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Novel Injector Techniques for Coal-Fueled Diesel Engines

Final Report

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For
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EXECUTIVE SUMMARY

This report, entitled "Novel Injector Techniques for Coal-Fueled Diesel Engines," describes the progress and findings of a research program aimed at development of a dry coal powder fuel injector in conjunction with the Thermal Ignition Combustion System (TICS) concept to achieve autoignition of dry powdered coal in a sinle-cylinder high speed diesel engine. This work was performed under the U.S. Department of Energy, Morgantown Energy Technology Center (DOE-METC) Contract Number DE-AC21-90MC26305.

The basic program consisted of concept selection, analysis and design, bench testing and single cylinder engine testing. An optional task for multi-cylinder engine testing was part of the program. However, the option was not funded.

The coal injector concept which was selected was a one moving part dry-coal-powder injector utilizing air blast injection. Adiabatics has had previous experience running high speed diesel engines on both direct injected coal-water-slurry (CWS) fuel and also with dry coal powder aspirated into the intake air. The Thermal Ignition Combustion System successfully ignited these fuels at all speeds and loads without requiring auxiliary ignition energy such as pilot diesel fuel, heated intake air or glow or spark plugs. Based upon this prior experience, it was shown that the highest efficiency and fastest combustion was with the dry coal, but that the use of aspiration of coal resulted in excessive coal migration into the engine lubrication system.

Based upon a desire of DOE to utilize a more modern test engine, the previous naturally-aspirated Caterpillar model 1Y73 single cylinder engine was replaced with a turbocharged (by use of shop air compressor and back pressure control valve) single cylinder version of the Cummins model 855 engine. Baseline testing of the engine with a standard diesel fuel injection system confirmed that the engine performed properly and provided baseline emissions information. The dry-powder-coal injection system was extensively analyzed, designed and redesigned multiple times, manufactured and installed on the engine.

The engine did run self sustained briefly (five minutes) on 100 percent dry-powdered-coal and the TICS chamber was self heating.

NOVEL INJECTOR TECHNIQUES FOR COAL-FUELED DIESEL ENGINES

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1.0 INTRODUCTION

This final report entitled "Novel Injector Techniques for Coal-Fueled Diesel Engines," is submitted to the U.S. Department of Energy, Morgantown Energy Technology Center (DOE/METC), to fulfill the requirements for Contract Number DE-AC21-90MC26305. It describes the results and findings of a research program aimed at the development of an air-blast-atomized dry-coal-powder fuel injector developed in conjunction with the Thermal Ignition Combustion System (TICS) to achieve autoignition of coal fuel in a high speed diesel engine.

The U.S. Department of Energy, Morgantown Energy Technology Center, has sponsored many research programs for the development of coal-fueled diesel engines [1-2]*. Most of these programs utilized coal-water-slurry (CWS) as the fuel form and relied upon pilot injection of diesel fuel to ignite the CWS in rather conventional diesel engines. The key demonstrator programs have been a CWS fueled locomotive developed by General Electric [3-4] and a stationary CWS fueled diesel power plant developed by A.D. Little/Cooper Bessemer [5-6]. Both of these programs utilize very similar high pressure CWS fuel injection systems with electronic control. One of the major problems identified during these programs has been excessive wear of fuel injection nozzle spray holes [3-5] and other fuel and fuel system related problems. To provide additional research into the fuel injection portion of the program, DOE-METC published a Program Research and Development Announcement (PRDA) on "Novel Injector Techniques for Coal-Fueled Diesel Engines" on August 28, 1989 to which Adiabatics, Inc. submitted a proposal on October 11, 1989. Based upon the proposal, Adiabatics, Inc. was awarded a two year contract on September 26, 1990 with an option for one additional year of effort.

1.1 BACKGROUND ON COAL INJECTION SYSTEMS

Research into coal injection systems for diesel engines started with the inception of the diesel engine by Rudulph Diesel [7] and continued virtually continuously in Europe over a period of approximately fifty years culminating in successful coal-fueled diesel engines [8]. These efforts were terminated by the start of World War II and were not resumed after the war.

Following worldwide energy disruptions in the seventies, the United States government started efforts to provide increased utilization of its most readily available (and lowest cost) fuel - coal. It was believed that coal could be an ideal fuel for diesel engines provided that several key technology problems were overcome; i.e., clean coal preparation and formulation, fuel injection, combustion, engine wear and exhaust gas cleanup. Programs were started to address each of these areas. The early participants in the fuel injection area were Southwest Research Institute, NIPER, Energy and Environmental Research Corporation and work in Europe by Sulzer. These programs and success in each of the other areas led to full scale coal-fueled diesel engine demonstration programs by General Electric, A.D. Little/Cooper Bessemer and EMD/SWRI.

1.1.1 CWS Injection System by General Electric

The investigation of CWS fuel combustion in the GE-7FDL research engine has used three types of CWS injection systems [3-4]. They are described as follows:

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* Numbers in parentheses designate references listed at the end.

- System I fuel injection equipment (FIE) consists of a modified standard size diesel fuel FIE with a CWS isolation pump placed between the high pressure pump and the injector to prevent injector pump plunger sticking. Due to the low 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 upscaled version of System I FIE capable of supplying CWS for the full load engine operation.

- System III FIE consists of an accumulator based CWS injection system with high injection pressure at the start of the injection cycle and operates independent of engine speed and load with electronic control of injection timing and flow. This injection system has been found to improve CWS burnout considerably at both full and part engine loads.

The system III FIE accumulator injection system uses a conventional jerk pump to pump diesel oil to a diaphragm pump. The CWS on the opposite side of the diaphragm is thereby pressurized and pushed into the accumulator injector. The accumulator volume of this injector is about 325 cc. The system has been sized to inject 3 gm of CWS per injection, with the injection pressure falling from 70 to 48 MPa as injection occurred. GE gas evaluated a number of different nozzle geometries - 10 to 12 holes and 0.39 to 0.51 mm hole diameter. The CWS fuel engine test results with this injector have been presented by Hsu et al. [4].

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

Two different types of CWS FIE have been designed and operated on the Cooper JS1 engine [5-6]. 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 multihole nozzle for atomization. CWS fuel was supplied either from a pressurized tank or from a holding tank using a Moyno pump. This system was very similar to GE's first two systems.

The second system is based on the Cooper-Bessemer common rail fuel system. Pressurized CWS is supplied by an accumulator and fuel metering is 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 approach.

1.1.3 Dry-Powder Coal Injection

Reference 7 provides an excellent discussion of dry-powder coal injection as developed and refined in Germany prior to World War II. This work thoroughly describes the development of many different types of dry-powder "Dust" injectors including injectors which used compressed air to atomize and inject the coal.

1.2 TICS CONCEPT FOR COAL-FUELED ENGINES

Adiabatics, Inc. has successfully completed five programs relative to coal-fueled diesel engines. Adiabatics' first government contract

(DE-AC21-84MC21099 - 1985) was an investigation on "Combustion Characteristics of Coal Fuels in Adiabatic Diesel Engines" for DOE/METC. This study produced some extremely interesting results [9-10]. The original program goal was to ignite fumigated powdered coal of about 5 micron average particle size by means of diesel pilot injection. It was found in the adiabatic, prechambered-engine, that the coal powder was able to ignite without aid from the diesel pilot. The investigation led to a simple, fumigated, coal burning engine without spark plug or diesel injection system that will thermally ignite powdered coal in the engine. The engine operated from one quarter to full load without a throttle valve in the intake system. U.S. and European patents have been granted to Adiabatics, Inc. for the Thermal Ignition Combustion System (TICS) concept discovered during this program (U.S. Patent No. 4,738,227).

The second coal-fueled engine program (DE-AC21-86MC23258, September 1986 to September 1988) was designed to further the development of a dry coal powder engine by resolving issues left open at the end of the first program. The most difficult problem (ignition timing control) was addressed by optimization and control of the precombustion chamber temperature, and by adding and controlling exhaust gas recirculation (EGR). An improved coal feed system for the fine coal powder was designed, fabricated and tested. This consisted of a one moving part device and resulted in consistent fuel metering and delivery for the coal-fueled engine operation. The test engine was run on 100% coal powder without any diesel pilot or heated intake air from 800 to 1800 rpm and idle to full load engine conditions. The coal-fueled engine was operated with three types of coal: Micronized Bituminous coal, 7 micron mean size; nonbeneficiated 1.6% ash content Bituminous coal, 21.3 microns mean size; and 7.1% ash content North Dakota Lignite coal, 29 microns mean size. Also, cold starting of the test engine was achieved on coal powder fuel only. The major problem observed with fumigation of coal powder to the intake air manifold was the inability of the piston rings to prevent excessive coal contamination of the lubricating oil. The lubrication system was, however, improved to separate coal particles from the contaminated lubricating oil and the wear on the ceramic coated piston rings and cylinder liner was found to be minimal [11-12].

The third program was a subcontract to Allison Gas Turbines (Contract No. DE-AC21-86MC22123) to perform an experimental investigation to determine the friction and wear (tribological) characteristics of a selected group of candidate piston ring and cylinder liner materials suitable for their EMD 16-1710 coal burning diesel engine [13].

The fourth program was "Fluidic Fuel Feed System" Contract No. DE-AC21-86MC23006 which attempted to develop a practical CWS injector using 100 percent fluidic (no moving part) technology. An injector was developed and engine tested; however, it was necessary to add at least two check valves to the injector to permit it to effectively operate in the engine. This "hybridization" of the fluidic injector eliminated the main advantages it might have had over conventional CWS injectors.

The fifth program which was highly successful was "Innovative Coal-Fueled Diesel Engine Injector," Contract No. DE-AC21-88MC25132 which utilized an innovative low pressure CWS injector to inject CWS directly into the TICS combustion chamber. Optimization of the TICS chamber geometry and injection characteristics has resulted in the ability to operate very efficiently over the entire operating range of the engine from idle to full load using only CWS fuel and maximum injection pressures of less than 3,000 psi compared to over 10,000 psi for all other researchers.

The experience of performing these five coal-fueled diesel research programs has taught the staff of Adiabatics, Inc. innumerable lessons concerning how to conduct research with these fuels. Systems are in place to specify, procure, ship, store, handle, mix, inspect, filter, and measure both dry coal powder fuel and CWS fuel. This experience did not come easily. Many difficulties have been overcome and each day of operating with these fuels provided new challenges. One major difficulty in working with coal fuel of any type is repeatability. It has been impossible to obtain consistent coal quality from any supplier and because the raw coal basestock has such wide variability, it is unlikely that the situation will ever be significantly improved. For this reason, it is important that the fuel handling and introduction systems and the engine combustion system be made tolerant and insensitive to large variations in fuel properties.

1.3 PROGRAM OBJECTIVES

The stated objective of the program is to develop new and novel injection techniques which will reduce or eliminate the present wear problems associated with the injection of coal-water slurries. The new and novel method will result in combustion and cylinder wall ash deposition which is comparable to current oil-fired configurations.

2.0 PROJECT DESCRIPTION

A program with two tasks was generated and performed as specified in the contract as Part III, Section J, Attachment A "Statement of Work". The first Task - Preliminary Engineering - consisted of subtasks to generate a Management Plan, to select a concept and generate a Test Plan, to conduct single cylinder experimental work and submit a topical report (this document). Task 2 - Development Engineering - was an optional task to apply the concept to a multi-cylinder engine and generate a final report. Per the direction of DOE/METC, Task 2 is not funded and will not be contracted. Therefore, the Topical Report from Task 1 is the Final Report for this contract.

2.1 TECHNICAL APPROACH

Based upon the successful results with the TICS combustion system used for all of the engine testing in the programs performed at Adiabatics and because it was the only combustion system which has demonstrated operation at all load and speed conditions without requiring diesel pilot fuel injection, it was decided to retain this concept for this program. Experience has shown us that coal fuel can be successfully introduced and burned in three distinct manners in the TICS diesel engine as follows:

Mode 1 - Fumigation	Either CWS or dry powder coal can be atomized in the intake air in the intake manifold and later ignited by the TICS chamber. The first programs at Adiabatics demonstrated this technique with dry powder coal. The CWS approach is probably best utilized in turbocharged engines which can use the elevated intake manifold temperature to evaporate the water from the slurry before it enters the combustion chamber. Fuel introduction can be either continuous or timed (intermittent). Ignition timing is accomplished by controlling the temperature of the TICS chamber and by use of controlled exhaust gas recirculation.

Mode 2 - Early Cycle	In this second approach either type of fuel is injected directly into the TICS chamber early in the compression stoke after the intake valve(s) close. The advantage of this approach over fumigation is that less raw fuel will be deposited on the cylinder liner and the intake valve seat and valve guide area will not be exposed to coal particles. Ignition timing control will be the same as for fumigation.
Mode 3 - Late Cycle	The last approach is injection of either type of fuel directly into the very hot TICS chamber just before engine top-dead-center. This approach has been successfully demonstrated with CWS. With this approach, there is no need for control of either the temperature of the TICS chamber or to use EGR to control timing.

Based upon the experience with running both dry powder coal and CWS fuels in a diesel engine, a strong bias towards the use of dry powder coal has been established at Adiabatics. This bias is based upon the fact that dry powder coal burns faster resulting in higher efficiency in medium and high speed engines and because CWS has proven to be extremely difficult to work with on a day by day basis.

The selection of injection mode favors late cycle injection over either fumigation or early cycle injection. The reason for this is the ease of control of ignition timing by directly controlling injection timing. Also it is believed that late cycle injection will significantly reduce the amount of coal which bypasses the combustion process and ends up contaminating the lubricating oil because the particles are not exposed to the oil cylinder which traps particulates in the boundary layer during compression.

The selection of dry powder coal as the fuel and late cycle injection required a new injection technique. As mentioned previously, Rudulph Diesel and others had perfected dry powder coal injection and used a system shown schematically in Figure 2.1-1. In this basic system, three valving functions must be performed in a prescribed timed sequence as illustrated in the figure. The first valve (A) performs the function of metering the powdered coal from the supply tank into the injector cavity (D). To maintain inherent safety in the system, the supply tank is sealed and uses an inert cover gas (such as nitrogen) over the coal at a pressure slightly over atmospheric. After valve (A) closes and seals off the supply tank, valve (B) opens and pressurizes the cavity (D) with air from a reservoir to a higher pressure than peak cylinder pressure. At about 10 to 30 degrees before top dead center (TDC) crankangle, valve (C) opens and the powdered coal is injected through valve (C) into the engine cylinder where it ignites and burns. Valve (C) is held open throughout the exhaust stroke so that the pressure in cavity (D) can be reduced to essentially exhaust manifold pressure. Valve (B) is closed late in the engine combustion to allow additional air to flow through cavity (D) to purge it of residual coal and to also provide additional air to the combustion chamber to improve the overall combustion efficiency. While it was possible to build injection systems based upon this schematic, most of those which were built looked like Rube Goldberg inventions. It is recognized that building a dry coal injector with three independent valves operating at different times is not practical and would not have a high chance of commercial success.

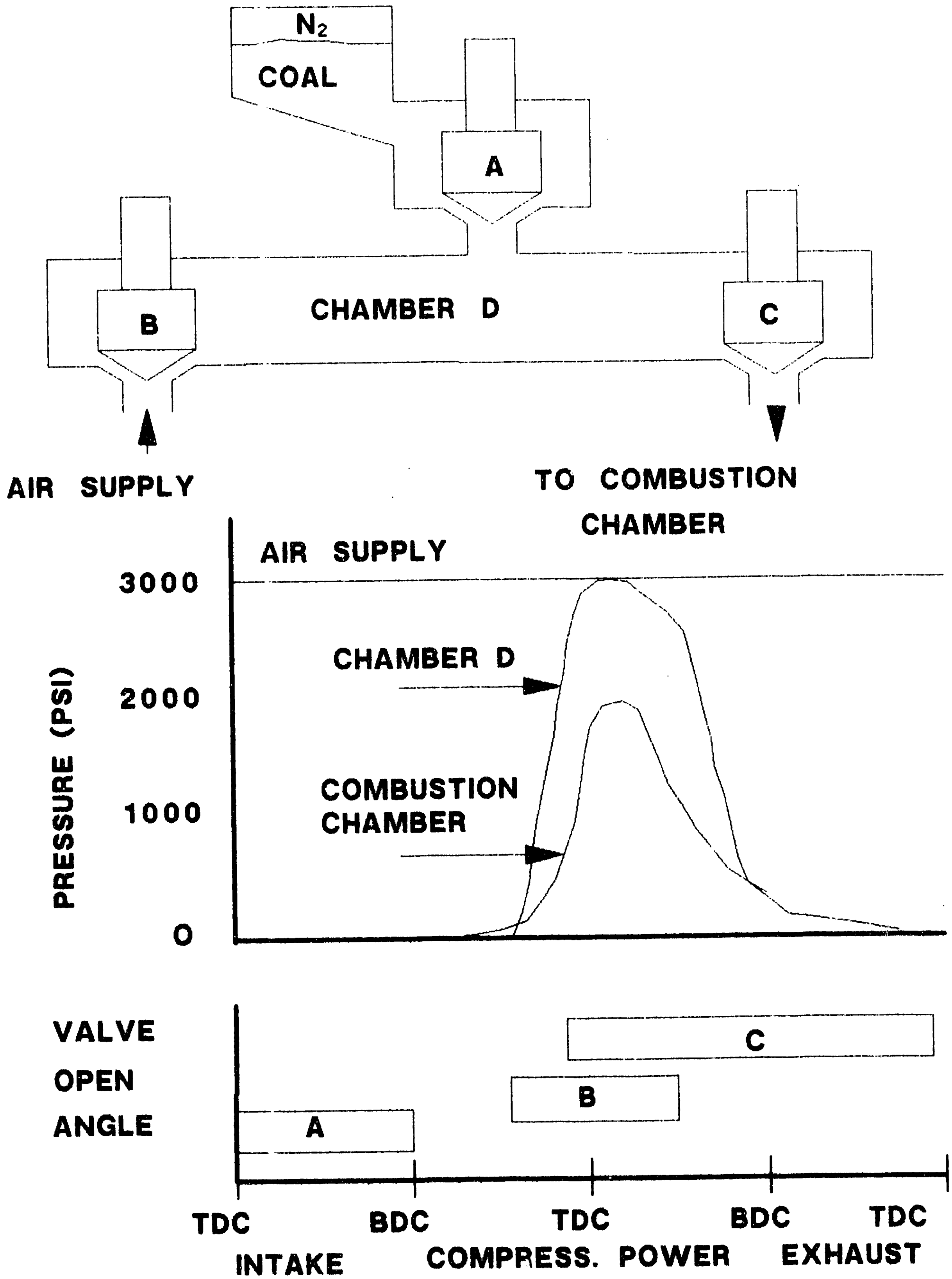

Figure 2.1-1 DRY COAL POWDER INJECTOR BASIC SCHEMATIC

2.2 DRY-COAL INJECTOR CONCEPT

Adiabatics produced a novel injector concept which performs all of the functions shown in Figure 2.1-1 with a simple one moving part device. The injector concept, shown schematically as Figure 2.2-1, consists of a plunger which is used to meter the fuel into a metering chamber and seal it off from the combustion chamber. It then moves and seals off the fuel supply and opens a valve port to pressurize the chamber with air. It then opens a port to allow the air to push the fuel into the combustion chamber. The figure shows the concept as applied to the Cummins NT855 diesel engine cylinder head with the Thermal Ignition Combustion System (TICS). The figure shows a side section and a top view. Looking at the section view, each component in the system is labeled. A description of each component follows:

Injector Valve

As shown, the "Injector Valve" is a cylinderical member which is closely fitted to a cylindrical bore in the "Coal Injector." The "Injector Valve" has a groove machined into its periphery which has one or both of its sides machined at an angle as shown on the left side of the groove to form a helix shape. The "Injector Valve" is both rotated and moved axially to accomplish injection metering and timing and all of its sealing functions. As shown the "Injector Valve" is in the "Metering" position at the left hand end of its axial travel and is rotated to the zero or no fuel flow position. To increase fuel flow, the "Injector Valve" is rotated such that the left side of the groove opens the port to the "Coal Supply" passage. The amount of coal metered will be dependent upon the area opened by rotating the "Injector Valve"; by the pressure difference between the "Coal Supply" and the groove in the "Injector Valve"; and by the length of time which the area is open. The "Injector Valve" is moved by the engine camshaft through a linkage similar to that used to actuate the conventional diesel fuel unit injectors. This approach gives a constant metering time (at any fixed engine speed) which decreases as engine speed increases. For a fixed speed and a fixed "Coal Supply" pressure, the metered flow is dependent only upon the open angle of the "Injector Valve."

To start the injection process, the "Injector Valve" is moved axially, to the right, by the engine camshaft until the left hand side of the groove seals off the coal supply port. It then continues to move until the right hand side of the groove uncovers the passage leading to the "TICS Chamber" and then opens the passage to the "Air Blast Storage Volume", which is at a higher pressure than the pressure in the "TICS Chamber." With both of these ports open, the air in the "Air Blast Storage Volume" flows through the groove in the "Injector Valve" and carries with it the coal fuel into the "TICS Chamber."

The "Injector Valve" is held in the injection position until late in the engine exhaust stroke at which time it is slowly moved to the left--first closing the passage to the "Air Blast Storage Volume" and then the passage to the "TICS Chamber." The "TICS Chamber" is closed last to enable the pressure in the groove to drop to the pressure level in the "TICS Chamber" which at this point in the cycle will be lower than that in the "Air Blast Storage Volume" to enable the use of lower "Coal Supply" pressures for metering. The "Injector Valve" then proceeds to move to the left until it uncovers the "Coal Supply" passage and metering starts again.

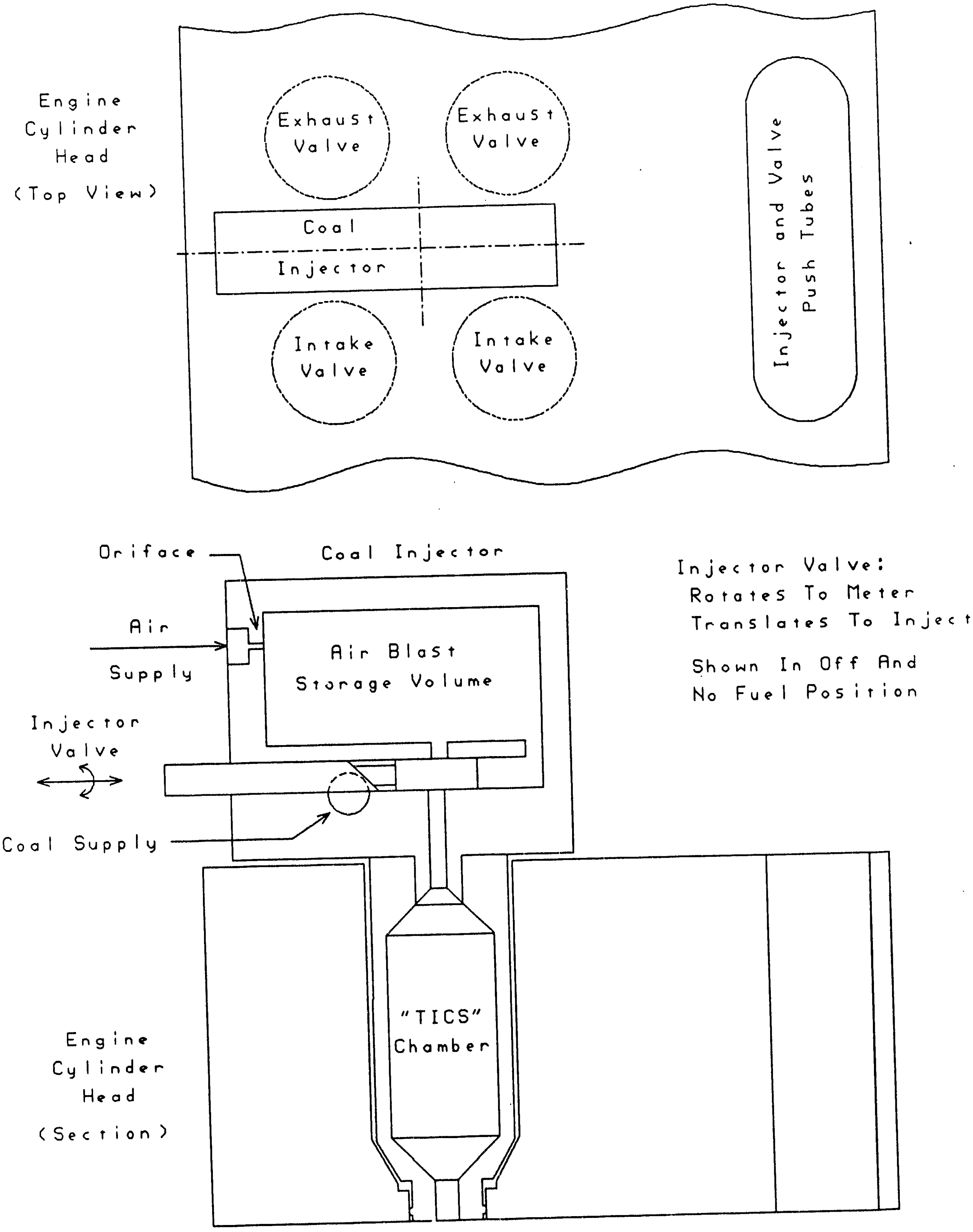

Figure 2.2-1 Novel Coal Injector Schematic

Coal Supply

The "Coal Supply" is a passage in the injector which contains the dry powdered coal. Based upon our experience with this fuel type, it is necessary to continuously flow the coal powder through this passage at all times to prevent passage plugging. It was planned that a centralized, sealed, coal hopper would be used which had an inert cover gas (such as nitrogen) to prevent the formation of explosive mixtures in the hopper. The coal was to be withdrawn from the hopper by a screw type feeder which was to continuously pump the dry powder coal through a single "Coal Supply" passage which was to flow through each "Coal Injector" in the engine. Following this circuit through the engine, the dry powder coal was to be either dumped back into the hopper or reintroduced directly into the screw type feeder. An alternative approach using a fluidized-stream and a gas powered ejector to flow the coal through the injector was to be explored, if necessary.

Air Supply

The air which is used to transport and atomize the coal is provided by a conventional three stage, intercooled piston type compressor at constant pressure (2,000 to 3,000 psi).

Orifice

Connecting the "Air Supply" to the "Air Blast Storage Volume" is an orifice which restricts the air flow. The purpose of the "Orifice" is to reduce the total air consumption used by the injector. This is accomplished by sizing the "Air Blast Storage Volume" and the "Orifice" such that the pressure in the "Air Blast Storage Volume" can be from zero to working pressure while the port is closed, and to limit the flow during the time the port is open.

One variation which was explored, but not utilized, was to incorporate an "Orifice" which is opened and closed by the motion of the "Injector Valve" such that the orifice is open during metering and closed during injection. This approach is the most efficient and results in the minimum air consumption and highest injection pressures. This could have been accomplished by adding an additional groove to the "Injector Valve" which opened a passage connecting the "Air Supply" to the "Air Blast Storage Volume."

Air Blast Storage Volume

The "Air Blast Storage Volume" is sized such that it contains only enough air to blast the fuel into the "TICS Chamber" and to purge the "Injector Valve" groove. The pressure in this volume will increase from approximately engine exhaust pressure at the end of the injection cycle to slightly below "Air Supply" pressure during the metering cycle.

2.3 TEST ENGINE AND INSTRUMENTATION

As mentioned earlier, the test engine for this program is a single cylinder version of the Cummins NT855 family of engines which is also referred to as the NH engine family. The engine from which the single cylinder engine is derived is a six cylinder heavy duty truck engine with a displacement of 14 liters. Table 2.3-1 is a listing of the key specifications of the single cylinder engine. Key portions of the engine including the block, crankshaft and balancer box were purchased from Cummins Engine Company by Adiabatics several years before the start of this program.

Table 2.3-1

NH-1 Single Cylinder Engine Specifications

Bore	140 mm	5.5 inches
Stroke	152 mm	6.o inches
Displacement	2.34 liters	142.5 cu in
Rated Speed	2,100 rpm	
Valve Number	4 (Two Intake - Two Exhaust)	
Rated Power	55 kW	74 bhp
Aspiration	Turbocharged and Aftercooled	
Compression Ratio	16:1	
Piston	Aluminum with Thermal Barrier Coating	
Liner	Cast Iron with Ceramic Coating	
Head	Cast Iron with Thermal Barrier Coating	
Top Ring	Cast Iron with Wear Coating	
Intermediate Ring	Cast Iron With Wear Coating	
Oil Ring	Standard	

Figure 2.3-1 is a photograph showing the engine at the start of this program. The engine required several modifications to prepare it for coal fuel operation. The first was to fabricate an isolation oil pan to separate the engine crankcase from the balancer box crankcase. The standard engine utilizes a single crankcase. The oil from the engine drains directly into the balancer box. Since the coal fueled engine has the potential to contaminate the oil and since the balancer box is an expensive one-of-a-kind mechanism with roller bearings, it was decided to completely separate the oiling systems. Figures 2.3-2 and 2.3-3 are photographs showing the isolation oil pan first mounted on the balancer box and then mounted on the bottom of the engine. To provide lubricating oil to the engine, the lube oil package which was developed for the Caterpillar 1Y73 single cylinder engine with the dual centrifugal filters to separate out the coal and ash particles was utilized as shown in Figure 2.3-4. A separate lubricating oil supply pump and filter was mounted on the engine base next to the balancer box to provide oil to the balancer box as shown in Figure 2.3-5. Also visible in this photograph is the intake air heater shown mounted on the wall at the right hand side, the air intake surge plenum mounted behind the engine, the engine flywheel (adapted from the Caterpillar 1Y73) and the oil, intake and exhaust plumbing.

Figure 2.3-6 is a photograph showing the installation of the coal hopper mounted above the Eaton eddy current dynamometer. Also visible are the coal supply and return augers which will be discussed later. Visible at the front of the engine are several of the instrumentation items, including the crankangle encoder and the thermocouple for liner temperature.

Figure 2.3-7 is a photograph of the insulated engine components including the cylinder head, liner and piston which enable the engine to be operated without any cooling water. The liner is run dry without any fluid on the outside of the liner. The cylinder head is also run dry with no fluids in the normal water cooling passages. Visible on the surface of the cylinder head on the left side cylinder (which is the only one used on this engine) is the inlaid thermal barrier coating which consists primarily of densified zirconia. The right side is standard. Figure 2.3-8 is a closeup of the piston showing the densified zirconia thermal barrier coating on the crown. The top piston ring is coated with a chrome carbide ceramic wear resistant coating. The second ring is coated with an alumina-titania matrix. The oil ring is a standard part.

Figure 2.3-9 is a photograph of the cylinder liner and piston following the baseline testing on diesel fuel. As can be seen, the cylinder bore is glassy smooth with a chrome-oxide ceramic coating for wear resistance.

Table 2.3-2 is a listing of the instrumentation which was used for this program showing each of the major items. A Dyn-loc IV digital dynamometer controller was utilized to provide the field excitation to the eddy current dynamometer to provide precise speed and load control. A data acquisition computer was used to acquire and record the test data. Figure 2.3-10 shows the control console with these two items and miscellaneous amplifiers and instrumentation systems. Figure 2.3-11 is a photograph of the emissions cart which houses the analyzers and systems to zero and span each analyzer before and after each test run. Figure 2.3-12 is a photograph of the particulates analyzer showing the compressors on the bottom and the gas flow meters in the middle with the timers and dilution tunnel temperature controls on the upper level. The actual tunnel is mounted next to the engine exhaust outlet to minimize line losses. A precision microbalance is used to weigh the amount of particulates collected on a Millipore filter mounted at the exit of the dilution tunnel.

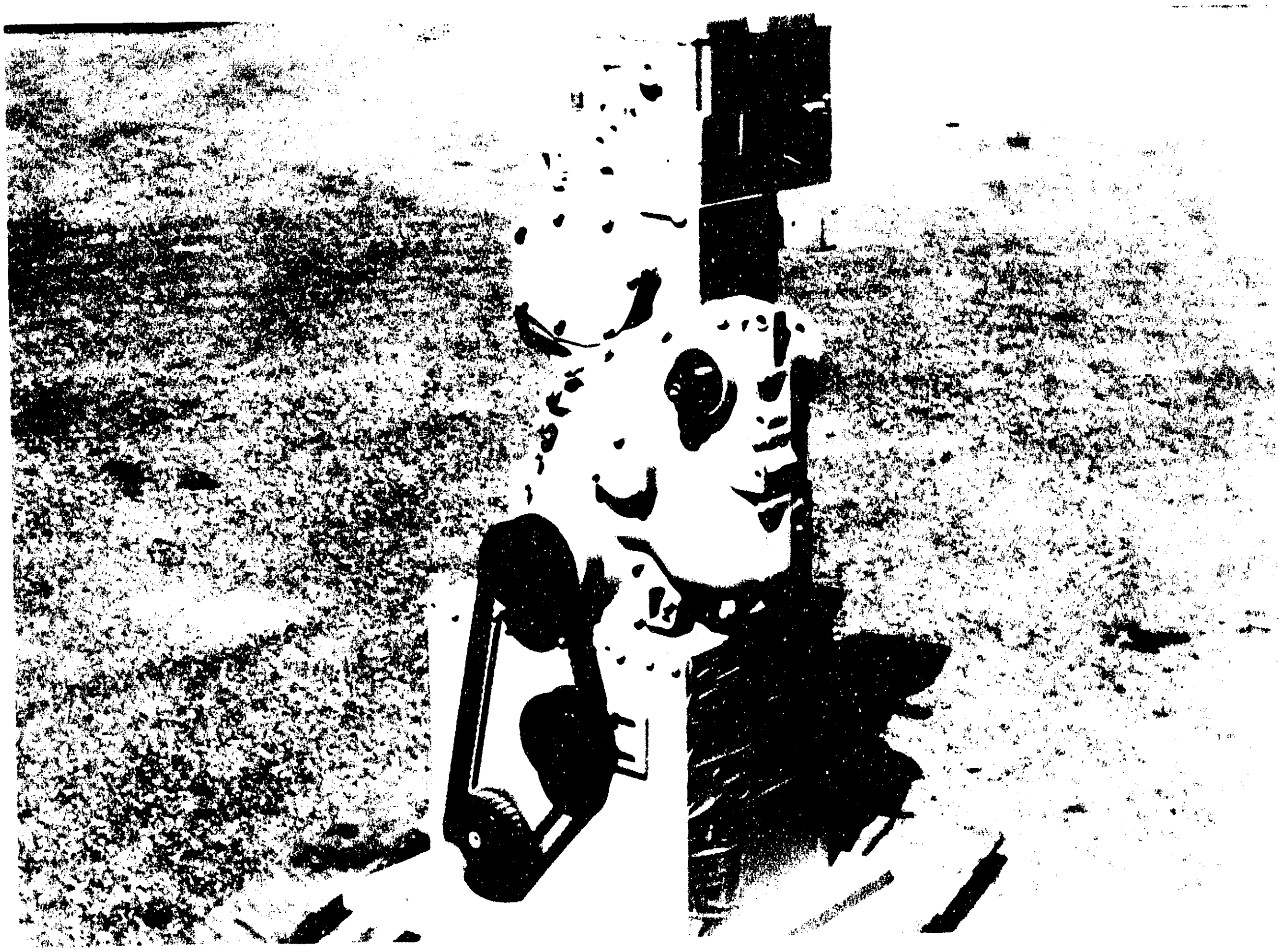

Figure 2.3-1 NH-1 Single Cylinder Engine

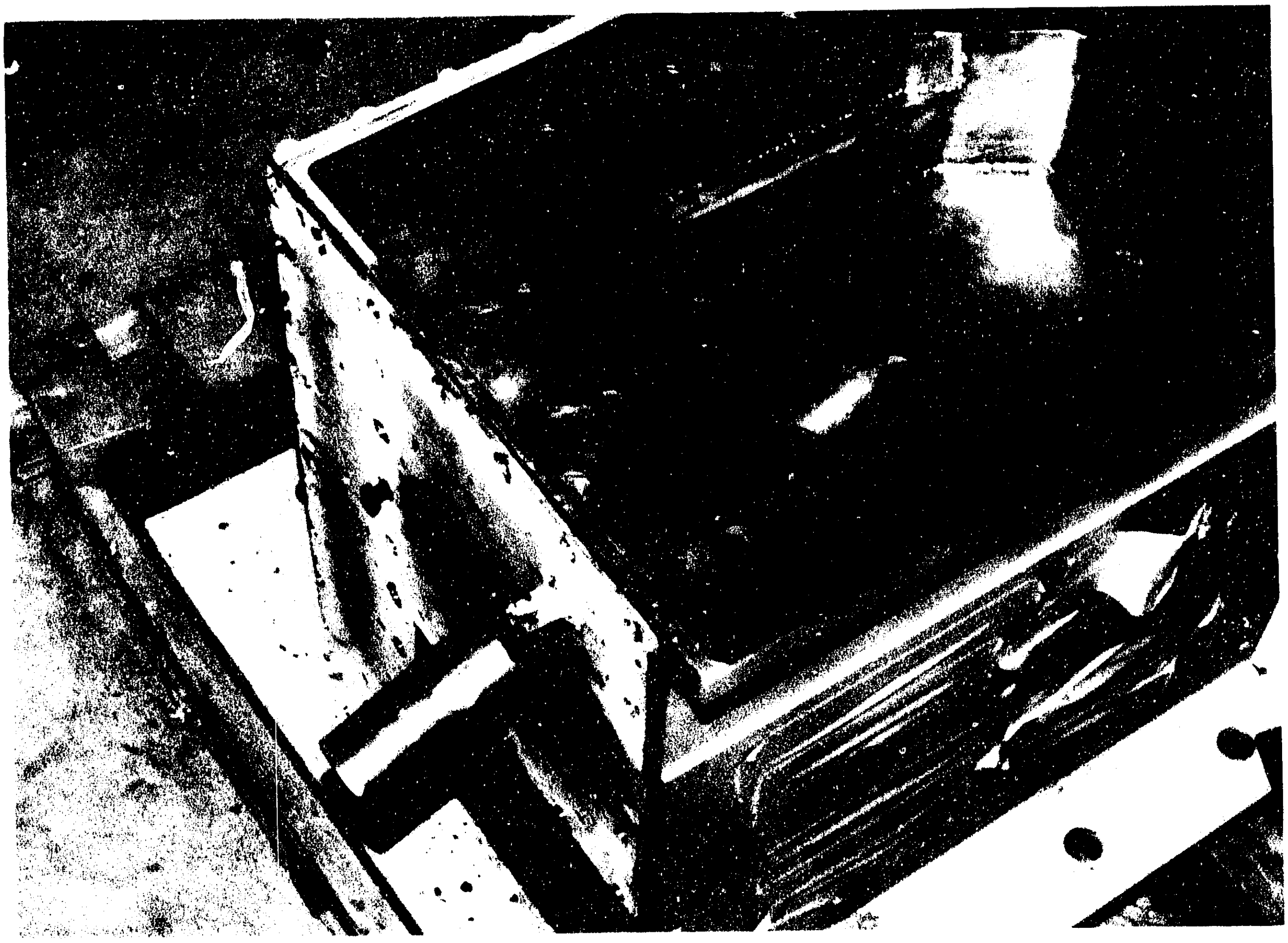

Figure 2.3-2 Isolation Oil Pan Mounted on Balancer Box

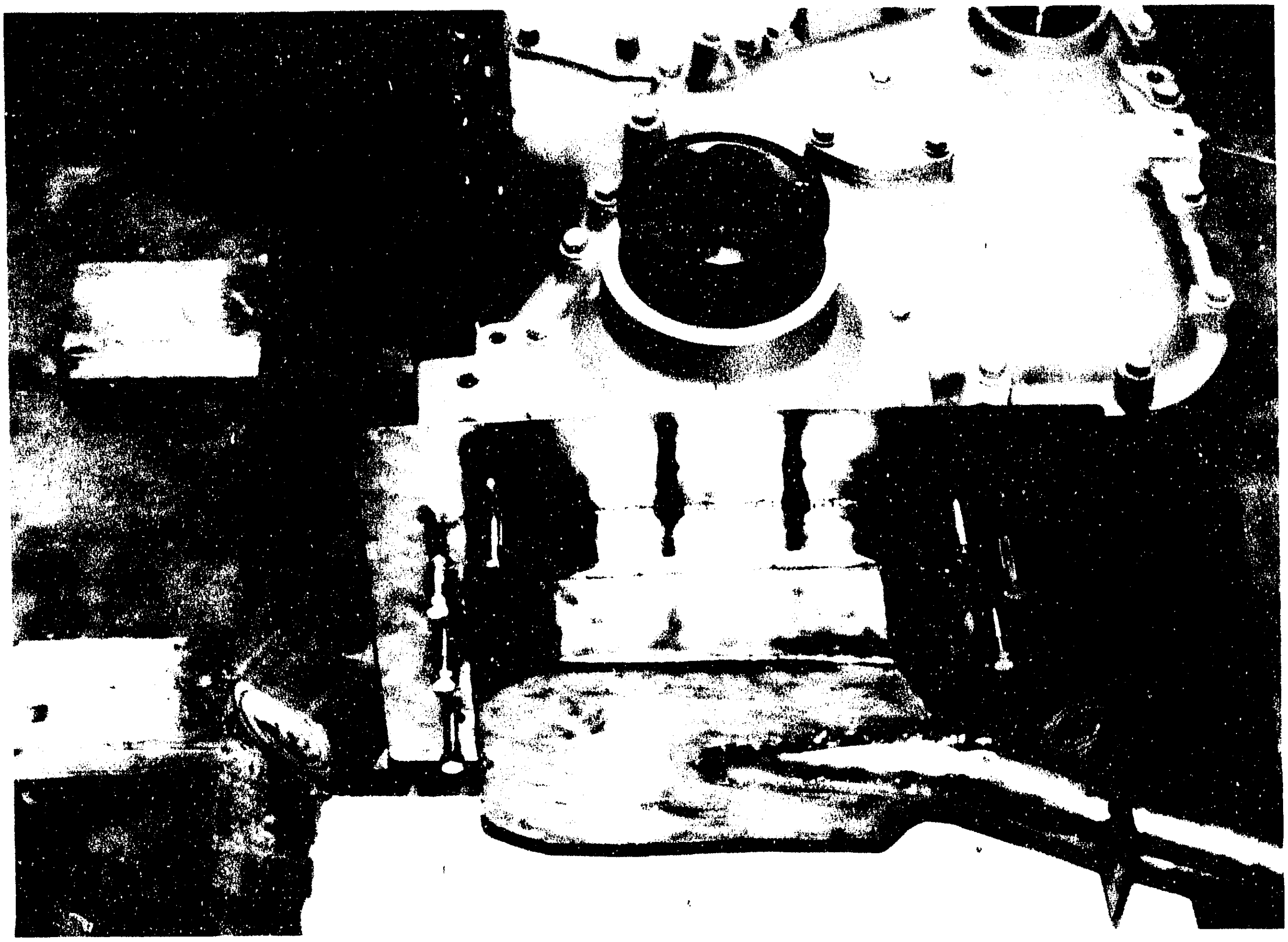

Figure 2.3-3 Isolation Oil Pan Mounted on Engine

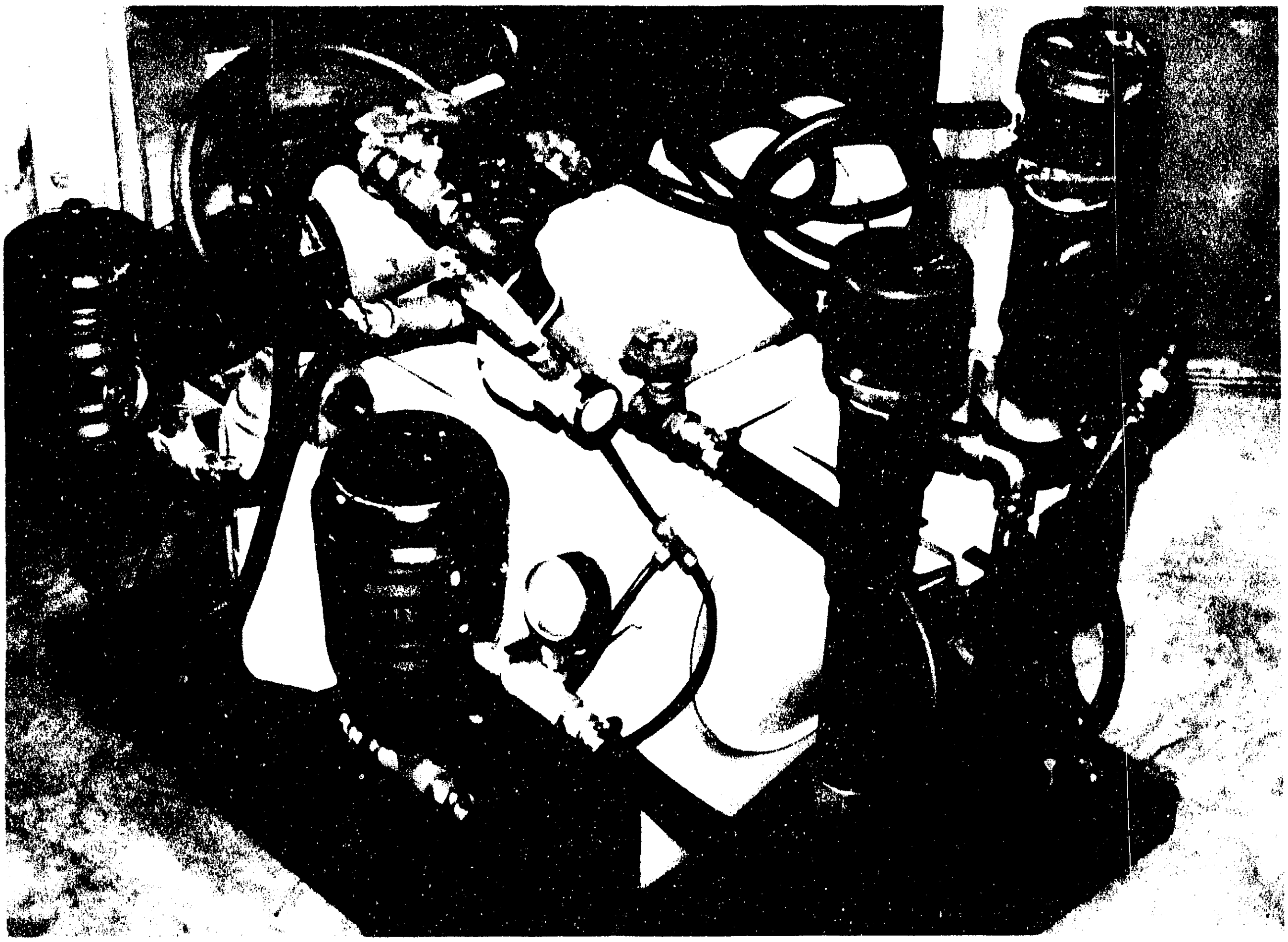

Figure 2.3-4 Engine Lubrication Supply and Filtration System

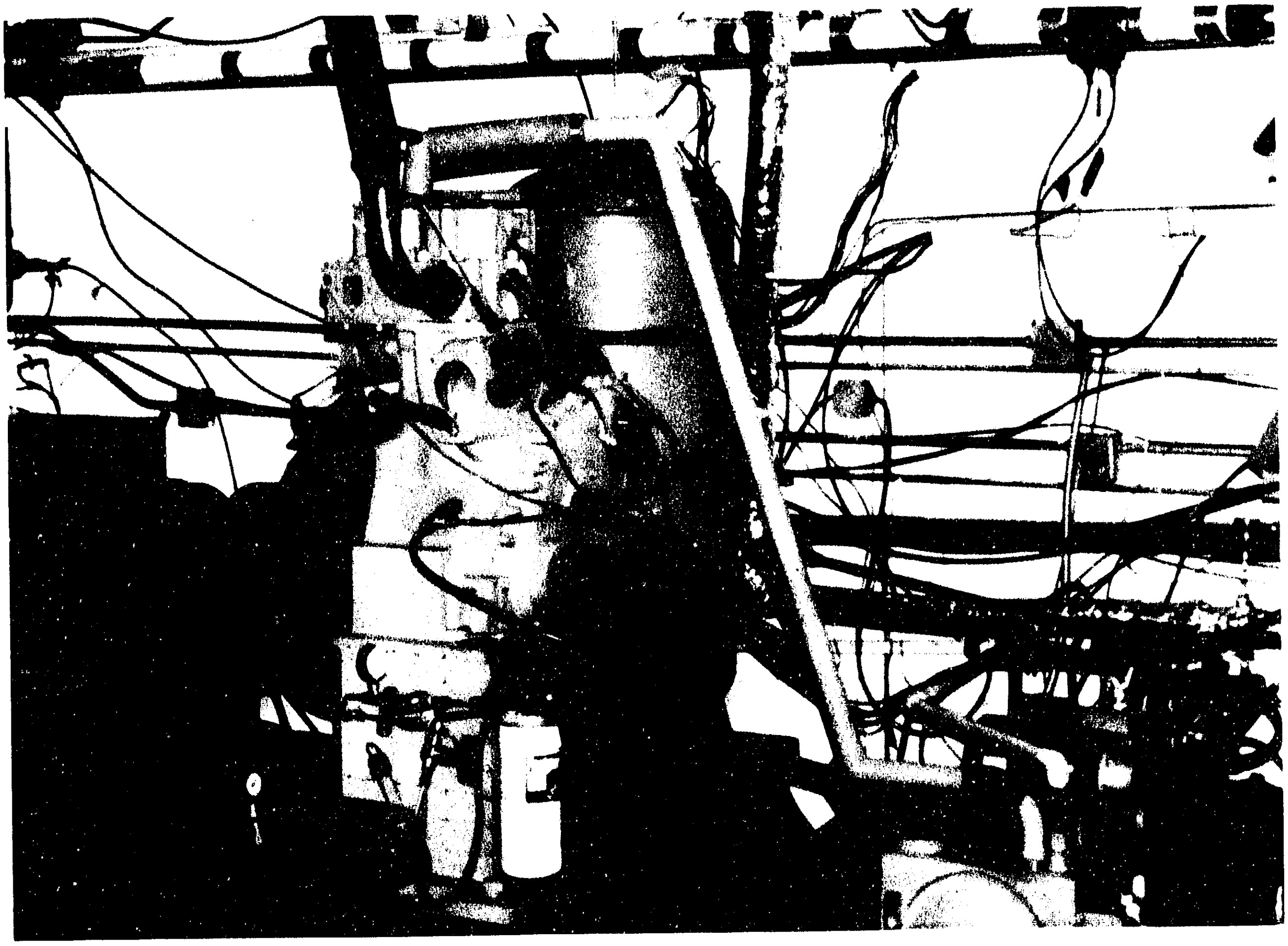

Figure 2.3-5 NH-1 Balancer Box Lube System

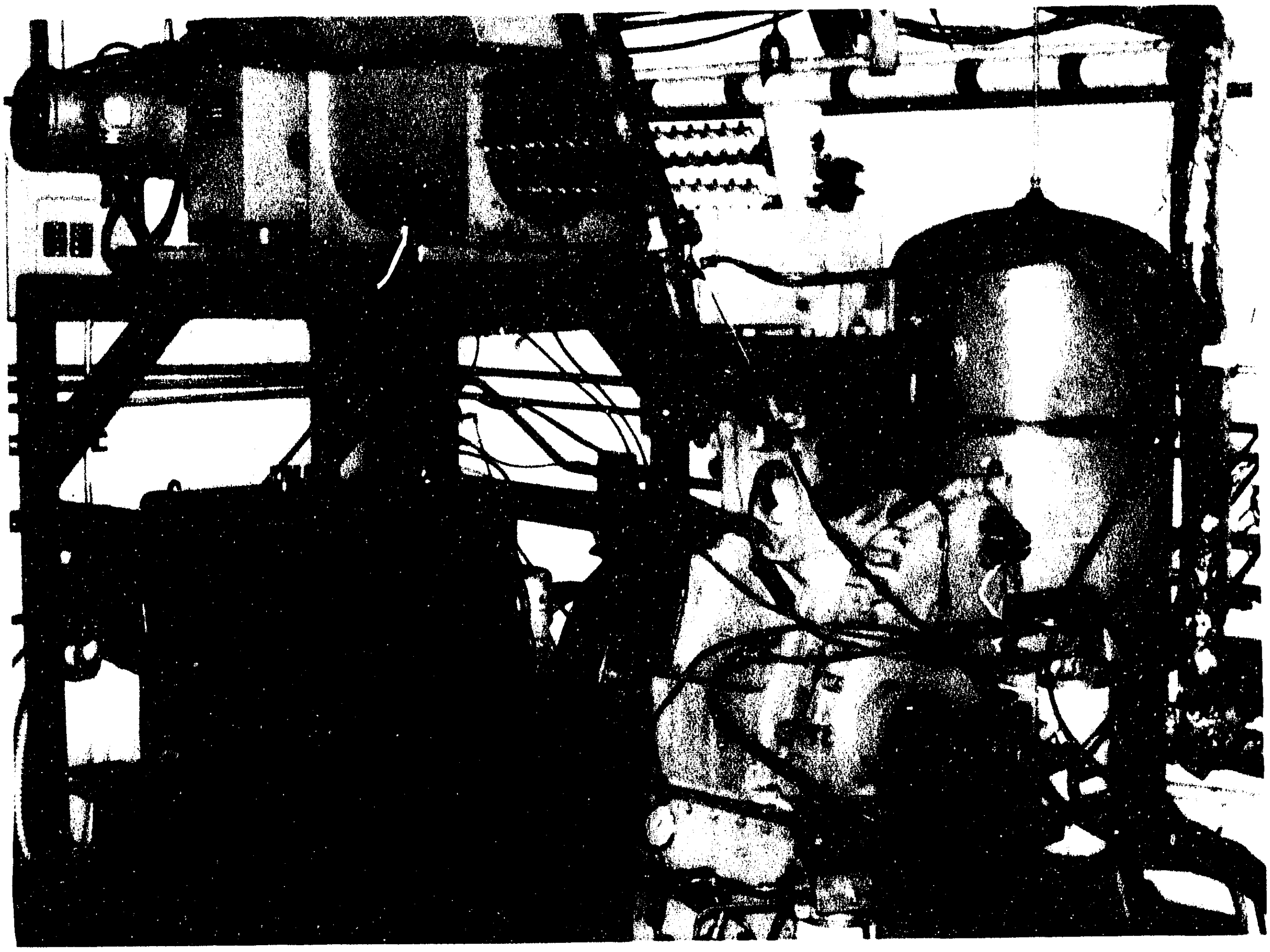

Figure 2.3-6 NH-1 Engine Installation

Figure 2.3-7 Insulated Engine Components

Figure 2.3-8 Piston

Figure 2.3-9 Cylinder Liner

Table 2.3-2

Test Instrumentation

Variable	Type
Engine Speed	60 Tooth Wheel and Magnetic Pickup
Load	Strain Bridge Load Cell
Crank Position	BEI Optical Encoder
Cylinder Pressure	AVL 8QP500CA Pressure Transducer
Ambient Air Temp.	Thermocouple
Air Temp. at Orifice	Thermocouple
Intake Air Temp.	Thermocouple
Exhaust Temperature	Thermocouple
TICS Wall Temp.	Thermocouple
Oil Temperatures	Thermocouples
Ambient Pressure	Recording Barometer
Humidity	Recording Humidistat
Airflow	ASME Sharp Edge Orifice Plate
Pressure at Orifice	Bourdon Tube Pressure Gage
Orifice Pressure Drop	Manometer
Exhaust Pressure	Manometer
Blow-by	Orifice and Manometer
Smoke	AVL BOSCH Type Sampling Meter
Particulates	Dilution Tunnel and Gravimetric
Supply Air Pressure	Piezoresistive Transducer
CO Emissions	Beckman 870 NDIR Analyzer
CO2 Emissions	Beckman 870 NDIR Analyzer
HC	Beckman 400A FID Analyzer
NOx	Beckman 955 Chemiluminescent Anal.

Figure 2.3-10 Control Console

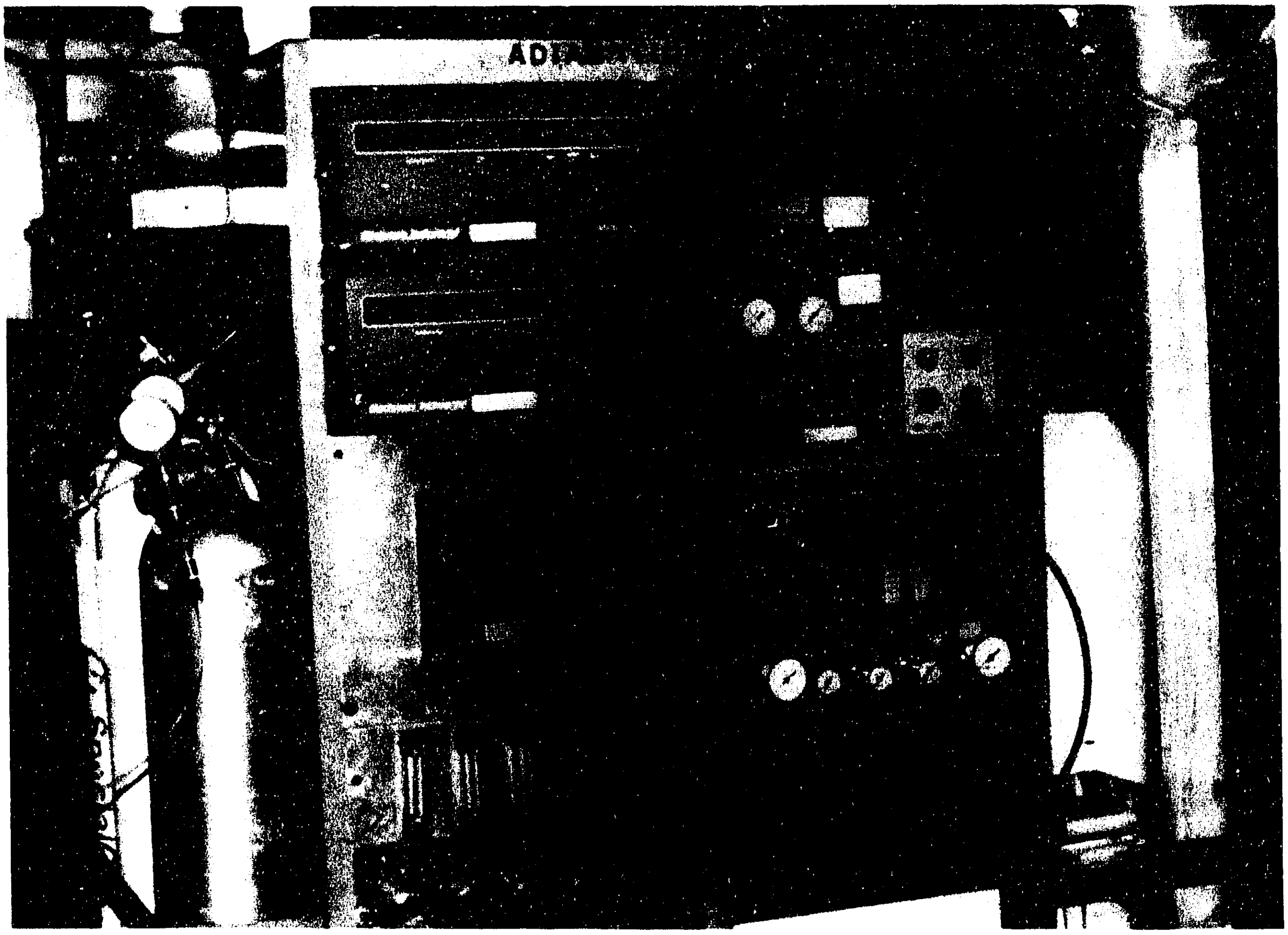

Figure 2.3-11 Emissions Cart

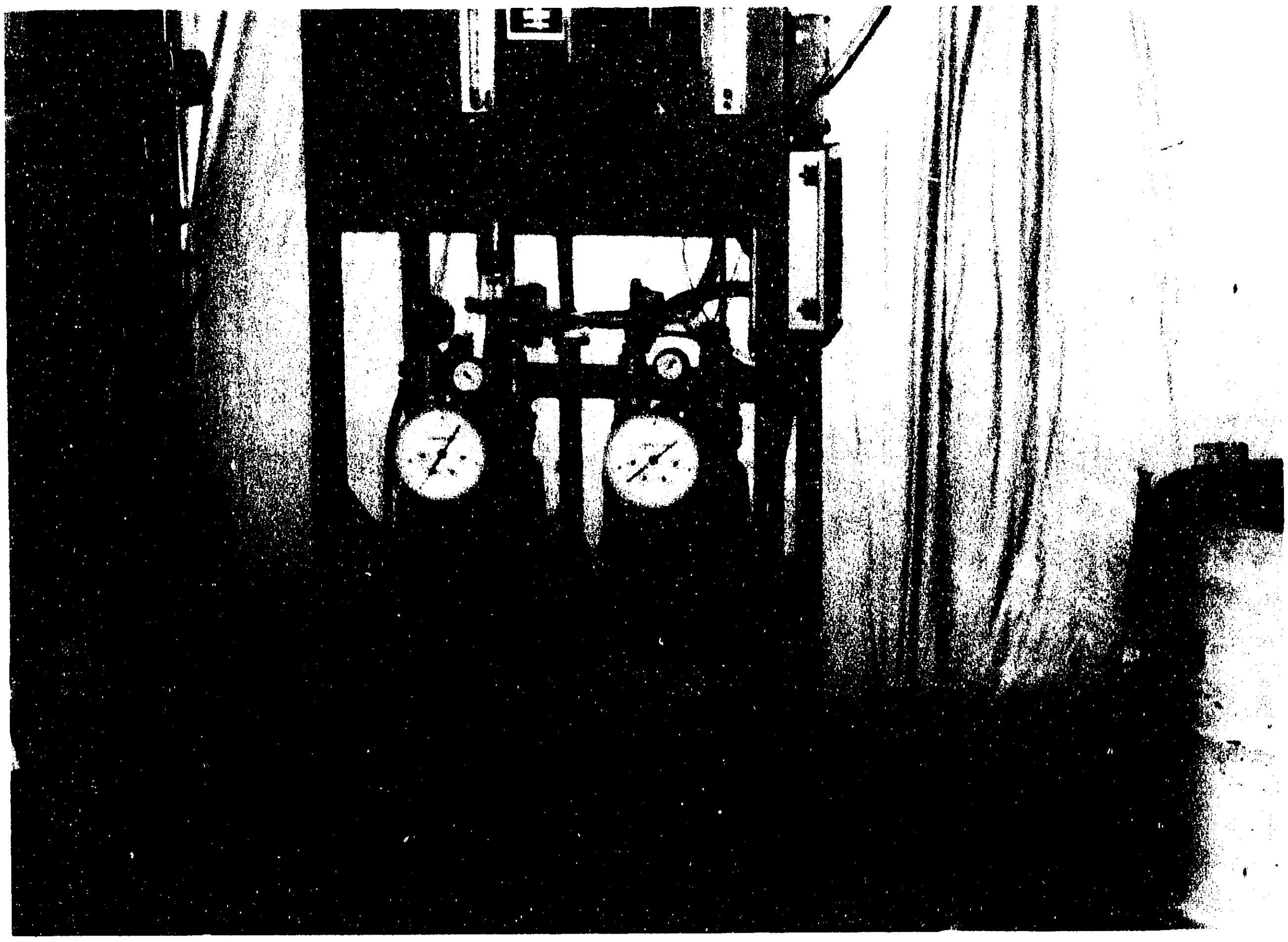

Figure 2.3-12 Particulates Analyzer

2.4 COAL FUEL SPECIFICATION

Following the approval of the selection of dry powdered coal as the fuel of choice for this program by METC, a search was started to locate a reliable source of dry powdered coal. The traditional sources were solicited including AMAX, Otisca and EERC. After very little success was encountered, it was suggested by the COTR that he had recently seen a demonstration of "Mulled" coal presented by Energy International and that consideration of this new fuel type should be included in the study. Energy International was contacted about the process of familiarization with this new fuel and Adiabatics obtained samples. "Mulled" type coal is a granular material of uniform particle size with a moisture content of approximately 35%. The very first samples which were shown to us at the Contractors Conference in July of 1991 were very free flowing and exhibited very favorable characteristics such as no misting and freedom from explosion hazards. For a more complete description of "Mulled" coal technology, please refer to the papers published by Energy International at the International Coal Conferences [14].

Additional samples and the final batch for engine testing were not as "dry" as the original "Mulled" material. Each additional batch had a wet, sticky consistency and would not free flow. The analysis of the final batch of "Mulled Coal" which was used for the engine testing is included as Attachment 1.

3.0 RESULTS AND DISCUSSION

The following paragraphs discuss the program results including all of the design, analyses, bench test and engine test results. The original schedule for accomplishing this work as submitted in the Test Plan is shown as Figure 3.0-1. The actual program took one month longer and was completed the end of July 1992. As the schedule shows, the program was quite ambitious with many simultaneous tasks including engine modification, test cell modification, diesel fueled engine tests, injector bench tests, injector analysis and injector design and fabrication all occurring in the first seven months. Figure 3.0-2 shows the actual program schedule plotted on top of the original plan.

In addition to the hardware portion of the program, there were two major presentations conducted during the execution of the program. The first was a paper and poster session presented at the Eighth Annual Contractors Review Meeting [15] and an A.S.M.E. paper presented at the 1992 E.T.C.E. meeting in Houston [16].

3.1 INJECTOR ANALYSIS RESULTS

A spreadsheet type dynamic analysis of the fuel injection system was generated to size system components and to determine the air requirements to operate the injector. The results of this analysis were documented separately and submitted to the COTR in January 1991 as "Air Requirements for 'Air Assist Fuel Injector'" which is included as Attachment 2. This simulation provided all of the basic sizing data for each of the injector components including flow areas, volumes and passage lengths.

3.2 INJECTOR DESIGN

Two generations of injector design were generated and fabricated during this program. The first design is shown in Figure 3.2-1 as it would be installed in the engine. The key features which should be noted from this original design are the following:

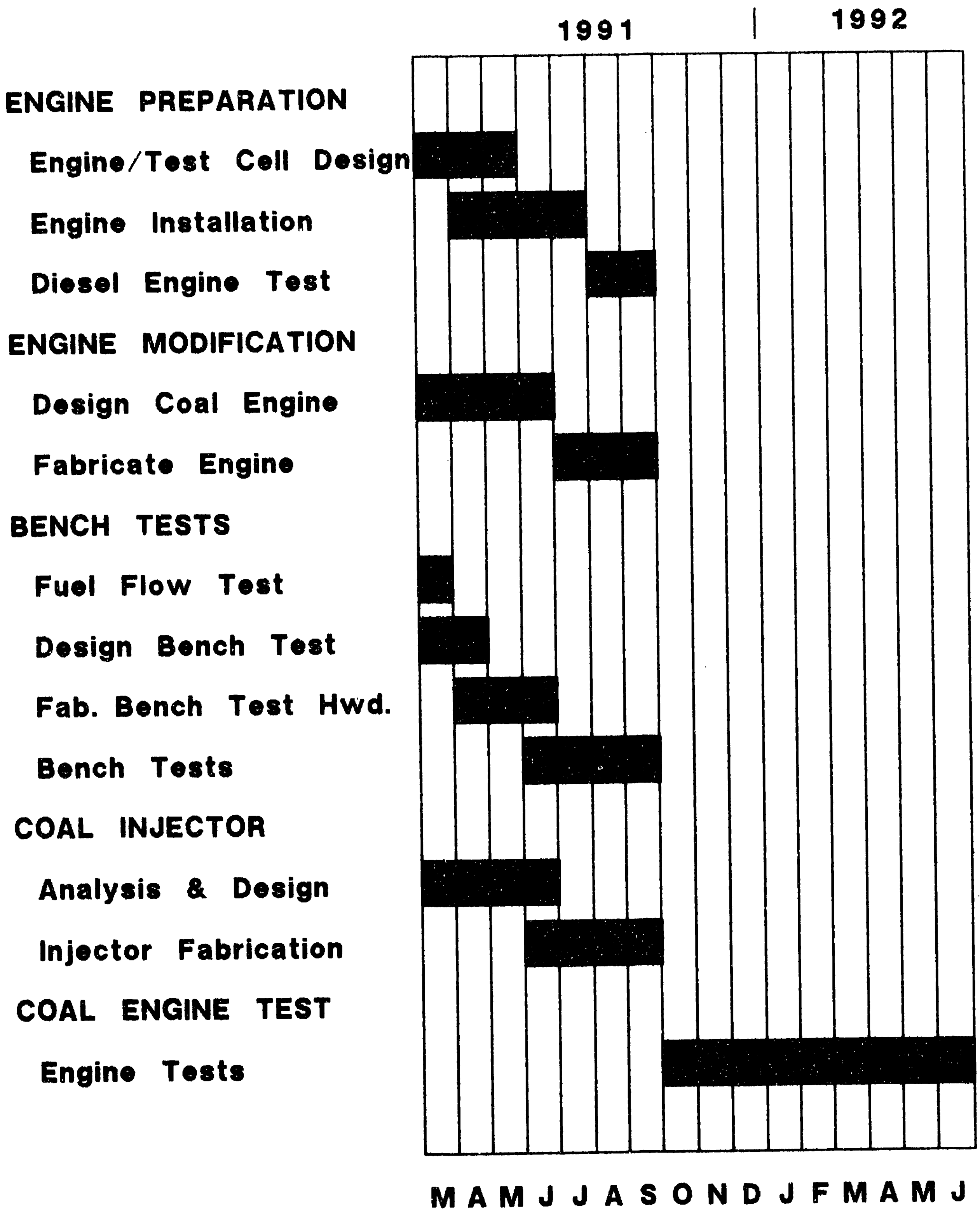

Figure 3.0-1 Program Schedule

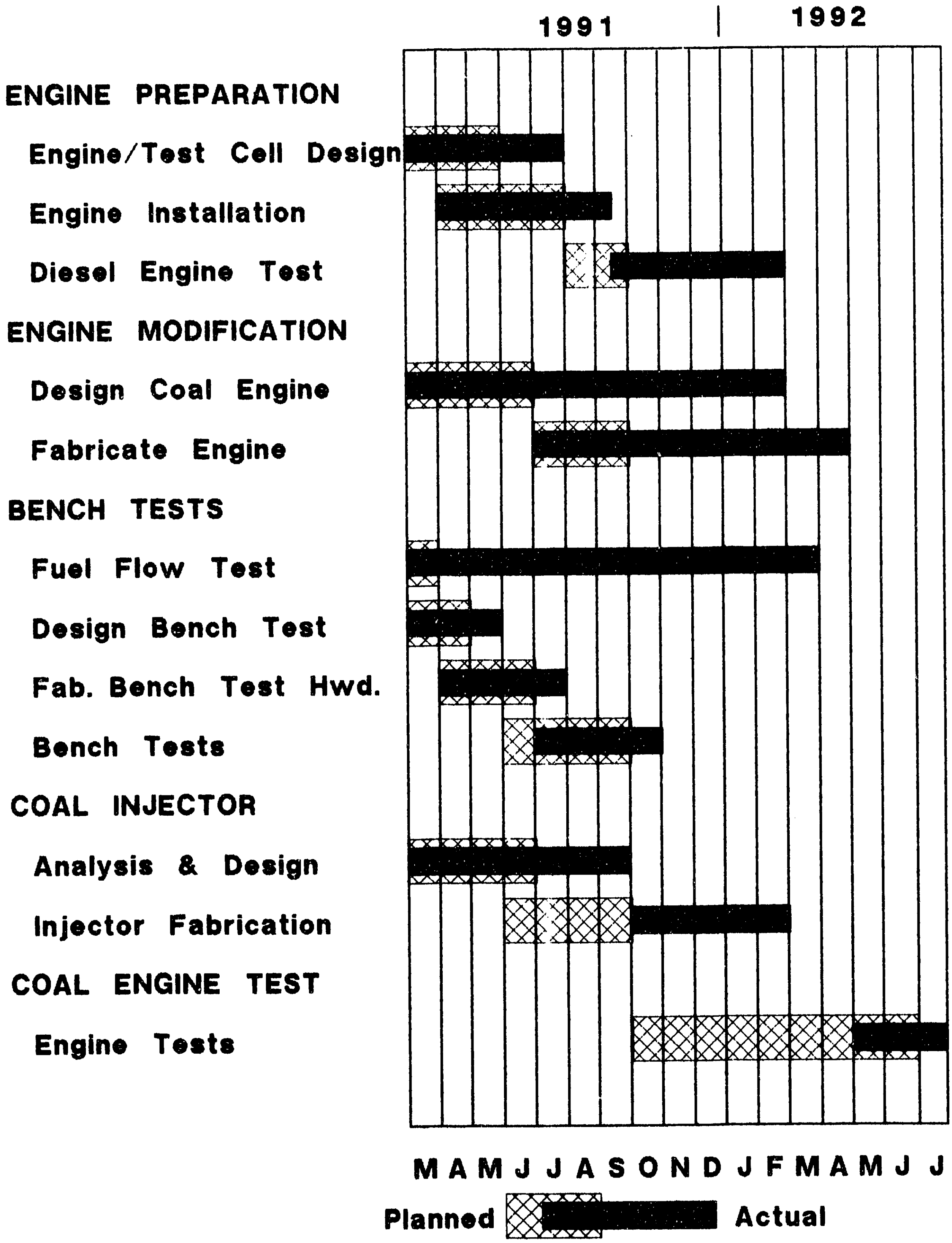

Figure 3.0-2 Actual Program Schedule

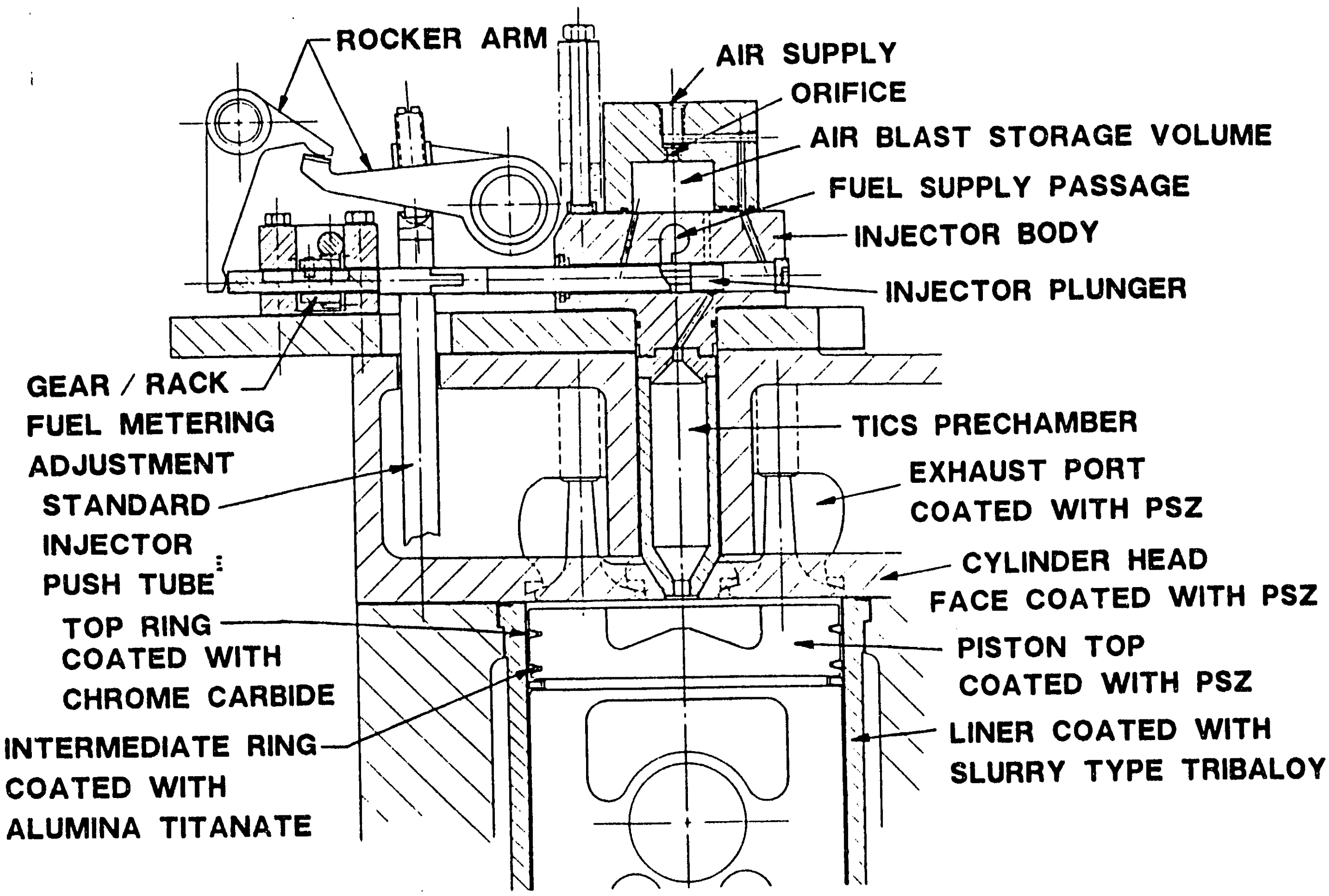

Figure 3.2-1 First Generation Injector Design

- o Standard fuel injector push tube and two new rocker arms to move the injector plunger.

- o The use of a gear rack to rotate the injector plunger to vary the fuel injection quantity.

- o The use of air pressure to preload the plunger against the rockers and eventually the camshaft. This eliminates the need for a return spring.

- o The use of a horizontal fuel supply passage which traverses the length of the engine and incorporates a continuous flexible auger running through the injector. This feature is highlighted in a cross section showing the injector and the coal feed system, Figure 3.2-2.

- o The use of bellville washers to load the injector and TICS chamber against the bottom of the cylinder head. The washers are designed to compensate for thermal expansion without excessively loading the head or injector.

- o The design required the use of "guideless" crossheads for the engine intake and exhaust valves because the fuel supply passage went through the engine area where these components are normally located. The use of this design was not considered risky as Cummins has introduced this design on their latest engines.

The key parts of this first design including the injector body, air blast storage volume and injection plunger were fabricated and used for the bench test portion of the program.

Several design deficiencies were discovered during the bench testing program which required major changes in the injector design and forced a new generation to be designed. At the same time, several design deficiencies were corrected. The second generation design is shown as Figure 3.2-3. Key differences between the two designs are as follows:

- o The rocker system to move the plunger was redesigned to move the plunger from the opposite end. This enabled the injector pushtube to be installed vertically instead of at an angle which would have caused sideload and clearance problems.

- o The fuel supply passage was brought in vertically with a single passage for each injector. As will be shown later, we were unable to make the other approach work. A schematic showing the vertical fuel feed and its attachment to the coal hopper is shown as Figure 3.2-4.

This design was fabricated completely and was used for the engine testing. A photograph of the second generation hardware including the TICS chamber is shown as Figure 3.2-5. In order to fit this new hardware into the engine, we designed and fabricated a modified rocker housing and cover. Figure 3.2-6 is a photograph showing the standard rocker housing on the left and the modified housing on the right showing the extension for injector clearance. Figure 3.2-7 shows the modified cover sitting atop the modified rocker housing. Figure 3.2-8 shows the two components assembled.

Figures 3.2-9 through 3.2-11 are three different views showing the second generation injector installed on the engine.

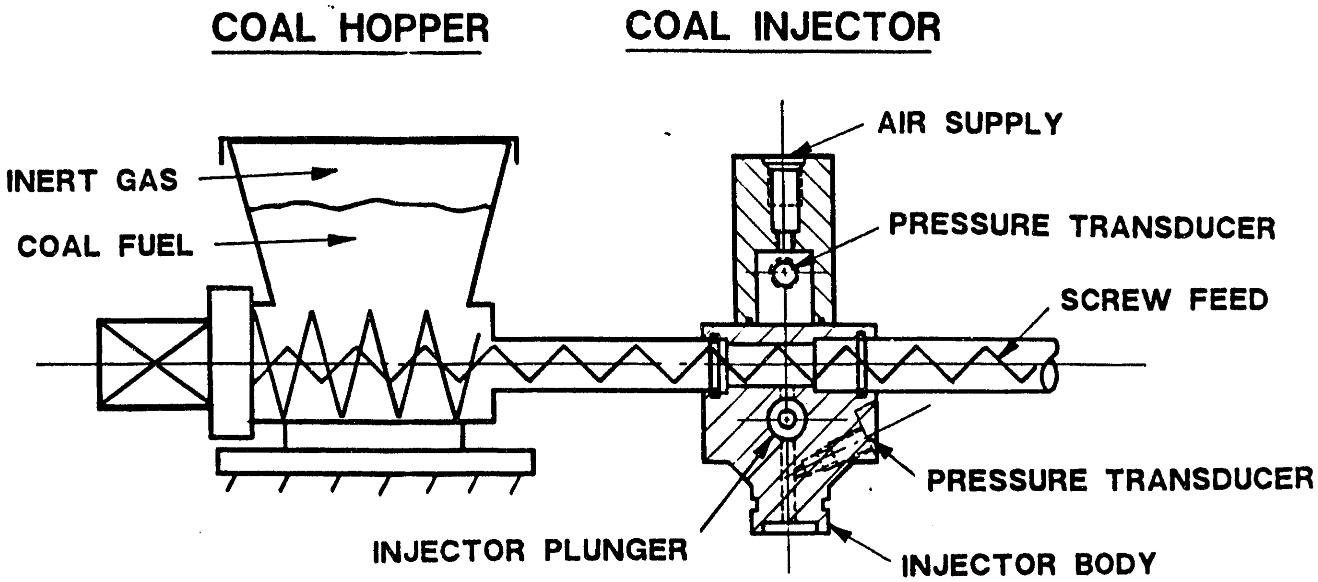

Figure 3.2-2 Coal Feed System and Injector

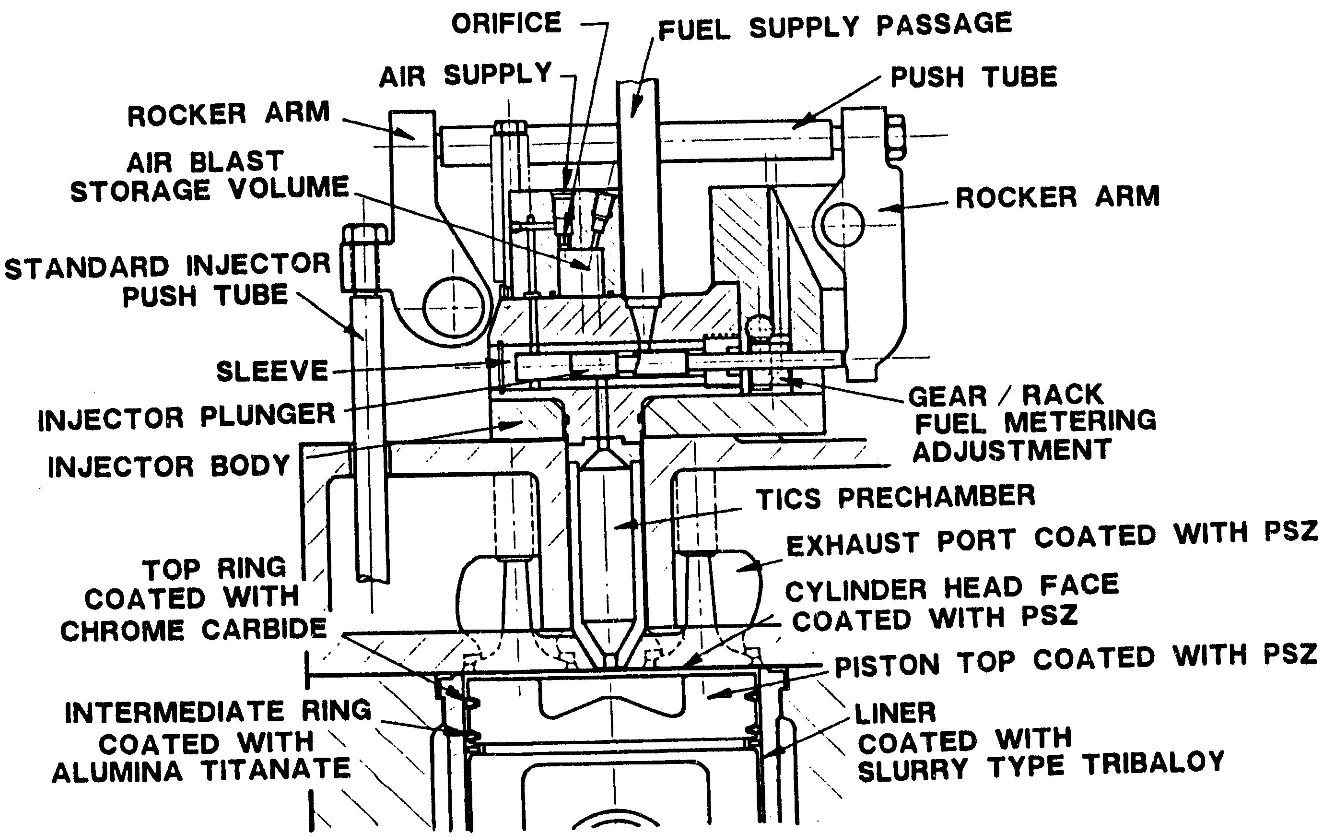

Figure 3.2-3 Second Generation Injector Design

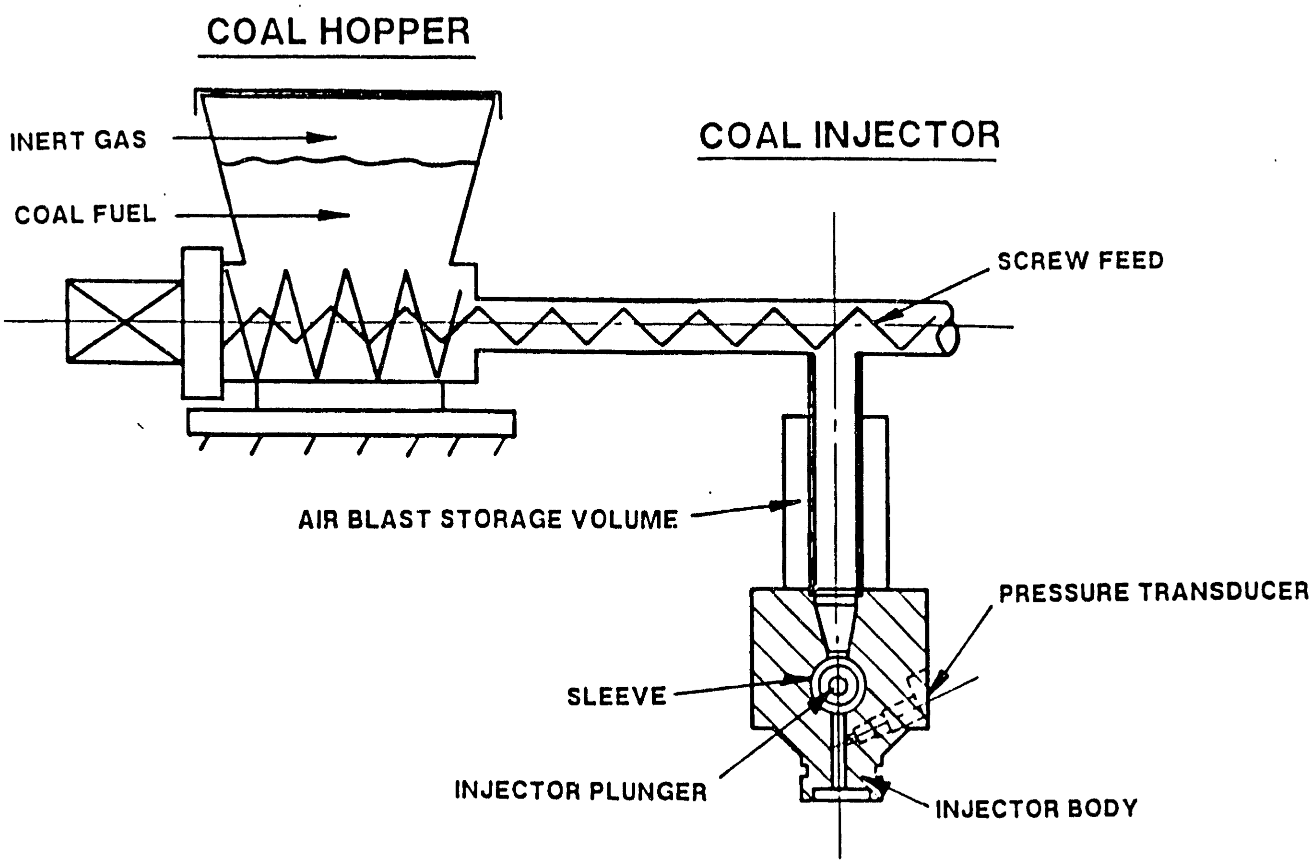

Figure 3.2-4 Second Generation Coal Feed System

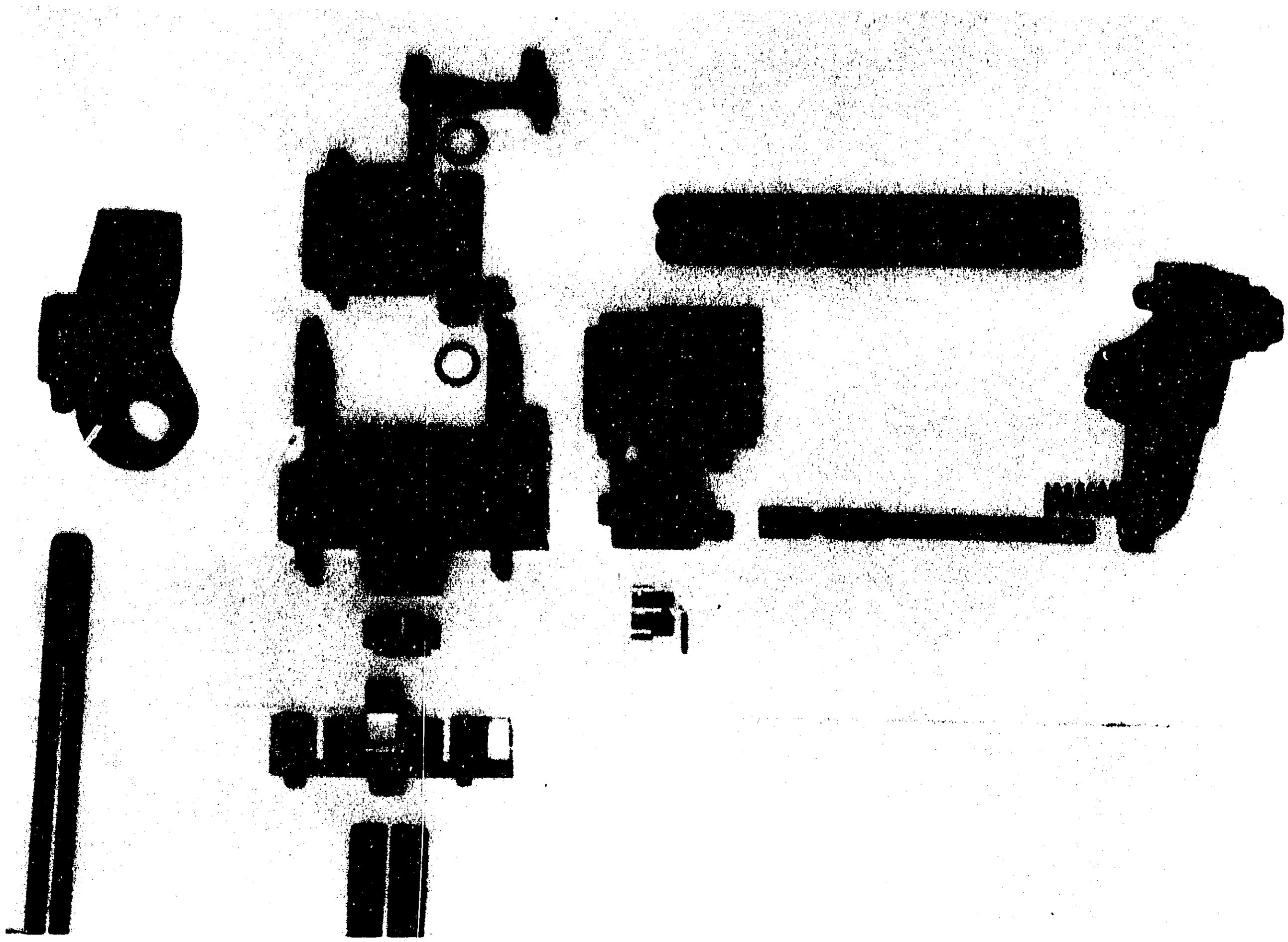

Figure 3.2-5 Second Generation Injection System Hardware

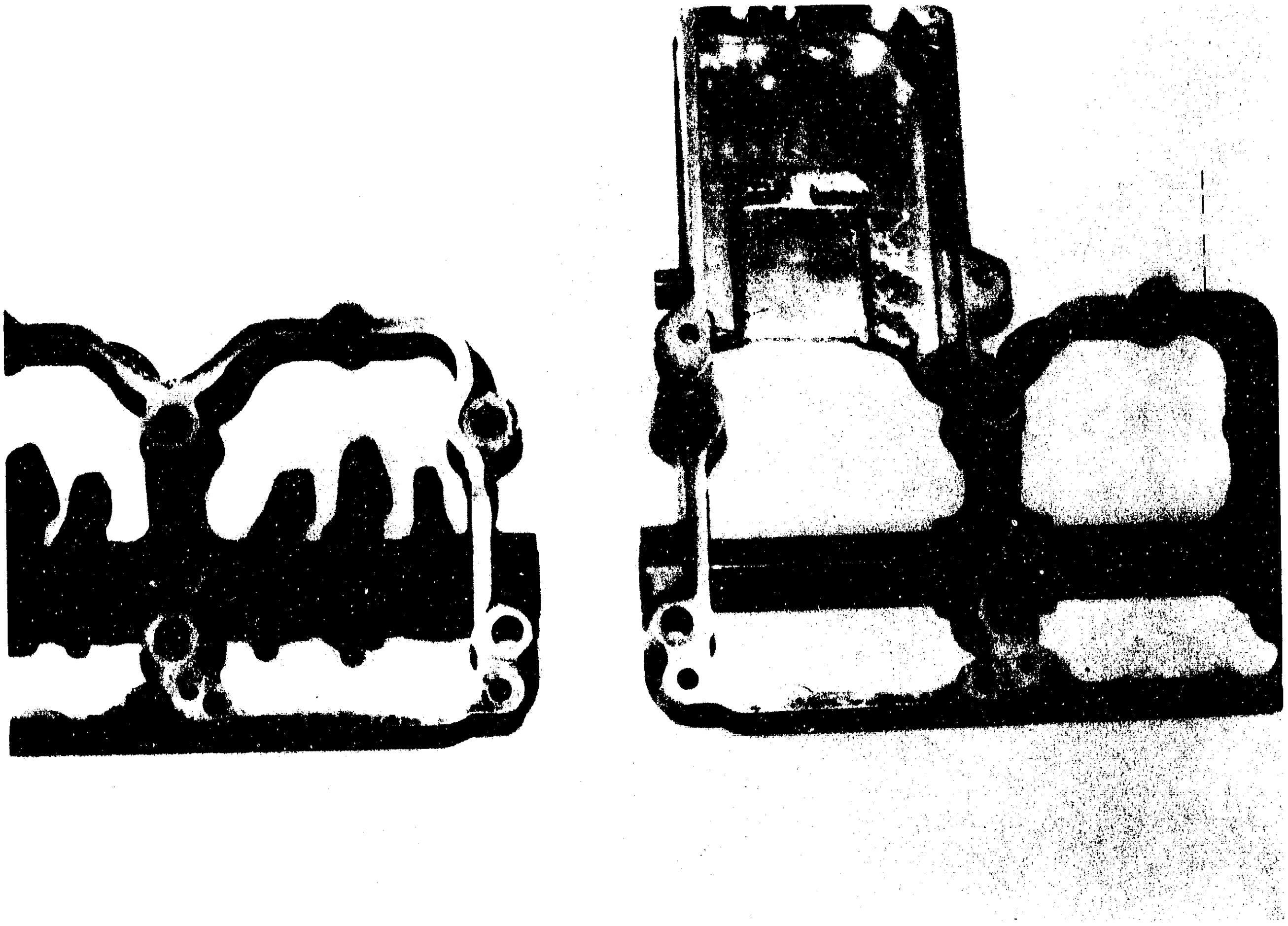

Figure 3.2-6 Standard and Modified Rocker Housings

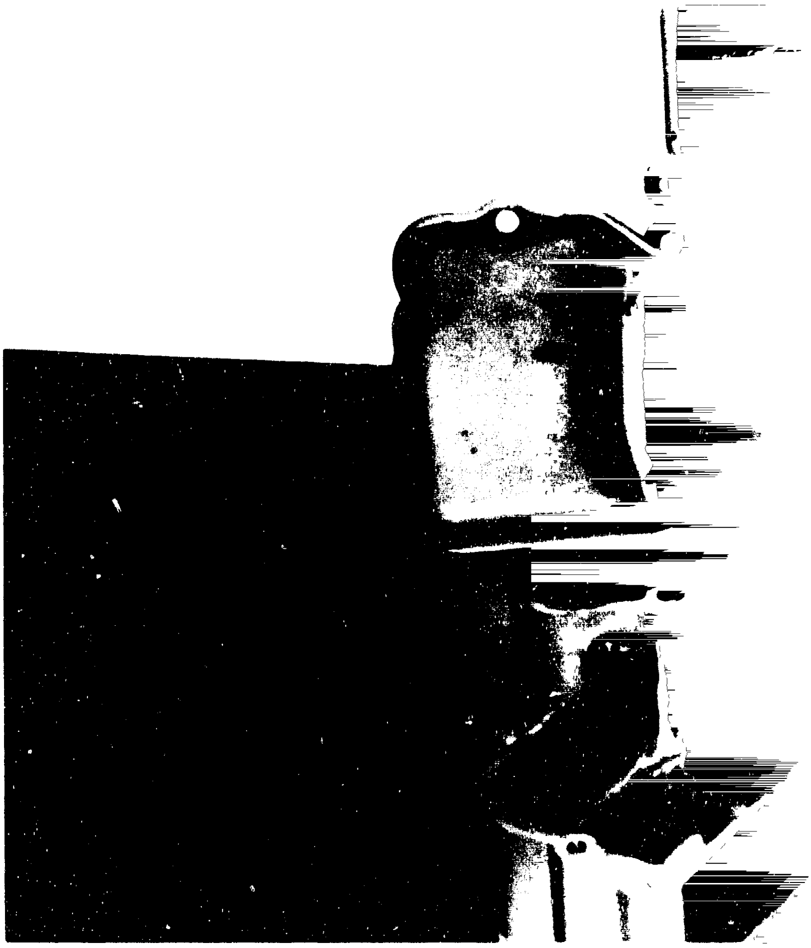

Figure 3.2-7 Modified Rocker Ho

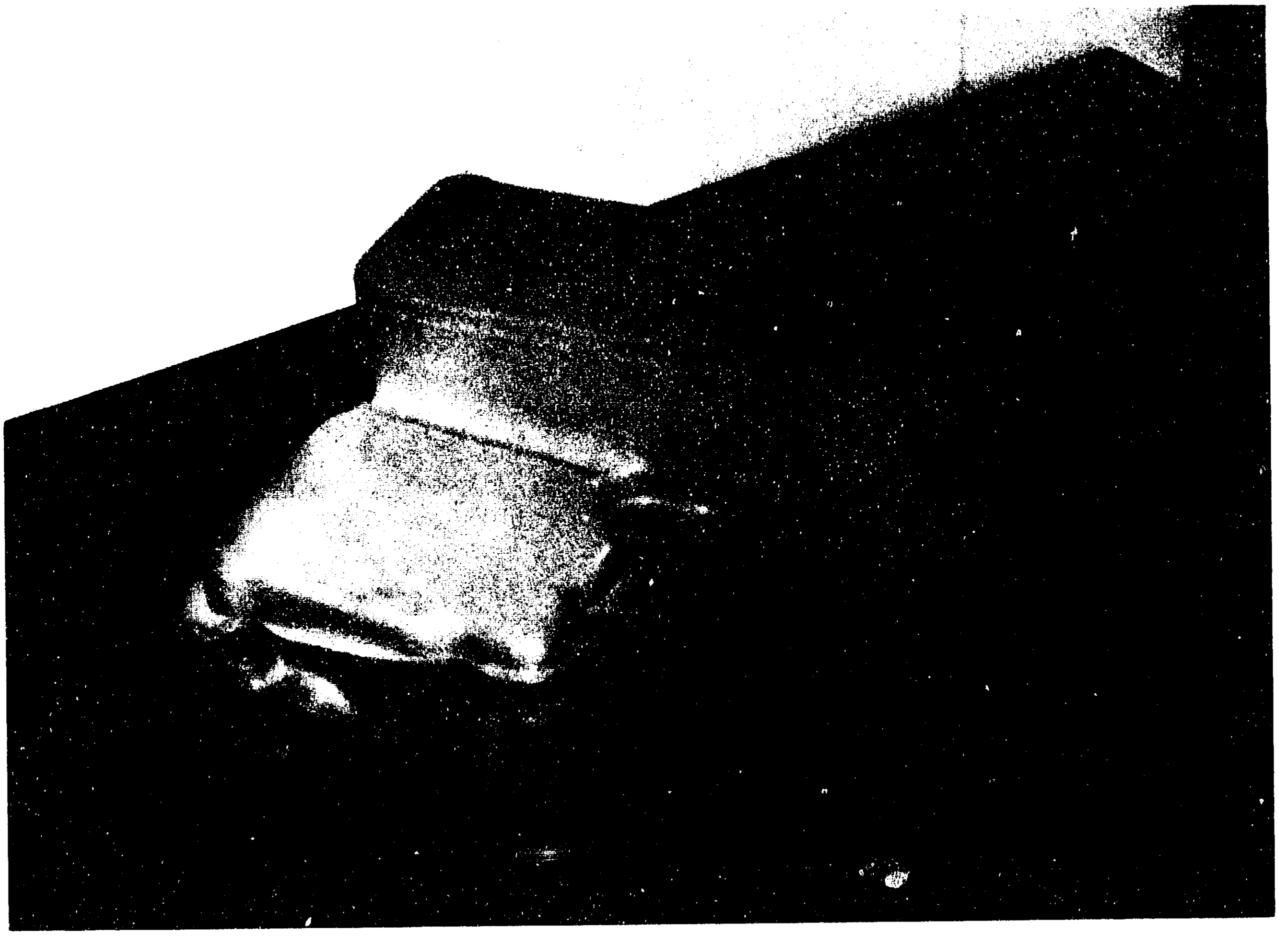

Figure 3.2-8 Assembled Rocker Housing and Cover

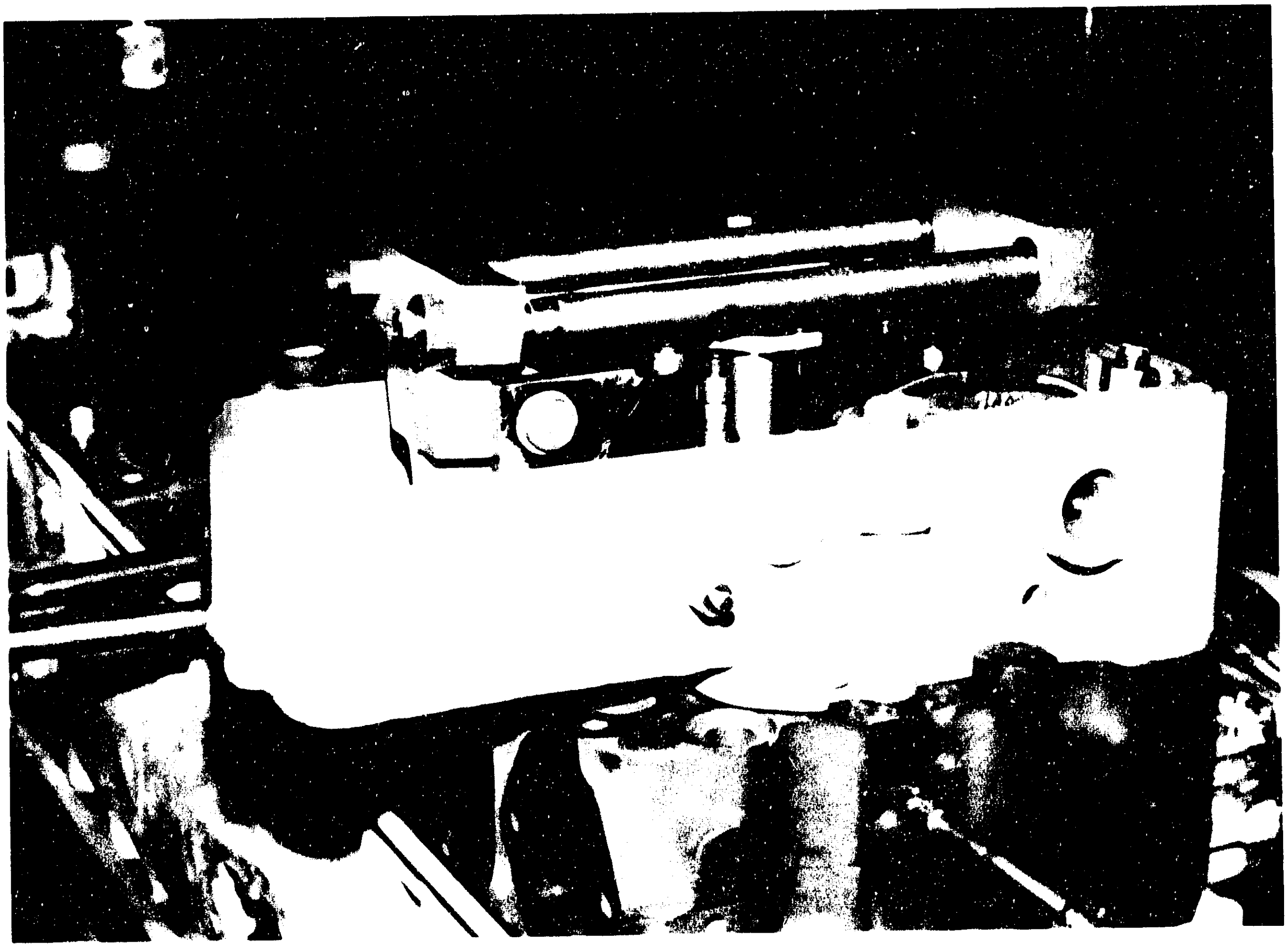

Figure 3.2-9 Injection Installation

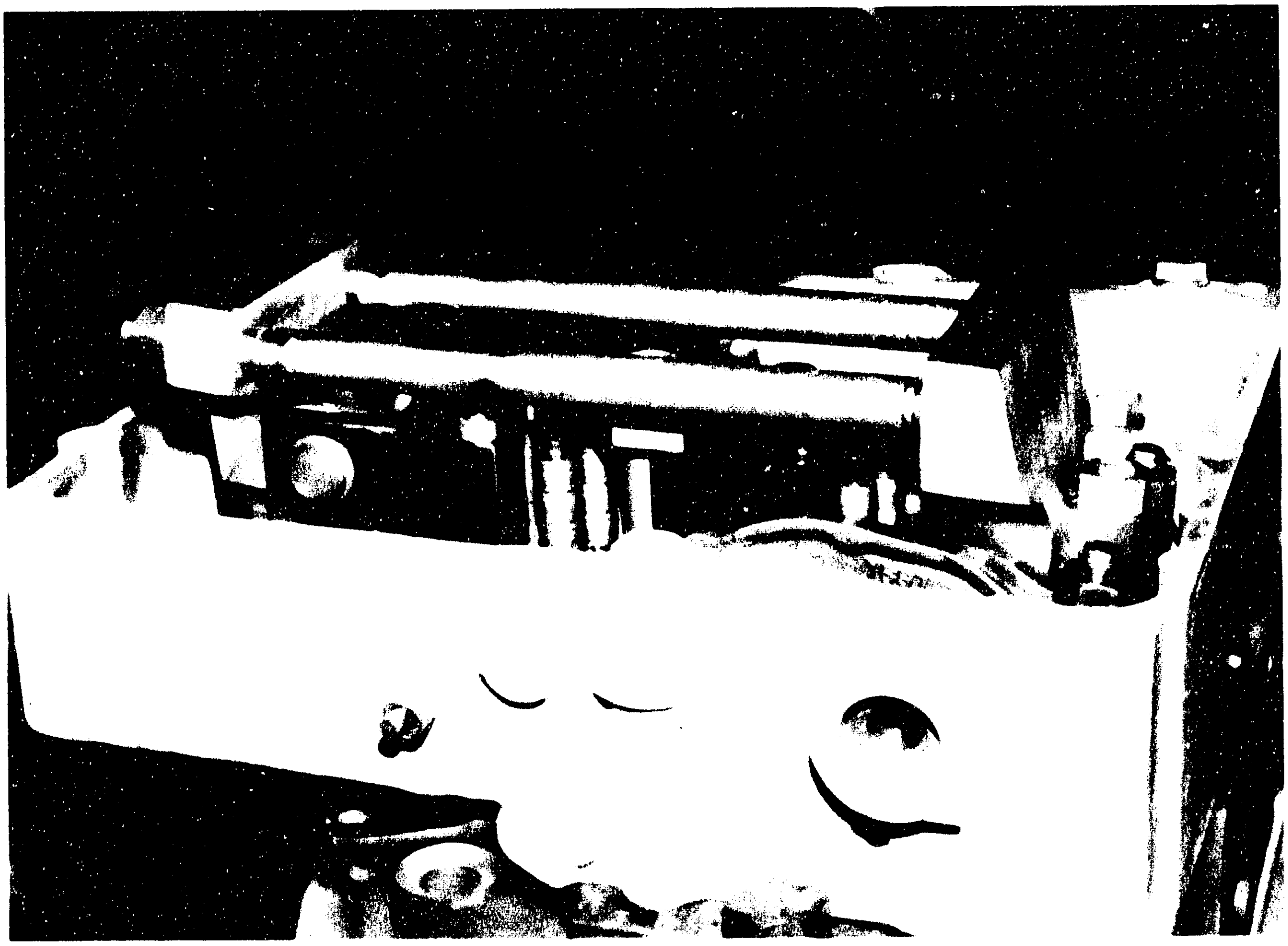

Figure 3.2-10 Injector Istallation

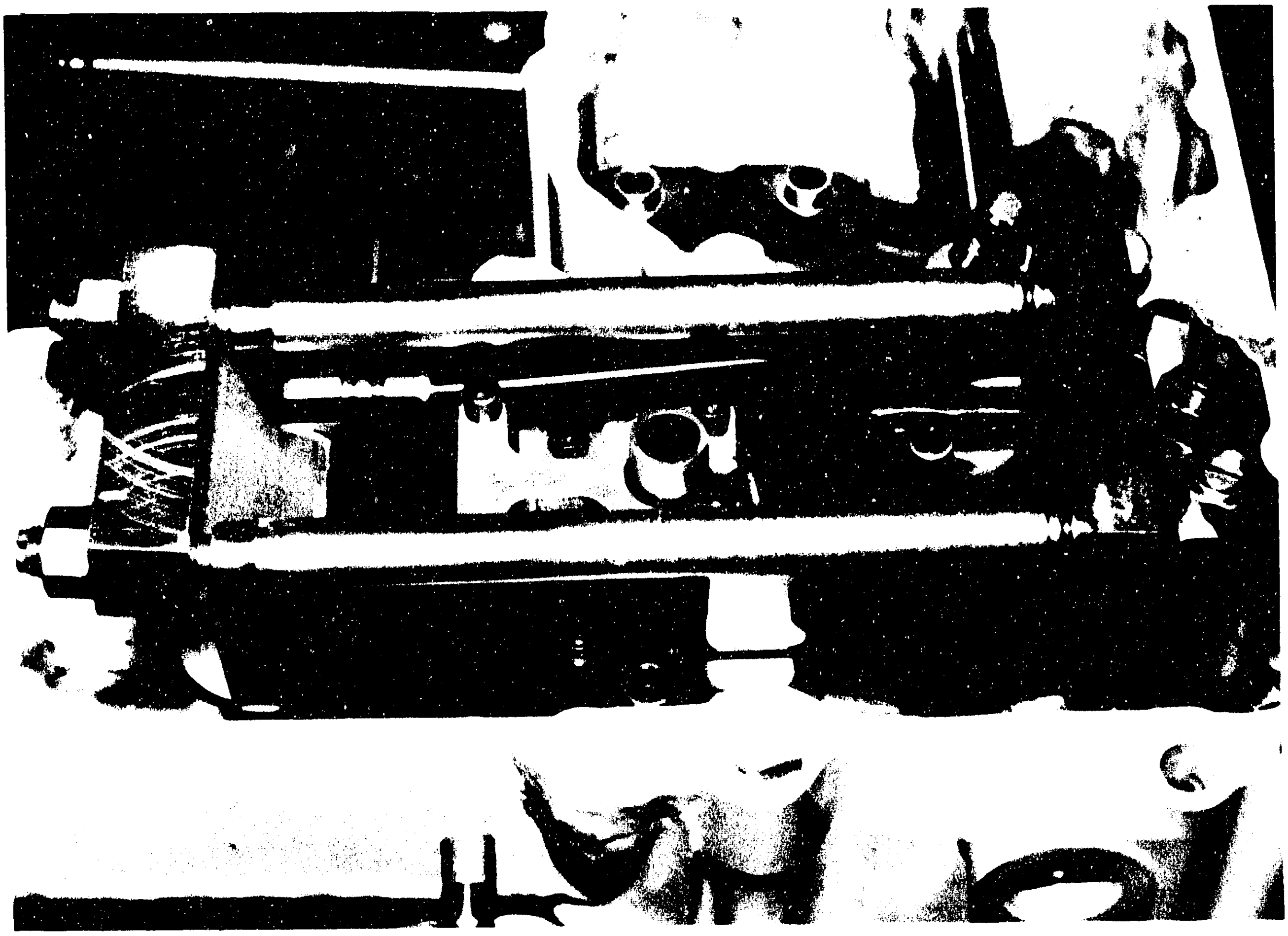

Figure 3.2-11 Injector Istallation

The last major item which had to be designed for the coal injection system was the coal supply system. As will be discussed in the bench test section, this item proved to be extremely difficult and frustrating to make work effectively. The final design consisted of using our existing coal hopper and screw feed system (Figure 3.2-12) to basically store and provide a continuous flow of the "Mulled Coal" to a second conical hopper located immediately above the fuel injector. Unfortunately, the coal at this point had agglomerated and was in chunks. To restore flow to the coal, a rotary sifter (similar to a flour sifter) was installed in the hopper directly below the coal inlet. A second screw feeder was positioned in the conical hopper below the sifter to maintain a constant coal level in the hopper. The conical hopper and the two screw feeders are shown in Figures 3.2-13 and 3.2-14 both with and without the tubes on the screw feeders. In the second photograph, the drive end of the sifter is visible as is an auxiliary air driven vibrator which was installed to improve flow. The two feeders are the same diameter and are driven at different speeds with the return feeder rotating faster than the supply feeder.

3.3 TEST RESULTS

As mentioned in the executive summary, the program did not result in successful running of the engine with the novel air blast injector. Therefore, this section of the report is centered upon providing results from the coal fuel testing and bench testing portions of the program as well as the limited attempts to run the engine on coal and the changes made to the injector during the engine testing phase.

3.3.1 BENCH TESTS

The bench testing consisted of two distinct series of tests. The first was testing of the coal fuel to select a fuel and determine its behavior. The second was bench testing of the complete injector assembly.

The first coal test was to utilize the existing variable speed screw feeder to determine how far dry powder coal fuel can be forced through a tube. The test was conducted using an Otisca prepared Blue Gem seam coal powder. The screw feeder was able to force the coal only 15 centimeters down a 3.2 centimeter diameter tube before the flow stopped. This computes to be a length to diameter ratio of less than five.

Continuous flow tests, using the auger system to drop coal into a pan, were conducted next as a function of coal type and moisture content. It was observed that the flow rate decreases as the moisture content increases and that the coal becomes progressively more lumpy.

To provide a means of determining flow of the coal, simple slump tests were conducted on a variety of coals. The test consisted of slowly dropping the coal on a flat plate until a pile with a diameter of about 5 centimeters was achieved. The height of the pile was then measured to determine slump height. Since the diameters were not always equal, to compare different results the ratio of height to diameter was used--the smaller the ratio, the better the flow. Test results are as shown in Table 3.3.1-1 and Figure 3.3.1-1. This data shows that the Otisca dry powder coal and the "Mulled Coal" from Energy International were very similar. The the best flow was achieved at about 15% moisture. It also shows that the worst flow is with very dry coal.

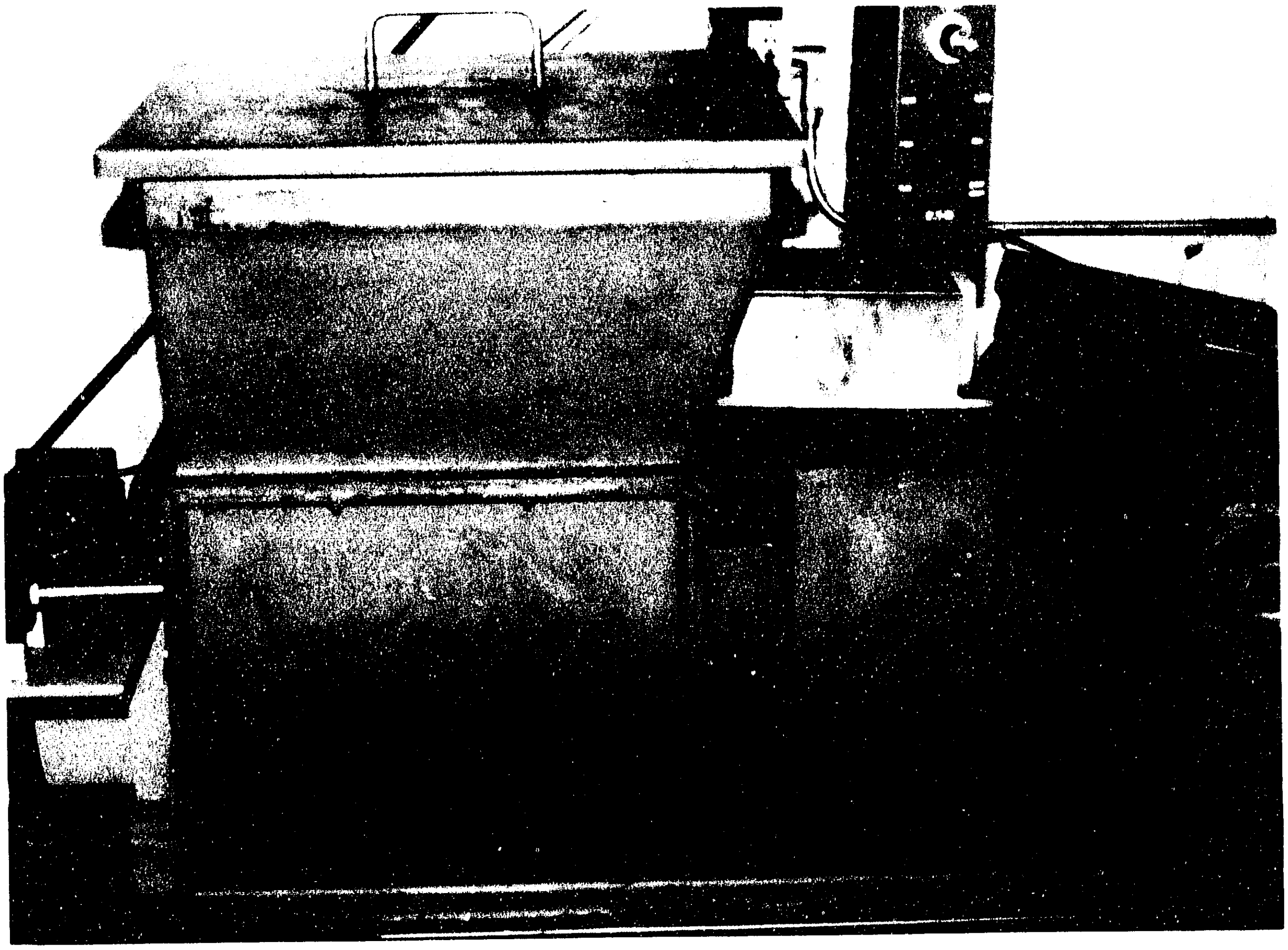

Figure 3.2-12 Coal Hopper and Screw Feeders

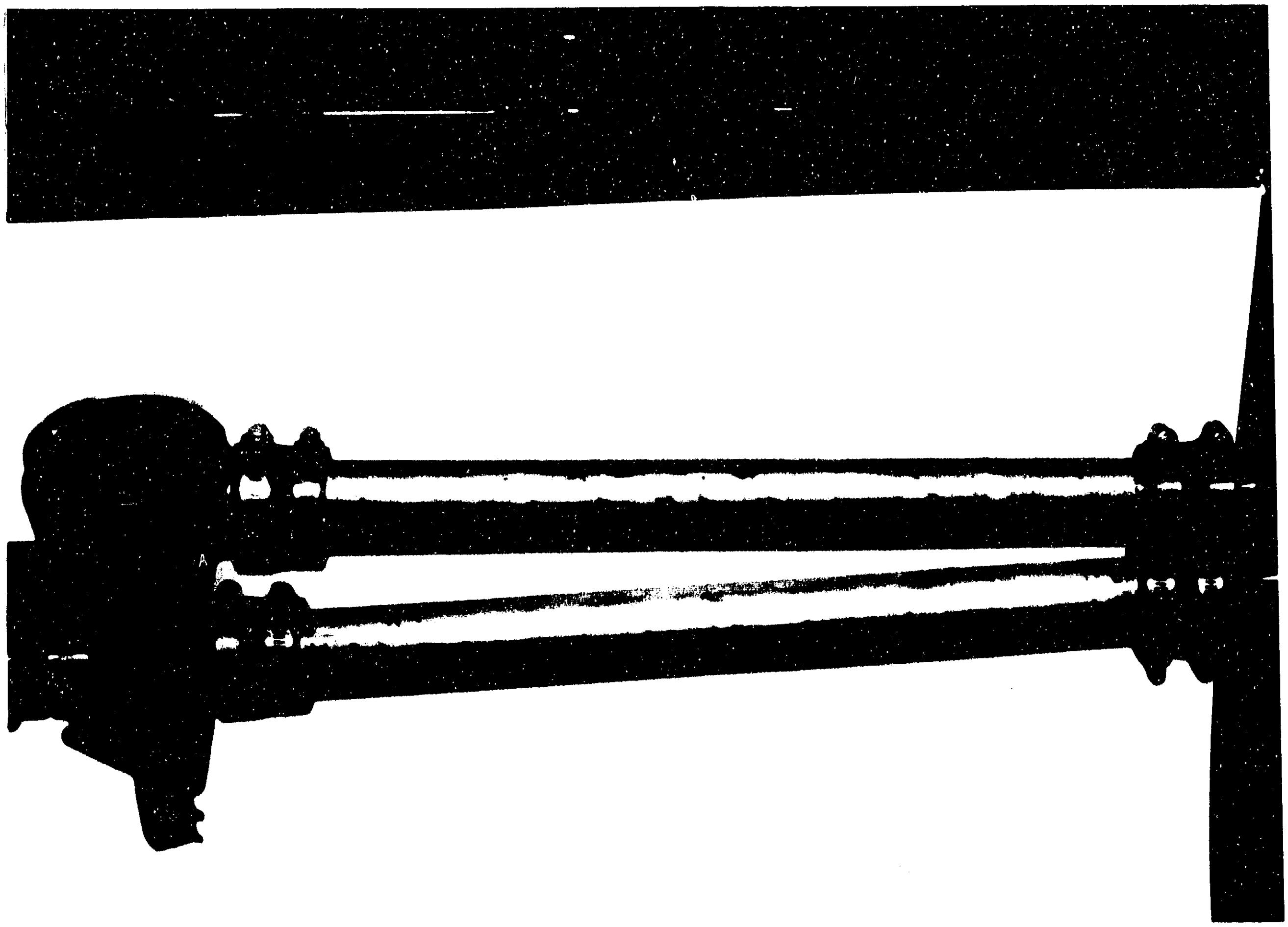

Figure 3.2-13 Conical Hopper and Screw Feeders

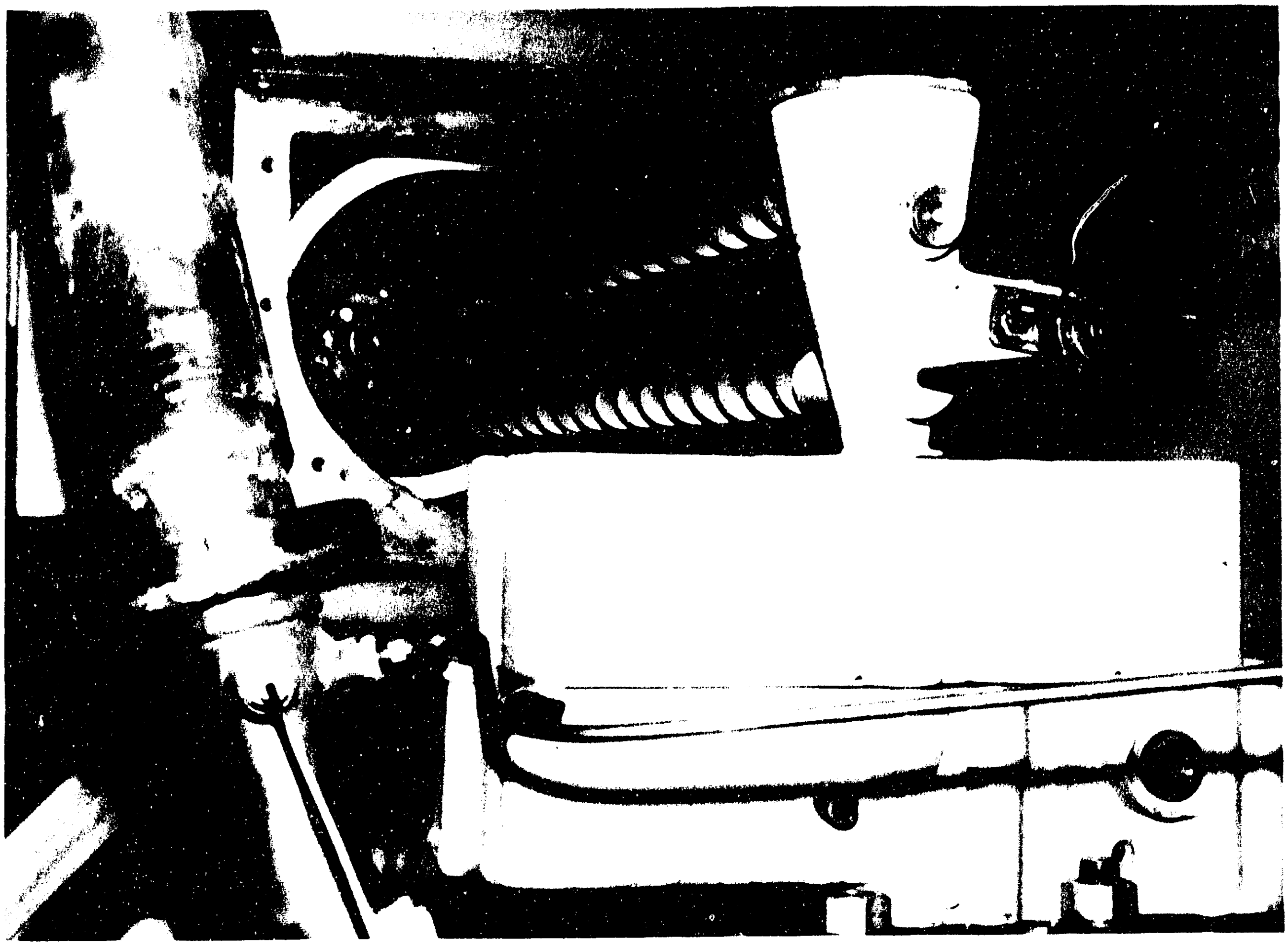

Figure 3.2-14 Conical Hopper and Screw Feeders

Table 3.3.1-1

COAL SLUMP TESTING RESULTS

DATE	COAL	MOISTURE percent	DIAMETER mm	HEIGHT mm	RATIO H/D
4-4-91	Otisca	35	63.5	30.2	0.47
4-4-91	Otisca	31	63.5	26.2	0.41
5-21-91	Otisca	30	50.8	23.0	0.45
5-21-91	Otisca	35	50.8	23.8	0.47
6-12-91	Mulled	30	50.8	23.8	0.47
6-12-91	Mulled	25	50.8	21.4	0.42
6-12-91	Mulled	20	50.8	21.4	0.42
6-12-91	Mulled	15	50.8	19.1	0.38
6-12-91	Mulled	10	50.8	25.4	0.50
6-12-91	Mulled	5	50.8	28.6	0.56
7-26-91	Mulled	38	50.8	20.6	0.41

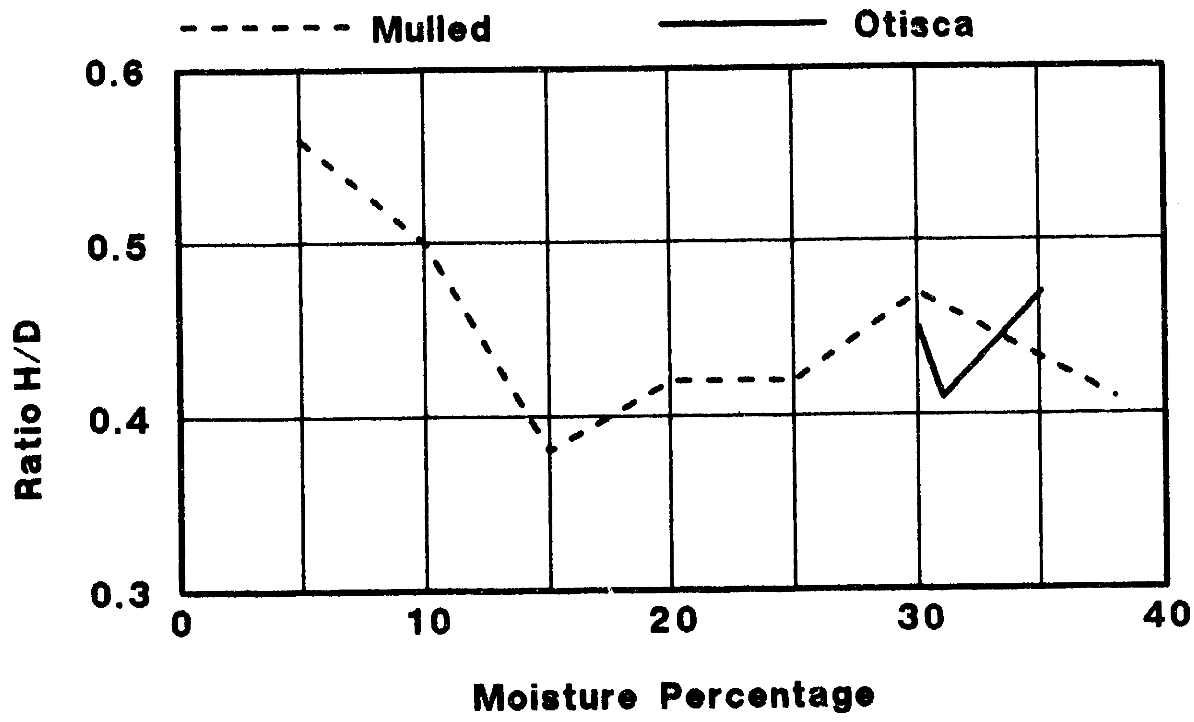

Figure 3.3.1-1 Coal Slump Testing Results

Figure 3.3.1-2 is a photograph of the top view of the injector bench test rig which consisted of a cam and cam driven system with a variable speed motor (shown on the left), a cam follower (center) and the coal injector with auger feed (right). An extensive series of tests were run on this rig using both coal and also water as the fuel. Many failures were also encountered on this rig, such as: Failure of the cam lobe (which was resolved by increasing lubrication); seizure of the injector plunger in the injector body (which necessitated making several plungers with progressively harder coatings); and failures of the coal feed system.

The first bench testing started on July 25, 1991 and stopped the same day due to cam failure. The cam was hard surfaced with a chrome oxide coating and the cam box was flooded with lubricant. On July 29, 1991, bench testing resumed and the cam quickly failed when the coating spalled off. Testing continued with a maximum injection frequency of 1,050 cycles per minute being achieved (this is equivalent to rated engine speed) without fuel. On August 23rd, a new cam was received and bench testing started with coal. Dry coal was injected for about fifteen minutes at low air blast pressure (100 psi). With higher air pressure, the coal blew backwards out of the coal feed auger. At this point, the injector body was modified to correct a machining error to correctly align the air passage and the passage to the combustion chamber. On September 3rd, the injector was run at 800 rpm with 600 psi air pressure and successfully pulsed coal powder out of the outlet. After this test, the plunger seized which required extensive cleaning. On the 11th and 12th of September, the rig was operated with water as the fuel and ran for about three hours at pressures between 1,000 and 2,000 psi. The system worked very well and the flow rate was easily varied using the helix on the plunger. On the 18th through the 20th of September, the rig was operated using CWS fuel at pressures up to 2,000 psi successfully. Additional testing was then conducted using dry powder coal. While the testing was successful, the injections were erratic. It was obvious that the feed system was not working properly. Many variations of the feed geometry were then tried, including restricting the outlet and installing a 90 degree turn on the outlet. During this testing, the plunger seized permanently and put a stop to the bench testing.

3.3.2 ENGINE TESTS

The results from the baseline diesel fuel testing of the Cummins NH-1 are included as Attachment 3. This includes data at two injection timings (the engine is equipped with a mechanical variable timing device) and has a repeat run of the second timing with particulate measurements.

The engine was started on aspirated diesel fuel. It was recognized that the engine would experience much more detonation on diesel fuel, but it eliminated the possible hazard of an explosion in the intake surge tank (which could have happened if the propane system failed to close). It was originally planned to start the coal engine testing by first starting the engine on aspirated propane to preheat the TICS chamber. However, following a safety review, it was decided that this introduced too large of a safety hazard. It was therefore not used.

The first series of tests with the coal injector installed were run without coal in the hopper (again for safety reasons in the event of excessive backflow into the coal system). The engine started easily on aspirated diesel fuel. We made several runs refining a procedure for heating the TICS chamber. On the final run, the detonation became severe and blowby increased dramatically. The engine was stopped. It was found that the cylinder head had failed both on the combustion surface and where one of the bolts retained the coal injector mounting plate.

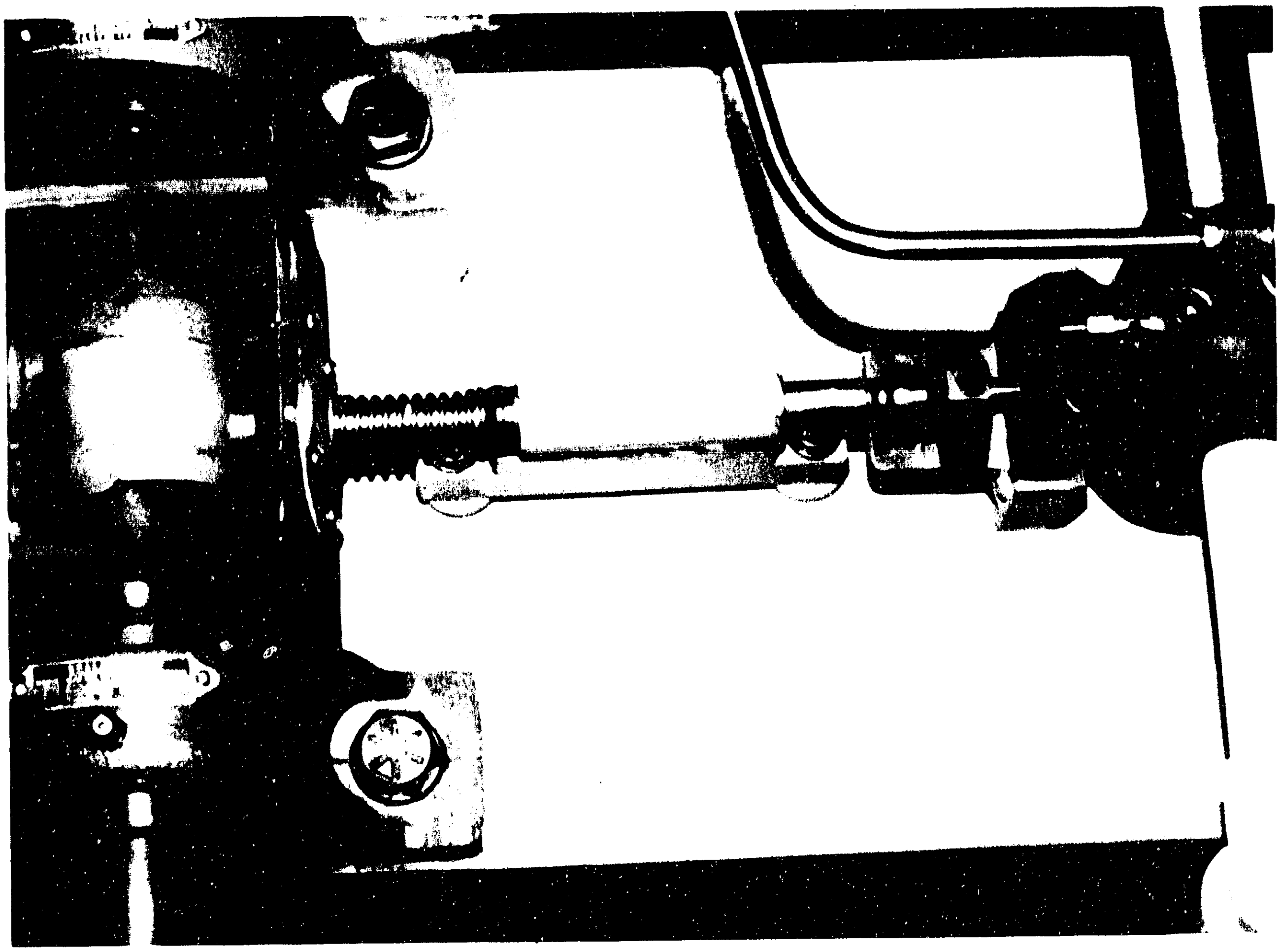

Figure 3.3.1-2 Bench Test Rig

A new cylinder head was prepared for the coal injector and testing resumed. This time, to prevent a recurrence of the previous failure, we started with motoring tests with coal in the injector. The first tests revealed that the injector sealing was not adequate--coal was being blown backwards into the hopper. To improve the sealing, square section teflon seal rings were installed in grooves which were machined on the injection valve (Figure 3.3.2-1). Testing with the seal rings showed that the leakage was slowed, but that there was still too much leakage to allow adequate coal to meter into the injector.

The injector was then hybridized by adding a solenoid controlled high pressure valve to time the air blast injection and shut off the air positively at all other times. This system, including the driver electronics, was installed on the engine and injector as shown in Figure 3.3.2-2. Motoring tests showed that this stopped the leakage. It showed that coal was being injected into the engine. On July 24, 1992, an attempt was made to start the engine using 100 percent dry powdered coal, using only heated intake air (93 C, 200 F.) to assist combustion. The engine ran self sustained at 320 to 360 rpm for five minutes after the starter was turned off. The prechamber outer wall temperature rose steadily to 182 C. (360 F.). At the end of this run, it was discovered that the drive motor had failed on the coal feed system which meant that the sifter was not running.

On July 31st, a new drive motor was installed. The testing was restarted using only coal fuel. This time the engine did not start. Therefore, a small amount of aspirated diesel fuel was used to fire the engine. It was then noticed that coal was being forced backwards into the hopper. The test was terminated. Inspection of the injector and engine revealed that the seals on the injector had failed. Also, the cylinder head was again cracked on the upper surface allowing the injector and TICS chamber to become loose (Figure 3.3.2-3). The testing was terminated due to the lack of time and funding, as well as no replacement cylinder head.

4.0 SUMMARY AND CONCLUSIONS

A novel air blast coal injector with only one moving part was designed, fabricated and engine tested. However, the program did not meet all of its goals as adequate engine testing was not completed. It is still believed that the injector concept is sound but that further refinement including either additional measurement equipment to assure that the desired diametral clearances are achieved in the test hardware or a design change to incorporate positive metal to metal sealing is required. The use of ceramic coatings on the injector valve eliminated scuffing of the valve with the Mulled Coal. The use of Teflon and rings is not recommended as failures were experienced with this approach.

It is also concluded that the Mulled Coal is currently not adequate for use as a dry powder coal fuel as it was too difficult to transport, dispense and meter.

The Mulled Coal did eliminate the explosion and aspiration hazard, and its properties did not appear to change during prolonged storage exposed to the atmosphere. Previous experience with dry coal highlighted the fact that the coal would pick up moisture from the atmosphere and become too sticky to flow.

Because there was no significant engine running on the coal fuel, no conclusion can be drawn relative to the effectiveness of the TICS combustion system when run on direct injected dry powdered coal. However, based on previous successful programs with aspirated dry coal and direct injected coal-water slurry, it is strongly believed that TICS will work with direct injected dry coal powder fuel.

5.0 RECOMMENDATIONS FOR FUTURE WORK

Before additional work is done with dry coal injection systems, it is recommended that additional work first be done to generate an acceptable fuel. A free flowing fuel (like dry sand) is required while retaining the non-misting characteristics of the Mulled Coal. The novel fuel injection system is available for future work both with and without the air solenoid valve. It is believed that with only a small amount of additional development, the original program goals can be achieved.

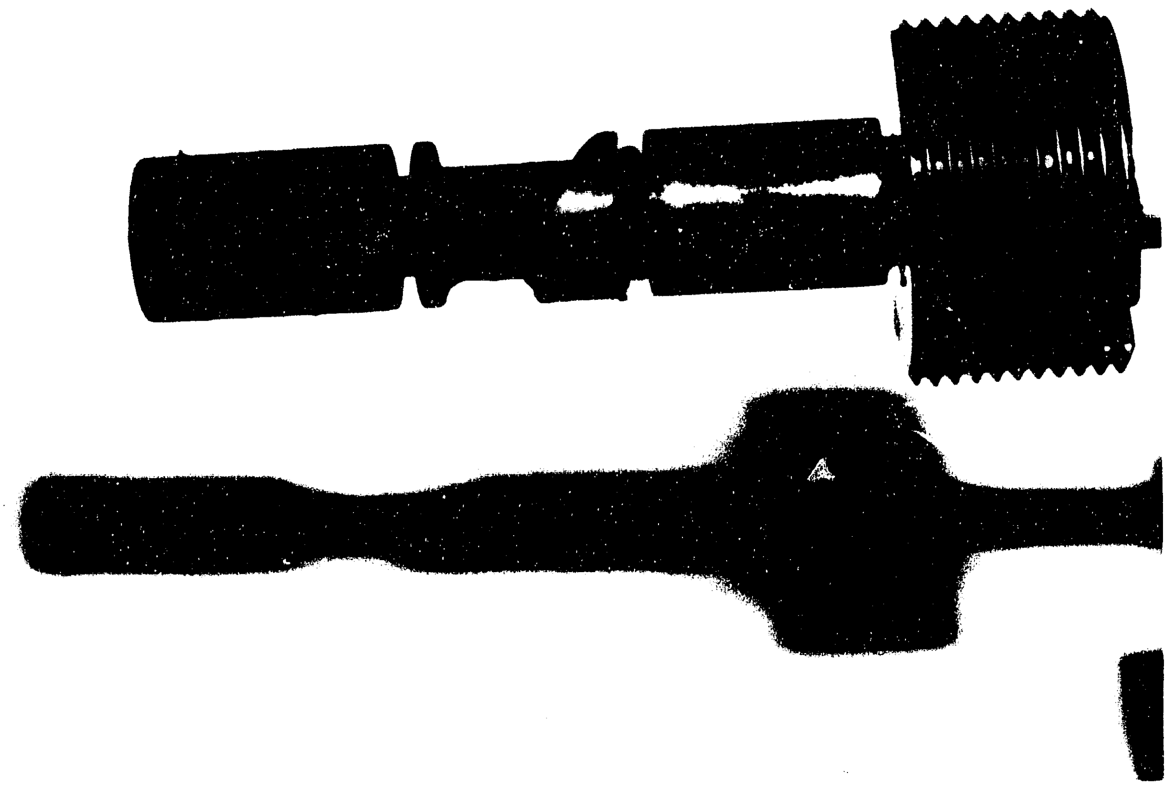

Figure 3.3.2-1 Injector Valve with Teflon Ring Grooves

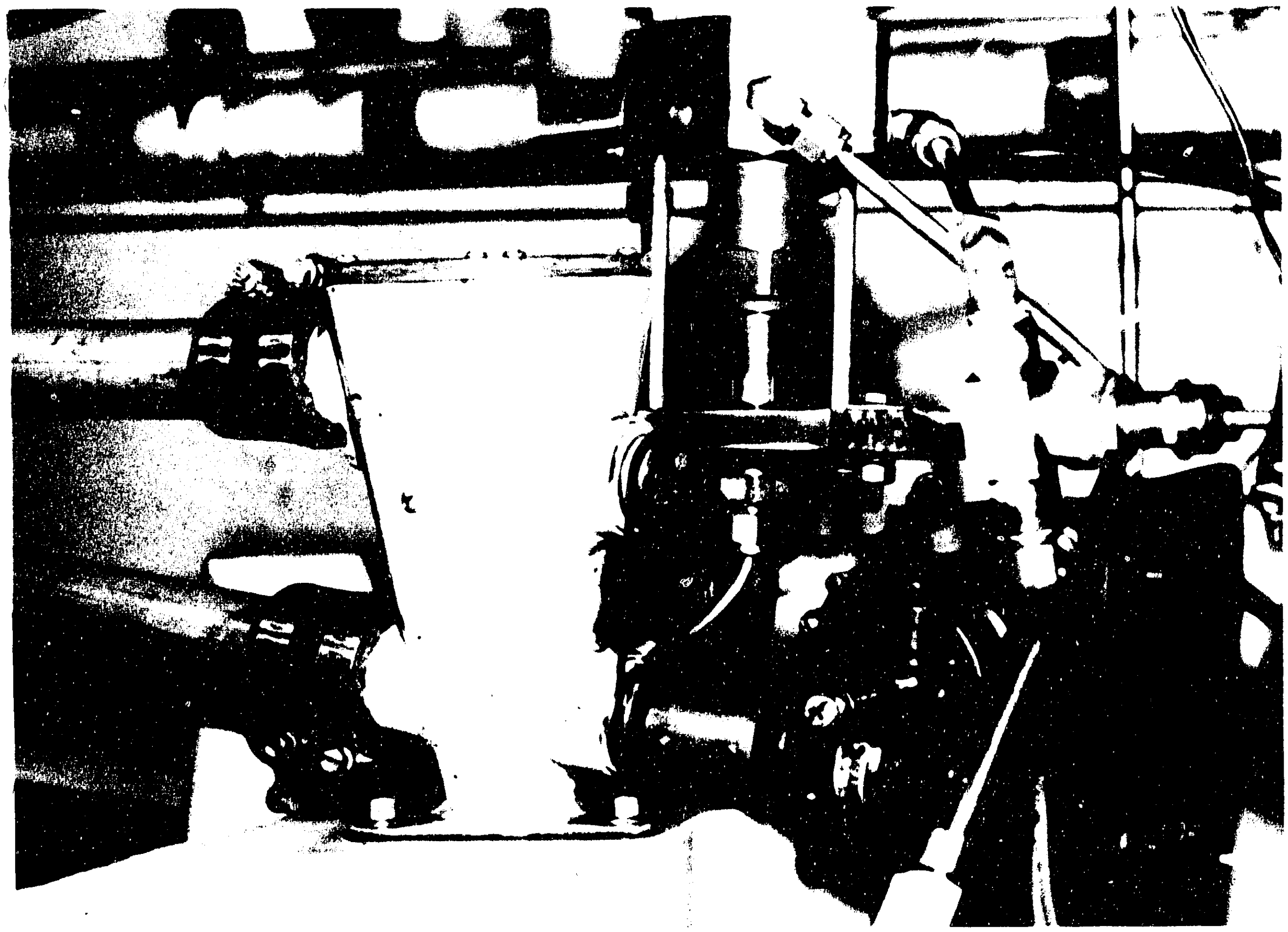

Figure 3.3.2-2 Gas Solenoid Valve

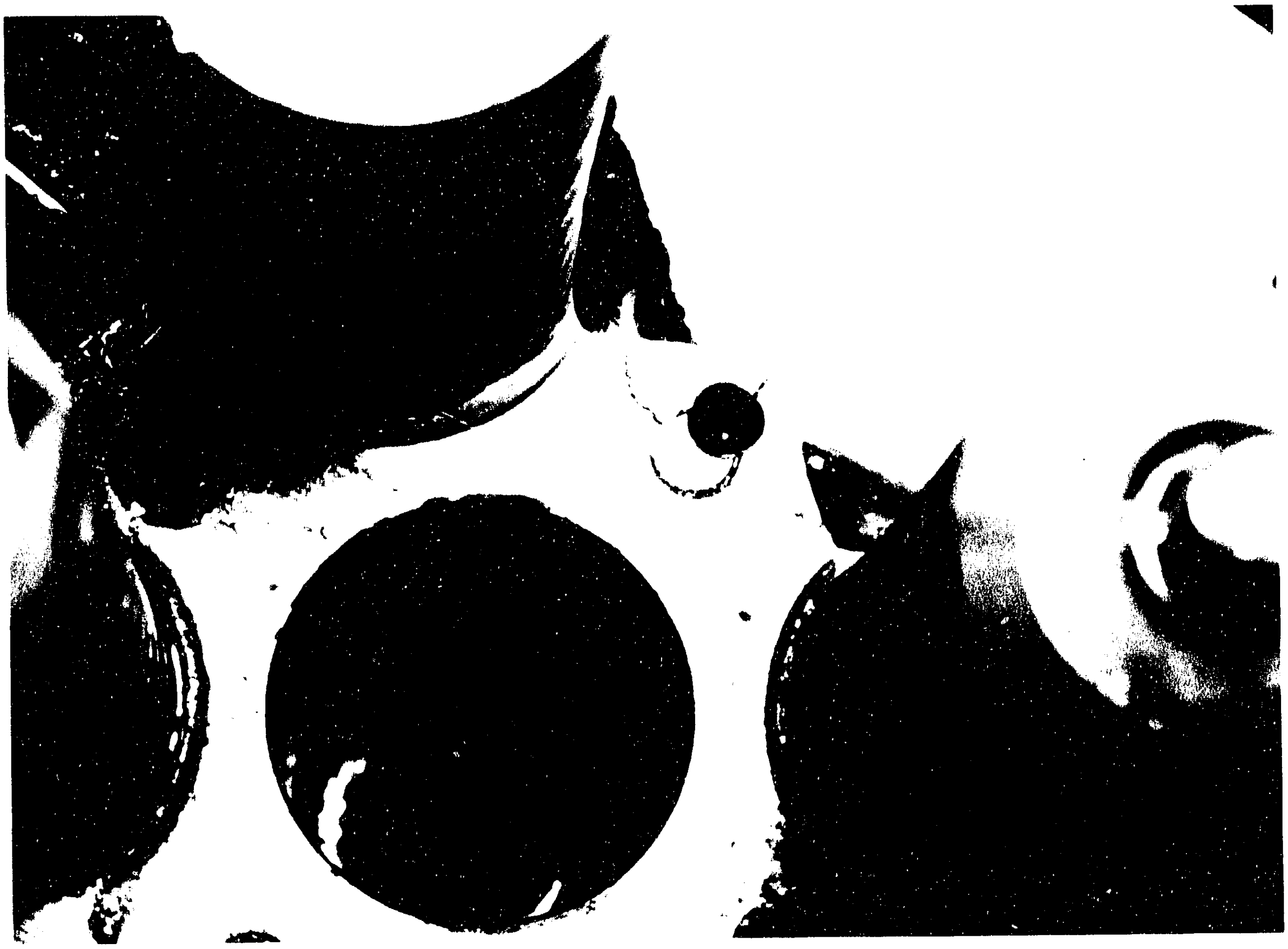

Figure 3.3.2-3 Failed Cylinder Head

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Attachment 1

********* FACSIMILE MESSAGE *********

ENERGY INTERNATIONAL CORPORATION
135 William Pitt Way
Pittsburgh, PA 15238
FAX # (412) 826-5378

DATE SENT	March 12, 1992	TIME SENT	4:45 PM
FROM	George Allison	SENDER's PHONE #	(412) 826-5364

TO: (name of person, company, address)	Telefax Number:
Mr. Pat Bageley Adiabatics Columbus, IN	(812) 372-4470
	Receiver's voice line

NUMBER OF PAGES FOLLOWING THIS ONE ~~one~~ two

OTHER MESSAGES, NOTES, REFERENCES, ETC. from SENDER:

Dear Pat,

Here is particle size data (from our Microtrac analyzer) on the mulled coal sample identified as UE3-381-MLD-E. along with analytical data for the feed coal, UE3-363-DCC-H
If you have any questions about this data, call me.

Ron Gense
for George Allison

If transmission is interrupted or incomplete, please contact our Facsimile operator at (412) 826-5355.
To Reply by FACSIMILE, please dial (412) 826-5378.

fadiabat
RWG02119

"up to 10 chars

MMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9

MICROTRAC DATA: DATA BASE UPDATE

measurem't/present'n#: 964 - 1

7997 0.69-704. SRA res: NORMAL

chan select bounds: 0.69- 704.00

progression: geom/sqrt2 # chans:20

sample date/time: 02/27/92 14:24

sample ident: ADIABATICS, INC.

sample ID : MULLED COAL

lot code: UE3-381-MLD-E

account #:48791 printer: OFF

run time: 10 sec. run #: 100/ 3

sample preparation code: 0

notes:

MMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM9

Esc-exit F2-commands

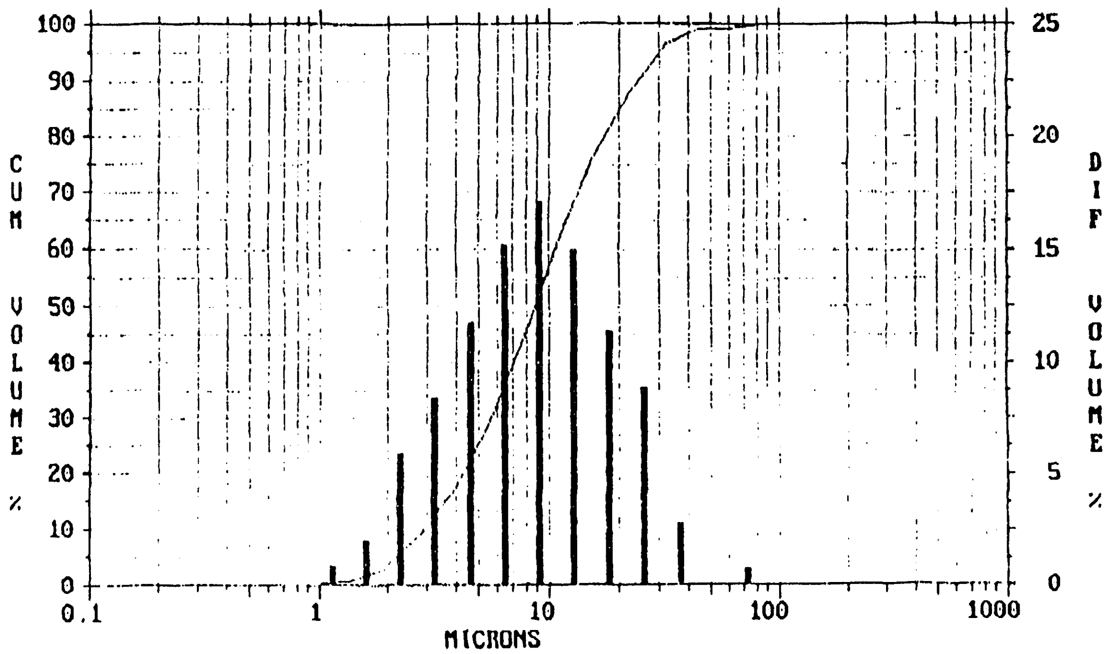
ch-top	%pass	%-ch
704.00	100.0	0.0
497.80	100.0	0.0
352.00	100.0	0.0
248.90	100.0	0.0
176.00	100.0	0.0
124.45	100.0	0.0
88.00	100.0	0.8
62.23	99.2	0.1
44.00	99.2	2.8
31.11	96.4	8.9
22.00	87.5	11.3
15.56	76.2	15.0
11.00	61.2	17.1
7.78	44.1	15.2
5.50	28.9	11.8
3.89	17.1	8.4
2.75	8.8	5.9
1.94	2.9	2.0
1.38	0.9	0.9
0.97	0.0	0.0

summary data	
dv:	0.0108
%10:	2.92
%50:	8.89
%90:	24.56
mv:	11.58
cs:	0.959
sd:	8.14
ma:	6.25

LMMMMMMMMMMMMMMMMMMM

parameters	
name	value
smpl amt	0.000
disprsnt	
disp amt	0.000
disp med	
dmed amt	0.000
agitat'n	
agit tim	0
circul'n	
circ tim	0
param #1	0.000
param #2	0.000
param #3	0.000

ADIABATICS, INC.
MULLED COAL
Record Number: 964



file:coalid   Sample Identification No.: UE3-363-DCC-H   No.: 363

SAMPLE INFORMATION

Bed Name:	Upper Elkhorn #3
Bed No.:	151
Local Name:	Taggart seam
Mining Co.:	Westmoreland Coal Co.
Mine Name:	Wentz #1
Wash Plant:	Wentz
State:	Virginia
County:	Wise
Amount:	~ 3 tons
Date Shpd:	June 26, 1991 to pulverizer.

ASH CHEMISTRY

SiO2	41.01 %
Al2O3	34.51 %
TiO2	1.52 %
Fe2O3	11.72 %
CaO	3.37 %
MgO	0.70 %
K2O	0.94 %
Na2O	1.00 %
SO3	2.07 %
P2O5	0.21 %
SrO	0.52 %
BaO	0.47 %
Mn3O4	0.06 %
BA Ratio:	0.23
T-250 TEMP.	2652 deg. F

PROXIMATE ANALYSIS (dry basis)

Moisture	0.00 %
Volatile Matter	36.87 %
Fixed Carbon	61.55 %
Ash	1.58 %
Sulfur	0.61 %
Btu/lb	15,187 15,431 MAF

ULTIMATE ANALYSIS (dry basis)

Carbon	84.84 %
Hydrogen	5.05 %
Nitrogen	1.57 %

ASH FUSION TEMP.: REDUCING

Initial	deg. F
Softening	deg. F
Fluid	deg. F

FREE SWELLING INDEX:

HARDGROVE GRINDABILITY:

FORM OF SULFUR

Pyritic	0.06 %
Sulfate	0.01 %
Organic (diff.)	0.54 %

Of 60 tons clean coal produced June 19-21 from sample ID# UE3-354-WRM-H, 3 tons were shipped to be pulverized to 70% -200 mesh, then delivered to PETC.

Attachment 2

ADIABATICS, INC.

Contract No. DE-AC21-90MC26305

The purpose of this report is to expand upon the design of the novel coal injector which was disclosed to METC via a Technical Progress Report dated January 17, 1991. The area which is addressed in this report is specifically the parasitic power requirements for the air powered injector. In a previous program to develop a fluidic injector, an air-operated vortex valve approach was developed and engine tested. This program was terminated because the parasitic power required to compress the air was excessive and amounted to about 25 percent of the total power output of the engine.

In summary, the result of a detailed analysis of the novel "Air Assist Fuel Injector" is that providing the air will require 2.7 percent of the net engine power at rated speed and load. This power level is acceptable and it is recommended that METC agree to the proposed concept selection so that Adiabatics can proceed to the next task (test plan).

In order to prepare this power requirement estimate, it was necessary to model the complete engine and injection system and perform a dynamic simulation. A "spreadsheet" type simulation approach was utilized which permitted the optimization process to be expedited by using on-line graphics. The following paragraphs and their references, tables and figures, provide documentation for the model and show the results of the optimization process:

MODEL: ENGINE: The "TICS" prechamber type engine was modeled as two distinct volumes. The "MAIN" volume (consisting of the volume enclosed by the cylinder wall, piston crown and cylinder head) varies as the crankshaft turns based upon the kinematics of the slider crank mechanism. A set of initial conditions for this volume is generated based upon empirical test data and geometric constraints. By specifying the compression and volume ratios of the TICS chamber to the total clearance volume, a clearance volume for the "MAIN" volume is established. Initial conditions for the pressure and temperature in the "MAIN" volume at the point of intake valve closure are used as variables to control the amount of air available for the combustion process. The second volume is the "TICS" volume (consisting of the precombustion chamber). While the physical volume of this space is fixed, there are two different flows into and out of its boundaries. The first is the fuel injector, which provides air and coal to the chamber (described in the following paragraph) and the "TICS" chamber throat, which is a fixed orifice that commumicates flow from the "TICS" chamber to and from the "MAIN" chamber. Both of these flow passages conduct a mixed flow consisting of either air or air and coal. In the case of the fixed orifice between the prechamber and the cylinder, flow first starts as compressed air flows from the engine cylinder into the "TICS" chamber. Later in the cycle, a mixture of air and coal and products of combustion flows into the cylinder, where it continues combustion. In each of the flow cases, the model calculates the flow of the compressible gases based upon either subsonic or choked flow.

A simplified burning and heat release model is utilized to simulate the heat addition from burning the coal in both the "TICS" and "MAIN" volumes. This model was generated and optimized to properly predict peak cylinder pressures and, approximately, the correct shape of the cylinder pressure history.

INJECTOR: The air blast portion of the injector was modeled as a fixed volume (consisting of a cylinder of a given diameter and length) which is precharged to a fixed pressure. At a preset crankangle position, the volume is connected to the "TICS" chamber by a fixed orifice. At a later preset crankangle, the orifice is closed. By keeping track of the amount of air which flows through the orifice during the valve open time, it is possible to quickly calculate the total amount of air required from the compressor system.

COMPRESSOR: The air compressor system is modeled as a three stage compressor with intercooling between the first two stages.

INPUTS:

TABLE 1 is a listing of the inputs to the program including sample values for the optimized full power operating condition: NOTE - **Highlighted** values are computed within the program.

VARIABLES:

TABLE 2 is a listing of the variables which are computed, compiled and listed in the spreadsheet at each even crankangle position.

OUTPUTS:

A set of sample output plots from the simulation is shown for the optimized rated power condition (corresponding to the inputs shown in TABLE 1) as follows:

Figure 1 Pressure history of the MAIN and TICS chambers plotted as a function of MAIN volume. This is the classic engine indicator card for the closed portion of the cycle (intake and exhaust valves closed). The bottom set of curves going from right to left traces the compression cycle and shows how the TICS chamber pressure lags the main chamber pressure. Once combustion starts the pressure in the TICS chamber becomes higher than in the MAIN chamber and stays higher through the expansion cycle. The indicated power shown in TABLE 1 is derived by integrating the area under the MAIN PV diagram.

Figure 2 This plot is the same as Figure 1 except that the log of the pressures is plotted against the log of the volume. On this curve the inflection points showing the start of injection and the start and end of combustion are clearly noticeable.

Figure 3 This plot shows MAIN and TICS chamber pressures as a function of crankangle (180 degrees is top-dead-center) and also shows the pressure history in the Blow Down chamber. The injector is timed to begin injection at 160 crank degrees (20 degrees before TDC) and ends 25 to 30 degrees after TDC to provide for purging of the injector. The initial pressure and the volume of the Blow Down chamber were selected to permit the pressure in the injector to fall to about 100 psi above the peak pressure in the prechamber to prevent backflow.

Figure 4 The flow rates through the TICS chamber throat and through the injector are shown on this graph. This graph illustrates that about one half of the air from the injector (and virtually all of the fuel) flows into the TICS chamber before the flow through the throat of the TICS chamber reverses and allows flow into the MAIN chamber.

Figure 5 This plot shows the weight of various substances in each chamber of the engine. The top curve is the total weight in the MAIN chamber. This value is essentially constant until the TICS chamber starts filling towards the end of the compression stroke. During combustion the total weight increases until it reaches a high point equilibrium after combustion is over. The TICS chamber weight is very small until it starts filling with air from the MAIN volume and further increases as air and coal are injected into it. Its weight then decreases as it loses product to the MAIN chamber. The weight in the

Blow Down chamber is essentially constant with only a small portion of its capacity being used during each injection. The last curve shows the cumulative coal injected into the engine.

Figure 6 This plot is the same as Figure 5 except that the MAIN chamber is excluded and the vertical scale is expanded.

Figure 7 This curve shows the velocity of the air flowing through the orifice in the injector leading into the TICS chamber. The velocity is plotted in inches per degree to impart a feeling as to the distance which the air (and fuel) will travel during each crank degree. The top portion of the trace shows a flat which occurs during the sonic (choked) portion of the flow history. A velocity of one inch per degree will require us to make the injector as close as possible to the TICS chamber to maximize the crispness of the start and end of injection.

Figure 8 This plot is the same as Figure 7 except that the flow is plotted as inches per second. The velocity of the air during the time when the coal is being injected is about 11,500 inches per second which is 650 miles per hour. This velocity should be more than adequate to transport the coal powder out of the groove in the valve plunger and to thoroughly scrub out all of the residual fuel.

OPTIMIZATIONS:

As previously mentioned each parameter of the design was iterated to find optimal values which resulted in obtaining adequate airflow at minimum power consumption. Two of these results at the engine rated power point are shown graphically as Figures 9 and 10. Figure 9 is a plot of compressor power expressed both as horsepower and percent of engine power as a function of Blow Down volume initial pressure. This plot shows the importance of keeping the pressure level as low as possible. The 2100 psi level was selected as being the lowest level which would maintain choked flow during the first part of the injection and also have adequately high velocities when the peak pressure in the TICS chamber reached its anticipated level of 1900 psi.

Figure 10 is a plot of compressor power requirement versus effective flow diameter for the air path in the injector. This shows the extreme sensitivity of this parameter as enlarging the orifice from 0.060 inch to 0.080 inch almost doubles the compressor requirement.

Table 3 is a compilation of some of the optimization data and includes engine operation at part loads and also reduced speed.

TABLE 1

INPUTS:

BORE	5.5	inches
STROKE	6.0	inches
STROKE/ROD LENGTH	0.5	
COMPRESSION RATIO	16.5	
TRAPPED PRESSURE	33.9	psia
TRAPPED TEMPERATURE	210.0	degrees F
TICS VOL/CLEARANCE VOL	0.28	
THROAT DIAMETER	0.2	inches
THROAT AREA	0.0314	square inches
TURBO PRESSURE RATIO	2.306	
ENGINE DISPLACEMENT	142.55	cubic inches
PISTON AREA	23.76	square inches
CLEARANCE VOLUME	9.197	cubic inches
WEIGHT OF AIR - MAIN	0.012	lbs
RATIO OF SPECIFIC HEATS	1.4	
TICS VOLUME	2.575	inches
ENGINE SPEED	2100	rpm
BRAKE MEAN EFFECTIVE PRESS	173.1	psi
DRY COAL HEATING VALUE	14100	BTU/lb
AIR/FUEL RATIO - DIESEL	30	
AIR/FUEL RATIO - DRY COAL	22.74	
COAL FLOW RATE	0.000535	lbs/injection
COAL HEAT FLOW	7932.2	BTU/minute
BRAKE THERMAL EFFICIENCY	35	percent
BRAKE POWER OUTPUT	65.4	horsepower
INDICATED POWER OUTPUT	91.9	horsepower
BLOWDOWN CAVITY LENGTH	2.0	inches
BLOWDOWN CAVITY DIAMETER	0.75	inches
BLOWDOWN CAVITY VOLUME	0.884	cubic inches
B.C. PRESSURE - INITIAL	2100.0	psi
B.C. TEMPERATURE - INITIAL	660.0	degrees F
B.C. AIR WEIGHT - INITIAL	0.00259	lbs
AIR CONSUMPTION - TOTAL	0.00019	lbs per injection
WEIGHT AIR/WEIGHT FUEL	0.356	
COMPRESSOR EFFICIENCY	60.0	percent
B.C. AIRFLOW	12.0	lbs/hour
COMPRESSOR INLET TEMPERATURE	60.0	degrees F
PER STAGE PRESSURE RATIO	5.23	
COMPRESSOR POWER/STAGE	0.595	horsepower
TOTAL COMPRESSOR POWER	1.785	horsepower
COMPRESSOR/ENGINE POWER	2.73	percent
COMPRESSOR OUTLET TEMP.	583.5	degrees F
DIAMETER OF INJECTOR ORIFICE	0.07	inches
AREA OF INJECTOR ORIFICE	0.003848	square inches
DISCHARGE COEFFICIENT	0.6	

TABLE 2

VARIABLES

CRANKANGLE (degrees)
CRANKANGLE (radians)
MAIN CHAMBER VOLUME
MAIN CHAMBER PRESSURE
MAIN CHAMBER TEMPERATURE
WEIGHT OF AIR AND COAL IN MAIN CHAMBER
TICS CHAMBER PRESSURE
TICS CHAMBER TEMPERATURE
WEIGHT OF AIR AND COAL IN TICS CHAMBER
FLOW RATE BETWEEN TICS AND MAIN CHAMBER
COAL FLOW RATE
CUMULATIVE COAL FLOW
HEAT RELEASE
WEIGHT OF AIR IN MAIN CHAMBER
WEIGHT OF COAL IN MAIN CHAMBER
WEIGHT OF AIR IN TICS CHAMBER
WEIGHT OF COAL IN TICS CHAMBER
WEIGHT OF AIR IN BLOWDOWN CHAMBER
PRESSURE OF AIR IN BLOWDOWN CHAMBER
TEMPERATURE OF AIR IN BLOWDOWN CHAMBER
FLOW RATE BETWEEN BLOWDOWN CHAMBER AND TICS CHAMBER
PRESSURE RATIO BLOWDOWN CHAMBER TO TICS CHAMBER
PRESSURE RATIO TICS CHAMBER TO MAIN CHAMBER
DENSITY OF AIR IN BLOWDOWN CHAMBER
FLOW VELOCITY THROUGH INJECTOR ORIFICE (inches per second)
FLOW VELOCITY THROUGH INJECTOR ORIFICE (inches per degree)

TABLE 3

ENGINE SPEED (rpm)	ENGINE POWER (bhp)	BLOWDOWN PRESSURE (psi)	COMPRESS POWER (bhp)	PERCENT OF ENG. POWER	LBS AIR/ LBS COAL (%)	AIR VELOCITY (in/deg)	ORIFICE DIAM. (in)
2100	24	1000	0.95	3.96	63.0	0.86	0.070
2100	42	1500	1.48	3.47	49.4	0.92	0.070
2100	65	2100	1.78	2.73	35.5	0.92	0.070
1500	17	1000	0.93	5.40	85.0	1.21	0.070
1500	31	1500	1.46	4.70	67.0	1.29	0.070
1500	47	2100	1.73	3.69	48.0	1.29	0.070
2100	65	2100	1.78	2.73	35.5	0.92	0.070
2100	66	2300	2.26	3.44	43.0	0.92	0.070
2100	66	2500	2.66	4.04	50.5	0.92	0.070
2100	66	3000	3.55	5.37	64.0	0.92	0.070
2100	65	2100	1.37	2.10	27.0	0.92	0.060
2100	65	2100	1.78	2.73	35.5	0.92	0.070
2100	66	2200	2.54	3.85	49.0	0.92	0.080

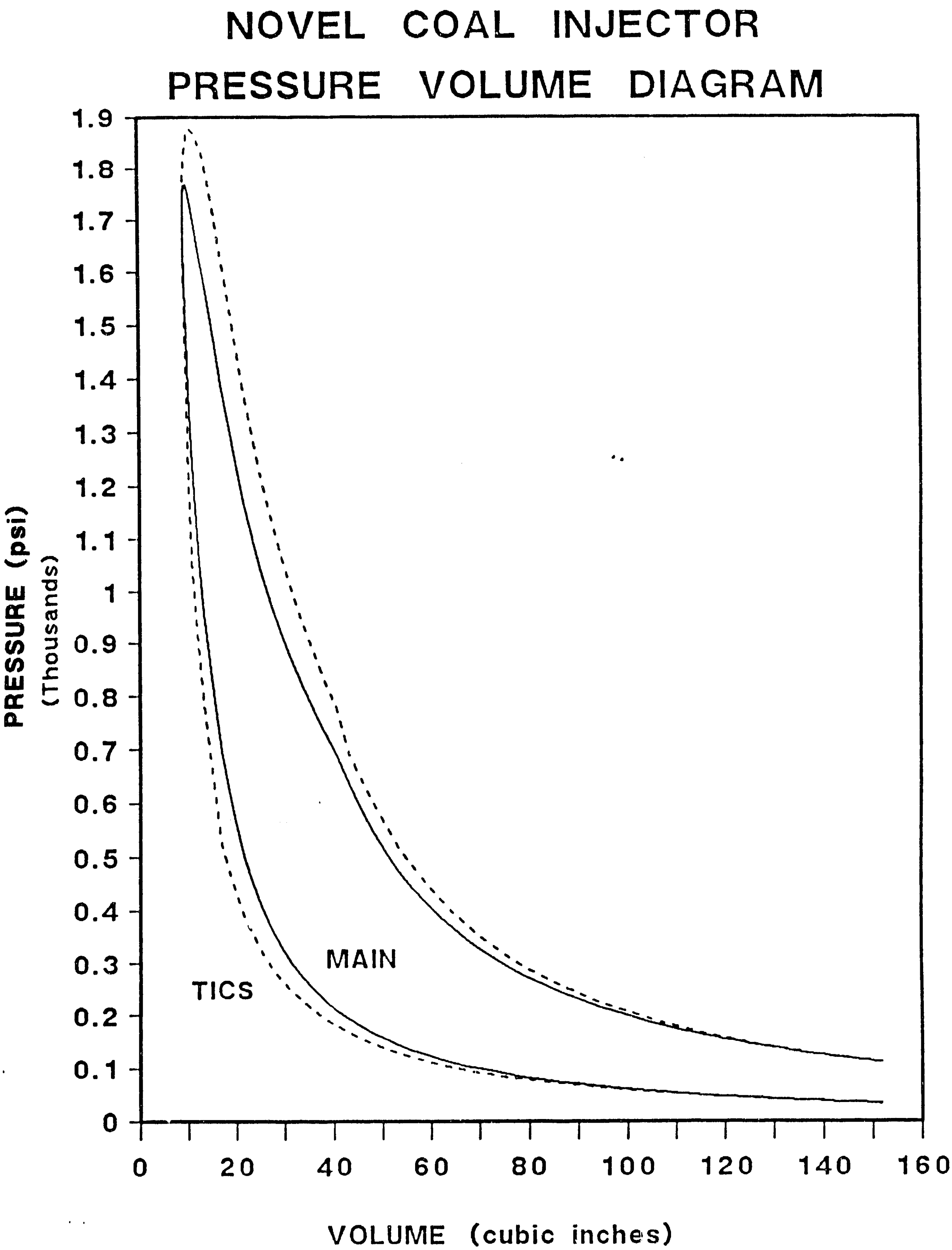

NOVEL COAL INJECTOR
PRESSURE VOLUME DIAGRAM
PRESSURE (psi)
(Thousands)
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
MAIN
TICS
0
20
40
60
80
100
120
140
160
VOLUME (cubic inches)

Figure 1

NOVEL COAL INJECTOR

PRESSURE VOLUME DIAGRAM

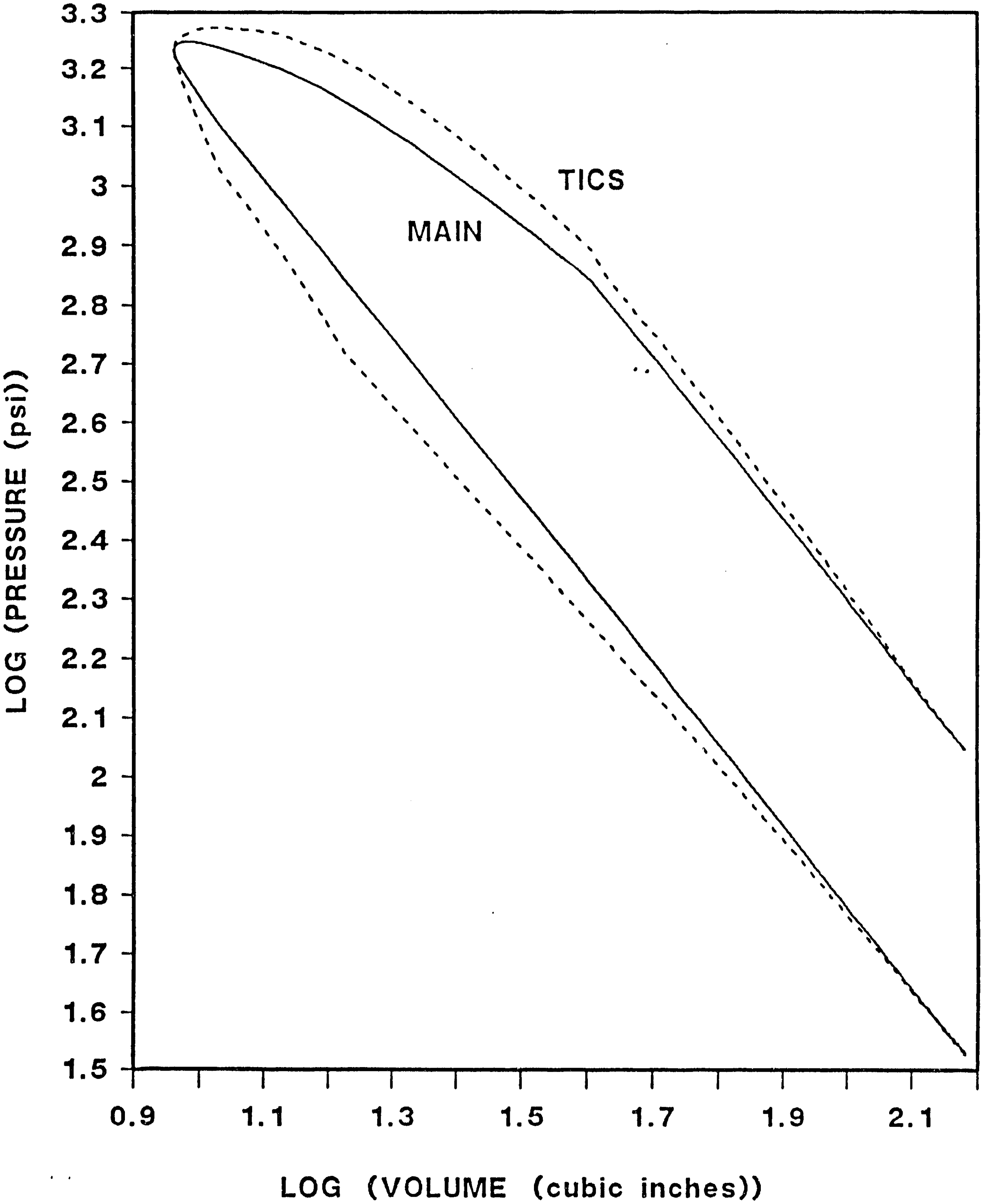


Figure 2

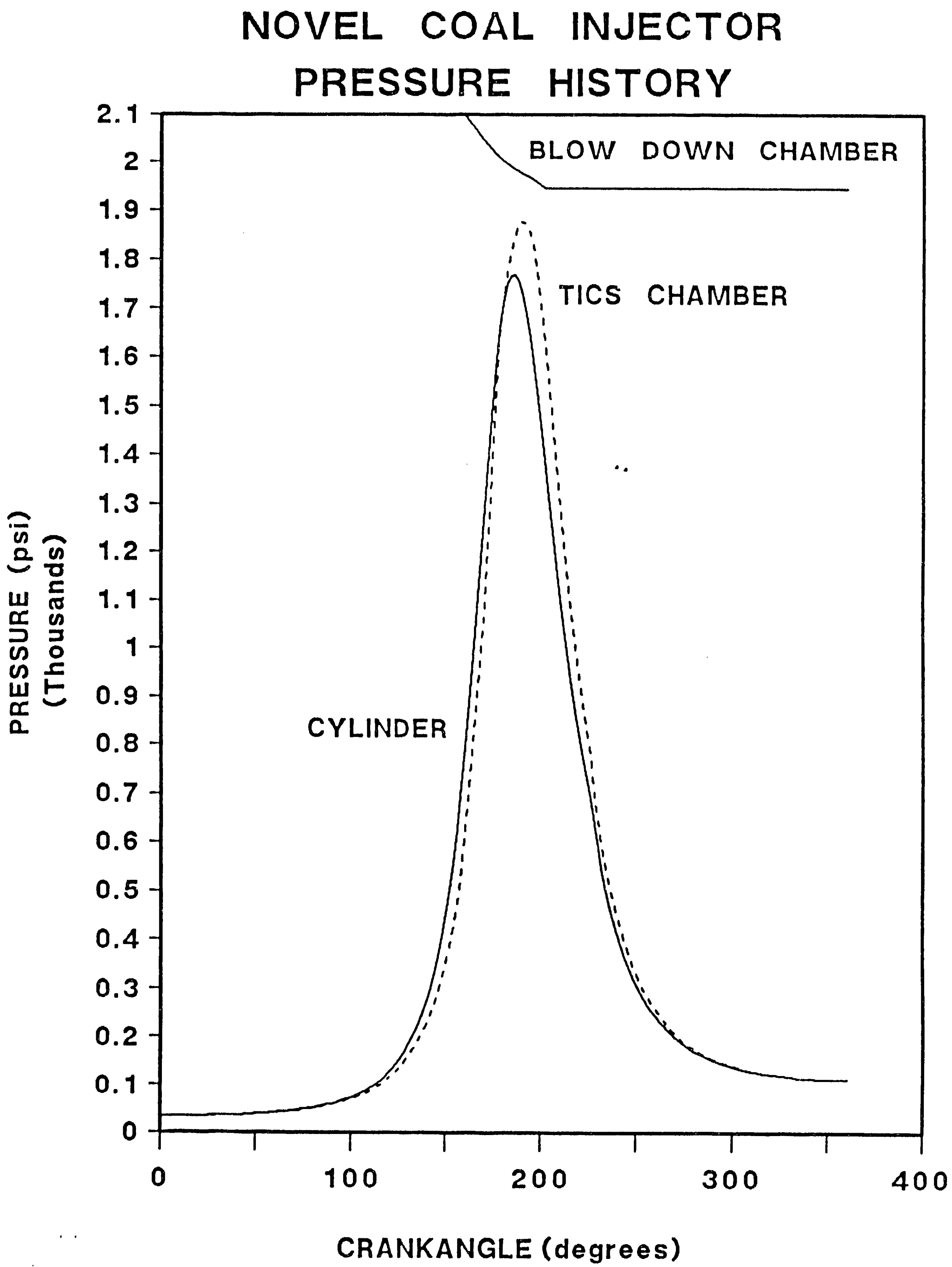

NOVEL COAL INJECTOR
PRESSURE HISTORY
BLOW DOWN CHAMBER
TICS CHAMBER
CYLINDER
PRESSURE (psi)
(Thousands)
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
CRANKANGLE (degrees)

Figure 3

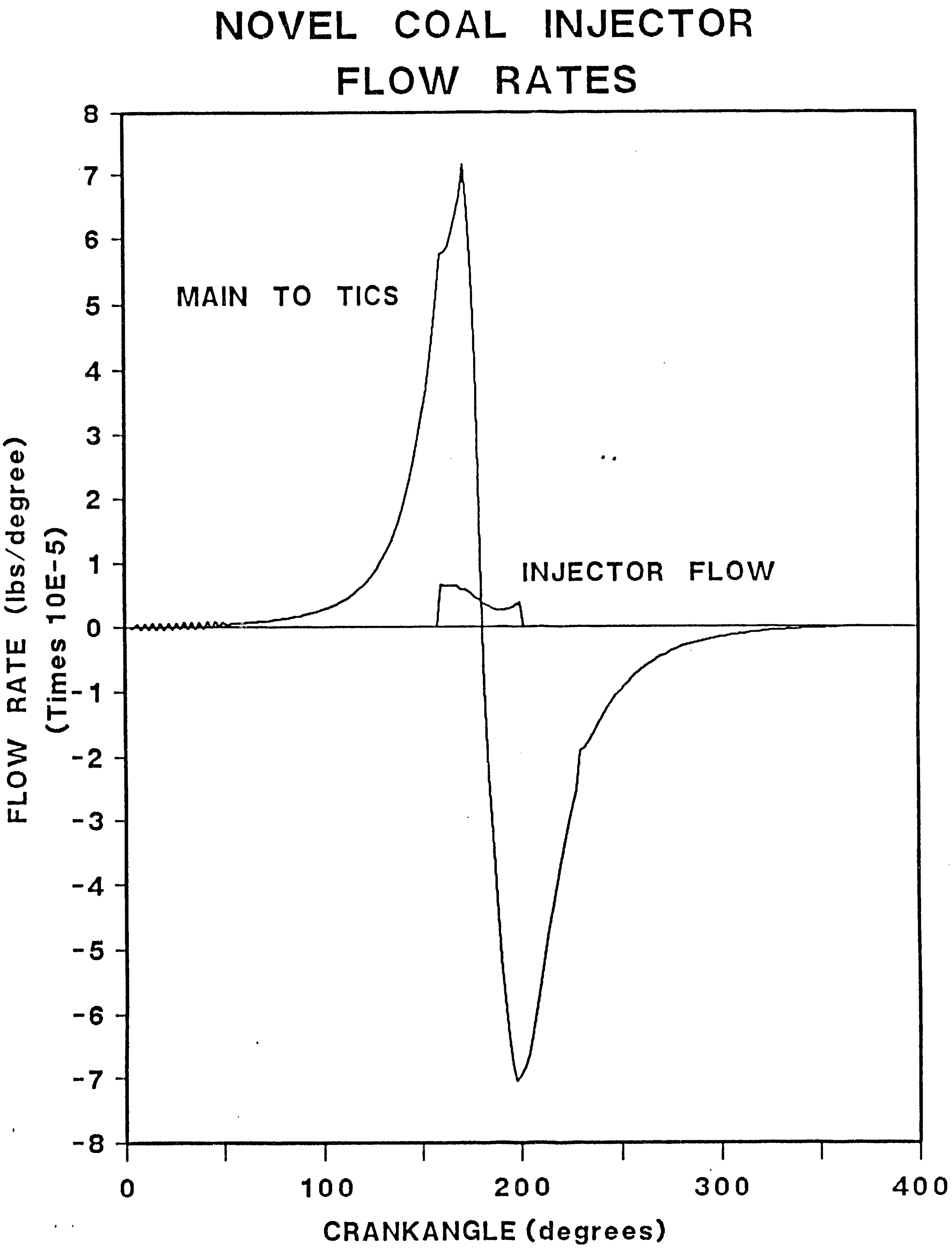

NOVEL COAL INJECTOR
FLOW RATES
MAIN TO TICS
INJECTOR FLOW
FLOW RATE (lbs/degree)
(Times 10E-5)
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
0
100
200
300
400
CRANKANGLE (degrees)

Figure 4

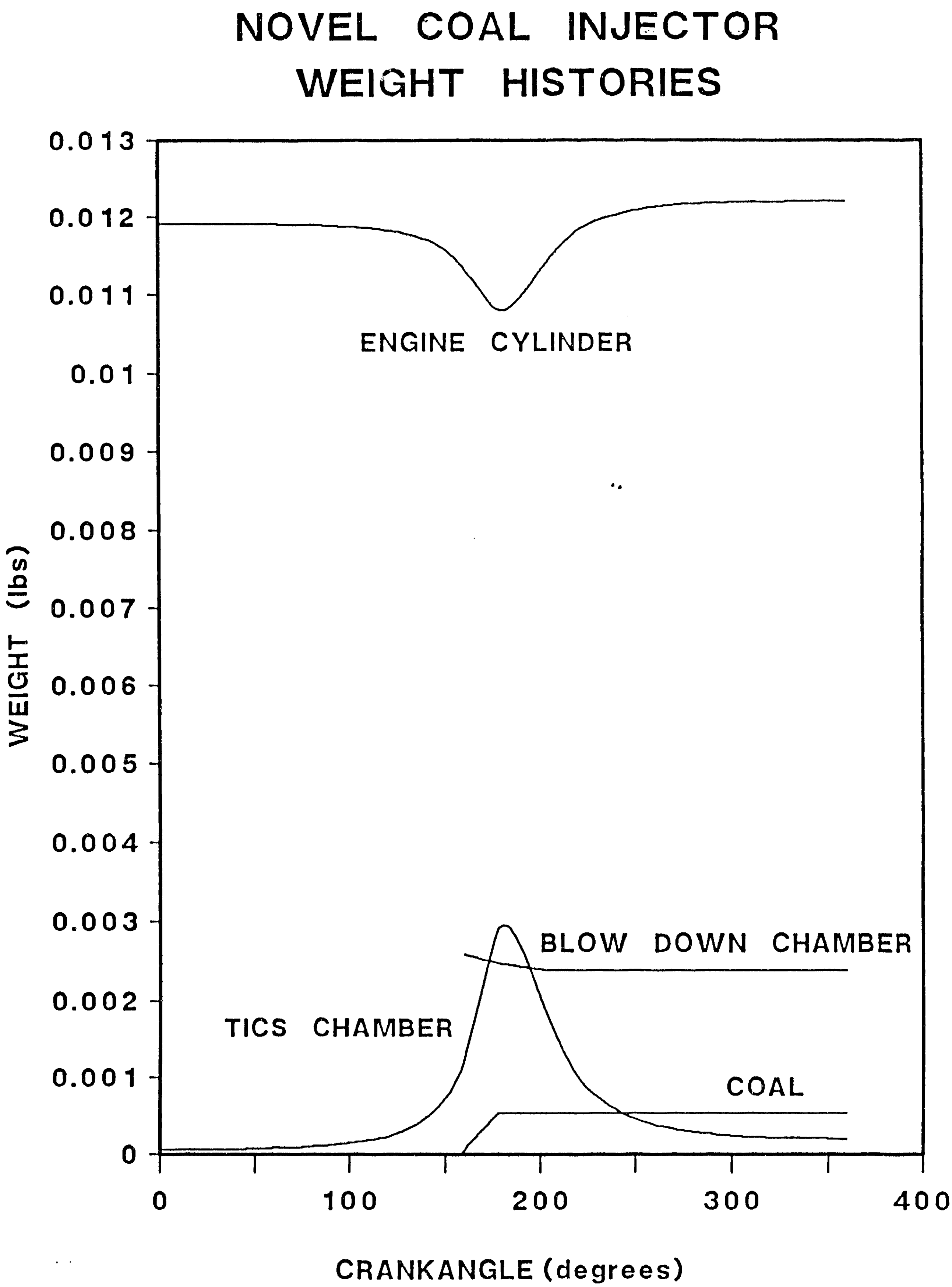

NOVEL COAL INJECTOR
WEIGHT HISTORIES
0.013
0.012
0.011
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
WEIGHT (lbs)
ENGINE CYLINDER
BLOW DOWN CHAMBER
TICS CHAMBER
COAL
0
100
200
300
400
CRANKANGLE (degrees)

Figure 5

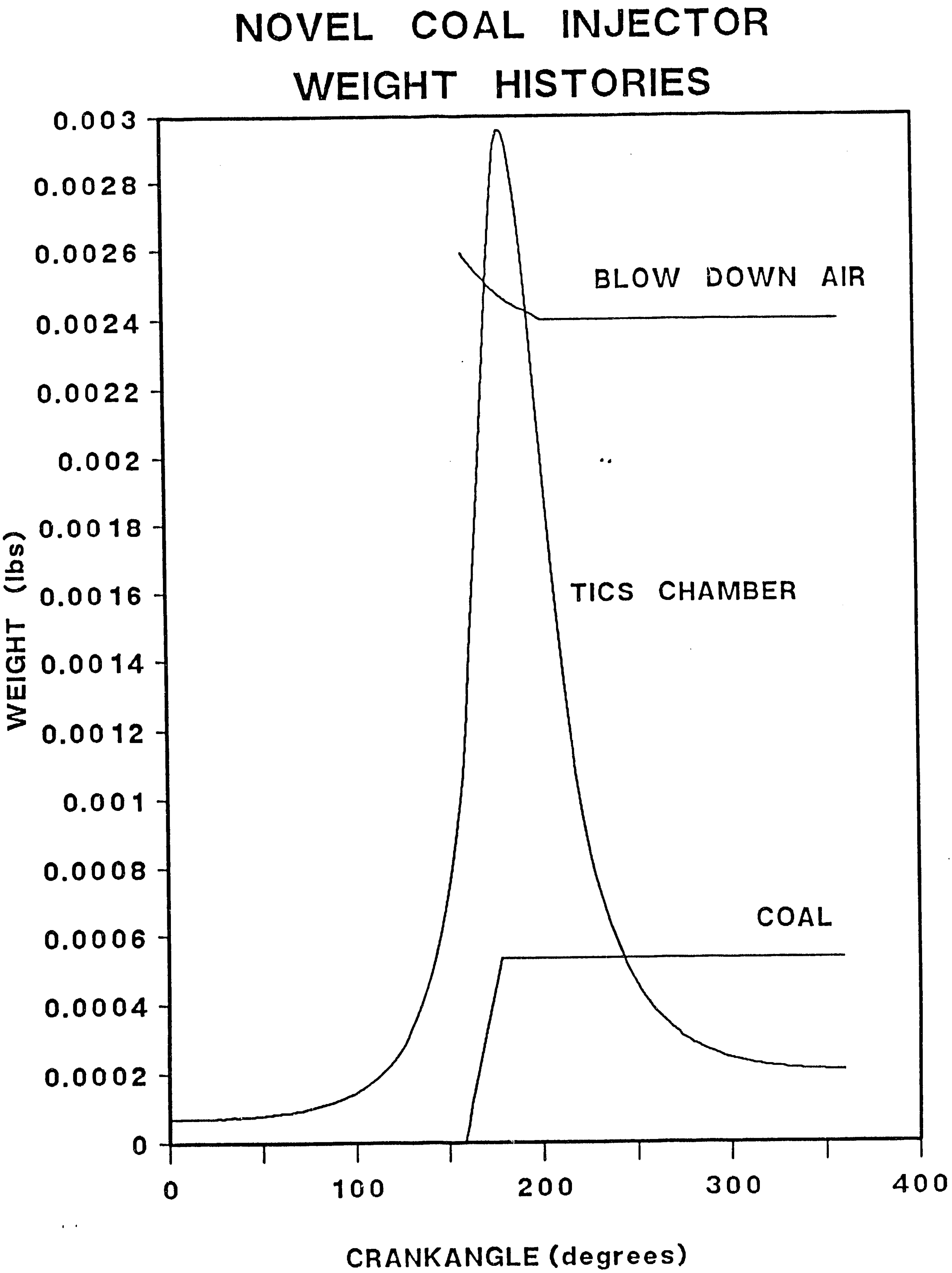

NOVEL COAL INJECTOR
WEIGHT HISTORIES
0.003
0.0028
0.0026
0.0024
0.0022
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
WEIGHT (lbs)
BLOW DOWN AIR
TICS CHAMBER
COAL
0
100
200
300
400
CRANKANGLE (degrees)

Figure 6

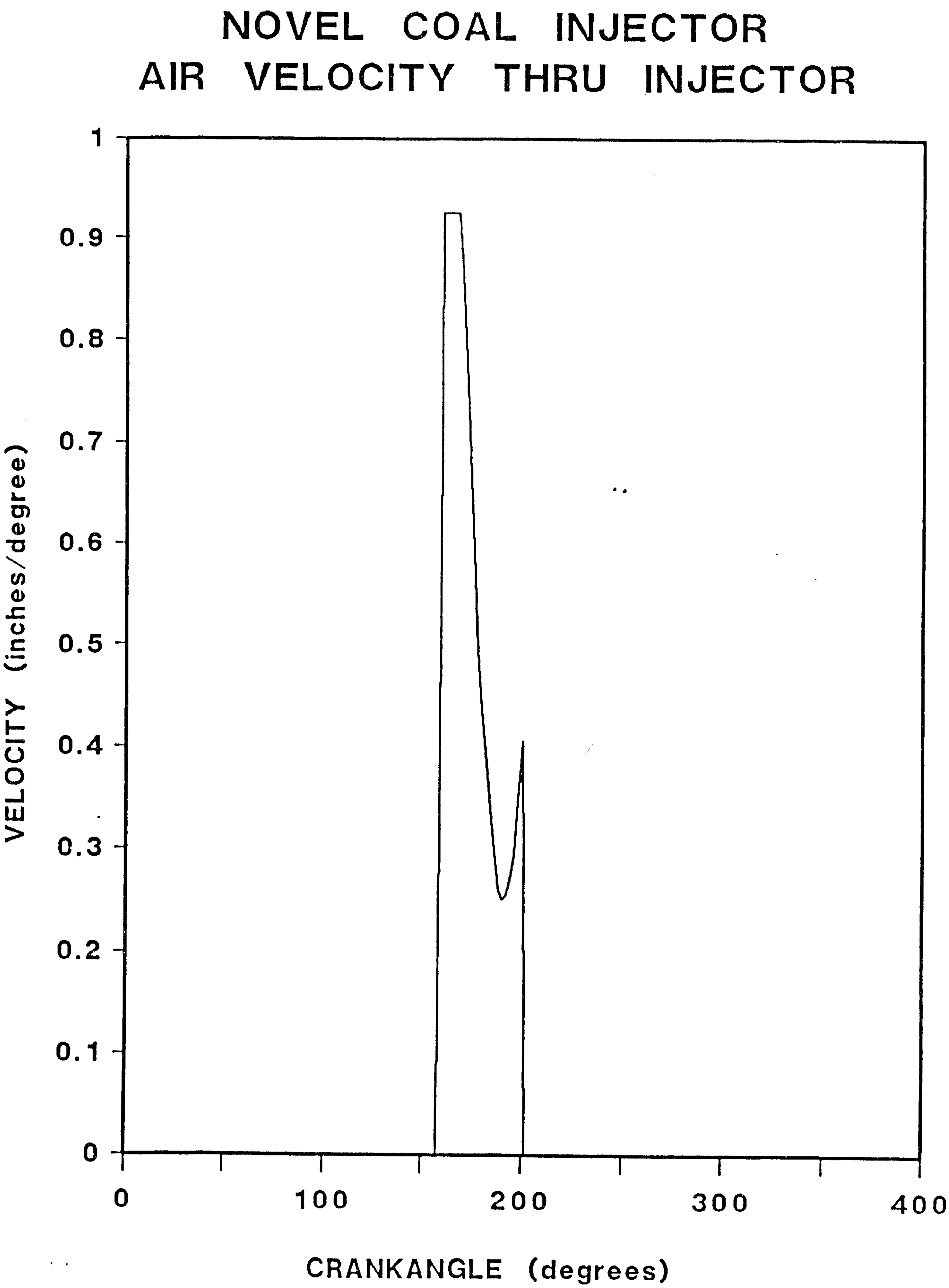

NOVEL COAL INJECTOR
AIR VELOCITY THRU INJECTOR
VELOCITY (inches/degree)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
CRANKANGLE (degrees)

Figure 7

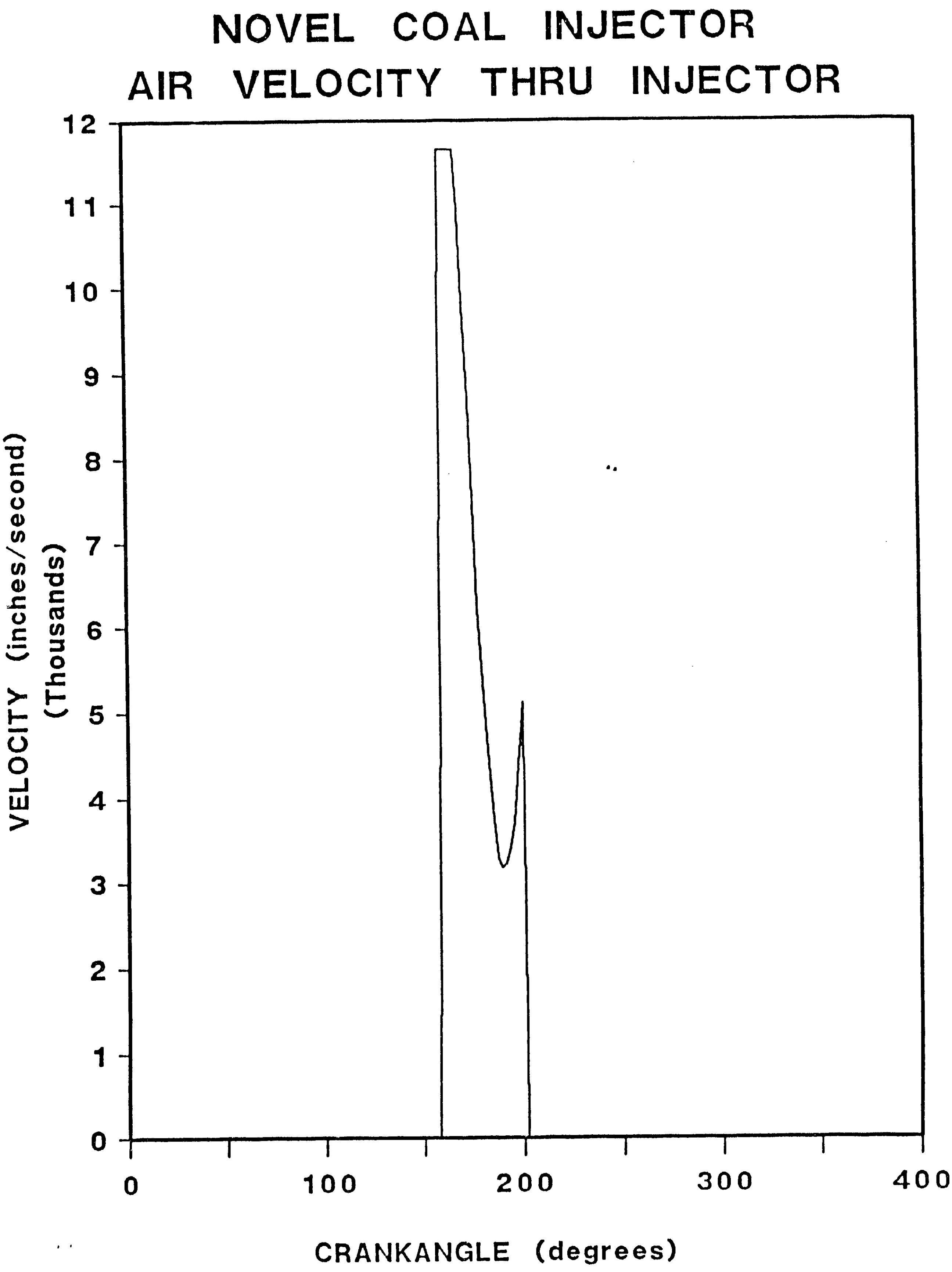

NOVEL COAL INJECTOR
AIR VELOCITY THRU INJECTOR
VELOCITY (inches/second)
(Thousands)
12
11
10
9
8
7
6
5
4
3
2
1
0
0
100
200
300
400
CRANKANGLE (degrees)

Figure 8

NOVEL COAL INJECTOR

AIR COMPRESSOR POWER REQUIREMENT

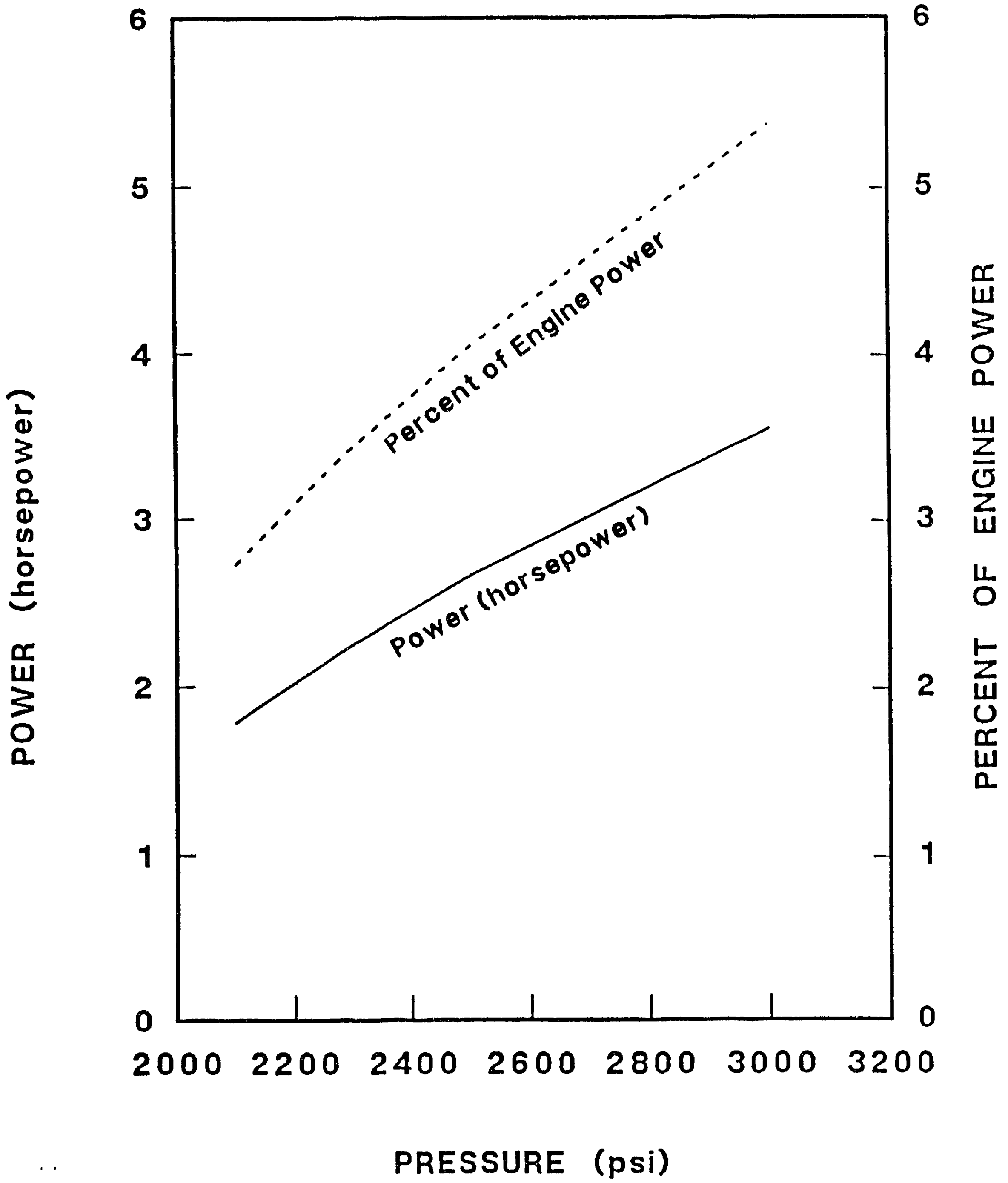


Figure 9

NOVEL COAL INJECTOR

AIR COMPRESSOR POWER REQUIREMENT

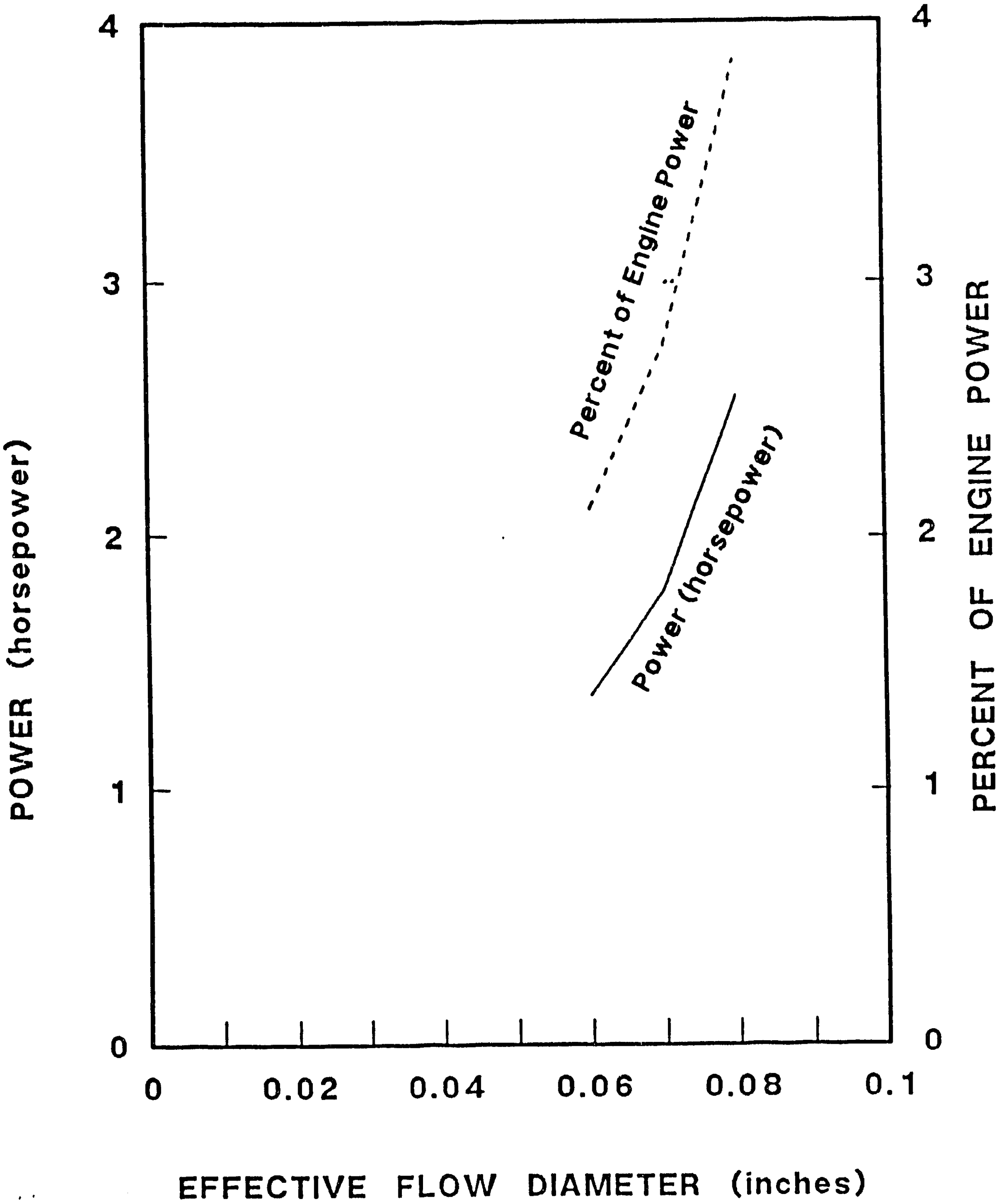


Figure 10

Point	Date	Time of Day	Injection Timing Position	RPM	Torque (N*m)	Torque (lbf*ft)	BHP (kW)	BHP (hp)	BMEP (kPa)	BMEP (psi)	Fuel Flow (kg)	Fuel Flow (lbs)
1	10/7/91	3:20	Pin # 4	1100	71.315	52.6	8.2152	11.017	383.655	55.644	0.113	0.250
2	10/7/91	3:50	Pin # 4	1100	68.468	50.5	7.8872	10.577	368.338	53.423	0.113	0.250
3	10/7/91	4:30	Pin # 4	1100	126.903	93.6	14.6187	19.604	682.701	99.017	0.113	0.250
4	10/22/91	3:10	Pin # 4	1700	113.887	84.0	20.2753	27.190	612.681	88.861	0.113	0.250
5	10/22/91	3:32	Pin # 4	1700	117.955	87.0	20.9994	28.161	634.562	92.035	0.113	0.250
6	11/4/91	2:05	Pin # 4	1500	70.230	51.8	11.0322	14.794	377.820	54.798	0.113	0.250
7	11/4/91	2:18	Pin # 4	.1500	69.553	51.3	10.9257	14.652	374.173	54.269	0.113	0.250
8	11/4/91	2:36	Pin # 4	1500	72.942	53.8	11.4581	15.366	392.407	56.914	0.113	0.250
9	11/4/91	3:02	Pin # 4	1500	123.513	91.1	19.4021	26.019	664.467	96.372	0.113	0.250
10	11/4/91	3:15	Pin # 4	1500	125.276	92.4	19.6790	26.390	673.949	97.747	0.113	0.250
11	11/4/91	3:30	Pin # 4	1500	122.564	90.4	19.2530	25.819	659.361	95.632	0.113	0.250
12	11/4/91	4:06	Pin # 4	1500	42.572	31.4	6.6874	8.968	229.026	33.217	0.113	0.250
13	11/4/91	4:20	Pin # 4	1500	33.759	24.9	5.3031	7.112	181.616	26.341	0.113	0.250
14	11/5/91	11:15	Pin # 4	1700	72.535	53.5	12.9134	17.317	390.219	56.596	0.113	0.250
15	11/5/91	11:26	Pin # 4	1700	77.552	57.2	13.8065	18.515	417.206	60.510	0.113	0.250
16	11/5/91	11:55	Pin # 4	1700	78.230	57.7	13.9272	18.677	420.853	61.039	0.113	0.250
17	11/6/91	1:00	Pin # 4	1700	73.213	54.0	13.0341	17.479	393.866	57.125	0.113	0.250
18	11/6/91	1:28	Pin # 4	1700	119.988	88.5	21.3615	28.646	645.503	93.622	0.113	0.250
19	11/6/91	1:55	Pin # 4	1700	125.140	92.3	22.2787	29.876	673.219	97.642	0.170	0.375
20	11/6/91	2:15	Pin # 4	1700	129.072	95.2	22.9787	30.815	694.371	100.709	0.170	0.375
21	11/6/91	2:38	Pin # 4	1700	123.242	90.9	21.9408	29.423	663.008	96.161	0.170	0.375
22	11/7/91	2:25	Pin # 1	1700	67.993	50.150	12.1048	16.233	365.785	53.052	0.113	0.250
23	11/7/91	2:25	Pin # 1	1700	70.230	51.8	12.5031	16.767	377.820	54.798	0.113	0.250
24	11/7/91	3:25	Pin # 1	1700	127.445	94.0	22.6890	30.427	685.619	99.440	0.170	0.375
25	11/7/91	4:00	Pin # 1	1700	143.783	106.1	25.5976	34.327	773.509	112.187	0.170	0.375
26	11/7/91	4:15	Pin # 1	1700	141.884	104.7	25.2597	33.874	763.298	110.706	0.170	0.375
27	11/8/91	10:45	Pin # 1	1500	67.248	49.6	10.5636	14.166	361.773	52.470	0.113	0.250
28	11/8/91	11:15	Pin # 1	1500	119.988	88.5	18.8484	25.276	645.503	93.622	0.113	0.250
29	11/8/91	11:40	Pin # 1	1500	154.968	114.3	24.3432	32.645	833.683	120.915	0.113	0.250
30	11/8/91	3:02	Pin # 1	1700	70.841	52.3	12.6117	16.913	381.102	55.274	0.113	0.250
31	11/8/91	3:40	Pin # 1	1700	124.123	91.6	22.0977	29.633	667.749	96.848	0.170	0.375
32	11/8/91	4:10	Pin # 1	1700	141.003	104.0	25.1028	33.663	758.557	110.019	0.170	0.375
33	12/20/91	10:40	Pin # 1	1700	71.247	52.6	12.6841	17.010	383.290	55.591	0.113	0.250
34	12/20/91	10:55	Pin # 1	1700	122.429	90.3	21.7960	29.229	658.632	95.526	0.170	0.375
35	12/20/91	11:25	Pin # 1	1700	141.071	104.1	25.1148	33.680	758.922	110.072	0.170	0.375
36	12/23/91	2:50	Pin # 1	1900	43.250	31.9	8.6056	11.540	232.673	33.746	0.170	0.375
37	12/23/91	3:10	Pin # 1	1900	70.095	51.7	13.9471	18.703	377.090	54.692	0.170	0.375
38	12/23/91	3:30	Pin # 1	1900	117.344	86.6	23.3486	31.311	631.280	91.559	0.170	0.375
39	12/23/91	3:45	Pin # 1	1900	141.478	104.4	28.1505	37.750	761.110	110.389	0.170	0.375
40	2/11/92	3:35	Pin # 1	1500	119.582	88.2	18.7845	25.190	643.315	93.304	0.170	0.375
41	2/19/92	3:45	Pin # 1	1500	118.971	87.8	18.6886	25.062	640.033	92.828	0.170	0.375
42	2/20/92	1:40	Pin # 1	1500	119.717	88.3	18.8058	25.219	644.044	93.410	0.170	0.375
43	2/21/92	10:00	Pin # 1	1500	119.853	88.4	18.8271	25.248	644.774	93.516	0.170	0.375
44	2/21/92	2:20	Pin # 1	1500	119.988	88.5	18.8484	25.276	645.503	93.622	0.170	0.375
45	2/25/92	4:10	Pin # 1	1500	118.768	87.6	18.6567	25.019	638.938	92.670	0.170	0.375
46	2/26/92	10:06	Pin # 1	1500	156.188	115.2	24.5348	32.902	840.248	121.867	0.170	0.375
47	2/26/92	11:10	Pin # 1	1700	122.158	90.1	21.7477	29.164	657.173	95.314	0.170	0.375
48	2/26/92	2:22	Pin # 1	1700	142.359	105.0	25.3441	33.987	765.851	111.077	0.170	0.375
49	2/26/92	4:05	Pin # 1	1900	116.870	86.2	23.2541	31.184	628.727	91.189	0.170	0.375
50	2/27/92	3:45	Pin # 1	1900	144.528	106.6	28.7574	38.564	777.521	112.769	0.170	0.375

Sample Time (min)	Fuel Flow (kg/hr)	Fuel Flow (lbs/hr)	BSFC (kg/kWh)	BSFC (lb/bhph)	Deltap in/H20	Orifice Pressure (in Hg)	Tank Pressure (in Hg)	Mass airflow (lbs/hr)	Mass airflow (kg/hr)	Air/Fuel ratio (x:1)	Exhaust Flow (kg/hr)	Exhaust Flow (kg/min)
3.1855	2.136	4.709	0.260	0.427	7.0	5.4	5.10	177.3	80.4	37.7	82.6	1.4
3.2610	2.086	4.600	0.265	0.435	8.0	5.6	4.9	189.4	85.9	41.2	88.0	1.5
1.9135	3.556	7.839	0.243	0.400	8.4	9.7	9.30	204.9	92.9	26.1	96.5	1.6
1.4920	4.560	10.054	0.225	0.370	24.0	21.7	20.15	385.8	175.0	38.4	179.6	3.0
1.3995	4.862	10.718	0.232	0.381	25.9	25.8	24.20	415.1	188.3	38.7	193.1	3.2
2.2640	3.005	6.625	0.272	0:448	15.4	10.2	9.25	280.2	127.1	42.3	130.1	2.2
2.3120	2.943	6.488	0.269	0.443	14.5	10.2	9.20	271.0	122.9	41.8	125.9	2.1
2.2430	3.033	6.687	0.265	0.435	14.5	8.1	7.15	263.5	119.5	39.4	122.6	2.0
1.4735	4.617	10.180	0.238	0.391	16.3	19.3	18.25	317.4	143.9	31.2	148.6	2.5
1.4245	4.776	10.530	0.243	0.399	15.1	15.9	14.95	295.4	134.0	28.1	138.8	2.3
1.4595	4.662	10.277	0.242	0.398	17.3	21.4	20.25	334.5	151.7	32.6	156.4	2.6
3.2965	2.064	4.550	0.309	0.507	15.3	8.0	6.90	268.2	121.7	58.9	123.7	2.1
3.7583	1.810	3.991	0.341	0.561	17.6	10.0	9.00	295.9	134.2	74.1	136.0	2.3
2.0250	3.360	7.407	0.260	0.428	21.2	14.8	13.55	343.0	155.6	46.3	158.9	2.6
1.9013	3.579	7.889	0.259	0.426	18.2	10.9	9.85	303.7	137.7	38.5	141.3	2.4
1.8517	3.674	8.101	0.264	0.434	17.9	8.8	7.75	293.0	132.9	36.2	136.6	2.3
1.9457	3.497	7.709	0.268	0.441	19.0	10.3	9.15	299.9	136.0	38.9	139.5	2.3
1.3337	5.101	11.247	0.239	0.393	25.0	26.0	24.40	404.3	183.4	35.9	188.5	3.1
1.8557	5.500	12.125	0.247	0.406	21.0	20.8	19.45	354.7	160.9	29.3	166.4	2.8
1.7435	5.854	12.905	0.255	0.419	20.4	19.4	18.10	341.2	154.8	26.4	160.6	2.7
1.9213	5.312	11.711	0.242	0.398	27.2	31.5	29.80	439.3	199.3	37.5	204.6	3.4
1.9776	3.441	7.585	0.284	0.467	21.1	14.5	13.1	340.6	154.5	44.9	157.9	2.6
2.0397	3.336	7.354	0.267	0.439	22.2	14.5	13.1	344.8	156.4	46.9	159.8	2.7
1.9220	5.310	11.707	0.234	0.385	26.8	31.5	29.9	444.1	201.5	37.9	206.8	3.4
1.6607	6.146	13.549	0.240	0.395	23.4	31.3	31.30	414.0	187.8	30.6	194.0	3.2
1.6723	6.103	13.454	0.242	0.397	25.1	35.1	33.50	444.7	201.7	33.1	207.8	3.5
2.4670	2.758	6.080	0.261	0.429	15.6	9.6	9.90	279.0	126.6	45.9	129.3	2.2
1.4730	4.619	10.183	0.245	0.403	15.5	15.9	14.60	297.5	134.9	29.2	139.6	2.3
1.1940	5.698	12.563	0.234	0.385	16.9	23.9	22.80	335.3	152.1	26.7	157.8	2.6
2.0437	3.329	7.340	0.264	0.434	21.9	14.6	13.10	349.8	158.7	47.7	162.0	2.7
1.9163	5.326	11.741	0.241	0.396	26.6	31.4	29.60	449.3	203.8	38.3	209.1	3.5
1.6750	6.093	13.433	0.243	0.399	25.4	35.0	33.00	450.0	204.1	33.5	210.2	3.5
2.0980	3.243	7.150	0.256	0.420	21.2	14.4	13.05	338.4	153.5	47.3	156.7	2.6
2.0008	5.101	11.246	0.234	0.385	28.6	31.8	29.50	464.1	210.5	41.3	215.6	3.6
1.7200	5.934	13.081	0.236	0.388	25.2	34.2	32.55	442.3	200.6	33.8	206.6	3.4
3.7630	2.712	5.979	0.315	0.518	25.5	13.5	11.85	367.3	166.6	61.4	169.3	2.8
2.7330	3.734	8.233	0.268	0.440	28.4	20.3	18.70	416.1	188.7	50.5	192.5	3.2
1.7180	5.940	13.097	0.254	0.418	29.0	32.1	30.10	467.5	212.1	35.7	218.0	3.6
1.5100	6.759	14.901	0.240	0.395	32.5	40.9	38.05	526.6	238.9	35.3	245.6	4.1
2.3297	4.381	9.658	0.233	0.383	15.7	15.9	14.50	301.0	136.5	31.2	140.9	2.3
2.3527	4.338	9.564	0.232	0.382	16.5	16.0	14.85	305.6	138.6	32.0	143.0	2.4
2.3073	4.423	9.752	0.235	0.387	16.0	15.8	14.80	300.1	136.1	30.8	140.5	2.3
2.2783	4.479	9.876	0.238	0.391	15.9	15.5	14.65	300.0	136.1	30.4	140.6	2.3
2.2597	4.516	9.957	0.240	0.394	15.7	15.5	14.45	295.5	134.0	29.7	138.6	2.3
2.2927	4.451	9.814	0.239	0.392	16.2	15.8	14.80	301.8	136.9	30.7	141.3	2.4
1.8563	5.498	12.121	0.224	0.368	17.3	24.3	23.20	341.7	155.0	28.2	160.5	2.7
2.0140	5.067	11.172	0.233	0.383	28.4	31.5	29.45	467.2	211.9	41.8	217.0	3.6
1.7053	5.985	13.194	0.236	0.388	24.4	34.7	32.65	441.7	200.3	33.5	206.3	3.4
1.7577	5.806	12.801	0.250	0.410	29.6	31.8	30.35	473.1	214.6	37.0	220.4	3.7
1.4760	6.914	15.244	0.240	0.395	30.7	39.7	38.10	519.3	235.5	34.1	242.5	4.0

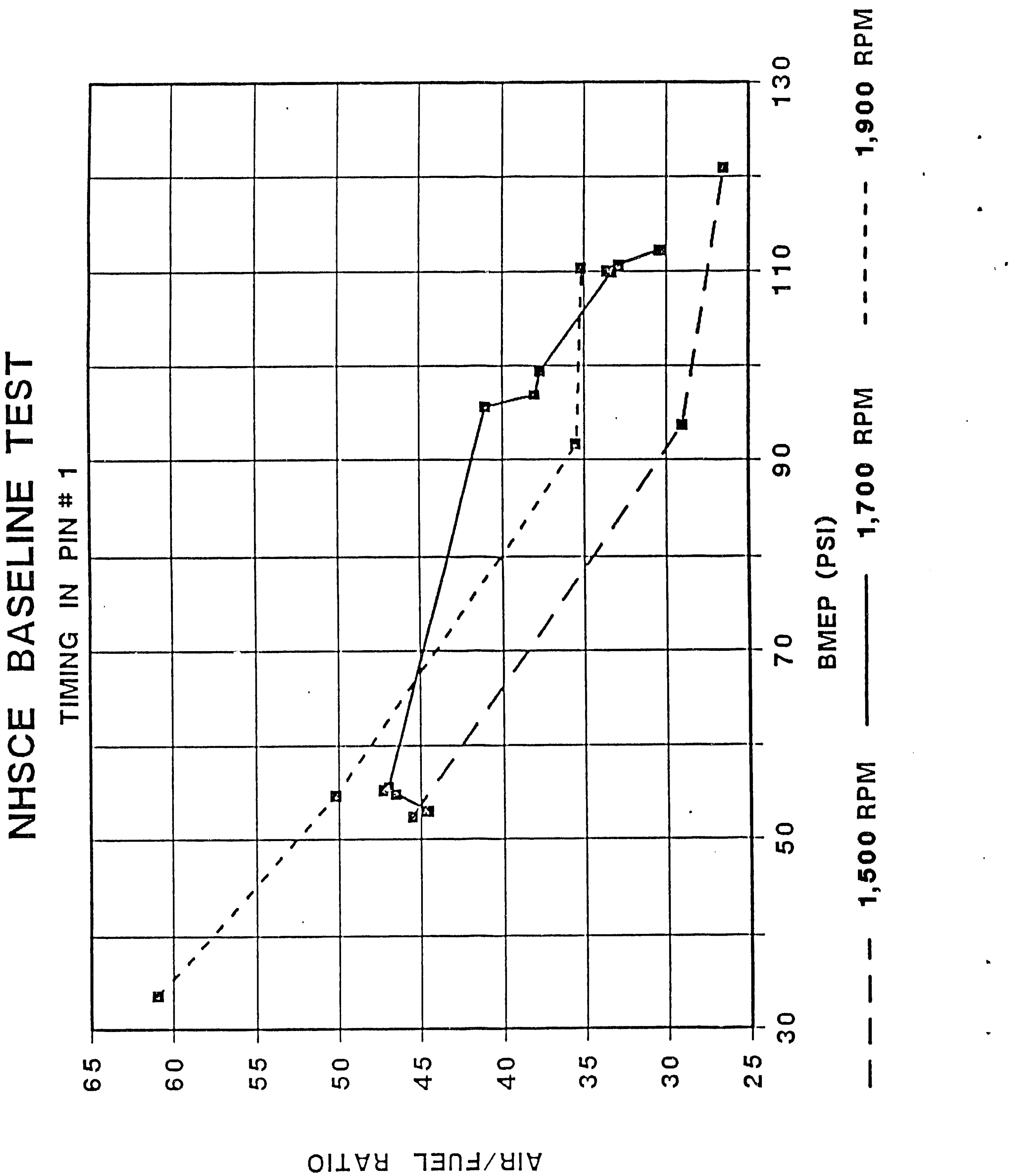
Exhaust pres (kPa)	Exhaust pres in/hg	Blowby pres (Pa)	Blowby pres in/H20	Oil Piston (psig)	Oil Crank (psig)	Fuel Rail (psig)	Baro\Pres (kPa)	Baro\Pres inchs-hg	Baro\Pres (psi)	Humidity (%)	Tank Temp (C)	Tank Temp (F)
17.61	5.2	49.82	0.2	60	55	14	101.355	29.93	14.70	26	48.89	120.0
15.92	4.7	24.91	0.1	60	55	14	101.253	29.9	14.69	25	49.56	121.2
24.72	7.3	24.91	0.1	60	55	28	101.253	29.9	14.69	25	47.39	117.3
57.06	16.9	174.36	0.7	60	50	53	100.610	29.71	14.59	41	72.50	162.5
65.87	19.5	199.26	0.8	60	50	55	100.576	29.70	14.59	39	77.94	172.3
33.86	10.0	24.91	0.1	50	55	23	101.931	30.10	14.78	17	61.50	142.7
36.23	10.7	24.91	0.1	50	55	23	101.931	30.10	14.78	17	62.83	145.1
21.33	6.3	24.91	0.1	50	55	22	101.931	30.10	14.78	18	62.39	144.3
65.36	19.3	49.82	0.2	50	52	46	101.931	30.10	14.78	18	79.28	174.7
54.86	16.2	24.91	0.1	60	50	45	101.931	30.10	14.78	18	80.56	177.0
60.28	17.8	49.82	0.2	60	50	47	101.931	30.10	14.78	19	82.56	180.6
25.40	7.5	24.91	0.1	40	55	14	101.931	30.10	14.78	15	51.94	125.5
28.11	8.3	49.82	0.2	40	55	13	101.931	30.10	14.78	14	51.72	125.1
47.41	14.0	49.82	0.2	55	55	30	101.592	30.00	14.73	19	75.56	168.0
34.20	10.1	24.91	0.1	55	53	28	101.592	30.00	14.73	20	73.83	164.9
28.45	8.4	24.91	0.1	55	51	27	101.592	30.00	14.73	20	73.61	164.5
33.86	10	24.91	0.1	60	55	27	96.512	28.50	14.00	22	76.50	169.7
67.05	19.8	49.82	0.2	60	56	57	96.174	28.40	13.95	21	97.39	207.3
58.25	17.2	74.72	0.3	60	55	56	96.174	28.40	13.95	21	97.78	208.0
55.88	16.5	74.72	0.3	95	52	56	96.174	28.40	13.95	21	99.00	210.2
74.16	21.9	74.72	0.3	58	55	60	96.174	28.40	13.95	21	102.11	215.8
61.46	18.15	74.72	0.3	60	55	28	101.592	30.00	14.73	27	75.11	167.2
47.41	14.00	49.82	0.2	60	55	28	101.592	30.00	14.73	23	76.00	168.8
99.05	29.25	74.72	0.3	60	55	62	101.592	30.00	14.73	20	101.00	213.8
96.17	28.4	74.72	0.3	60	55	62	101.592	30.00	14.73	26	119.17	246.5
102.95	30.4	74.72	0.3	60	55	64	101.592	30.00	14.73	32	122.39	252.3
35.90	10.6	24.91	0.1	60	55	20	102.202	30.18	14.82	15	67.44	153.4
54.69	16.2	24.91	0.1	60	53	44	102.168	30.17	14.82	14	81.00	177.8
77.21	22.8	49.82	0.2	80	55	55	102.100	30.15	14.81	13	94.83	202.7
48.09	14.2	74.72	0.3	45	55	25	101.931	30.10	14.78	12	76.25	169.3
98.54	29.1	74.72	0.3	65	55	60	101.931	30.10	14.78	12	102.39	216.3
107.01	31.6	74.72	0.3	65	55	68	101.931	30.10	14.78	14	123.33	254.0
50.29	14.85	49.82	0.2	45	55	27	97.375	28.75	14.12	39	78.61	173.5
104.98	31.00	74.72	0.3	65	55	59	97.375	28.75	14.12	38	83.33	182.0
106.16	31.35	74.72	0.3	65	55	69	97.375	28.75	14.12	34	122.56	252.6
40.81	12.1	74.72	0.3	60	53	21	97.375	28.75	14.12	35	71.00	159.8
60.11	17.8	74.72	0.3	60	51	35	97.375	28.75	14.12	32	86.83	188.3
105.15	31.1	99.63	0.4	60	50	66	97.375	28.75	14.12	36	119.28	246.7
120.39	35.6	99.63	0.4	60	45	75	97.375	28.75	14.12	28	132.44	270.4
47.41	14.0	49.82	0.2	60	52	40	100.576	29.70	14.59	66	81.67	179.0
45.38	13.4	24.91	0.1	60	52	41	99.222	29.30	14.39	33	81.39	178.5
49.10	14.5	24.91	0.1	60	55	42	99.899	29.50	14.49	34	81.89	179.4
46.39	13.7	24.91	0.1	60	55	42	100.237	29.60	14.54	35	81.50	178.7
46.39	13.7	24.91	0.1	60	55	41	100.068	29.55	14.51	36	81.11	178.0
50.63	15.0	49.82	0.2	60	55	40	99.222	29.30	14.39	30	81.11	178.0
75.86	22.4	49.82	0.2	60	52	58	99.052	29.25	14.37	32	94.58	202.3
96.17	28.4	74.72	0.3	60	52	60	99.052	29.25	14.37	42	84.89	184.8
111.58	33.0	0.00					98.815	29.18	14.33	32	124.72	256.5
100.24	29.6	74.72	0.3	60	52	60	98.815	29.18	14.33	36	122.44	252.4
127.16	37.6	99.63	0.4	60	52	77	99.052	29.25	14.37	50	137.06	278.7

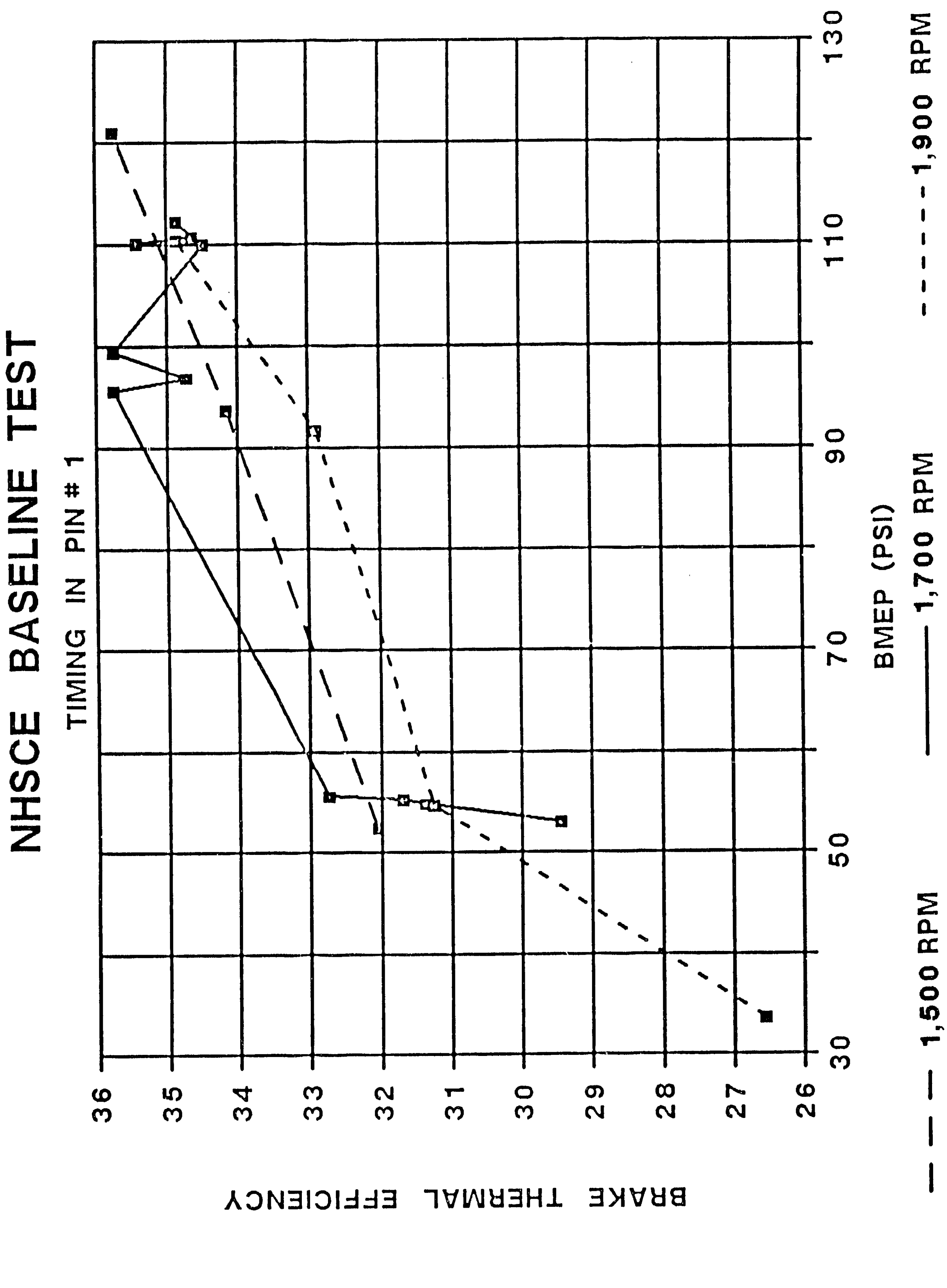
Intake Orifice (C)	Intake Orifice (F)	Exhaust Temp (C)	Exhaust Temp (F)	Oil Temp (C)	Oil Temp (F)	Liner Exhaust (F)	Liner Intake (F)	Emission CO (ppm)	Emission CO gm/bhphr	Emission CO (gm/kWhr)	Emission CO lbs/MMBtu	Emission CO2 (%)
16.67	62	398.89	750	82.22	180	292	305	211	1.5	2.1	0.43	5.7
18.33	65	400.56	753	92.22	198	307	320	215	1.7	2.3	0.47	5.4
18.89	66	540.00	1004	90.56	195	331	360	955	4.5	6.1	1.35	8.27
32.33	90.2	520.58	969.04	94.44	202	354	389	327	2.1	2.8	0.67	5.7
34.33	93.8	519.44	967	102.78	217	373	410	300	2.0	2.7	0.62	5.4
18.17	64.7	432.22	810	88.89	192	313	336	201	1.7	2.3	0.45	4.6
19.67	67.4	440.00	824	89.44	193	318	326	201	1.7	2.2	0.45	4.5
20.44	68.8	447.22	837	91.11	196	326	351	240	1.9	2.5	0.51	4.7
21.50	70.7	575.00	1067	95.00	203	374	416	705	3.9	5.2	1.18	6.3
20.17	68.3	626.11	1159	95.56	204	400	451	1018	5.2	6.9	1.54	7.1
20.22	68.4	544.44	1012	96.67	206	383	418	450	2.6	3.5	0.79	5.7
25.11	77.2	343.33	650	91.11	196	296	313	152	2.0	2.7	0.48	3.1
24.00	75.2	297.78	568	90.00	194	286	304	123	2.3	3.0	0.48	2.4
24.33	75.8	447.78	838	93.33	200	325	352	197	1.7	2.3	0.49	4.4
23.94	75.1	501.67	935	94.44	202	345	371	280	2.1	2.8	0.58	5.0
24.56	76.2	517.78	964	96.11	205	355	381	375	2.7	3.6	0.73	5.5
29.00	84.2	484.44	904	92.78	199	335	362	248	1.9	2.6	0.52	4.9
33.22	91.8	527.78	982	97.22	207	381	411	379	2.4	3.2	0.73	5.4
28.50	83.3	621.11	1150	93.33	200	406	443	1377	7.4	9.9	2.18	6.6
34.83	94.7	660.56	1221	97.22	207	421	457	1433	7.2	9.7	2.05	7.5
37.17	98.9	509.44	949	93.89	201	391	410	308	2.1	2.8	0.62	5.0
25.22	77.4	458.33	857	92.22	198	315	340	213	2.0	2.7	0.51	4.4
32.33	90.2	440.00	824	94.44	202	325	342	215.5	2.0	2.7	0.54	4.1
34.56	94.2	538.89	1002	94.44	202	371	393	244	1.6	2.1	0.50	5.4
35.22	95.4	633.33	1172	95.56	204	420	448	822	4.5	6.0	1.35	6.6
31.11	88	599.44	1111	86.11	187	417	444	435	2.6	3.5	0.77	5.9
20.22	68.4	422.22	792	95.56	204	304	329	184	1.6	2.2	0.45	4.3
23.28	73.9	600.00	1112	91.67	197	374	413	688	3.7	4.9	1.09	7.1
25.44	77.8	643.33	1190	93.89	201	403	439	1209	5.6	7.6	1.75	7.9
21.67	71	421.67	791	90.00	194	315	331	195.5	1.8	2.4	0.50	4.1
25.50	77.9	531.67	989	93.33	200	370	396	246	1.7	2.3	0.50	5.1
27.56	81.6	595.00	1103	94.44	202	405	432	544.5	3.3	4.4	0.98	5.8
21.28	70.3	437.22	819	90.56	195	317	341	189	1.7	2.3	0.48	4.1
22.89	73.2	503.89	939	87.78	190	336	376	197.5	1.4	1.9	0.44	4.8
25.67	78.2	582.78	1081	91.11	196	389	430	498	3.0	4.0	0.91	6.2
21.22	70.2	365.56	690	90.56	195	285	306	124	1.8	2.4	0.40	2.7
23.11	73.6	432.22	810	96.11	205	324	348	208	2.1	2.8	0.56	3.7
24.39	75.9	588.89	1092	105.56	222	388	426	455	3.1	4.1	0.87	5.4
27.44	81.4	613.33	1136	115.56	240	423	465	549	3.5	4.6	1.04	5.7
17.17	62.9	559.44	1039	98.89	210	371	407	408	2.2	3.0	0.69	18.4
21.39	70.5	545.56	1014	91.67	197	379	386	329	1.8	2.4	0.57	6.7
22.50	72.5	570.00	1058	90.00	194	337	393	444.5	2.4	3.2	0.74	7.1
19.56	67.2	566.11	1051	92.78	199	342	406	465	2.5	3.4	0.76	7.2
25.00	77	545.56	1014	93.89	201	341	395	497	2.6	3.5	0.80	7.4
22.56	72.6	551.11	1024	91.11	196	326	387	554	3.0	4.1	0.92	6.8
18.33	65	616.67	1142	92.22	198	381	436	795.5	3.8	5.0	1.21	7.9
17.67	63.8	490.00	914	93.33	200	324	371	213	1.5	2.1	0.48	5.1
21.33	70.4	601.11	1114	95.56	204	390	429	388	2.3	3.1	0.70	6.3
23.83	74.9	572.78	1063	86.67	188	381	420	402	2.7	3.7	0.80	5.7
15.94	60.7	617.22	1143	96.67	206	378	427	562	3.4	4.6	1.03	6.4

Emission O2 (%)	Emission HC (ppm)	Emission HC gm/bhphr	Emission HC (gm/kWhr)	Emission HC lbs/MMBtu	Emission NOx (ppm)	Emission NOx gm/bhphr	Emission NOx (gm/kWhr)	Emission NOx lbs/MMBtu	Smoke (Bosch)	Cyl-Pres File Name	Vol Eff h.v.	Brake Ther.Eff 18512
12.9	50.0	0.2	0.2	0.05	620	7.4	9.9	2.05	1.6	1007bdf	80.52	32.18
13.0	70.0	0.3	0.4	0.08	545	7.2	9.6	1.97	1.5		85.86	31.63
8.9	110.0	0.3	0.3	0.08	451.5	3.5	4.7	1.05	2.2	1007cdf	82.61	34.40
16.0	70.0	0.2	0.3	0.07	859	9.0	12.1	2.90	1.8	1020adf	83.60	37.20
16.4	70.0	0.2	0.3	0.07	869	9.5	12.7	2.96	1.9	1020bdf	84.62	36.14
14.2	40.0	0.2	0.2	0.04	551	7.7	10.3	2.05	1.4	1104adf	84.99	30.72
14.2	50.0	0.2	0.3	0.06	543	7.4	9.9	1.99	1.5		82.64	31.06
13.4	50.0	0.2	0.3	0.05	557	7.0	9.5	1.93	1.7	1104bdf	84.66	31.61
11.7	250.0	0.7	0.9	0.21	1634	14.8	19.9	4.51	2.4	1104cdf	82.70	35.16
11.0	140.0	0.4	0.5	0.11	1652	13.8	18.5	4.11	2.9	1104ddf	82.97	34.47
12.3	150.0	0.4	0.6	0.13	1540	14.8	19.9	4.43	2.1	1104edf	84.40	34.56
15.1	80.0	0.5	0.7	0.12	280	6.1	8.2	1.44	1.1	1104fdf	83.70	27.11
15.4	60.0	0.5	0.7	0.12	255	7.7	10.4	1.64	1.2	1104gdf	87.55	24.51
15.6	60.0	0.3	0.4	0.07	539	7.8	10.5	2.19	1.6	1105adf	86.05	32.16
14.8	60.0	0.2	0.3	0.06	590	7.1	9.6	2.00	2.1	1105bdf	83.14	32.28
14.0	80.0	0.3	0.4	0.08	624	7.2	9.7	1.99	2.4	1105cdf	84.51	31.71
14.5	60.0	0.2	0.3	0.06	622	7.9	10.6	2.13	1.8	1106adf	87.09	31.19
13.8	250.0	0.8	1.1	0.24	968	10.1	13.6	3.07	2.0	1106bdf	88.83	35.04
12.6	450.0	1.2	1.6	0.35	1602	14.2	19.0	4.15	3.2	1106cdf	86.26	33.89
11.0	150.0	0.4	0.5	0.11	1700	14.1	18.9	4.00	3.5		85.60	32.85
14.3	190.0	0.6	0.8	0.19	1428	15.8	21.1	4.71	1.5	1106ddf	88.77	34.56
13.9	100.0	0.5	0.6	0.12	534	8.2	11.1	2.10	1.9	1107adf	85.90	29.44
14.6	110.0	0.5	0.7	0.14	539	8.1	10.9	2.21	1.7		87.20	31.36
13.4	140.0	0.5	0.6	0.14	1746	18.8	25.2	5.83	1.5	1107bdf	87.15	35.75
12.3	250.0	0.7	0.9	0.20	2318	20.8	27.9	6.27	1.5	1107cdf	85.39	34.85
13.1	280.0	0.8	1.1	0.25	2236	21.8	29.2	6.53	1.3	1107ddf	87.14	34.63
15.4	100.0	0.4	0.6	0.12	561.5	8.1	10.9	2.26	1.3	1108ADF	87.37	32.05
11.9	220.0	0.6	0.8	0.17	1794	15.7	21.1	4.65	2.7	1108BDF	83.53	34.14
11.6	250.0	0.6	0.8	0.18	2406	18.5	24.7	5.71	2.2	1108CDF	83.37	35.74
14.9	90.0	0.4	0.6	0.11	538.5	8.2	11.0	2.25	1.6	1108DDF	88.12	31.70
13.0	180.0	0.6	0.8	0.18	1574	17.6	23.6	5.30	1.5	1108EDF	88.42	34.72
12.1	310.0	0.9	1.2	0.28	2072	20.5	27.5	6.13	1.4	1108FDF	88.39	34.47
15.9	150.0	0.7	0.9	0.19	437	6.4	8.6	1.81	1.4	1223A	89.90	32.73
15.1	160.0	0.6	0.8	0.17	1084	12.7	17.0	3.93	1.6	1223B	88.13	35.75
13.4	390.0	1.1	1.5	0.35	1698	16.5	22.2	5.07	1.8	1223C	89.60	35.41
17.2	150.0	1.1	1.4	0.24	218.5	5.1	6.8	1.17	1.1	1223D	86.26	26.55
16.0	190.0	0.9	1.3	0.25	358.5	5.9	7.8	1.58	1.7	1223E	88.14	31.25
14.2	360.0	1.2	1.6	0.34	1164	12.9	17.2	3.66	2.0	1223F	86.93	32.89
13.6	420.0	1.3	1.8	0.39	1574	16.3	21.8	4.90	1.9	1223G	88.48	34.85
13.8	215.0	0.6	0.8	0.18	1150	10.2	13.7	3.17	1.9	1223G	85.54	35.88
3.6	166.0	0.5	0.6	0.14	1032.5	9.3	12.5	2.92	2.4	1108CDF	87.47	36.05
4.7	441.0	1.2	1.6	0.36	1172.5	10.4	13.9	3.19	2.2	1108CDF	85.91	35.57
4.9	480.0	1.3	1.7	0.39	1062.5	9.4	12.6	2.86	2.7	1108CDF	86.17	35.17
4.4	640.0	1.7	2.3	0.51	1102.5	9.6	12.9	2.90	2.7	1108CDF	84.97	34.92
4.6	474.0	1.3	1.7	0.39	1232.5	11.0	14.8	3.35	2.1	1108CDF	86.58	35.07
4.1	685.0	1.6	2.1	0.52	2518	19.5	26.1	6.30	2.0	1108CDF	85.72	37.34
5.4	571.0	2.0	2.7	0.63	912.5	10.8	14.4	3.35	1.5	1108CDF	88.73	35.91
4.8	700.0	2.0	2.7	0.62	2288	22.0	29.6	6.76	1.6	1108CDF	88.65	35.43
5.1	802.0	2.7	3.6	0.79	1062.5	11.9	16.0	3.46	1.7	1108CDF	88.56	33.51
4.9	800.0	2.4	3.2	0.73	1530	15.3	20.5	4.60	1.5	1108CDF	89.14	34.80

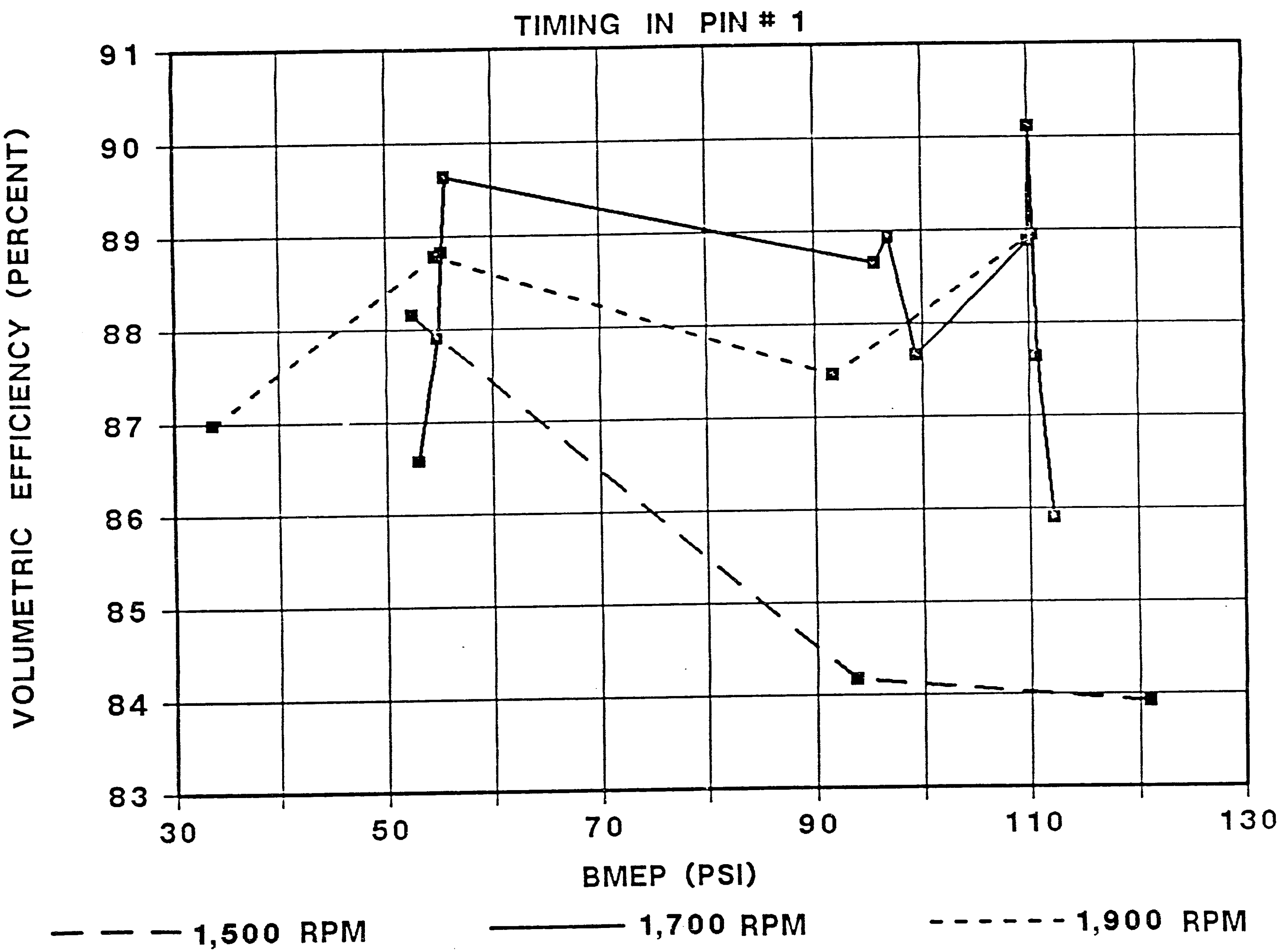
F/A btu/lb	DILUTION START (liters)	DILUTION END (liters)	DILUTION RATE (l/min)	TOTAL START (liters)	TOTAL END (liters)	TOTAL RATE (l/min)	TIME (sec)	SAMPLE RATE (l/min)	DILUTION RATIO	FILTER CLEAN (grams)	FILTER DIRTY (grams)	FILTER DRIED (grams)
0.026553												
0.024291												
0.038261												
0.026058												
0.025821												
0.023645												
0.023938												
0.025378												
0.032077												
0.035644												
0.030720												
0.016965												
0.013490												
0.021594												
0.025978												
0.027644												
0.025709												
0.027819												
0.034184												
0.037825												
0.026658												
0.022273												
0.021326												
0.026358												
0.032723												
0.030253												
0.021790												
0.034232												
0.037470												
0.020981												
0.026132												
0.029850												
0.021127												
0.024229												
0.029573												
0.016279												
0.019786												
0.028012												
0.028294												
0.032088												
0.031289	5670.28	6227.37	37.13933	4586.56	5201.69	41.00866	900	3.869333	9.598380	0.0868	0.0885	0.09
0.032493	5670.28	6227.37	37.13933	4586.56	5201.69	41.00866	900	3.869333	9.598380	0.0864	0.0863	0.0864
0.032918	5670.28	6227.37	37.13933	4586.56	5201.69	41.00866	900	3.869333	9.598380	0.0826	0.0849	0.0849
0.033694	5670.28	6227.37	37.13933	4586.56	5201.69	41.00866	900	3.869333	9.598380	0.0844	0.0955	0.0855
0.032522	5670.28	6227.37	37.13933	4586.56	5201.69	41.00866	900	3.869333	9.598380	0.0836	0.0838	0.0838
0.035466	5670.28	6227.37	37.13933	4586.56	5201.69	41.00866	900	3.869333	9.598380	0.0866	0.087	0.0895
0.023913	5670.28	6227.37	37.13933	4586.56	5201.69	41.00866	900	3.869333	9.598380	0.0828	0.0834	0.0834
0.029873	5670.28	6227.37	37.13933	4586.56	5201.69	41.00866	900	3.869333	9.598380	0.0842	0.0843	0.0846
0.027058	5670.28	6227.37	37.13933	4586.56	5201.69	41.00866	900	3.869333	9.598380	0.0839	0.0846	0.065
0.029356	5670.28	6227.37	37.13933	4586.56	5201.69	41.00866	900	3.869333	9.598380	0.086	0.0868	0.0856

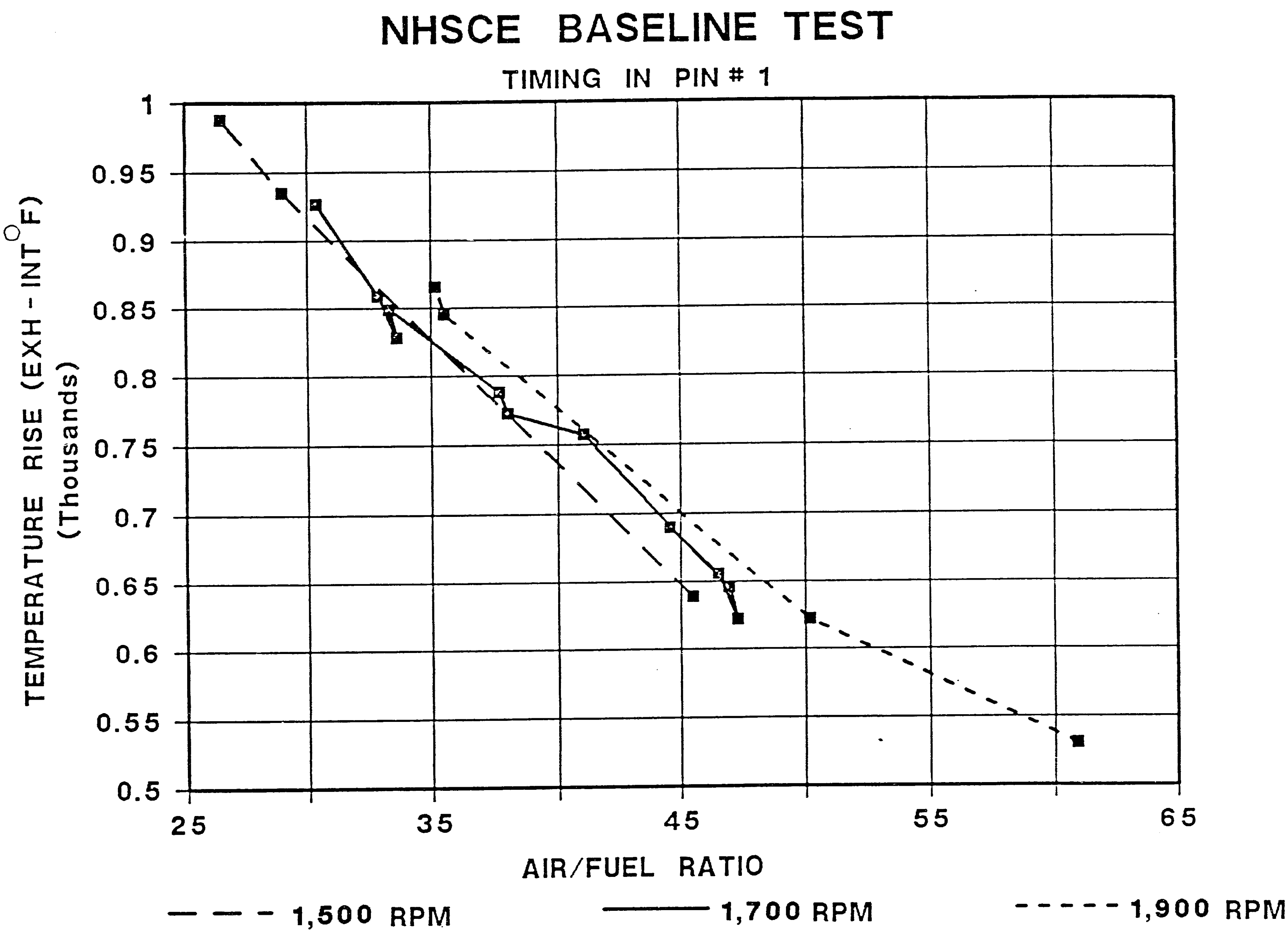
WET PART (grams)	DRY PART (grams)	AROM. (grams)	WET PART (g/hphr)	DRY PART (g/hphr)	AROM. (g/hphr)	SAMPLE FLOW (lb/hr)	SAMPLE RATIO
0.0017	0.0032	-0.0015	0.142344	0.267941	-0.12559	0.600834	0.001906
-0.0001	0	-0.0001	-0.00812	0	-0.00812	0.604935	0.001952
0.0023	0.0023	0	0.186029	0.186029	0	0.606986	0.001958
0.0111	0.0011	0.01	0.885521	0.087754	0.797767	0.605961	0.001983
0.0002	0.0002	0	0.016581	0.016581	0	0.600834	0.001928
0.0004	0.0029	-0.0025	0.028689	0.208001	-0.17931	0.599809	0.001695
0.0006	0.0006	0	0.065627	0.065627	0	0.599809	0.001253
0.0001	0.0004	-0.0003	0.008946	0.035785	-0.02683	0.598373	0.001315
0.0007	0.0011	-0.0004	0.072908	0.114570	-0.04166	0.598373	0.001231
0.0008	-0.0004	0.0012	0.073945	-0.03697	0.110918	0.599809	0.001122

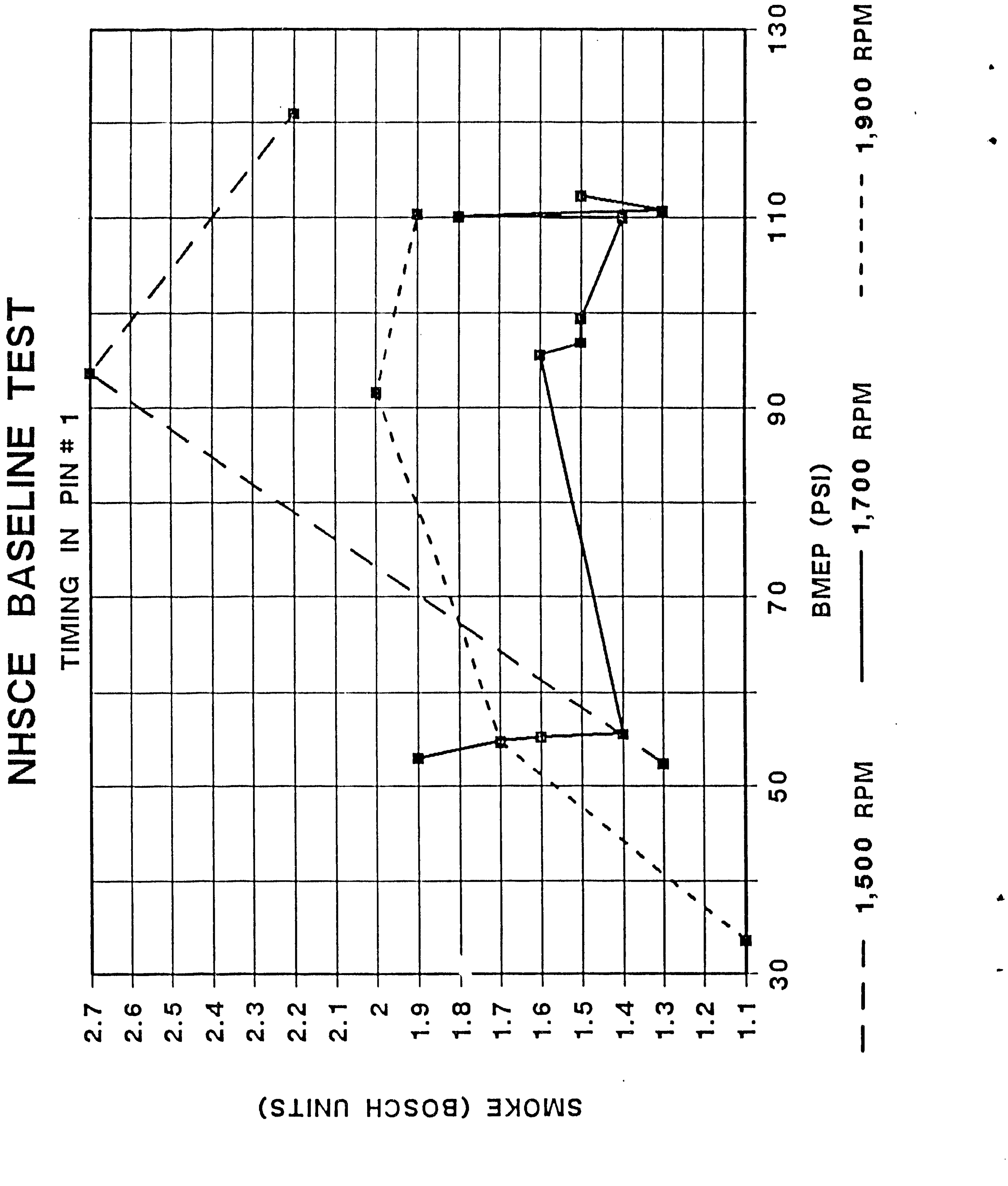

NHSCE BASELINE TEST
TIMING IN PIN # 1
BMEP (PSI)
30
50
70
90
110
130
AIR/FUEL RATIO
65
60
55
50
45
40
35
30
25
1,500 RPM
1,700 RPM
1,900 RPM


NHSCE BASELINE TEST
TIMING IN PIN # 1
BRAKE THERMAL EFFICIENCY
36
35
34
33
32
31
30
29
28
27
26
30
50
70
90
110
130
BMEP (PSI)
— — — 1,500 RPM
———— 1,700 RPM
- - - - - - 1,900 RPM

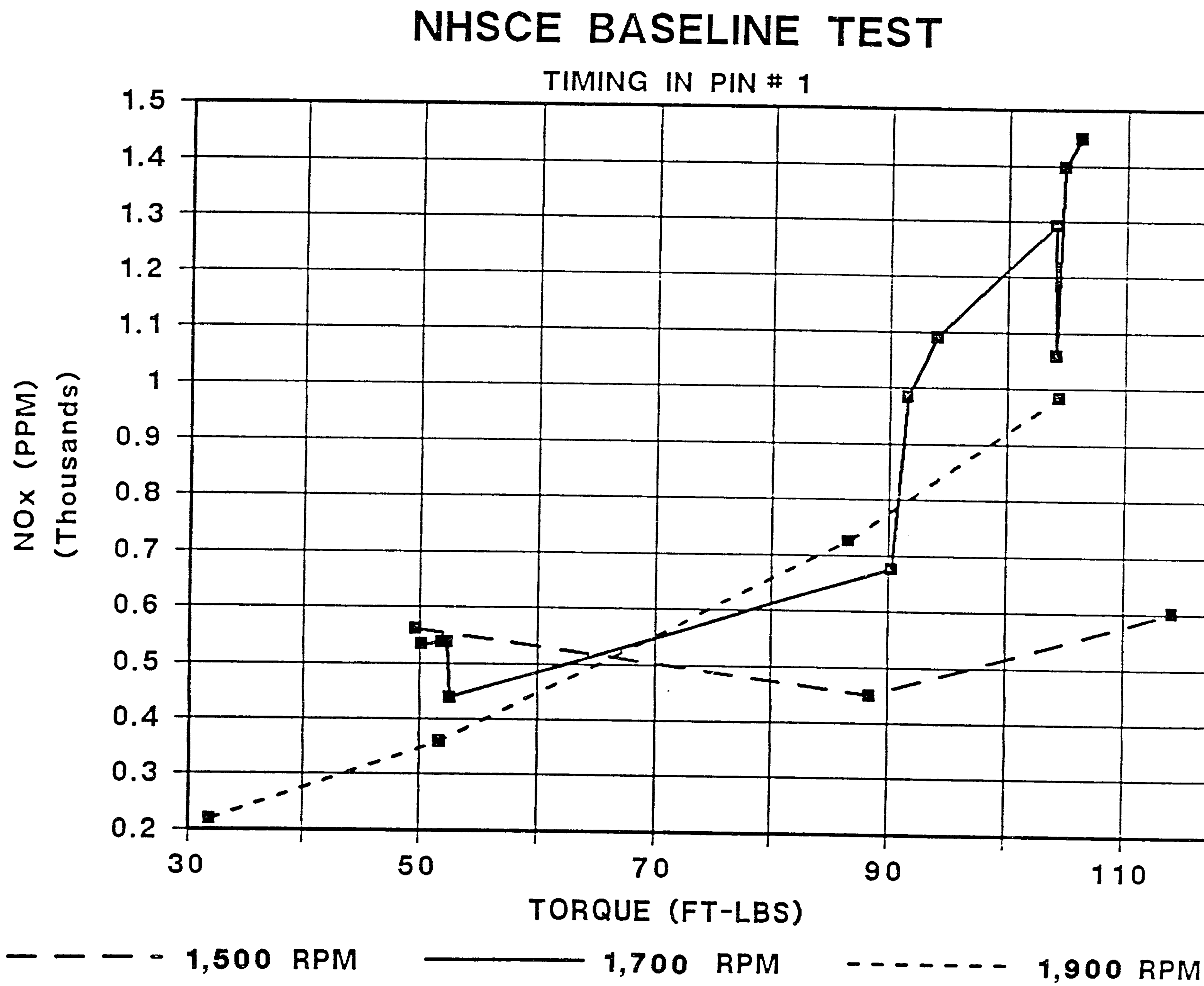
NHSCE BASELINE TEST




NHSCE BASELINE TEST
TIMING IN PIN # 1
TEMPERATURE RISE (EXH - INT °F)
(Thousands)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
25
35
45
55
65
AIR/FUEL RATIO
1,500 RPM
1,700 RPM
1,900 RPM

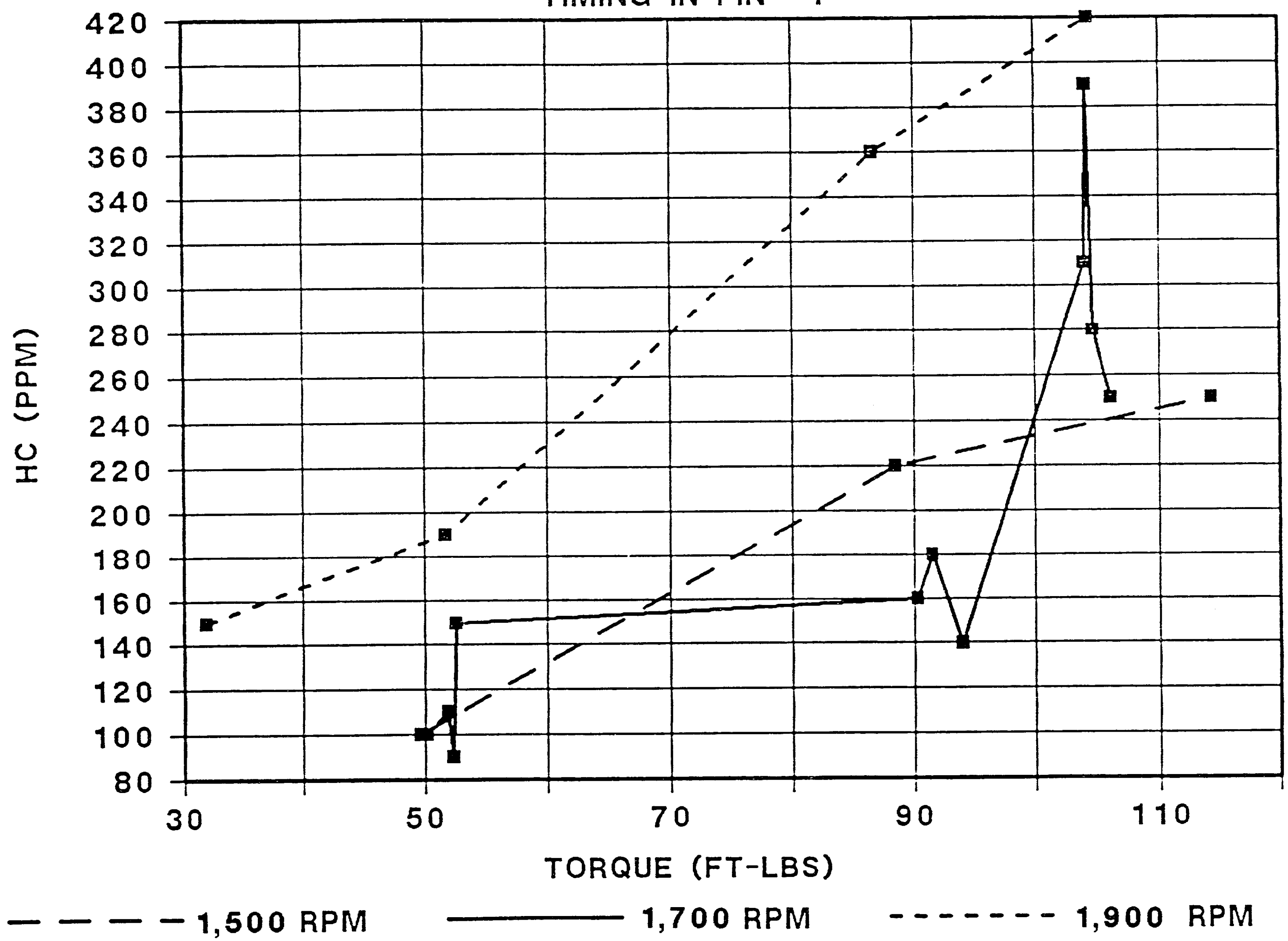


NHSCE BASELINE TEST
TIMING IN PIN # 1
SMOKE (BOSCH UNITS)
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
30
50
70
90
110
130
BMEP (PSI)
1,500 RPM
1,700 RPM
1,900 RPM


NHSCE BASELINE TEST
TIMING IN PIN # 1
NOx (PPM)
(Thousands)
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
30
50
70
90
110
TORQUE (FT-LBS)
1,500 RPM
1,700 RPM
1,900 RPM

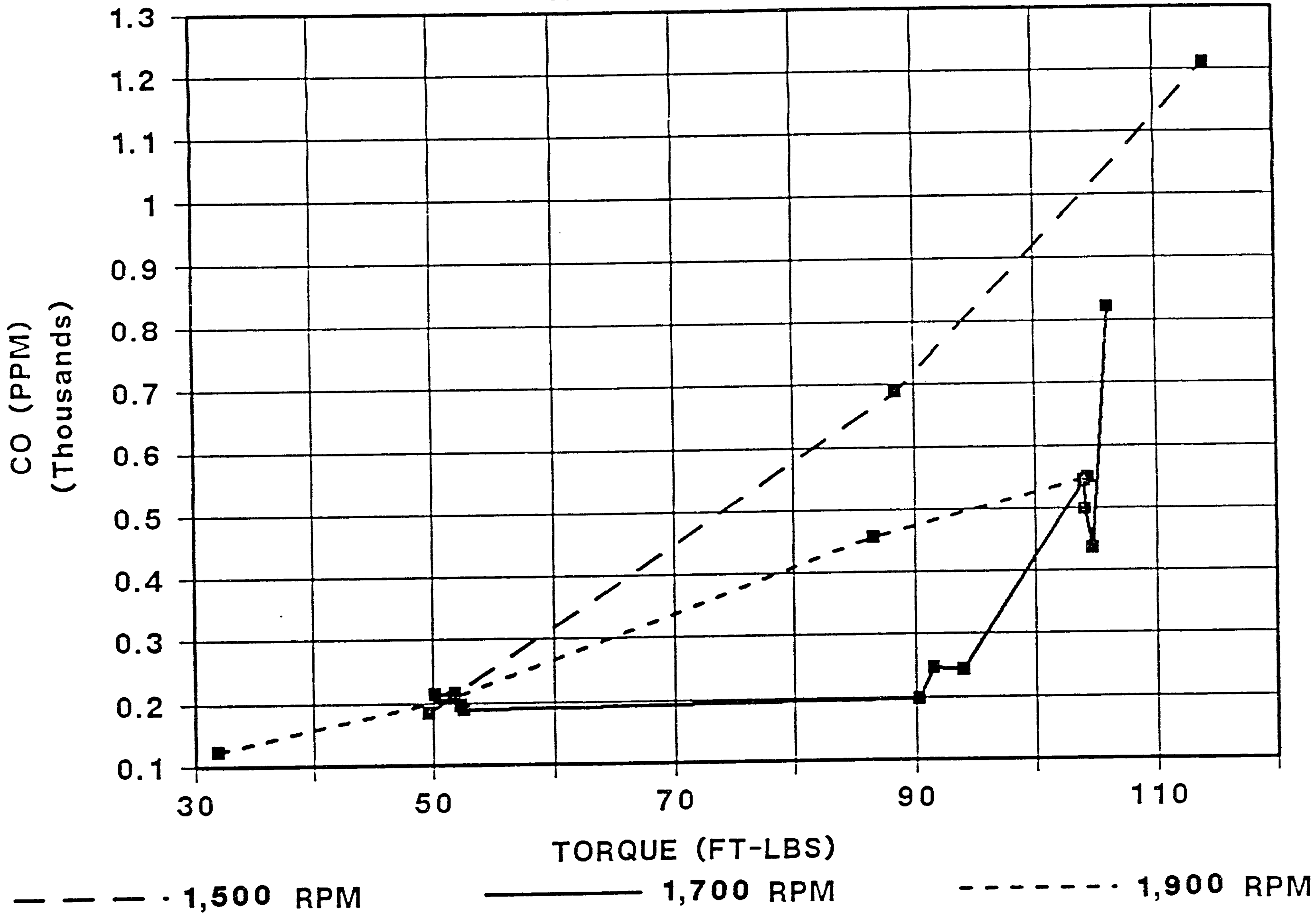
NHSCE BASELINE TEST

TIMING IN PIN # 1



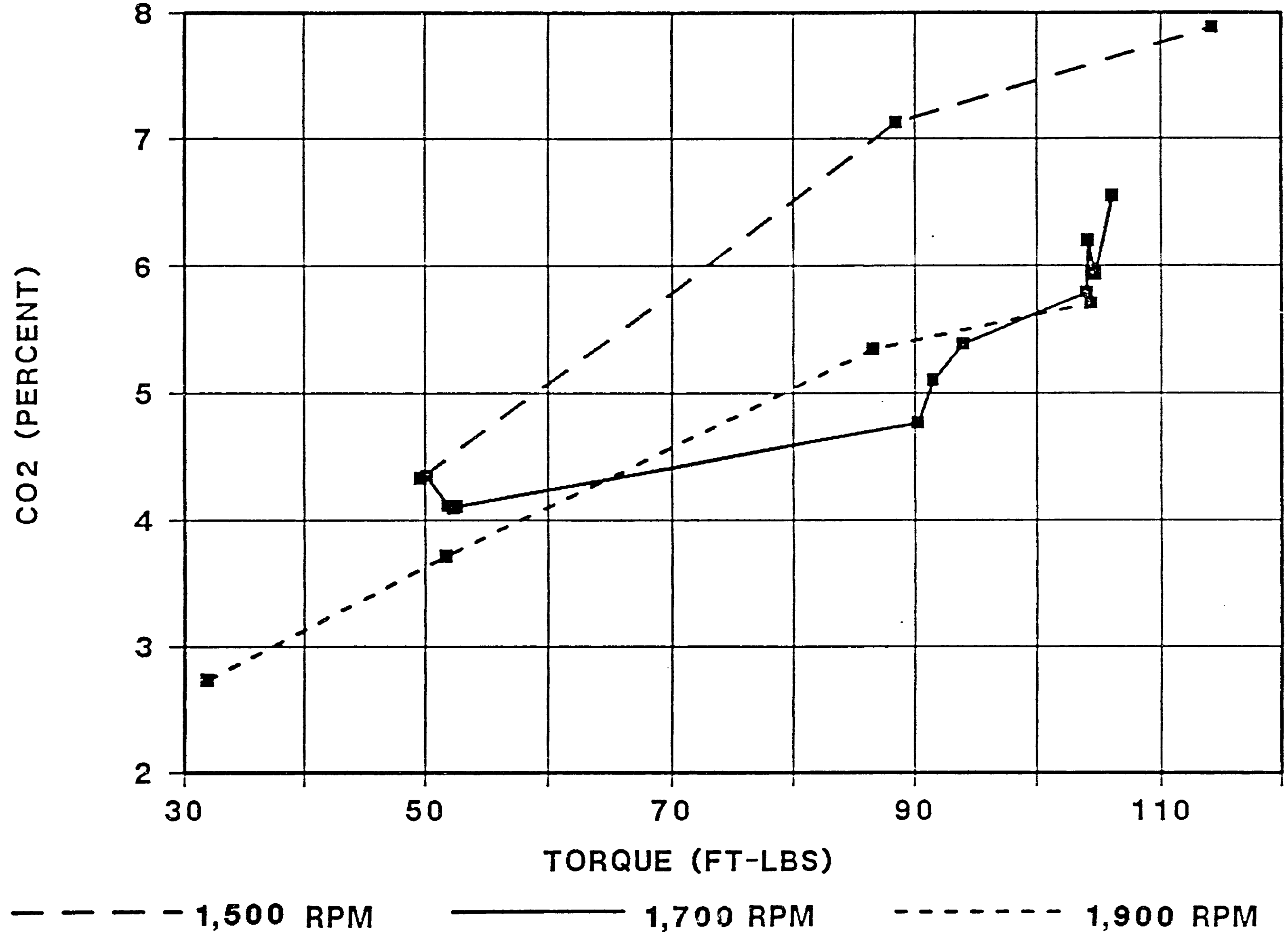
NHSCE BASELINE TEST

TIMING IN PIN # 1



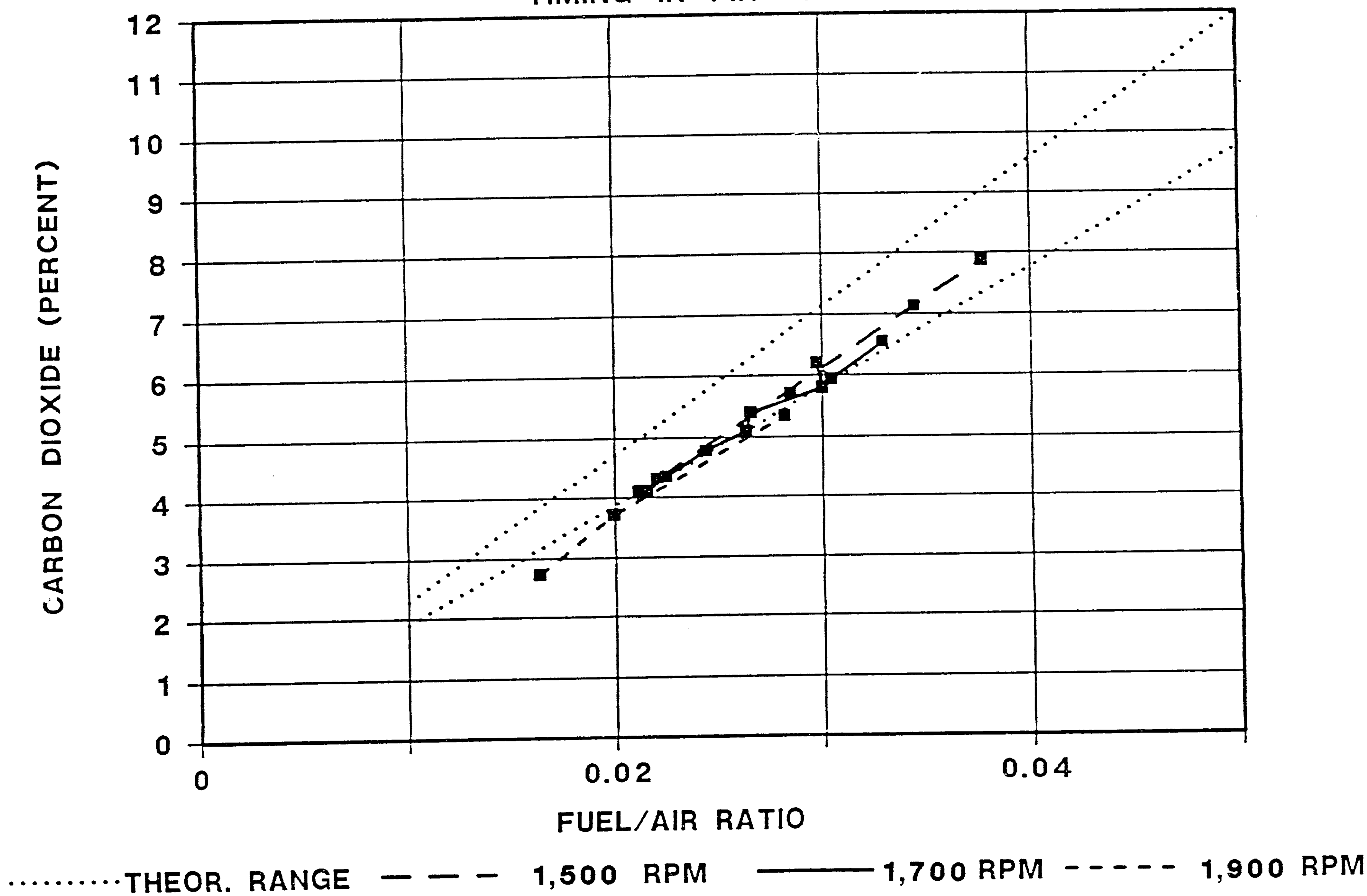
NHSCE BASELINE TEST

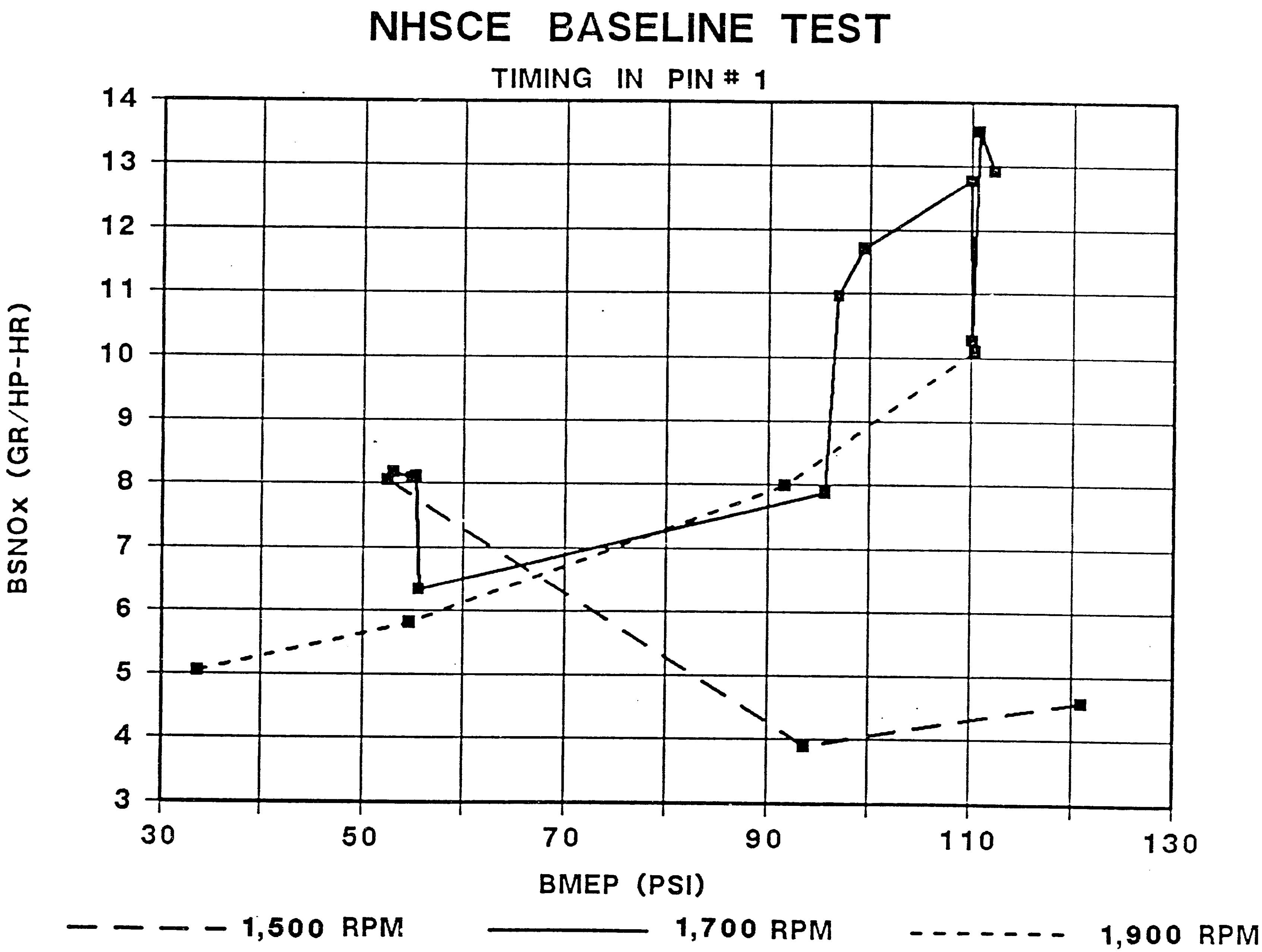
TIMING IN PIN # 1



NHSCE BASELINE TEST

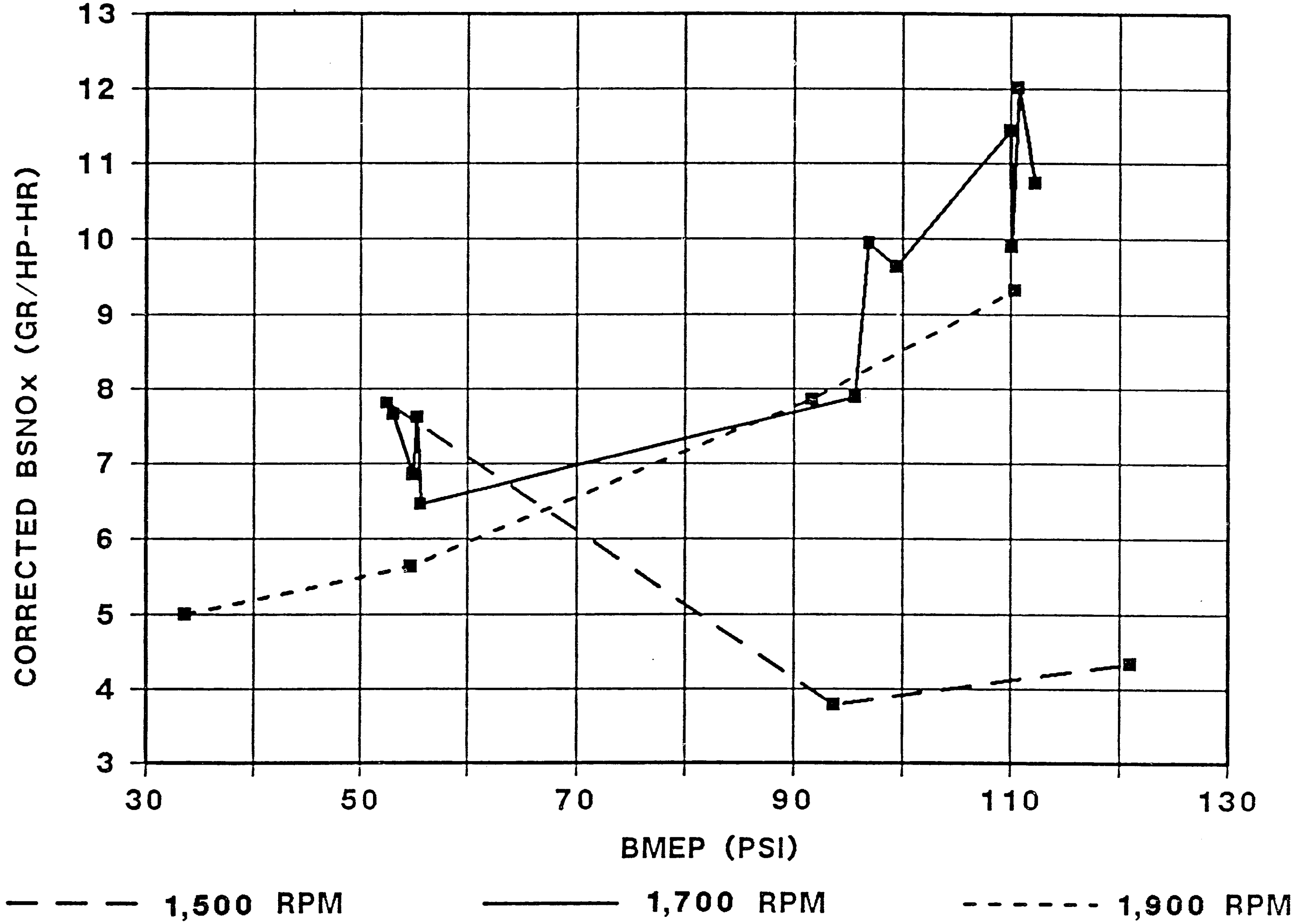
TIMING IN PIN # 1




NHSCE BASELINE TEST
TIMING IN PIN # 1
BSNOx (GR/HP-HR)
14
13
12
11
10
9
8
7
6
5
4
3
30
50
70
90
110
130
BMEP (PSI)
1,500 RPM
1,700 RPM
1,900 RPM

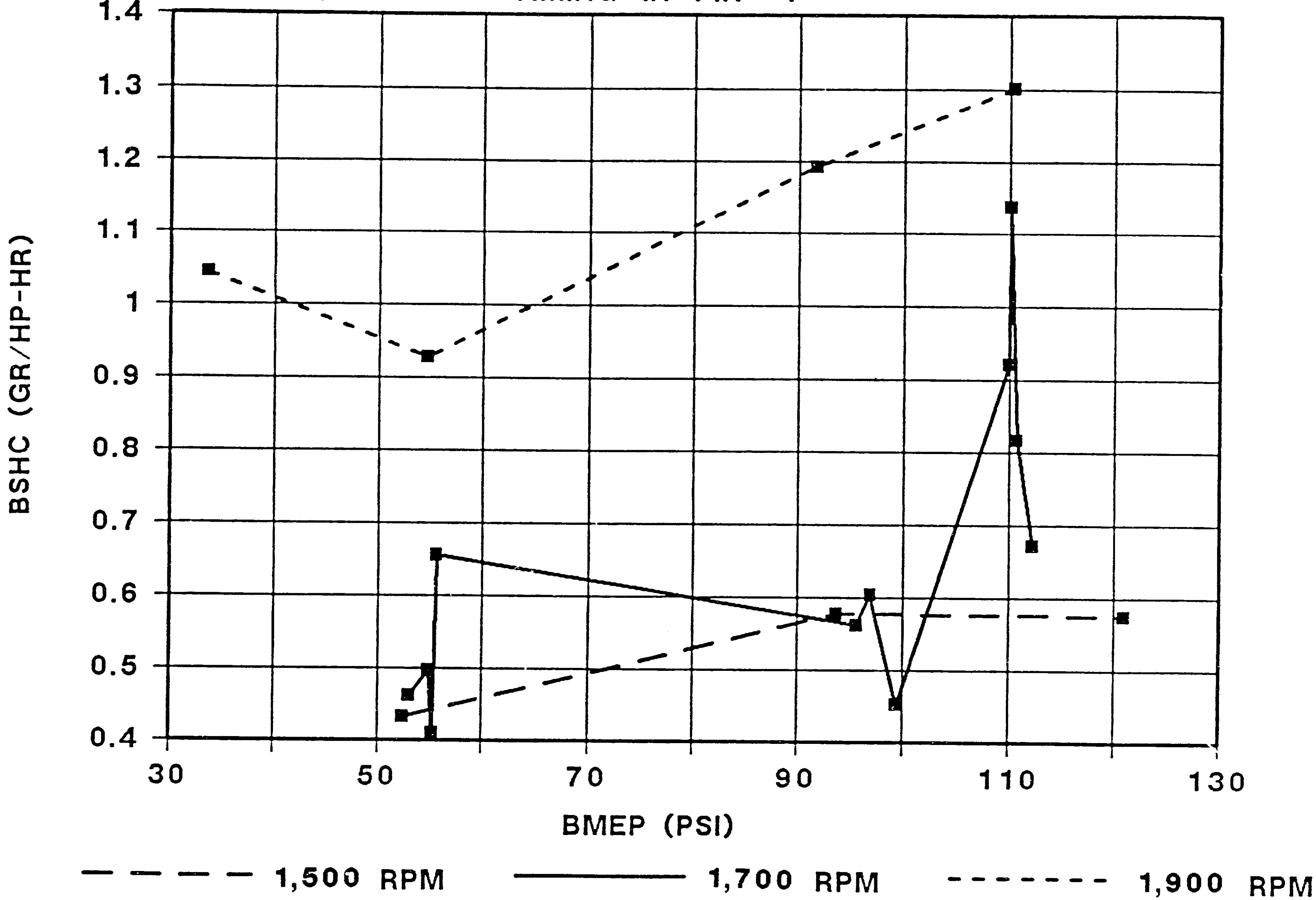
NHSCE BASELINE TEST

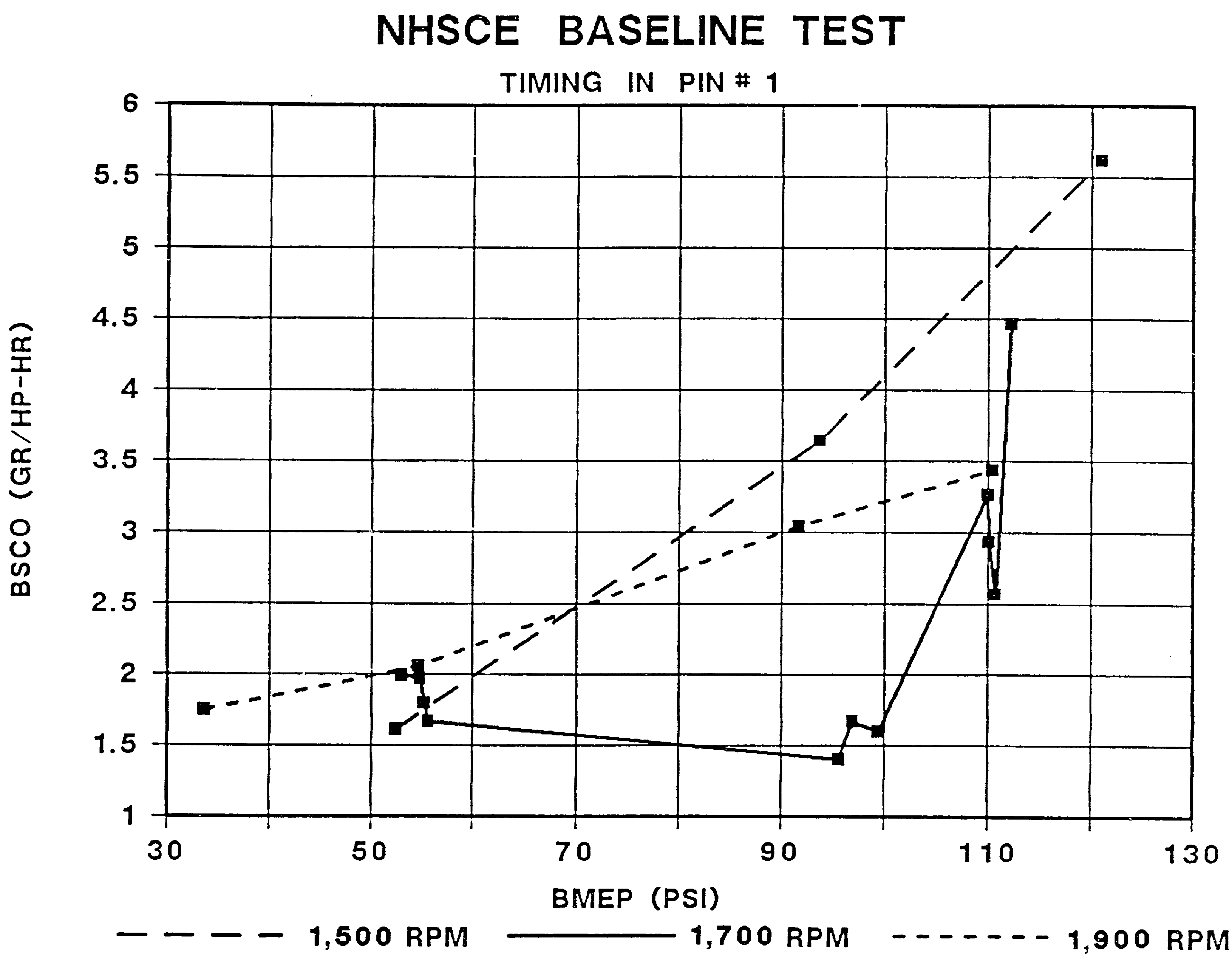
TIMING IN PIN # 1



NHSCE BASELINE TEST

TIMING IN PIN # 1




NHSCE BASELINE TEST
TIMING IN PIN # 1
BSCO (GR/HP-HR)
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
30
50
70
90
110
130
BMEP (PSI)
1,500 RPM
1,700 RPM
1,900 RPM

END

DATE FILMED

4 / 7 / 93