DOE/PC/30297--T10

RECEIVED BY TIC OCT 18 1982

ASSESSMENT OF PULVERIZED-COAL-FIRED
COMBUSTOR PERFORMANCE

MASTER

Seventh
Quarterly
Technical Progress Report
for the Period
April 1 - June 30, 1982

DOE/PC/30297--T10

DE83 001045

W. Richter
W. Clark
R. Payne

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Energy and Environmental Research Corporation
18 Mason
Irvine, CA 92714-4190

August 1982

Prepared for Pittsburgh Energy Technology Center
Department of Energy

Under Contract No. DE-AC22-80PC30297

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
1.0	INTRODUCTION AND SCOPE	1-1
2.0	SUMMARY OF PROGRESS TO DATE	2-1
3.0	TECHNICAL PROGRESS	3-1
3.1	Task 1--Model Improvement and Engineering Analysis . . .	3-1
3.1.1	2-D Furnace Heat Transfer Code	3-1
3.1.2	Heat Transfer Study for the Pilot-Scale Furnace of Task 3	3-3
4.0	TASK 2--REACTOR STUDIES	4-1
4.1	Theory	4-1
4.2	Experimental Data Points	4-2
4.3	Results	4-5
4.4	Calculations	4-19
4.5	Discussion and Plans	4-27
5.0	TECHNICAL PROGRESS: TASK 3--FIRETUBE SIMULATOR TESTS . . .	5-1
5.1	Experimental Facilities	5-1
5.2	Fuels	5-3
5.3	Test Plan	5-5

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
3-1 Temperature distributions in coal-fired pilot-scale furnace computed for different volumetric firing densities	3-8
3-2 Net heat flux densities through side wall refractories and surface temperatures of refractories in coal-fired pilot-scale furnace computed for different firing densities	3-9
3-3 Distribution of unburnt fixed carbon computed along coal-fired pilot-scale furnace for different volumetric firing densities	3-10
4-1 Particulate probe	4-6
4-2 Burnout: effect of coal size and type	4-9
4-3 Burnout: effect of combustion gas composition (stoichiometry)	4-10
4-4 Burnout: effect of residence time	4-11
4-5 Fly ash size distribution: coal size (Utah coal)	4-12
4-6 Fly ash size distribution: coal size (Four Corners coal)	4-13
4-7 Fly ash size distribution: stoichiometry	4-15
4-8 Fly ash size distribution: residence time	4-16
4-9 Extinction efficiency: coal size and type	4-17
4-10 Extinction efficiency: stoichiometry and residence time effects	4-18
4-11 Mie calculations: baseline	4-20
4-12 Mie calculations: wavelength	4-21
4-13 Mie calculations: imaginary component	4-22
4-14 Mie calculations: real component	4-23
5-1 Schematic of versatile coal/gas furnace to be used on pilot-scale studies	5-2
5-2 Burner assembly	5-4

LIST OF TABLES

<u>Table</u>		<u>Page</u>
3-1	Input Conditions and Model Parameters for Computation of Heat Transfer in Pilot-Scale Furnace	3-5
4-1	Ultimate Analyses of Aerodynamically Classified Coals	4-3
4-2	Detailed Measurements Test Matrix	4-4
4-3	Particulate Analyses	4-7
4-4	Extinction Coefficient Calculations	4-25
4-5	Experimental and Theoretical Extinction Coefficients	4-26
5-1	Fuels to be Used in Pilot-Scale Tests	5-5
5-2	Proposed Test Conditions for Pilot-Scale Tests	5-7

1.0 INTRODUCTION AND SCOPE

There are substantial economic incentives to explore the possibility of converting boilers and other industrial processes from natural gas or oil to pulverized-fuel firing; however, such a change can have a considerable impact on the thermal performance of the system, due mainly to:

- Fuel specific adiabatic flame temperatures.
- Different flow and combustion patterns in the furnace.
- Differences in the type and concentration of radiative species, especially particles, in the combustion products.
- Ash deposition on heat transfer surfaces.

This program is concerned with the provision of a technology base to expedite the conversion of industrial processes from oil and gas to coal and other pulverized fuels. It addresses primarily the impact of fuel type on the thermal performance of a combustor. The program incorporates two experimental tasks and is constructed around an analytical task (Task 1) which will identify and upgrade a family of computer programs required to undertake thermal performance analysis studies. These analytical tools will thus be used to predict the effects of parameters such as fuel type and furnace variables on combustor performance, and to identify those properties which have a major impact on thermal performance. The second task uses a combustion reactor to screen the key variable identified in Task 1 and to provide data on the properties of coal particulate matter which affect heat transfer performance. Verification of the engineering analytical approach will be provided by measurements made in a pilot-scale furnace in the third task.

2.0 SUMMARY OF PROGRESS TO DATE

During the seventh quarterly period of the program, efforts have been reduced on the analytical tool development and verification task, but have focused on the bench-scale experimental reactor studies, and on preparations for the pilot-scale furnace tests.

In previous quarters the selection, upgrading, and verification of the required furnace heat transfer models have been reported. These models have been used in a series of parametric screening calculations in order to identify those parameters and model assumptions which most affect the accuracy of furnace performance prediction. Such studies have shown that for larger oil-fired furnaces, and even for furnaces fired with low-ash coal, the gaseous radiating species make a major contribution to total heat transfer. A number of sample computer model applications have been run for both hypothetical and actual operating boiler configurations. These results demonstrate the importance of coal fly ash as a radiating species, and highlight the significant impact of wall deposits on boiler thermal performance. In the present period, the level of effort on this task has been substantially reduced pending the generation of experimental data for model verification purposes. Some work has continued on the documentation of the 2D code for temperature and heat flux predictions, and a limited number of computer runs have been carried out to assist in the selection of pilot-scale experimental conditions.

In the experimental portion of the program, work has continued on data taking in the laboratory-scale, controlled-flow reactor. experimental data have been generated for two coals, fired in discrete size fractions over a range of combustion conditions. This work will be supplemented by more general data for five coals obtained from screening studies in a larger bench-scale furnace. Work has also started in preparation for the pilot-scale combustion studies in a nominal 1×10^6 Btu/hr (0.3 MW) experimental furnace. In the present reporting period this work has concerned mainly the preparation of the furnace and experimental systems, and the specification of a test plan.

3.0 TECHNICAL PROGRESS

3.1 Task 1--Model Improvement and Engineering Analysis

The work of Task 1, carried out during previous research periods, has had four major objectives, namely:

- Selection and testing of suitable analytical models to study coal combustor performance.
- Screening studies to identify essential parameters of thermal behavior of furnaces.
- Upgrading of the selected general furnace heat transfer model.
- Application to existing combustion chambers.

The development of the model has reached a stage where further improvement requires information on radiative properties to be measured in Task 2, and some furnace performance data to be supplied by Task 3. While this information is being generated, efforts on Task 1 have been reduced during the reported research period. The main efforts have been directed towards two points:

- Coding of the 2-D version of a general heat transfer model (deliverable with the final project report).
- Application of 3-D model in order to support the design of the pilot-scale furnace used for the coal tests in Task 3.

In the following, the basic features of the 3-D computer program as well as major results of the design study will be described.

3.1.1 2-D Furnace Heat Transfer Code

The 2-D code for computation of heat transfer in cylindrical furnaces is written in close analogy to an upgraded version of the 2-D heat transfer model developed in the past (Ref. 1). The 2-D model has the following features. It is essentially based on a zone method of analysis. The zones are of annular geometry with rectangular cross-section. Provided sufficient storage and computing time is available, and provided a large amount of input data can be handled, there is no restriction concerning the fineness of zone arrangement. This program feature is possible by use of dynamic arrays of field variables.

Axial and radial extension of the zones can vary (nonequidistant mesh) and corners of the furnace contour with right angles can be considered in order to simulate a burner inlet or a chimney constriction.

The most prominent part of the model is the calculation of exchange of thermal radiation between all zones of the furnace. The radiation model is based on the Semistochastic Method described in earlier reports and papers (Refs. 1-3). Compared to a computation in a 3-D cartesian arrangement of furnace zones tracking of beams of radiation in the 2-D system is more complicated since beams may cross twice the same annular zone between emission and reflection at a wall or between two reflections at wall zones. Thus, the part of the program concerning beam tracking has been rewritten. During the radiation exchange calculation rotational symmetry of emission of beams is taken into account. Symmetry with respect to an axial position (although seldom encountered) can also be considered.

Exchange of real radiation (i.e., radiation dependent on wavelength) is calculated with a weighted-gray-gas approach with n gray components. n may be chosen freely; the coefficients, however, must be provided by the user. Optical properties and concentration of radiating species from which (weighted) gray gas absorption coefficients are derived must be prescribed either as constants or as input field variables at each zone.

The radiative exchange model yielding the radiation fluxes of each zone for a given temperature field can optionally be coupled with total energy balances for zones with initially unknown temperatures. The total energy balances for annular volume zones are based on prescribed total and fuel mass flows across each axial and radial zone boundary. Volumetric heat release rates are then calculated from the zonal fuel flow rates. Turbulent diffusion of sensible heat can be considered by assigning additional reciprocal mass flow rates at each boundary of a volume zone. Convective heat transfer between volume and surface zones is calculated by use of prescribed convective heat transfer coefficients. Total energy balances of surface zones are based on given values for thickness and heat conduction coefficients of wall layers or wall deposits.

The total energy balances are solved iteratively for zonal temperatures. For volume zones, a combined Gauss-Seidel/Newton-Raphson technique is applied,

whereas temperatures of surface zones are obtained from a Newton-Raphson scheme alone.

Since the radiative fluxes used in the energy balance are affected with a certain statistical error due to the stochastic nature of the radiation model, computed temperatures reveal fluctuations which in turn contribute further to the statistical error of calculated heat fluxes. However, with increasing number of iterations, ensemble averaging of heat fluxes over prescribed number of iteration cycles can be initiated. Thus, complete convergence of the total energy balance, with arbitrary small statistical error of temperatures and heat fluxes, can be achieved.

During each iteration cycle, all variables and coefficients dependent on temperature are updated. In particular, mean specific heats of the combustion products are computed using higher order polynoms for each species (Ref. 4).

Additional features of the 2-D program will be a general stoichiometric calculation for complete burnout in order to obtain inlet mass flows, composition of combustion products, etc., depending on furnace operating conditions. Input and output routines are coded in a flexible manner. Fields of furnace variables can be read in from card deck or from disc. The latter will be the case when a partially converged solution is available. A complete printout of all 2-D arrays of variables may be initiated after each iteration. At the conclusion of the iteration process, a final radiative balance will be printed in order to prove conservation of radiative exchange.

3.1.2 Heat Transfer Study for the Pilot-Scale Furnace of Task 3

In order to relate furnace performance data obtained at pilot-scale to a full-scale combustion chamber, it is necessary to maintain the same residence time and temperature level in both installations. Provided the same mean temperature level can be achieved, the residence time of a pilot- and a full-scale furnace will be equal if volumetric firing densities are the same. However, for the same volumetric firing density, the surface firing density, which is a major variable of furnace heat transfer, increases with characteristic dimension of the furnace. Thus, smaller furnaces will have lower exit temperatures than larger ones for a given volumetric firing density. The

same temperature level, however, can be retained by partial insulation of furnace walls, by for instance using refractory tiles.

During the redesign of the pilot-scale furnace for the testing of Task 3, the question arose to what extent the furnace side walls had to be covered by refractory in order to obtain representative exit temperatures for volumetric firing densities typical of coal-fired boiler combustion chambers. For this purpose, a parametric study was carried out with the general 3-D furnace heat transfer program. In the following, major input conditions and some results of this study are reported.

The test section of the pilot-scale furnace is cylindrical. It has a length of 3.2m and a diameter of 0.6m. This cylindrical chamber was replaced in the present study by a rectangular volume of the same length and of the same ratio of volume to surface area. Typical volumetric firing densities in coal-fired combustion chambers lie in the range between 0.1 and 0.25 MW/m³ and typical furnace exit temperatures range from 1100 to 1400 K. The present parametric study of the pilot-scale furnace was carried out for the following three firing densities: 0.13, 0.25, and 0.38 MW/m³. The lower limit of investigated firing densities was increased, since a firing density as low as 0.1 MW/m³ would probably cause flame stability problems in the pilot-scale furnace.

Further important input conditions and model parameters of the study are listed in Table 3-1. The coal chosen for the investigation was the high-volatile coal, Illinois #6, which is considered to be a coal with average properties in comparison to the other coals to be investigated in Task 3. The present study was carried out assuming heat insulation to be affected by refractory tiles of 0.05m thickness and 0.72 W/mK thermal conductivity. The emissivity of the refractory material was assumed to be 0.5.

The main result of the current investigation was that the furnace side walls had to be coated by refractory along the whole furnace. With refractory tiles covering only the first half of the furnace, exit temperatures of 780 K, 990 K, and 1110 K were predicted for the volumetric firing rates of 0.13 MW/m³, 0.15 MW/m³, and 0.38 MW/m³, respectively. Predicted exit temperatures for complete coverage were 1022 K, 1200 K, and 1380 K, respectively. Thus, it was decided to carry out the p.f. trials with this latter

TABLE 3-1. INPUT CONDITIONS AND MODEL PARAMETERS FOR COMPUTATION OF HEAT TRANSFER IN PILOT-SCALE FURNACE

Quantity	Dimension	Value
Furnace Geometry	m	3.2 x 0.6 ϕ
Geometry of Modeled Furnace	m	3.2 x 0.6 x 0.6
Net Volumetric Fuel Heat Release Rate	MW/m ³	0.13
	"	0.25
	"	0.38
<u>Composition of Illinois No. 6 Coal</u>		
Proximate Analysis:		
Fixed Carbon	kg/kg	0.3810
Volatiles	"	0.3560
Moisture	"	0.1690
Ash	"	0.0940
Ultimate Analysis:		
C	kg/kg _{wf}	0.6942
H	"	0.0488
N	"	0.0124
O	"	0.1002
S	"	0.0293
Ash	"	0.1131
Upper Heating Value of Coal	kJ/kg	24376.1
Weight Mean Particle Diameter	μm	69.0
Weight Percent, less 75 μm	%	66.5
Excess Air	%	10
Primary Air	% Stoichi.	20
Temperature of Primary Air	K	333
Temperature of Sec. Air	K	478
Thickness of Side Wall Refractories (only for computation of heat con- duction)	m	0.05
Conductivity of Side Wall Refrac- tories	kW/m $\cdot$ K	0.00072

TABLE 3-1. (Concluded)

Quantity	Dimension	Value
Front Wall Refractories		Adiabatic
Eff. Temp. of Furnace Exit	K	478
Emissivity of Refractories (Side and Front)	-	0.5
Emissivity of Furnace Exit Plane	-	1.0
Conv. Heat Transfer Coefficient	$\text{kW/m}^2\text{K}$	0.0116
Zone Arrangement	-	2 x 2 x 16
Axial Extension of Uniform Heat Release Due to Combustion of Volatiles	m	1.2 m
Number of Ash Particles per Coal Particle	-	5
Soot Concentration in Heat Release Zone Due to Combustion of Volatiles	$\text{kg/m}^3_{n,\text{wet}}$	$644 \cdot 10^{-6}$

configuration. Figure 3-1 shows temperature distributions along the furnace predicted in this case for the three volumetric firing rates. Insulation by the refractory is not complete and predicted net heat flux densities through the insulation are shown in Figure 3-2. These fluxes will also be measured calorimetrically and can be used along with other measurements to verify the furnace heat transfer model. Figure 3-2 also reveals predicted distributions of temperatures of the inner surfaces of the refractories. Figure 3-3 finally shows the calculated distribution of unburned fixed carbon along the furnace. The values calculated at the exit plane are 0.7 percent, 1.7 percent, and 2.6 percent for the increasing values of volumetric firing rates mentioned above. This corresponds to a carbon content of fly ash of 2.8 percent, 6.5 percent, and 9.5 percent, respectively. The values corresponding to the two lower firing rates are in the range which is typically encountered in coal-fired boiler combustion chambers.

Figure 3-1. Temperature distributions in coal-fired pilot-scale furnace computed for different volumetric firing densities.

Figure 3-2. Net heat flux densities through side wall refractories and surface temperatures of refractories in coal-fired pilot-scale furnace computed for different firing densities.

Figure 3-3. Distribution of unburnt fixed carbon computed along coal-fired pilot-scale furnace for different volumetric firing densities.

REFERENCES

1. Richter, W. Models for Coal Combustor Performance. Topical Report. Prepared for the Pittsburgh Energy Technology Center Department of Energy under Contract No. DE-2280-PC30297 (1981).
2. Richter, W. and M. P. Heap. A Semistochastic Method for the Prediction of Radiative Heat Transfer in Combustion Chambers, WSS. The Combustion Institute, 1981 spring Meeting, Paper '81-17.
3. Richter, W. and M. P. Heap. The Impact of Heat Release Pattern and Fuel Properties on Heat Transfer in Boilers. 1981 ASME Winter Annual Meeting, Paper 81 WA/HT27.
4. Gordon, S., and B. S. McGride. Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, Chapman-Jouquet Detonations; NASA SP-273, 1971.

4.0 TASK 2--REACTOR STUDIES

The Reactor Studies task of this program is designed to provide information on those fly ash parameters which affect the thermal performance of coal-fired combustors. This task has been divided into two subtasks: a screening subtask, in which the effect of coal composition and combustion conditions on radiative properties is determined; and a detailed measurements subtask, in which size distribution and composition of the solid phase as a function of time and combustion conditions are studied. Due to earlier experimental difficulties these subtasks are now being carried out in two different experimental furnaces. The detailed measurements task is carried out in a small laboratory backfired reactor system which fires coal at a rate of 5 g/m. The screening studies are carried out in a larger bench-scale combustor firing at a rate of approximately 2.5 kg/hr. Both experimental facilities have been fully described in previous quarterly reports.

In the present reporting period the detailed measurements portion of the Reactor Studies task has been completed. The following sections contain a discussion of the experimental data and their implications.

4.1 Theory

A number of parameters must be known in order to calculate the absorption coefficient of particles generated in pulverized coal combustion. Sarofim and Hottel (1978) give the following equation for the extinction, absorption, or scattering efficiency of a combustion cloud.

$$E = 1 - \exp \left[-1.5 f_v L \int_0^1 \frac{Q dM}{D} \right]$$

where E = Extinction, absorption, or scattering efficiency

Q = Extinction, absorption, or scattering coefficient

f_v = Volume fraction of particulate in the combustion cloud

L = Path length through combustion cloud

M = Mass fraction of particles of diameter greater than D

In the first instance it can be assumed that Q coefficients and densities are

independent of particle size, and an average Q extinction can be calculated as the above equation reduces to:

$$Q = \frac{\ln (1-E) \rho}{-1.5 C L \sum \frac{dM}{D}}$$

where ρ = particle density

C = particle concentration

The Q coefficients will, however, be dependent upon particle size, although in the initial reduction of experimental data the above equation is used to calculate average values of Q. In later stages of the evaluation, Q coefficients are calculated from Mie theory assuming a particle size dependency and based upon an assumed particle refractive index.

The experiment determination of an exact value of Q thus requires several parameters to be accurately measured. Used in conjunction with Mie theory calculations, the detailed measurements have proven to be sufficiently accurate to assess the relative importance of these parameters. However, absolute determination of Q will be done on the larger scale screening studies where higher E values and steadier flows make accurate measurements more feasible.

4.2 Experimental Data Points

Two coals have been tested in the Detailed Measurements section of the program: Four Corners and Utah, both high-volatile bituminous coals. Each coal was tested at two aerodynamically classified size ranges: 30-50 microns and 50-70 microns. Table 4-1 shows the Ultimate analysis for each size cut for each coal. Note that the ash composition changes with size cut, with more of the ash being concentrated in the smaller size cut, especially for the Utah coal.

Particulate and radiometric measurements were taken at seven nominal data points listed in Table 4-2. These conditions investigate the effects of coal type, coal size, combustion stoichiometry, and residence time on the size, composition and radiative properties of their combustion particulate. Four Corners 50-70 micron coal burned out to 5 percent oxygen with a 460 millisecond residence time was chosen as the baseline data point. Effects

TABLE 4-1. ULTIMATE ANALYSES OF AERODYNAMICALLY CLASSIFIED COALS

Coal	Size (microns)	C (% dry)	H (% dry)	N (% dry)	S (% dry)	Ash (% dry)	O* (% dry)	Moisture (% wet)
Four Corners	30-50	58.97	4.36	1.35	0.87	18.56	15.89	6.19
Four Corners	50-70	59.92	4.53	1.41	0.84	17.30	16.00	5.45
Utah	30-50	74.01	5.58	1.54	0.72	4.30	13.85	4.95
Utah	50-70	75.00	5.78	1.56	0.68	2.68	14.30	3.76

*By difference.

TABLE 4-2. DETAILED MEASUREMENTS TEST MATRIX

Test Variable	Coal	Size (microns)	Gas Concentration	Residence Time (msec)
Coal Type	Utah	30-50	5% O ₂	460
Coal Type	Four Corners	30-50	5% O ₂	460
Coal Type	Utah	50-70	5% O ₂	460
Coal Type	Four Corners	50-70	5% O ₂	460
Coal Size	Utah	30-50	5% O ₂	460
Coal Size	Utah	50-70	5% O ₂	460
Coal Size	Four Corners	30-50	5% O ₂	460
Coal Size	Four Corners	50-70	5% O ₂	460
Background Gas Stoichiometry	Four Corners	50-70	5% O ₂	460
Background Gas Stoichiometry	Four Corners	50-70	2% O ₂	460
Background Gas Stoichiometry	Four Corners	50-70	2% CO	460
Residence Time	Four Corners	50-70	5% O ₂	460
Residence Time	Four Corners	50-70	5% O ₂	230

of coal type were investigated by comparing the Utah coal with the Four Corners coal; effects of coal size were investigated by comparing 30-50 micron size coals with 50-70 micron size coals; effects of stoichiometry were investigated by comparing results obtained at approximately 2 percent CO, 2 percent O₂, and 5 percent O₂ in the combustion gas; and effects of residence time were investigated comparing throughputs resulting in 230 ms and 460 ms residence times. In addition, radiometric measurements alone were taken for the baseline coal at variable stoichiometry for the shorter residence time.

The backheated reactor, described in previous quarterly reports was maintained at wall temperatures of around 1300 C. Particulate and radiometric measurements were taken in the access module, where the baseline combustion gas had cooled to around 1070 C as measured by suction pyrometer. Radiometric measurements were taken through narrow-pass filters at wavelengths of 2.2 and 3.6 microns and through a window which passes the entire effective spectrum (0.5-12 microns). A light chopper was used between the blackbody source and the reactor and the extinction efficiency of the combustion cloud was calculated as described in the Fifth Quarterly Report (Ref. 2). Particulate samples were taken isokinetically through the probe shown in Figure 4-1. The 22 mm ID water-cooled stainless steel probe had a 51 mm uncooled sharp-edged extension to minimize disturbance of the flow pattern. Purge nitrogen was used to avoid sampling while the data point was being set up. Samples were trapped on a fiber filter directly beneath the probe, after passing through a smooth gradual (30°) reducer from 22 mm to 9 mm. The filtered gas was passed through a water trap, a sample pump, and a rotameter set for isokinetic flow, precalculated based on stoichiometry, reactor throughput, and the ratio of probe area to reactor area. Particulate samples were analyzed at EER for C-H-N-Ash, and were sent to Micromeritics for density measurements using a Helium Pycnometer, and for size distribution measurements using a Sedigraph, a technique which uses low energy X-rays to measure concentration at decreasing sedimentation depths with increasing time.

4.3 Results

Particulate samples and radiometric measurements were taken for the data points listed in the previous section. Results of the physical and chemical analyses are shown in Table 4-3.

Figure 4-1. Particulate probe.

TABLE 4-3. PARTICULATE ANALYSES

Coal	Size (microns)	Gas Con- centration	Residence Time (msec)	Density g/cm ³	Mass Median Size (microns)	C % (dry)	H % (dry)	N % (dry)	Ash % (dry)	Burnout* (%)
Utah	30-50	5.0% O ₂	460	2.334	20.0	1.55	0.05	0.03	97.85	99.91
Utah	50-70	4.8% O ₂	460	2.340	30.0	8.19	0.07	0.09	91.05	99.68
Four Corners	30-50	5.0% O ₂	460	2.015	22.0	0.36	0.05	0.02	99.19	99.89
Four Corners	50-70	5.3% O ₂	460	1.981	27.5	1.93	0.06	0.02	96.80	99.43
Four Corners	50-70	2.3% O ₂	460	2.016	24.5	5.95	0.09	0.07	92.76	98.15
Four Corners	50-70	1.5% CO	460	1.995	24.5	19.25	0.16	0.17	77.25	92.81
Four Corners	50-70	4.8% O ₂	230	2.071	26.5	2.89	0.03	0.01	96.81	99.14

$$*\text{Burnout} = 1 - \frac{C_f \text{Ash}_c}{C_c \text{Ash}_f} \times 100 \text{ Percent}$$

Subscripts: C - Coal
F - Flyash

Densities for the Utah samples were around 2.3 g/cm^3 and densities for the Four Corners samples were around 2.0 g/cm^3 , independent of coal size and combustion conditions. Mass median fly ash particle size increased with increasing coal particle size and appeared to decrease as stoichiometry became richer and as residence time became shorter. Nitrogen and hydrogen contents of the fly ash samples were always small, but carbon burnout varied with coal size and type and with stoichiometry and residence time. Figure 4-2 shows that the Utah coal, with a greater heating value, had slightly greater burnout than the Four Corners coal, and that for both coals carbon burnout decreased with increasing coal particle size. Figure 4-3 shows that carbon burnout in the 50-70 micron Four Corners coal increased as the stoichiometry became leaner (as oxygen increased or carbon monoxide decreased in the combustion gas). Figure 4-4 shows that carbon burnout of the same coal increased only slightly with increasing residence time at residence times above 230 msec.

Mass median diameter, as expected, decreased with decreasing coal size, but utilization of a single size parameter can be deceptive as it tells little about the actual size distribution. Figure 4-5 shows that the distributions were quite sharp for the fly ashes obtained from the combustion of the Utah coals. Most of the fly ash was in the 18-36 micron range for the 30-50 micron coal and in the 24-51 micron range for the 50-70 micron coal. This indicates that the bulk of the ash in the Utah coal was extrinsic, existing as discrete ash particles rather than intermixed coal/ash particles. For such particles, application of a Stoke's Law correction factor inversely proportional to the square root of the density (assumed to be 2.3 g/cm^3) 30-50 micron aerodynamically classified coal should contain ash particles in the 20-33 micron range, and 50-70 micron coal should contain 33-46 micron ash.

Distributions were somewhat broader for the Four Corners coals, as shown in Figure 4-6. The mass distribution peak again fell within the extrinsic ash range, but a greater proportion of fines was observed. Surprisingly, the coarse coal produced more fines (particles below 5 microns) than the fine coal. Comparing these results with the burnout results of Figure 4-2, it appears that the increase of fines with increasing coal particle size is due to decreased burnout and to soot formation in the locally rich regions surrounding the large particles. This is reinforced by the variable

Figure 4-2. Burnout: effect of coal size and type.

Figure 4-3. Burnout: effect of combustion gas composition (stoichiometry).

Figure 4-4. Burnout: effect of residence time.

Figure 4-5. Fly ash size distribution: coal size (Utah coal),

Figure 4-6. Fly ash size distribution: coal size (Four Corners coal).

stoichiometry results shown in Figures 4-7 and 4-3. Fines increased and burnout decreased as the combustion stoichiometry became richer. Figure 4-8 shows only a slight increase in fines with decreasing residence time.

Radiometric measurement results were in qualitative agreement with particulate sample results. Effects of coal size and type on combustion cloud extinction efficiency for the 5 percent oxygen, 460 msec data point are shown in Figure 4-9. Actual data were taken at oxygen concentrations varying between 3.7 percent and 7.0 percent and a concentration factor was applied to normalize the extinction efficiencies to 5 percent oxygen. The low-ash Utah coal had unfiltered extinction efficiencies around 4 percent. This was due almost exclusively to gas absorption (CO_2 and H_2O) because filtered (2.2 and 3.6 micron) extinction efficiencies were very small (less than 0.6 percent) in comparison. The medium-ash Four Corners coals had slightly higher unfiltered extinction efficiencies (4.4 percent for the 50-70 micron coal increasing to 5.1 percent for the 30-50 micron coal). Almost a third of this extinction appeared to be due to particulate as filtered extinctions measured about 1.1 percent for the larger coal and 1.7 percent for the smaller coal. Essentially the same values for extinction efficiency were measured for the Four Corners coal at both the 2.2 and the 3.6 micron wavelengths.

Effects of stoichiometry and residence time on the extinction efficiency of the particulate cloud generated in the combustion of Four Corners 50-70 micron coal can be seen in Figure 4-10. Stoichiometry had a marked effect. Filtered extinction efficiencies increased as the stoichiometry became richer from around 1 percent at 5 percent O_2 to around 2 percent at stoichiometric combustion to around 4 percent at 2 percent CO . Unfiltered extinction efficiency increased in a similar fashion from around 4.5 percent to 6.5 percent to 8 percent as combustion gas concentrations went from 5 percent O_2 to 0 percent O_2 , to 2 percent CO . The increase in particulate extinction efficiency as the stoichiometry becomes richer agrees with the particulate sample results, suggesting that soot formation can significantly increase the fine particle concentration and the total surface area resulting in an increase in extinction efficiency. No differences were observed between extinction efficiencies measured at wavelengths of 2.2 microns and at 3.6 microns.

Figure 4-7. Fly ash size distribution; stoichiometry.

Figure 4-8. Fly ash size distribution: residence time.

Figure 4-9. Extinction efficiency: coal size and type.

Figure 4-10. Extinction efficiency: stoichiometry and residence time effects,

Residence time also appeared to have little effect as extinction efficiencies measured at 230 msec were virtually the same as those at 460 msec.

4.4 Calculations

Calculations were performed utilizing Mie theory to estimate the effects of wavelength and of imaginary and real components of the index of refraction on extinction, absorption, and scattering coefficients of individual particles over the size range of interest (0.1 to 100 microns). Figure 11 shows the results for the baseline case where wavelength (λ) is 3.6 microns and the complex index of refraction consists of a real component (n) equal to 1.55 minus an imaginary component (κ) equal to 0.4i. For large diameters, the absorption coefficient slowly converges to 0.9 and the scattering coefficient quickly converges to 1.2, thus the extinction coefficient approaches 2.1. For small diameters, absorption and scattering decrease rapidly with scattering becoming negligible at diameters below 0.5 microns. Absorption, scattering, and extinction coefficients all peak at about 3 microns. Effects of wavelength on extinction coefficient are shown in Figure 4-12. Curves for wavelengths of 2.2 microns and for 3.6 microns are similar except that the 2.2 micron curve is displaced toward smaller particle diameters by a factor of 0.61 (2.2/3.6).

The imaginary component of the index of refraction can have a marked effect on extinction coefficient. Figure 4-13 shows extinction coefficients for a wavelength of 3.6 microns at $n = 1.55$ and κ varying between 0.05i and 0.8i. At large diameters, the extinction coefficient converges to 2.1 for all κ . Extinction efficiencies peak at a particle diameter of about 3 microns with the magnitude of the peak decreasing with increasing κ from about 3.7 at $\kappa = 0.05i$ to about 2.5 at $\kappa = 0.8i$. Extinction coefficient decreases with decreasing diameter at small particle diameters, falling more rapidly for lower values of κ .

The real component of the index of refraction has a much smaller effect on extinction coefficient within the limits expected for fly ash. Figure 4-14 shows extinction coefficients for a wavelength of 3.6 microns at $\kappa = 0.4i$ and n varying between 1.45 and 1.65. Extinction curves are similar except at particle diameters around 3 microns where the peak extinction coefficient varies from around 2.8 at $n = 1.65$ to around 2.5 at $n = 1.45$.

Figure 4-11. Mie calculations; baseline.

Figure 4-12. Mie calculations: wavelength.

Figure 4-13. Mie calculations: imaginary component.

Figure 4-14. Mie calculations: real component.

Calculations of the extinction coefficient were performed utilizing the formula discussed in section 4.1.

$$Q_{\text{ex}} = \frac{\ln(1-E) \rho}{-1.5 C L \sum \frac{dM}{D}}$$

The average measured values of the extinction efficiency (E) were used, corrected to the same oxygen concentration as the particulate samples; the particle densities (ρ) as measured by helium pycnometer were used. The particle concentrations (C) were calculated from the stoichiometric combustion of the coals of Table 4-1 to produce the particulate of Table 4-3 at the average measured temperature at the sample point of 1070 C. The 51 mm pathlength (L) was the width of the reactor. The integrated fractional mass to diameter ratios ($\sum [dM/D]$) were calculated from the size distributions of Figures 4-5 through 4-8.

Intermediate values and the results of the above calculations are shown in Table 4-4. Wide variations are seen, but in general the values of the extinction coefficient are much smaller than expected as shown in Table 5 which compares the experimental extinction coefficients of Table 4 with those calculated from Mie theory using the measured particle size distribution and an assumed index of refraction of 1.55-0.4i. Possible explanations for the discrepancies lie in the uncertainties of many of the measurements and assumptions. The measured extinction efficiencies were quite low, especially for the Utah coals with low ash concentrations, making measurement difficult. The particle density and optical properties were assumed to be independent of particle size, unlikely if the larger particles are composed of fly ash and the smaller particles are soot. The concentration was calculated assuming negligible loss to the walls of the reactor. The purge flows, through the optic probes were assumed to have a negligible effect on the path length. The size distributions were taken from extractive particulate samples with the assumption that no bias was introduced due to probe wall loss or particle agglomeration or breakup.

TABLE 4-4. EXTINCTION COEFFICIENT CALCULATIONS

Coal	Size	Gas Con- centration	Residence Time (msec)	Wavelength (microns)	E (%)	ρ (g/cm ³)	C (g/m ³)	L (cm)	$\frac{dM}{D}$ (%/micron)	Q_{ex}
Utah	30-50	5.0% O ₂	460	2.2	0.25	2.33	3.91	5.08	5.08	1.07
				3.6	0.47					1.98
Utah	50-70	4.8% O ₂	460	2.2	0.448	2.34	2.61	5.08	7.22	3.35
				3.6	0.413					3.09
Four Corners	30-50	5.0% O ₂	460	2.2	1.62	2.01	21.13	5.08	6.36	1.46
				3.6	1.72					1.54
Four corners	50-70	5.3% O ₂	460	2.2	1.02	1.98	19.61	5.08	7.23	0.86
				3.6	1.02					0.86
Four Corners	50-70	2.3% O ₂	460	2.2	1.39	2.02	24.05	5.08	10.15	0.70
				3.6	1.39					2.70
Four Corners	50-70	1.5% CO	460	2.2	3.20	2.00	32.93	5.08	16.57	0.72
				3.6	3.20					0.72
Four Corners	50-70	4.8% O ₂	230	2.2	0.89	2.07	20.11	5.08	8.37	0.66
				3.6	0.97					0.72

TABLE 4-5. EXPERIMENTAL AND THEORETICAL EXTINCTION COEFFICIENTS

Coal	Size (microns)	Gas Con- centration	Residence Time (msec)	Wavelength (microns)	Experimental Q_{ex}	Mie Calculation		
						Q_{ex}	Q_{scat}	Q_{ABS}
Utah	30-50	5.0% O_2	460	2.2	1.07	2.32	1.19	1.13
				3.6	1.98	2.42	1.20	1.22
Utah	50-70	4.8% O_2	460	2.2	3.35	2.33	1.19	1.15
				3.6	3.09	2.33	1.14	1.19
Four Corners	30-50	5.0% O_2	460	2.2	1.46	2.25	1.19	1.06
				3.6	1.54	2.34	1.19	1.14
Four Corners	50-70	5.3% O_2	460	2.2	0.86	2.33	1.18	1.15
				3.6	0.86	2.30	1.12	1.18
Four Corners	50-70	2.3% O_2	460	2.2	0.70	2.31	1.12	1.19
				3.6	0.70	2.15	0.99	1.16
Four Corners	50-70	1.5% CO	460	2.2	0.72	2.01	0.88	1.13
				3.6	0.72	1.69	0.69	0.99
Four Corners	50-70	4.8% O_2	230	2.2	0.66	2.37	1.18	1.19
				3.6	0.72	2.32	1.11	1.21

4.5 Discussion and Plans

The major conclusion that has arisen from the results of the detailed measurements concerns the impact of soot formation on extinction (and presumably absorption) in combustion particulate clouds. Factors which tend to increase soot formation such as larger particles and richer stoichiometries also tend to increase particulate cloud extinction efficiency. Thus, soot formation could have a significant influence on heat transfer in a boiler, particularly in staged combustion or in combustion of high sooting or large particle size coals.

The influence of fly ash appeared to be minor when compared with gas absorption; however, the results of the detailed measurements using monosize coals may not apply to full size distribution coals. Fine ash and coal/ash particles may contribute significantly to the total particulate surface area and to the resulting absorbance/emittance of the combustion particulate. Thus, it is very important to investigate coals with complete size distributions in the screening studies.

The screening studies, to be concluded in the next quarter, will build upon the detailed measurements, addressing many of the operational and measurement problems of the detailed measurements. The larger scale of the screening studies will provide many advantages. Steady feeding of fine coal will be possible allowing complete size distributions to be studied. Wall effects will be much less due to the decreased volume-to-surface area ratio. Higher extinction efficiencies leading to more accurate measurements are expected due to longer path length and increased fines.

REFERENCES

1. Sarofim, A. F., and H. C. Hottel. Proceedings of the 6th International Heat Transfer Conference. Vol. 6. Hemisphere Publishers. Washington (1978). pp. 199-217.
2. Richter, W., W. Clark, R. Payne. Assessment of Pulverized-Coal-Fired Combustor Performance. Contract No. DE-AC22-80PC30297. Fifth Quarterly Technical Progress Report, March 1982.

5.0 TECHNICAL PROGRESS: TASK 3--FIRETUBE SIMULATOR TESTS

In this program task, pilot-scale combustion tests are to be carried out in a firetube boiler simulator facility, modified for coal firing. There are two main objectives of this present series of pilot-scale combustion studies. The first is to provide an experimental data base against which the predictive capabilities of the furnace performance model developed under Task 1 of this program can be verified. Here the primary emphasis will be on furnace thermal performance and how this is affected by conversion to coal firing and by fuel type. The second objective is to provide more detailed experimental data for the validation of those model assumptions which are typically required to define the radiative characteristics of coal ash particulate matter. This forms an extension of the laboratory-scale studies carried out under Task 2.

In the present reporting period, effort has been initiated on this experimental task. The work carried out to date has concerned mainly the definition of a program plan, and a start on the preparation of the experimental furnace, its auxiliary systems and the necessary instrumentation. It is anticipated that this work will be completed in September 1982 when data taking can commence.

5.1 Experimental Facilities

The furnace to be used for these studies is a package boiler simulator designed for a nominal firing capacity of 0.88 MW (3×10^6 Btu/hr). The furnace has the capability of firing gaseous, liquid, and slurried fuels and is currently being modified to accommodate solid fuels, including coal. The firing rate for coals will vary between 0.15 MW (0.5×10^6 Btu/hr) and 0.44 MW (1.5×10^6 Btu/hr) since this range more closely approximates the firing density (MW/m^3) normally associated with industrial and utility coal-fired boilers. Figure 5-1 shows a schematic of the furnace and its auxiliary systems.

The furnace itself is constructed from separate calorimetric elements through which an organic coolant is circulated. This provides a nominal wall temperature of 200 C (400 F) and permits the determination of the axial distribution of heat flux. For the purposes of this present experimental program, the furnace will be lined with refractory to reduce the overall level

Figure 5-1. Schematic of versatile coal/gas furnace to be used on pilot-scale studies.

of heat extraction to approximately 50 percent of the thermal input. This will result in flue gas temperatures of approximately 1000 C (1850 F) and a thermal environment close to that of coal-fired combustion systems. For the experimental furnace, coal will be prepared off-line in a large-scale coal milling installation and will be fired through an indirect bin-and-screw feed system. A gas-fired air preheater provides for combustion air preheat levels up to 370 C (700 F). Air flows to all burner channels can be separately metered and controlled, and sample systems are available for in-flame and stack gaseous species measurements. Thermocouples are located at various positions to monitor the temperatures of the furnace, coolant, and input streams.

The burner to be used on this program is shown in Figure 5-2. Air can be injected axially and/or tangentially through a set of swirl vanes near the front of the burner assembly. This allows the degree of swirl to be controlled by varying the distribution of the air between the two streams. The pulverized coal is transported pneumatically to the burner and is injected through a pipe on the center axis. The coal injector may be either a straight axial jet or may incorporate a spreader to provide a divergent coal stream. This arrangement makes it possible to investigate two basically different coal flame types. An axial coal injection, coupled with low- or moderate-combustion air swirl will produce long flames, with a mixing history typical of corner-fired systems; while divergent coal injection and a high swirl will produce short, intense flames typical of wall-fired systems.

5.2 Fuels

The fuels to be used in this program comprise one gaseous fuel and three coals. The gaseous fuel will represent the baseline case for comparison, and will be either a commercial-grade propane containing approximately 95 percent propane and 4 percent impure combustibles, or natural gas.

Three coals have been selected from those tested in the laboratory-scale experiments. Two coal properties have been shown to be of greatest importance in determining the thermal performance of combustors. These are the ash content of the coal and its calorific value. The coals selected include a limited, though significant, variation in these parameters. Some

Figure 5-2. Burner assembly.

properties of the selected fuels are shown in Table 5-1. All coals are available in the DOE coal bank and will be used on other DOE programs.

TABLE 5-1. FUELS TO BE USED IN PILOT-SCALE TESTS

Fuel	Region	Coal Rank	Percent Ash (As Received)	Heating Value (Btu/lb) (As Received)
Gas (C_3H_8)	--	--	0	19,930
Four Corners	New Mexico	HVCB	20.7	10,200
Hiawatha-Wattis	Utah	HVB	7.8	12,600
Illinois #6	Illinois	HVC	10.4	11,600

5.3 Test Plan

In order to achieve the task objectives, it is proposed to divide the pilot-scale studies into two separate efforts. The first will take the form of screening studies, where the effects of a range of input parameters on furnace thermal performance will be investigated. In the second, a limited number of test conditions will be selected and detailed in-furnace measurements performed. Those input variables which have been determined to be important, and thus form the basis for the selection of test conditions, include:

- Air flow rates and temperatures
- Fuel flow rate
- Fuel properties
 - Ultimate and proximate analysis
 - Size distribution
 - Composition of ash
- Burner parameters.
 - Mixing
 - Stoichiometry

Table 5-2 presents the selected test conditions and includes variations in fuel type, firing rate, flame type, coal fineness, and excess air ratio for each coal. The gas-fired condition represents the baseline case, and will provide thermal performance data for the furnace operating on a clean fuel. Comparable conditions are included for each of the three pulverized-coal fuels to provide a direct assessment of the effect of fuel type. The remaining conditions represent changes in each of the independent variables for each coal.

Table 5-2 also identifies the type of measurements to be made for each test condition.

The measurements necessary to collect the data can be classified into three categories:

- I - Measurements to verify the model and gross comparison of fuels.
- II - Detailed measurements to define the particle cloud and its properties.
- III - Support measurements to identify the parameters that affect the total thermal properties of the cloud.

Current state-of-the-art technology will be used on all the methods. The measurements in each category are described below.

Category I

These measurements represent the basic measurements for the screening studies and concentrate on the generation of overall furnace performance data. The measurements included in this category are:

1. Measurement of all input conditions, including mass flow rate and temperature of all input streams.
2. Flue-gas composition-- O_2 , CO_2 , CO , NO_x .
3. Flue gas temperature. In addition, a traverse of temperature across the furnace exit plane will be made to check for temperature profiles which must be taken into account in the model.
4. Flue gas particulate sampling. Measurements will be made in the stack to determine the fly ash mass loading (gm/m^3) and to obtain a sample for "burn-out" determination. In addition, a cascade

TABLE 5-2. PROPOSED TEST CONDITIONS FOR PILOT-SCALE TESTS

	Firing Rate 10 ⁶ Btu/Hr	Flame Type	Coal Grind %<74 μ m	Excess Air Ratio	Air Preheat °C	Measure- ments Category
Gas	1.0	Short	--	1.10	300	I
Hiawatha -Wattis	0.5	Short	70	1.25	300	I
	1.0	Short	70	1.25	300	I,II,III
	1.0	Long	70	1.25	300	I
	1.0	Short	70	1.10	300	I
	1.0	Short	85	1.25	300	I
	1.5	Short	70	1.25	300	I
Illinois #6	0.5	Short	70	1.25	300	I
	1.0	Short	70	1.25	300	I,II,III
	1.0	Long	70	1.25	300	I
	1.0	Short	70	1.10	300	I
	1.0	Short	85	1.25	300	I
	1.5	Short	70	1.25	300	I
Four Corners	0.5	Short	70	1.25	300	I
	1.0	Short	70	1.25	300	I,II,III
	1.0	Long	70	1.25	300	I
	1.0	Short	70	1.10	300	I
	1.0	Short	85	1.25	300	I
	1.5	Short	70	1.25	300	I

impactor will be used to obtain the fly ash size distribution in order to investigate how this important parameter is affected both by firing conditions and fuel type.

5. Total net heat flux distribution to the furnace walls will be determined by measuring the coolant temperature rise across each furnace segment.
6. Axial distribution of incident heat flux at the furnace walls will be measured using an ellipsoidal radiometer and/or a total heat flux meter probe.
7. Axial profile of CO concentration within the flame will be determined by sampling and analysis. This measurement will permit a definition of the extent of the heat release zones for input into the computer model.

Category II

Measurements in this category will be made primarily to determine the properties of the fly ash particulate cloud and wall deposit layers. These measurements are more detailed and time-consuming than those of Category I, and will therefore be made for a limited number of conditions only. One condition per coal is proposed, as indicated in Table 5-2. The measurements of Category II will be made in addition to those of Category I and include:

1. Radiant emission and extinction of the fly ash particulate cloud. These measurements will be made using an IR detector in combination with a blackbody source and chopper as in the Task 2 studies. The measurement utilizes diametrically opposite pairs of sampling ports, and measures the radiant properties of the particulate cloud within this line-of-sight. These measurements will be made at two axial locations within the furnace: one downstream of the flame zone and prior to the exhaust, and the second within the luminous flame itself.
2. Local measurements of temperature, gaseous species concentration and particulate mass loading. Radial profiles at a number of axial locations will be obtained using the probing techniques described

previously. Special attention will be paid to those axial locations at which particle cloud radiation measurements are made.

3. Ash deposition measurements will be made using a controlled temperature heat flux probe. Measurements of the rate of change of heat flux and inspection of the ash deposit layer at the conclusion of the measurement will permit an assessment of the relative rate of deposition for the different coals. In addition, the surface temperature of the deposit will be measured in-situ using two-color optical pyrometry, and radiation measurements will be made to determine the ash deposit emissivity. Similar measurement will be made at the furnace refractory wall surface to provide emissivity data for input into the model.

Category III

The measurements in this final category will be carried out to gain additional information as needed to more fully analyze and interpret the data. These include analyses that can be performed on site or by outside laboratories. Such analyses include:

- Proximate and ultimate analyses on coals and chars (including C.H.N. on a Perkin-Elmer Elemental analyzer and sulfur analysis with a Leco furnace).
- B.E.T. surface area.
- Scanning electron microscopy for particle shape.
- Analysis of the ash for mineral and trace species.
- Particulate composition for various elements by size fraction.

Extensive analysis on the particulate will be limited for these studies because of the cost.