | 47 | △ |
| ························ | SWIRL | 0.91 | 47 | ▬ |
| • • • • • • • • • • • • | SWIRL | 1.10 | 40 | ● |
| — — — — — — — | SWIRL | 1.10 | 34 | ■ |
| ━━ ━━ ━━ | SWIRL | 0.91 | 54 | ▲ |
| —··—··—··—··— | SWIRL | 0.91 | 47 | ◇ |

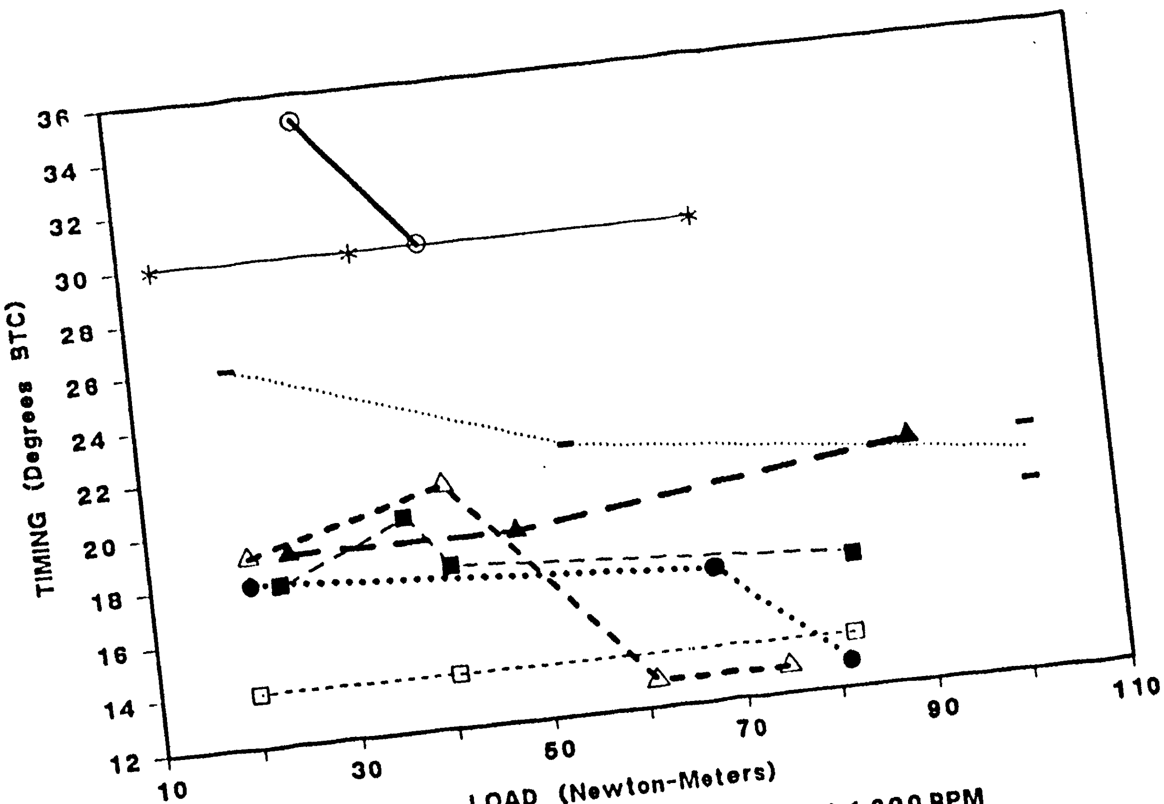


Figure 5.2.2-2 Beginning of Injection Timing at 1,000 RPM

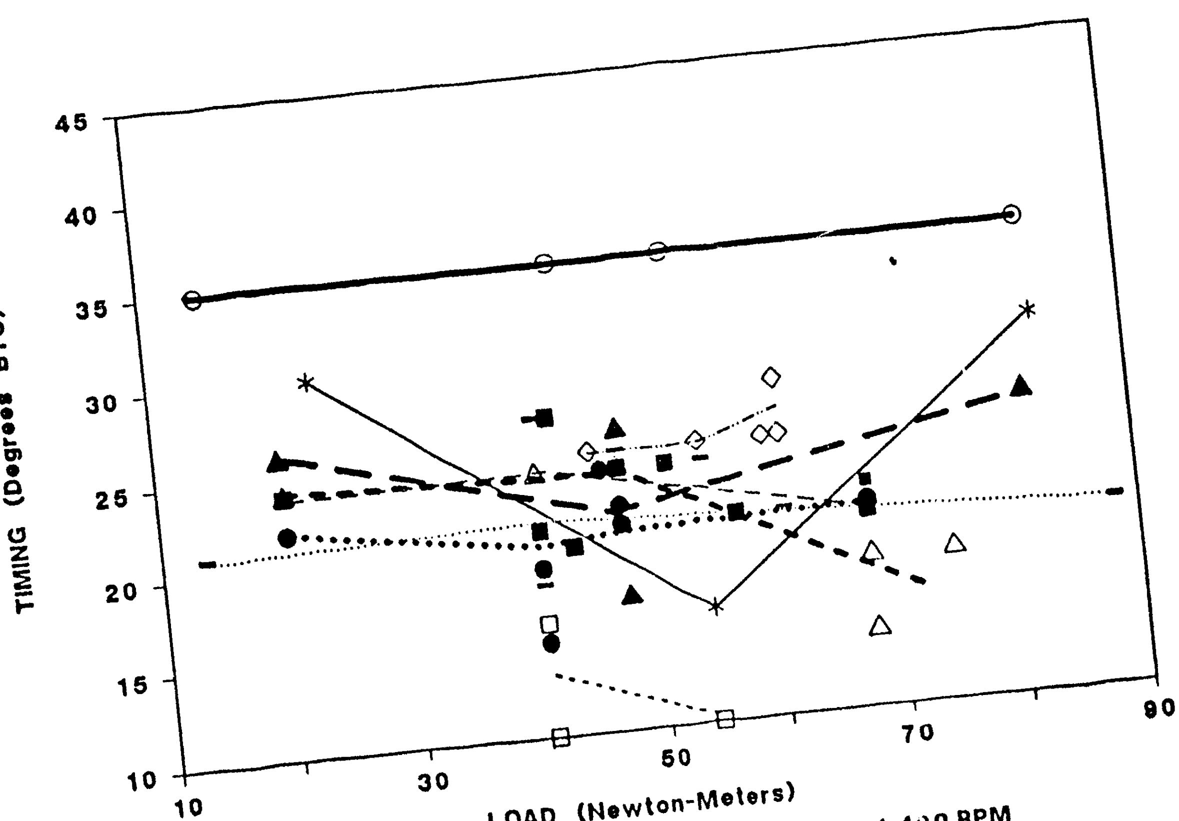


Figure 5.2.2-3 Beginning of Injection Timing at 1,400 RPM

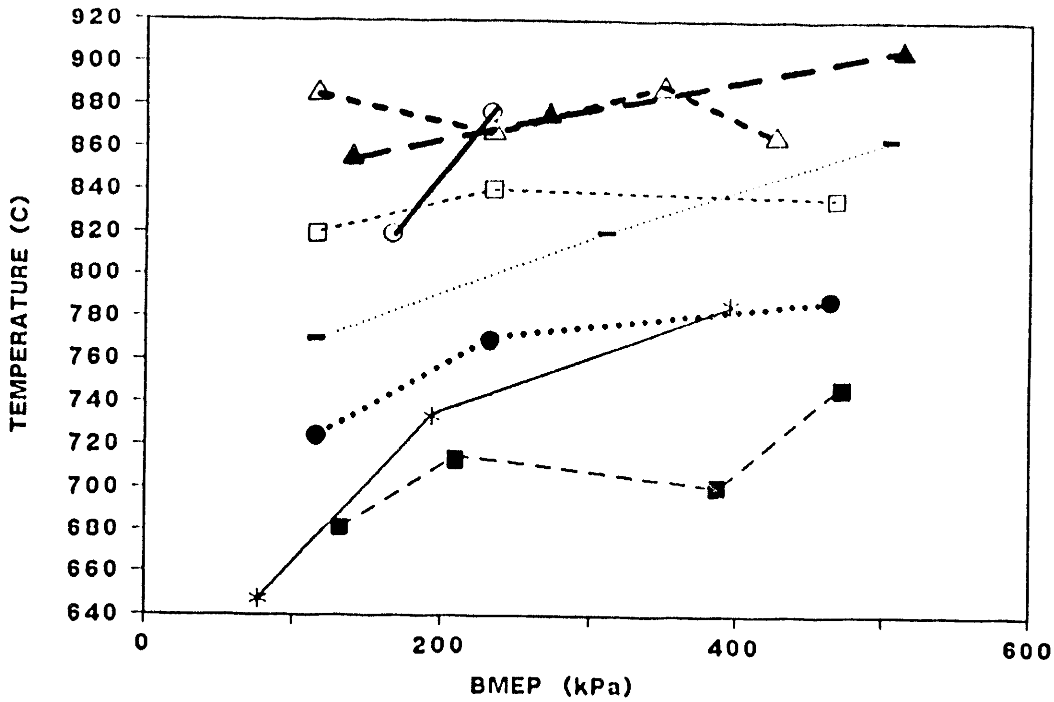



Figure 5.2.3-1 Lower Prechamber Temperature at 1,000 RPM

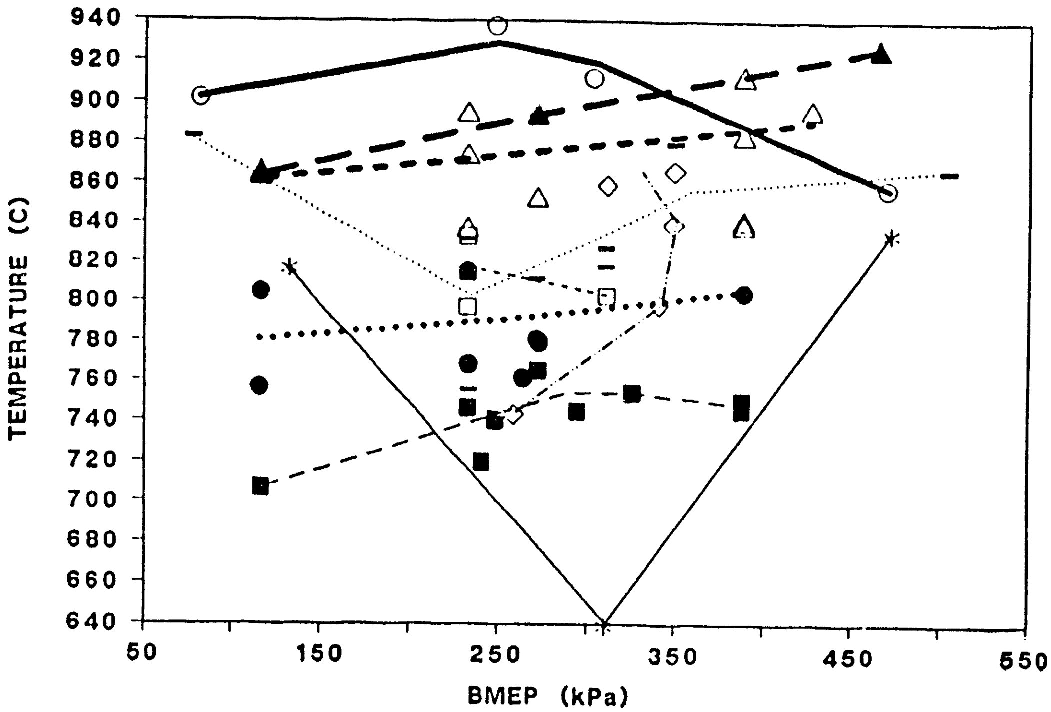



Figure 5.2.3-2 Lower Prechamber Temperature at 1,400 RPM

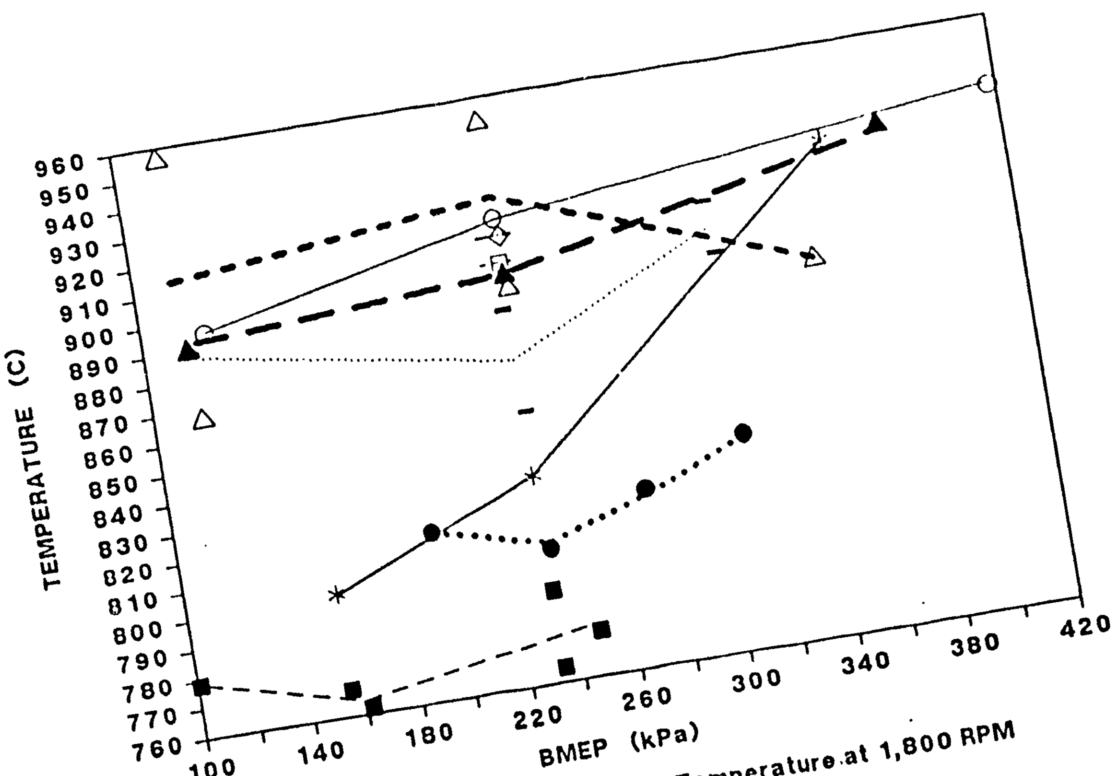



Figure 5.2.3-3 Lower Prechamber Temperature at 1,800 RPM

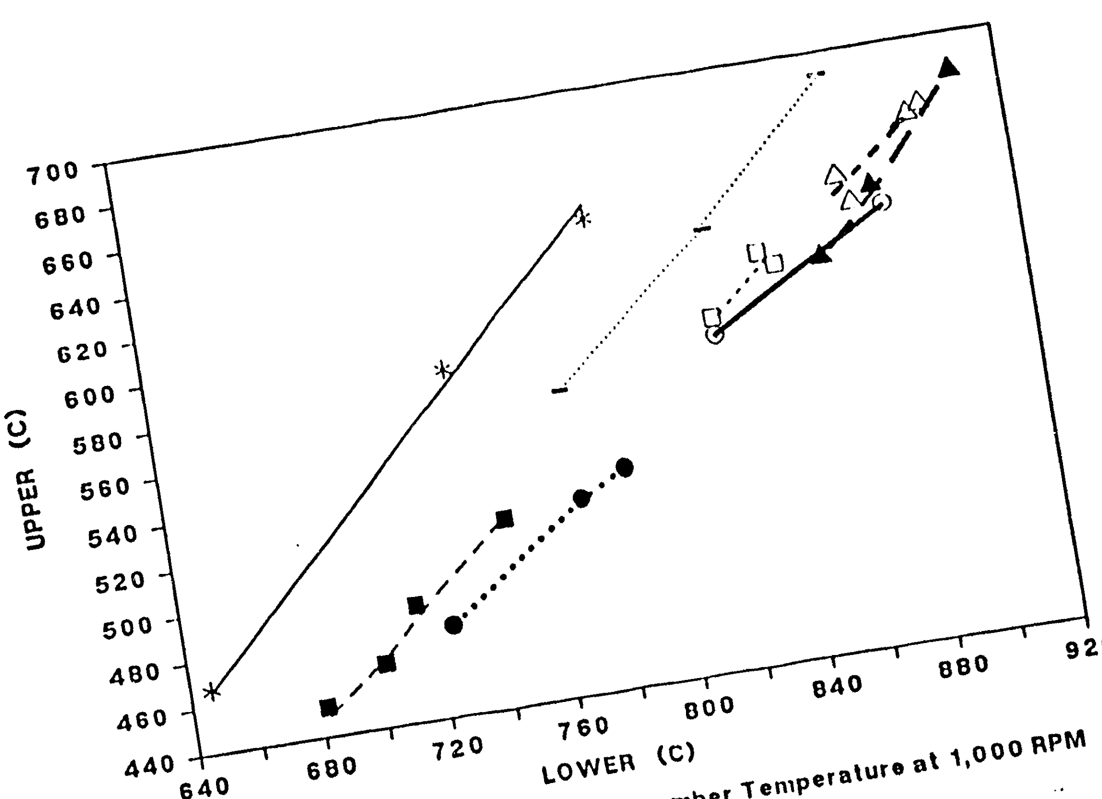



Figure 5.2.3-4 Upper VS. Lower Prechamber Temperature at 1,000 RPM

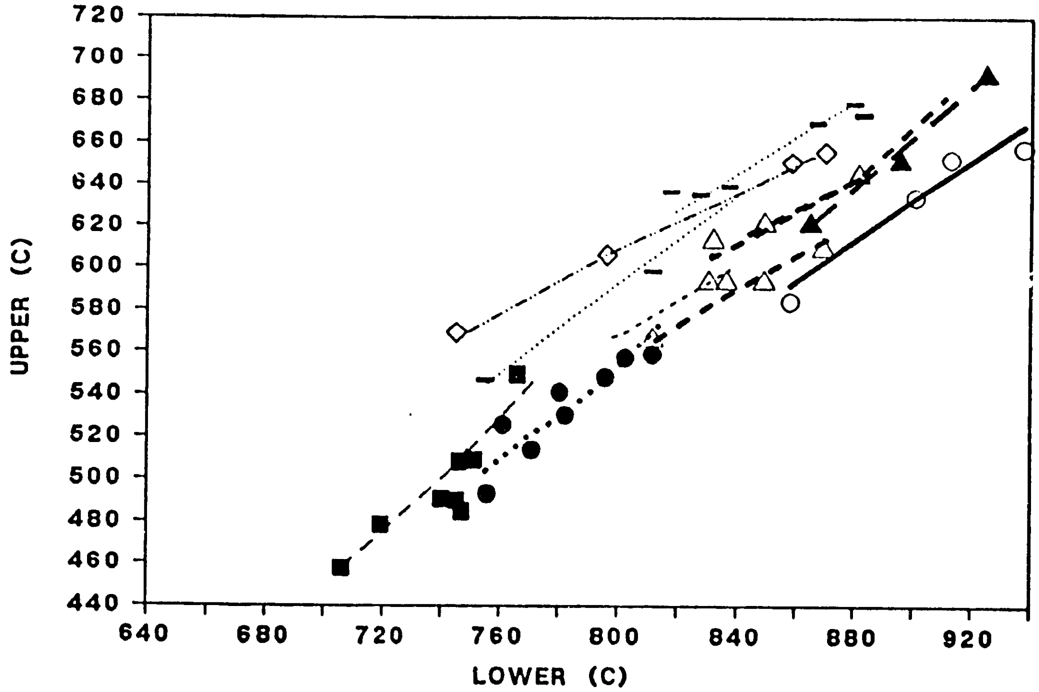


Figure 5.2.3-5 Upper VS. Lower Prechamber Temperature at 1,400 RPM

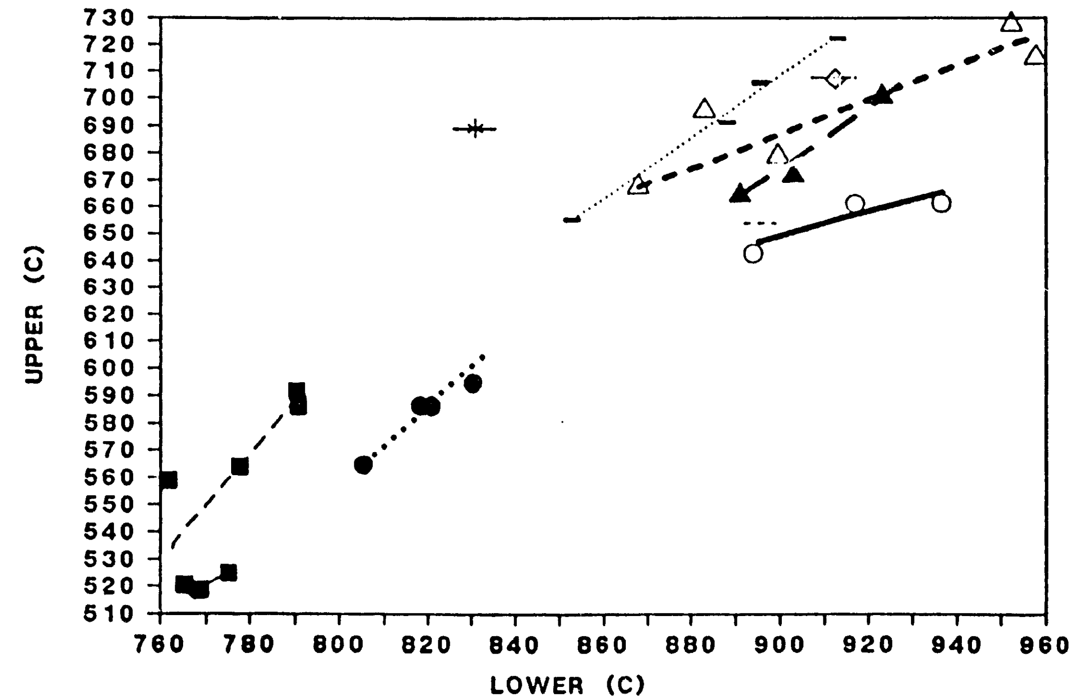


Figure 5.2.3-6 Upper VS. Lower Prechamber Temperature at 1,800 RPM

Table 5.2.4-1

## SUMMARY OF PRECHAMBER VOLUMES TESTED

| TEST NUMBER | PRECHAMBER VOLUME (CC) | % TOTAL CLEARANCE VOLUME | COMPRESSION RATIO | INJECTOR NOZZLE DIAMETER (MM) |
|---|---|---|---|---|
| 1 | 54 | 34.4 | 15:1 | 0.91 |
| 2 | 47 | 31.4 | 15.7:1 | 1.0 |
| 3 | 40 | 28.0 | 16.4:1 | 1.0 |
| 4 | 34 | 24.8 | 17.1:1 | 1.0 |
| 5 | 20 | 13.5 | 15.8:1 | 1.0 |

TEST #5 WOULD NOT RUN ON 100% CWS

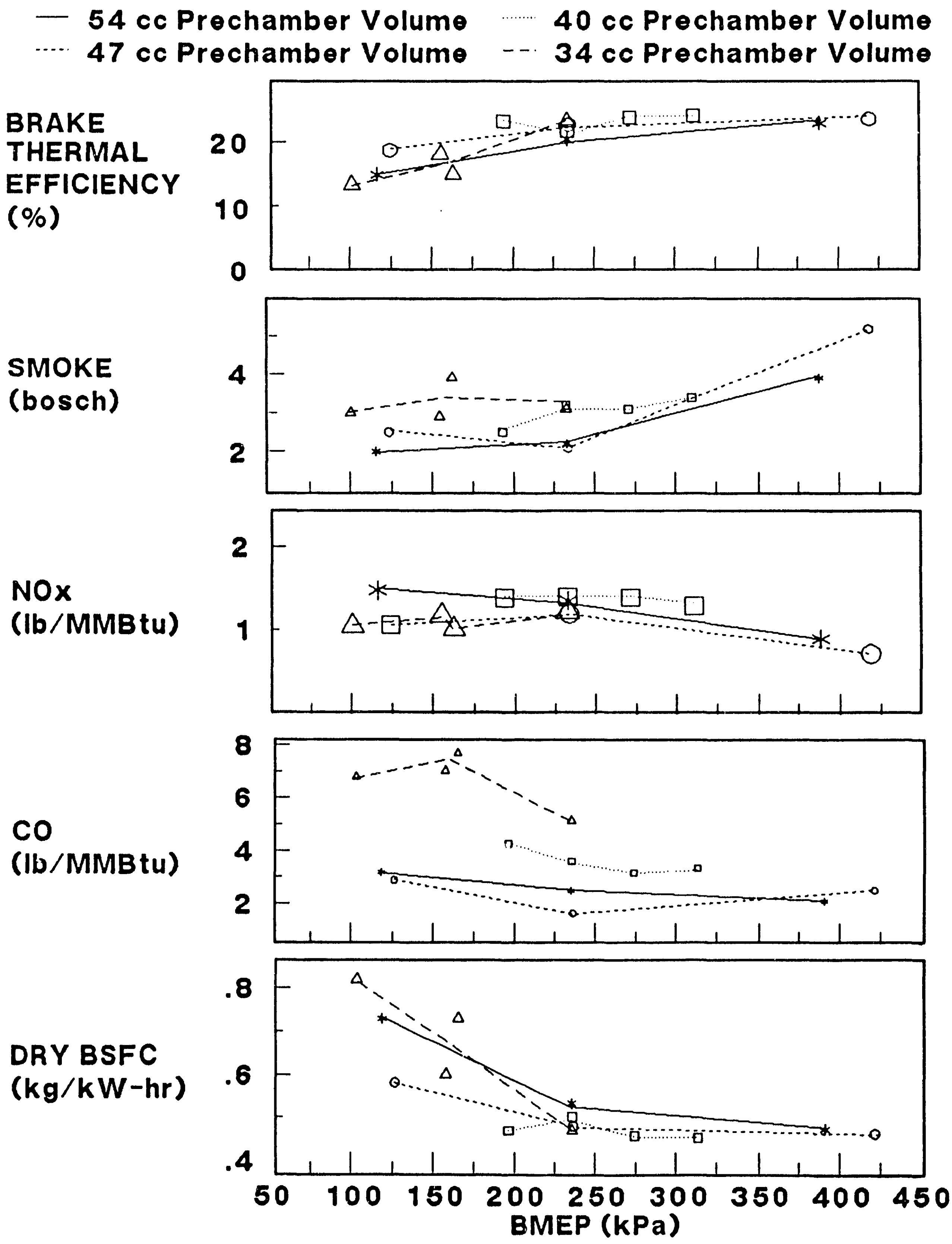



**Figure 5.2.4-1 Effect of Prechamber Volume at 1,800 RPM**

thermal barrier washer was added between the cylinder head and the precombustion chamber to increase and stabilize the temperature of the precombustion chamber, during the tests. The effect of injector orifice for this configuration is shown in Figure 5.2.5-1 and it can be seen that peak power was produced with the largest nozzle hole diameter.

### 5.2.6 Effect of CWS Injection Pressure

Figure 5.2.6-1 is a plot of the test results using the swirl type prechamber at 1,400 rpm comparing injection pressures of 13.8 MPa (2,000 psi) and 20.7 MPa (3,000 psi.) Examination of this figure shows that the higher injection pressure results in improved engine performance in all aspects except NOx emissions (which was the result of hotter combustion).

### 5.2.7 Effect of Exhaust Gas Recirculation

The effect of exhaust gas recirculation (EGR) is depicted in Figure 5.2.7-1. In general, there is a significant reduction in NOx with increased EGR. However, the load could not be maintained beyond 15 percent EGR. As can be seen from the figure, there is a significant improvement in NOx (40 percent reduction at 5 percent EGR and 75 percent reduction at 10 percent without much deterioration in performance). Beyond 10 percent EGR diminishing returns are achieved in NOx reduction and drastic increases in CO and smoke were observed.

### 5.2.8 Particulate Measurements

A simple full flow system with a ceramic particulate filter has been used to measure the particulates. A photograph of the system is shown in Figure 5.2.8-1. The filter was made up of Lithium, Alumina Silicate ceramic foam with 2.56 pores per mm (from Hi-Tech Ceramics, Inc.) and was capable of filtering particles as small as 5 microns. The particulate filter was installed in the exhaust manifold and the exhaust gas was made to flow through the filter for a specific periodic time (1 to 2 minutes) during steady state running. A high temperature valve system was used to divert the exhaust gas through the filter and the exhaust flow was diverted back through the regular manifold when the exhaust back pressure increased to 25.4 cm (10 inches) of water. The exhaust flow through the filter was controlled by the actuation of Dezurik pneumatic shut off valves. The particulate measurements were determined from the difference in weight of the dry filter (the filters were dried at 104$^{o}$C in an oven) before and after the collection of the particulates.

The particulate tests were each conducted at 1,800 rpm and are summarized in Table 5.2.8-1. This table shows the smoke reading, the smoke reading converted to soot concentration in mg/liter, the particulate reading in grams per hour and the particulate reading converted to a concentration in the exhaust flow also expressed in mg/liter. Quality control problems were encountered with the ceramic filters which resulted in a breakdown of some of the filters accompanied by loss of ceramic material. This was probably the reason for the low particulate reading for point 0121GCL. Examining the smoke and particulates concentration levels show there is a roughly linear correlation between the two measurements. The last column in the table lists the flow rate of ash for each test point. Comparing this rate to the particulate deposition rate, the particulate filter is collecting about 60 percent of the ash from the coal.

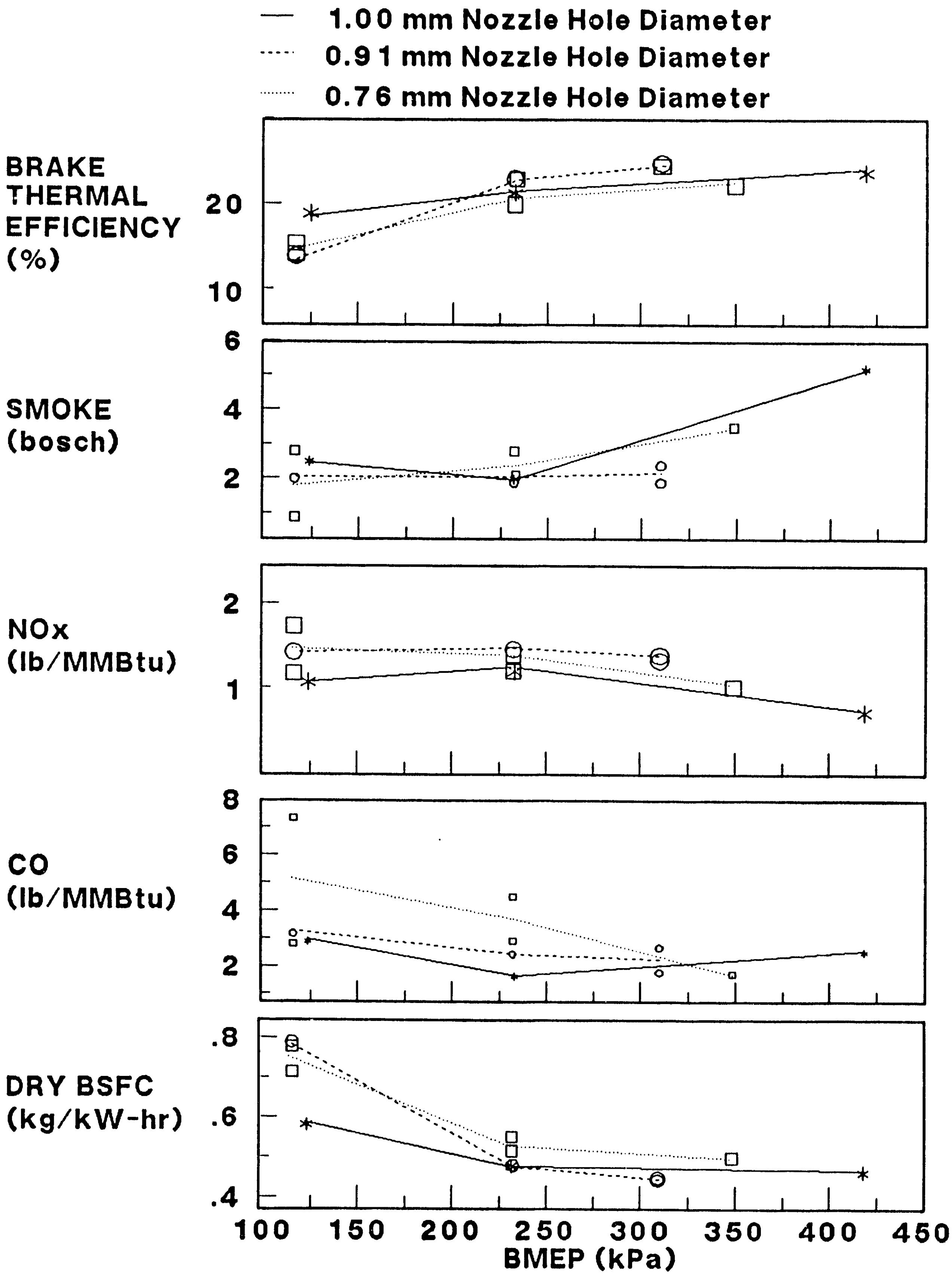



Figure 5.2.5-1 Effect of Nozzle Hole Diameter at 1,800 RPM

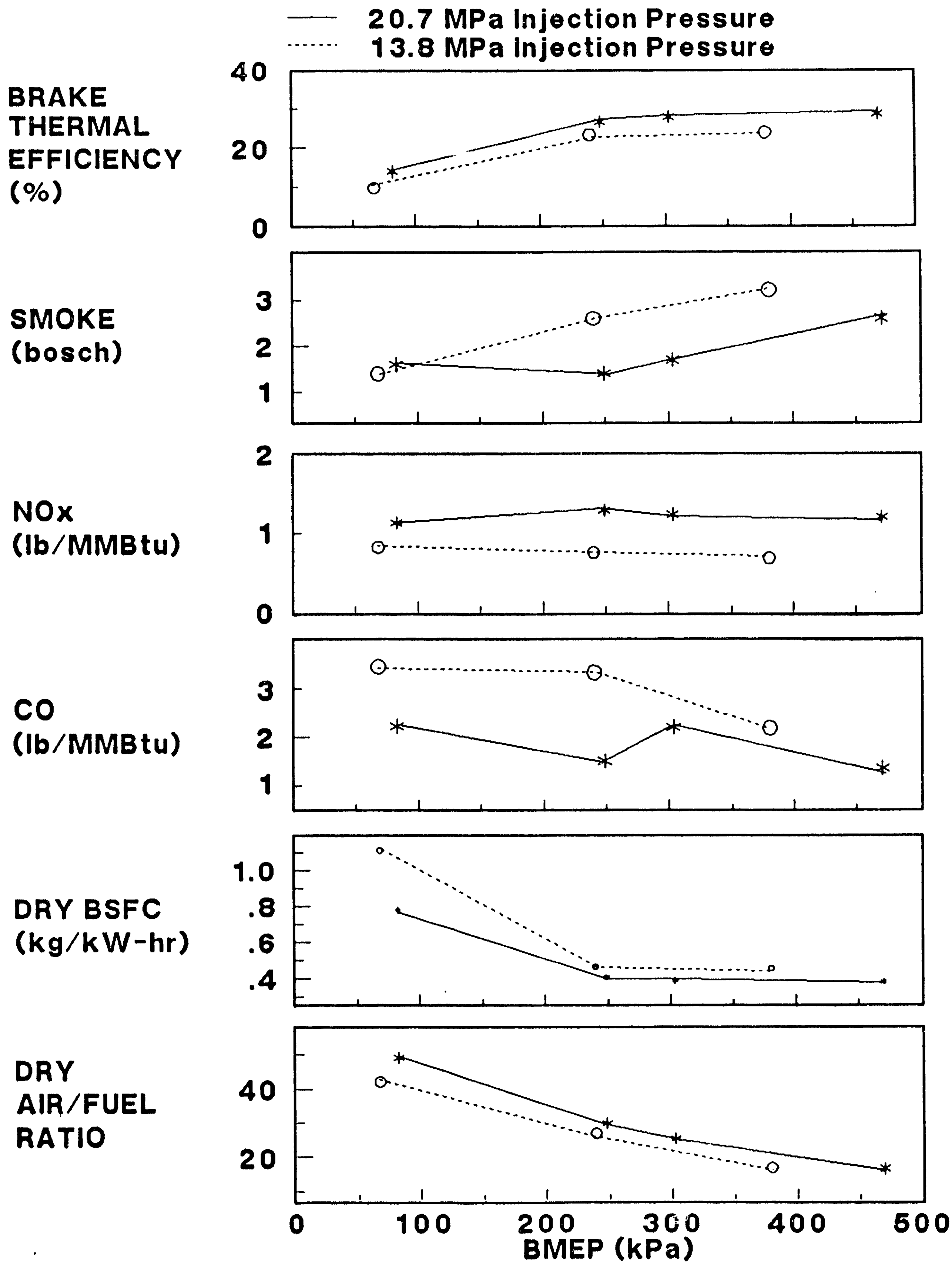



Figure 5.2.6-1 Effect of Injection Pressure at 1,400 RPM

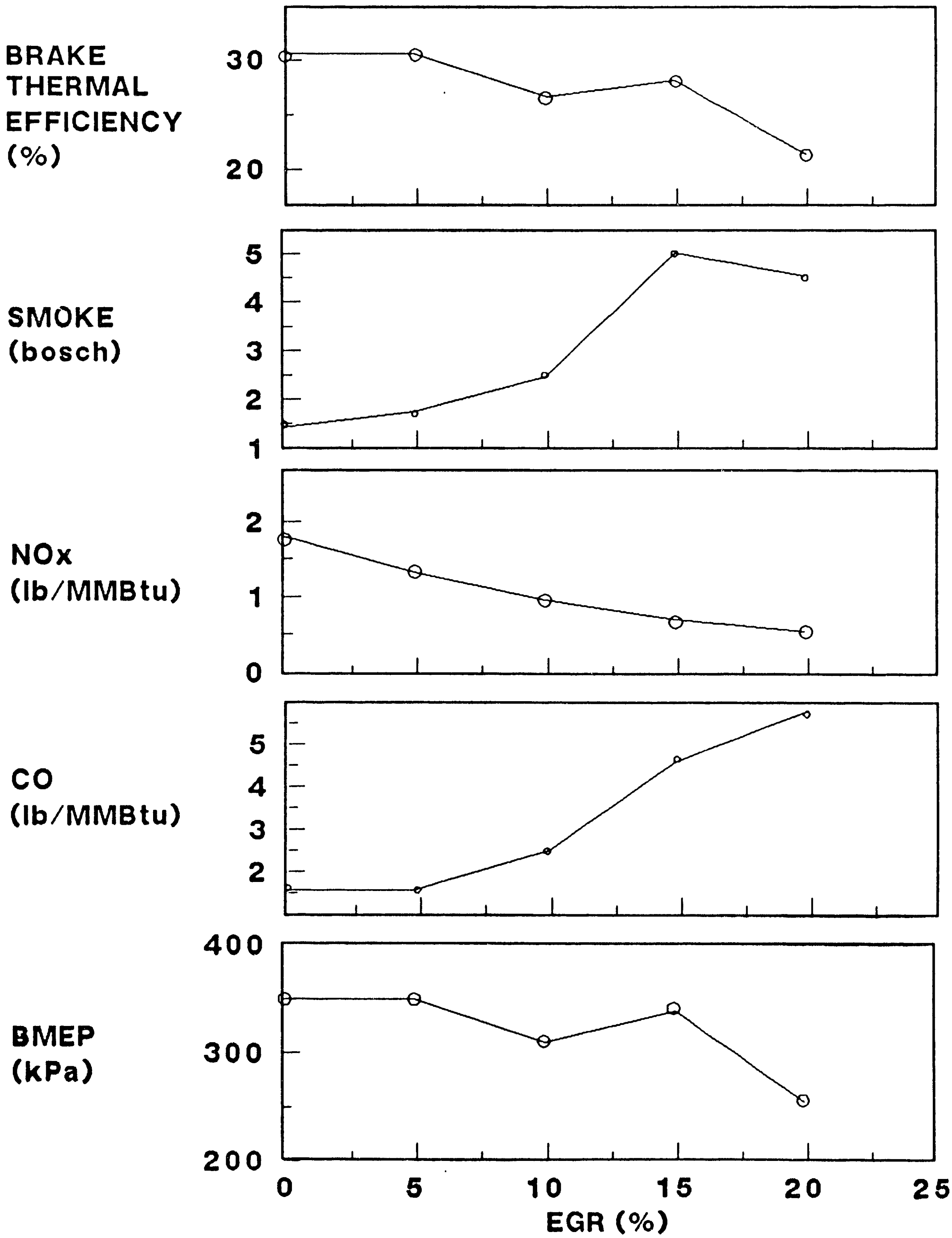
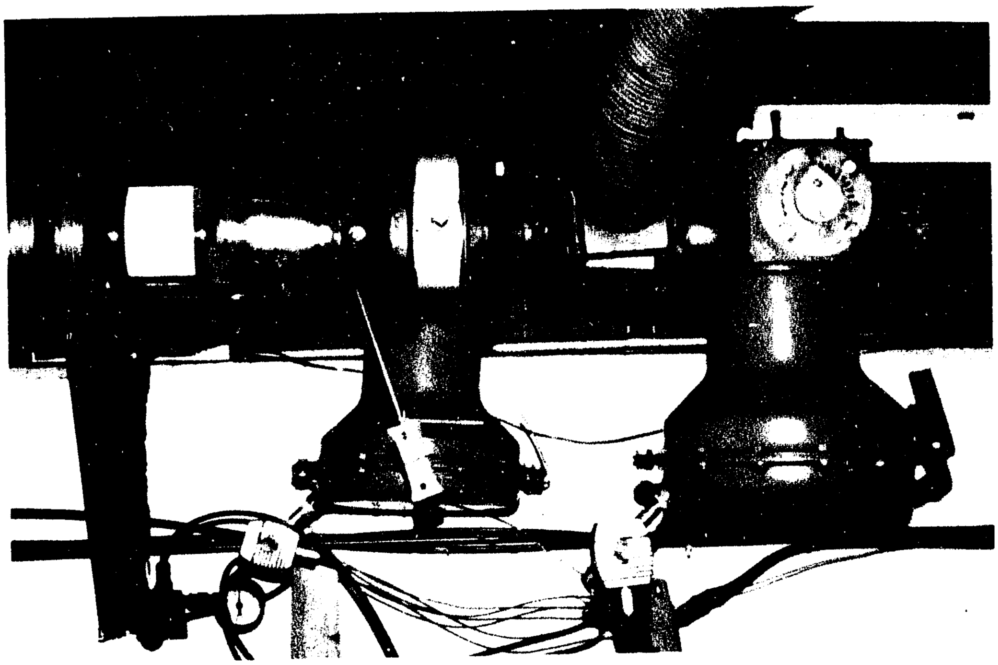



**Figure 5.2.7-1 Effect of EGR at 1,400 RPM**



AI-241-18

Figure 5.2.8-1 Ceramic Particulate Sampling System

Table 5.2.8-1

Correlation Between Smoke and Particulates

| | Smoke | | | Particulates | |
|---|---|---|---|---|---|
| Point | Bosch Number | Equivalent Soot Concentration at 15.6°C & 30"HG (mg/liter) | Filter Loading (gm/hr) | Equivalent Particulate Density at 15.6°C & 30"HG (mg/liter) | Ash in Fuel (gm/hr) |
| 1211FCL | 3.1 | 0.152 | 58.3 | 0.699 | 83.5 |
| 0103CCL | 3.6 | 0.191 | 48.6 | 0.579 | 85.8 |
| 0131FCL | 2.6 | 0.124 | 32.2 | 0.403 | 57.0 |
| 0121GCL | 1.4 | 0.053 | 3.6 | 0.046 | 74.7 |

### 5.2.9 Emissions and Performance Summary

In addition to the data presented in each of the above sections relating to single aspects of the engine design a series of summary graphs were prepared to show the engine performance and emissions results for all of the testing. These graphs utilize the plot legends described in Table 5.2.2-1 to identify each engine configuration. The graphs are as follows:

| | | |
|---|---|---|
| Figure 5.2.9-1 | BSFC vs TORQUE | 1,000 rpm |
| Figure 5.2.9-2 | BSFC vs TORQUE | 1,400 rpm |
| Figure 5.2.9-3 | BSFC vs TORQUE | 1,800 rpm |
| Figure 5.2.9-4 | Brake Thermal Efficiency vs BMEP | 1,000 rpm |
| Figure 5.2.9-5 | Brake Thermal Efficiency vs BMEP | 1,400 rpm |
| Figure 5.2.9-6 | Brake Thermal Efficiency vs BMEP | 1,800 rpm |
| Figure 5.2.9-7 | Engine Temperature Rise vs A/F | 1,000 rpm |
| Figure 5.2.9-8 | Engine Temperature Rise vs A/F | 1,400 rpm |
| Figure 5.2.9-9 | Engine Temperature Rise vs A/F | 1,800 rpm |
| Figure 5.2.9-10 | Engine Temperature Rise vs A/F | all speeds |
| Figure 5.2.9-11 | Hydrocarbons vs Torque | 1,000 rpm |
| Figure 5.2.9-12 | Hydrocarbons vs Torque | 1,400 rpm |
| Figure 5.2.9-13 | Hydrocarbons vs Torque | 1,800 rpm |
| Figure 5.2.9-14 | NOx vs BMEP | 1,000 rpm |
| Figure 5.2.9-15 | NOx vs BMEP | 1,400 rpm |
| Figure 5.2.9-16 | NOx vs BMEP | 1,800 rpm |
| Figure 5.2.9-17 | CO vs BMEP | 1,000 rpm |
| Figure 5.2.9-18 | CO vs BMEP | 1,400 rpm |
| Figure 5.2.9-19 | CO vs BMEP | 1,800 rpm |
| Figure 5.2.9-20 | Smoke vs BMEP | 1,000 rpm |
| Figure 5.2.9-21 | Smoke vs BMEP | 1,400 rpm |
| Figure 5.2.9-22 | Smoke vs BMEP | 1,800 rpm |

### 5.2.10 Wear Data Summary

During Phase II a total of 45 hours and 40 minutes of 100 percent CWS engine testing was performed. Wear data for the injector nozzle hole and piston rings are presented in Tables 5.2.10-1 and 5.2.10-2 respectively. From Table 5.2.10-1, it can be summarized that the M2 tool steel experienced wear throughout almost all the engine testing. Variations in the wear rate can be explained because Table 5.2.10-1 does not account for the time when both coal and diesel fuel were supplied to the engine. Table 5.2.10-2 shows that significant ring wear was experiened. Figure 5.2.10-1 shows a side view of the piston after 28.1 hours of 100 percent CWS engine testing. It can be seen from the photograph that the chrome carbide coated top ring had become too hot during engine testing and had allowed deposits to form below the top ring reversal area. The top ring has also lost its tension. The loss of ring tension is the likely cause for the excessive wear on the intermediate and oil rings since particles were allowed to pass the top ring.

Cylinder liner wear during all the Phase II CWS engine testing was never significant. One chrome oxide coated liner was used for all of the Phase II testing. The wear during the last 28.1 hours of testing, the liner diametral wear was less than 0.0013 mm (0.0005 inch) and was still within the specifications required by the engine manufacturer.

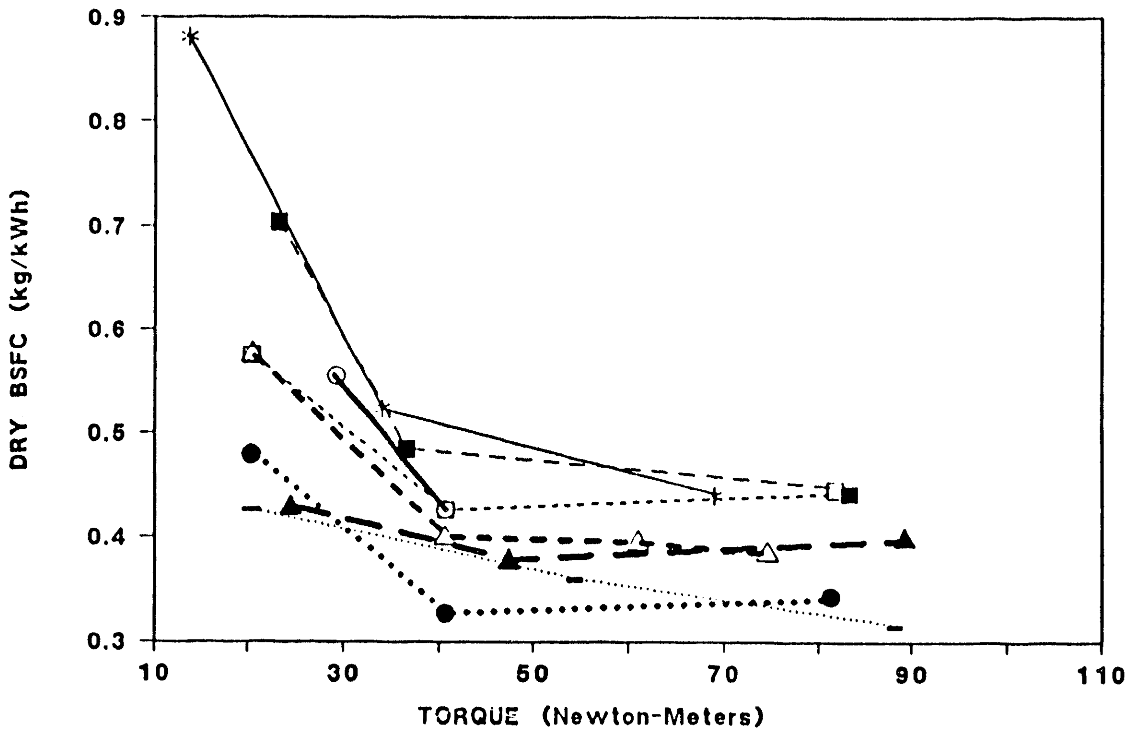



Figure 5.2.9-1 Brake Specific Fuel Consumption at 1,000 RPM

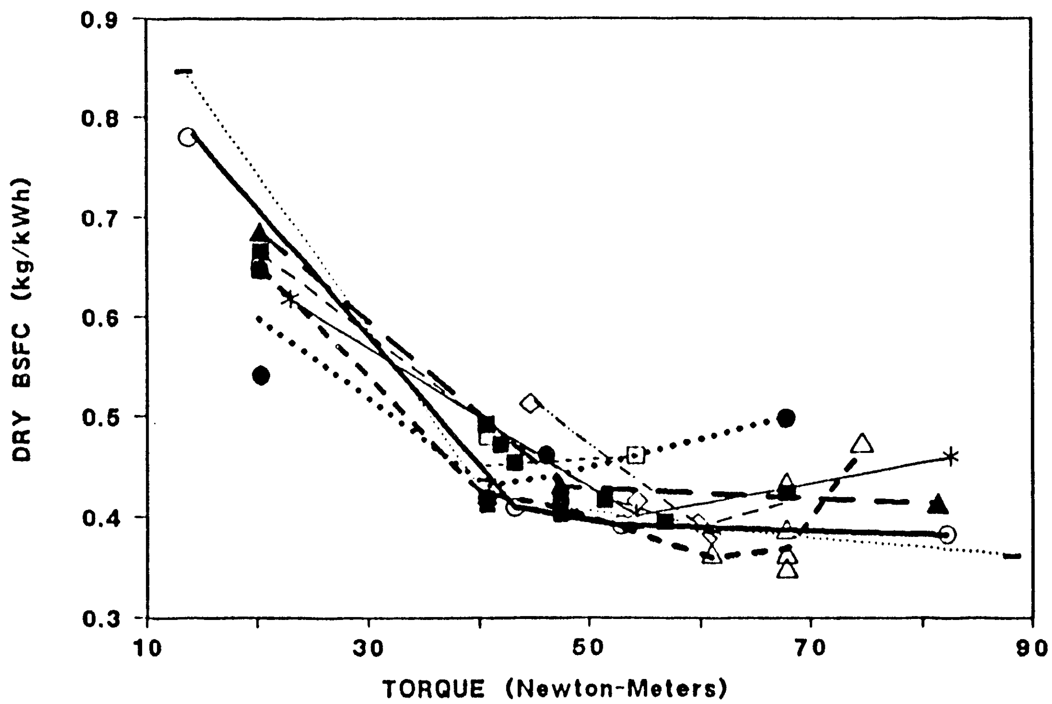



Figure 5.2.9-2 Brake Specific Fuel Consumption at 1,400 RPM

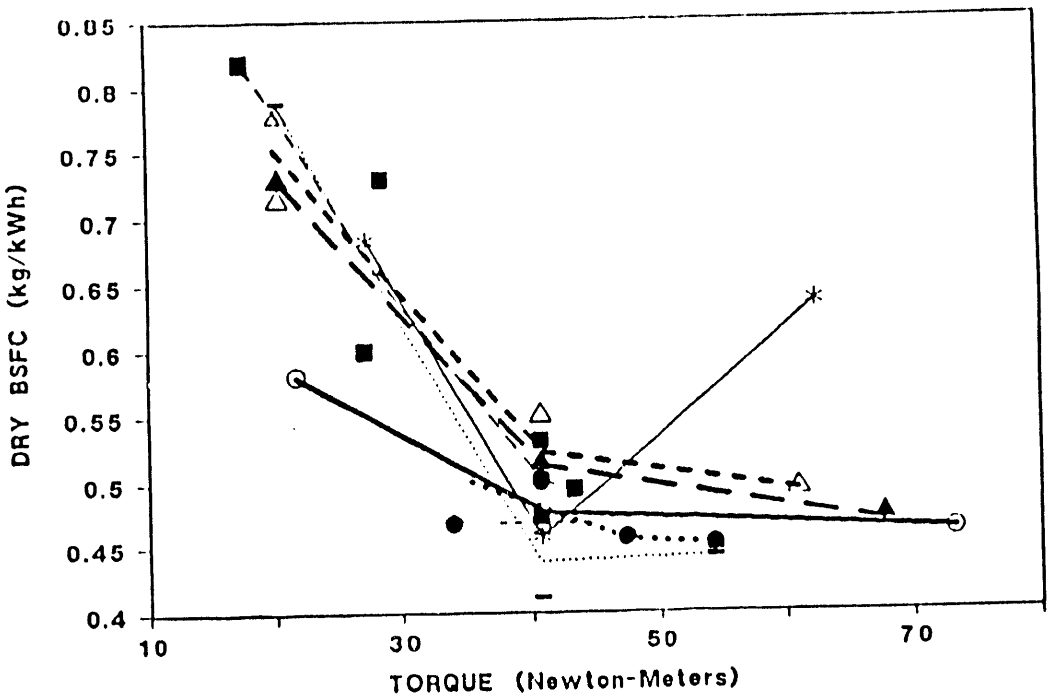



Figure 5.2.9-3 Brake Specific Fuel Consumption at 1,800 RPM

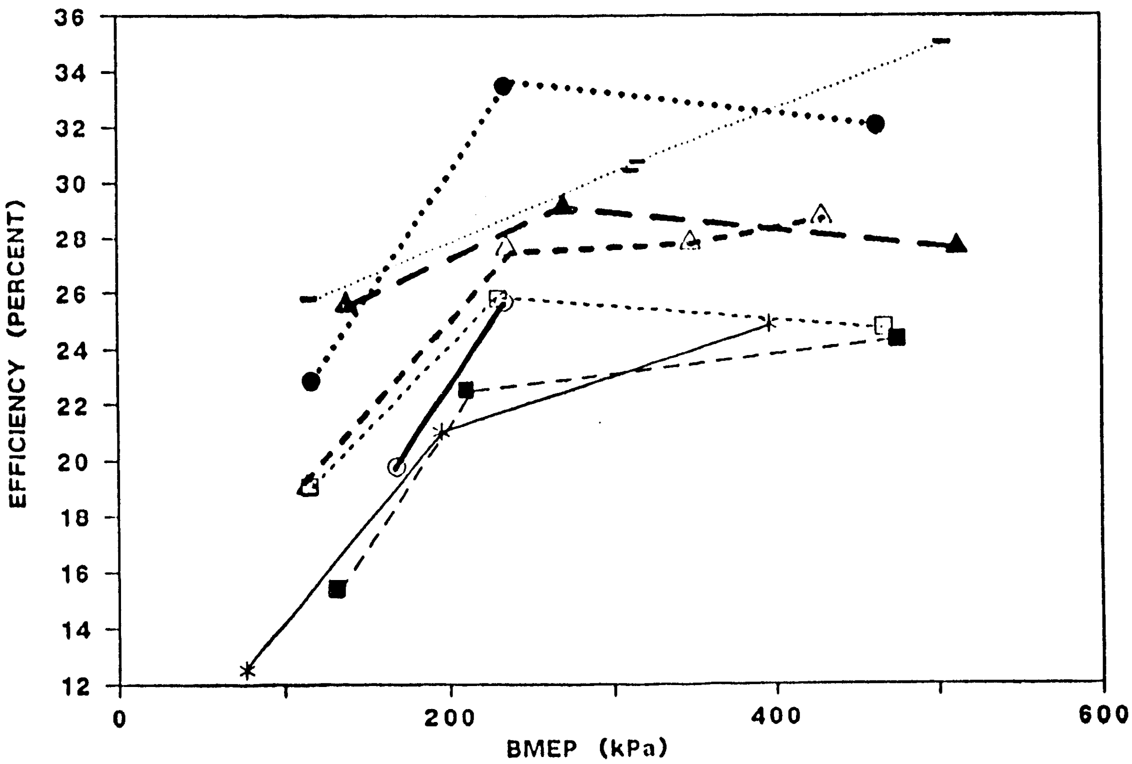



Figure 5.2.9-4 Brake Thermal Efficiency at 1,000 RPM

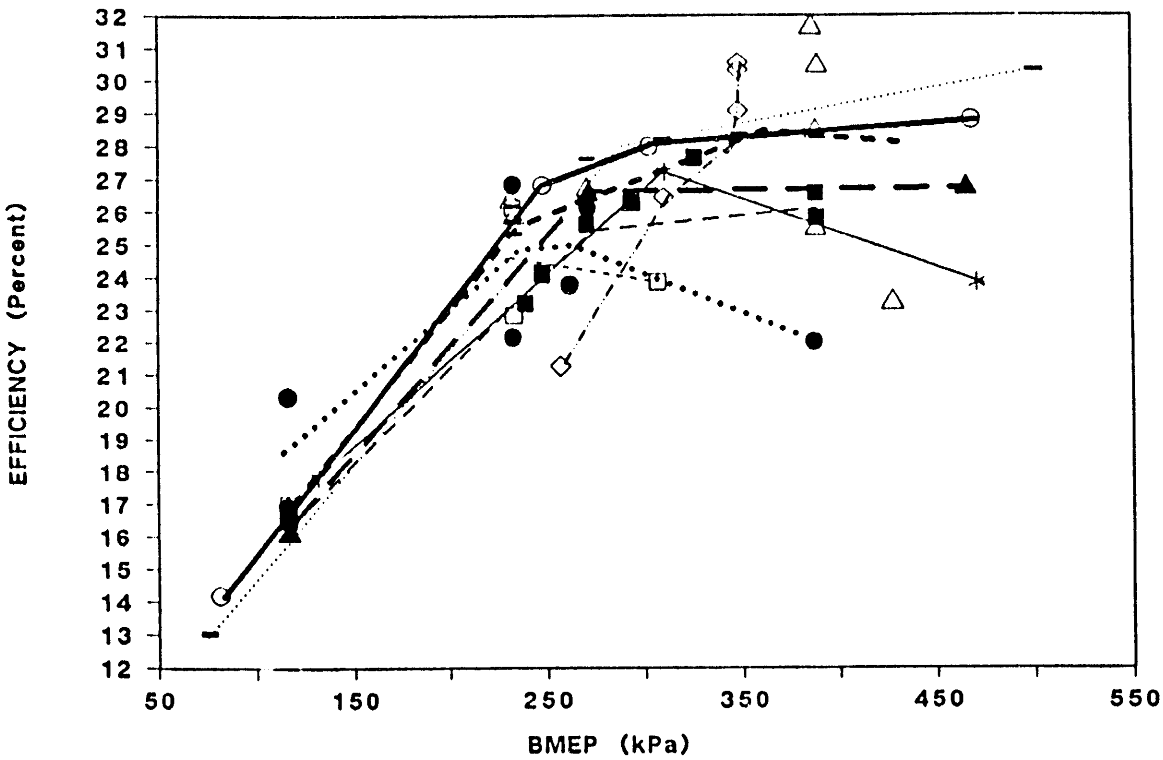



Figure 5.2.9-5 Brake Thermal Efficiency at 1,400 RPM

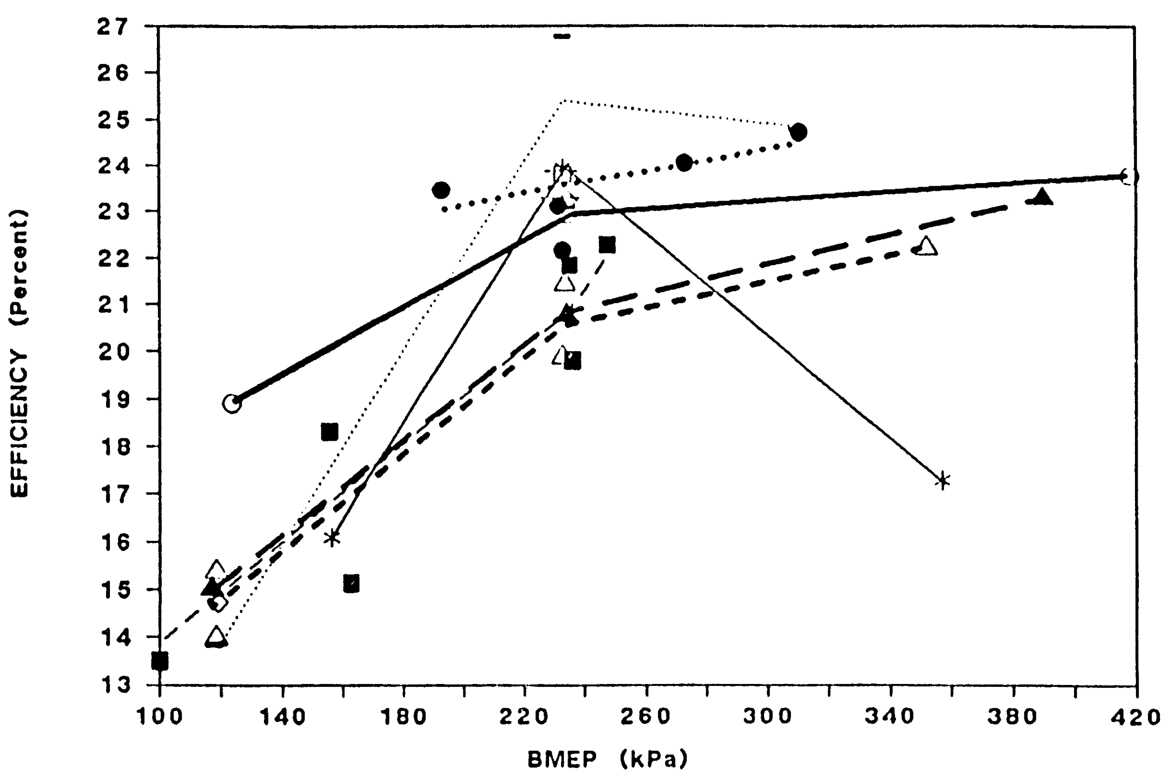



Figure 5.2.9-6 Brake Thermal Efficiency at 1,800 RPM

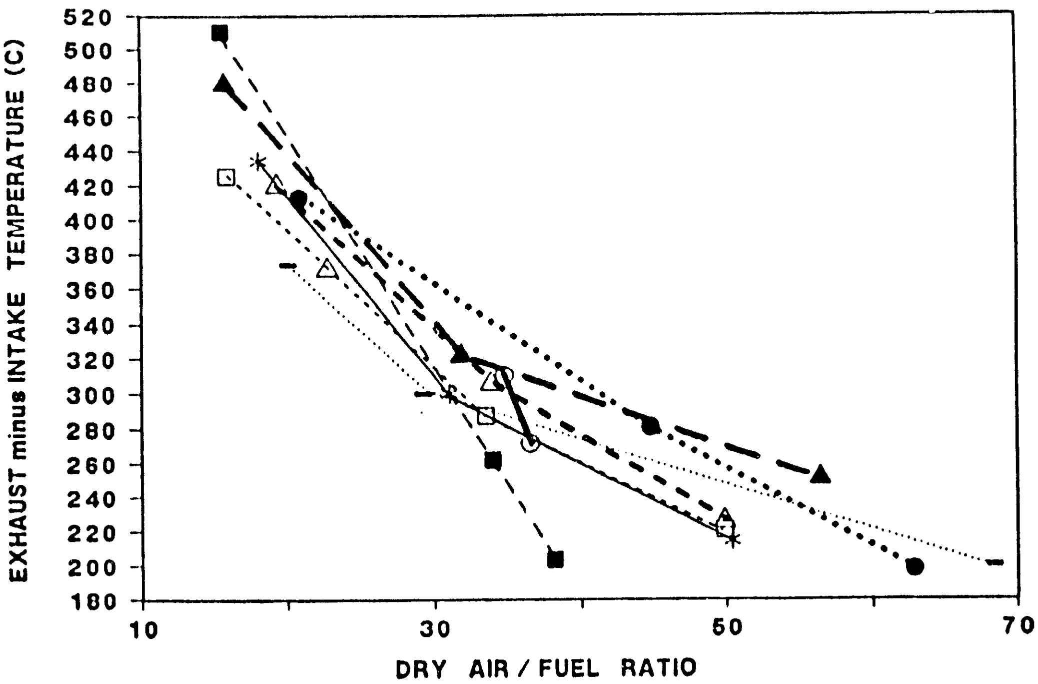



Figure 5.2.9-7 Engine Temperature Rise at 1,000 RPM

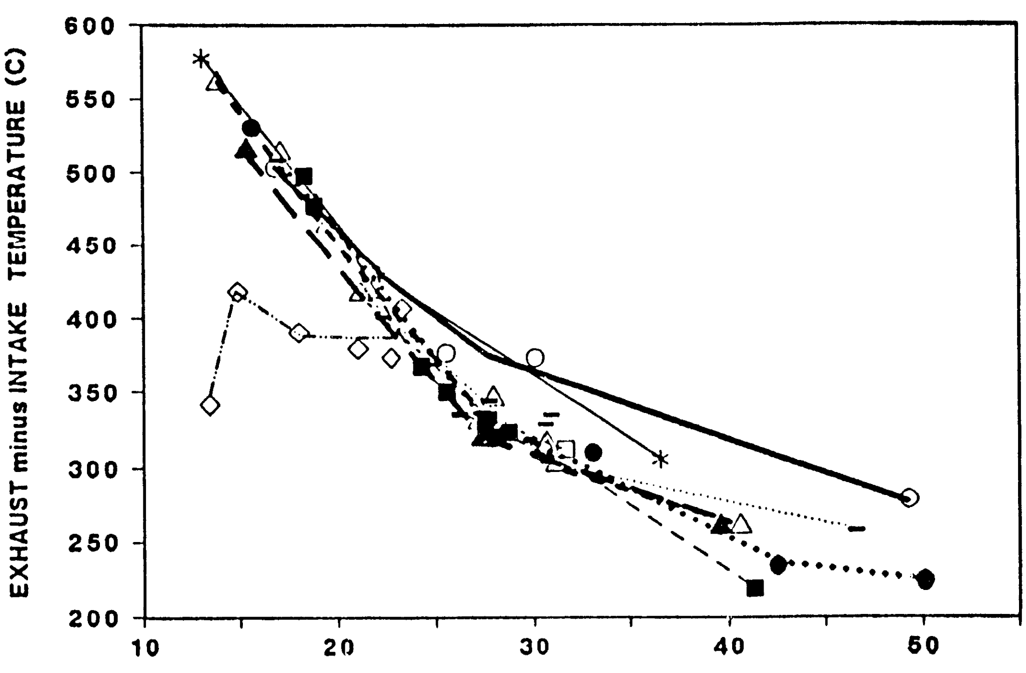



Figure 5.2.9-8 Engine Temperature Rise at 1,400 RPM

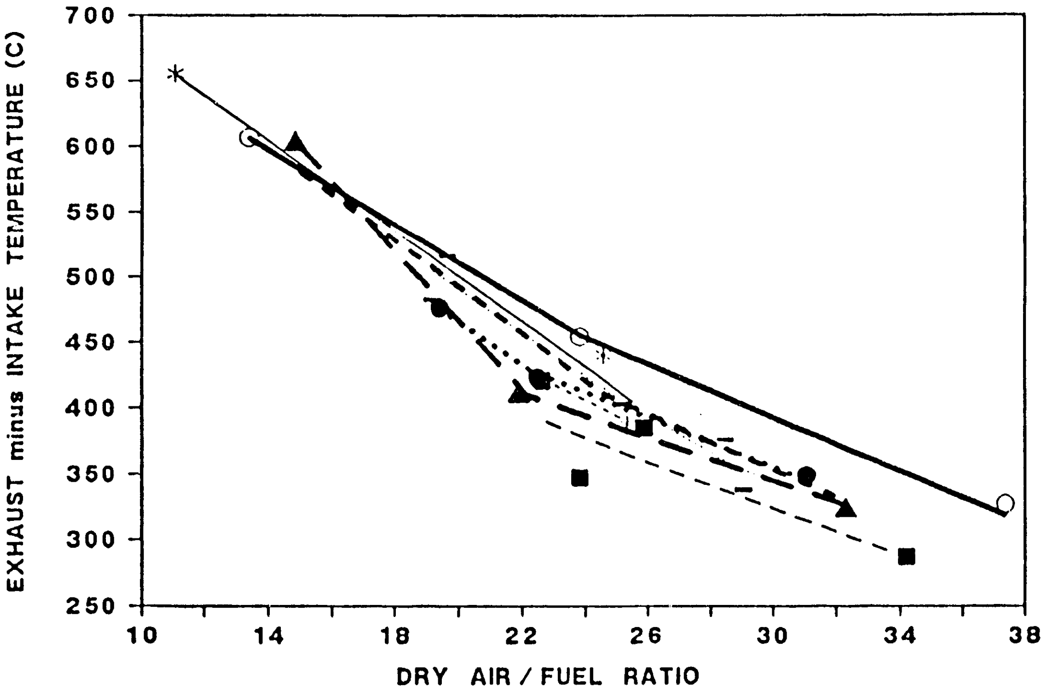



Figure 5.2.9-9 Engine Temperature Rise at 1,800 RPM

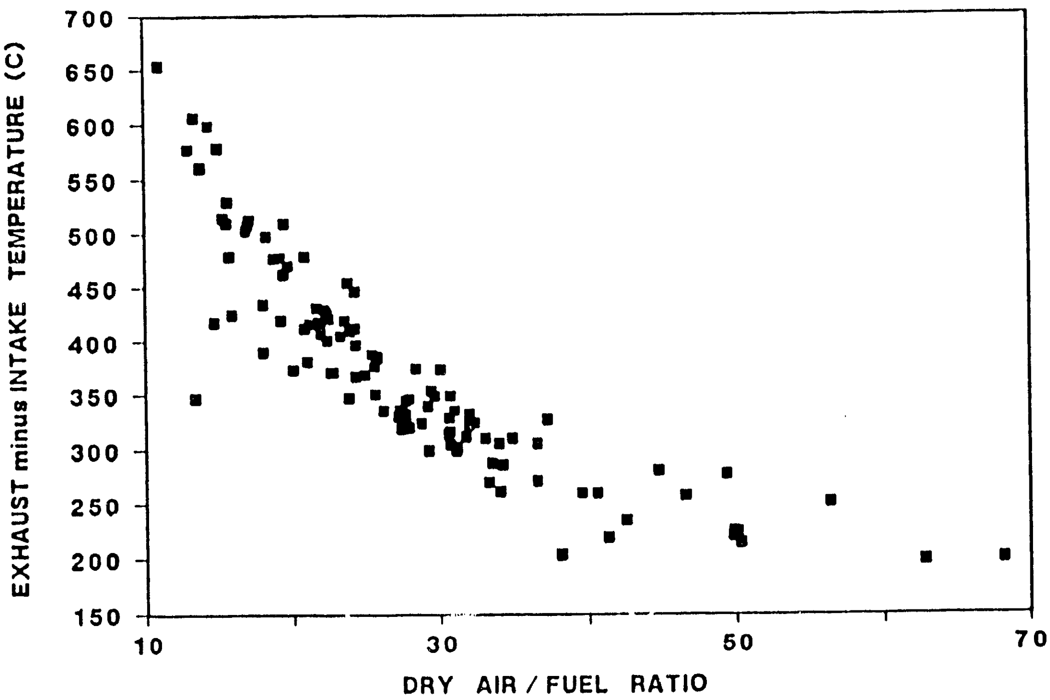



Figure 5.2.9-10 Engine Temperature Rise for All Speeds and All Loads

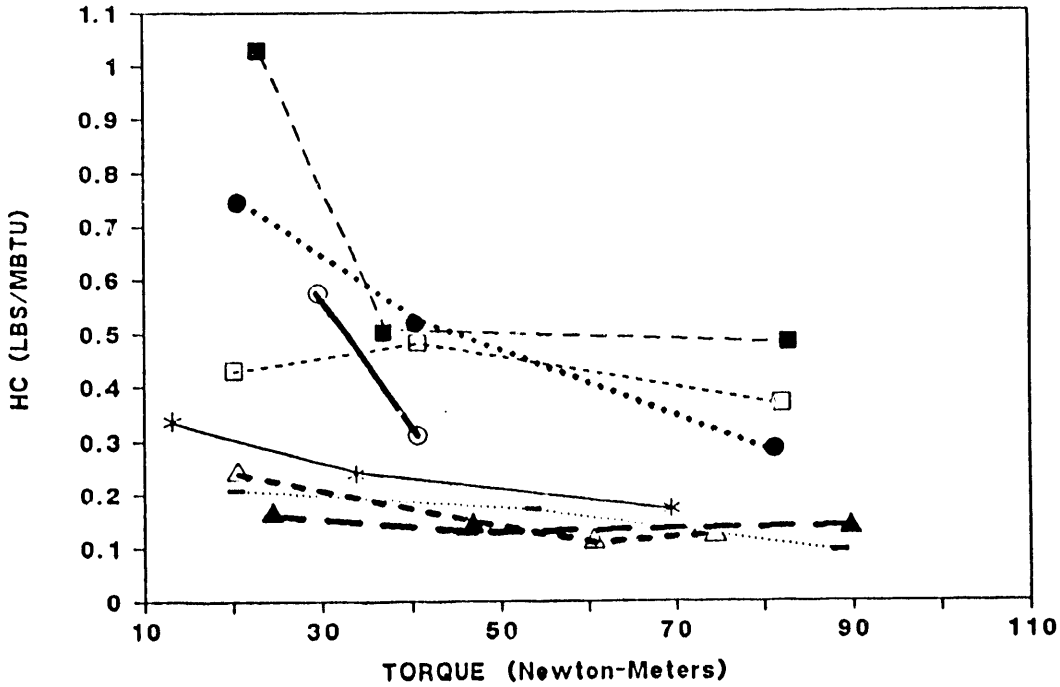



Figure 5.2.9-11 Hydrocarbon Emissions at 1,000 RPM

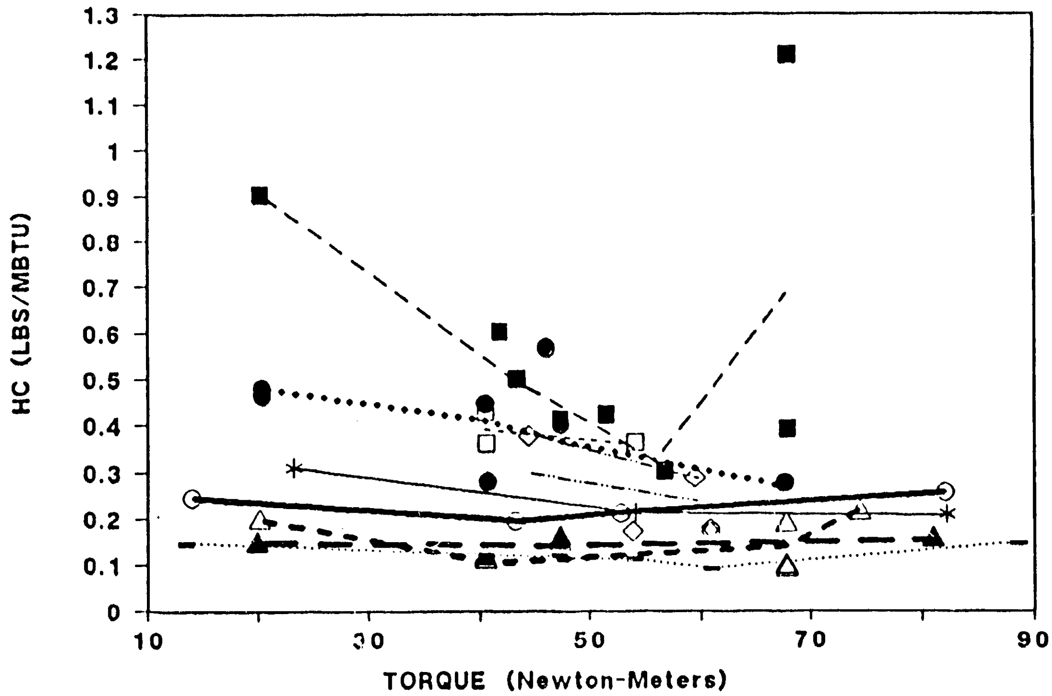



Figure 5.2.9-12 Hydrocabon Emissions at 1,400 RPM

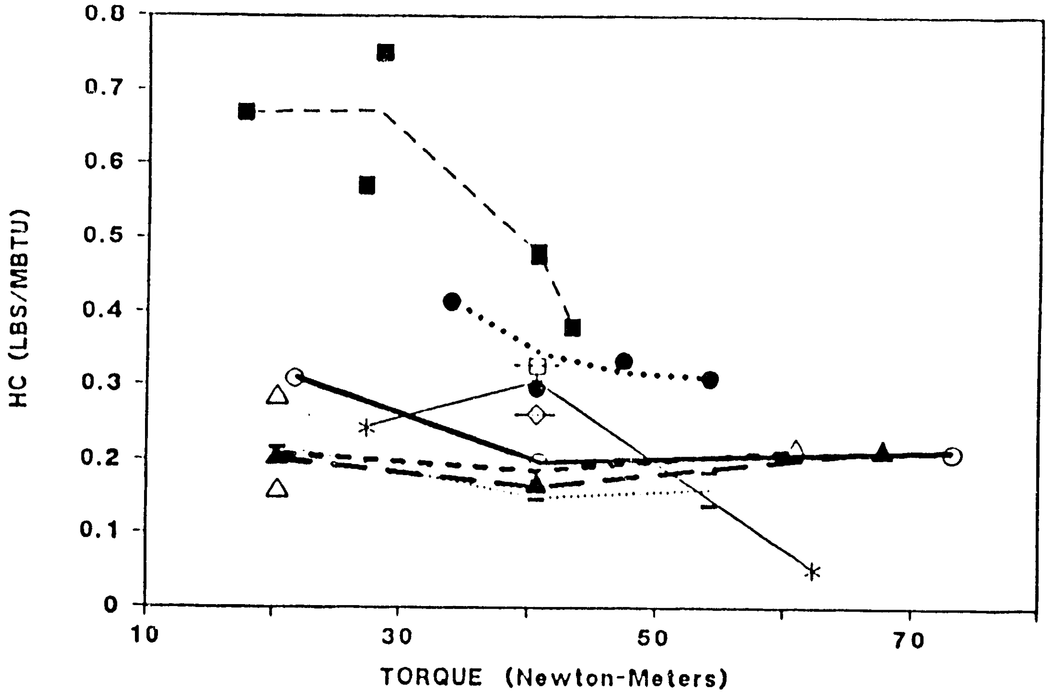



Figure 5.2.9-13 Hydrocarbon Emissions at 1,800 RPM

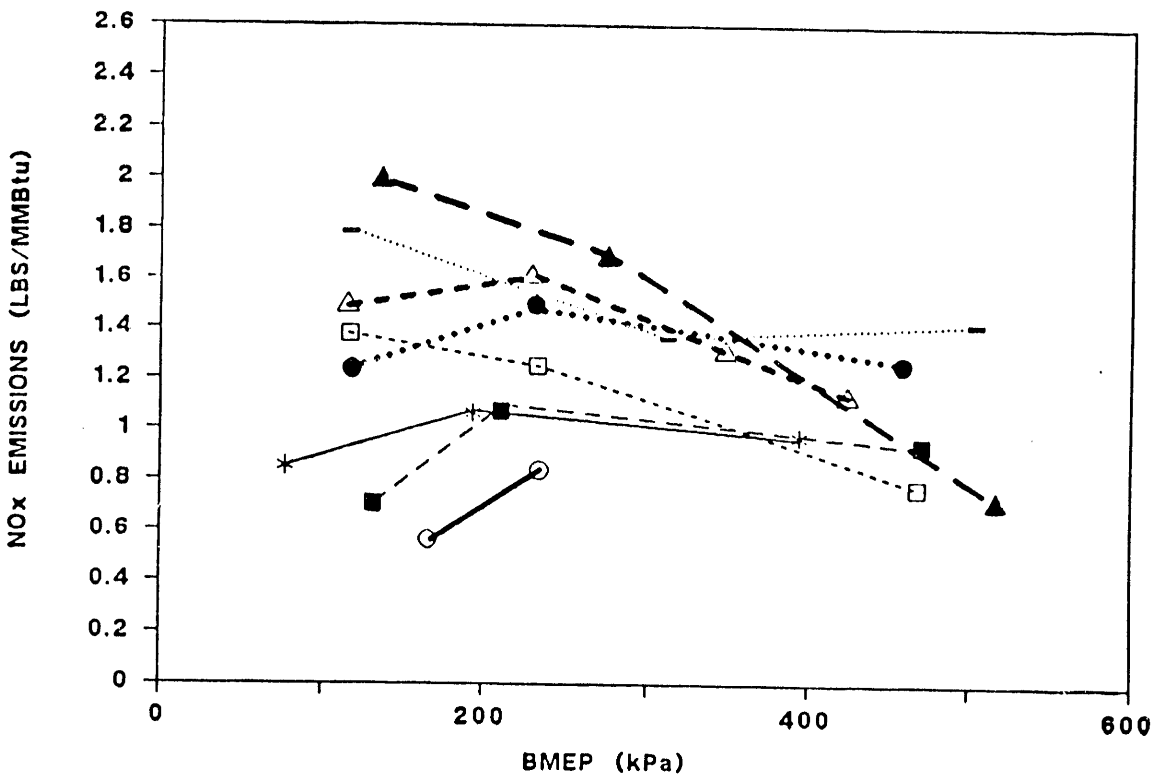



Figure 5.2.9-14 NOx Emissions at 1,000 RPM

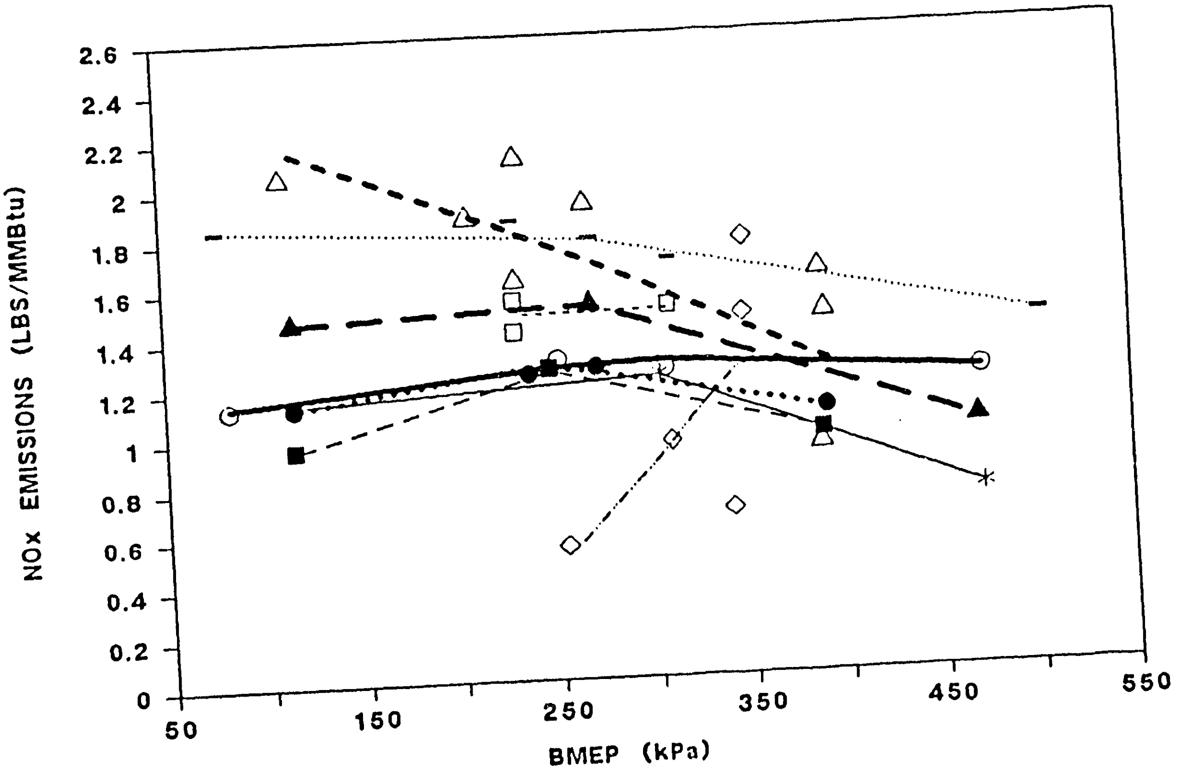



Figure 5.2.9-15 NOx Emissions at 1,400 RPM

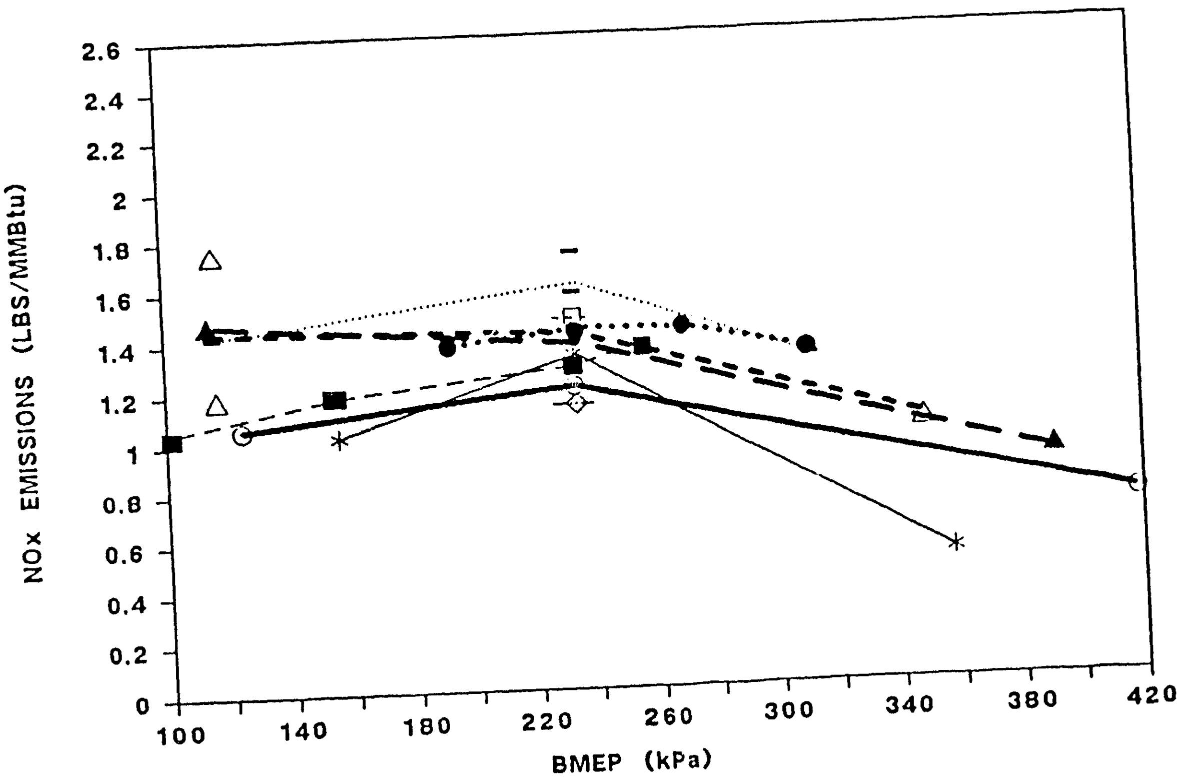



Figure 5.2.9-16 NOx Emissions at 1,800 RPM

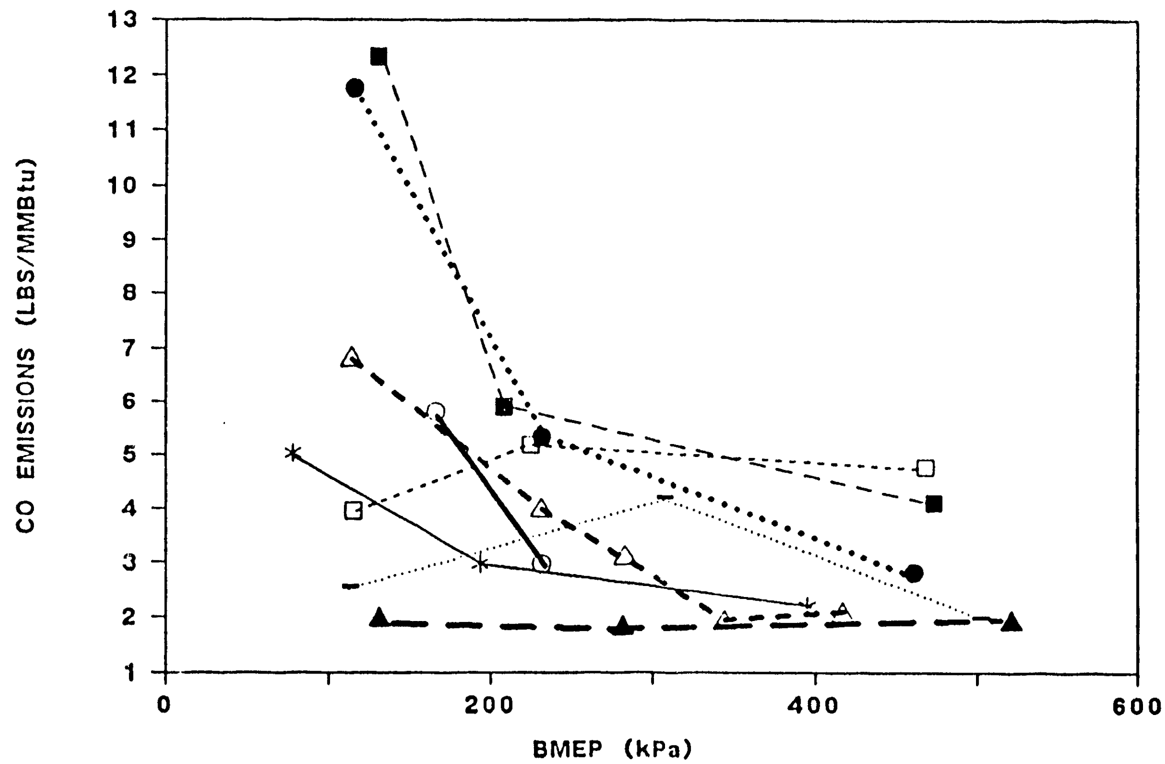



Figure 5.2.9-17 Carbon Monoxide Emissions at 1,000 RPM

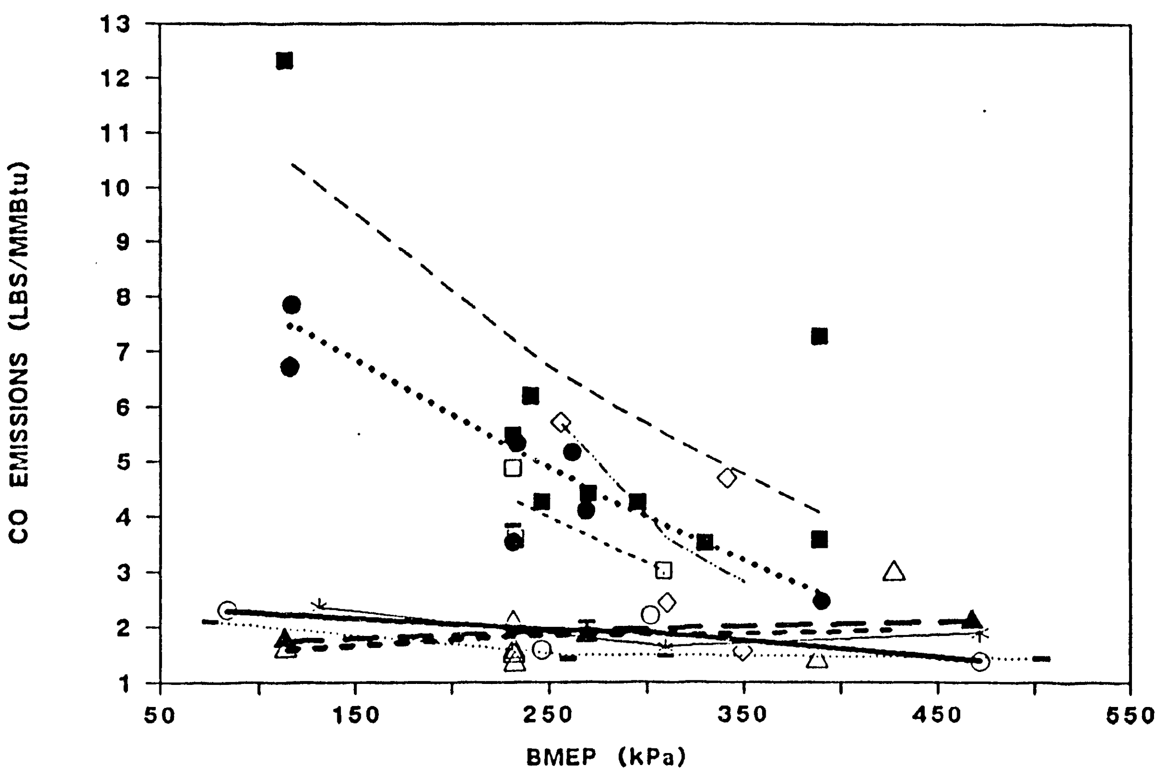



Figure 5.2.9-18 Carbon Monoxide Emissions at 1,400 RPM

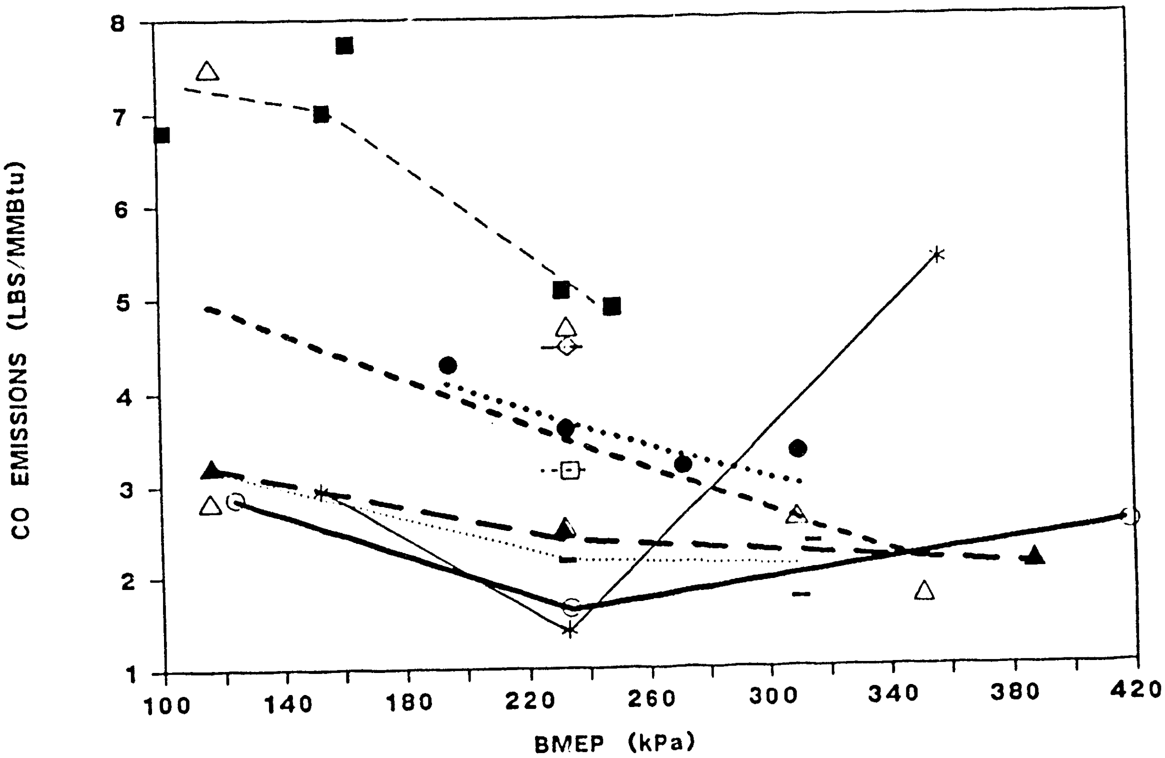



Figure 5.2.9-19 Carbon Monoxide Emissions at 1,800 RPM

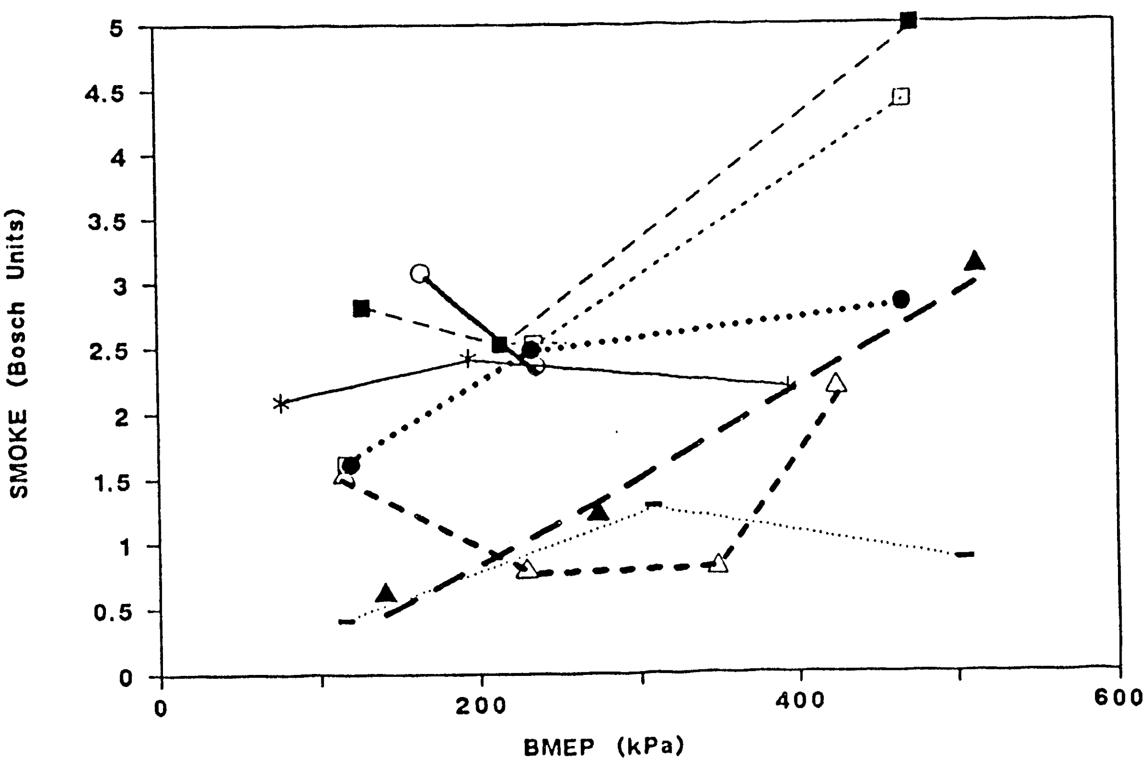



Figure 5.2.9-20 Exhaust Smoke at 1,000 RPM

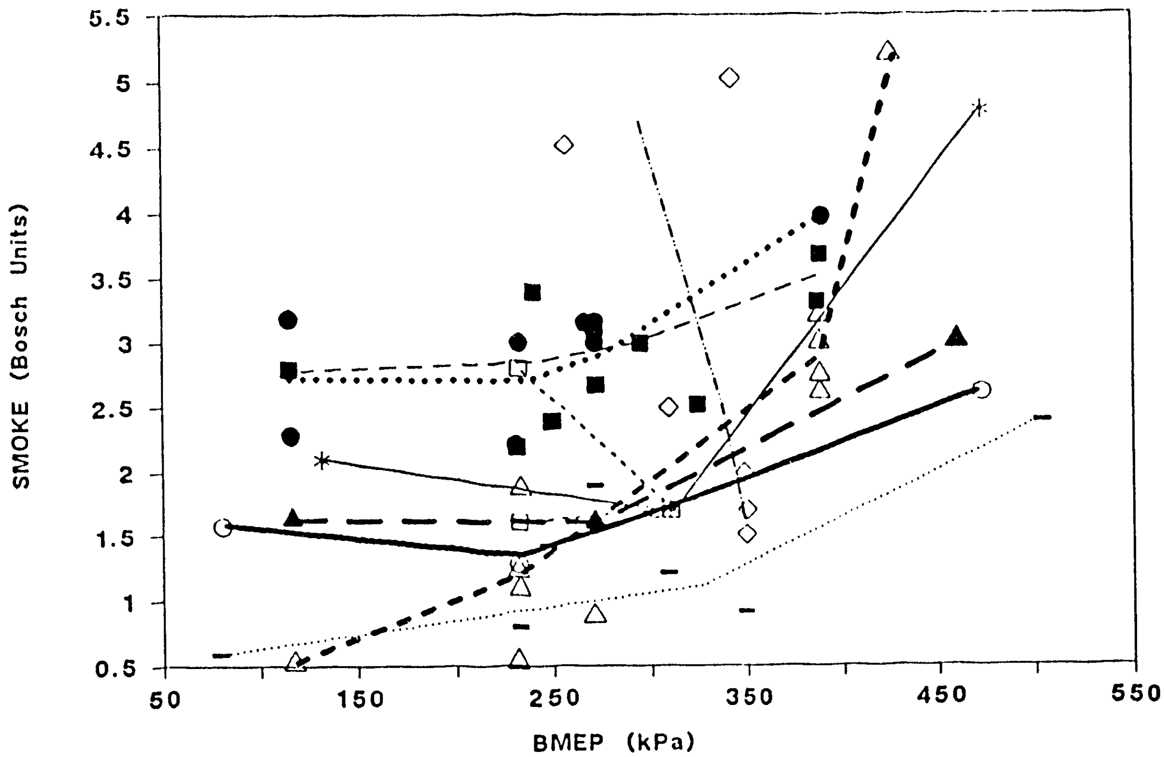



Figure 5.2.9-21 Exhaust Smoke at 1,400 RPM

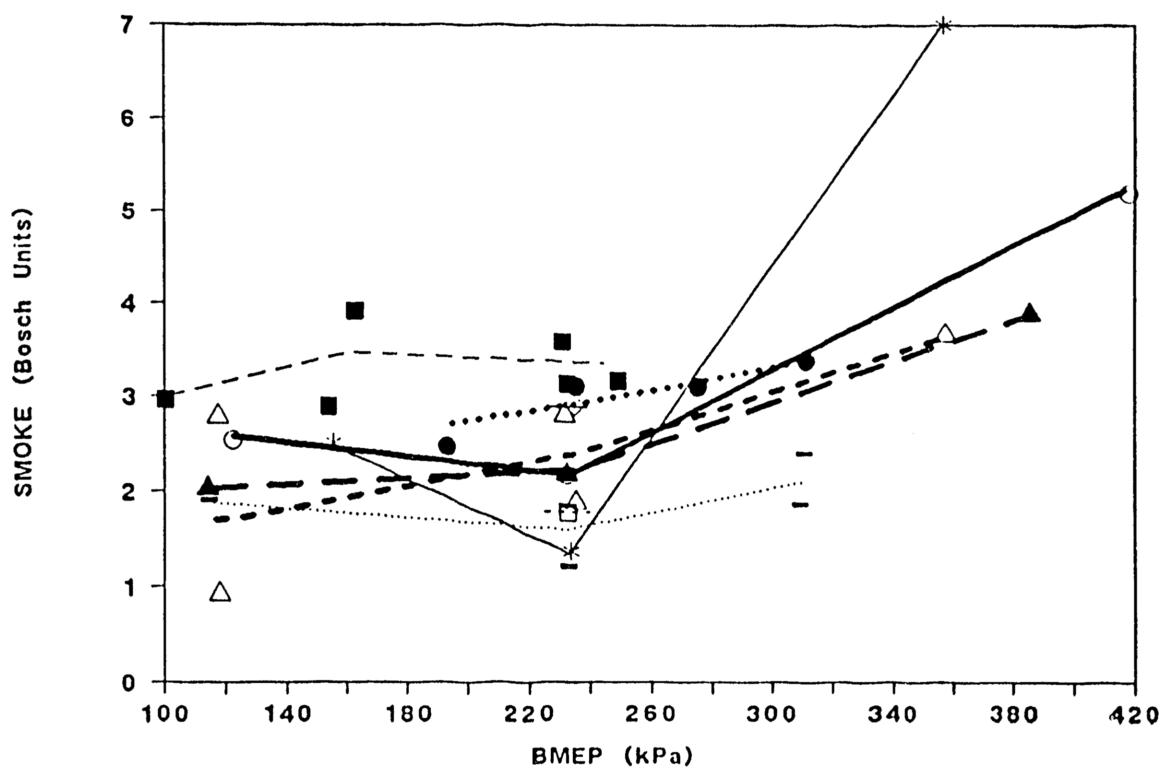



Figure 5.2.9-22 Exhaust Smoke at 1,800 RPM

Table 5.2.10-1

**SUMMARY OF PHASE II CWS-FUELED ENGINE TESTS AND NOZZLE HOLE WEAR DATA**

| NOZZLE ID | NOZZLE HOLE SIZE MM (INCH) BEGIN | NOZZLE HOLE SIZE MM (INCH) END | 100% CWS TESTING TIME (MIN) | FLOW AREA INCREASE (%) | WEAR RATE MM/MIN X $10^{-4}$ (IN/MIN) X $10^{-6}$ |
|---|---|---|---|---|---|
| A | 0.940 (0.037) | 1.054 (0.0415) | 240 | 25.7 | 4.76 (18.8) |
| B | 0.978 (0.0385) | 1.016 (0.040) | 320 | 7.9 | 1.191 (4.7) |
| C | 1.016 (0.040) | 1.016 (0.040) | 250 | 0 | 0 |
| D | 1.016 (0.040) | 1.080 (0.0425) | 245 | 12.9 | 2.542 (10.2) |
| E | 1.067 (0.042) | 1.10 (0.0435) | 390 | 7.3 | 0.977 (3.8) |
| F | 1.067 (0.042) | 1.092 (0.043) | 365 | 4.8 | 0.696 (2.7) |
| G | 0.737 (0.029) | 0.749 (0.0295) | 315 | 3.5 | 0.403 (1.6) |
| H | 0.914 (0.036) | 0.927 (0.0365) | 615 | 2.8 | 0.207 (0.8) |

A & B = STANDARD SINGLE HOLE NOZZLE

C THROUGH H = REPLACEABLE SPRAY ORIFICES MACHINED FROM M2 TOOL STEEL

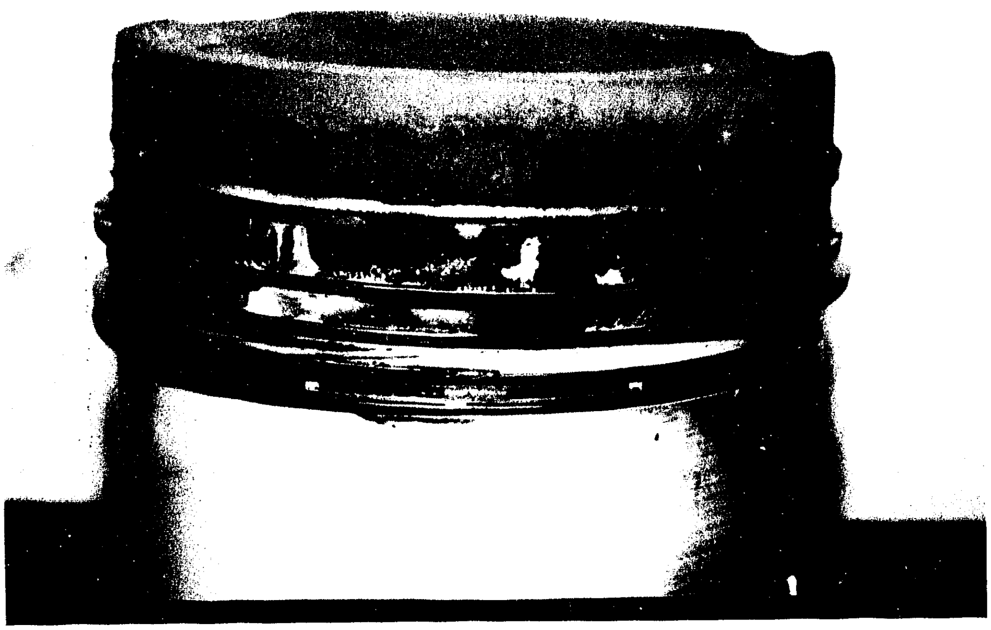
TOTAL 100% CWS ENGINE TESTING FOR PHASE II: 45.7 HOURS

Table 5.2.10-2

# SUMMARY OF PISTON RING WEAR

| | WEIGHT (GRAMS) | | END GAP | | RADIAL RING WEAR |
|---|---|---|---|---|---|
| | BEFORE | AFTER | BEFORE (MM) | AFTER (MM) | (MM) |
| TOP RING (CHROME CARBIDE COATED) | 48.0 | 47.0 | 0.74 | 1.143 | 0.064 |
| TOP INTERMEDIATE RING (STANDARD - CHROME COATED GREY IRON) | 33.7 | 33.4 | 0.51 | 0.74 | 0.037 |
| BOTTOM INTERMEDIATE RING (STANDARD - CHROME COATED GREY IRON) | 33.4 | 33.3 | 0.51 | 0.76 | 0.040 |
| OIL RING (STANDARD - CHROME COATED GREY IRON) | 39.6 | 39.4 | 0.58 | 0.89 | 0.049 |

TOTAL TIME
100% CWS ENGINE TESTING:
28.1 HOURS



AI-232-23

Figure 5.2.10-1 Caterpillar Piston after 28.1 Hours of 100% CWS Engine Operation

## 5.3 TECHNICAL CONCERNS

Various operational and maintenance difficulties were encountered during this investigation and it is important to note these difficulties for the future.

### 5.3.1 Coal Water Slurry Quality and Handling

Despite the attempts to avoid problems which previous researchers have encountered with CWS, several additional severe problems were encountered during this program. The problems included non-recoverable settling during shipping and storage, agglomeration caused by contact with hydrocarbon liquids, and foreign particle contamination. Other difficulties such as extreme property changes caused by small changes in the percentage of water in the slurry and clogging and plugging problems were experienced. Like other researchers, it was found that the slurry had to be kept in continuous motion to minimize these problems. The presence of large particles (both foreign and coal based) resulted in the need to filter the fuel (Figure 5.3.1-1). Another real problem has been the disposal of contaminated CWS which must presently be treated as a hazardous waste.

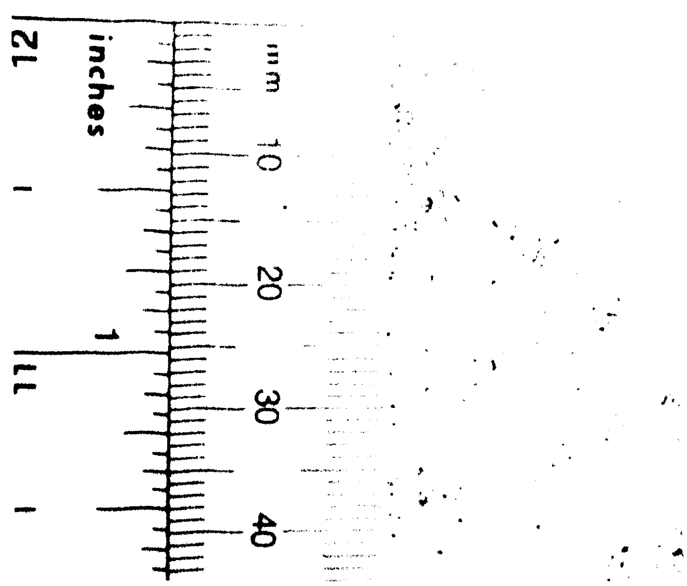
### 5.3.2 Engine Contamination

Coal particles (both burnt and unburnt) were found in three different areas of the engine after testing. Ash particles were found on the exhaust valve rotators and springs. These particles had slipped through the clearance between the valve stem and the valve guide. At no time during testing did these deposits present any problem (such as valve sticking, failure to rotate, etc.). Ash and unburnt coal contacted the cylinder liner causing ring wear and large deposits above the top ring reversal area. The last area of coal contamination was the product of the first two areas. The ash and unburnt coal that slipped past the valve guides and rings contaminated the oil. Two centrifugal oil filters were used to remove the coal contaminants (Figure 5.3.2-1 is a photograph of one filter after eight hours of 100 percent CWS testing). During this time period the engine was run extensively at very high loads to determine maximum power output and was occasionally run in overfueled condition which aggravated the migration of coal into the oil. Therefore, the accumulation during this eight hour run was higher than normal.

### 5.3.3 Deposit Formation in PCC and on Piston

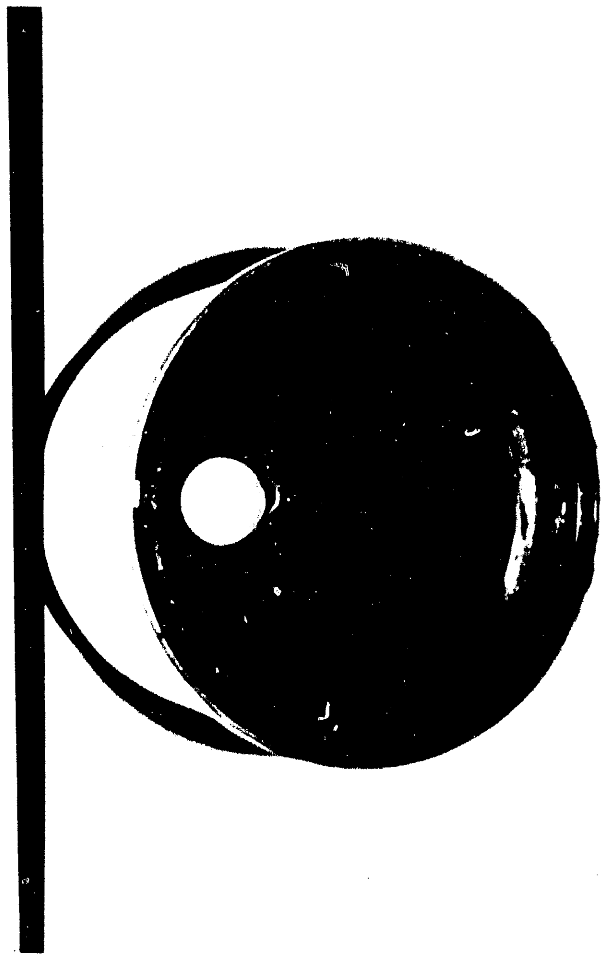
Adiabatics, Inc., moved to a new facility during the middle of the Phase II program. The first tests at the new facility with 100 percent CWS fuel showed deposit formation at the throat of the prechamber. Figure 5.3.3-1 shows typical deposits including loose deposits collected on a magnet. Engine operation including efficiency and the power output were similar at the old and new facilities so long as the deposits were light.

Further investigation showed the deposit formation in both the swirl type and pepper pot type prechambers. These deposits deteriorated the engine performance. It was confirmed that the deposits form when burning slurry from different batches, including that which was used at Adiabatic's former facility (where the deposit formation was minimal). It has been also found that all the deposits can be attracted to a magnet. Samples from two batches of slurry were analyzed and found to have an iron content between 300 to 400



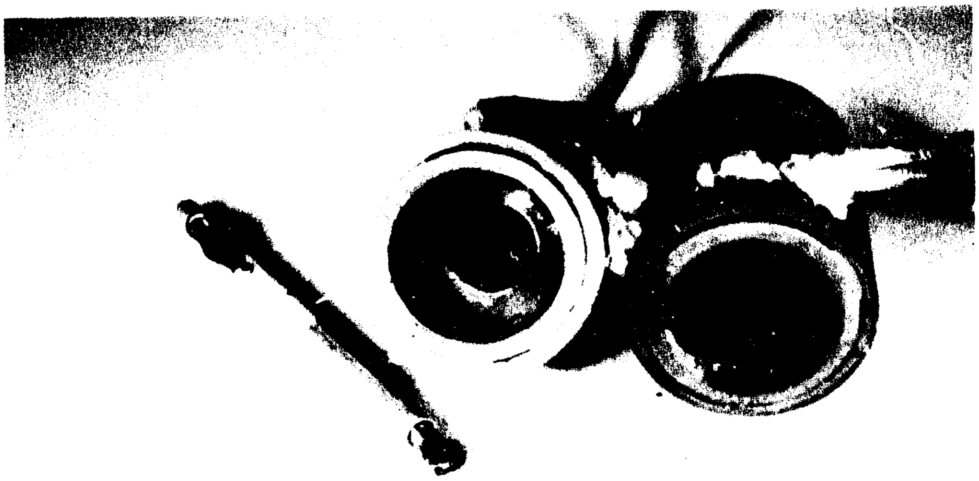
AI-234-23

Figure 5.3.1-1 Large Particles Filtered Out of CWS Before Testing Began



AI-233-18A

Figure 5.3.2-1 Load Contaminants Collected in Centifugal Filter After 8 Hours of 100% CWS Engine Testing



AI-214-16A

Figure 5.3.3-1 Pepper Pot Type Prechamber After One Hour of 100% CWS Engine Testing With Blue Gem Seam Coal ppm. The analysis of the prechamber deposits has revealed a concentration of 20 percent iron and 0.13 percent nickel. The PCC material has been changed to Haynes alloy no. 230 from Hastelloy X as the 230 material has a significantly lower iron content and the same deposit formation has been experienced. Further, the deposit formation did not change with a change in PCC temperature from 871°C to 982°C (1,600 to 1,800°F).

Precombustion chambers have been weighed before and after testing to confirm that the deposit formation was not due to the corrosion of the Hastelloy X or 230 alloy.

The location and appearance of the deposits suggests that the deposits are a slag formation which is deposited on the inner surface as a liquid which then runs down the walls until it reaches a cooler section of the prechamber near the throat where it solidifies. Examination of a paper [15] sent by Mr. Cary Smith shows that a similar problem of scale deposit formation was experienced in the boiler tubes of fossil fueled utility systems. The deposits described in the paper were a form of iron oxide called magnetite which are created by a chemical reaction between the surface of the steel tubes and the steam flowing through them. It is possible that the deposits, formed in the engine testing, could be also a form of magnetite and needs to be confirmed. At this point, it is quite plausible to think that the deposits were coming from the burning of the CWS fuel. Based upon the amount of iron in the deposits and the amount of iron in the coal-fuel it is possible that all of the deposits are coming from the ash in the fuel.

### 5.3.4 Nozzle Orifice and Cylinder Head Cracking

Problems with cracking the spray insert orifice in the nozzle cap and cracking of the cylinder head were encountered during the engine testing. The orifice was corrected by increasing the load bearing area of the orifice and providing two holes into the cooling passage of the injector nozzle to allow cooling water to contact the spray insert orifice.

The cylinder head cracking problem (Figure 5.3.4-1) was the result of a large thermal expansion mismatch between the Caterpillar cast iron head and the Hastelloy X prechamber material. The problem was corrected by installing belleville washers in the prechamber hold-down system to allow the prechamber to grow without introducing additional loads into the head.

## 6.0 CONCLUSIONS

The work conducted during this program was successful in developing an electronically controlled, hydraulically actuated CWS-injection system operating at low injection pressures of 13.8 to 20.7 MPa (2,000 to 3,000 psi). Also, the program objectives of 100 percent CWS-fueled engine operation with the TICS concept without the use of external ignition assist sources up to 1,800 rpm speed were achieved. The high level of ignition energy in TICS chamber enabled the unassisted combustion of CWS fuel at all speeds and loads in the test engine. The nozzle wear data showed less wear of the nozzle hole as compared to the wear data reported for other CWS injectors. Further, a wear-resistant coating or harder material for the nozzle hole extends the CWS injector nozzle life for operation with the CWS fuels.

AI-217-1A

Figure 5.3.4-1 Cracked Cylinder Head

The Kentucky Blue Gem seam CWS-fueled engine test results show high heat release rates and short combustion duration. The heat release analysis shows a significant portion of the CWS fuel burning in the premixed combustion mode. An increase in CWS injection pressure from 13.8 to 20.7 MPa was seen to increase the peak heat release rate. Performance data for coal powder, CWS and diesel-fueled engine tests show higher cylinder pressure and heat release rates for coal powder and CWS as compared to diesel fuel. 100 percent CWS-fueled engine test data up to 1,800 rpm speed range shows maximum brake thermal efficiency of 33.5 percent at 1,000 rpm. However, the brake thermal efficiency in a multi-cylinder CWS-fueled engine will be even higher. The test engine operation was optimized during the Phase II program with additional parametric optimization studies on the CWS injection and combustion. Amongst them includes: Improved performance with the swirl chamber PCC design and larger PCC volume. There exist optimum values of PCC temperature, nozzle orifice size, injection timing and percent EGR. Further, gaseous emissions, smoke and particulate measurements were made. There appears to be some correlation between smoke and particulates.

## 7.0 RECOMMENDATIONS FOR FUTURE WORK

Based on the results and findings of this program, the following recommendations are suggested for future work on the CWS injectors and engines:

- Evaluate CWS injection and combustion characteristics in a multi-cylinder engine with the TICS concept. For this purpose, a 4 or 6 cylinder engine can be modified with the CWS injection system and air gap insulated TICS chambers operating at high temperatures.

- Further investigate wear-resistant coatings and materials for the nozzle hole to increase its life.

- Improve CWS injector by making changes for its normally closed operation and direct solenoid actuation of the plunger. This will eliminate need for the servo-fluid (and servo-fluid pump and other accessories) and make the CWS injector more compact and commercially viable.

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