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LOW EMISSION COMBUSTOR TECHNOLOGY PROGRAM

Final Report Volume II for the Period April—November 1984

By
H. G. Lew
J. L. Toof

February 1985

Work Performed Under Contract No. AC21-82MC20228

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

By
Westinghouse Electric Corporation
Concordville, Pennsylvania

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Prepared for

U.S. Department
Assistant Secretary for Fossil Energy

Prepared By

Westinghouse Electric Corporation
Power Generation Operations Division
Concordville, Pennsylvania 19331

FOREWORD

This program was funded by the Morgantown Energy Technology Center of the Department of Energy. The Program Manager is Mr. Nelson F. Rekos, Jr.

The work was carried out by the Westinghouse Electric Corporation at its Power Generation Operation Division, Concordville, Pennsylvania. Dr. Henry G. Lew is the Westinghouse Program Manager.

The project also has the support and participation of K. Rieke, J. Emory, R. Bunce, B. Pilla, J. Marlow, C. Bowden and Advanced Combustion Development Center (CTSD) personnel, of Westinghouse; and Professor J. M. Beér, Massachusetts Institute of Technology.

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SUMMARY

The work described in this report is part of the DOE/METC Low Emission Combustor Technology Program to evaluate coal water mixtures (CWM) in a low emission staged rich/lean combustor -- the Multiannular Swirl Burner (MASB) -- for stationary combustion turbines.

This Final Report, Volume II contains the results of the last set of combustion tests of this combustor with CWMs and methane fuels. This set of tests includes the testing of the cooled deposition pin designed for ash deposition measurements and a particulate sampling probe. Preliminary collection of particulates and pin deposits was made.

Combustion test results for CWM (62 percent by weight) with a methane (38 percent) pilot show the high combustion efficiencies, up to 88 percent. All test results including those reported earlier show that efficiencies up to 99.5 percent are obtained for CWM and methane mixture (72 percent/28 percent) for this combustor and 53 percent for CWM alone.

Results reported here indicate that CWM with only 50 percent solid loading is a marginal fuel at the heat release rates being attempted for this metal wall combustor and that a higher heat content fuel is required.

Section 1

INTRODUCTION

This is the Final Report, Volume II, of the Low Emission Combustor Technology program (Contract DE-AC21-82MC20228). This program has the objective of evaluating coal water mixtures (CWM) in a low emission staged rich/lean combustor for stationary combustion turbines.

The combustor selected for the evaluation was the Multiannular Swirl Burner (MASB), which had been shown to be fuel-flexible and to have low emissions in a previous work (1)*. The fuels that were considered were distillate oil, petroleum residual, and coal-derived liquid (SRC-II). The demonstration included stable combustion for these fuels, with combustion efficiency greater than 99.5 percent. This performance (2) was later extended to the combustion of coal gases with heating values from 104 Btu/Scf to 254 Btu/Scf, and with efficiencies greater than 99 percent.

The primary goal of this program was to evaluate CWM combustion with this fuel-flexible MASB. To this end the MASB configuration was modified to enable it to burn CWM efficiently and with minimum NO_x production. The development work for this aspect of the program and the combustion tests of the MASB in oil, methane, and CWM have been covered in the Topical Report - Comprehensive Data Report (3); and in the Final Report, Volume I (4).

The development work reported here encompasses two additional areas:

- Additional tests to improve combustion efficiency
- Initiation of a test program to obtain information on the deposition characteristics of burning CWM.

Section 2 discusses the MASB combustor configuration utilized in these tests, including modifications. The test facility described in Section 3 includes the combustor rig and the CWM forwarding system, as well as a discussion of the preparation work for the measurement of ash deposition characteristics from the combustion of CWM. Cooled deposition pins have been designed to collect the deposits due to the coal ash. In addition, a particulate probe was inserted upstream of the deposition pins to characterize the particles prior to their impact on the pins. The cooled pins and the particulate probe are described in this section.

Section 4 contains the CWM fuel characteristics for the fuel used in the combustion tests, which were made in the Westinghouse combustion development test facility. These tests used the CWM (50 percent solid loading) fuel as in the previous tests (3). Operational performance data and particulate measurements were obtained for this CWM at comparable conditions, and the results are discussed in Section 5. Section 6 contains the conclusions and recommendations.

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*Number in parentheses refers to References at the end of each section.

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1. Lew, H.G., et al, "Low NO_x Heavy Fuel Combustor Concept Program, Phase I - Combustion Technology Generation, Final Report," NASA CR-165482 (October, 1981).

2. Sherlock, T.P., et al, "Low NO_x Heavy Fuel Combustor Concept Program, Phase IA - Combustion Technology Generation. Coal Gas Fuels. Final Report," NASA CR-165614 (February 1982).

3. Lew, H.G. and Toof, J.L., "Comprehensive Data Report - Low Emission Combustor Technology Program," DOE/METC Contract DE-AC21-82MC20228 (September 1984).

4. Lew, H.G. and Toof, J.L., "Final Report, Volume I - Low Emission Combustor Technology Program," DOE/METC Contract DE-AC21-82MC20228 (September 1984).

Section 2

COMBUSTOR CONFIGURATION

2.1 MULTIANNULAR SWIRL BURNER

The Multiannular Swirl Burner (MASB) selected for this program is a 10 inch diameter metal-wall combustor, which was designed to burn CWM as well as liquid and gaseous fuels.

As shown in Figure 2-1, swirlers 1 and 2 introduce primary air into the rich zone of the burner, swirler 3 provides quench/lean-burn air, and swirler 4 admits dilution air. A recirculation region is established in the rich zone by swirlers 1 and 2 and the expansion of the flow. Swirl angles of 76°, 77°, 62° and 66° (respectively) were selected for the four swirlers as a result of aerodynamic flow field modeling and other design considerations. Geometrical design of the swirlers was determined on the basis of Reference (1).

Liquid fuels (No. 2 distillate oil and CWM) are sprayed into the primary zone (Figure 2-1) by a continuous air atomizing nozzle (a) specifically designed by Parker Hannifin for CWM use. This nozzle is described in Section 2.2. Gaseous fuel (methane) is discharged through swirler 1 by six tubes manifolded together in the neck of the combustor (b).

The only ceramic used in this burner is a quarl that forms the conical dome at the upstream end (Figure 2-1) of the primary zone (c). The purpose of the ceramic quarl is to provide a divergence angle that is conducive to recirculation. A larger, all-metal quarl is located midway along the burner (d). The purpose of the metal quarl is to physically separate the rich and lean zones of the combustor and to promote recirculation in the rich zone. The metal quarl was removed for the last test in this program series to delay the mixing of air from swirler 3 and, therefore, avoid over-quenching the burning coal char. Some internal cooling of the primary zone is provided by air from swirler 2. Likewise, the metal quarl and the lean zone are cooled by swirlers 3 and 4, respectively. Auxiliary external cooling is provided by two impingement cylinders (g).

Snap button hole plugs (e) that can be drilled with various hole sizes are employed in the neck of the combustor to provide an easy means for adjusting the air to swirlers 1 and 2. For the last test, variable geometry was also added to permit the control of air flow to swirler 1.

Metal bosses are located in the wall of the primary zone just downstream of the ceramic quarl for mounting an ultraviolet detector and a propane torch igniter (f).

Multiannular Swirl Burner operating conditions and hardware modifications during this portion of the test program are tabulated in Section 5.

Key

1,2,3,4 Swirlers
A Liquid Fuel Nozzle
B Gas Fuel Inlet
C Ceramic Quarl
D Metal Quarl
E Hole Plugs
F Ultra-violet and Igniter Bosses
G Impingement Cooling Cylinders

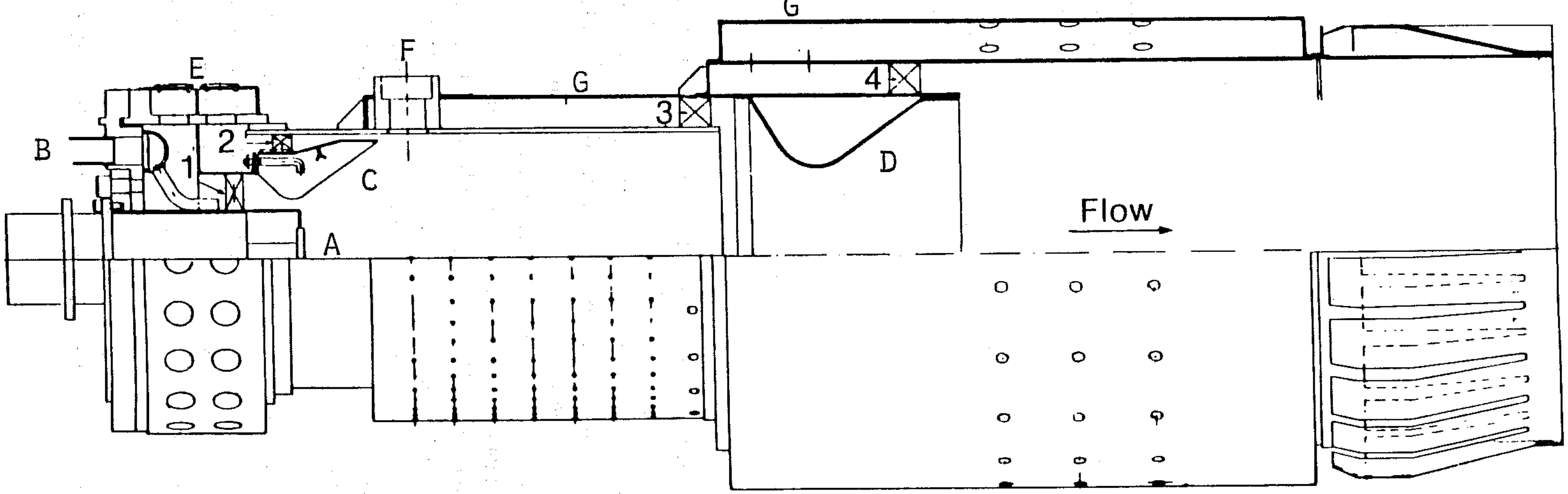

Figure 2-1. Multiannular Swirl Burner for CWM Combustion

2.2 FUEL NOZZLE

The requirements for effective CWM atomization are stringent and include small droplets, low spray momentum, and high reliability. All these were considered for this program.

Small droplets increase the overall rate of water evaporation from the CWM. In addition, if agglomeration of coal particles takes place as the water evaporates, then the size of the agglomerated particle will be proportional to the size of the original droplet. This agglomeration (if formed) in turn affects the time required for char burnout. Therefore, small droplets reduce the total amount of time required for slurry combustion by reducing the time required for evaporation of the water and, if agglomeration occurs, combustion of the coal char.

Low spray momentum is desirable to avoid interference with the flow patterns in the primary zone of the combustor. In the MASB the existence of and/or the size and strength of primary zone recirculation depend on the balance between axial and tangential momentum. Large axial spray momentum could adversely affect the establishment of recirculation and, therefore, the stability of the burner.

The requirement of reliability refers to the ability of the nozzle to deliver small droplets over a wide range of flow conditions and to avoid plugging. Frequent nozzle problems encountered during combustion testing could therefore be avoided.

Due to the importance of nozzle performance in CWM combustion, a series of atmospheric spray tests was conducted to select a nozzle for this program. Five candidate nozzles were tested on water and CWM with performance evaluated primarily on the appearance of the spray in high speed photographs. These nozzles were the Westinghouse T-Jet, Westinghouse B-4, Delavan Swirl Air, Parker Hannifin, and Sonotek. The results of these tests are discussed in the Comprehensive Data Report (2). Of the five nozzles tested, the Parker Hannifin nozzle designed for CWM provided the smallest drop size and widest turn-down range and did not plug with slurry. It was therefore selected for use in combustion testing. A drawing and a photograph of the Parker Hannifin nozzle are shown in Figures 2-2 and 2-3.

The one potential disadvantage of the Parker Hannifin nozzle is the high spray momentum. This effect was minimized during combustion testing by swirling the atomizing air in the same direction as the burner combustion air. During the test program the spray angle was varied from 55 to 110 degrees by changing the nozzle tip components. For the last test these tip components provided shearing of the CWM by atomizing air from two sides; in earlier tests the fuel was sheared from only one side.

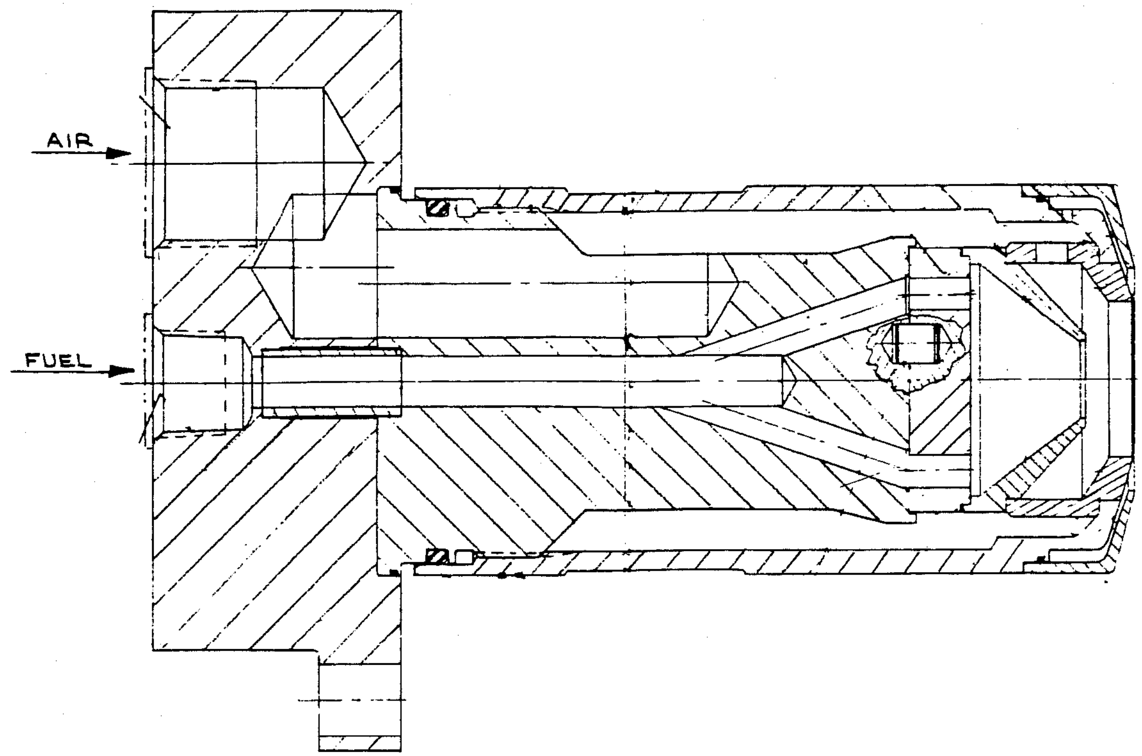

Figure 2-2. Assembly Drawing of Parker Hannifin CWM Nozzle

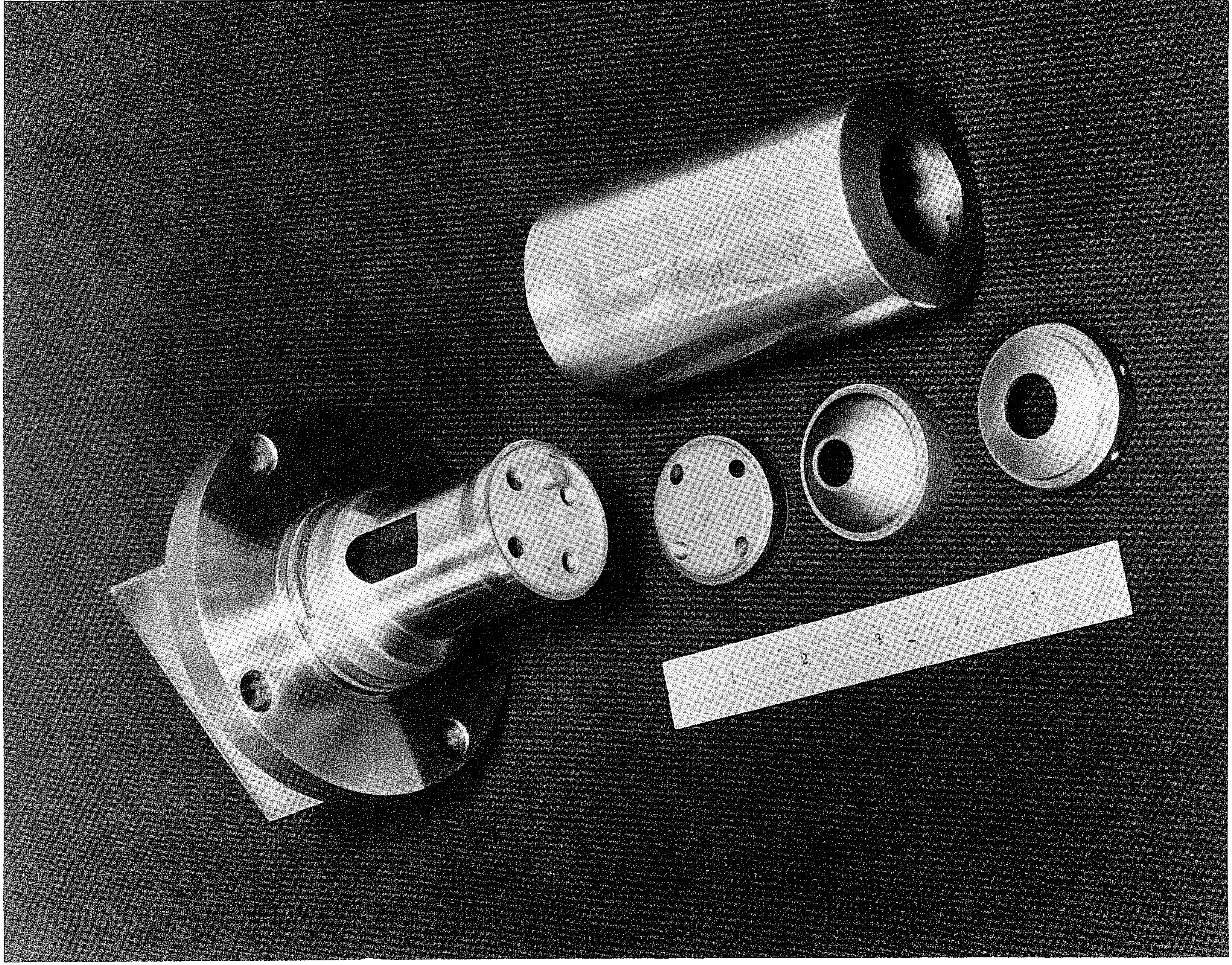

Figure 2-3. Photograph of the Parker Hannifin CWM Nozzle - Exploded View.

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1. Lieblein, S., "Experimental Flow in Two-Dimensional Cascades," Aerodynamics Design of Axial-Flow Compressors, Revised, Johnson, I.A., and Bullock, R.O. Editors, NASA SP-36 (1965).

2. Lew, H. G. and Toof, J. L., "Comprehensive Data Report, Low Emission Combustor Technology Program," DOE/METC Contract DE-AC21-82MC 20228 (September 1984).

Section 3

TEST FACILITY

3.1 TEST RIG, FACILITY AND INSTRUMENTATION SYSTEMS

The test rig utilized in this program is shown in Figure 3-1. The cylindrical reverse flow combustor rig permits testing with various length combustors, and accommodates the Multiannular Swirl Burner (MASB) for CWM combustion by the addition of a cylindrical section at the front end. The rig is designed so that the rig shell contains various penetrations for special instrumentation.

Rig inlet air is admitted through an internal manifold that directs the air to cool the combustor exit instrumentation duct before it enters the reverse flow combustor shell. Two rows of instrumentation rakes are located in this duct and are removable without disassembling the rig. The front row consists of five radial thermocouple rakes, and the rear row has five air-cooled radial gas sampling rakes. Combustion products pass from the burner through a transition duct, which expands from a 10 inch diameter at the MASB outlet to a 16.6 inch diameter at the instrumentation plane. A separate converging duct designed to provide exit velocities in the range of 300-500 fps for deposition testing was also fabricated but was not used during the test program reported here.

The rig includes windows and a periscope to permit viewing the combustor exit. High pressure purge air protects these viewing devices from impingement of the hot exhaust gases. The periscope is housed in a water-jacketed support with small, air-purged opening for viewing along the rig axis. A color television camera is installed to display the periscope image on a monitor in the control room. The periscope and color television system provide for this observation on a sustained basis in a safe location, and also permit video tape recording for post-test analysis. The exhaust section of the rig is water-jacketed, thus allowing for exhaust spray cooling water injection downsteam of the viewing devices to avoid obscuring the observed area.

Figure 3-2 shows the facility process flow system. Table 3-1 lists the facility air and fuel system flow, pressure and temperature capabilities. The main air supply to the rig has a maximum flow capability of 85 lb/sec at 325 psig. In addition, atomizing air required for the CWM nozzle can be provided by a boost compressor up to 3.1 lb/sec at 600 psig delivery pressure. A high temperature atomizing air supply was added during the course of this program by means of a counter flow concentric tube heat exchanger. It uses combustor inlet air at 200 psia, 800°F to heat 0.1 pps of atomizing air to temperatures in excess of 500°F. Non-vitiated preheat air is available through two indirect-fired heaters. Preheated air flows can be obtained up to a maximum temperature of 900°F and full system pressure.

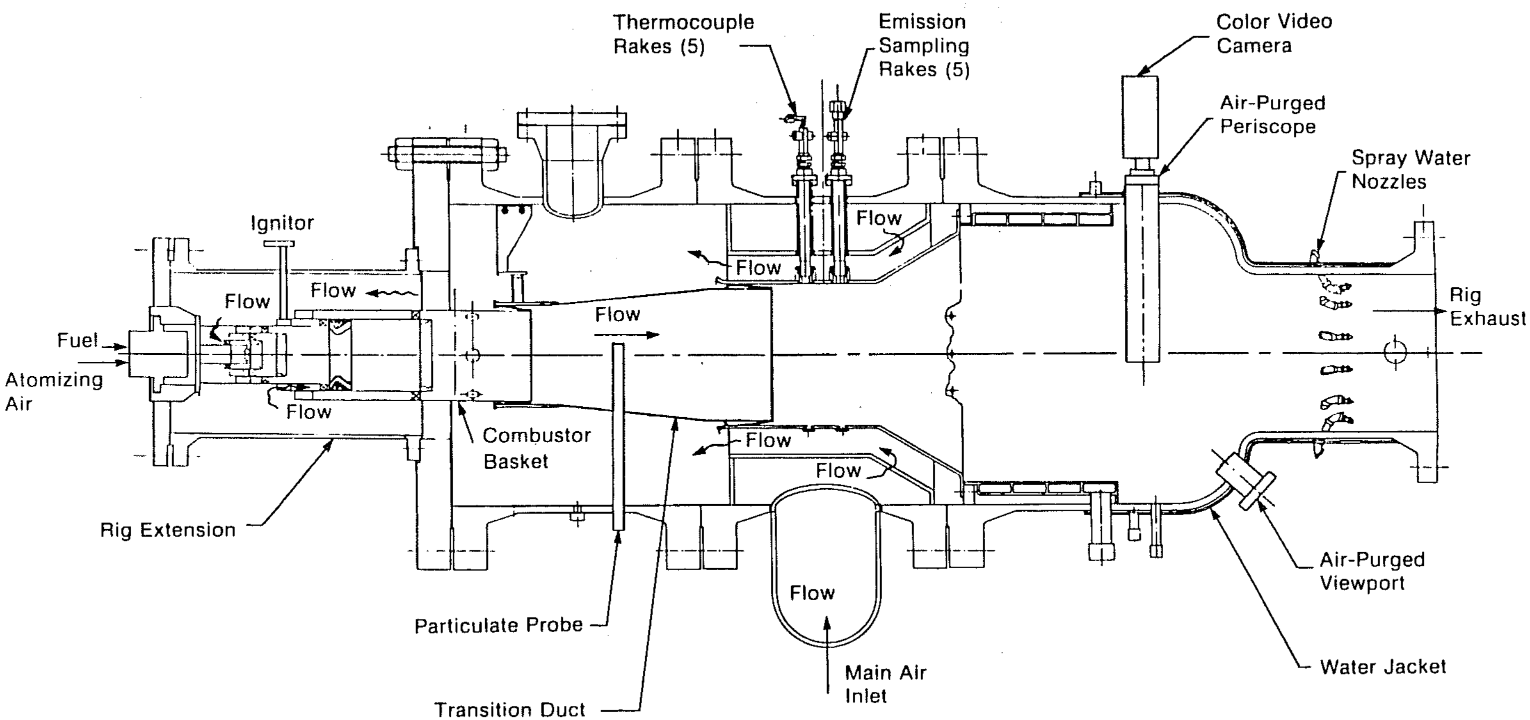

Figure 3-1. Schematic of Test Rig

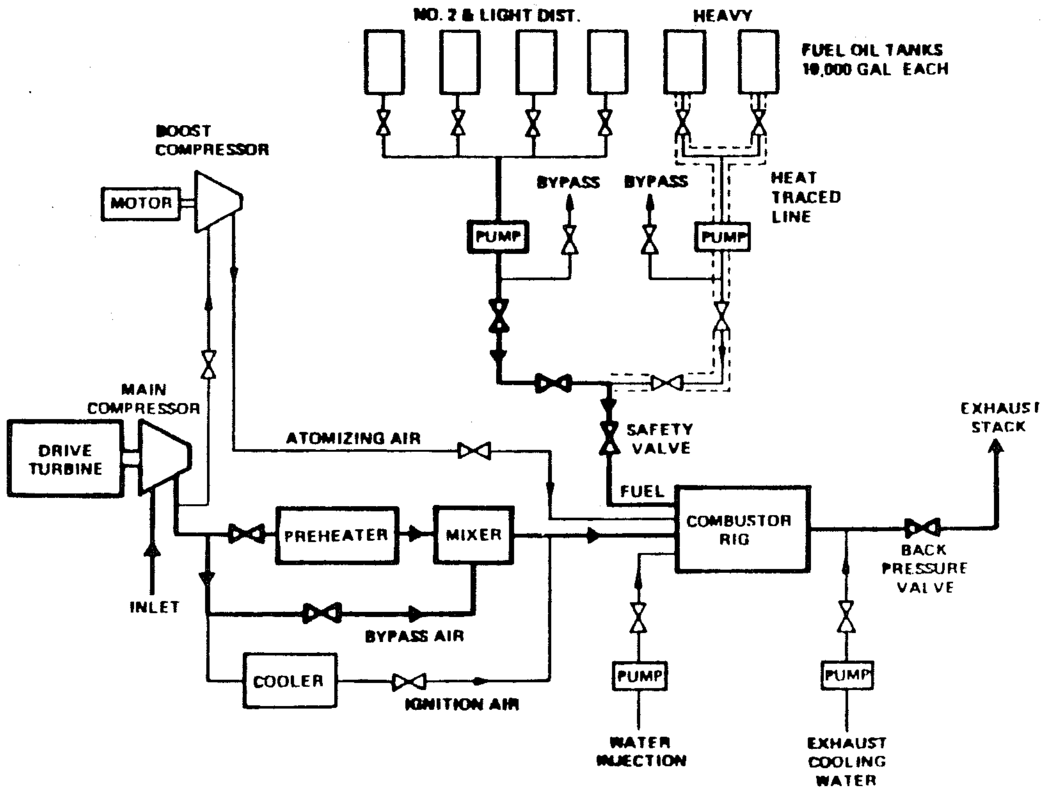

Figure 3-2. Combustor Test Rig Process Flow Chart

Table 3-1

RIG SYSTEM CAPABILITIES

System	Flow	Pressure	Temperature
Process Air Compressor	85 lb/sec	325 psig	300°F
Process Air Preheater	95 lb/sec	325 psig	1100°F
Process Air to Combustion Rig	85 lb/sec	285 psig	900°F
Atomizing Air to Rig	3.1 lb/sec	600 psig	125°F
Fuel Oil Supply to Combustion Rig (Distillate or Heated)	25 gpm	1550 psig	350°F

Main air flow and inlet air temperatures are controlled by valves establishing the flow through the preheaters. The rig exhaust backpressure valve establishes the combustor system pressure level.

The fuel system, in addition to the methane and CWM forwarding systems described below, consists of a fuel tank farm with capabilities for supplying No. 2 GT fuel oil or other liquid fuels such as crudes, residuals, heavy distillates, and coal liquids in either a heated or non-heated condition.

An on-line metered injection system of pyridine into the fuel oil is provided. The pyridine allows for the simulation of fuel bound nitrogen effects. Fuel oil flow control valves include high turndown-ratio metering valves and upstream bypass valves that set the metering valve supply pressures. Gaseous methane fuel is supplied to the combustor rig from a manifold of twenty type T high pressure cylinders containing 356 SCF each. Methane flow to the rig is metered by pressure regulators, isolation ball valves, and a control valve. Methane flow rate is measured by means of an ASME sharp-edge orifice. Ignition of the initial methane/air flow is provided by a propane fueled torch igniter, which is ignited by a high voltage spark plug.

Coal Water Mixture Forwarding System

A schematic of the system supplying CWM to the MASB fuel nozzle is shown in Figure 3-3. The CWM is supplied from a 500 gallon capacity run tank and is transferred from 55 gallon barrels by a Wilden air-operated diaphragm pump. Prior to transfer, each barrel of CWM is stirred to uniform consistency with a Lightnin air-driven drum mixer.

A 3/4 horsepower Cleveland tank mixer is used to maintain a consistent mixture in the run tank. A Moyno model 6M3 progressing cavity pump is gravity fed from the run tank and is powered by a 3 horsepower variable speed Dynamatic drive providing a pump speed control range of 0-400 rpm. The pump speed is the primary control of CWM flow rate to the fuel nozzle which can be changed locally or from the laboratory control room. A pump discharge rupture disc rated at 450 psi protects the pump and drive in the event of a slurry feed system flow blockage.

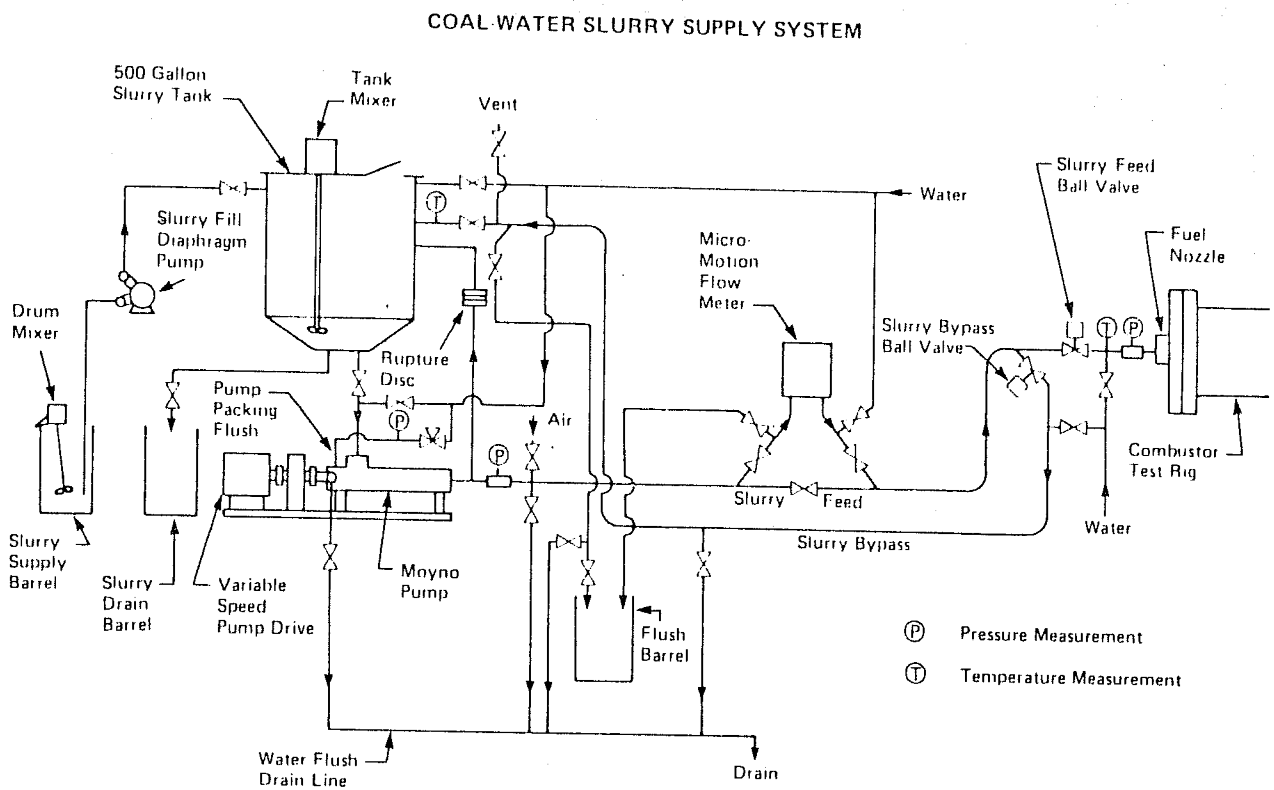

Figure 3-3. Coal Water Mixture Forwarding System

The CWM flow rate to the fuel nozzle is measured by a Micro Motion model C50 flow meter which provides an output signal directly proportional to mass flow. This signal is displayed in the control room adjacent to the pump speed control. A water connection is provided for flushing the flow meter during operation, if necessary, while the CWM flow bypasses the meter.

The CWM flow can be directed either to the fuel nozzle or to a bypass return to the run tank by two air operated ball valves which operate in unison. Flow rate is established through the return line, by setting pump speed, and then switched to the fuel nozzle. A water connection is provided to cool the fuel nozzle prior to CWM flow and to flush the nozzle when slurry flow is completed. A fuel system trip, resulting from loss of flame signal, overtemperature, or other specified events, automatically switches the CWM flow back to the run tank.

The CWM pump discharge pressure and fuel nozzle supply pressure are indicated by transducers connected to Ronningen-Petter Iso-Spools, which transmit pressure via a flexible sleeve rather than a pipe wall tap which would readily be clogged by slurry. CWM temperatures at the fuel nozzle and run tank return are measured by chromel-alumel thermocouples. All CWM system instrumentation, including pressures, temperatures, and flow, is input to the laboratory data acquisition system, which in turn displays data converted to engineering units on control room CRT monitors.

A water flush system is provided for purging the CWM supply system following operation. A flush barrel collects the high concentration discharge which can then be suitably disposed of. Final flush water and system drain water are directed to the laboratory drain. The system can be flushed and drained while retaining the CWM in the run tank for short term storage. Residual CWM in the run tank following operation can be emptied into storage barrels for later use. The run tank itself can then be flushed with water and drained. Continuous water flush is provided for the Moyno pump packing gland. A shop air connection to the CWM system allows blow-out and dry-out following water flush and drain.

This CWM fuel forwarding system was tested using the CWM in a flow test prior to the combustion tests. It has been operational without problems throughout all tests.

Instrumentation and Emission Measurement System

Instrumentation is provided for monitoring and recording rig operating conditions. Pressures, temperatures, and airflows are measured at several rig planes. Fuel flows are measured by turbine-type flow meters for oil, by the Micro Motion meter for CWM and by an ASME orifice for methane.

Analysis of combustor rig exhaust emissions is provided by a sampling system that maintains the sample composition, and by on-line instruments that measure the constituents. Standard emission instrumentation (Table 3-2) includes analyzers for CO, CO_2, O_2, NO_x, UHC and smoke. Smoke is measured by both ASTM and SAE filtering smoke meter techniques.

Table 3-2

EMISSION INSTRUMENTATION

Emission Constituent	Method	Manufacturer
NO_x	Chemiluminescence	TECO
CO	Infrared	HORIBA
CO_2	Infrared	HORIBA
O_2	Electrochemical Cell	Westinghouse
UHC	Flame Ionization	AID
Smoke	ASTM	Bacharach RDC
Smoke	SAE	Roseco

Data Acquisition System

The primary components of the Development Center data acquisition system include a digital acquisition system, an analog acquisition system, and a 14-channel Honeywell 96 tape recorder. A Hewlett Packard model 1000F mini-computer and associated peripherals control the respective systems, process data on line, and direct readouts and displays during a test. The analog tape recorder provides a permanent record of all raw data obtained during testing.

Data output modes of the system include a high speed print-out of data converted to engineering units, a digital display CRT terminal with variable update timing, and a digital tape formatted for further computer processing to obtain final performance calculations and plots.

3.2 DEPOSITION PIN DESIGN

Corrosion, deposition and erosion (CDE) in gas turbines depend on the type and amount of ash in the fuel, the characteristics of the combustion process, the turbine inlet temperature, the turbine hot parts metal temperature, and the aerodynamics of the turbine expansion gas path. Ash in the fuel is the principal source of CDE. The combustion process determines the particle size and chemistry of corrosion-causing and deposit-forming material. The turbine inlet temperature strongly influences the chemistry and physical condition of deposits; the metal temperatures and use of additives determine the magnitude and mode of corrosion attack on turbine blades; and the aerodynamics of the turbine expansion gas path influence deposition and erosion characteristics.

Since the type and amount of ash in the fuel is the most influential in CDE, the chemical makeup and the absolute and relative concentrations of the ash in a fuel can be used to estimate the degree of corrosion and deposition in a given turbine with a well defined operating condition.

A CWM will contain higher concentrations of ash than conventional fuels. It may contain known species of trace metals that are harmful to the gas turbine as well as other unknown species. In addition, the CWM consists of particles of a discrete size, a condition that does not exist in liquid fuels. When the CWM is burned in a combustor, the size of ash particles in the turbine expansion gas that emerges from the combustor and impacts turbine blades and vanes depends on several factors, including particle size distribution of the mixture, efficiency of fuel nozzles, degree and mode of fuel atomization, degree of particle agglomeration in the combustor, and residence time. For these reasons, the preliminary preparation to determine the deposition characteristics of burning a CWM in a gas turbine combustor through testing is included in this report.

The preparation work includes the design and fabrication of cooled circular pins to measure the deposition characteristics and a converging transition duct to increase the velocity of the combustor exhaust that will be exposed to the pins. These higher gas velocities simulate turbine conditions. These velocities are estimated to be on the order of 300 ft/sec at a pressure of 10 atm.

The air cooled deposition pins, shown in Figure 3-4, are 1/2-inch diameter. These pins are made of superalloy (IN617) and are instrumented to measure leading edge metal temperatures at three locations. These metal temperatures can be controlled over a range of 800°F to 1600°F for gas temperatures up to 2000°F. There are two configurations for the cooling air discharges. One configuration is a discharge from the back-side of the pins at the bottom into the base region. The discharged air is then aligned in the same direction as the gas flow. A second configuration is an axial discharge through the bottom of the pin. Each of the pins is held in a pin holder inserted into the rig wall. Four pins are arranged radially in the plane.

This design allows the actual simulation of turbine conditions, whereby a cooling rate is set and maintained after a set initial metal temperature. The resulting metal temperature is a consequence of the deposition process and the gas stream.

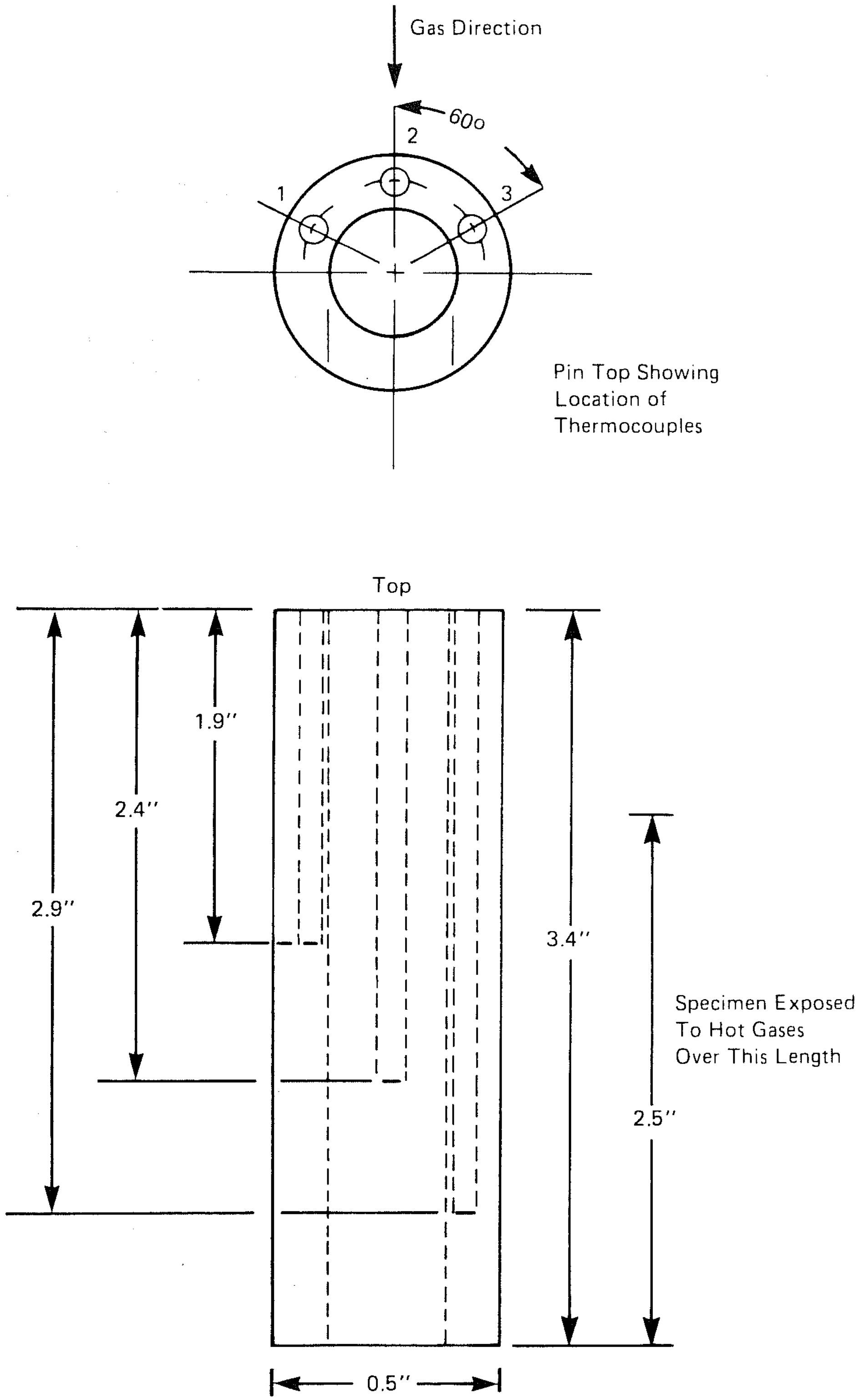

Figure 3-4. Deposition Pin Design for Bottom Discharge of Cooling Air

3.3 PARTICULATE SAMPLING PROBE

The probe used for collecting particulate samples is shown in Figures 3-5 to 3-7. It is water cooled and has a conical shaped sampling tip that extends upstream from the body of the probe into the flow stream. The cooling water flow can be adjusted to control the temperature of the sample.

As the particulate laden sample is withdrawn through the probe it passes through the sampling train shown in Figure 3-8. A straight run of tubing is employed between the probe and the filter to avoid dropping out any of the particulate in bends or restrictions. The filter holder is heated to avoid condensation of water. Downstream of the filter a needle valve is used to throttle the flow of particle-free gas. Most of the pressure drop through the system is taken across this valve. Next, any water vapor is removed in a series of gas impingers immersed in an ice water bath. A rotameter is used in conjunction with the throttle valve to adjust the flow rate for isokinetic conditions at the probe tip. The final component in the sampling train is a dry test meter that measures the gas flow during the sampling period.

Other features of the system include a bypass around the sampling train, reverse flow air purge to clear the probe (if necessary), and a mechanism for traversing the probe radially across the burner outlet flow path. (The location of the particulate probe in the test rig can be seen in Figure 3-1.)

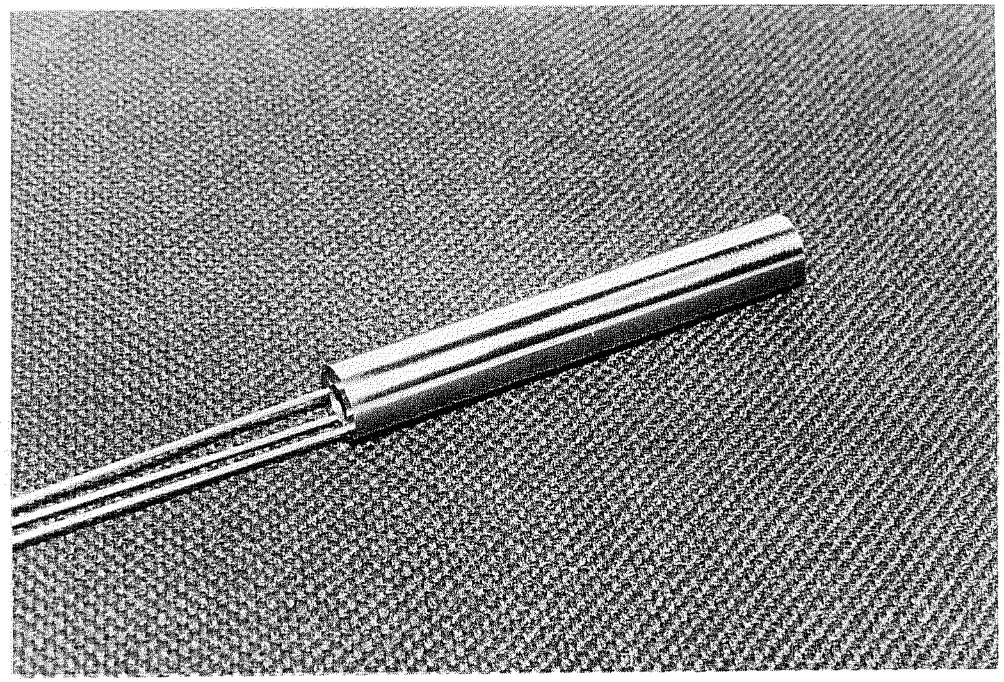

Figure 3-5. Photograph of Deposition Pin Before Test Showing the Thermocouples Leads

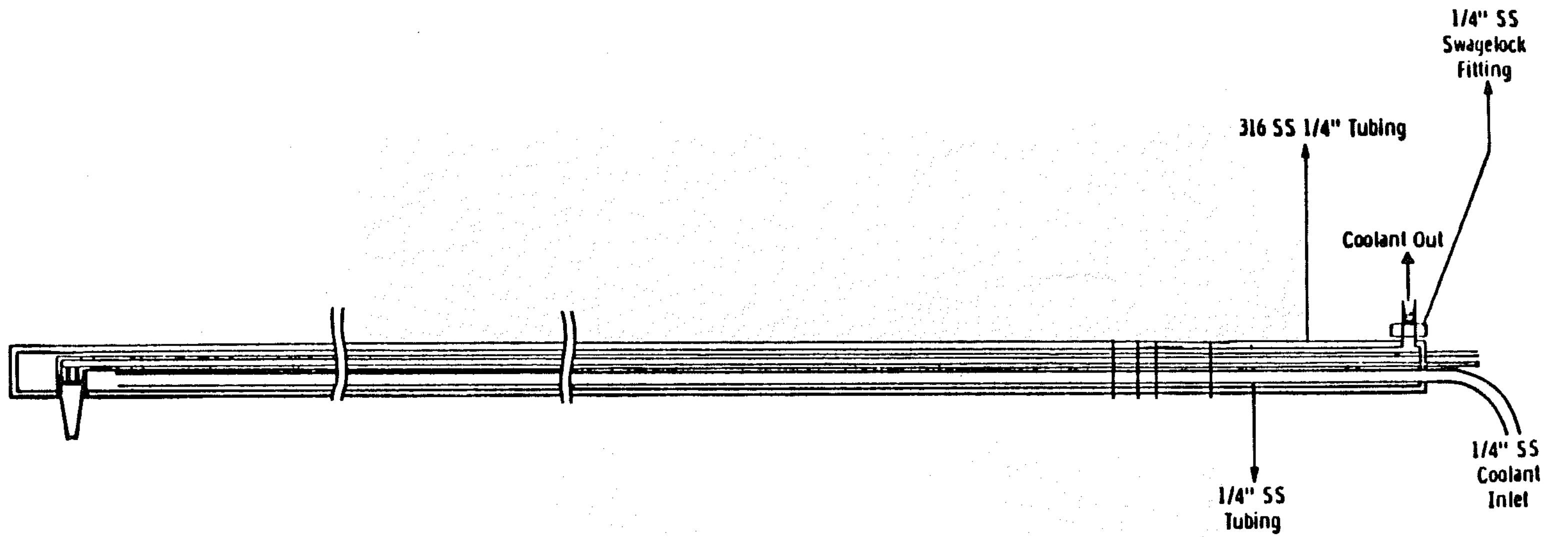

Figure 3-6. Particulate Sampling Probe

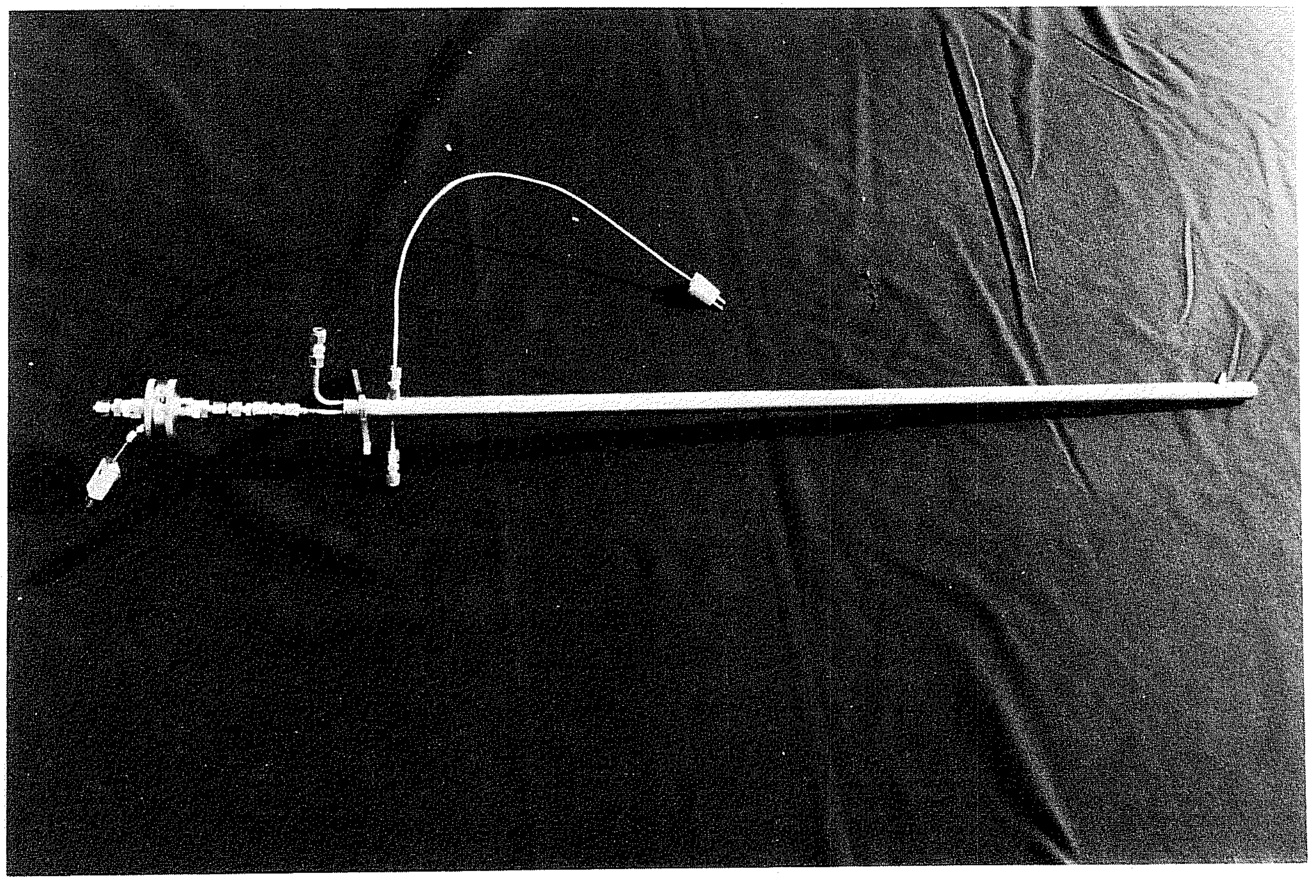

Figure 3-7. Photograph of Particulate Sampling Probe

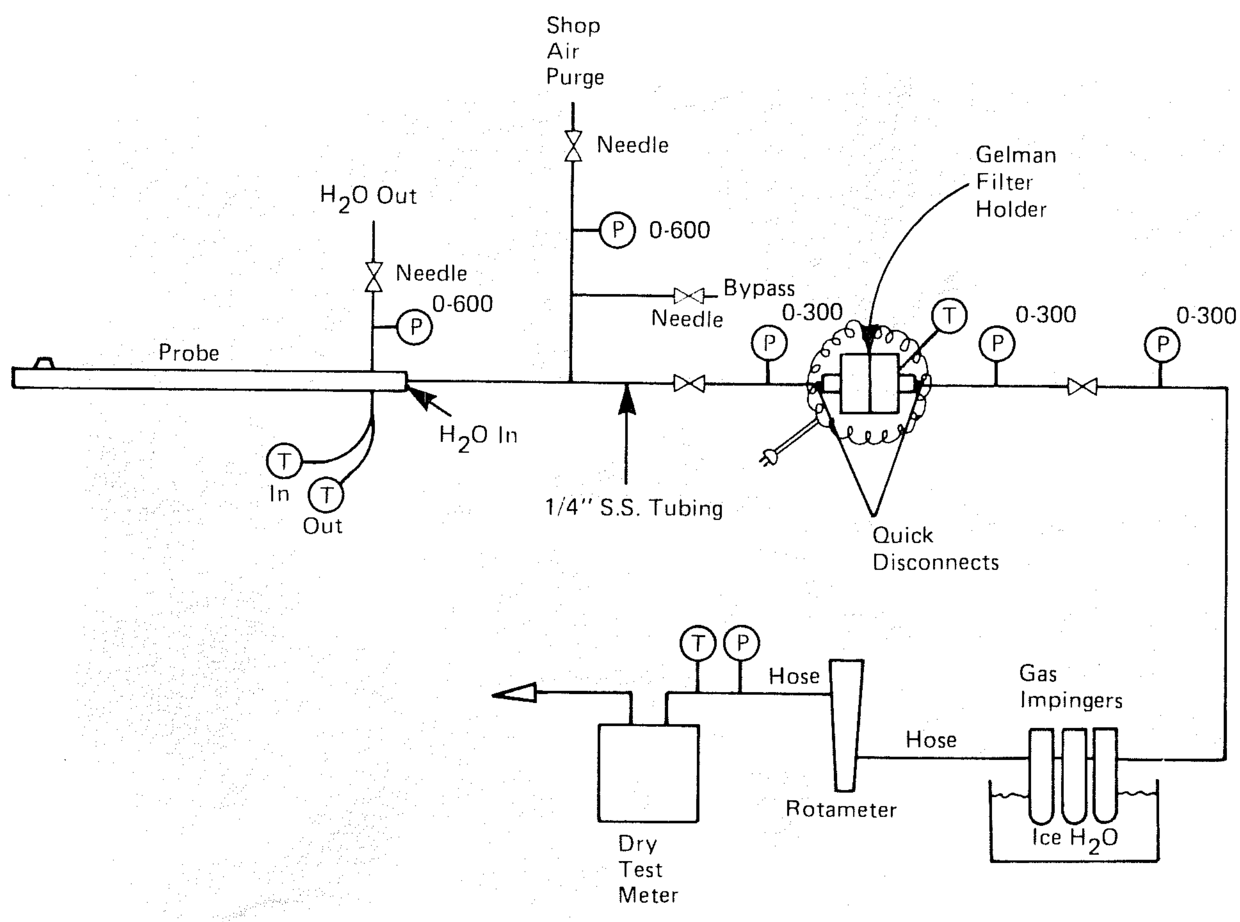

Figure 3-8. Schematic of Particulate Collection System

Section 4

FUEL CHARACTERISTICS

4.1 COAL WATER MIXTURE (CWM)

The CWM fuel, supplied by Otisca, is produced by the Company's Otisca T-Process. This fuel is a mixture of micronized coal particles, water, and additive and has a solid concentration (by weight) of 50.8 percent, an additive of less than 1 percent, and a coal particle size of 100 percent 10 X 0 micron. A typical distribution (from one drum) is shown in Figure 4.1 in a Rosin-Rammler plot. This plot shows that the distribution of particle size follows the Rosin-Rammler distribution closely with a dispersion constant of about 1.4 and with 99 percent of the mass particles smaller than 10 microns. The mode for this typical distribution is at 3.2 microns. The particle size distribution on the composite sample produced by proportionately blending samples from each drum is given in Table 4-1. The particle sizes of the composite sample follows closely that of the typical distribution shown in Figure 4-1.

Table 4-1

PARTICLE SIZE DISTRIBUTION

Diameter Line Number	Diameter Micrometers	Mass Percent	Mass Percent Finer
14	11.3	5.00	100.00
13	8.0	9.37	94.99
12	5.7	17.87	85.62
11	4.0	19.66	67.74
10	2.8	18.46	48.08
9	2.0	11.85	29.61
8	1.4	7.66	17.76
7	1.0	4.19	10.09
6	0.7	2.74	5.90
5	0.5	3.15	3.15

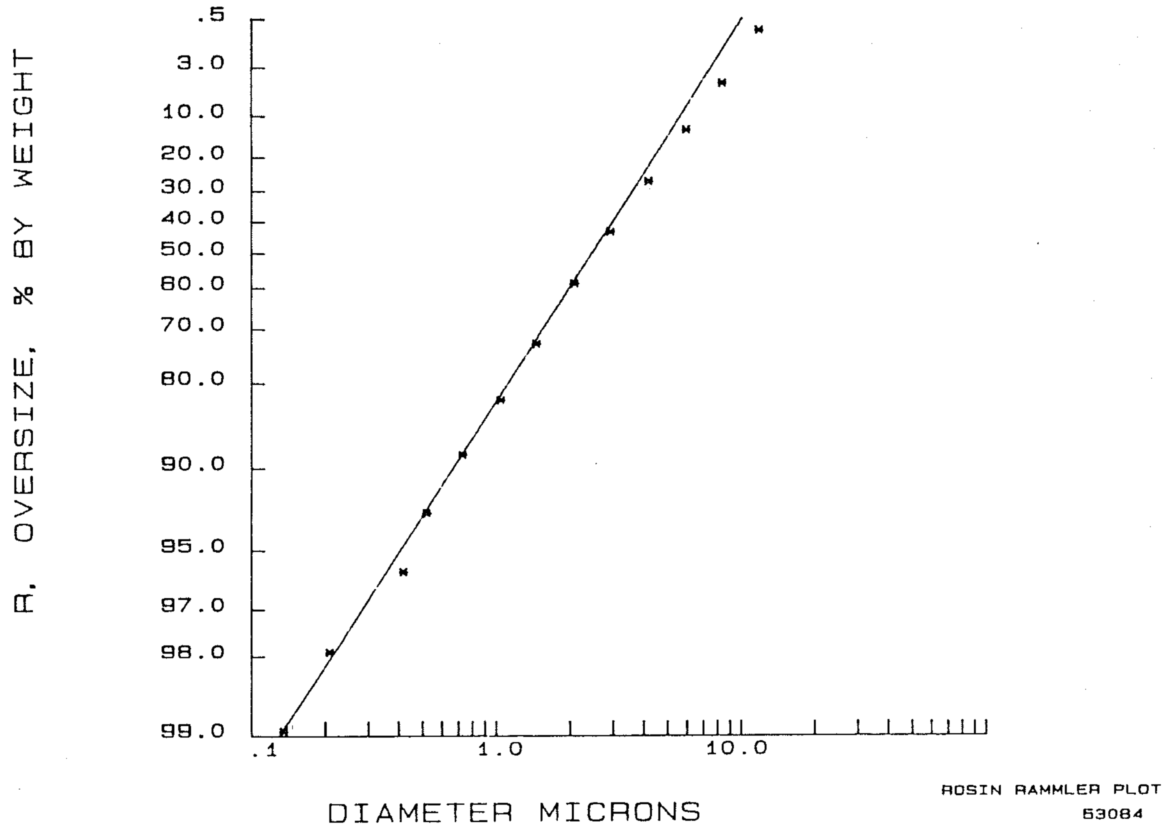

Figure 4-1. Particle Size Distribution - Rosin-Rammler Plot for Typical CWM (Otisca)

The CWM used Eastern Appalachian bituminous coal and the ultimate analysis of the parent coal (from Otisca) is given in Table 4-2.

Table 4-2

ULTIMATE ANALYSIS OF PARENT COAL OF OTISCA CWM

Element	WT%
C	77.72
H	5.24
N	1.65
Cl	0.19
S	1.99
Ash	7.09
O	6.72

The composite lot properties, including proximate analysis of the CWM fuel, are summarized in Table 4-3. This table includes the fuel and rheological properties. The ash content of the slurry is 0.98 percent reduced from the parent coal value of 7.09 percent.

Table 4-3

CWM SPECIFICATIONS COMPOSITE LOT ANALYSIS

Property		Analysis Method**	BTU/lb	Lb./MBTU
Gross Heating Value of Coal in Slurry, Btu/lb Moisture Free		(Note A)	14,100	70.9
Net Heating Value, Slurry, Btu/lb		(Note A)	7,163	139.6
Viscosity @ 20°C (68°F)		(Note E)	301 cp at 112 S^{-1}	
Proximate/Ultimate Analysis, Slurry*			Weight %	Lb./MBTU
Sulfur	% in slurry	(Note F)	0.72	0.51
Ash	% in slurry	D3174	0.98	0.59
Moisture	% in slurry	D3173	2.05	
Volatile Carbon	% in coal, dry basis*	D3172	41.81	
Fixed	% in coal, dry basis*	D3172	55.16	
Particle Sizing, top size		D185	10 micrometers	
volume mean size		(Note D)	4 micrometers	
Coal loading of Slurry Wt.% (Note B)		D3173	50.8	
Free Swelling Index, Coal (Note C)		D720	7	
Ash Fusion Temperature Reducing IT		D1857	2,300°F	
Slurry Density		(Note D)	9.36 Lb./gal.	

*For analysis of slurry using methods calling for use of solids, the slurry will be evaporated to dryness before beginning the analysis. Thus, any additives will be included. Where analysis of coal is called for, the cleaned coal used in the slurry will be analyzed. The methods specified that begin with the letter D are ASTM standards.
**See Table 4-4 for Notes A to F.

Table 4-4

ANALYSIS METHOD FOR CWM ANALYSIS OF TABLE 4-3

A See ASTM D122 for definition. Tests performed using a Parr bomb calorimeter.

B The moisture in the slurry is consistent with coal loading. The value of moisture reported is usable in calculating the ultimate analyses on a dry basis.

C The free swelling index must be performed on the raw parent coal. The Otisca OTP coal is too fine for this analysis.

D Particle sizing is performed using a Micromerities Sedigraph 5000L. When necessary, these data are combined with standard seive screen data.

E Performed using a Haake Rotovisco Model RV-3. Density determined using a pycnometer.

F LECO sulfur analysis technique standardized using D3177.

Section 5

COMBUSTION TEST DATA

This Final Report, Vol. II, covers the last three tests (D015.1, D016.0 and D017.0) of the Low Emission Combustor Technology Program. Important test data are summarized in this Section; a more detailed tabulation appears in Appendices A1, A2 and A3. The results of earlier tests were reported in References 1 and 2.

5.1 COMBUSTION EFFICIENCY

The emphasis in the tests reported here was on obtaining high combustion efficiency on CWM. Methane was used as a startup fuel and also as a pilot fuel when burning CWM. Operating conditions and burner modifications for the test series are summarized in Table 5-1, which includes Test D014.1 for comparison. The best results from earlier CWM tests were obtained in D014.1.

Table 5-1

SUMMARY OF OPERATING CONDITIONS AND BURNER MODIFICATIONS

	D014.1	D015.1	D016.0	D017.0
Pressure (psia)	119-169	110	102-164	18-175
Air Flow (pps)	3.2-4.3	4.0	4.1-7.5	1.6-8.5
Air Temp. (°F)	757-805	757	571-764	464-701
Nozzle Position	Throat of Ceramic Quarl	Throat of Ceramic Quarl	Withdrawn 1"	Withdrawn 1"
Spray Angle	70°	110°	110°	55°
Metal Quarl	Yes	Yes	Yes	No
Flow Area Distribution (%)				
Swirler #1	18.0	6.6	17.8	12.0
Swirler #2	13.8	15.5	13.6	14.6
Swirler #3	32.9	22.9	20.2	21.6
Swirler #4	14.7	31.9	28.0	30.0
Spring Leakage	20.6	23.2	20.4	21.8

During Test D017.0 variable geometry was employed to control the air to swirler #1. Best flame stability was obtained with the percentage of air listed in Table 5-1, and this setting was maintained for all CWM test points. Swirler flow area percentages are based on calculated design flow areas.

Combustion efficiencies measured during the four tests are plotted in Figure 5-1 as a function of the ratio of methane pilot fuel to CWM (The results obtained in D014.1 were not repeated in the subsequent three tests). Also, the complete transfer from methane to CWM achieved in D014.1 was not duplicated. Combustion efficiencies were also plotted versus inlet air temperature, burner primary zone equivalence ratio and burner primary zone residence time. Little or no functional dependency was found with these variables.

Due to the low combustion efficiencies determined by exit thermocouples, emissions were generally not taken during coal slurry test points to avoid fouling the sampling system. However, emissions were taken during one CWM test point in D017.0. The 2500 ppmv CO and 2000 ppmv UHC measured could not account for the 60 percent combustion efficiency measured by exit thermocouples indicating that most of the ineffficency was tied up in particulates. (Particulate measurements are discussed in Section 5.3.) Emissions measured during methane test points were typically 1 or 2 ppmv each of CO and UHC indicating essentially complete combustion.

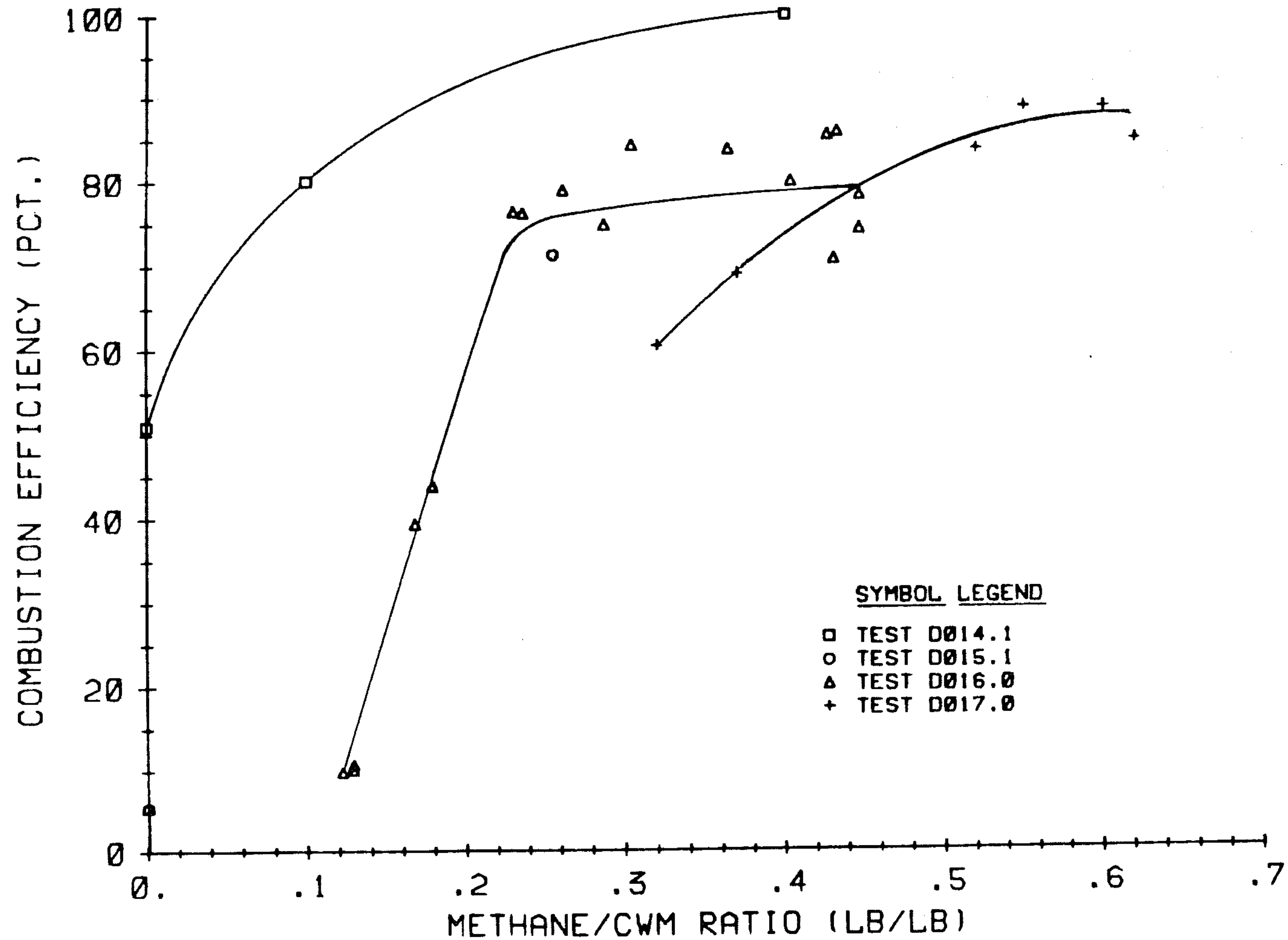

Figure 5-1 Combustion Efficiency on Methane/CWM Mixtures

5.2 OTHER RESULTS

Calculated primary zone stoichiometries, burner and primary zone heat release rates and primary zone residence times are listed in Table 5-2. Ranges are shown for CWM test points during each test. Values for individual test points can be found in the Appendices.

Table 5-2

STOICHIOMETRIES, HEAT RELEASE RATES* AND RESIDENCE TIMES**

	D014.1	D015.1	D016.0	D017.0
Primary Zone Equivalence Ratio	.14-1.06	.97	.59- .96	.46- 1.17
Burner Heat Release Rate	.10- .59	.56	.45- .80	.32- 1.80
Burner Heat Release Rate X η_c	.03- .42	.40	.08- .59	.41- 2.99
Primary Zone Heat Release Rate	.31-1.77	2.19	1.88-2.90	1.77-11.98
Primary Zone Heat Release Rate X η_c	.09-1.72	1.56	.28-2.46	1.33- 7.20
Primary Zone Residence Time	14.8-18.8	18.2	9.5-18.6	4.0 -13.1

*10^6 Btu/Hr Ft^3 Atm.
**MS

Primary zone equivalence ratio is based on air from swirlers 1 and 2, atomizing air and all fuel entering the burner. This parameter was varied from lean to rich with little observed effect on stability or combustion efficiency. Stability was adversely affected if the air to swirler #1 was reduced below 10 percent of the main air flow.

Burner heat release rates are based on the entire fuel flow. Primary zone heat release rates are based on methane plus coal volatiles, which are assumed to be 60 percent of the heating value of the coal. Typical CWM heat release rates attempted during this program are 0.5 x 10^6 Btu/hr ft^3 atm for the burner and 2 X 10^6 Btu/hr ft^3 atm in the primary zone. These are about an order of magnitude larger than those reported by other researchers (3, 4).

Bulk residence times in the primary zone were 10-18 ms with the exception of one test point that was run at atmospheric pressure. These times exceed the 5 ms required for evaporation of water and devolatilization of coal for the 40-50 µm SMD droplets produced by the Parker Hannifin nozzle (3).

Burner outlet temperature profiles for the MASB burning mixtures of methane and slurry are shown in Figures 5-2 and 5-3 for Tests D016.0 and D017.0. The various symbols are for different probes that extend radially into the flow path. Burner outlet temperature was about the same in both cases, 1416°F vs. 1439°F. The figures show that removing the metal quarl from the burner between Tests D016.0 and D017.0 had little effect on the outlet profile. In both cases the patterns are desirably flat.

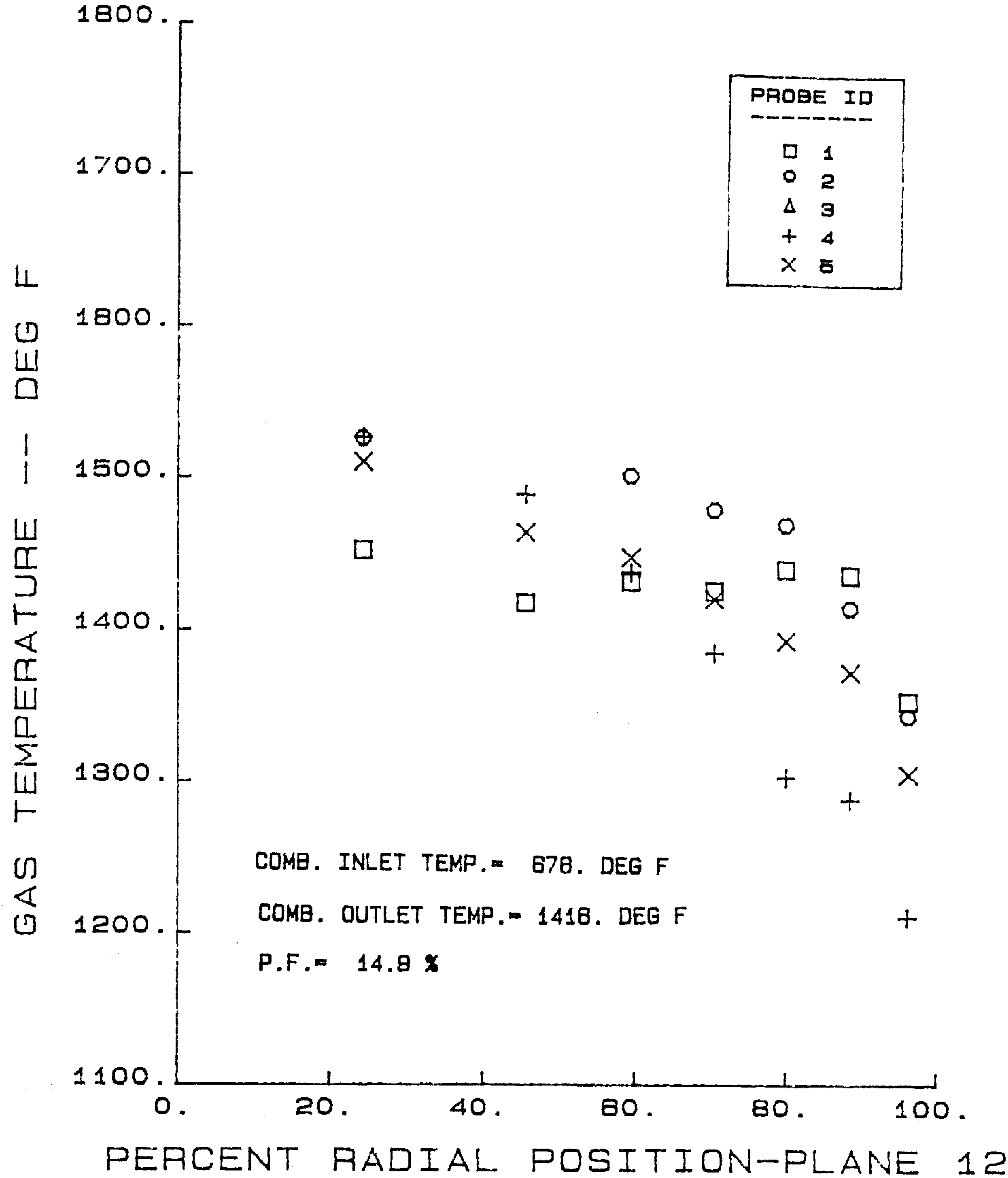

Figure 5-2. Radial Burner Outlet Temperature Profile, Test D016.0

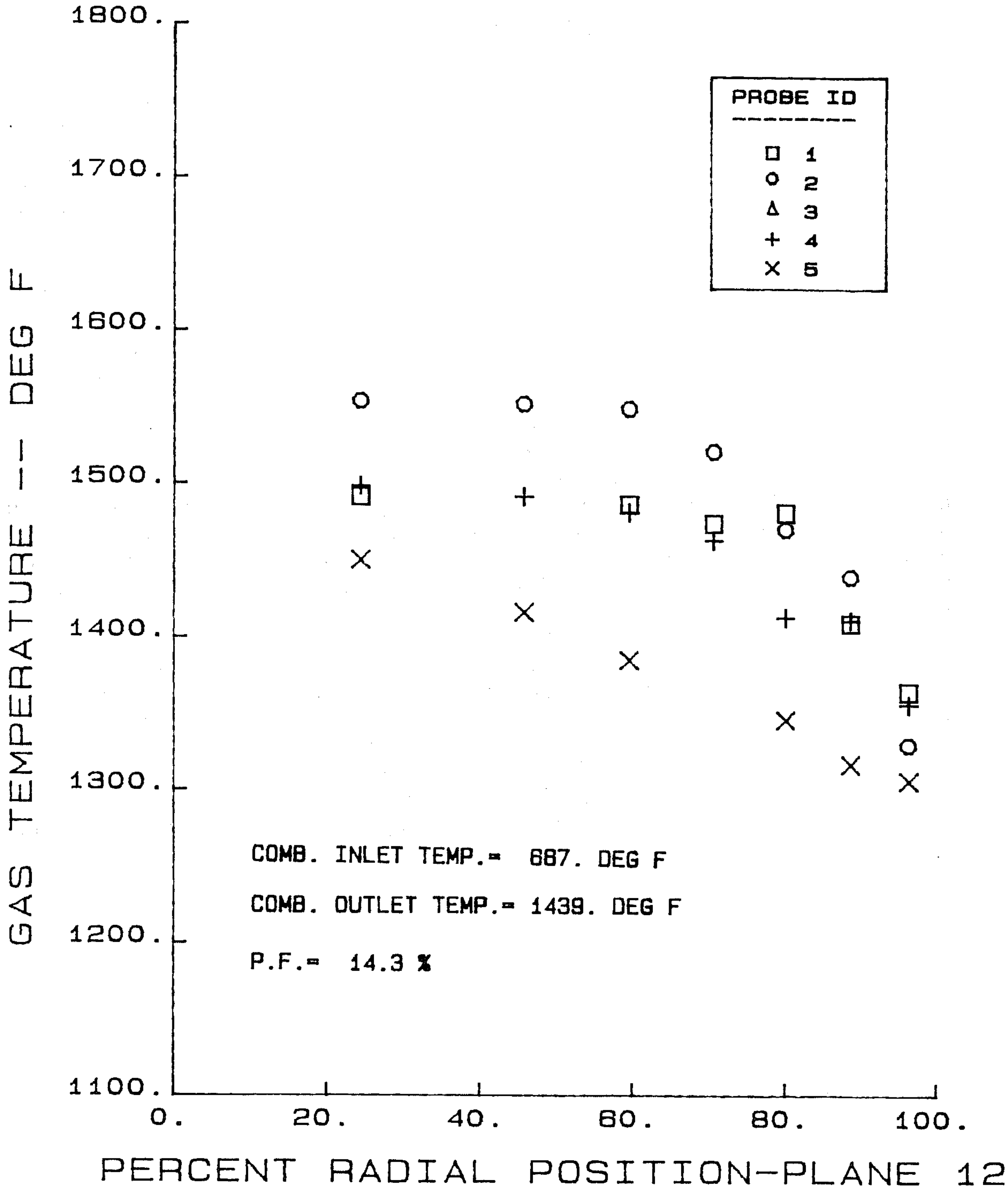

Figure 5-3. Radial Burner Outlet Temperature Profile, Test D017.0

5.3 PARTICULATE SAMPLES

Scanning electron micrographs (SEM) of particulates collected during Test D016.0 are shown in Figures 5-4 and 5-5. The two samples were collected on the axis of the duct and four inches from the axis respectively. The radius of the duct at the sampling plane (See Figure 3-1) is 7 inches. The large strands are filter material and the somewhat smaller particulates can be seen attached to the strands. The particulates are less than 10μm indicating that no agglomeration of coal particles has taken place. Elements identified by non-quantitative energy dispersive spectroscopy (EDS) were Na, Al, S, K, Ca, Fe, Mg and Ni. (Carbon and hydrogen cannot be detected by this technique.)

The particulate loading at the 4 inch radial position was an order of magnitude larger than on the axis, but was an order of magnitude lower than that required to explain the combustion efficiency as measured by exit thermocouples. Apparently the concentration gradient is very large with most of the particles either sprayed or centrifuged to the outside of the flow. Inert particle trajectories calculated by the flow field analysis (1) for 10μm particles show that they generally follow streamlines near the combustor wall. If the particles were centrifuged, then there would be concern that they were larger than 10μm and that agglomeration was taking place that did not show up in the particulate samples which were taken closer to the center of the duct. However, particles were also collected on a deposition pin which was located on the outer boundary of the flow passage at the emissions sampling plane (Figure 3-1).

Figure 5-6 shows that the particles collected on the pin were larger than those collected by the probe but were still less than 10μm, again indicating that agglomeration was not taking place. Elements found by EDS analysis of the pin deposit were S, Mg, Al, K, Ca and Fe. Figure 5-7 is a post-test photograph (Figure 3-5 is a photograph of pre-test pin) of a deposition pin showing a thicker deposit at the periphery of the flow (near the nut). The particulate sample in Figure 5-6 was taken from this region of the thicker deposit.

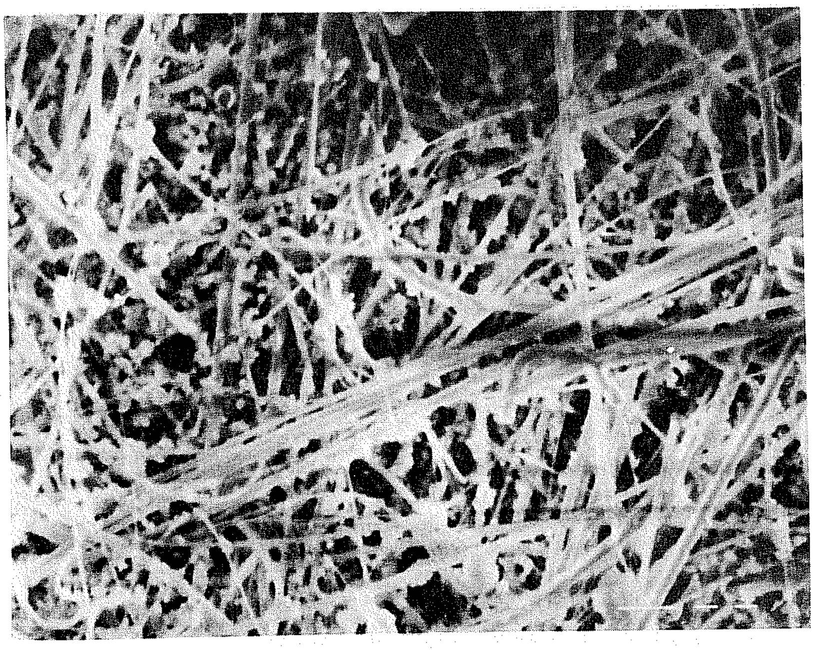

Figure 5-4. Particulate Sample taken on Axis of Flow, Test D016.0

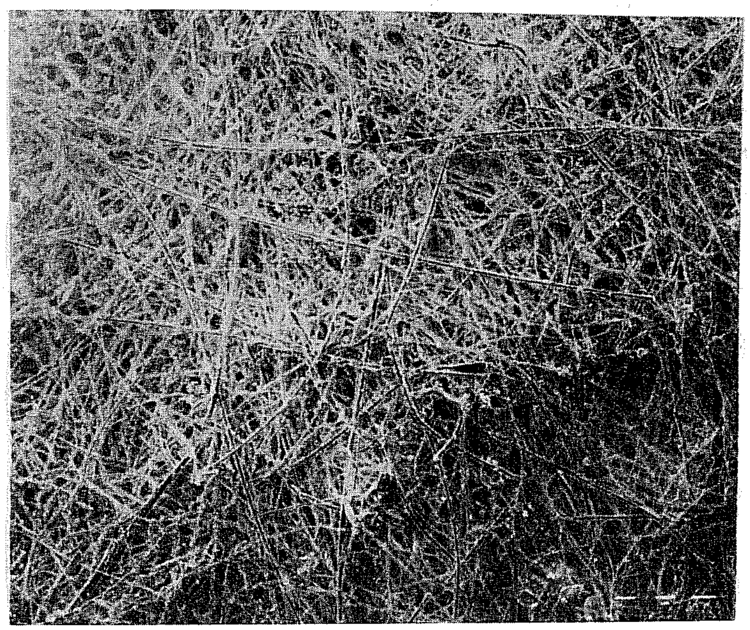

Figure 5-5 Particulate Sample Taken 4 Inches from Axis, Test D016.0

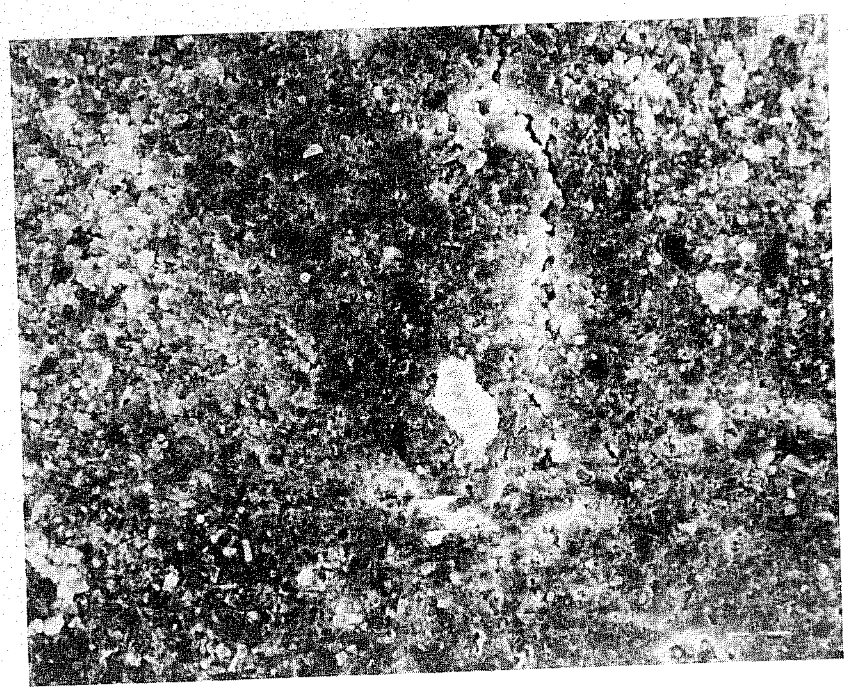

Figure 5-6. Particulate Sample Collected on Deposition Pin, Test D016.0

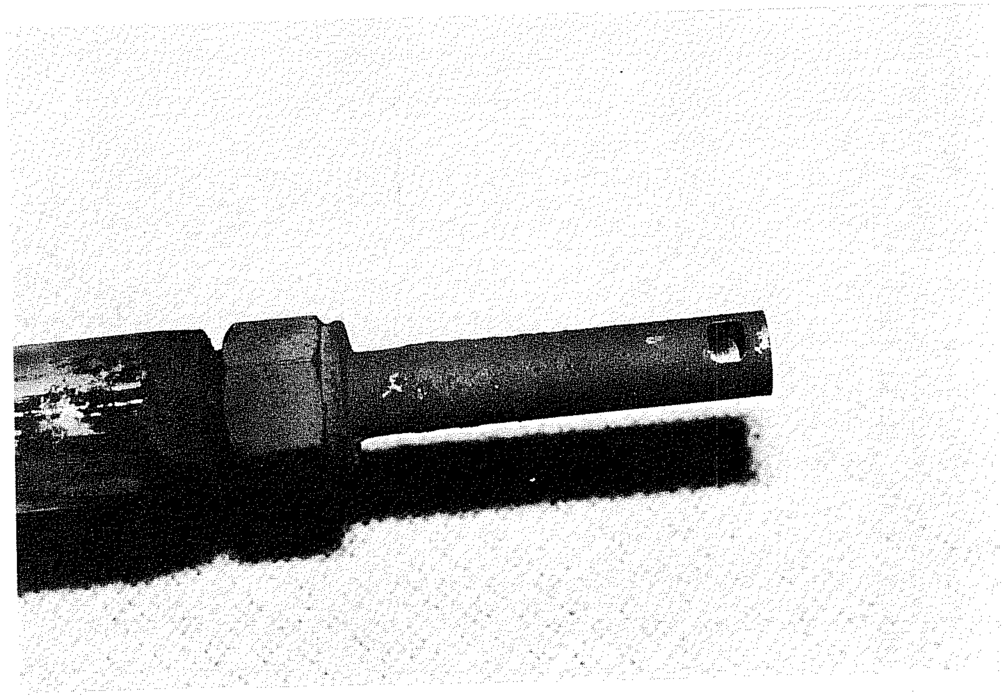

Figure 5-7. Post-Test Photograph of Deposition Pin

REFERENCES

1. Lew, H. G. and Toof, J. L., "Comprehensive Data Report, Low Emission Combustor Technology Program," DOE/METC Contract DE-AC21-82MC20228 (June 1984).

2. Lew, H. G. and Toof, J. L., "Final Report, Low Emission Combustor Technology Program," DOE/METC Contract DE-AC21-82MC20228 (May 1984).

3. Walsh, P.M., et. al., "Ignition and Combustion of Coal-Water Slurry in a Confined Turbulent Diffusion Flame," Twentieth Symposium (International) on Combustion, August, 1984.

4. Waltermire, D.M. Grimm, U. Anderson, R. J., "Performance Characterization of an Atmospheric Pressure Combustor for Ultra-clean Coal Water Mixtures," DOE/METC/84-25 (DE84011990), April 1983.

Section 6

CONCLUSIONS AND RECOMMENDATIONS

The Low Emission Combustor Technology Program was to evaluate the feasibility of the combustion of coal water mixture (CWM) in the Multiannular Swirl Burner (a gas turbine combustor). The results are contained in the Comprehensive Data Report (1) the Final Report, Volume I (2) and this report (Final Report, Volume II). The former reports contain the design of the MASB for CWM combustion, the test facility modifications, the fuel characteristics and selection, and combustion tests with CWM, methane, #2 distillate, and #2 distillate with the addition of pyridine for the simulation of fuel bound nitrogen effects. In addition, the Comprehensive Data Report contained the numerical model of the MASB combustor flow field, the fuel nozzle spray tests, and the method for the data analysis including the equations used.

Further combustion tests of the Multiannular Swirl Burner (MASB) burning coal water mixture are discussed in this report. Air-cooled deposition pins have been designed, and preliminary tests have shown their capability in collecting coal ash deposits on the metal surface for an initial preset metal temperature. In addition, an isokinetic particulate sampling probe and collection system have been implemented and particulate samples have been obtained in the tests. Six tests were performed in the Low Emission Combustor Technology Program; one test used No. 2 distillate fuel oil, and five tests used a coal water mixture. The CWM fuel used in all the tests contains 50 percent solids with a maximum particle size of 10μm.

The results of the first three tests were presented in the Comprehensive Data Report (1) and the Final Report, Volume I (2). In those tests combustion efficiencies up to 99.5 percent were achieved with a mixture of CWM and methane (72 percent/28 percent by weight). In addition, a complete transfer from methane to a stable CWM flame was accomplished. Combustion efficiency when burning CWM alone was 53 percent. During the program, burner heat release rates of one-half million Btu/hr ft^3 atm were achieved -- which is an order of magnitude larger than rates reported by other researchers (see Refs. 5-3 and 5-4). This was accomplished burning a CWM containing 53 percent water in a metal wall combustor.

The primary objective of the three tests presented in this report was to improve the CWM combustion efficiency obtained in the earlier tests. A number of changes were made to the burner (air distribution, spray angle, nozzle position) and in the operating conditions (air flow, air temperature, pressure) throughout the test program with very little effect on performance. No improvement in combustion efficiency was obtained. It appears at this point that either a more significant change is required in the burner or that the fuel is the limiting factor.

Given the stability achieved in the MASB with methane and distillate fuels and in light of information on the stability of oil flames with water injection (3), it seems that the energy content of the CWM fuel must be improved. The ratio of water to volatiles is too high in the present CWM to consistently provide a stable flame at the heat release rates being attempted. Experience indicates that a solids concentration of at least 60 percent is required to provide an acceptable water to volatiles ratio for stability. Such a fuel was originally planned for this program but was not available with sufficiently small sized coal particles at the time.

Potential improvements in the MASB combustor have also been identified. The diameter of the primary zone should be increased to 12 inches. This will increase the residence time available for evaporation and devolatilization and, more important, will provide more room for establishing a recirculation zone. Also, the recirculation zone should be lengthened to prevent high velocity injected fuel particles from passing through the recirculation region before water evaporation and some devolatilization can take place. This could be accomplished with the reverse injection of air (or fuel) approximately twelve inches downstream of the existing fuel nozzle position.

Principal conclusions from this program can be summarized as follows:

- Combustion tests on methane and No. 2 fuel oil shown high efficiencies in a 10 inch diameter MASB with forced vortex design.
- Combustion of a CWM with 50 percent solids in a gas turbine combustor is possible but improvement in the combustion efficiencies is required.
- A transfer from methane to CWM at load has been demonstrated for a metal wall combustor.

Based on the above discussion, specific recommendations to improve stability and combustion efficiency can be summarized as follows:

- Increase the energy content of the fuel. Candidates would be a CWM with 60-75 percent solids or a coal/methanol/water mixture.
- Increase the diameter of the primary zone of the burner to widen the recirculation zone.
- Add reverse injection of air (or fuel) to lengthen the recirculation zone.
- Use ceramic lining on the combustor walls to decrease the heat loss and thereby increase the flame stability.

REFERENCES

1. Lew, H.G. and Toof, J.L., "Comprehensive Data Report - Low Emission Combustor Technology Program," DOE/METC Contract DE-AC21-82MC20228 (September 1984).

2. Lew, H.G. and Toof, J.L., "Final Report, Volume I - Low Emission Combustor Technology Program," DOE/METC Contract DE-AC21-82MC20228 (September 1984).

3. Moorman, R. J. and Long, C.H., "Design, Development and Testing of a Swirl Type Gas Burner with Flue Gas Recirculation for NO_x Control," ASME 73-PW-21 (1973).

APPENDICES

Data from Tests D015.1, D016.0 and D017.0 are tabulated in Appendices A-1, A-2 and A-3. For each test no fuel was burned in Run 1 (cold flow), methane was burned in Run 2 and mixtures of methane and CWM were burned in the remaining runs.

APPENDIX A-1

TEST D015.1 04-10-84

Combustor Test Summary

Description	Run 1	Run 2	Run 3
Combustor Inlet Temp. - °F	723.	766.	757.
Atomizing Air Temp. - °F	648.	664.	617.
Combustor Exit Temp. - °F	655.	1376.	1423.
Adiabatic Exit Temp. - °F	721.	1482.	1696.
Combustor Temp. Rise - °F	-66.	612.	670.
Peak Temp. Plane - °F	704.	1576.	1626.
Pattern Factor - Plane 12	-.742	.327	.303
Comb. Inlet Pressure - psia	117.60	120.50	109.51
Main Air Flow - pps	3.088	4.032	3.963
Atomizing Air Flow - pps	.083	.080	.102
Total Air Flow - pps	3.171	4.112	4.065
Methane Flow - pps	.000	.042	.024
Slurry Flow - pps	.000	.000	.094
Oil Flow - pps	.000	.000	.000
Fuel/Air Ratio	0.00000	0.01021	0.02903
Reference Velocity - fps	21.66	28.70	31.57
Continuity Velocity - fps	20.42	42.98	48.85
Comb. Eff. - Delta T - %	0.00	0.00	71.05
Comb. Eff. - Emissions - %	0.00	0.00	0.00
Pri. Zone Equiv. Ratio	0.00	0.74	0.97
Burner H.R.R. - *	0.00	0.40	0.56
Burner H.R.R. X η_c -*	0.00	0.40	0.40
Pri. Zone H.R.R. -*	0.00	1.98	2.19
Pri. Zone H.R.R. x η_c -*	0.00	1.98	1.56
Pri. Zone Res. Time - ms	0.00	21.6	18.2
CH_4/CWM - lb/lb	0.00	0.00	0.26

*10^6 Btu/hr ft^3 atm (H.R.R. = Heat Release Rate)

APPENDIX A-2

TEST D016.0 05-30-84

Combustor Test Summary

Description	Run 1	Run 2	Run 3	Run 4
Combustor Inlet Temp. - °F	642.	576.	571.	607.
Atomizing Air Temp. - °F	67.	58.	491.	524.
Combustor Exit Temp. - °F	502.	1214.	1344.	1490.
Adiabatic Exit Temp. - °F	626.	1394.	1564.	1863.
Combustor Temp. Rise - °F	-140.	638	773.	883.
Peak Temp. Plane - °F	568.	1471.	1521.	1723.
Pattern Factor - Plane 12	-.475	.403	.228	.264
Comb. Inlet Pressure - psia	120.5	123.0	164.3	155.9
Main Air Flow - pps	3.361	3.569	4.628	4.103
Atomizing Air Flow - pps	.099	.098	.096	.096
Total Air Flow - pps	3.460	3.667	4.724	4.199
Methane Flow - pps	0.000	.040	.038	.044
Slurry Flow - pps	0.000	0.000	.085	.102
Oil Flow - pps	0.000	0.000	0.000	0.000
Fuel/Air Ratio	0.00000	.01079	.02609	.03463
Reference Velocity - fps	18.20	17.95	17.51	17.10
Continuity Velocity - fps	15.96	29.15	30.80	31.42
Comb. Eff. - Delta T - %	0.00	0.00	77.93	70.35
Comb. Eff. - Emissions -%	0.00	99.98	0.00	0.00
Pri. Zone Equiv. Ratio	0.00	0.56	0.73	0.96
Burner H.R.R. -*	0.00	0.37	0.45	0.56
Burner H.R.R. X η_c -*	0.00	0.37	0.36	0.39
Pri. Zone H.R.R. -*	0.00	1.85	1.88	2.32
Pri. Zone H.R.R. x η_c -*	0.00	1.85	1.47	1.63
Pri. Zone Res. Time - ms	0.00	17.8	17.9	18.6
CH_4/CWM lb/lb	0.00	0.00	0.45	0.43

*10^6 Btu/hr ft^3 atm

APPENDIX A-2

TEST D016.0 05-30-84

Combustor Test Summary

Description	Run 5	Run 6	Run 7	Run 8
Combustor Inlet Temp. - °F	633.	649.	675.	701.
Atomizing Air Temp. - °F	550.	567.	591.	597.
Combustor Exit Temp. - °F	1518.	1420.	1416.	1398.
Adiabatic Exit Temp. - °F	1827.	1618.	1563.	1636.
Combustor Temp. Rise - °F	883.	771.	741.	697.
Peak Temp. Plane - °F	1818.	1579.	1527.	1521.
Pattern Factor - Plane 12	.343	.207	.150	.176
Comb. Inlet Pressure - psia	155.0	149.8	150.7	151.1
Main Air Flow - pps	4.514	5.370	5.963	6.360
Atomizing Air Flow - pps	.095	.092	.087	.082
Total Air Flow - pps	4.609	5.462	6.050	6.442
Methane Flow - pps	.046	.042	.040	.041
Slurry Flow - pps	.103	.104	.110	.143
Oil Flow - pps	0.000	0.000	0.000	0.000
Fuel/Air Ratio	.03232	.02656	.02487	.02850
Reference Velocity - fps	19.30	23.90	26.87	29.29
Continuity Velocity - fps	35.08	40.81	44.91	47.42
Comb. Eff. - Delta T - %	74.01	79.57	83.39	74.58
Comb. Eff. - Emissions -%	0.00	0.00	0.00	0.00
Pri. Zone Equiv. Ratio	0.91	0.74	0.67	0.73
Burner H.R.R. -*	0.58	0.57	0.57	0.65
Burner H.R.R. X η_c -*	0.43	0.45	0.48	0.48
Pri. Zone H.R.R. -*	2.42	2.35	2.31	2.58
Pri. Zone H.R.R. x η_c -*	1.79	1.87	1.93	1.92
Pri. Zone Res. Time - ms	17.0	14.2	13.0	12.2
CH_4/CWM lb/lb	0.45	0.40	0.36	0.29

*10^6 Btu/hr ft^3 atm

APPENDIX A-2

TEST D016.0 05-30-84

Combustor Test Summary

Description	Run 9	Run 10	Run 11	Run 12
Combustor Inlet Temp. - °F	728.	753.	758.	763.
Atomizing Air Temp. - °F	613.	624.	631.	634.
Combustor Exit Temp. - °F	1425.	1570.	1414.	1409.
Adiabatic Exit Temp. - °F	1544.	1714.	1539.	1584.
Combustor Temp. Rise - °F	697.	816.	656.	646.
Peak Temp. Plane - °F	1513.	1665.	1520.	1510.
Pattern Factor - Plane 12	.126	.117	.162	.156
Comb. Inlet Pressure - psia	148.5	150.9	149.9	149.5
Main Air Flow - pps	6.768	6.618	6.939	7.447
Atomizing Air Flow - pps	.088	.089	.087	.086
Total Air Flow - pps	6.856	6.707	7.026	7.533
Methane Flow - pps	.045	.053	.038	.040
Slurry Flow - pps	.104	.124	.125	.153
Oil Flow - pps	0.000	0.000	0.000	0.000
Fuel/Air Ratio	.02171	.02630	.02316	.02559
Reference Velocity - fps	32.24	31.84	33.63	36.40
Continuity Velocity - fps	51.94	54.15	52.61	56.62
Comb. Eff. - Delta T - %	85.43	84.98	83.99	78.69
Comb. Eff. - Emissions -%	0.00	0.00	0.00	0.00
Pri. Zone Equiv. Ratio	0.62	0.74	0.60	0.64
Burner H.R.R. -*	0.60	0.70	0.59	0.68
Burner H.R.R. X η_c -*	0.51	0.59	0.50	0.54
Pri. Zone H.R.R. -*	2.49	2.90	2.35	2.64
Pri. Zone H.R.R. x η_c -*	2.13	2.46	1.97	2.08
Pri. Zone Res. Time - ms	11.5	11.7	11.2	10.4
CH_4/CWM lb/lb	0.43	0.43	0.30	0.26

*10^6 Btu/hr fT^3 atm

APPENDIX A-2

TEST D016.0 05-30-84

Combustor Test Summary

Description	Run 13	Run 14	Run 15	Run 16
Combustor Inlet Temp. - °F	764.	762.	722.	721.
Atomizing Air Temp. - °F	637.	633.	622.	620.
Combustor Exit Temp. - °F	1417.	1399.	819.	814.
Adiabatic Exit Temp. - °F	1624.	1599.	1645.	1655.
Combustor Temp. Rise - °F	653.	637.	97.	93.
Peak Temp. Plane - °F	1536.	1512.	952.	947.
Pattern Factor - Plane 12	.182	.177	1.368	1.440
Comb. Inlet Pressure - Psia	149.5	149.3	104.4	104.5
Main Air Flow - pps	7.310	7.467	5.333	5.196
Atomizing Air Flow - pps	.087	.089	.090	.091
Total Air Flow - pps	7.397	7.555	5.422	5.287
Methane Flow - pps	.039	.038	.021	.021
Slurry Flow - pps	.165	.165	.163	.163
Oil Flow - pps	0.000	0.000	0.000	0.000
Fuel/Air Ratio	.02760	.02691	.03404	.03476
Reference Velocity - fps	35.84	36.57	36.57	35.60
Continuity Velocity - fps	55.96	56.63	40.02	38.87
Comb. Eff. - Delta T - %	75.98	76.16	10.68	10.11
Comb. Eff. - Emissions -%	0.00	0.00	0.00	0.00
Pri. Zone Equiv. Ratio	0.67	0.65	0.73	0.75
Burner H.R.R. -*	0.70	0.69	0.80	0.80
Burner H.R.R. X η_c -*	0.53	0.53	0.09	0.08
Pri. Zone H.R.R. -*	2.69	2.66	2.85	2.85
Pri. Zone H.R.R. x η_c -*	2.04	2.03	0.30	0.29
Pri. Zone Res. Time - ms	10.5	10.3	9.8	10.0
CH_4/CWM lb/lb	0.24	0.23	0.13	0.13

*10^6 Btu/hr ft^3 atm.

APPENDIX A-2

TEST D016.0 05-30-84

Combustor Test Summary

Description	Run 11	Run 18	Run 19	Run 20
Combustor Inlet Temp. - °F	719.	721.	721.	719.
Atomizing Air Temp. - °F	620.	598.	598.	598.
Combustor Exit Temp. - °F	808.	1055.	1054.	1023.
Adiabatic Exit Temp. - °F	1636.	1486.	1485.	1495.
Combustor Temp. Rise - °F	88.	334.	333.	304.
Peak Temp. Plane - °F	943.	1226.	1226.	1206.
Pattern Factor - Plane 12	1.529	.512	.517	.602
Comb. Inlet Pressure - psia	104.1	102.2	102.2	102.3
Main Air Flow - pps	5.288	5.504	5.514	5.361
Atomizing Air Flow - pps	.089	.089	.089	.091
Total Air Flow - pps	5.377	5.593	5.603	5.452
Methane Flow - pps	.020	.022	.022	.021
Slurry Flow - pps	.164	.123	.123	.125
Oil Flow - pps	0.000	0.000	0.000	0.000
Fuel/Air Ratio	.03425	.02588	.02584	.02669
Reference Velocity - fps	36.28	38.20	38.27	37.13
Continuity Velocity - fps	39.58	49.47	49.52	47.15
Comb. Eff. - Delta T - %	9.81	43.84	43.74	39.32
Comb. Eff. - Emissions -%	0.00	0.00	0.00	0.00
Pri. Zone Equiv. Ratio	0.73	0.59	0.59	0.60
Burner H.R.R. -*	0.79	0.68	0.68	0.68
Burner H.R.R. X η_c -*	0.08	0.30	0.30	0.27
Pri. Zone H.R.R. -*	2.82	2.54	2.54	2.51
Pri. Zone H.R.R. x η_c -*	0.28	1.11	1.11	0.99
Pri. Zone Res. Time - ms	9.8	9.5	9.5	9.7
CH_4/CWM lb/lb	0.12	0.18	0.18	0.17

*10^6 Btu/hr ft^3 atm

APPENDIX A-3

TEST D017.0 08-16-84

Combustor Test Summary

Description	Run 1	Run 2	Run 3
Combustor Inlet Temp. - °F	710.	751.	667.
Atomizing Air Temp. - °F	80.	83.	224.
Combustor Exit Temp. - °F	523.	1064.	1439.
Adiabatic Exit Temp. - °F	691.	1556.	1961.
Combustor Temp. Rise - °F	-187.	314.	773.
Peak Temp. Plane - °F	570.	1295.	1550.
Pattern Factor - Plane 12	-.251	.735	.143
Comb. Inlet Pressure - psia	132.0	157.3	23.5
Main Air Flow - pps	3.185	3.062	3.116
Atomizing Air Flow - pps	.099	.100	.100
Total Air Flow - pps	3.284	3.162	3.216
Methane Flow - pps	0.000	.035	.031
Slurry Flow - pps	0.000	0.000	.096
Oil Flow - pps	0.000	0.000	0.000
Fuel/Air Ratio	0.00000	.01094	.03952
Reference Velocity - fps	16.75	14.16	92.25
Continuity Velocity - fps	14.13	17.86	184.83
Comb. Eff. - Delta T - %	0.00	40.50	60.14
Comb. Eff. - Emissions -%	0.00	99.99	0.88
Pri. Zone Equiv. Ratio	0.00	0.64	1.17
Burner H.R.R. -*	0.00	0.25	2.99
Burner H.R.R. X η_c -*	0.00	0.25	1.80
Pri. Zone H.R.R. -*	0.00	1.27	11.98
Pri. Zone H.R.R. x η_c -*	0.00	1.27	7.20
Pri. Zone Res. Time - ms	0.00	30.2	4.0
CH_4/CWM lb/lb	0.00	0.00	0.32

*10^6 Btu/hr ft^3 atm

APPENDIX A-3

TEST D017.0 08-16-84

Combustor Test Summary

Description	Run 4	Run 5	Run 6
Combustor Inlet Temp. - °F	493.	487.	484.
Atomizing Air Temp. - °F	366.	377.	379.
Combustor Exit Temp. - °F	1040.	994.	954.
Adiabatic Exit Temp. - °F	1114.	1062.	1041.
Combustor Temp. Rise - °F	547.	507.	470.
Peak Temp. Plane - °F	1192.	1051.	999.
Pattern Factor - Plane 12	.278	.114	.097
Comb. Inlet Pressure - psia	171.7	176.4	176.7
Main Air Flow - pps	8.224	8.612	8.706
Atomizing Air Flow - pps	.100	.100	.101
Total Air Flow - pps	8.324	8.713	8.807
Methane Flow - pps	.044	.041	.042
Slurry Flow - pps	.073	.074	.068
Oil Flow - pps	0.000	0.000	0.000
Fuel/Air Ratio	0.1404	.01329	.01250
Reference Velocity - fps	26.94	27.26	27.40
Continuity Velocity - fps	43.04	42.43	41.60
Comb. Eff. - Delta T - %	88.13	88.15	84.30
Comb. Eff. - Emissions -%	0.00	0.00	0.00
Pri. Zone Equiv. Ratio	0.51	0.47	0.46
Burner H.R.R. -*	0.45	0.42	0.41
Burner H.R.R. X η_c -*	0.40	0.37	0.35
Pri. Zone H.R.R. -*	1.92	1.78	1.77
Pri. Zone H.R.R. x η_c -*	1.69	1.57	1.49
Pri. Zone Res. Time - ms	13.0	12.8	12.8
CH_4/CWM lb/lb	0.60	0.55	0.62

*10^6 Btu/hr ft^3 atm

APPENDIX A-3

TEST D017.0 08-16-84

Combustor Test Summary

Description	Run 7	Run 8
Combustor Inlet Temp. - °F	476.	464.
Atomizing Air Temp. - °F	360.	365.
Combustor Exit Temp. - °F	1147.	903.
Adiabatic Exit Temp. - °F	1283.	1103.
Combustor Temp. Rise - °F	671.	439.
Peak Temp. Plane - °F	1240.	986.
Pattern Factor - Plane 12	.139	.188
Comb. Inlet Pressure - psia	134.2	139.2
Main Air Flow - pps	6.188	6.767
Atomizing Air Flow - pps	.100	.100
Total Air Flow - pps	6.289	6.867
Methane Flow - pps	.042	.031
Slurry Flow - pps	.081	.084
Oil Flow - pps	0.000	0.000
Fuel/Air Ratio	.01954	.01672
Reference Velocity - fps	25.72	26.68
Continuity Velocity - fps	44.74	39.83
Comb. Eff. - Delta T - %	83.20	68.77
Comb. Eff. - Emissions -%	0.00	0.00
Pri. Zone Equiv. Ratio	0.68	0.53
Burner H.R.R. -*	0.58	0.47
Burner H.R.R. X η_c -*	0.48	0.32
Pri. Zone H.R.R. -*	2.44	1.93
Pri. Zone H.R.R. x η_c -*	2.03	1.33
Pri. Zone Res. Time - ms	13.1	12.6
CH_4/CWM lb/lb	0.52	0.37

*10^6 Btu/hr ft^3 atm

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