SINGLE STAGE TOROIDAL FLOW COAL FIRED MHD COMBUSTOR

J.O.A. Stankevics, C.C. Stewart
R.C. Beals, and A.C.J. Mattsson
Avco Everett Research Laboratory, Inc.

Abstract

Studies and testing conducted over the last three years at The Avco Everett Research Laboratory, Inc. (AERL) have considerably advanced the state-of-the-art of MHD coal-fired combustor design and operation. A prototype 20 MW_t MHD coal-fired combustor was designed, fabricated, and tested under a contract to the Department of Energy. The slagging MHD coal combustor design concept is a single-state configuration which enables high overall thermal efficiency to be obtainable also with high rejection of ash-slag particles. The vertical combustor has a downward flow, a cylindrical chamber, and a horizontal exit nozzle for conveying the potassium seeded plasma to a MHD generator channel. Three coaxial oxidizer coal injector jets introduce preheated air/oxygen from a vitiation heater into the combustor. Combustion experiments were conducted at operating pressures up to 6 atm and yielded the following data: combustion plasma temperature of 2650-2800°K, electrical gas conductivity of 6 to 7 mhos/meter, carbon utilization greater than 99.5%, and stable steady state operation. At the conclusion of the test phase, examination of the combustion and auxiliary equipment indicated no combustor malfunction or hardware degradation.

I. Introduction

A durable and efficient coal cumbustor is a necessary part of the overall system to achieve successful magnetohydrodynamic (MHD) power generation. The design objectives used for the AERL 20 MW_t coal-fired combustor were as follows:

(a) To maximize combustor performance (electrical gas conductivity) consistent with program requirements.

(b) To provide design and engineering data, obtained through combustion experiments at a 20 MW_t size, for scaleup to 50 MW_t.

(c) To design and utilize a Performance Evaluation Model (PEM) to measure electrical conductivity of the seeded combustion products.

(d) To design a 50 MW combustor based on the data developed and achieved in items (a) and (b).

These design objectives resulted in the following combustor features as shown in Fig. 1, (Ref. 1):

1. A vertical single-stage toroidal flow unit having a cylindrical chamber, and a horizontal exit nozzle for directing the seeded combustion gas to a MHD generator channel.

2. Three air/oxygen vitiation heaters which discharge to coaxial oxidizer coal injectors. The inflowing reactant jets coalesce near the combustor centerline and form a vertical moving jet directed toward the combustion dome of the chamber.

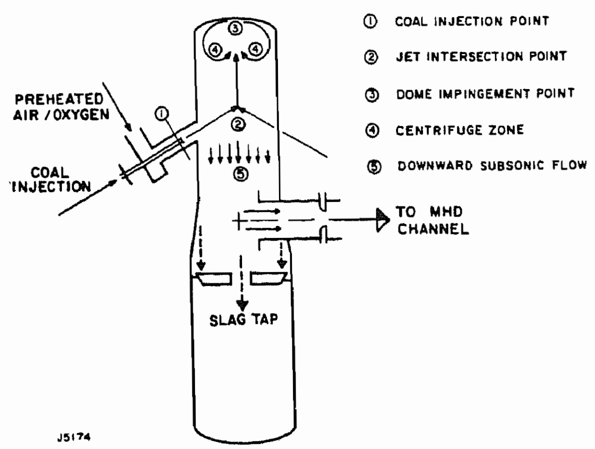


Fig. 1. Schematic of 20 MW_t Coal Combustor, Showing Jet Impingement and Flow Pattern of Combustion Gases

3. The radial acceleration of the recirculating vortex flow is the prime mechanism for mineral/slag droplet removal from the combustion gases. A self-renewing slag coating forms on the water-cooled combustor wall and flow deflector baffles. The molten slag flows down the combustor walls and is collected at the bottom of the slag tap.

4. A dense-phase coal feed system to minimize cold carrier gas entering the combustion chamber.

5. A dry seed counter-flow injection system using K_2CO_3 granular particles, resulting in uniform mixing with the combustion gas and rapid ionization in the combustor discharge duct.

6. A Performance Evaluation Module (PEM) based on units designed and tested for MHD application at AERL.

This paper describes the design configuration, development of the vitiation heaters, coal-feed system, combustor unit, analytical modeling, and the performance test results of the AERL 20 MW_t coal-fired MHD combustor.

II. Combustor Configuration and Development

1. Key Combustion Events in the AERL Combustor

The approach taken in the design of the AERL 20 MW_t combustor is outlined in Fig. 1. It is based on AERL's background in both development testing, and analytical and experimental combustion and gasification work with coal, as well as our understanding of MHD channel and system requirements (Ref. 2-6). The slagging MHD coal combustor concept shown in Fig. 1 is a single-stage configuration which enables the achievement of high overall thermal efficiency, and a design approach which emphasizes controlled thermochemistry of coal reaction, compactness, and slag control. Fig. 1 shows a unit having a downward flow, a cylindrical combustion chamber, and a horizontal exit duct for conveying the plasma to a MHD generator channel.

A trapped toroidal vortex driven by the reactant input flow inertially separates mineral/ash particulates. It also promotes coal combustion product homogeneity and highly efficient and stable combustion.

The three coaxial oxidizer coal injectors shown in Fig. 1 introduce preheated ir/oxygen from a vitiation heater. Coal injection in the oxidizer flow promotes .xing, and rapid coal particle heat-up and volatilization. This injection scheme .nimizes the time required for heterogeneous char burnout.

The inflowing jets coalesce near the combustor centerline and form a vertical jet directed toward the stagnation region of the combustor dome. In the highly turbulent stagnation region, the reacting flow is turned to form a radial wall jet which forms a toroidal vortex in the corner of the dome. The radial acceleration of the recirculating vortex flow is the prime mechanism for mineral/slag droplet removal from the combustion gases. A self-renewing slag coating forms on the water-cooled combustor wall and flow deflector baffles. Heterogeneous gasification reactions with the larger size char particles trapped on the slag coating further reduces heat loss. The inside walls of the combustor are grooved to aid slag retention. The molten slag flows down the combustor walls and is collected at the bottom of the slag tap. High temperature combustion gas leaves the vortex in the dome section of the combustor and descends as a turbulent low subsonic flow. A horizontal discharge duct and subsonic converging nozzle accelerate the combustion products to an exit Mach number of M $\simeq$ 0.30.

Dry granular potassium carbonate (K_2CO_3) is used as an ionizing seed. It is injected in a counter-flow pattern into the high-temperature (2700°K-2800°K) combustion products in the exit duct of the combustor.

2. Modeling of Coal Particle Combustion and Fluid Mechanics of Combustor

In the design of the 20 MW_t coal-fired combustor system, AERL employed analytical models which were based on combustion experiments. The AERL Coal Combustion Code was previously developed to describe coal gasification by thermal pyrolysis under various reactor conditions (Ref. 4-5).

Calculations of the combustion rate of Montana Rosebud coal in oxygen enriched vitiated air have been made for the 20 MW_t combustor. The calculated fraction of each daf coal particle size burned in the combustor is shown in Fig. 2. The standard coal particle size distribution for the 20 MW_t combustor is taken to be 70% through a 200 mesh grid. It is represented by seven finite particle sizes ranging from 6 to 190 μm diameter.

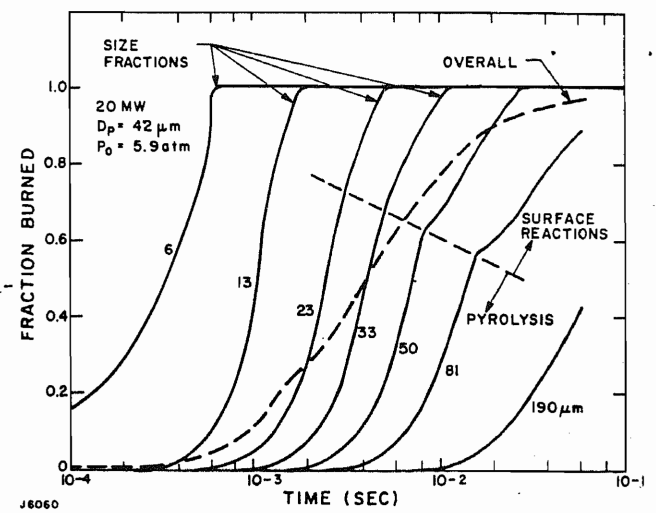


Fig. 2. Fraction Burned of Coal Particles Based on 20 MW_t Combustor Kinetics

The dominant initial combustion process for each particle size is thermal pyrolysis. After the particle is fully pyrolized (charred), the heterogeneous reactions between the coal gaseous species on the surface of the coal particle dominate.

For the 20 MW_t combustor, a representative residence time for the coal particle is about 30 msec. At this time, as seen in Fig. 2, 94% of the daf coal has been burned. The larger particles will be separated from the combustion gas stream along with ash particles by the centrifugal effects in the corner of the combustor dome section, and many of them will stick to the slag-covered wall where oxidation of the residual particles will proceed.

Also, AERL used computer codes (Ref. 7-9) in coal combustor performance studies for thermochemical equilibrium plasma composition and transport property calculations. Fig. 3 shows a sample of the results of equilibrium plasma calculations made to confirm of 20 MW_t coal combustor performance demonstration test requirements (Ref. 10).

Besides the analytical flow field modeling efforts for the combustor, cold flow studies using water tunnel and air particle system for general combustor flow field definition and for observation of mixing and transport processes were conducted. Based on these measurements and other data (Ref. 11-14), a flow model describing gas motion, entrainment and particle mixing was used in the analysis of the combustor flow behavior.

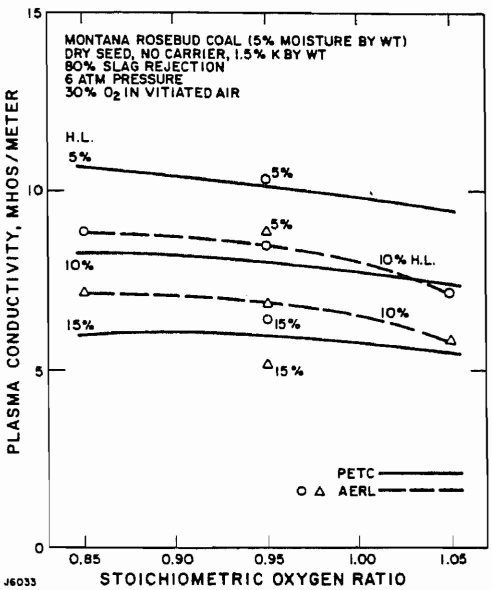


Fig. 3. Conductivity vs Stoichiometric Oxygen Ratio of 20 MW_t Coal Combustor Performance

The nature of particle trajectories in the free-vortex swirling flow are, to a large degree, governed by the Stokes number and were calculated using Ref. 15-16. Using the calculated particle velocities, the Stokes number of the average particle size is larger than St>3.0, for a number of radial wall jet streamlines, indicating an enhanced centrifugual slag separation. Uniform slag deposits were observed in the corner of the dome during the 20 MW_t combustor tests.

The slag flow and wall coating in the 20 MW_t combustor is primarily dependent on centrifugal separation, slag viscosity, backing wall temperature, combustion gas dynamics, shear flow, and gravity. AERL has studied extensively the slag flow characteristics of electrode wall coatings and developed a slag flow model and code (Ref. 6,17). The slag code was used in the combustor design to determine slag surface temperature, heat loss to the walls, and slag thickness.

AERL has also developed a computed code to predict physical processes and vapor diffusion of mineral matter during coal particle degradation in the combustor. The time scales for mineral matter to fuse and to evaporate are important from the point of view of slag rejection, and for scaling the distance between the coal injector and combustor dome.

3. Design Features of 20 MW_t Combustor

Several key design criteria for the test combustor were established based on past development experience, and they are noted below:

a) The combustor configuration should be modularized so that individual components can be modified or replaced at a minimum cost.

b) The combustor should be rugged and durable in order to maintain its integrity over an extended test period.

c) The design should allow fexibility to increase combustion residence time by adding combustion chamber length in a simplified manner.

A double-walled 20 MW_t combustor was completely designed, and detailed manufacturing drawings were made for super alloy fabrication. The double-wall concept is relatively simple to design and construct. Water cooling is by turbulent forced convection, and is conventional. Certain components of this design, such as the exhuast duct and seed injectors were completed and tested in the final demonstration tests of the experimental 20 MW_t combustor described subsequently.

A simplified test version of the 20 MW_t coal combustor shown in Fig. 4 was designed and constructed using pool cooling. The purpose was to obtain early test data and to permit rapid experimental modifications during the combustor development phase. The combustor length was deliberately made greater than required for complete combustion.

Mechanical design features of the combustor include:

1) Extensive use of standard carbon steel tube welding components for low cost, easy welding, and relatively good thermal conductivity.

2) Water cooling. Flexible water seals admit vitiation burners and instrumentation through the pool cooling jacket walls.

3) Free standing main burner. Thermal growth is unconstrained.

4) Slag retaining grooves on inside surfaces of the walls.

5) Batch collection of slag in a removable bucket.

6) Burner pressure is controlled by a converging nozzle, sized for the design mass flow rate, pressure, and temperature. The nozzle is cooled by forced convection.

7) A forced convection cooled exhaust duct downstream of the nozzle. Quench water is introduced 48 in. downstream of nozzle.

The burner walls are water cooled. High heat flux zones such as the combustor dome and coal/oxidizer injection port were cooled by turbulent forced convection. Lower heat flux zones such as the combustor wall were pool cooled.

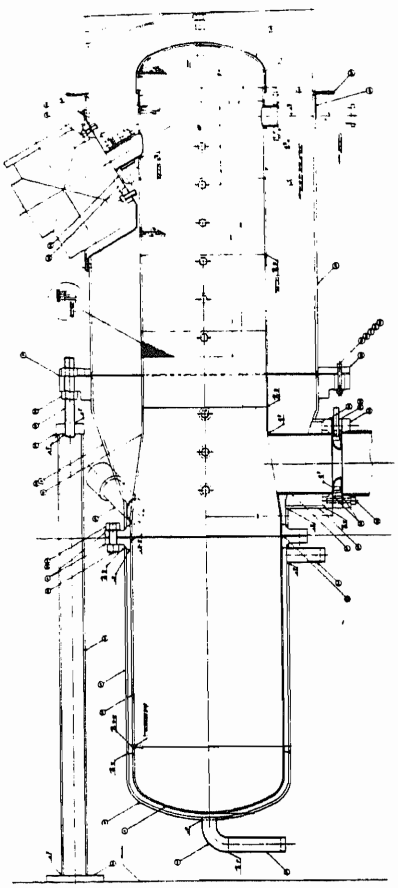


Fig. 4. Pool Cooled 20 MW_t Experimental Combustor

High heat flux gas-side surfaces of the burner are grooved to retain slag. Grooves are initially filled with zirconia to facilitate slag adhesion.

The 20 MW combustor test rig had the necessary dianostic instrumentation to assess heat loss, carbon burnout efficiency and combustion stability. Nine ports for gas sampling and optical pyrometry were incorporated in the combustion chamber.

The initial design of the combustor shown in Fig. 4 underwent modifications to increase slag rejection. Conical slag collecting baffles, and jet deflectors were added to the combustor during the development tests.

Fig. 5 shows the final modifications made to the pool cooled 20 MW_t experimental combustor. Combustor volume was reduced to the value indicated by experiments to be sufficient to complete combustion.

4. Construction of the 20 MW_t Experimental Combustor

The construction details of the combustor assembly are shown in Fig. 5. The material selected for construction of the coal combustor was carbon steel to minimize material costs. The coal combustor assembly consists of three subassemblies, i.e., a) a combustor section which has three externally mounted equally spaced vitiation burners, and internally, a slag tap, jet deflector, and baffle; b) exit duct section, horizontally mounted to the side of the combustor; and c) a slag bucket section and slag tap which is flange mounted to the bottom of the combustor.

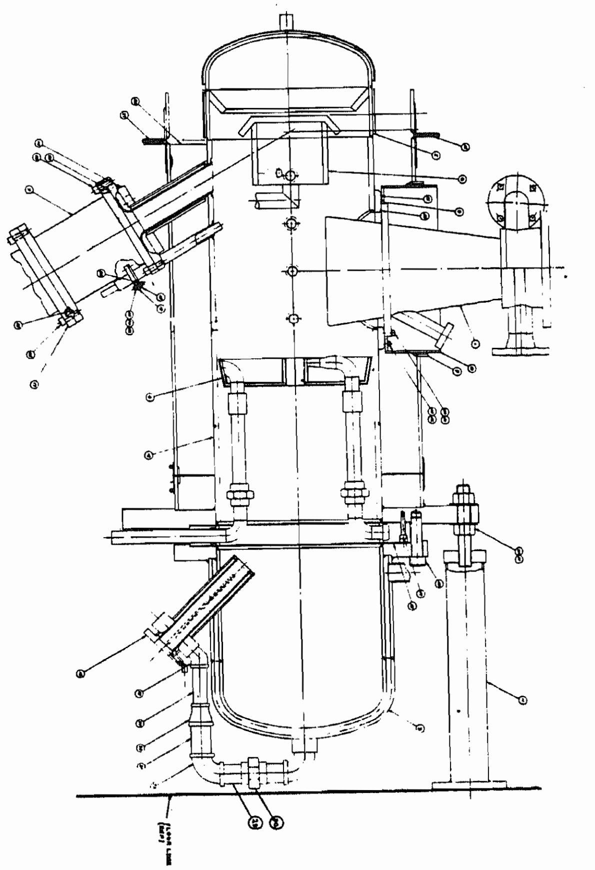


Fig. 5. Final Modification of Pool Cooled 20 MW_t Experimental Combustor for Phase II Program

The combustor section has both an inner and outer cylinder vertically mounted and welded to a base flange. The outer cylinder is a 30 in. OD pipe, ~12 ft. long and open at the top end. It serves as the water pool and cooling jacket.

The inner cylinder consists of a 20 in. OD pipe ~36 in. long having a 0.650 in. wall thickness with machined circumferential grooves. The uppor portion of the cylinder houses the slag catching baffles. Contained within this section is also a double-walled, conical shaped water-cooled baffle assembly which is welded to the cylinder wall.

A dome assembly is welded to the top of the cylinder section. The dome assembly consists of a 20 in. OD pipe end cap with circumferential grooves. Attached to the exterior of the inner dome is an outer dome. A pipe is welded to the hole in the top center of the outer dome to provide for water-cooled forced convection of the dome section.

Three water-cooled injector (coal/oxidizer nozzles are externally mounted by welding to the inner and outer cylinders. They are positioned 120° apart from each other and are inclined at 30° from the horizontal to provide an upward flow directed toward the center of the dome. Three vitiation burner extensions with double walls and water-cooled are 12 in. long and flange mounted.

Three water-cooled injectors installed coaxially in the vitiation burner cross penetrate into the vitiation burner extensions to direct and deliver a regulated flow of powdered coal into the combustor.

A conical discharge duct assembly shown in Fig. 5 has triple cone structure and was built using Incoloy alloy 800H material. The entrance section of the duct in the combustor chamber is water-cooled, as well as the inside surface of the exit duct. Mounted in the duct are three seed nozzles which inject dry potassium carbonate seed, counterflow at a 30° angle from the exit flow axis.

A jet deflector assembly was fabricated of carbon steel parts consisting of two different diameter pipes. The jet deflector, in the combustor cylinder, is located in a position such as to permit the fuel and oxidizer jet interception in the vertical center of the inner pipe, and then forms a single jet directed upward to the center of the dome. The deflector is fitted with water cooling pipes which are also used to hold the deflector in position.

Located in the combustor section and positioned below the exhaust discharge duct is a slag tap and flange assembly. A hole is bored through the two bottom plates and two tubes are welded to the plates to provide an opening in the center of the tap for coal slag overflow and discharge. The slag tap is mounted on two vertical pipes which serve as the cooling water input and output to the slag tap.

Assembled below the combustor and the slag tap flange, is a slag bucket. A hole is bored through both the inner and outer walls of the slag bucket to position and align the gas tap. The gas tap induces a flow of exhaust gases through the center nole of the slag tap so as to prevent slag freeze up.

Supporting the coal combustor assembly are three support legs equally spaced 120° apart.

5. Vitiation Heater Development

An air-cooled vitiation heater design was selected for application to 20 MW_t coal-fired combustor development testing.

In order to obtain temperature up to 3000°F, vitiation heater designs were evaluated which are used for turbojet can combustors. Based on test results at the Avco Lycoming Division, a combustor operated in the temperature range of 2500-3350°F with combustion efficiency above 97% was selected for the 20 MW_t combustor design. One added feature of the turbojet can combustor is that it employs a self-contained air cooling system. The combustor also has negligible heat loss operating at the inlet air temperatures.

Fig. 6 shows the resulting vitiation heater and the coal injector configuration designed for 10 atm operating pressure and an inlet air mass flow of 3 lb/sec.

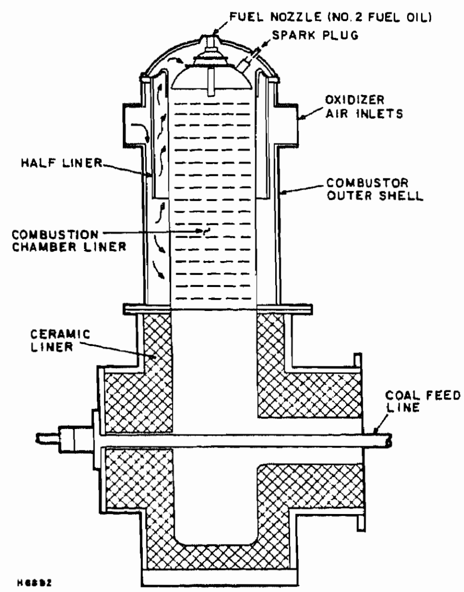


Fig. 6. Air-Cooled Vitiation Heater/Coal Injector

6. Development of Coal Feeder System

A coal supply and feed system was designed and constructed for the 20 MW_t combustor. The coal hopper is a mobile unit having 120 ft^3 capacity, or 4000 lbm of powdered coal. The hopper is pressurized with dry nitrogen gas. Three tooth-wheel feeders transfer coal from the bottom of the hopper to coal-feed lines which connect to the three water-cooled injectors on the main combustor. Coal is transported by nitrogen gas.

Extensive calibrations were made of the coal feeders to determine the coal mass flow rate as a function of feeder rpm, pressure difference across the feeder, and the nitrogen carrier gas flow rate. When the coal-feed system is operated at the design coal flow rate, solids to gas mass ratio of 10:1 was obtained which resulted in a steady dense phase conveying of the pulverized coal to the combustor.

Three BLH load cells support the coal hopper at three points and provide electronic monitoring of the coal weight during the combustor operation.

7. Seed Injection System

The design requirements of the seed injection system were (1) to achieve uniform mixing of the combustion gas and seed with minimum residence time, and (2) to prevent transport of the dry potassium carbonate particles and vapor to the slag flowing on the wall. It was initially proposed that seed be injected into the high temperature gas in the combustor discharge duct as shown in Fig. 5 after the combustion is completed.

Three seed injectors are equally spaced around the conical discharge duct and inject the dry granular seed in a counter-flow pattern. The counter-flow injection scheme in the exit duct was designed to optimize the seed ionization residence time and to minimize seed loss to the slag.

As part of the work to prepare the seed transport and injection system for high-temperature combustor operation, shake-down tests of the pressurized Petrocarb seed-feed supply system and injectors were conducted in a subsonic flow duct.

Based on the cold flow seed injection tests, dry seed pneumatic transport from the three hoppers with a Petrocarb system has been proven to be technically feasible for continuous coal combustor operation. Uniform dry seed injection and mixing were achieved in the simulated discharge duct up to loading ratios of seed to N_2-carrier gas mass of 12.

8. Performance Evaluation Module (PEM)

The PEM was built based on the units designed and tested for MHD application at AERL. The purpose of the PEM was to measure plasma electrical conductivity from the combustor output stream. Fig. 12 depicts the arrangement of the combustor, PEM, and exhaust train.

III. 20 MW_t Combustor Testing Results and Discussion

The development testing of the Avco 20 MW_t coal-fired combustor was done at the AERL Haverhill facility. There were three phases of combustor testing: 1) initial combustor characterization, 2) combustor development to improve slag rejection and 3) final combustor modification to reduce heat loss and incorporate the seed injection system for demonstration tests.

1. Instrumentation for 20 MW_t Combustor

The 20 MW_t coal combustor test rig incorporates diagnostic instrumentation for measurement of flow rates, pressures, temperatures, and chemical composition. There are also ports for visual and optical observation.

The gas composition is measured in real time using on-line gas analysis of CO, CO_2, and O_2 from multiple sampling locations along the combustor axis. Particles may also be captured from the quenched exhaust flow for proximate, ultimate and ash analysis. For gas analysis, sample gas may be extracted from ports located at 6-in. axial increments along the combustor wall. A sampling probe is also available for taking radial gas samples at any axial location.

2. Initial Combustor Testing

Initial characterization tests of the 20 MW_t combustor as shown in Fig. 4 were done and measurements were obtained of combustor efficiency, heat loss, combustor gas, wall temperatures, and slag rejection. Pittsburgh Seam Eastern Bituminous Coal and Montana Rosebud coal was used. The combustor was opened after each test run and examined to observe the slagging characteristics.

The combustor was operated at pressures of >5.6 atm, mass flows ~9.2 lb/sec and achieved combustor gas temperatures of ~2700°K with heat loss. Heat loss from the combustor was measured to be in the range of 12%-14%. Based upon gas and ash tracer analyses, combustion efficiency was calculated to be 99+ percent. Initial slag rejection was ~39%. The average test time was ~90 min consuming ~4500 lbs of coal.

3. Heat Loss Measurements

Average heat flux measurements were made in the dome and the cylindrical sidewall of the combustor. Shown in Fig. 7 are average dome and sidewall heat fluxes over a range of stoichiometries for 2900°F vitiated air preheat temperatures. The heat flux tends to increase with stoichiometry. Under fuel lean or slightly rich conditions, this is consistent with increasing radiative and convective heat transfer for a fluid of increasing enthalpy. At nearly stoichiometric combustion mixtures using Pittsburgh coal, the average sidewall heat fluxes were ~85 W/cm². The dome heat flux at this condition is about 130 W/cm² for 2900°F vitiated air preheat.

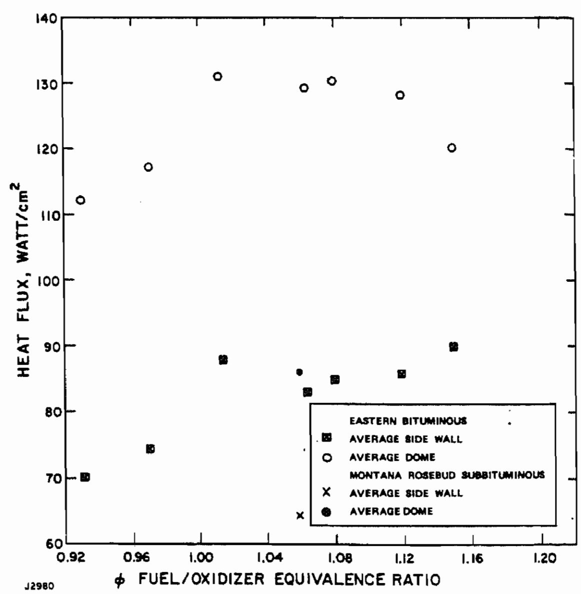


Fig. 7. Combustor Heat Flux, 2900°F Vitiated Air Temperature, 21% O_2 by Volume, and Mass Flow 9.2 lb/sec

Combustor operation with the Pittsburgh Seam Bituminous coal shows a higher heat loss than obtained with the Montana Rosebud Subbituminous Coal for the same air preheat. This is due to the higher specific gas enthalpy of the Eastern coal which has a higher heating value, and lower mineral matter and moisture content, thus causing a higher enthalpy transport from the gas to the slagging combustor wall.

4. Combustion Gas Analysis and Carbon Burnout

Gas composition measurements were made throughout the combustor volume. Both axial and radial gas analyses measurements were made under various combustor conditions. Fig. 8 shows a typical radial profile of the gas composition after ~21 ms

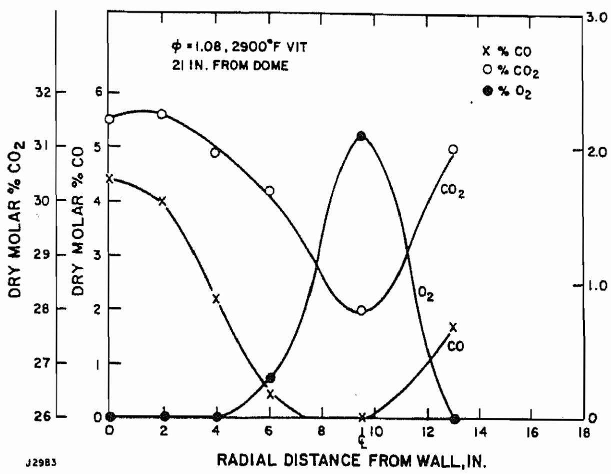


Fig. 8. Combustion Gas Analysis, Radial Traverse

plug flow residence time. It is seen that there is a slight central core of O_2 with increasing concentrations of CO and CO_2 near the wall. Although the gas stream in the coalesce region of the input jets is not completely mixed, integration of the radial gas profile indicates essentially complete carbon burnout. After 39 ms, the profile is flat, indicating relatively complete mixing and combustion. Shown in Fig. 9 are typical axial combustion gas distributions along the wall of the combustor. The decreasing axial concentration of CO and increasing axial concentration of CO_2 is, as seen in Fig. 10, indicative of a central core of O_2 gradually mixing and combusting with the CO near the wall.

Based upon gas analysis, heat loss data, and chemical analysis of the captured slag, the coal combustion efficiency (carbon burnout) was calculated as a function of the combustor length. Fig. 10 is a plot of the combustor length (or residence time) required for optimal combustion performance at various stoichiometries. For increasingly fuel rich stoichiometry, longer times are required to maximize the combustor performance. Also shown in Fig. 10 is the theoretical heat loss at the optimal combustor length for various stoichiometries. For 5% fuel rich combustion, the optimum combustor length is ~38 in. and corresponds to a heat loss of ~8% of the fuel input, with combustion efficiency of nearly 100%.

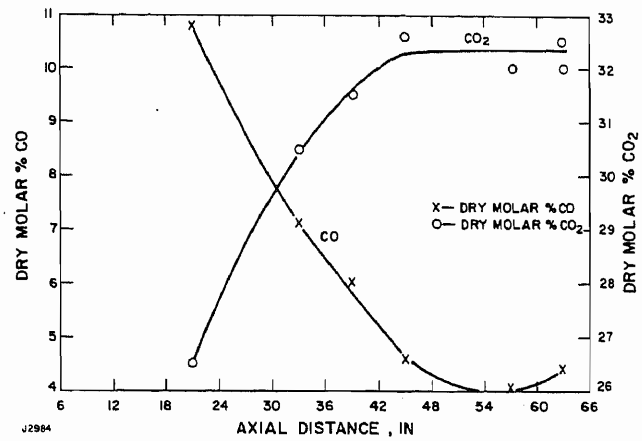


Fig. 9. Combustion Gas Analysis, Wall Samples T_{VIT} = 2900°F

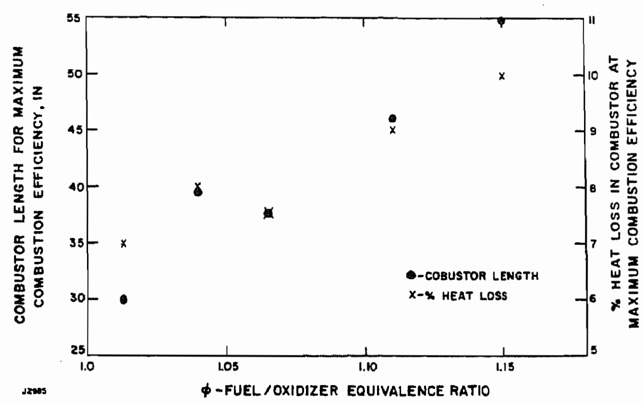


Fig. 10. Combustor Length for Maximum Efficiency

5. Slag Control

To reduce heat loss and to maximize slag rejection, it is important to develop a stable uniform slag layer on the combustor wall. This slag layer entrains slag droplets from the gas stream which flow down the wall. Operating experience has shown that a grooved wall structure in which the grooves are filled with a castable ceramic provides an excellent surface for slag adhesion. Fig. 11 shows a photograph of the dome and sidewall surfaces covered with a slag layer. As seen, the slag layer is initiated in the dome region and is seen to gradually flow downward by gravity and viscous shear forces. After equilibrium slagging conditions were established, the slag layer surface was found to be uniform and well bonded to the grooved wall. Slag layer thickness ranged from 1.5 - 3 mm.

The slag rejection during the initial combustor tests was about 39%. The subsequent tests were directed toward improving the slag rejection measured initially. Modifications were made to (1) increase slag stickiness in the slag separation zone, (2) to reduce entrainment of wall slag flow by the exhaust duct, (3) to trap flying particles reaching the slag bucket, and (4) to improve directional control at the jet impingement zone. After combustor modifications by adding conical slag catching baffles to the centrifuge zone of the combustor and by using tubular jet deflector to direct the coal oxidizer jets upward to the dome slag rejection from ~70 to 83% was achieved with sea coal. The test runs with Montana coal achieved only ~49% to 60% slag rejection. It has been tentatively concluded that 8.8% moist Montana coal ignites later than sea coal. This would possibly account for the reduced slag rejection with Montana coal. A possible remedy is to increase the time available for ignition, and to dry the Montana coal to 5% moisture content.

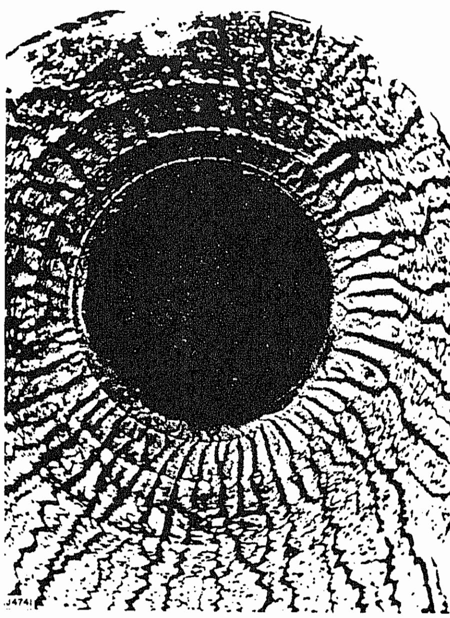


Fig. 11. Photograph of Slag Deposit on Combustor Dome and Walls after 1 Hr:53 Min Cumulative Coal Firing, T_{VIT} = 2500°F, Variable Stoichiometry

6. Demonstration Tests of 20 MW_t Coal Combustor

A final series of 20 MW_t coal-fired combustor demonstration tests were performed with a Performance Evaluation Module (PEM) to establish the combustor output gas conductivity, combustor heat loss and slag rejection. The final 20 MW_t combustor configuration for these tests is shown in Fig. 5 with a reduced combustor volume to be sufficient for complete carbon burnup and O_2 consumption. Fig. 12 shows the arrangement of the 20 MW_t combustor assembly, the PEM and an exhaust train. A photograph shown in Fig. 13 depicts the same components of the combustor test configuration as they are installed in the actual test cell. The combustor was operated at nominal flow and pressure conditions during each test as specified by DOE. Table 1 represents the required operating conditions for the combustor, and Table II lists the coal specifications for the tests.

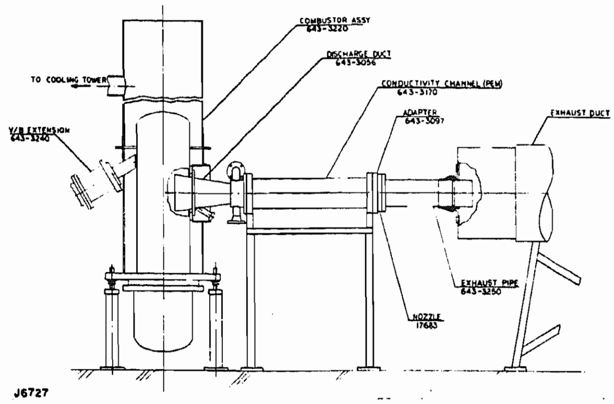


Fig. 12. 20 MW_t Coal-Fired Combustor Test Configuration

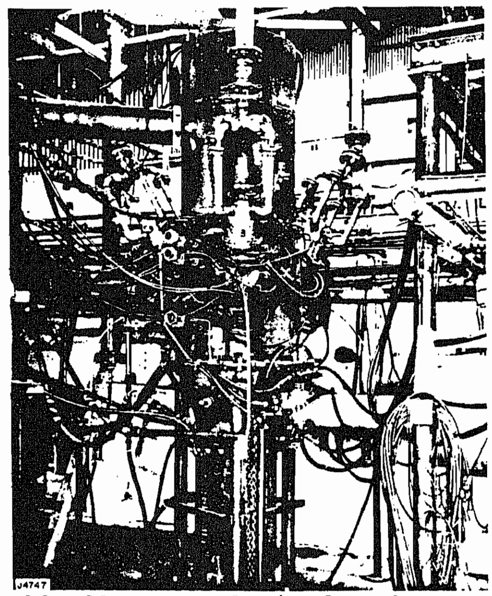


Fig. 13. 20 MW_t Coal-Fired Combustor Demonstration Test Configuration

For each demonstration test, the total thermal input into the combustor (coal, fuel oil, oxygen, and air) was at a nominal level of 20 MW_t. Nominal flow rates of fuel oil, air, and oxygen are given in Table III and correspond overall to 2900°F "enriched vitiated air" containing 30 mole percent O_2 available for coal combustion. The flow rate of coal was determined so that the stoichiometric oxygen ratio was 0.95. Dry potassium carbonate (K_2CO_3) was used to seed the combustion gases; the flow rate of seed introduced in each case was adjusted to the mass flow rate of K atoms corresponding to 1.5 weight percent of the mass flow rate of all constituents entering the PEM.

Fig. 14 shows an example of the mass flow rates of fuels, oxidizer and seed for the 20 MW_t coal-fired combustor during a demonstration test. The additional time before coal startup reflects time spent to insure that all systems are operational.

Table 1. Operating Conditions (DOE)

	Flow Conditions Nominal	Tolerance	Other Data
Coal			See (1) and (2) below
No. 2 Fuel Oil	1,042 lb/hr	± 2%	HHV 19500 ± 500 BTU/lb Temp. 85° ∓ 25°F
Air, Dry Basis	15,810 lb/hr	± 2%	Not to exceed 600°F
Oxygen	7,660 lb/hr	± 2%	Temp. 75° ± 35°F
Stoichiometric Oxygen Ratio	0.95	± 0.05	See (2) below
Stagn. Pressure at PEM Inlet	6.0 atm	± 0.5 atm	
Seed (K_2CO_3)	1.5% K by wt. of total flow	± 0.15 wt %	

(1) Coal composition must comply with Table II

(2) Flow rate to be determined according to DOE requirements

Table II.

Coal Specifications (DOE)

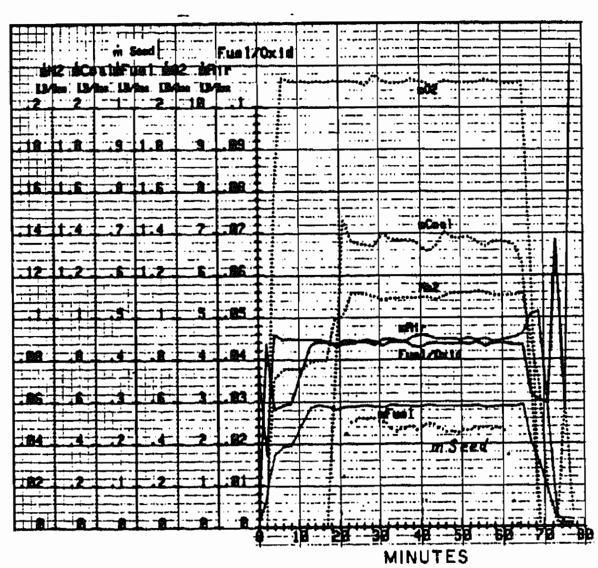
	DOE Montana Nominal	Rosebud Range
1.0 Ultimate Analysis, Moisture Free%		
Hydrogen	4.6	2.8- 6.4
Carbon	65.6	61.8-69.4
Nitrogen	1.0	0.6- 1.2
Oxygen	14.7	N/A
Sulfur	1.1	0.4- 5.0
Ash	13.0	10.0-16.0
2.0 Ash Analysis, %		
SiO_2	48.6	22-55
Al_2O_3	21.6	12-25
CaO	14.8	5-20
Fe_2O_3	8.0	2-20
MgO	4.7	2.2- 7.0
TiO_2	0.8	0.2- 1.4
K_2O	0.7	0- 1.5
Na_2O	0.4	0- 1.2
P_2O_5	0.4	0.1- 0.7
3.0 Proximate Analysis, Moisture Free		
Volatile	N/A	34-42
Fixed Carbon	N/A	43-52
4.0 Moisture, As Fired, %	5.0	0-10
5.0 Heating Value		
Btu/lb (Dry Basis)	11,300	± 6%

Table III.

Nominal Flow Rates

	Units	Quantity
Fuel	GPM #/Sec	2.4 0.29
Oxygen	#/Sec	2.12
Air	#/Sec	4.4
Coal	#/Sec	1.34
N_2 Carrier Gas	#/Sec	0.134
Seed	#/Sec	0.226

Combustor pressure as a function of elapsed time during the test is shown in Fig. 15. After the steep rise which accompanies initiation of coal flow, the pressure is steady indicating good combustion stability and varies little during the final 20 min of



EXPERIMENTAL COAL COMBUSTOR TEST RUN #39

Fig. 14. Mass Flow Rates as Function of Time

test prior to coal flow shut-off. Evidence of good combustion stability of the combustor was also observed from the high frequency static pressure transducers located at the PEM inlet. Pressure fluctuations of less than ± 1 psi were few and infrequent.

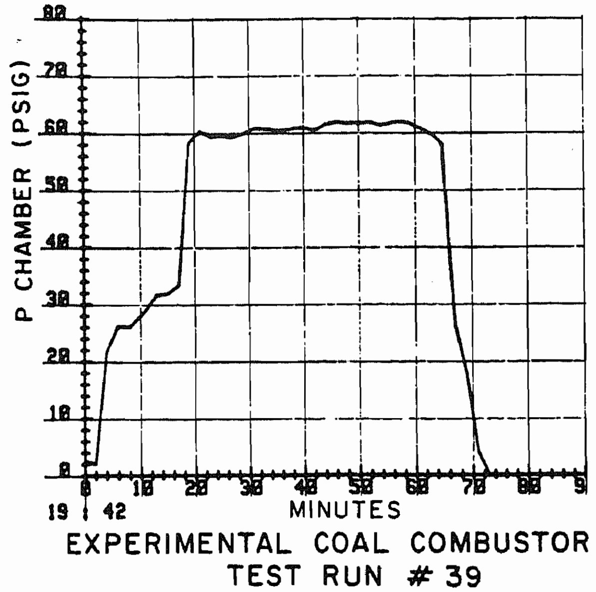


Fig. 15. Combustor Pressure as Function of Time

Fig. 16 shows plasma electrical conductivity measured by the PEM. Measurements are taken over eleven PEM frames as a function of elapsed time. In Fig. 16a, final 20 min of testing is shown. Fig. 16b shows the measured conductivity during the full test time. After subtracting 1 mho/m to account for the parallel current path through the slag wall layer and the PEM insulation, the plasma conductivity is estimated to vary from 6 to 7 mho/m. This agrees with values computed for the thermochemical equilibrium of the specified combustion mixtures, and with the measured combustor loss.

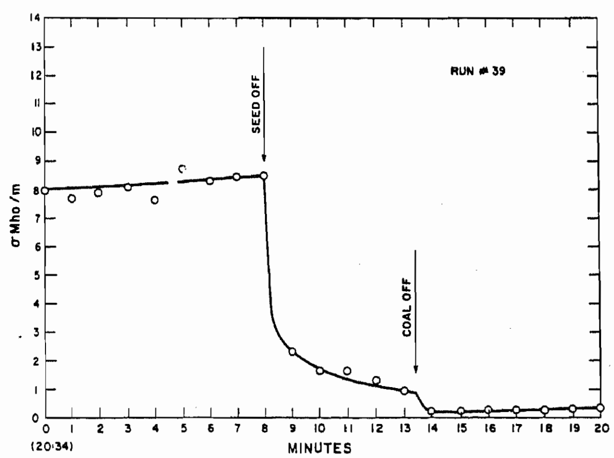


Fig. 16a. Average of Conductivity for Segments #18 through #28

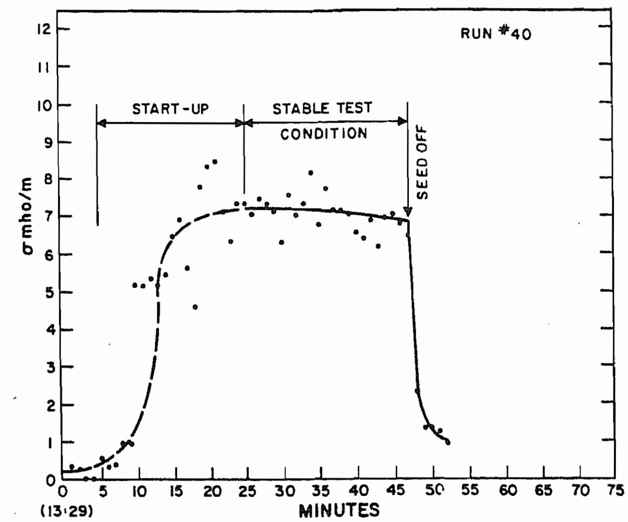


Fig. 16b. Average of Conductivity for Segments #13 through #28

Slag rejection for the three demonstration tests were about 40% of ash throughput which is lower than the 60-80% slag removal obtained during development tests. The low slag rejection values obtained for the demonstration tests were caused by failure and subsequent removal of the jet deflector.

The total combustor assembly heat loss which influences the measured gas conductivity was 17-18% for the demonstration test runs. A wall heat loss of 1.9% was measured in the PEM from its entrance to the center of the active measurement section. The measured heat loss data are in agreement with heat losses along the channel as computed by the Avco MHD Channel Code.

The Avco MHD Code for calculating the average gas conductivity in the PEM channel, accounting for heat losses and the boundary layer effects of the constant area PEM channel, gives 5.2 mho/m at the center of the test section. The measured plasma conductivity values are higher than the computed average channel conductivity values. The discrepancy between the measured and calculated gas conductivity values is due to the following factors or their combination:

a) The applied correction due to PEM wall current leakage is too small, and

b) the measured combustor heat loss values are too conservative.

Considering the limited number of gas conductivity tests performed and the accuracy obtainable in this type of measurement, a realistic gas conductivity value should be about ~5.5 mho/m for the conditions in the PEM test section from the output stream of the 20 MW_t coal-fired combustor.

IV. Conclusions

AERL has designed, built and successfully tested a single stage toroidal flow

20 MW_t coal-fired combustor with high ash/slag rejection. Systematic combustor development and combustion tests were conducted at operating pressures up to 6 atm and yielded combustion plasma temperatures in the range of 2650-2800°K with carbon combustion utilization greater than 99.5%. A uniform plasma conductivity was obtained with the AERL combustor and can be provided for a MHD generator. The combustor operation was stable and no transient characteristics were present during the start-up and shut down phase. No combustor malfunction or associated hardware degradation were noticed after more than 50 hours of testing.

The one-stage AERL 20 MW_t coal-fired combustor has generated very high thermal throughput per volume of $\dot{Q} \simeq 130$ MW/m^3 (~22 MW/m^3 atm) with high combustion efficiency of 99+%. The combustor unit has the necessary design features and flexibility to be scaled and optimized to a larger size commercial plant combustor.

V. Acknowledgment

The support of DOE, and the advice and helpful discussions with Dr. Ralph Carabetta, the DOE program manager, and other members of the Pittsburgh Energy Technology Center and MHD Division staff are greatfully acknowledged. The authors are indebted to Fred E. Becker for design of the vitiation heater system and for his participation in the initial combustor tests.

References

1. Avco/AERL, Inc., "Coal-Fired Combustor Development Project, Phase II, "Final Technical Report, ET-10787-3, UC-90g, Avco Everett Research Laboratory, Inc., Oct. 1980.
2. Stickler, D.B. and Barnes, R.T., "CDIF Combustor Design, Final Report," to Argonne National Laboratory, III, Avco Everett Research Laboratory, Inc., (June 1976).
3. Smith, N. and Petty, S., et al., "Joint US-USSR Experimental Studies of the Dependence of Plasma Electrical Conductivity on Plasma Temperature Performed in Avco Mark VI MHD Facility." Proceedings of the 15th Symposium, Engineering Aspects of MHD, Philadelphia, May 24-26, 1976.
4. Stickler, D.B., Becker, F.E. and Ubhayakar, S.K., "Combustion of Pulverized Coal in High Temperature Preheated Air," AIAA Paper 79-0298, (January 1979).
5. Ubhayakar, S.K., Stickler, D.B., and Gannon, R.E., "Modeling of Entrained Bed Gasifier," Fuel, 56, (July 1977).
6. Stickler, D.B. and DeSaro, R., "Electrode System Maintenance Progress in Slagging MHD Electrodes," Final Report EPRI AF 1223, (1979).
7. Gordon, S. and McBride, B.J., "Computer Program for Calculation of Complex Chem. Equilibrium Composition, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouquet Detonations," NASA SP-278, March 1976.
8. Svehla, R.A. and McBride, B.J., "FORTRAN IV Computer Program for Calculations of Thermodynamic and Transport Properties of Complex Chemical Systems," NASA TN D-7026, January 1973.
9. Avco Everett Research Laboratory, Inc., "Thermochemical Equilibrium Programs, P21C" (1964).
10. Carabetta, R.A. and Mayne, A.E., "Technical Requirements for the 20 MW_t Combustor Demonstration Tests," Draft Report, MHD Project Management Division, Pittsburgh Energy Technology Center/DOE, May 1980.
11. Knight, C., "Coal Combustor Flow Modeling," AERL Internal Memo (May 1979).
12. Hill, B.J., "Measurement of Local Entrainment Rate in the Initial Region of Axisymmetric Turbulent Air Jet," J. Fluid Mech., 51, (1972).
13. Donaldson, C., Dup and Snedeker, R.S., "A Study of Free Jet Impingement, Part I, Mean Properties of Free and Impinging Jets," J. of Fluid Mech., 45 (1971).
14. Poreh, M., Tsuei, Y.G. and Cermak, J.E., "Investigations of a Turbulent Radial Wall Jet," J. of Applied Mechanics, (June 1967).
15. Dring, R.P. and Suo, M., "Particle Trajectories in Swirling Flows," J. of Energy, 2, (July/August 1978).
16. G. Rudinger, "Fundamentals of Gas-Particle Flow," Handbook of Powder Technology, Vol. 2, Elsenier Scientific Publishing Co., (1980).
17. Annamalai, K., "Burning of Char on Slagging Walls," AERL Internal Memo (Sept. 1979).