DOE/MC/20228-1649
(DE85003534)

LOW EMISSION COMBUSTOR TECHNOLOGY PROGRAM

Final Report for the Period October 1, 1982—October 31, 1984

By
H. G. Lew
J. L. Toof

September 1984

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

Technical Information Center
Office of Scientific and Technical Information
United States Department of Energy

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Printed Copy A04
Microfiche A01

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts (ERA); Government Reports Announcements* and Index *(GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication NTIS-PR-360 available from NTIS at the above address.

DOE/MC/20228-1649
(DE85003534)
Distribution Category UC-93

LOW EMISSION COMBUSTOR PROGRAM

Final Report
October 1, 1982 - October 31, 1984

By
H. G. Lew
J. L. Toof

September 1984

Work Performed Under Contract DE-AC21-82MC20228

Prepared For
U.S. Department
Assistant Secretary for Fossil Energy

Prepared By
Westinghouse Electric Corporation
Combustion Turbine Systems Division
Concordville, Penna. 19331

FOREWORD

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

The work is carried out by the Westinghouse Electric Corporation at its Combustion Turbine Systems Division, Concordville, PA. Dr. Henry G. Lew is the Westinghouse Program Manager.

The project also has the active support of K. Rieke, P. Holden, J. Emory, G. Vermes, R. Kuznar, Dr. D. Carl of Westinghouse; Professor J. M. Beer, Massachusetts Institute of Technology, MA; and Drs. A. Singhal, A. Przekwas and L. Tam of CHAM of North America Inc. AL.

The authors thank the aforementioned for their generous efforts.

CONTENTS

FIGURES

FIGURES

TABLES

SUMMARY

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

The program objective was to make this evaluation with the Multiannular Swirl Burner (MASB). The MASB configuration was scaled up from the 5 inch diameter previously tested to a 10 inch diameter and modified for the combustion of CWM and for testing at 3 to 10 atmospheres pressure and 2000°F (1094°C) turbine inlet temperature. This testing was performed in the Westinghouse Advanced Combustor Development Rig at Concordville, Pa. Testing was done with CWM and #2 fuel oil for comparison. In addition, #2 fuel oil doped with pyridine was used to simulate the effect of fuel bound nitrogen on NO_x production.

The design of the MASB for CWM combustion has encompassed several subtasks which provided valuable design data. These include numerical combustor flow field calculations by the computer code CORA 2-83, nozzle spray tests on CWM to select the proper nozzle, and the selection of the appropriate CWM.

Test results to date on the MASB operating in both the rich-lean mode and lean-lean mode indicate that CWM combustion in a metal walled combustor such as the MASB is feasible. The NO_x results for oil show an increase in the NO_x from the 5 inch MASB obtained previously. Combustion efficiencies greater than 99.9% were obtained on oil. CWM combustion with a methane gas pilot has shown combustion efficiencies up to 99.5%. However, combustion to date of CWM alone has only shown combustion efficiencies up to 53%.

Combustion tests are continuing to complete this evaluation.

Section 1

INTRODUCTION

This document reports the results of the Low Emission Combustor Technology Program conducted under Contract DE-AC21-82MC20228 with the Morgantown Energy Technology Center of DOE. The objective of this program is to evaluate coal water mixture (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 emission in previous work(1).*

The primary goal of this program was to evaluate CWM combustion with this fuel-flexible MASB. To achieve this goal a number of tasks were undertaken. These areas of work are critical to the design and fabrication of the MASB which would be adequate for testing CWM combustion at pressures from 3 to 10 atms and turbine inlet temperatures up to 2000°F (1094°C). The required areas of work are itemized as follows:

- Sizing and design of CWM MASB with residence time requirements for efficient combustion of coal particles.
- Fuel forwarding system and spray atomization of CWM.
- Numerical calculation of the MASB flow field.
- Demonstration of the MASB viability for CWM combustion with tests at conditions cited above.

Sizing requires a scale-up of the 5 inch MASB to 10 inch diameter and a positioning of the combustor elements to minimize fuel and wall interaction.

The CWM fuel is a non-Newtonian fluid with higher viscosities than fuel oils. The flow of CWM requires special considerations in the fuel forwarding system because of this viscosity behavior. In particular, a specially designed spray nozzle has been selected to spray the CWM efficiently.

The CWM fuel contains finely ground coal particles immersed within water droplets. Careful management of the fuel and air distributions is required to achieve a stable combustion with the added considerations of devolatilization and char burn-out. A recirculation zone is required in the primary zone. This aspect of the design has been assisted by numerical calculations of the MASB flow field with chemical reaction for oil (or gas) combustion.

---

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

The CWM MASB was tested in the combustion development test facility at Westinghouse CTSD/Concordville, PA to determine combustion stability with CWM, with various combinations of methane and CWM, with #2 fuel oil, and with methane. Emissions were monitored so as to obtain the NO_x emission with the CWM which has about 1.65% (wt) of fuel bound nitrogen in the coal particles.

Section 2 describes the MASB from the previous work (1) which had demonstrated the potential of this combustor for further development. The combustor design aspects which must be considered for the modification of the MASB for CWM combustion are covered in Section 3. In addition, a design tool - the numerical calculations of the MASB flow field pertinent to the design is also given in this section. Section 4 contains the MASB combustor final design configuration. A description of the test facility which includes the test rig and the fuel forwarding system and the fuel characteristics are covered in Section 5 and 6 respectively. The selection of the CWM fuel is a critical item in application to gas turbines. Finally the combustion test results are discussed in Section 7. Section 8 contains the conclusions and recommendations resulting from these test results.

REFERENCES

1. Lew, H. G. et al, "Low NO_x and Fuel Flexible Gas Turbine Combustors" Journal of Engineering for Power, Vol. 104, 303-313, April 1982 (also NASA CR 165482, Oct. 1981).

Section 2

MULTIANNULAR SWIRL BURNER (MASB)

The test combustor selected for the investigation of CWM combustion conducted in this program was the Multiannular Swirl Burner (MASB). The combustor design was developed in an earlier work (1) in a DOE sponsored project to conceptualize, design and demonstrate the viability of low emission gas turbine combustors for utility and industrial application. NO_x performance was emphasized for heavy, nitrogen bearing fuels, including distillate oil, petroleum residuals and synthetic fuel oil such as SRC-II. A number of fuel flexible combustor process concepts were identified that met the low emission objectives. One of the configurations recommended for further development was the Multiannular Swirl Burner based on J. Beér's design (2). This integral burner utilizes the rich-lean process to minimize NO_x from the combustion of nitrogen-bearing fuels such coal water mixtures (CWM). The MASB has the advantages of an all-metal structure, does not require additional upstream film cooling, and has a low pressure loss characteristic.

The MASB is formed by a group of axially displaced concentric rings as shown schematically in Figure 2-1. Each pair of adjacent rings forms an annulus through which combustion air flows. Tangential velocity is imparted to the air as it passes through swirler vanes in each annulus. This arrangement permits control of the axial and swirl velocity distribution in the burner. As a result of the combination of swirling flow and the divergent passage formed by the concentric rings, a toroidal recirculation zone is formed in the upstream end of the burner. This region provides aerodynamic flame anchoring via recirculation of hot combustion products and permits stable operation over a wide turndown range without the need for bluff body stabilizers. Since the MASB is cooled by combustion air flowing in the annular passages between rings, there is no need for film cooling air. Therefore, the burner can be all metal and still have all of the combustion air available to regulate the internal flow and mixing patterns.

Rich-lean staged combustion can be implemented by controlling the axial and radial spacing of the rings. When operated in the staged combustion made as a low-NO_x burner a fuel-rich partially-stirred recirculation zone is formed in front of the fuel nozzle. The fuel-rich gases are mixed with cooler air along the boundaries of the recirculation zone which rapidly reduces the mixture temperature below a limit conducive to thermal NO_x formation. Combustion is completed in a temperature range that is high enough to burn out soot and combustible gases, but low enough to minimize the formation of thermal NO_x. With this rich/lean staging of combustion air, fuels containing chemically bound nitrogen can be burned in the MASB with relatively low conversion to NO_x as demonstrated in References (1) and (3).

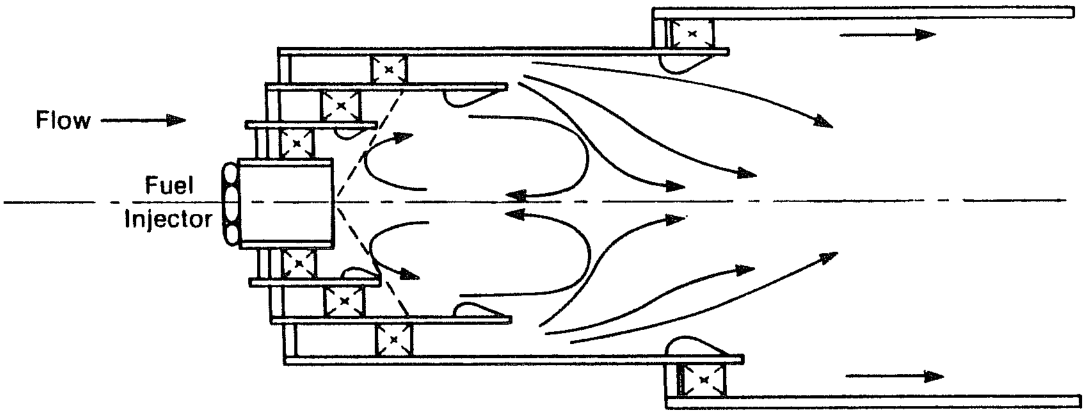

Figure 2-1 Multiannular Swirl Burner Schematic

A 5 inch diameter version of the MASB was tested in a previous program (1,3) with an emphasis on achieving low-NO_x operation. Fuels were ERBS (Experimental Referee Broadened Specification aviation turbine fuel-NASA) distillate oil, SRC-II coal derived liquid and a 258 Btu/SCF coal gas. The SRC-II contained 0.8 weight percent nitrogen and the coal gas was doped with 0.48 to 1.06 volume percent NH_3 to simulate fuel nitrogen. Inlet pressure was 11 atmospheres for all three fuels while inlet air temperature was about 650°F for the liquid fuels and 775°F for the coal gas. Emissions performance is listed in Table 2-1.

Table 2-1

EMISSIONS PERFORMANCE OF 5 INCH MASB

	ERBS	SRC-II	Coal Gas
NO_x @ Rated Engine Output (ppmv)	80-90	160-170	80 (no NH_3)
Fuel Nitrogen Conversion (%)	---	20	10-24(with NH_3)
Smoke (SAE)	11-43	Very Low-18	---
Combustion Efficiency (%)	99.0-99.9	99.8-99.9	---

The five inch diameter MASB emissions (Table 2-1) show that low conversion of fuel bound nitrogen to NO_x characteristic of rich/lean burners was obtained. Pressure loss for this burner was two to four percent over the range of airflows tested with a turn down ratio of 5.

The NO_x performance of the 5 inch burner, the attractiveness of its all metal design and the potential ease of its modification for CWM combustion led to the selection of the MASB as the test combustor for this program. The design of the 10 inch diameter MASB for CWM combustion is discussed in Section 4.

REFERENCES

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. Beer, J. M., "Improvements in or Relating to Burners for Pulverized Coal or Like Solid Fuel or for Liquid or Gaseous Fuel", British Patent No. 45652 (1965).

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

Section 3

COMBUSTOR DESIGN CONSIDERATIONS

The design of the MASB combustor tested in this program was initiated by scaling up (using geometric similarity principles) the previously tested 5 inch diameter version (1, 2) to a 10 inch diameter size with appropriate modification to accommodate the combustion of CWM fuel. In this design the primary zone of the burner was sized to allow evaporation of the water, ignition of the coal particles, combustion of the coal volatiles and conversion of fuel bound nitrogen to N_2. The lean or secondary reaction zone was designed to burn out the residual coal char.

A number of factors were considered before finalizing the design of the 10 inch combustor. These factors include the time required for CWM combustion, rich-lean operation for low NO_x emissions, combustion aerodynamics for ignition and flame stability and wall cooling for acceptable burner life. These design criteria are discussed in Sections 3.1 to 3.2. A design tool in implementing these criteria is the numerical calculation of the MASB flow field. Section 3.3 contains an example of these calculations which are given in detail in the Comprehensive Data Report (5).

3.1 FACTORS CONSIDERED IN THE DESIGN

CHARACTERISTIC TIMES FOR CWM COMBUSTION

The combustion of CWM involves four sequential processes. Initially the water surrounding and within the coal particles must be evaporated. Next, the particle is heated to its ignition temperature. Once ignited, combustion of the coal volatiles takes place by pyrolysis and gas phase reactions. Combustion of the remaining solid char completes the sequence.

Characteristic times for these processes have been calculated by Beér and Vermes (3). A summary of their results for 50μm and 10μm particles with one particle per water droplet is shown in Table 3-1.

The total time required for the combustion of 10μm coal particles is approximately equal to that available in industrial gas turbine combustors. This points to the need for finer pulverization of coal in gas turbine applications than in boiler and furance use where coal particle sizes are typically 50μm and above. Residence time considerations led to the selection of the CWM fuel described in Section 6 which has a particle top size specification of 10μm. Another advantage of the smaller particle size is correspondingly smaller ash particulate and therefore, reduced erosion of turbine blades and vanes.

Table 3-1

CHARACTERISTIC TIMES FOR PROCESSES IN A CWM FLAME

Process	Time (ms) 50μm particles	10μm particles
Droplet Vaporization	3.2	0.2
Particle Heat-up	2.0	0.1
Particle Devolatilization	10.0	10.0
Char Burning		
Diffusional Control	40.0	1.6
Chemical Control (1 atm.)	15.0	3.0
Chemical Control (10 atm.)	1.5	0.3
Total Time Required		
1 atm.	~55	~14
10 atm.	~55	~12

It is seen from Table 3-1 that the incremental time required for combustion as particle size increases from 10μm to 50 μm is primarily due to the increase in the char burning time; the increment due to vaporization is much less significant. Therefore, although 10μm coal particles are required to avoid excessive char burning times, larger droplets of 50μm diameter containing several particles could be tolerated without significantly increasing the total time requirement. This, of course, is contingent on avoiding agglomeration of coal particles as the water evaporates.

This characteristic time analysis shows that if the rich zone of the burner is designed for the vaporization, heat-up and devolatilization of 10μm coal particles with one particle per water droplet, then a residence time of 10 ms must be provided. Relaxing the atomization requirements to allow droplets of about 50 μm diameter with several particles per droplet would increase the required rich zone residence time to 15 ms.

RICH-LEAN OPERATION

Rich-lean staged combustors are particularly suited for NO_x reduction with fuels containing high amounts of bound nitrogen such as coal. There are two zones into which the combustor is divided. A deficiency of combustion air is introduced in the first zone to maintain a fuel-rich equivalence ratio. Between zones, quench air is added rapidly to make the mixture fuel-lean. Combustion is then completed in the lean zone.

Ideally, the rich zone is operated in the so called low NO_x trough which is illustrated in Figure 3-1 (4). At 65 percent theoretical air (an equivalence ratio of about 1.6) the sum of the equilibrium concentrations of atomic nitrogen containing species (NO, HCN, NH_3) is at a minimum. This is important for low emissions because the NO passes through the lean zone unreacted and the HCN and NH_3 are readily oxidized to NO_x in the lean zone. Sufficient residence time (~5ms) must be provided in the rich zone to allow the chemistry to approach equilibrium. In a CWM application this time must be added to the times required for evaporation, particle heat-up and devolatilization which was discussed in Section 3.1.

In a liquid or gaseous fuel application, quench air is added as rapidly as possible to minimize the time at or near a stoichiometric mixture and therefore, minimize the formation of thermal NO_x. With CWM care must also be taken to limit the amount of air added so that the mixture temperature is maintained above 2000°F so that the char burn-out is not quenched.

IGNITION AND FLAME STABILITY

Ignition and flame stability in the MASB are achieved in the same manner as in radial jet combustors, via recirculation of hot combustion products. This recirculation continuously ignites the incoming fuel/air mixture. In the MASB the size and strength of the recirculation region are dependent, for a given divergent rich zone geometry, upon the axial and swirl velocity distribution in the burner. Fuel spray momentum will also affect rich zone aerodynamics and care must be taken that the axial spray momentum is not so high as to destroy the recirculation region.

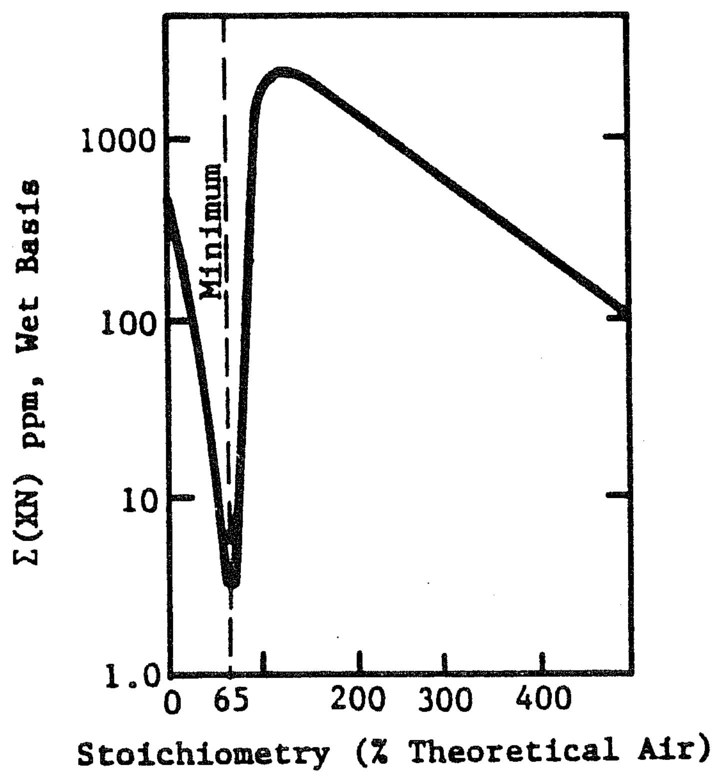

Figure 3-1 Sum of Equilibrium Concentrations of Atomic Nitrogen Containing Species as a Function of Stoichiometry Source: Folsom, B.A., et al, ASME 79-GT-185 (1979) (4).

3.2 RESIDENCE TIME REQUIREMENTS

Residence time requirements were estimated for both the primary and secondary zones and used for sizing these zones. Coal particle burning times from experiments were used for the estimates of char burn-out. A detailed discussion of the procedure has been given in the companion report entitled "Comprehensive Data Report" (5). The CWM fuel as given in Section 6 was used.

As pointed out in the last section the optimum conditions for char burn-out are a gas temperature close to 2000°F and with sufficient oxygen for maximum burning. The char burning time was estimated assuming the burn-out occurs in two sequential steps. The burning occurs first at a temperature of 2900°F after passing the rich zone and, after addition of air, it completes the burning at 2000°F. An example of the char burn-out time for different coal particle size is given in Figure 3-2. It is seen that the char burn-out times for the 10μm and 50μm are within the order of the characteristic times of Table 3-1.

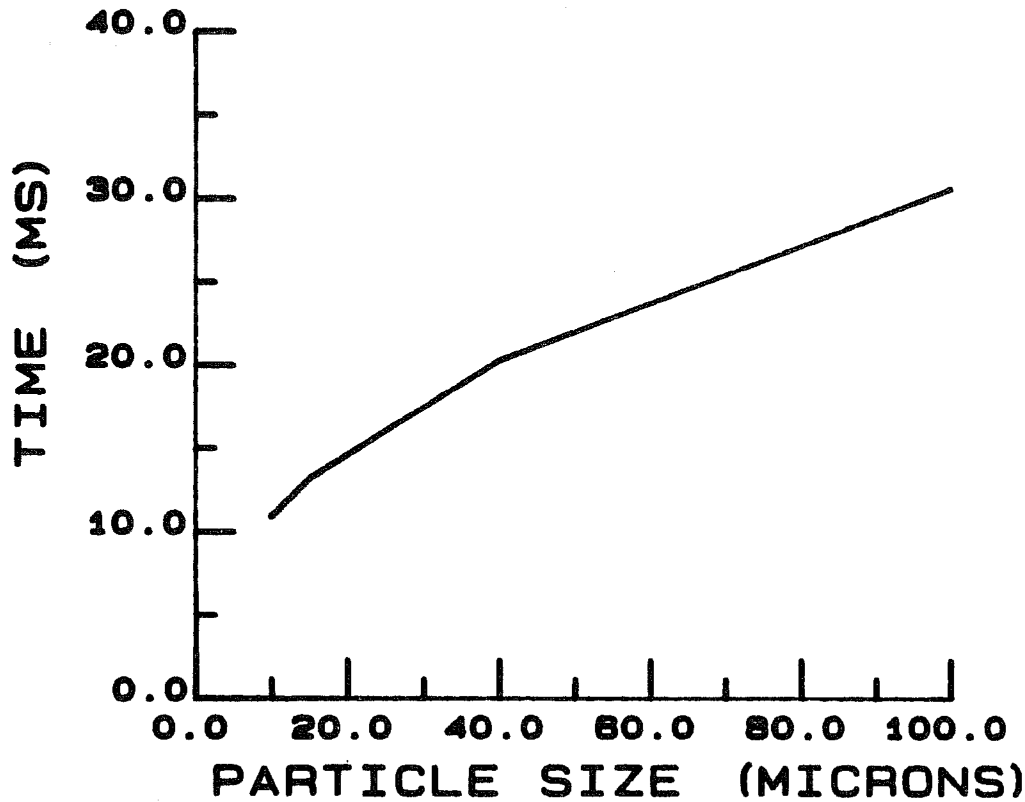

Figure 3-2 Char Burn-Out Time for Different Coal Particle Sizes at Temperature of 2000°F and Pressure of 3.4 ATM

The principal results are summarized in Table 3-2. Additional information at other conditions is given in the Comprehensive Data Report (5).

Table 3-2

RESIDENCE TIMES*

	MS
Rich Zone	10
Lean Zone	7

*BOT = 2000°F, Pressure = 3.5 ATM

These residence times were used in the initial sizing of the primary and secondary zones.

3.3 FLOW FIELD CALCULATIONS FOR OIL AND GAS COMBUSTION

The effects of airflow distribution, swirl angles, burner geometry and fuel spray momentum on MASB aerodynamics were investigated by numerical finite difference calculations of the MASB combustion flow field. These were obtained as part of the combustor design. These calculations were performed by CHAM of North America, Inc. under subcontract to Westinghouse using the CORA2-83 code (Combustion and Radiation Analyzer, 2 Dimensional; upgraded version 1983). This code calculates the combustor internal characteristics for the axially symmetric turbulent swirling chemically reacting radiating flow field for the combustion of gaseous or liquid fuels. Strong swirls are emphasized in these computations since applied Swirl Numbers of the order of 3 are of interest in the present CWM MASB. The chemical kinetic model used in the computations is a two step hydrocarbon oxidation with carbon monoxide as the intermediate species; NO_x formation is by the Zeldovich mechanism. The k, ε turbulent transport model and a four flux radiation model are part of the code.

The CORA2 code solves the system of nonlinear, hydrodynamic equations by a finite difference technique using the primitive variables of pressure-velocity in an implicit formulation. This method of solution has been shown to be convergent using underrelaxation. A detailed discussion of the equations, method, and numerical results is given in the Comprehensive Data Report (5).

RESULTS PERTINENT TO DESIGN

As an example the combustor flow field is computed for oil combustion using the MASB dimensioned for CWM combustion in accordance with the criteria discussed in Section 2. In this case it is assumed that the oil is injected through a hollow cone spray. A computational grid of 36 X 12 (axial and radial directions respectively) with unequal intervals is used. The conditions of 50 psia pressure and 4.24 pps air flow rate correspond to a typical test condition. The inlet air temperature is 650°F and inlet fuel temperature is 100°F. Equal mass flows of atomizing air and fuel are used for this case. The maximum axial distance in which this flow field is computed is 3.9 ft; this length is used so that boundary conditions can be easily set at the exit. Figure 3-3 shows both the geometric configuration of the MASB and the streamlines of the flow in a plane containing the axis of symmetry. The recirculation zone in the primary zone is shown in Figure 3-3 and the axial velocities in the central region are quite small downstream of the large quarl. The air is split between the four swirlers in the percentages of (12/6/40/48) normalized to 4 lbs/sec. The largest amount of air enters just ahead and behind the large quarl. These computations are for the swirl distribution created by swirl angles of 76°, 72°, 77° and 78° corresponding to swirlers #1 to 4 respectively. One notes the stable recirculation pattern in the primary zone for this flow field calculation.

The axial and swirl velocity distributions for typical axial locations are shown in Figures 3-4 and 3-5. The axial velocity distribution shows a reversed flow in the primary zone. At the axial length of 2.79 ft (.80 m) this component of the velocity has become 45.9 ft/sec (14 m/s) at the axis increasing radially to 188 ft/sec (57.3 m/s) at the outer diameter. The maximum axial velocity occurs under the largest quarl and this value is 551 ft/sec (168 m/s) at the flow symmetry axis. The swirl velocity has a forced vortex distribution shape in the primary zone and retains this shape downstream due to the axially displaced swirlers. An interesting quantity which relates the swirl intensity of different flows is the local flow swirl number (6). This swirl number distribution (Figure 3-6) along the combustor as calculated from the flow velocities shows a maximum value of 1.3 at a location immediately aft of the last swirler and varies between 0.3 and this value. The local swirl number is an indication of the staged swirl distribution. The value of the applied swirl number is about 3.

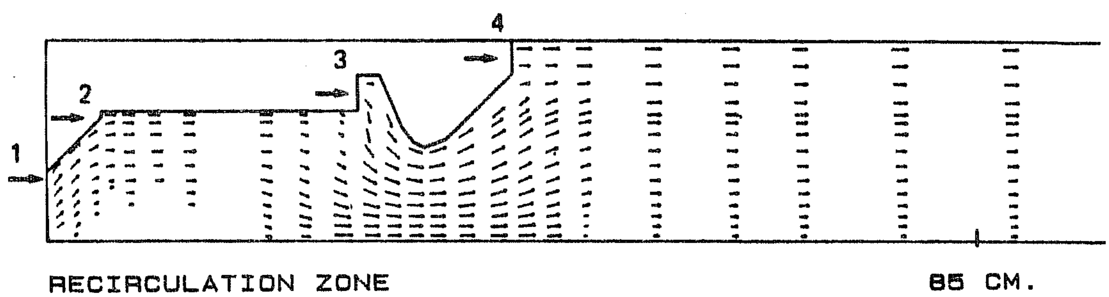

Figure 3-3 Velocity Vector Contours in a Symmetry Plane

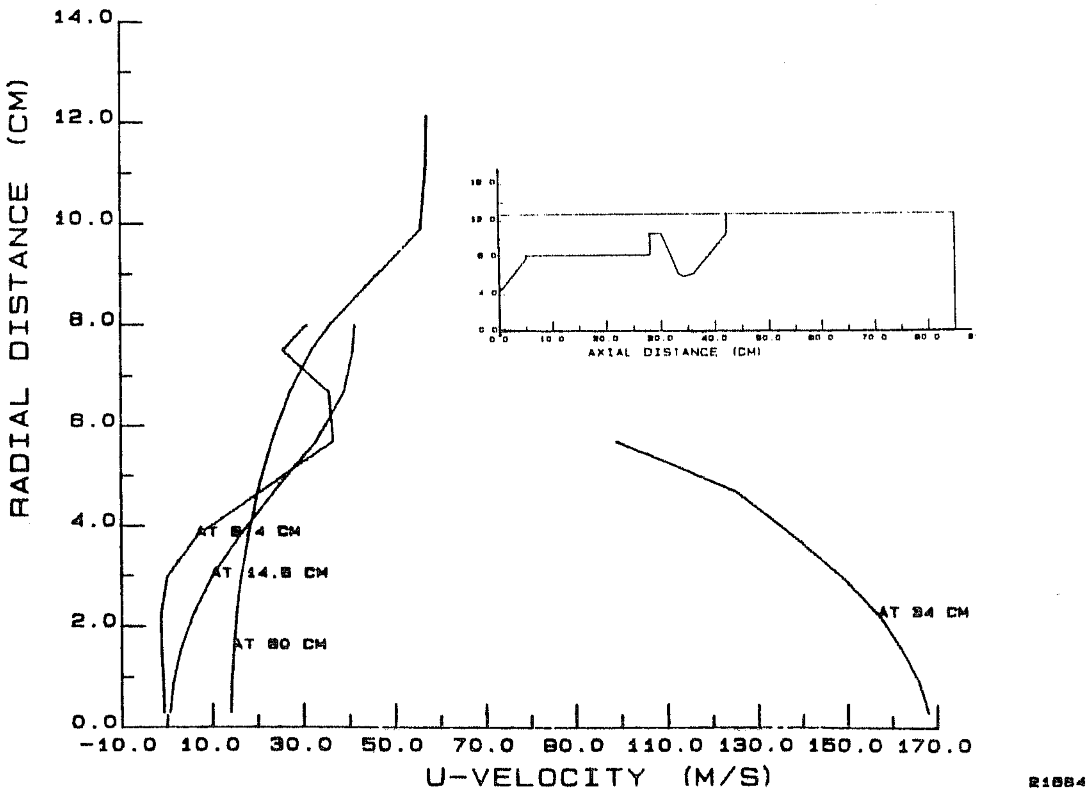

Figure 3-4 Axial Velocity Distributions at Different Axial Locations of the Combustor

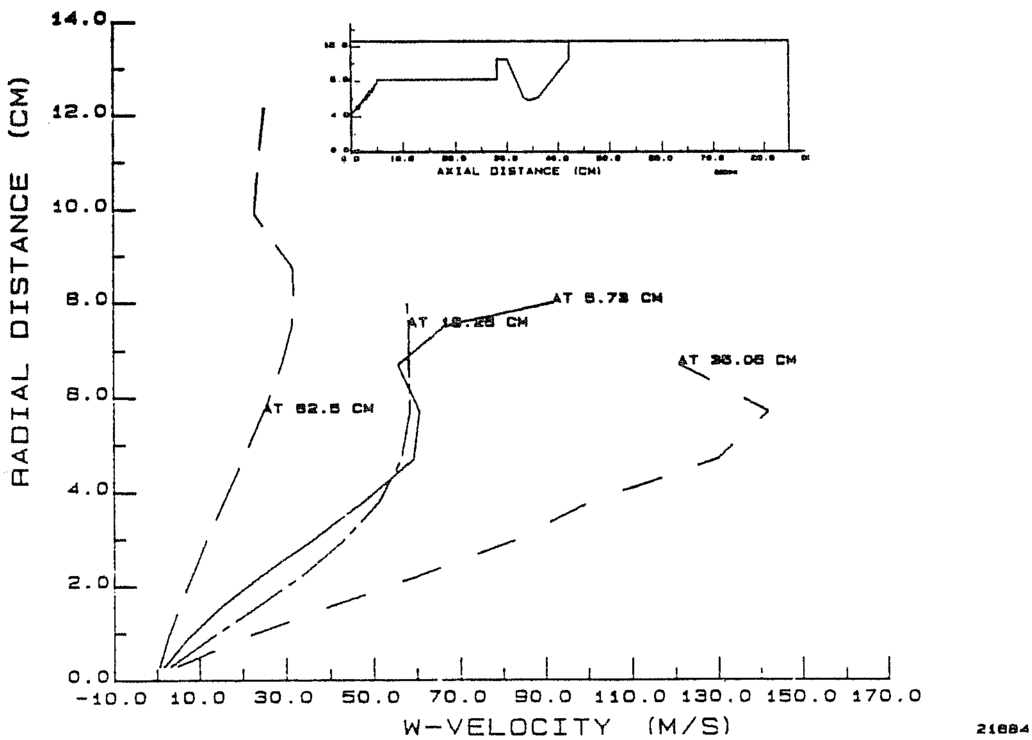

Figure 3-5 Swirl Velocity Distributions at Different Axial Locations of the Combustor

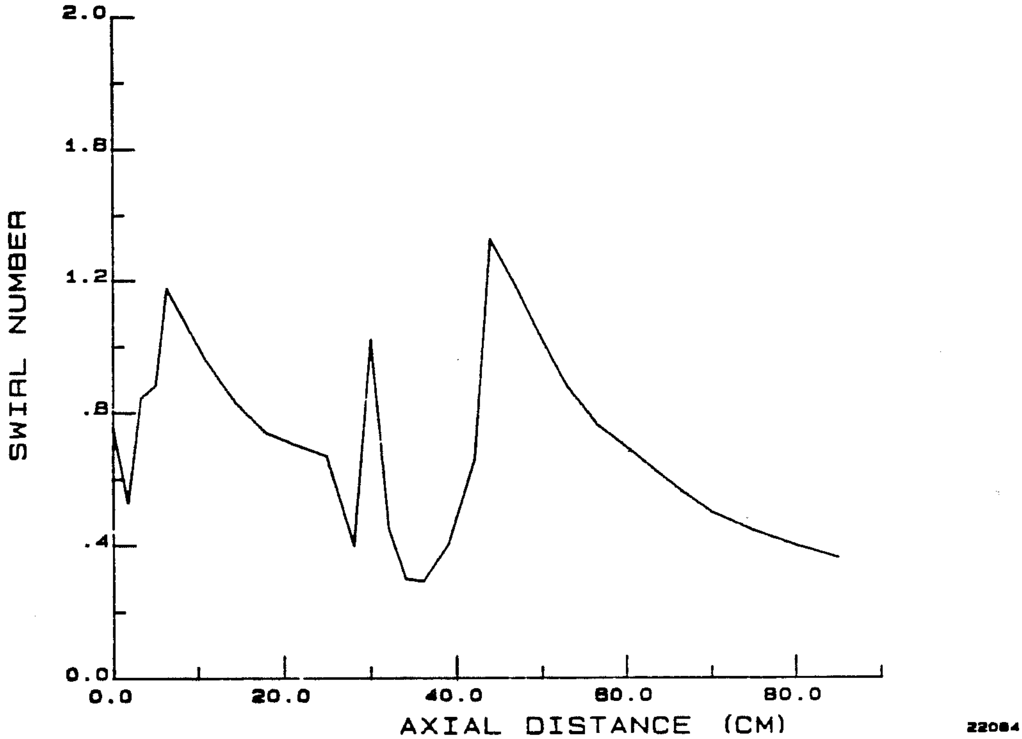

Figure 3-6 Local Swirl Number Distribution Along the MASB Length

The temperature contours are shown in Figure 3-7. At the location of 2.79 ft (.85 m) the temperature varies from 2294°F (1530°K) at the axis to 1682°F (1190°K) next to the combustor wall. The highest temperature occur in the primary zone and reaches 3140°F (2000°K). It is expected that the wall temperature in this zone will have high values. Test results indicate that this trend was valid. The radial variation of the temperature indicates that the higher temperature occurs at the axis of symmetry of the flow (with the highest near the largest quarl) since cooled air continually flows through each swirler. The adiabatic temperature rise for this combustion condition is achieved on the average across the exit cross section. In this geometry the fuel remaining at the third swirler location is about 2% of the amount injected.

Some inert particle trajectories were calculated separately. For this combustor condition the trajectory of typical 2μm particles is shown in Figure 3-8; the trajectory indicates that these particles are following the streamlines of the flow. Trajectories of 10μm particles tend to swirl around the combustor walls.

Contour	Value (°K)	Contour	Value (°K)
1	700.	6	1400.
2	900.	7	1500.
3	1000.	8	1600.
4	1200.	9	1800.
5	1300.	10	2000.

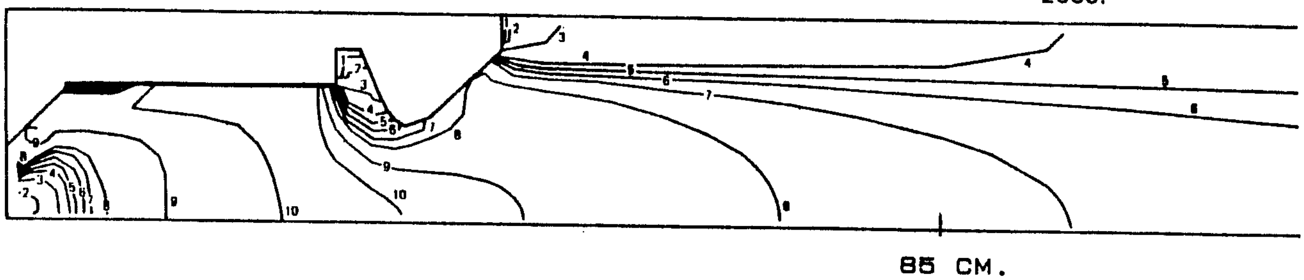

Figure 3-7 Temperature (°K) Contours in a Symmetry Plane

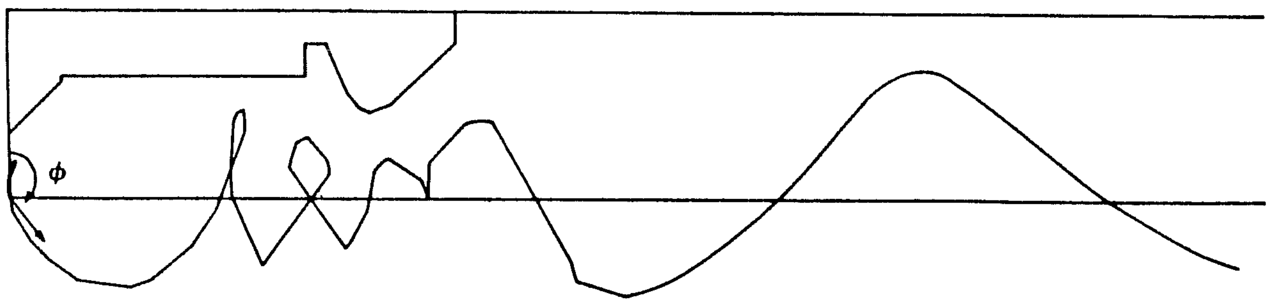

Figure 3-8 Inert Particle Trajectories, 2μm Diameter

A summary of the principal results of the flow field calculations as detailed in the Comprehensive Data Report (5) follows:

- There is a recirculation zone in the primary zone of the MASB for most of the swirl distributions. The recirculation zone location and intensity can be pre-selected by a combination of swirl distributions and fuel flow geometry.

- The recirculation zone is larger in the cold flow than in the chemical reactive one. A thermal expansion of hot combustion products creates larger axial pressure variation in the reactive case.

- For lower fuel flow rates ∿20 gph the recirculation zone is slightly more intensive probably due to the fuel swirl momentum.

- Comparison of results of contra-rotating and co-rotating air swirls indicates that in the co-rotating swirls and low fuel load case a recirculation zone exists in the secondary zone.

- In most of the combustion test cases, the liquid hydrocarbon is totally reacted within the upstream part of the burner. Similarly, carbon monoxide (CO), which is generated near the fuel entry, is totally burned within the burner.

REFERENCES:

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). Also, Journal of Engineering for Power, Vol. 104, 303-313, (April 1982).

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 CR165614 (February, 1982).

3. Beér, J. M. and Vermes, G., "Gas Turbine Combustor for Coal Water Mixture," Proceedings, International Conference on Combustion of Tomorrow's Fuels, Santa Barbara, CA. (November, 1982).

4. Folsom, B. A., et al, "The Effects of LBG Composition and Combustor Characteristics on Fuel NO_x Formation", ASME 79-GT-185 (1979).

5. Lew, H. G. and Toof, J. L., "Comprehensive Data Report, Low Emission Combustor Technology Program, Topical Report," (June, 1984).

6. Beér, J. M. and Chigier, N.A., Combustion Aerodynamics, Applied Science Publishers, Ltd., 1972, pp 106-107.

Section 4

COMBUSTOR FINAL DESIGN CONFIGURATION

4.1 FINAL DESIGN

Design considerations discussed in Section 3 provided input for the final design of the 10 inch diameter MASB test combustor. A drawing and a photograph of the combustor are shown in Figures 4-1 and 4-2 respectively. It differs from the 5 inch MASB tested in a previous program (1, 2) in several respects. This combustor is 10 inches in diameter and has been operated over a wider range of pressures. It also provides a forced rather then a free vortex and was designed to burn CWM as well as liquid and gaseous fuels.

Referring to Figure 4-1, swirlers 1 and 3 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 (3).

Liquid fuels (No. 2 distillate oil and CWM) are sprayed into the primary zone by a continuous air atomizing nozzle specifically designed by Parker Hannifin for CWM use. This nozzle is described in Section 4.2. Gaseous fuel (methane) is discharged through swirler 1 by six tubes manifolded together in the neck of the combustor.

The only ceramic used in this burner is a quarl which forms the conical dome at the upstream end of the primary zone. The purpose of the ceramic quarl is to provide a divergence angle that is conducive to recirculation and to establish a hot surface to assist flame anchoring. A second larger all metal quarl is located midway along the burner. 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. Figure 4-3 is a photograph of the test combustor looking axially upstream showing swirler 4, the metal quarl, ceramic quarl, swirler 1 and the fuel nozzle.

Snap button hole plugs which can be drilled with various hole sizes are employed in the neck of the combustor providing an easy means for adjusting the air to swirlers 1 and 2.

Metal bosses are located in the wall of the primary zone just downstream of the ceramic quarl for mounting an ultra-violet detector and a propane torch igniter.

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.

4.2 LIQUID FUEL NOZZLE

Requirements for the CWM atomizing nozzle used in this Program include small droplets, low spray momentum and high reliability.

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 depends 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 fo 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 were 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.

Of the five nozzles tested, the Parker Hannifin nozzle designed for CWM provided the smallest drop size and widest turn-down range. It did not plug with slurry (See Ref. 4). It was therefore selected for use in combustion testing. 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. Additional information on the spray test is given in the Comprehensive Data Report (4).

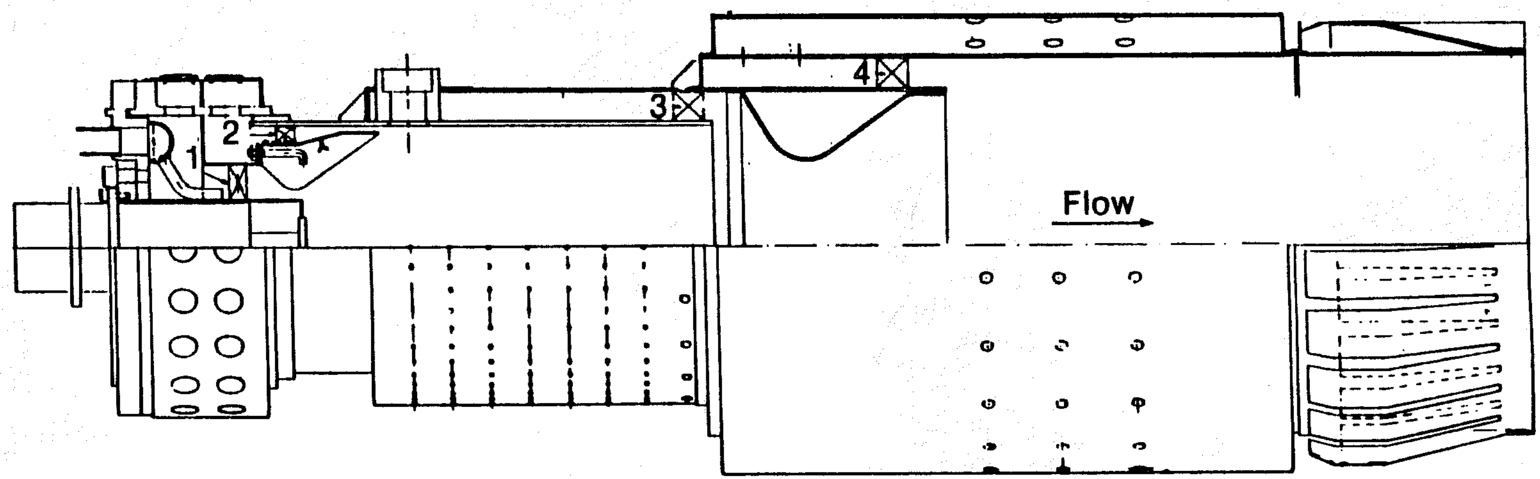

Figure 4-1 Multiannular Swirl Burner for CWM Combustion

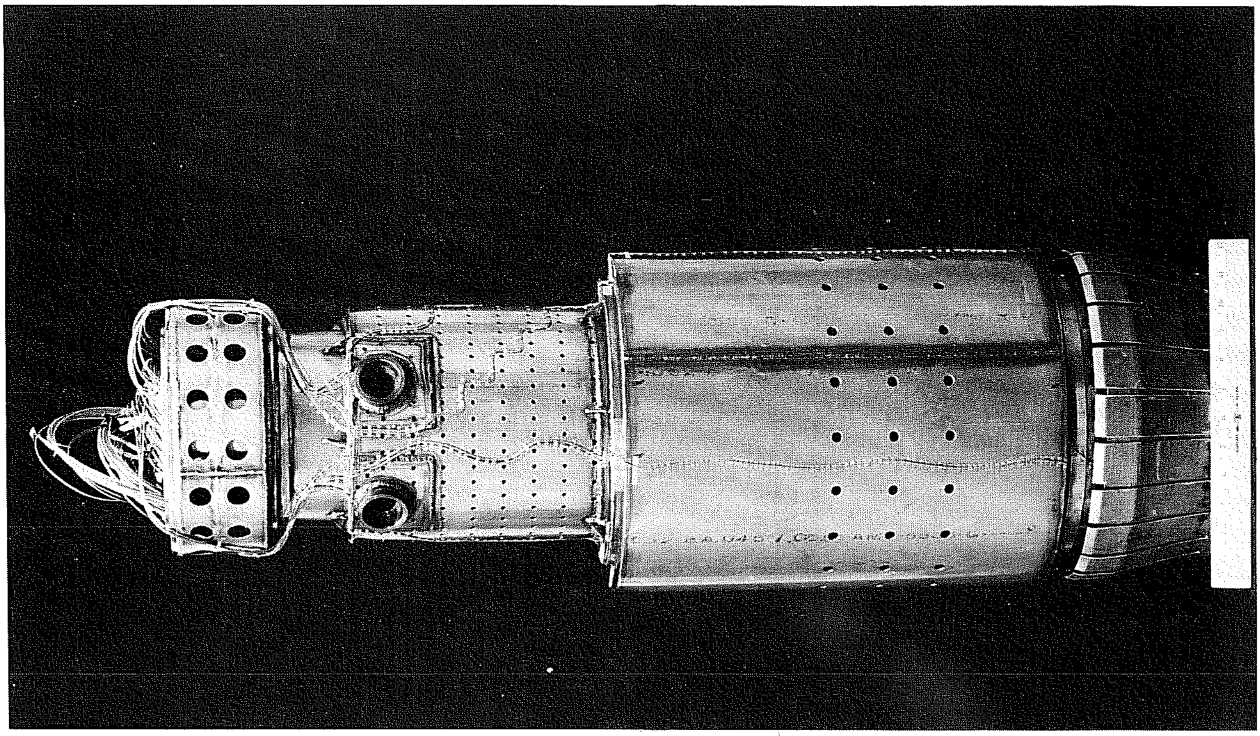

Figure 4-2 Multiannular Swirl Burner - Side View

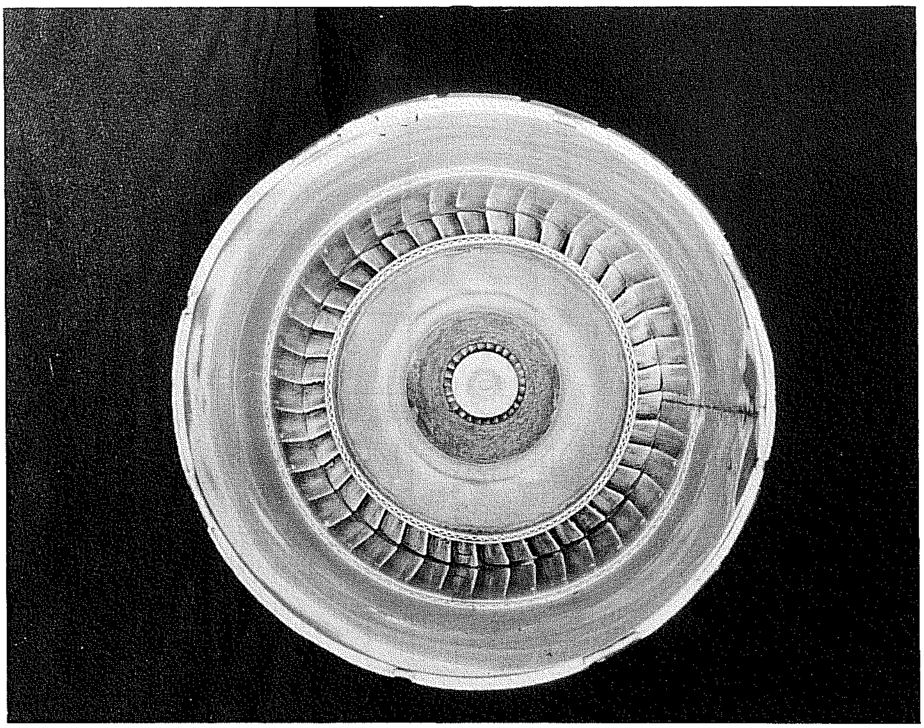

Figure 4-3 Multiannular Swirl Burner - Upstream Axial View

REFERENCES:

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). Also, Journal of Engineering for Power, Vol. 104, 303-313, (April 1982).

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 CR165614 (February, 1982).

3. 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).

4. Lew, H. G. and Toof, J. L., "Comprehensive Data Report, Low Emission Combustor Technology Program, Topical Report," (June, 1984).

Section 5

TEST FACILITY

5.1 TEST RIG DESCRIPTION

The test rig utilized in this program is shown in Figures 5-1 and 5-2. The cylindrical reverse flow combustor test rig permits testing with various length combustors and accommodated the Multiannular Swirl Burner (MASB) for CWM combustion by the additon of a cylindrical section at the front end. The rig is designed so that the rig shell contains various penetrations for special instrumentation, etc.

Figure 5-3 shows the facility process flow system. Rig inlet air is admitted through an internal manifold which directs the air to cool the combustor exit instrumentation duct prior to entering 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 of five air-cooled radial gas sampling rakes. The rig includes sight 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 permits 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 obscuration of the observed area.

Table 5-1 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.

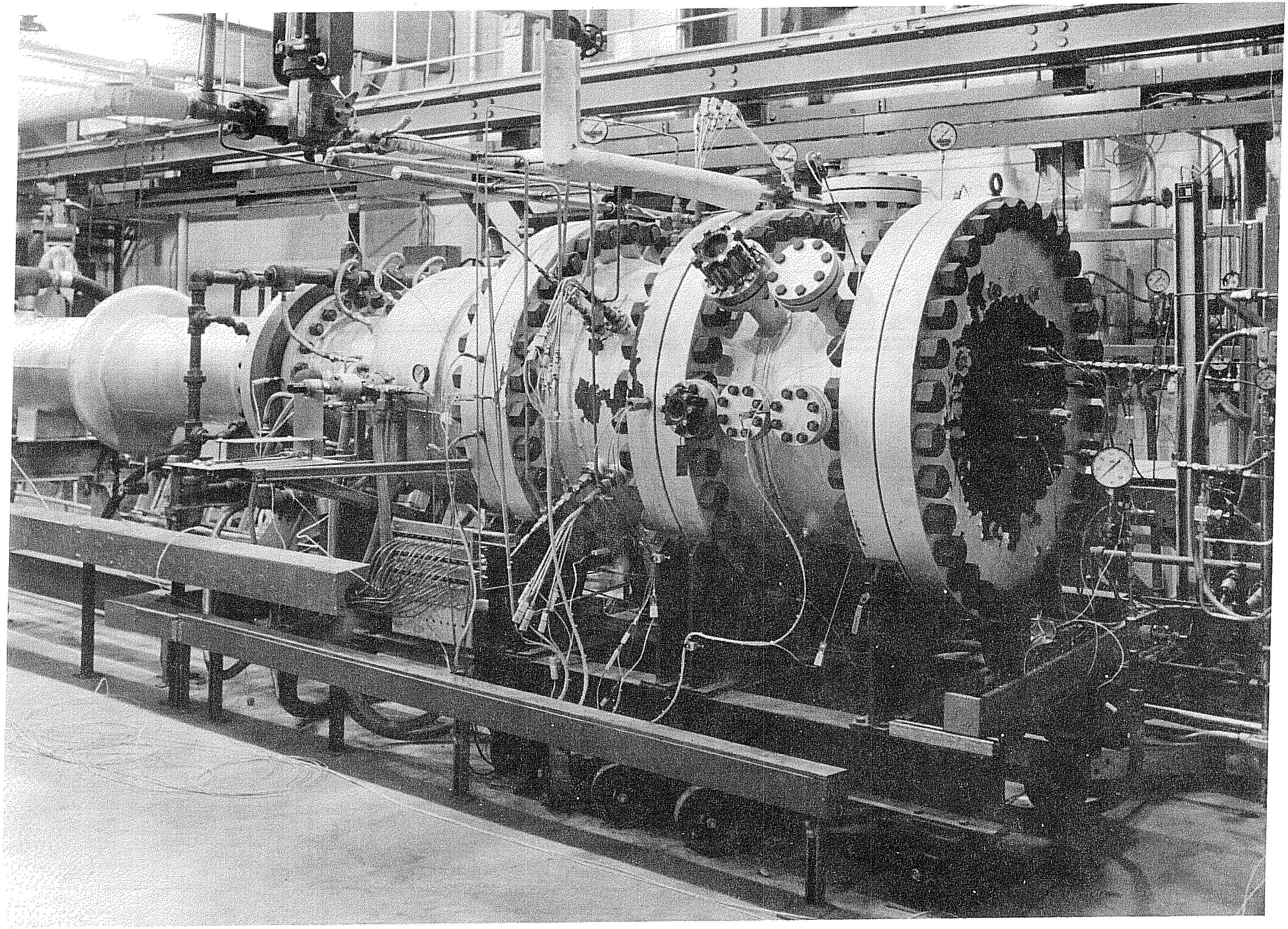

Figure 5-1 High Pressure Combustor Test Rig

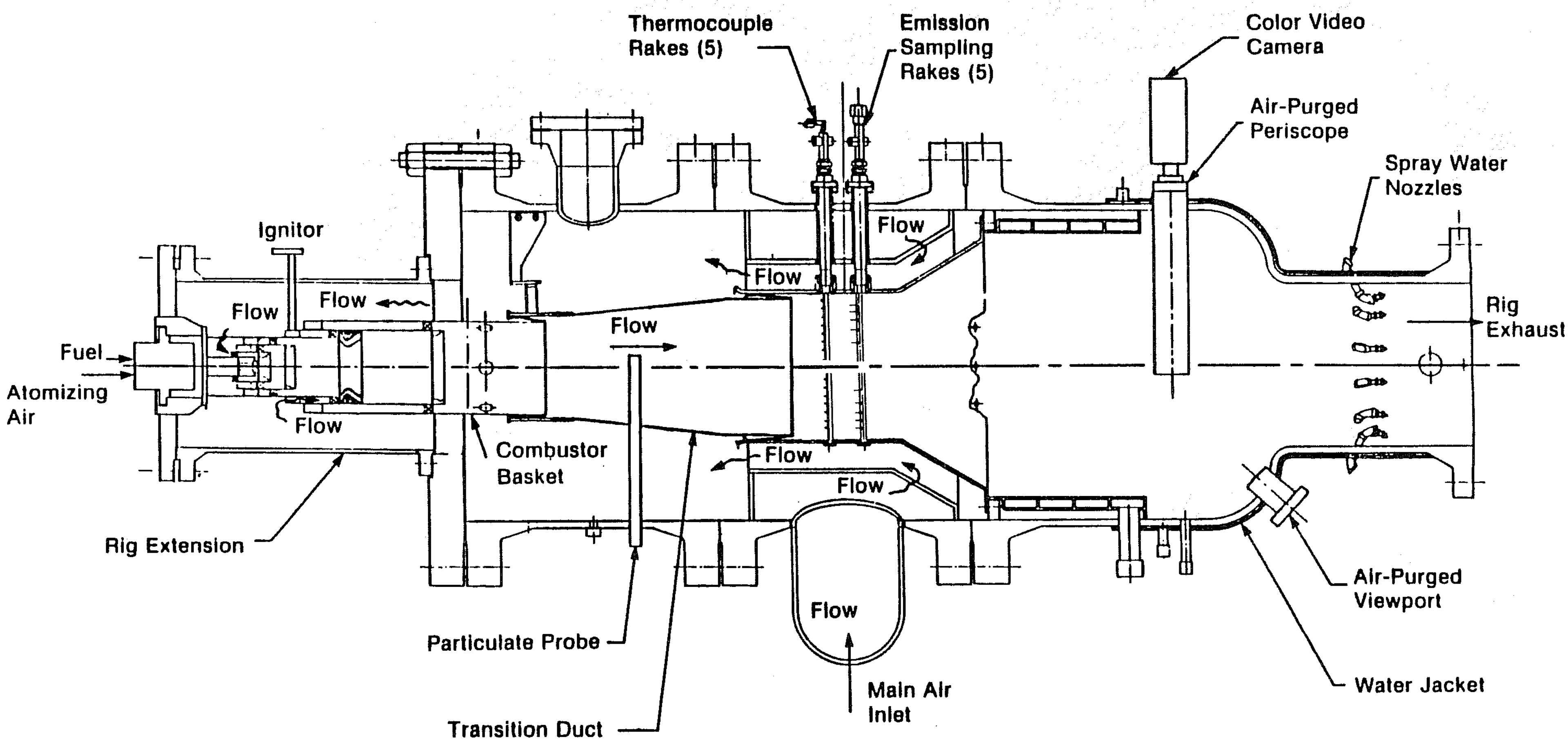

Figure 5-2 Schematic of Test Rig

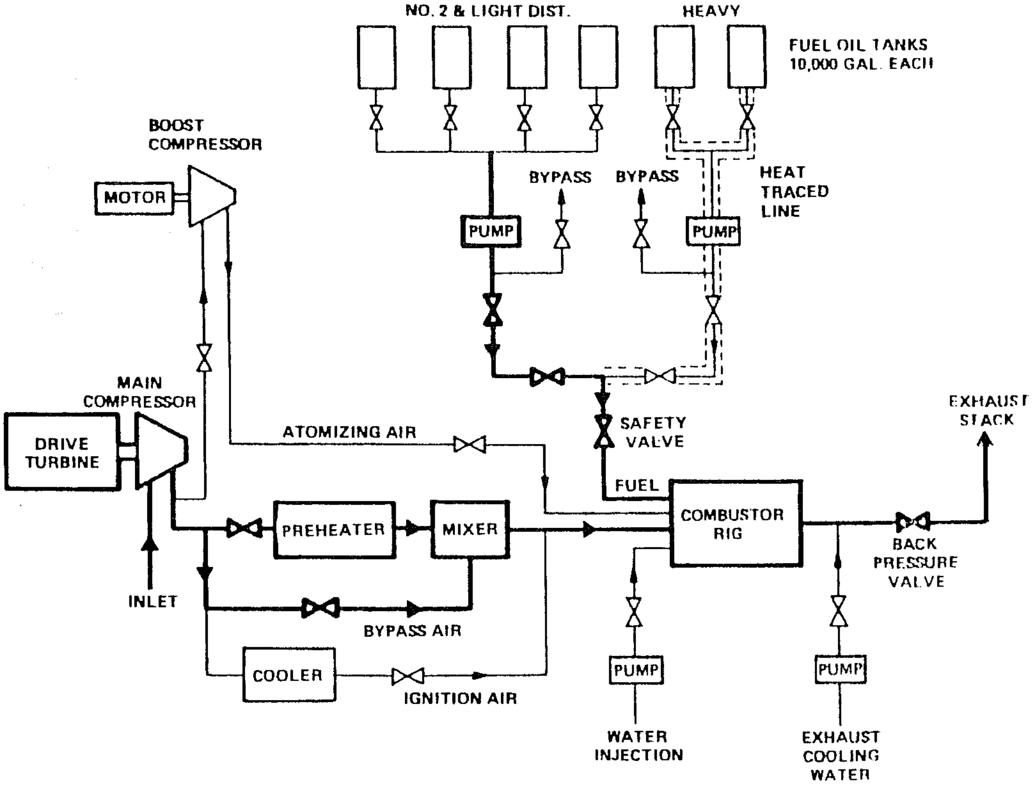

Figure 5-3 Combustor Test Rig Process Flow Chart

Table 5-1

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 back-pressure 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, coal liquids etc. 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. Pressure regulators, isolation ball valves and a control valve meter methane flow to the rig. 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.

5.2 COAL WATER MIXTURE FORWARDING SYSTEM

A schematic of the system supplying CWM to the MASB fuel nozzle is shown in Figure 5-4. 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. A photograph of the CWM forwarding system is shown in Figure 5-5 and shows this tank. 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.

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.

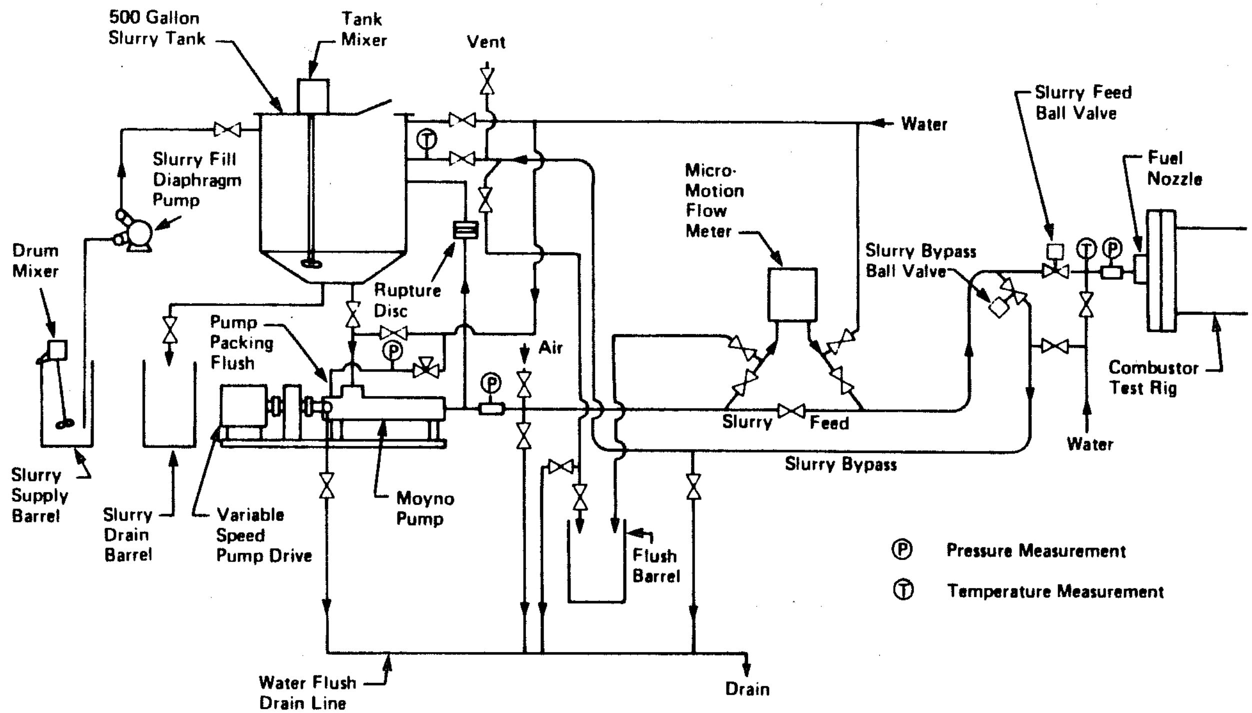

Figure 5-4 Coal Water Slurry Supply System

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 is 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 (see below) in a flow test prior to the combustion tests. It has been operational without problems throughout all tests.

5.3 INSTRUMENTATION AND EMISSION MEASUREMENT SYSTEM

Instrumentation is provided for monitoring and recording of the rig operating conditions. Pressures, temperature, 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 5.2) 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 5-2

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

5.4 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 minicomputer 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.

Section 6

FUEL CHARACTERISTICS

6.1 COAL WATER MIXTURE (CWM)

The CWM fuel, supplied by Otisca (in 55 gallon drums), is produced by their 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%, an additive of less than 1% and a coal particle size consist of 95% 10 X 0 micron. A typical distribution (from one drum) is shown in Figure 6.1 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% 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 shown on Figure 6-2 and Table 6-1.

The particle size distribution of the composite sample follows closely that of the typical distribution shown in Figure 6.1.

Table 6-1

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

The CWM used Eastern Appalachian bituminous coal and the ultimate analysis of the parent coal as given by Otisca from an ASTM (D3176) is given in Table 6-2.

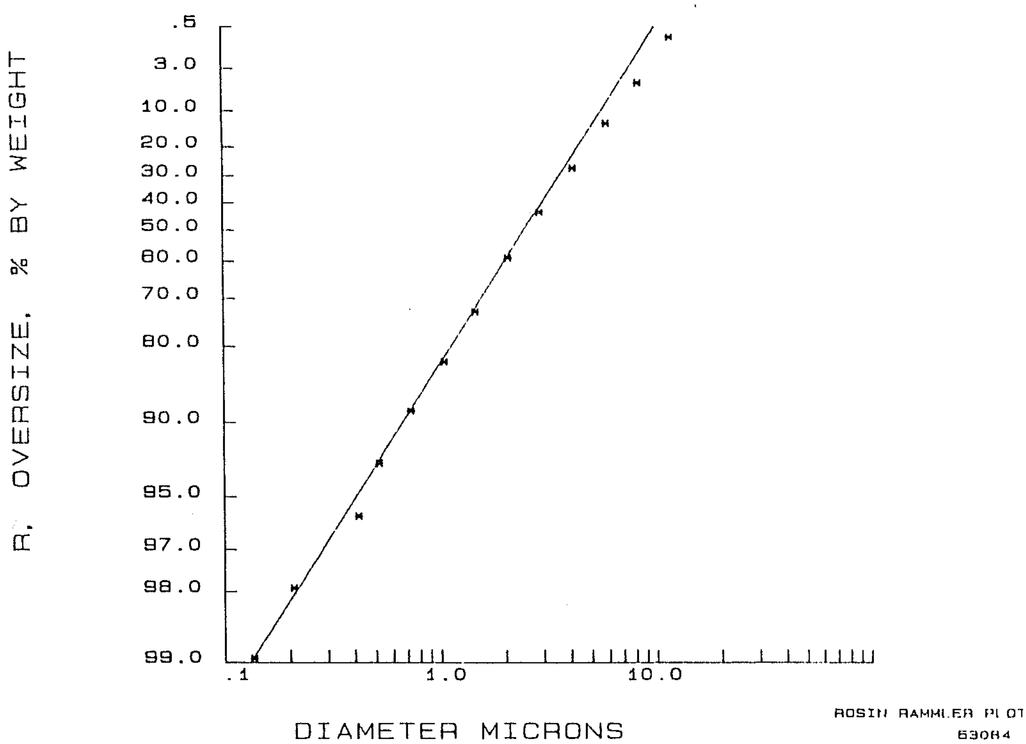

Figure 6-1 Particle Size Distribution - Rosin-Rammler Plot for Typical CWM Otisca

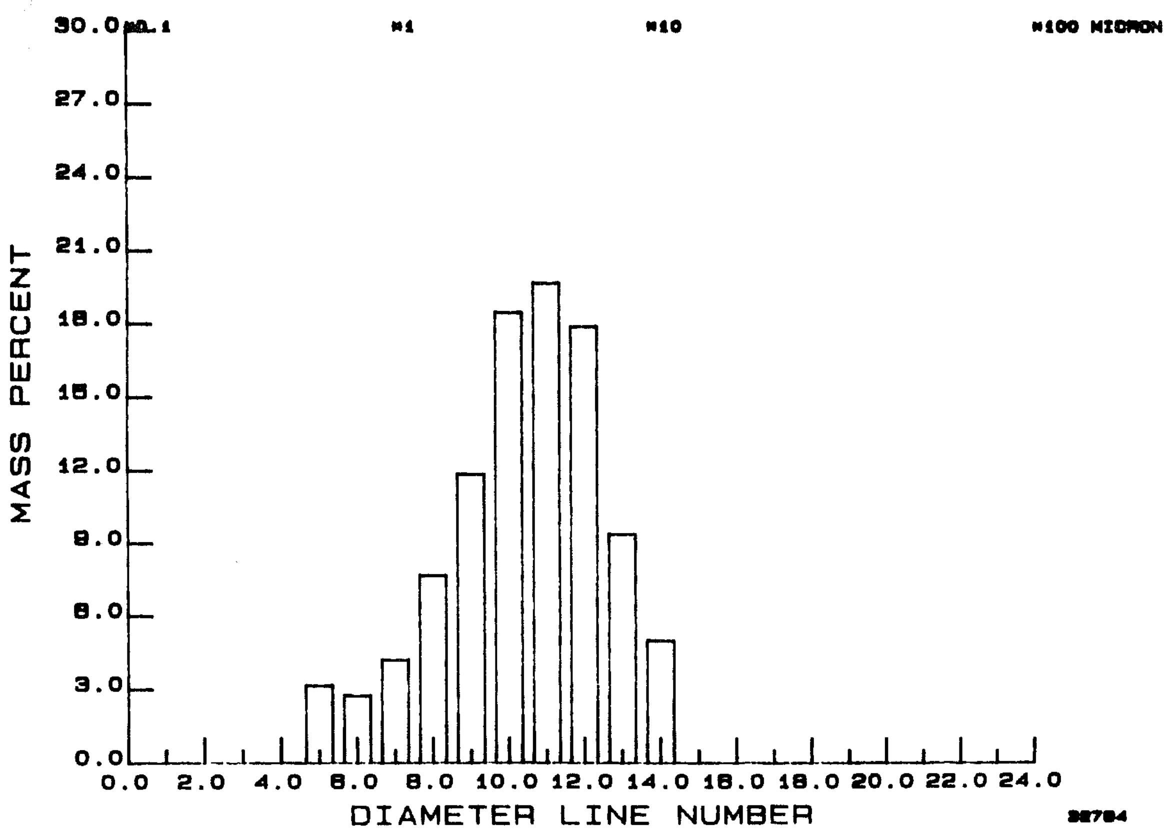

Figure 6-2 Particle Size Distribution of Composition Sample of 18 Drums of CWM

Table 6-2

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 6-3. This table includes the fuel and rheological properties. It is noted that the ash content of the slurry is 0.98% reduced from the parent coal value of 7.09%.

The composite CWM viscosity data is given in Figure 6-3 as a function of shear rate. It is noted that the viscosity of the CWM increases with increasing shear rate for this range of shear rates, i.e. the CWM is dilatent. Although this characteristic is not desirable since it may lead to poor atomization of the slurry, the nozzle spray tests (Section 4.7) show that the selected Parker Hannifin nozzle performance is more than adequate.

The flame temperature of the CWM fuel is shown on Figure 6-4 for the conditions of the combustion tests in Section 7.0. It is noted that the flame temperature for a give fuel-air ratio is lower by a few hundred degrees than that for oil and methane.

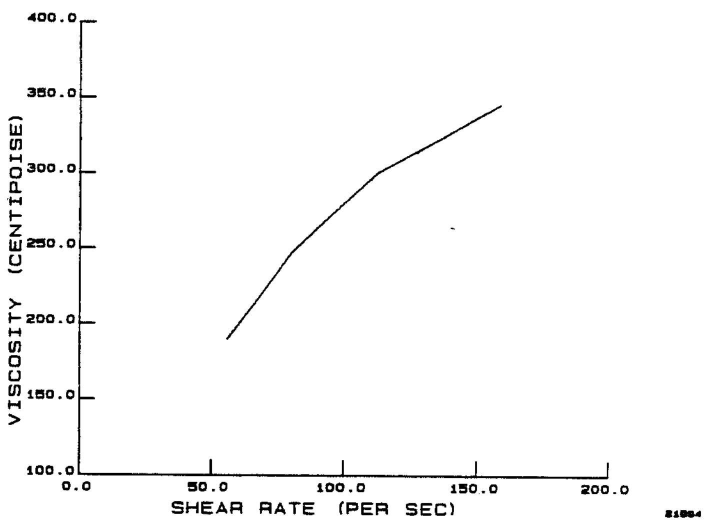

Figure 6-3 Viscosity Variation with Shear Rate (per sec) of Composite Sample of CWM

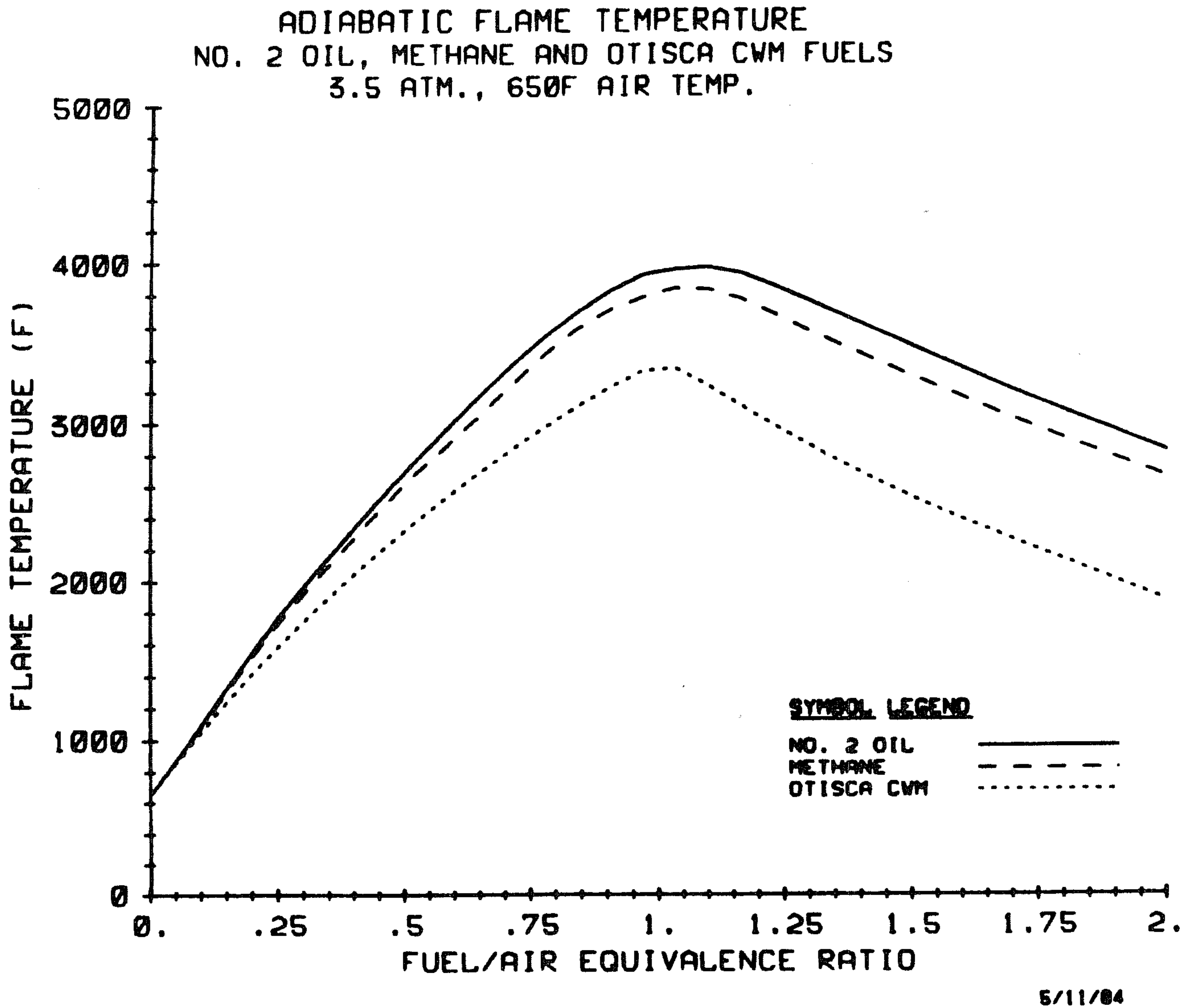

Figure 6-4 CWM Fuel Flame Temperature Under Combustion Test Conditions

Table 6-3

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 volume mean size	D185 (Note D)	10 micrometers 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.	

+Analysis supplied by Otisca.
*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 6-4 for Notes A to F.

Table 6-4

ANALYSIS METHOD FOR CWM ANALYSIS OF TABLE 6-3

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.

6.2 FUEL OIL

One test used #2 fuel oil so as to obtain combustion characteristics for comparison with the CWM fuel results. The properties of #2 distillate used in the data analysis are given in Table 6-5. Fuel analysis (Kjeldahl nitrogen method) was performed to check the weight of pyridine added to the fuel oil for the simulation of fuel bound nitrogen.

Table 6-5

NO. 2 FUEL OIL PROPERTIES

Specific Gravity	.85
Hydrogen, wt. %	12.74
Nitrogen, wt. %	.01
Sulfur, wt. %	0.
Carbon, wt. %	87.25
Oxygen, wt. %	0.
Net Heat of Combustion Btu/lb	18330.

Section 7

MASB TEST RESULTS

The results of the combustion tests conducted during this program are presented in this section and the on-going tests will be reported separately in a Topical Report.

Fuels for the initial test were methane and No. 2 distillate oil. During certain test points the oil was doped with pyridine to investigate the effect of fuel bound nitrogen (FBN) on NO_x emissions. Fuels for the subsequent tests were methane and CWM. The emphasis in these tests was on obtaining high combustion efficiency on CWM.

7.1 OIL AND GAS TESTS

Test results using the fuels methane, No. 2 distillate oil and No. 2 distillate oil doped with pyridine are given in this section. This doping provided up to approximately 1 percent fuel bound nitrogen by weight.

The primary test objectives were to shake-down the facility, rig and combustor on methane and No. 2 oil and evaluate the performance of the MASB as a rich/lean low-NO_x burner.

Nominal operating conditions were a pressure level of 3.5 atm., main air temperature and flow of 650°F and 4 pps and atomizing air temperature and flow of 70°F and .051 pps. During the test the combustor temperature rise varied from 445 to 1268°F, the FBN varied from 0 to 0.97 weight percent and the reference velocity varied from 49 to 64 fps. Throughout the test carbon monoxide was 50 ppm or less and unburned hydrocarbon was less than 1 ppm corresponding to combustion efficiencies in the range of 99.8 to 99.9 percent.

NO_x as measured on No. 2 distillate oil was adjusted to a nominal set of operating conditions and plotted in Figure 7-1 as a function of combustor temperature rise. The levels shown are roughly twice those of a previously tested 5 inch diameter MASB (1). Differences in operating conditions between the two burners were such that the effects of air temperature, reference velocity and pressure on NO_x all cancel. The difference in measured NO_x levels can be attributed to combined effects and these are geometric effects such as the ratio of the burner diameter and the increased axial spacing between swirlers in the 10 inch MASB, and aerodynamic effects due to a different swirl distribution.

In Figure 7-1 the primary zone equivalence ratio varied from 0.73 at the lowest load point to 1.87 at the highest. The primary zone is defined as the entire region up to the location of the third swirler (see Figure

4-6). Primary zone stoichiometry appears to have little effect on NO_x since NO_x emissions continue to climb linearly as the primary zone passes from lean to rich with increasing load. Thermal NO_x is apparently being formed wherever the flame passes from rich to lean.

NO_x results for test points during which No. 2 oil was doped with pyridine are listed in Table 7-1

Table 7-1

NO_x RESULTS WITH FUEL BOUND NITROGEN

FBN (wt. %)	0.64	0.95	0.97
Combustor Temp. Rise (°F)	541	733	1273
NO_x Measured (ppmv wet)	78	130	375
Fuel NO_x 100% Conv.(ppmv wet)	112	232	456
Fuel NO_x (ppmv wet)	26	50	219
FBN Conversion (%)	23.2	21.6	48.0

The fuel NO_x in Table 7-1 was determined from Figure 7-2. The vertical difference on the graph between the measured levels with the doped fuels and the clean fuel baseline is attribtued to fuel NO_x. The fuel bound nitrogen conversion efficiency of 21.6 percent obtained with 0.95 weight percent FBN is comparable to the 20 percent efficiency obtained on a 0.80 weight percent FBN coal derived liquid fuel tested in the 5 inch MASB(1). For the test point with 0.97 weight percent FBN both the measured NO_x and calculated FBN conversion were very high. However, there is some question as to whether the high NO_x level should be attribtued to fuel NO_x. During this test point a burner instability was detected which caused a longer flame in the lean zone of the burner. It is perhaps more reasonable to conclude that the high NO_x measured was the result of high thermal NO_x rather than high fuel NO_x.

In Figure 7-2 the primary zone equivalence ratio varied from 0.84 at the lowest load point to 2.00 at the highest. Calculated FBN conversion efficiencies appear anomalous with low conversion when the primary zone is near stoichiometric and apparent high conversion efficiency when the primary zone is rich. High NO_x with a rich primary zone can be explained by the observed burner instability as described above. Low conversion efficiency with a stoichiometric primary zone could be explained either by a mixing limitation causing a localized rich region in the recirculation zone or by a richer primary zone than was expected based on calculated flow areas. The first explanation would seem more likely since measured pressure loss was in agreement with the total calculated flow area. Primary zone residence times were 11 to 12 ms which are adequate for fuel nitrogen reactions to approach equilibrium.

Outlet temperature plots at low and high firing rates are shown in Figures 7-3 and 7-4 respectively. A layer of relatively cool air from swirler 4 can be seen at the periphery of the flow. The hotter core is very flat at the low firing rate and is more center peaked at high firing rate. As a result, pattern factor increases with firing rate, a trend that is opposite to that of most gas turbine combustors.

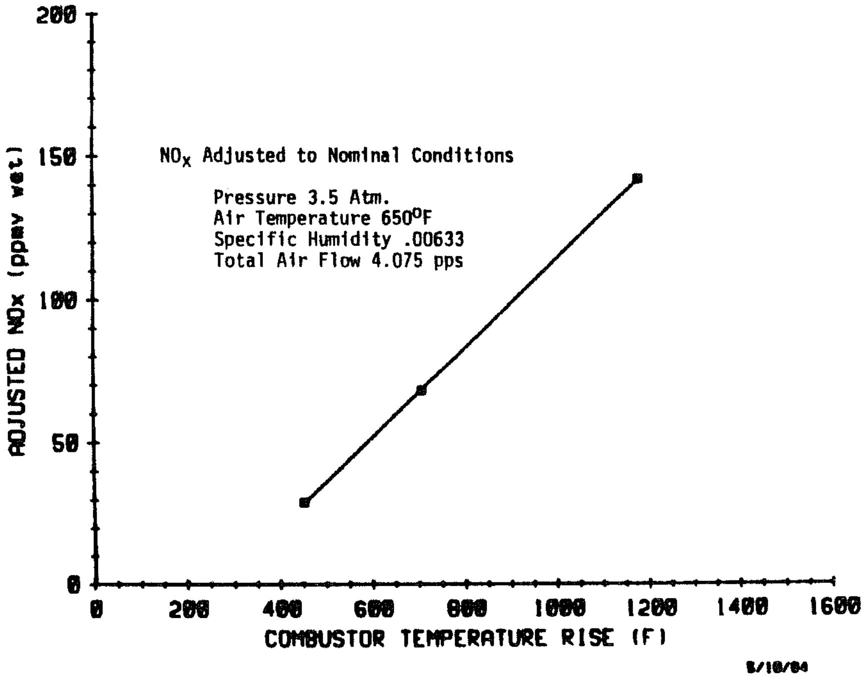

Figure 7-1 MASB NO_x Emissions on No. 2 Fuel Oil

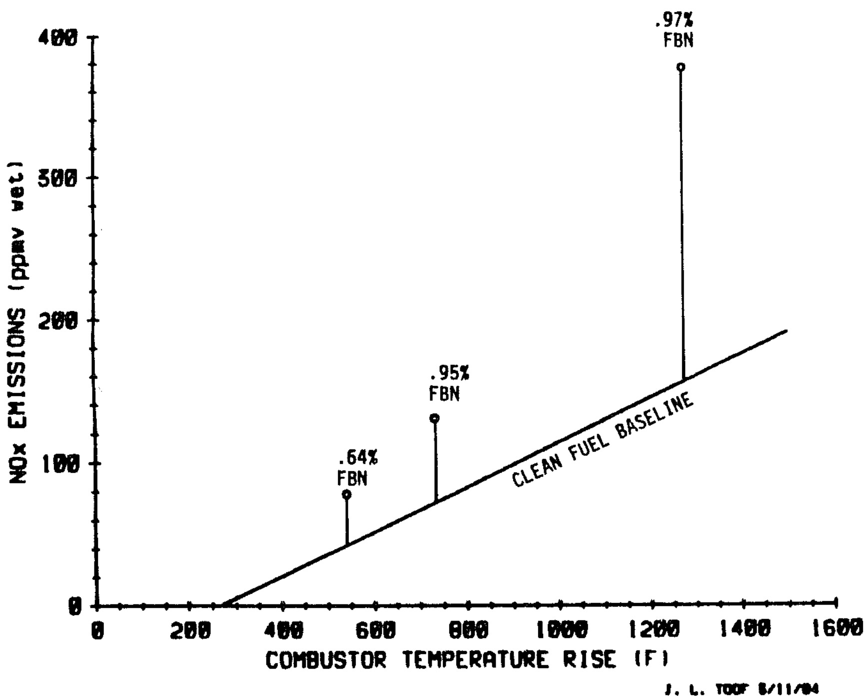

Figure 7-2 MASB NO_x Emissions on Fuel Oil Doped with Pyridine

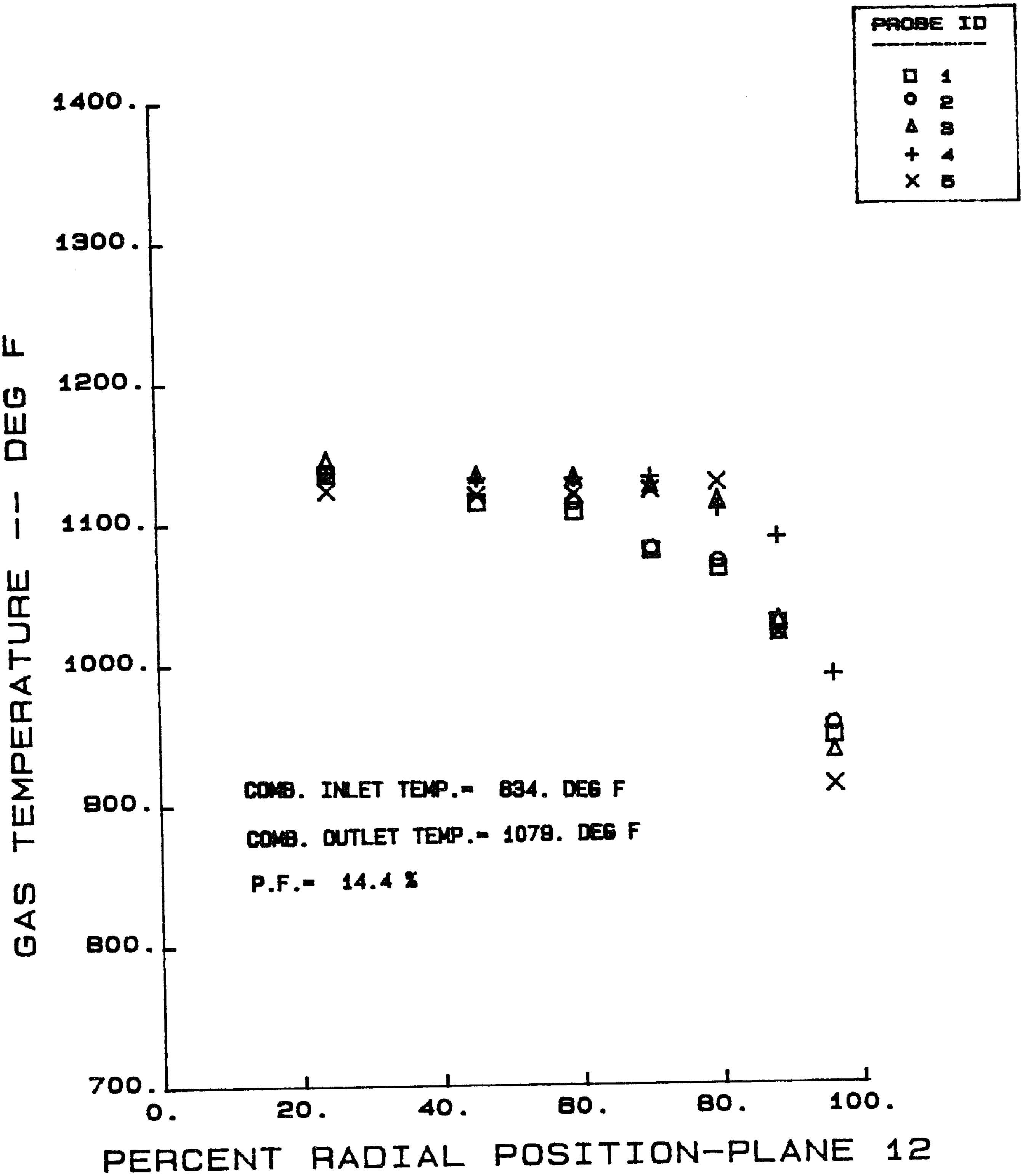

Figure 7-3 Radial Outlet Temperature at Low Load

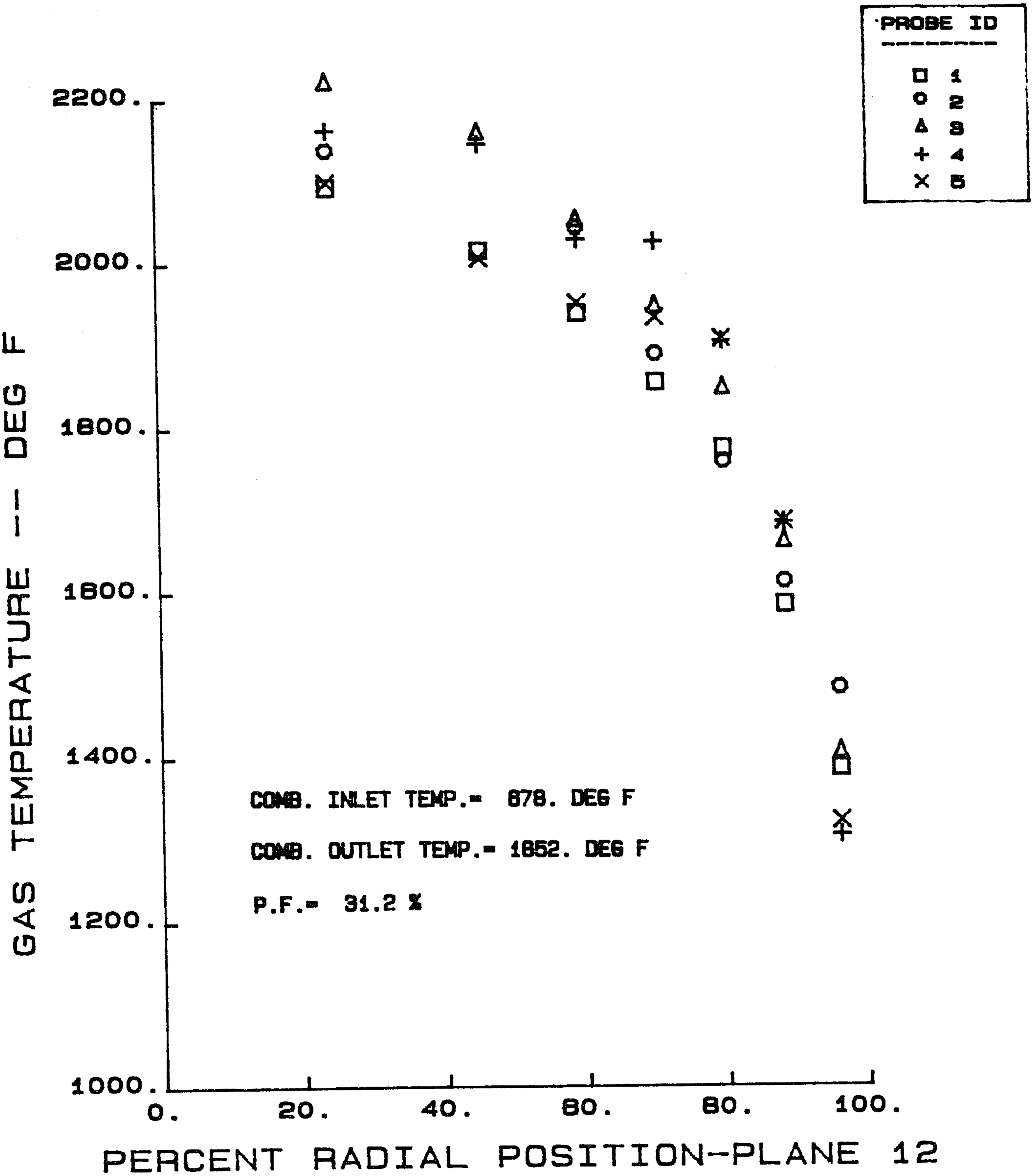

Figure 7-4 Radial Outlet Temperature at High Load

Reference velocity was varied from 49 to 64 fps during the test and the MASB remained stable over this range. The instability mentioned above was apparently caused by an overly rich primary zone because the burner was stable at another test point with equal reference velocity of 64 fps but leaner primary zone (lower load). Stable operation was achieved at primary zone heat release rates ranging from 2.5 to 7.0 10^6 Btu/hr ft^3 atm. which are comparable to those expected of a gas turbine combustor.

Results from the combustion of oil and of gas can be summarized as follows:

- The ignition and fuel transfer sequence involving the propane torch, methane pilot and distillate oil primary fuel was successful.
- Combustion efficiency on both methane and distillate oil was high, 99.8-99.9 percent.
- NO_x emissions on undoped oil were about twice those of the subscale MASB which was attributed to geometric or aerodynamic effects.
- At low firing rates the conversion of fuel bound nitrogen was about the same as in the subscale MASB in spite of an apparent near stoichiometric primary zone.
- At high firing rates an observed rich burner instability may have effected fuel NO_x data and made interpretation difficult.

7.2 CWM TESTS

The principal test results to date for the combustion of CWM were obtained at a pressure level of 10 atmospheres and nominal main air temperature and flow at 800°F and 3 pps. In addition, the nominal atomizing air temperature and flow was increased to 650°F and 0.094 pps from the oil tests. For the results reported here the burner airflow distribution was modified to improve combustion efficiency. This represented a departure from the rich/lean design.

Some initial test points were obtained on a mixture of methane and CWM. The combustion efficiency results are shown in Figure 7-5 as a function of methane/CWM mass ratio at a constant load of 70%. A significant result was the 99.5 percent combustion efficiency obtained at a methane/CWM ratio of 0.4.

The radial outlet temperature plot for the 99.5 efficiency point is shown in Figure 7-6. As was observed previously on oil the profile is very flat in the center with a thin cooler layer at the periphery. The pattern factor of 8.0 percent obtained on this mixture of CWM and methane is quite low and is better than that obtained on oil.

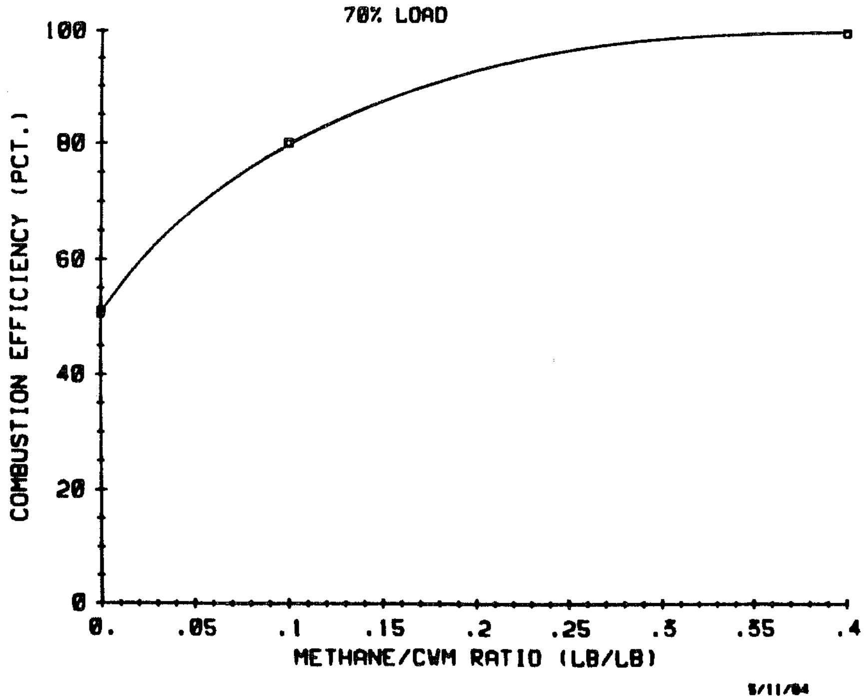

Figure 7-5 Combustion Efficiency for Different Methane/CWM Ratios

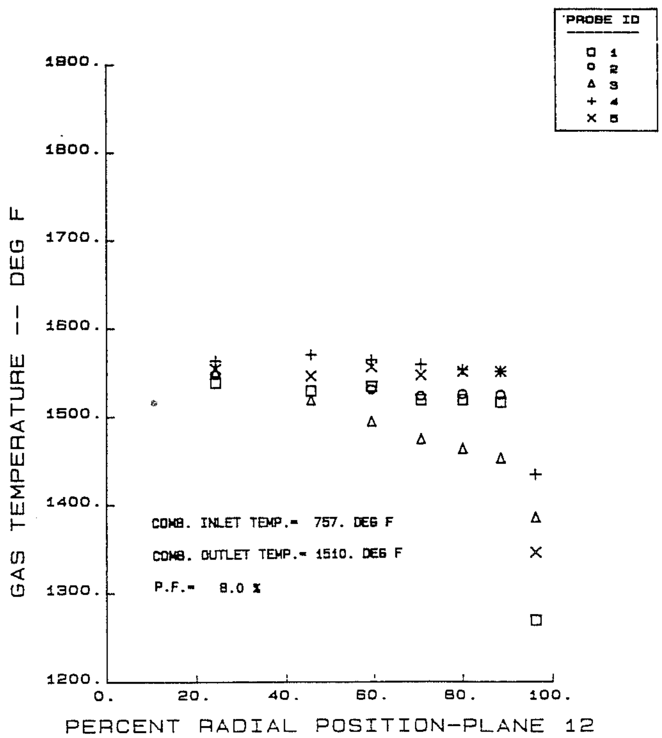

Figure 7-6 Radial Outlet Temperature for Methane/CWM Fuel Mixture Combustion

A complete fuel transfer from methane to CWM was achieved. Combustion efficiency burning CWM alone is shown in Figure 7-7 as a function of load. Load is defined by the adiabatic burner outlet temperature, i.e. by the temperature that would have been obtained at a combustion efficiency of 100 percent. An adiabatic burner outlet temperature of 2000°F corresponds to 100% load. The combustion efficiency on CWM was 29 percent at zero load (idle), peaked at about 52 percent at mid load and dropped off to 37 percent at full load. Although the ultraviolet signal was erratic when burning CWM alone, the burner never blew out.

The calculated primary zone equivalence ratios on CWM varied from 0.14 at zero load to 1.06 at full load. Primary zone stoichiometry did not correlate well with combustion efficiency, i.e., a near stoichiometric primary zone did not yield the highest efficiency. The highest efficiency was obtained at an equivalence ratio of about 0.5. A similar observation had been made with respect to FBN conversion in the oil test results, the primary zone behaved as if it were richer than the calculated equivalence ratio. Possible explanations were a mixing limitation causing a localized rich region in the recirculation zone or a richer primary zone than was expected based on calculated flow areas. As before, the first explanation seems more likely in light of agreement between measured pressure loss and total calculated flow area. More specifically, the air from swirler 1 alone rather than the total primary zone airflow may determine combustion efficiency and stability.

Although primary zone stoichiometry did not correlate with combustion efficiency, one parameter which did was the ultraviolet signal. The loss of ultraviolet signal at points of low combustion efficiency would indicate that the flame is lifting off the nozzle and the stable recirculation of hot combustion products is deteriorating. Primary zone residence times ranged from 15 to 19 ms and were otherwise sufficient for the slurry combustion process.

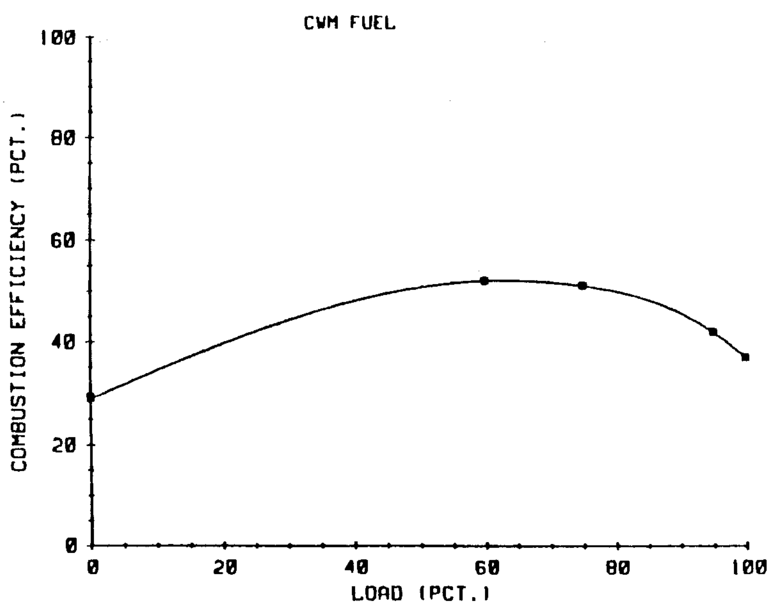

Figure 7-7 Combustion Efficiency for Different Load Conditions

Emissions are listed in Table 7-2. Combustion inefficiency represented by CO and UHC at the low efficiency points cannot account for the measured burner outlet temperatures indicating that some coal was passing through the burner unreacted. Combustion efficiency when burning CWM alone was too low to draw conclusions about the measured NO_x levels.

Table 7-2

MEASURED EMISSIONS

Methane/CWM (lb/lb)	.40	.10	0
Load (%)	70	70	100
Combustion Efficiency (%)	99.5	80	37
NO (ppm wet)	81	80	75
NO_x (ppm wet)	133	110	102
CO_2 (% dry)	2.795	2.60	3.185
CO (ppm dry)	500	3150	2875
O_2 (% dry)	17.175	17.95	17.00
UHC (ppm wet)	20	350	300
Smoke (Bach.)	6.3	---	---

Important results can be summarized as follows:

- 99.5 percent combustion efficiency at a methane/CWM ratio 0.40 by mass.
- 80 percent combustion efficiency at a methane/CWM ratio of 0.10 by mass.
- 37-52 percent combustion efficiency when burning CWM alone at loads ranging from 100% to 60% based on fuel flow.
- A turndown ratio of 4.7 for oil combustion.
- Correlation of ultraviolet signal and combustion efficiency indicating a need to improve the recirculation zone of the burner.

REFERENCES

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).

Section 8

CONCLUSIONS AND RECOMMENDATIONS

The program to evaluate coal water mixture with the MASB combustor has not been completed at this date. Tests in progress will be reported in a separate Topical Report.

This program has demonstrated that it is feasible to burn CWM with the MASB combustor. A CWM fuel forwarding system has been designed and fabricated and has been shown to be suitable for spraying CWM for a combustion turbine combustor. No operational problems of this system have been encountered. The program to date has demonstrated stable combustion of a 50 percent solids CWM. A fuel transfer from methane to CWM at load has also been demonstrated. Combustion efficiencies in the range of 99.8 to 99.9 percent were obtained on both methane and No. 2 distillate oil and up to 99.5 percent with a mixture of methane and CWM. However, the combustion efficiency when burning CWM alone was typically 50 percent and requires improvement. The MASB, a metal wall combustor which has been aerodynamically designed to provide the appropriate energy inputs for devolatilization of the coal particles in the CWM and the burn-out of the char particles has been used to burn the CWM. Results indicate combustor can be designed for CWM combustion. Moreover the analytic flow field calculation have been a useful design tool in this respect. The MASB design has provided a volumetric heat release rate of one-half million Btu/hr-ft^3-atm whereas most CWM combustion to date has been performed in facilities/boilers with heat release rate of at least one order of magnitude lower.

Principal conclusions can be summarized as follows:

- Combustion tests on methane and #2 fuel oil show high efficiences in a 10 inch diameter MASB with forced vortex design.
- Combustion is possible in a gas turbine combustor for a CWM with 50% solids. Stable combustion with this CWM has been achieved but efficiency requires improvement.
- A transfer from methane to CWM at load has been demonstrated.
- The use of a metal wall combustor for CWM fuel has been demonstrated.
- Visual observation of the combustion process indicates no major inconsistency with analytic flow field calculations.

Indications during the tests are that the combustion efficiency can be further increased by improvement of the recirculation zone of the burner and/or a modification of the coal particle residence times. This increase can be achieved by adjustment of the individual air swirler flows, the pressure or the fuel spray axial momentum. The efficiency could also be increased by increasing the energy content of the fuel.

Specific recommendations based on these results to date are:

- Improve the MASB design using the present combustion test data base and with the assistance of the numerical computer model.
- Evaluate ash deposits from the combustion of these fuels on cooled pins to assess the deposition problem. Some results for coal water mixture will be available under this program.
- Perform combustion tests to determine the effects of different coal particle sizes and different ash content.
- Increase the energy content of the fuel CWM by increasing the solids loading to the range of 60-75% solids and evaluate the combustion characteristics.
- Evaluate the combustion charactersitics of micronized coal powder with the MASB combustor.
- Evaluate the combustion of a slurry of coal and methanol; this mixture would effectively increase the energy content per lb of slurry and improve the primary combustion zone performance.