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COAL COMBUSTION AEROTHERMOCHEMISTRY RESEARCH

Final Report

By

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December 15, 1980

Work Performed Under Contract No. AC01-79ER10029

TRW Defense and Space Systems Group
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Redondo Beach, California

U. S. DEPARTMENT OF ENERGY

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ENERGY TECHNOLOGY DEPARTMENT
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ABSTRACT

On the basis of extensive aerothermochemistry analyses, laboratory investigations, and combustor tests, significant headway has been made toward improving the understanding of combustion phenomena and scaling of high swirl pulverized coal combustors. A special attempt has been made to address the gap between scientific data available on combustion and hardware design and scaling needs.

Both experimental and theoretical investigations were conducted to improve the predictive capability of combustor scaling laws. The scaling laws derived apply to volume and wall burning of pulverized coal in a slagging high-swirl combustor. They incorporate the findings of this investigation as follows:

Laboratory Investigations

- laser pyrolysis of coal at $\sim 10^6$ K/sec and 2500K
- effect of coal particle shape on aerodynamic drag and combustion
- effect of swirl on heat transfer
- coal burnout and slag capture for 20 MW_T combustor tests for fine and coarse coals.

Analyses

- burning particle trajectories and slag capture
- particle size and aerodynamic size
- volatilization extent and burnout fraction
- preheat level.

As a result of this work, the following has been gained: an increased understanding of basic burning mechanisms in high-swirl combustors and an improved model for predicting combustor performance which is intended to impact hardware design and scaling in the near term.

NOMENCLATURE

a	Thermal diffusivity
A	Cross Sectional Area
B	Constant defined by equation (2-13)
C_{fr}	Skin friction coefficient for resultant shear
C_{Hr}	Stanton number based on resultant velocity
C_{Hu}	Stanton number based on axial velocity
C_p	Specific heat
d	Diameter
D	Diameter of combustor
d_d	Drag diameter
d_v	Volume diameter
d_{ST}	Stokes' diameter
D_f	Fringe spacing
f_D	Doppler frequency shift
g	Gravitational acceleration
h	Heat transfer coefficient
ΔH	Heat of combustion per unit mass of mixture

I	Radiation power density
k	Thermal conductivity
K	von Karman constant
K_{oe}	Mass friction of oxygen in mainstream
k_s	Equivalent sand height for roughness
L	Length of combustor; beam path length
L	Monin-Obukov length
$\dot{m}$	Mass flow rate
m_d	Dry ash-free mass
$\dot{m}_{O_2W}$	Mass flux of oxygen to wall per unit area
m_v	Devolatilized mass
$\dot{M}_{O_2}$	Total mass flux of oxygen in mainstream
$\dot{M}_{O_2W}$	Total mass flux of oxygen to wall
N	Number density
Nu	Nusselt number
P	Power; pressure
q	Heat flow rate

q_e	Resultant velocity
q^*	Shear velocity based on resultant shear
r	Radius
R	Gas content
R	Radius of combustor
Re	Reynolds number
t	Time
T	Temperature
u	Axial component of velocity
V	Volume; velocity
x	Length along combustor

Greek

α	Absorptivity
β	Extinction coefficient
ϵ	Emissivity
θ	Time; temperature rise
λ	Wave length
μ	Viscosity

ν	Kinematic viscosity
π	Power
π^*	Power density
ρ	Density
σ	Stefan-Boltzmann constant
τ	Time constant

Subscripts

o	Initial
e	Conditions at outer edge of boundary layer
f	Final; fluid
g	Gas
i	Inlet
l	Liquid
L	Length
p	Particle
s	Solid
T	Terminal
w	Conditions at wall

x

Exit

λ

Wave length dependence

1. INTRODUCTION

1.1 PROGRAM RATIONALE

This work reports an investigation of two fundamental coal combustion problems: in-flight (or volume) burning and wall burning. These have rather broad validity and general application insofar as coal combustion is applied to gasification, indirect heat and MHD power generation. These problems are not meant to be the only ones of importance. Slag dynamics and control are certainly of equal importance. An attempt has been made to provide a balanced combustion research effort close to the basic disciplines of aerodynamics, thermodynamics and chemistry to permit the generation of ideas which can impact the hardware development in this area in the near term. The central issue to these two problems is scaling combustor size; this is inherently dependent on where particle burning actually takes place, in the volume or at the wall. Resolution of this issue is required in order to maintain a high level of performance during scale-up.

Whereas the generation of very basic combustion data has been supported by DoE and others, the use of these data combined with phenomenological concepts governing process operation has not grown nearly fast enough to bridge the gap between combustion sciences and hardware development. It is the intent and purpose of this investigation to test certain ideas on how coal burning processes are influenced by injection and heating conditions, and then provide scaling laws for these phenomena which can be used as a guide in large-scale hardware development efforts.*

1.2 MAJOR COMBUSTION RESEARCH ISSUES

Several major combustion research issues have surfaced as a result of the progress TRW has made in its pulverized coal combustor development program on IR&D and customer contracts. The first involves how to scale and concurrently maintain the high performance being achieved on the high swirl MHD combustor concept sponsored by DoE. The burning rates observed in these tests markedly exceeded simple theoretical predictions based upon free-flight (in the volume) and wall burning. The early discrepancy between theory and experiment caused us to reexamine the phenomena governing

*Much of the early work was published in England [1,2].

the combustion processes. On the basis of this look into free-flight burning, we have identified two critical assumptions which need experimental verification. These were examined in a series of two basic experiments which address combustion caused by rapid particle heating (large volatiles release) and particle shape effects. For wall burning, we had developed a scaling theory which included the effects of buoyancy and wall roughness and provided energy densities close to what is observed. Here a simple laboratory experiment was conducted to verify the basic concepts, while a 20 MW_T combustor experiment was run to validate the scaling laws.

1.3 SUMMARY OF RESULTS

The overall objective of this investigation was directed to improving the reliability of predicting performance of high-swirl pulverized coal combustors.

1.3.1 Analysis and Scaling

Objective

- To predict the performance of high swirl pulverized coal combustors so that subscale combustors can be scaled up to commercial sizes on a rational basis.

Analysis Summary

- An existing particle combustion code was used to evaluate effects of...
 - Particle trajectories on burning and slag capture
 - Particle size and aerodynamic drag size
 - Burnout fraction
 - Volatilization extent
 - Preheat level
 - Design changes which alter flow
 - Approximations made in scaling laws
- Scaling laws were developed for high temperature stoichiometric combustion.
- Simulator data used to develop heat and mass transfer analysis for wall burning.

Scaling Law Summary

- Start with a high performance subscale combustor and evaluate constants in the scaling relationship.
- For small devices ($R \ll 1$ meter) wall combustors are likely to have higher power densities.
- Wall combustors are ultimately limited by maximum tolerable velocity (Δp , M , τ).
- For larger devices free flight combustion yields higher power densities.
- Free flight combustors are limited by combustion time and ultimately by maximum velocity.

1.3.2 Rapid Heating Coal Pyrolysis Experiment

Objective

- To measure volatiles release under high heating rates in order to assess combustion enhancement.

Pyrolysis Summary

- Laser pyrolysis of coal particles at measured rates of up to 10^6 K/sec and 2500 K has been achieved.
- Vaporization, to some degree, of all metal oxides, suggests the use of a different measurement technique to quantify volatilization extent.
- Strong radiation coupling of volatiles was observed... a phenomena about which little is known.
- Large volatiles release is common to high swirl combustors and significantly influences combustion intensity.

1.3.3 Coal Particle Shape Effects

Objective

- To determine the effect of coal particle shape on aerodynamic drag and combustion.

Shape Effects Summary

- It has been discovered that aerodynamic drag size can be significantly different than the physical size (coal particle size) distribution.

- This difference may cause a significant difference in burning coal particle trajectories and hence the burning patterns, slag capture and performance of a combustor.
- The design of high performance combustors must take account of these facts to achieve satisfactory performance at large scale.

1.3.4 Wall Combustion Simulator Experiment

Objective

- To identify and quantify the mixing mechanism(s) controlling efficient wall burning.

Simulator Results

- Large heat transfer rates have been measured consistent with large mass transport and mixing between the core flow and wall.
- Swirl level has a significant effect on heat transfer.
- At simulator scale, the data show that buoyancy is not nearly as important as turbulent mixing which correlates reasonably well.
- Data can be used to provide design inputs on wall heat transfer.

1.3.5 Combustor Tests

Objective

- To test a large scale combustor and assess performance for volume and wall burning.

Test Summary

- Five tests were run at $\sim 15 \text{ MW}_T$ (55M BTU/HR) level.
- Coarse coal and fine coal were tested to assess wall and volume dominated combustion.
- Measurements indicated peak combustion intensity for both cases for which...
 - 60% of the coarse coal was estimated to have been burned at the wall, and
 - 100% of the fine coal was burned in the volume.
- Good agreement between measured and predicted slag capture was also achieved.

1.4 REPORT ORGANIZATION

The analytical work, which includes modeling of the various phenomena in a pulverized coal combustor, is discussed in Section 2. Volume and wall burning conditions are modeled, scaling laws developed, and burnout patterns are shown (Appendix B contains more of the burnout patterns). The experimental portion of this study is discussed in Sections 3, 4 and 5. In Section 3, two free-flight burning related phenomena are discussed. These are the effect of rapid heating and pyrolysis and the effect of particle shape on their trajectories and the overall burnout pattern. In Section 4, wall burning phenomena are investigated. Finally, in Section 5, the results of the 20 MW_T pulverized coal combustion tests are reported. Some details of the design of the pinhole camera, which allowed on-line observations inside the fired combustor, are given in Appendix A. Scanning electron micrographs of slag recovered from the combustion tests are shown in Appendix C.

2. COMBUSTION ANALYSIS

2.1 OBJECTIVES AND ENGINEERING CONSIDERATIONS

The objective of combustion analysis is to predict the performance of high swirl pulverized coal combustors so that subscale combustors can be scaled up to commercial sizes on a rational basis. The early combustion models markedly underpredicted the combustor performance. Based on these models a much larger combustor would be required to obtain the performance observed experimentally. Some of the key features that are desired to be produced are thermodynamic properties of combustion products leaving the combustor, size and configuration of combustor required for complete combustion, and distribution of slag deposited on combustor walls.

Recent improvements in the combustion analysis are described in this section which result in predictions which are in much closer agreement with experiments. Based on the governing parameters in these analyses some simple scaling laws are described.

2.2 FREE FLIGHT BURNING

2.2.1 Analysis

In early studies of combustion in cyclone combustors at TRW [3, 4], the results showed very little combustion of the coal particles during free flight for nominal combustor conditions. This led to a tentative conclusion that combustion takes place primarily on or near the combustor walls under those operating conditions.

An important feature of these analyses was the effect of the large number of coal particles on the air stream passing through the particles. In the early stages of particle heating the air stream is cooled by the particles thus limiting the heat transfer. Later, after ignition takes place, the air is depleted of oxygen as it passes through the particles thus limiting the burning. Both of these effects lead to longer burnout times than would be predicted on the bases of single particle combustion.

More recently some new features have been added to the analysis which should lead to more rapid burnout [5]. First it is recognized

that pulverized coal consists of a distribution of sizes. The smaller particles will most certainly burn out in free flight, and, because of their smaller numbers, the large particles will not have as great an effect on the air stream. Therefore, in this analysis a realistic distribution of particle sizes is used. (Further, according to Section 3.2, it becomes apparent that drag size rather than physical distribution is pertinent.) A typical distribution obtained from measurements of Montana Rosebud coal is shown in Figure 2-1. The effect of the particles on the air stream is included by accounting for the change in air properties across each size group. Furthermore, the air stream entering each group of particles is modified by the effects of the upstream particles. In this way, the calculation of the various groups of particles is coupled. Approximately ten groups of particles are used.

Another feature which should lead to more rapid burnout is that of increased devolatilization at high temperatures. It has been observed that at high temperatures both the rate of volatilization and the amount of material which comes off as volatiles, can increase significantly [6-8]. As much as seventy percent of the dry ash-free mass has been observed to come off as volatiles as compared to approximately thirty percent indicated by a standard ASTM test of the material. In order to include this feature, the correlation of Kobayashi [6] was used for the volatilization rate.

The fixed carbon burns in heterogeneous combustion. In previous work [4] the burning rate was set to zero until an ignition temperature was reached after which diffusion controlled combustion occurred. In the recent analysis chemically rate controlled combustion is allowed to occur at lower temperatures until the surface temperature is sufficiently high for diffusion of oxygen to the surface to control the combustion rate.

Another improvement in the analysis accounted for departures from Stokes flow drag. The correlation of Carlson and Hoglund [9] was used. This correlation accounts for a wide range of conditions including large free path compared to particle size and strong convection effects. Similar corrections for heat and mass transfer given by Carlson and Hoglund were also used.

Figure 2-1. MEASURED MASS DISTRIBUTION 200 MESH MONTANA ROSEBUD COAL

The flow field in a cyclone combustor is extremely complex. Rather than attempting to predict the flow field completely for various operating conditions, the present approach is to utilize the results of cold flow simulator tests for overall features and to modify the flow field based on mass and energy balances. The main features of the flow field are shown in Figure 2-2. It was observed in the cold flow simulator tests by Dailey at TRW [10] that the flow patterns reported by Syred and Beer [11] apply here for an inlet away from the headend wall. The flow entering the combustor splits and goes up into the headend while the rest goes downstream. The region where this reverse flow takes place is confined to radii larger than about 70% of the combustor radius. Some measurements of the azimuthal velocity in the simulator are shown in Figure 2-3. The results for the case with a slag baffle in place are modeled fairly well by assuming solid body rotation at radii below about 35% of the combustor radius and potential flow outside of this region. With no slag baffle the azimuthal velocity is radically different with virtually no potential flow region. Of course with a single side inlet there is some asymmetry to the flow field which cannot be accounted for in the present combustion theory.

Some results of the recent analysis are shown in Figures 2-4 to 2-8. These results are for the distribution of particle sizes shown in Figure 2-1. When these calculations were made the coupling between sheets of various particle sizes was not yet in operation in the program. Subsequent calculations, with this feature included, showed some delay in combustion of the small particles due to shielding by large particles upstream but virtually the same results for the larger particles.

The trajectories are shown in Figure 2-4. The flow conditions are nominal for the TRW 20 MW combustor. It can be seen that the trajectories fall in a narrow band and that all except the 203 μm particle burn out before striking the wall.

The corresponding mass loss as a fraction of the initial dry ash-free mass for each particle size is shown in Figure 2-6. The burning occurs very suddenly and is widely separated spatially. This is probably the

Figure 2-2. FLOWFIELD FEATURES IN COMBUSTION CHAMBER

Figure 2-3. AZIMUTHAL VELOCITY MEASUREMENTS IN SIMULATOR BY DAILEY

Figure 2-4. PARTICLE TRAJECTORIES

Figure 2-5. TIME OF FLIGHT

Figure 2-6. MASS LOSS

Figure 2-7. ENVELOPE OF TOTAL MASS LOSS

Figure 2-8. TEMPERATURE DISTRIBUTION

reason that coupling the sheets does not have a large effect on the majority of the distribution. Also shown for each segment of the distribution is the volatile mass loss. In each case this turns out to be greater than eighty percent of the dry ash free mass although the initial volatile mass was 30 percent. Thus rapid volatilization plays a major role in the combustion process. The envelope of these mass loss results weighted by the distribution of Figure 2-1 is shown in Figure 2-2. It can be seen that about half of the particle mass is burned out before the particles reach the reverse flow region.

The corresponding particle temperatures are shown in Figure 2-8. Temperatures at burnout range from 2100°K to 2700°K. As with the mass loss, considerable spatial separation occurs indicating that coupling may not be a large effect.

2.2.2 Scaling

A figure of merit for combustor performance is the specific power density

$$\pi^* = \frac{\pi}{pV} \quad \text{MW/atm-m}^3 \quad (2-1)$$

Neglecting losses the power produced is the mass flow times the heat of combustion.

$$\pi = \rho u A \Delta H \quad (2-2)$$

Thus the specific power density can be expressed as:

$$\pi^* = \frac{u}{L} \frac{\Delta H}{RT} \quad (2-3)$$

The heat of combustion and the gas temperature are fixed by considerations such as, for MHD combustors, desired electrical conductivity. Therefore the specific power density is determined by the quantity $\tau = L/u$ which is a characteristic time for the combustor.

If the combustor operates at low subsonic velocities, choking effects and total pressure losses will not be a large factor. Therefore the characteristic time for the combustor will depend primarily on required particle heating and combustion times. It might be assumed that if a combustor is optimized at a small size the way to scale up for similar geometry and constant pressure is to scale the power with combustor volume and all the velocities with length.

A numerical experiment was carried out to test the validity of this simple scaling idea. Coal particle trajectories were calculated for a 20 MW combustor assuming all particles were either 23 μm , 50 μm , 108 μm or 231 μm . The trajectories are shown in Figure 2-9. The entire combustor was then scaled as suggested above to give a 2500 MW combustor. Oxidizer and coal injection velocities were scaled up with the length. The results are shown in Figure 2-10. Comparison of the results shows that for this extreme scale up the trajectories and location of burnout are pretty similar. As might be expected the largest and smallest particles are affected the least. The large particles have a very weak interaction with the gas while the smallest ones depart very little from Stokes drag law and heat and mass transfer in a quiescent medium. The corrections due to Carlson and Hoglund [9] have the largest effect on the 108 μm and 50 μm particles. In fact the 108 μm particles in the larger combustor behave almost like the 50 μm particle in the smaller device.

20 MW COMBUSTOR
NORMAL 200 MESH
NO BAFFLE

Figure 2-9. BURNING COAL PARTICLE TRAJECTORIES

2500 MW COMBUSTOR
NORMAL 200 MESH
NO BAFFLE

Figure 2-10. BURNING COAL PARTICLE TRAJECTORIES

2.3 WALL BURNING

2.3.1 Analysis

A common operating mode for a cyclone combustor is one in which coal particles are either injected near the wall or forced through the air by centrifugal effects in a time too short for any significant free-flight combustion to occur. Combustion then takes place on the outer cylindrical wall. In order for combustion to be completed, sufficient oxygen must diffuse to the outer wall. Assuming that the overall stoichiometry is correct, this means all of the oxygen in the main flow must diffuse to the outer wall in the region of burning. The actual combustion process depends upon many factors such as chemical rate control processes, volatilization rate, heat transfer to the particles and the motion of the particles along the wall. For simplicity attention will be focused on the diffusion of oxygen to the surface. This could be a limiting part of the combustion process.

It can be shown that for a Lewis number of unity with all oxygen consumed at the surface, the flux of oxygen to the outer surface is:

$$\dot{m}_{O_{2w}} = K_{oe} \rho_e u_e C_{Hu} \quad (2-4)$$

It was shown in Reference 12 that even in the presence of a strong azimuthal velocity component the usual flat plate boundary layer equations govern the flow. The total oxygen mass flow to the outer wall is given by

$$\dot{M}_{O_{2w}} = 2 \pi R K_{oe} \rho_e u_e \int_0^x C_{Hu} dx \quad (2-5)$$

The oxygen in the main flow is given by

$$\dot{M}_{O_2} = \rho_e u_e K_{oe} \pi R^2 \quad (2-6)$$

The ratio of the total flux to the wall to the main flow is then

$$\frac{\dot{M}_{O_{2w}}}{\dot{M}_{O_2}} = \frac{2 \int_0^x C_{Hu} dx}{R} = \frac{4x}{D} \bar{C}_{Hu} \quad (2-7)$$

For an ordinary smooth flat plate flow, the Stanton number at Reynolds numbers in the range of 10^5 would be about 0.0037. A typical length to diameter ratio may be on the order of 3.0. For these conditions equation 2-7 yields

$$\left[\frac{\dot{M}_{O_{2w}}}{\dot{M}_{O_2}} \right] = 0.044 \quad (2-8)$$

This indicates that less than five percent of the oxygen could reach the wall. It is well known, however, that turbulent transport can be greatly enhanced in a cyclone combustor. Furthermore, experimental data with swirling flow combustors at TRW indicate virtually no unburned carbon under most operating conditions. Three possible mechanisms that could be responsible for enhanced turbulent transport are:

- Increase in turbulence level due to azimuthal component of velocity
- Buoyancy effects
- Wall roughness effects.

A preliminary analysis has been derived in which all of these effects are included.

Based on reasoning similar to that of Von Karman [13], Rott and Lewellen [14], and that of Reference 12 it can be shown that for a turbulent flow with swirl the skin friction coefficient based on the resultant shear stress and velocity has the functional form for a smooth wall

$$\frac{C_{fr}}{4j} = f_1 \left[(1510)^j \frac{q_e}{u_e} \frac{q_e x}{v} \right] \quad (2-9)$$

Similarly for a rough wall

$$\frac{C_{fr}}{4j} = f_2 \left[j \frac{q_e}{u_e} \frac{x}{k_s} \right] \quad (2-10)$$

In these expressions, as in Reference 12, $j=0$ for no buoyancy and $j=1$ for strong buoyancy. The quantity q_e is the resultant velocity while u_e is the axial component of the velocity and k_s is the equivalent sand height characterizing the roughness. The correlations of the form (2-9) and (2-10) result from the idea that the magnitude of the turbulent transport is affected by the resultant velocity but the convection of momentum depends upon the axial component of velocity. The functional forms f_1 and f_2 can be taken from Schlichting [15] (see Figure 2-11).

Consideration of energy conservation leads to Reynolds analogy in the form

$$C_{Hr} = \left(\frac{10}{3}\right)^j \frac{C_{fr}}{2} \quad (2-11)$$

The Stanton number based upon the axial velocity is the usual parameter used for heat exchange data correlation. This Stanton number C_{Hu} is related to C_{Hr} by

$$C_{Hu} = \frac{q_e}{u_e} C_{Hr} \quad (2-12)$$

An indication of the importance of buoyancy can be obtained from the Monin-Obukov [16] length based upon the resultant shear stress and the centrifugal acceleration.

$$L = -\frac{q^{*3}}{KB}, \quad B = \frac{v_e^2}{R} \frac{(-q_H)}{c_p \bar{T} \rho} \quad (2-13)$$

In terms of the coefficients this length can be expressed as

$$\frac{L}{R} = -\left(\frac{q_e}{v_e}\right)^2 \frac{\bar{T}}{K(\bar{T}_w - \bar{T}_e)} \left(\frac{C_{fr}}{2C_{Hr}}\right) \left(\frac{C_{fr}}{2}\right)^{\frac{1}{2}} \quad (2-14)$$

From Section 4 which describes cold flow heat transfer data obtained in a swirling flow simulator

$$\frac{C_{fr}}{2} \approx 0.003 \text{ and } q_e \approx v_e. \text{ Hence } \frac{L}{R} \approx -\frac{\bar{T}}{(\bar{T}_w - \bar{T}_e)} \times 0.14 \quad (2-15)$$

Figure 2-11. EFFECT OF STRONG BUOYANCY AND SWIRL ON SKIN FRICTION.

The quantity $\bar{T}/\Delta T$ for the simulator data ranged from about 9 to 200. Under all these conditions the Monin - Obukov length is large compared to the combustor radius and would be even larger compared to the boundary layer thickness. Under these conditions buoyancy effects would be expected to be small. For the combustor, however, if all combustion takes place on the wall, it is not as easy to rule out buoyancy effects. In this case if $T_w \gg T_e$ the quantity $\bar{T}/\Delta T$ would approach a limit near 0.5. Then the Monin - Obukov length could be small compared to the radius of the combustor and possibly small compared to the boundary layer thickness.

The roughness correlation of equation (2-10) has not yet been investigated in the simulator. The smooth wall correlation of equation (2-9) gives fairly good agreement with simulator experiments as described in Section 4.

2.3.2 Scaling

For a wall combustor which is limited by oxygen flux to the wall, the power produced is

$$\pi = \frac{M_{o2w}}{K_{oe}} \Delta H = \left(\frac{4L}{D} \bar{C}_{Hu} \right) \rho u A \Delta H \quad (2-16)$$

The specific power density is then

$$\pi^* = \left(\frac{4L}{D} \bar{C}_{Hu} \right) \frac{u}{L} \frac{\Delta H}{RT} \quad (2-17)$$

The quantity in parenthesis is the ratio of the oxygen mass flux to the wall to that in the mainstream. In an optimized combustor this quantity is unity. Thus in order to have the same power density a scaled up combustor should have the velocity scale with combustor length just as for the free flight burning combustor. However, for a wall combustor the ratio of wall to freestream oxygen flux should be maintained in the neighborhood of unity.

It can be shown that the Stanton number, including the effects of both roughness and buoyancy, is given by

$$\overline{C}_{Hu} = \frac{q_e}{u_e} \left(\frac{40}{3}\right)^j \times 0.0202 \left(4 \frac{q_e}{u_e} \frac{L}{k_s}\right)^{-0.221} \quad (2-18)$$

Thus in order to maintain the proper oxygen flux to the surface

$$R \propto \left(\frac{q_e}{u_e} L\right)^{1-0.221} \quad (2-19)$$

and

$$\pi \propto L \cdot \left(\frac{q_e}{u_e} L\right)^{2-0.442} \quad (2-20)$$

It can be seen that it is not possible to maintain both geometrical similarity and flow field similarity for the wall combustor.

2.4 RECOMMENDATIONS

The following additional work is recommended to improve the analysis:

- Extend free flight combustion analysis to fuel rich combustion
- Develop wall combustion analysis
- Extend model for slag flow control and capture
- Incorporate analyses, laboratory experiments and combustor tests into scaling laws.

2.4.1 Free Flight Combustion Analysis

In some regions of combustors the coal particles may be in a fuel rich environment. Such conditions often occur near the coal injection point where only a portion of the oxidizer flow passes through the coal particles and furthermore this flow may contain products of combustion in some regions. These conditions are also prevalent in gasifiers, and for this reason alone further analysis is necessary.

In a fuel rich environment the main oxidizers may be CO_2 and H_2O instead of O_2 . Account must be taken of rate limiting steps for these reactions including poisoning by products of combustion and pore diffusion effects.

2.4.2 Wall Combustion

Although most of the ingredients for a wall combustion analysis are now available the analysis is not as fully developed as the free flight combustion analysis. An important feature that needs clarification is the dynamics of particle motion in the neighborhood of the wall and the interaction of particles with a slag layer. Once such a model is obtained the results of the present studies of turbulent flow in a swirling combustor can be utilized to develop a heat transfer and combustion model for particles adjacent to the wall.

2.4.3 Slag Flow Control and Capture

The free flight combustion model can now be used to predict where slag particles are deposited on the combustor walls. This should be combined with a model of slag flow dynamics. Such a model was developed in Reference [17]. It was shown that the slag flow can be dominated by aerodynamic shear stresses or by gravitational effects. The recent work on wall heat transfer and shear stress can be used to improve this model. In addition it would be desirable to add some new features such as realistic deposition distribution for the slag, the effect of vaporization, the effect of additives and analysis of end plate slag layers.

2.4.4 Scaling Laws

As more refined analyses and laboratory experimental data become available the results should be incorporated into predictions for scaling up from subscale to commercial size.

3. FREE FLIGHT BURNING

For a very high swirl pulverized coal combustor, modeling calculations predict that the coal is centrifuged to the walls rapidly and burns there. There are possible mechanisms which could alter this prediction and thereby provide for substantial free-flight combustion in the combustor volume. Two such mechanisms have been investigated. First, the enhanced devolatilization due to rapid heating of the coal particles and second, the particle shape effect on the trajectories of the burning particles. Both of these effects are discussed in detail in the following sections.

3.1 RAPID HEATING, PYROLYSIS EXPERIMENT

3.1.1 Objectives and Engineering Considerations

The purpose of the experiment was to determine if a rapid heating of coal particles in a pyrolysis zone can affect their subsequent burnout times. There has been much speculation in the literature suggesting that coal particles subject to very high heating rates may burn out in less time than coal particles brought to the ignition point gradually.

Evidence found in the literature indicates that rapid pyrolysis of coal affects the rate of devolatilization [7, 8] as well as the physical state of the coal [7]. The subject has been given ample attention in the literature. (See, for instance, the "Colloquium on Combustion and Related Processes in Energy Production From Coal," in the 16th Symposium (International) on Combustion, The Combustion Institute, 1976.)

Basically, four different techniques have been applied in rapid coal pyrolysis studies. An electrically heated grid on which coal particles are scattered has been used by various investigators [18-20]. The temperature and heating rates are usually measured with a thermocouple positioned on the screen among the coal particles. This technique allows testing under various pressure levels, different atmospheres (e.g., inert or various levels of oxygen, etc), controlled heating rate and final temperature. Heating rates of up to 10^4 K/sec are reported.

One problem with this approach is that the heating of the coal particles is nonuniform. The particles are heated by conduction through their contact with the grid surface. Further, the measured temperature is that of the thermocouple element rather than the coal.

A flow furnace into which the coal sample is introduced and immediately exposed to a high temperature environment is another technique for the study of coal pyrolysis [21-23]. In some cases the hot environment is achieved by an arc heated plasma, and in others, by actual combustion of the coal. Heating rates, calculated from the flow conditions and the initial and final coal temperature, of the order of up to 10^6 K/sec have been reported.

Rapid heating of coal particles has been studied in shock tubes [24, 25] where particle temperature is calculated from the gas temperature rise across the shock. Temperature rise of around 10^5 K/sec have been reported.

A less conventional technique, namely laser irradiation of coal particles, is becoming very popular among researchers in the field of coal pyrolysis. In most cases a pulsed laser, although occasionally a cw laser [26], is used to heat a stationary sample. The volatile matter is then analyzed using a gas chromatograph [27], mass spectrometer [28], or a "time of flight" mass spectrometer [29, 30]. Laser irradiation of a falling coal particle with a pyrometric measurement of the particle temperature were reported as well [31].

Of the various techniques, the use of cw laser irradiation is perhaps the most versatile. Combined with an optical temperature measurement, the laser irradiation technique allows for the direct measurement of the particle heating rate under various levels of energy flux. In principle, the final temperature of the particle and the heating rate can be separately controlled. In practice there are two limitations, however, and these will be discussed in more detail in succeeding sections. One of these is the laser power and the intensity profile of the beam. The other is the latent heat of volatilization, an unknown which affects the temperature rise in the particle. Among the other advantages of the laser pyrolysis technique is the precise control of energy flux, the duration of exposure to the energy flux, the possible control of the atmosphere and the pressure and temperature of the surrounding medium.

For these reasons and because of the availability of high power laser systems for the present investigation and the vast experience in operation of lasers acquired by the personnel in the performing organization, the laser pyrolysis technique was selected for this study.

3.1.1.1 Heating Rate Considerations

Although a time resolved temperature measurement of coal particles in an actual combustion hardware has not been accomplished heretofore, it is customary in the literature to report heating rates which are calculated values. These heating rates are based on certain heat transfer and coal property assumptions and usually do not include heat consumption due to melting and volatilization. Numerical values range from 10^4 to 10^5 K/sec in pulverized coal furnaces [32] and 10^6 to 10^7 K/sec for flames propagating through coal dust explosion galleries [33].

In the remainder of this section it will be shown that laser beam heating of coal particles can be utilized to simulate other heating mechanisms present in actual combustion hardware, mainly convective and radiative heating.

The heating of a coal particle in a furnace by convection is discussed first. The energy balance for a small particle heated uniformly is

$$Nu \frac{k_g}{d_p} \pi d_p^2 (T_g - T_p) = \rho_p \frac{\pi d_p^3}{6} C_p \left(\frac{dT_p}{dt} \right)_c$$

Where the left hand side of the equation expresses the product of the convective heat transfer coefficient on the surface area of the sphere and temperature difference. The right hand side of the equation is the temporal heat content. Using the following relationship

$$Nu = 2 + 0.37 Re^{0.6} Pr^{0.33},$$

the convective heat transfer coefficient can be calculated. Unless strong recirculation current or swirling flow conditions prevail, the Reynolds number based on the relative (slip) velocity between the particle and the gas, is typically $Re \approx 1-2$, which may be categorized as Stoke's flow regime. For the present analysis the assumption of $Nu = 2$ will not introduce an error larger than a few percent. The heating rate due to convection is, therefore

$$\left(\frac{dT_p}{dt} \right)_c = \frac{6 Nu K_g (T_g - T_p)}{\rho_p C_p d_p^2}$$

For radiation, the heat balance is given by

$$\sigma \pi d_p^2 \epsilon_p (T_g^4 - T_p^4) = \rho_p \frac{\pi d_p^3}{6} C_p \left(\frac{dT_p}{dt} \right) r,$$

when the radiation comes from the surrounding gas. This is a simplified approach, which assumes that the gas is optically thick, which yields an upper limit to the heating by radiation. The heating rate due to radiation is therefore

$$\left(\frac{dT}{dt} \right) r = \frac{6\sigma \epsilon_p (T_g - T_p)}{\rho_p d_p C_p}$$

Figure 3-1 shows the effect of particle diameter on the heating rate for two gas temperatures, 1000 K and 2000 K, due to convection alone, radiation alone and the combined effect. The values were calculated for some average assumed properties

$$k_p = 3 \times 10^{-3} \text{ cal/sec-cm-K}$$

$$k_g = 1.6 \times 10^{-4} \text{ cal/sec-cm-K @ } T_g = 1000 \text{ K}$$

$$k_g = 2.8 \times 10^{-4} \text{ cal/sec-cm-K @ } T_g = 2000 \text{ K}$$

$$\rho_p = 1.25 \text{ g/cm}^3$$

$$C_p = 0.25 \text{ cal/gm-K}$$

$$\epsilon_p = 0.9$$

$$\text{and } \sigma = 1.36 \times 10^{-12} \text{ cal/sec-cm}^2\text{-K}^4$$

As far as the assumption of uniform heating of the particle, it can be shown that the temperature difference between the outer surface of the sphere and its center is small for the case of large Biot modulus, k_p/hr_0 .

$$\text{Using } Nu = \frac{hd}{k_g}, \text{ we get } \frac{k_p}{hr_0} = \frac{2k_p}{Nu k_g} = \frac{k_p}{k_g}$$

(for $Nu \approx 2$ in convective heating only). The assumption of convective

heating only is justified here in light of Figure 3-1 in which radiation is shown to be less important than convection heat transfer, at least at the initial time period. Figure 3-2 (reproduced from Reference 34) may be used now to determine the temperature distribution within a particle.

The largest time constant, $a\theta/r_0^2$, in the figure is 1.5. The thermal diffusivity is

$$a = \frac{k_p}{\rho_p C_p} = \frac{3 \times 10^{-3}}{1.25 \times 0.25} \quad 10^{-2} \frac{\text{cm}^2}{\text{sec}}.$$

Thus a time constant of 1.5 corresponds to 3.75 msec for a 100 μm particle, or to 0.0375 msec for a 10 μm particle, or to 0.375 μsec for a 1 μm particle.

The nondimensional number expressing the temperature rise may be expressed as

$$\frac{T_{r/r_0} - T_{\theta=0}}{T_{\infty} - T_{\theta=0}},$$

where $T_{\infty} - T_{\theta=0}$ is the initial temperature difference between the gas and the particle, and $T_{r/r_0} - T_{\theta=0}$ is the temperature difference between any point within the particle and the initial particle temperature (assumed to be uniform). It should be noted that the nondimensional temperature as defined above is complementary to the temperature in Figure 3-2.

The figure shows that the temperature rise at the center of the particle ($r/r_0=0$) and at the surface ($r/r_0=1$), for the time constant 1.5, is 0.32 and 0.38 respectively. In other words only a small temperature gradient exists inside the particle.

It would be noteworthy to compare the time constant for convective heating of the particle with the relaxation time (the time it takes the particle to accommodate to the gas velocity) $\rho_p d_p^2/18\mu$. The relaxation time is 39.0 msec for a 100 μm particle, 0.39 msec for a 10 μm particle, and 3.9 μsec for a 1 μm particle. Thus heating takes place on a time scale shorter than that of the particle accommodation to the gas stream.

Figure 3-1. ESTIMATED HEATING RATES AS A FUNCTION OF PARTICLE DIAMETER

CONDUCTION OF HEAT IN THE UNSTEADY STATE

Figure 3-2. DIMENSIONLESS TEMPERATURE DISTRIBUTION IN A SPHERE SUBJECTED TO SUDDEN CHANGE IN ENVIRONMENT TEMPERATURE.

3.1.1.2 Laser Heating

Heating of a particle with laser beam radiation is considered next. The heat transfer to a surface irradiated by a beam of power density I is

$$q_{in} = \alpha A I = \alpha \frac{\pi d_p^2}{4} I$$

where α is the surface absorptivity at the given radiation wavelength and at the given surface temperature.

Heat loss by convection is

$$q_{out} = \frac{Nu k_g}{d_p} \pi d_p^2 (T_p - T_g).$$

The energy balance becomes

$$\rho_p \frac{\pi d_p^3}{6} C_p \frac{dT_p}{dt} = \alpha \frac{\pi}{4} d_p^2 I - \frac{Nu k_g}{d_p} \pi d_p^2 (T_p - T_g).$$

After rearrangement:

$$\rho_p d_p^2 C_p \frac{dT_p}{dt} = \frac{3}{2} \alpha d_p I - 12 k_g (T_p - T_g),$$

where $Nu = 2$ was assumed.

For steady radiation intensity and constant gas temperature the solution is

$$T_p(t) - T_p(0) = \left[\frac{\alpha d_p I}{8 k_g} + (T_g - T_p(0)) \right] \left[1 - \exp\left(-\frac{12 k_g t}{\rho_p C_p d_p^2}\right) \right].$$

If, however, the laser radiation intensity changes along the particle path according to

$$I = I_0 \exp\left[-\frac{t_f - t}{\tau_1}\right],$$

the energy balance equation becomes:

$$\frac{\rho_p C_p d_p^2}{12 k_g} \frac{dT_p}{dt} + (T_p - T_g) = \frac{1}{8} \frac{\alpha d_p}{k_g} I_0 e^{-(t_f - t)/\tau_1}$$

Or

$$\tau \frac{d\theta}{dt} + \theta = \beta I_0 e^{-(t_f - t)/\tau_1}.$$

Here

$$\tau = \rho_p C_p d_p^2 / 12 k_g,$$

$$\theta = T_p - T_g,$$

and

$$\beta = \alpha d_p / 8 k_g.$$

The particle exposure duration to the laser beam, t_f , is related to the particle velocity v_p and beam width s , by $t_f = s/v_p$.

The boundary condition is $\theta(0) = 0$, and the solution to the equation is

$$\theta(t) = \frac{\beta I_0 e^{-t/\tau_1}}{1 + \tau/\tau_1} [e^{t/\tau_1} - e^{-t/\tau}],$$

Final temperature of the particle as it emerges out of the beam at time $t = t_f$ is

$$\theta_f = \frac{\beta I_0 e^{-t_f/\tau_1}}{1 + \tau/\tau_1} [e^{t_f/\tau_1} - e^{-t_f/\tau}].$$

Therefore:

$$\theta(t) = \theta_f \frac{e^{t/\tau_1} - e^{-t/\tau}}{e^{t_f/\tau_1} - e^{-t_f/\tau}}.$$

The heating rate is given by

$$\frac{d\theta}{dt} = \frac{\theta_f}{e^{t_f/\tau_1} - e^{-t_f/\tau}} \left[\frac{1}{\tau_1} e^{t/\tau_1} + \frac{1}{\tau} e^{-t/\tau} \right].$$

Two cases may be investigated. They are the uniform beam profile or fast particle heating case, and the variable beam profile or slow particle heating case.

I. For the case of a uniform beam, i.e., $1/\tau_1 = 0$:

$$\theta(t) = \theta_f \frac{1 - e^{-t/\tau}}{1 - e^{-t_f/\tau}}, \quad \text{and} \quad \frac{d\theta}{dt} = \frac{\theta_f e^{-t/\tau}}{\tau(1 - e^{-t_f/\tau})}.$$

Hence

$$\frac{d\theta}{dt}_{t=0} = \frac{\theta_f}{\tau(1 - e^{-t_{f1}/\tau})} \quad \text{and} \quad \frac{d\theta}{dt}_{t=t_{f1}} = \frac{\theta_f e^{-t_{f1}/\tau}}{\tau(1 - e^{-t_{f1}/\tau})}$$

The heating rate starts at a high value and decreases due to the rise in convection losses as the particle temperature goes up. At $t_{f1}/\tau = 3$ the heating rate is already small and

$$\dot{\theta}_0 = \frac{d\theta}{dt}_{t=0} = \frac{\theta_f}{\tau(1 - e^{-3})}, \quad \dot{\theta}_{f1} = \frac{d\theta}{dt}_{t=t_{f1}} = \frac{\theta_f e^{-3}}{(1 - e^{-3})}$$

Hence:

$$\dot{\theta}_0 / \dot{\theta}_{f1} = \frac{1}{e^{-3}} = 20.1.$$

II. For the case of a non-uniform beam the initial and final heating rates are

$$\frac{d\theta}{dt}_{t=0} = \frac{\theta_f e^{-t_{f2}/\tau_1}}{1 - \exp[-t_{f2}/\tau - t_{f2}/\tau_1]} \left[\frac{1}{\tau_1} + \frac{1}{\tau} \right]$$

and

$$\frac{d\theta}{dt}_{t=t_{f2}} = \frac{\theta_f e^{-t_{f2}/\tau_1}}{1 - \exp[-t_{f2}/\tau - t_{f2}/\tau_1]} \left[\frac{e^{t_{f2}/\tau_1}}{\tau_1} + \frac{e^{-t_{f2}/\tau}}{\tau} \right]$$

Again, for $t_{f2}/\tau_1 = 3$, and taking $\tau_1 = 20\tau$, which implies that $t_{f2}/\tau = 60$,

$$\dot{\theta}_0 = \frac{d\theta}{dt}_{t=0} = \frac{(21/20) \theta_f e^{-3}}{\tau(1 - e^{-63})}, \quad \dot{\theta}_f = \frac{d\theta}{dt}_{t=t_{f2}} = \frac{\theta_f e^{-3}}{\tau(1 - e^{-63})} \left[\frac{e^3}{20} + e^{-60} \right].$$

Therefore,

$$\frac{\dot{\theta}_0}{\dot{\theta}_f} = \frac{21}{[e^3 + 20 e^{-60}]} \frac{21}{e^3} = 1.04$$

The temperature and heating rate histories for the two cases are shown schematically in Figure 3-3. It should be noted, however, that the time scale is different for the two cases, i.e., for the uniform beam the scale is 1/20 of that of the exponential beam. Assuming that in both cases the beam width is the same, the particle velocity in the former case is 20 times as large as in the latter case. In other words, if a particle is introduced into the nonuniform beam at the free fall (terminal) velocity, it would have to be carried at 20 times that velocity through the uniform beam in order to reach the same final temperature.

The final temperature for both cases is:

$$\theta_f \approx \beta I_0 = \frac{\alpha d_p}{8 k_g} I_0$$

The effect of particle size is shown in table 3-1, where the final temperature for all particles is set to about 2000 K, when the ambient atmosphere is N₂.

TABLE 3.1. EFFECT OF PARTICLE SIZE
ON THE FREE-FLIGHT PYROLYSIS EXPERIMENTAL REQUIREMENTS

Particle Diameter	d_p [μm]	25	50	100
Beam Intensity	I_0 [KW/cm^2]	6.85	3.42	1.71
Characteristic Time for Heating*	τ [m/sec]	2.5	10.2	40.7
Characteristic Settling Time	τ_v [m/sec]	2.44	9.75	39.0
Terminal Velocity	V_T [cm/sec]	2.13	8.51	34.0
Particle Velocity in Nonuniform Beam	V_{p2} [cm/sec]	34	8.51	2.13
Particle Velocity in Uniform Beam	V_{p1} [cm/sec]	680	170	42.50

* Based on $k_g = 0.639 \times 10^{-4}$ cal/sec-cm-k @ 300 K.

Figure 3-3. TEMPERATURE AND HEATING RATE HISTORY OF A PARTICLE HEATED BY A LASER BEAM OF POWER DENSITY I .

The beam width, based on the requirements set by the 50 μ particle is equal to $S = V_{p1} \times 3\tau = V_{p2} \times 3\tau_1 = 60V_{p1} \tau \approx 5.2$ cm.

A beam width of 5.2 cm may be inconvenient for the particular case. Thus, the width may be changed provided that the particle velocity is changed such that the proper exposure time (3τ) is maintained. In the above table, the case of 100 μ m particle is not practical since V_{p2} is smaller than the terminal velocity which can not be easily achieved under normal circumstances.

At this point it is again emphasized that the calculations neglect heat of vaporization considerations. However, in [35] there is an analysis of a carbon particle in a laser radiation field in air. That model takes into account the diffusion of carbon and carbon monoxide from the surface, and of oxygen to the surface. The model also accounts for combustion, latent heat of vaporization and thermal reradiation as well as convection losses. The main conclusions from the model are that the particle heats up uniformly, and that the dominating processes are combustion* and heat loss by convection, all other mechanisms being minor.

Finally, in order to demonstrate the marked effect of heating rate on devolatilization it will be shown that a final particle temperature in the vicinity of 2000 K is required. To prove this, experimental data reported in [6] is used to derive a mathematical correlation between the rate of devolatilization and the temperature. The correlation may be expressed as:

$$\frac{dm'_y}{dt} = k(T) [g(T)m_D - m'_V],$$

where

$$g(T) = \frac{0.3 + 65 e^{-\frac{7552}{T}}}{1 + 65 e^{-\frac{7552}{T}}}$$

$$\text{and } k(T) = 2 \times 10^5 [\exp(-\frac{12588}{T})] \times [1 - 65 \exp(-\frac{7552}{T})].$$

*For our pyrolysis experiment, combustion effects are minimal.

By the time all the volatiles are out, $dm'_v/dt = 0$, and therefore

$$\frac{m'_v}{m_D} = g(T_f)$$

where T_f is the final particle temperature. In order to have a volatile fraction of about 70% this final temperature should be 1943 K.

In order to estimate the time required for volatilization at that temperature, the rate equation is solved assuming a constant temperature. The solution is

$$\frac{m_v}{m_D} = (1 - e^{-k(T) t}) g(T).$$

From this equation, the characteristic time is

$$\tau_c = \frac{3}{k(T)} = 4.2 \times 10^{-3} \text{ sec @ } T = 2000 \text{ K.}$$

The above calculations indicate that at particle temperature of about 2000 K the mass of devolatilized matter should be significantly higher than the conventional ASTM analysis indicates. Of course these numbers do not take into account variations from one coal to another, and other unknown properties. The figures serve only as a guideline for setting the experimental requirements and expectations.

To summarize, in the foregoing analysis it has been shown that an experiment can be designed such that under a controlled level of laser irradiation, and coal particle size and velocity, various levels of particle heating rate can be achieved. Further, the particles can be analyzed before and after exposure to the radiation to yield data in regards to the degree of volatilization. Particle final temperature and heating rate are the independent variables and the degree of devolatilization is the dependent parameter.

To the best of our knowledge, an experimental approach such as the one described here has not been reported in the literature. The technique, therefore, is still in a stage where further development is needed. The

next section describes the development and the consideration leading to the present experimental apparatus.

3.1.2 Experimental Setup and Procedures

The conceptual design of the experiment provides for a controlled flow rate of pulverized coal particles in a selected atmosphere of an inert carrier gas through a feed nozzle. The coal flows through an open test cell in which it is subjected to the laser radiation, and eventually is collected into a suction tube. The gas and coal are separated in a cyclone separator and the gas is further filtered before entering the vacuum pumping system. A schematic of the test setup is shown in Figure 3-4. The various components in the system, design considerations and experimental procedures are discussed next.

The Coal Feed System. The coal feeder, a TRW-modified early model of the "Sylco Fine Powder Feeding Apparatus" by Sylvester and Company Engineering, Cleveland, Ohio is shown schematically in Figure 3-5. Basically it consists of a sealed powder container and a variable speed screw assembly which are mounted on a special electromagnetic vibrator. The screw enters the sealed powder container through a special packing gland and emerges on the other side where it terminates in a carburetor where the powder is mixed with the carrying gas stream. A constant speed motor and a variable speed mechanism are utilized to drive the screw and provide a controlled rate of powder feed. The variable speed unit can be adjusted by means of a hand wheel, and the setting of the mechanism may be used as an indicator of the feed rate once a calibration is performed for a given coal.

To ensure a constant feed and to prevent aggregation of the powder particles, the vibrating unit causes the powder to constantly turn over and mix in the sealed container. A potentiometer is used to govern the amplitude of vibrations for various types or densities of materials. The feed mechanism may handle powders in the range from 60 mesh down to 1 or 2 microns. Feed screws of different pitch may be used to change the range of feed rate. The calibration curve for the feeder is shown in Figure 3-6.

Figure 3-4. EXPERIMENTAL SETUP SIDE VIEW

PARTICLE FEEDER

Figure 3-5. SCHEMATIC OF THE COAL FEEDER

Figure 3-6. COAL FEED RATE CALIBRATION CURVE

Coal Nozzle and Collection System. The coal supply nozzle consists of three concentric tubes. The coal particles and the carrier gas are introduced through the inner tube, and the stream of gas and coal is further diluted in the middle tube. The diluted stream of coal/carrier gas flows through an open test cell and is collected into two concentric suction tubes. In order to keep the coal stream and the ambient atmosphere around the open test cell separated, a "curtain" gas is introduced through the outer nozzle tube as shown schematically in Figures 3-4 and 3-7. The particles are quenched by the low temperature (ambient) gas as they enter the collection tubes, in which swirl inducers help to separate the gas and particles. The nozzle and the suction tubes can also be seen in Figure 3-8 in which a hot wire anemometer probe is positioned for flow field characterization.

Flow Field and Particle Velocity Measurement. In order to ensure a proper flow field in the open test cell, i.e., a flow field in which the velocities are uniform and predictable, the suction and the feed flow rates have to be matched. This is easily done by properly metering the flows; the verification, however, is more complex. Two approaches were taken for the study of the flow field in the open test cell. First a hot wire anemometer was used to map the gas flow field. Results are reproduced schematically in Figure 3-9. Only half the flow field, between radial position $r/R=0$ and $r/R=1$ (where R is the outer radius of the supply tube), is shown since the insertion of the body of the probe beyond that point introduced too much disturbance in the flow. Hence, the other half of the flow field had to be measured from the opposite direction; as it turned out, the flow field was symmetric when measured this way.

Next, the coal particle velocities were measured utilizing a home made LDV system. The optical layout is shown in Figure 3-10 and a schematic of the instrumentation in Figure 3-11. A brief description of the instrumentation follows.

The detector in this LDV system is a photo diode model HP4220 pin diode which is reverse biased through a $10K\Omega$ resistor at -22 volts. The signal is outcoupled through a $0.47 \mu\text{fd}$. capacitor to a video amplifier.

Figure 3-7. DESIGN OF THE COAL NOZZLE AND COLLECTOR

Figure 3-8. A PHOTOGRAPH OF THE COAL SUPPLY NOZZLE AND THE COLLECTION PROBE (158318-79-15)

Figure 3-9. HOT WIRE MEASUREMENT OF THE FLOW FIELD AT MID DISTANCE BETWEEN NOZZLE AND COLLECTOR FOR HALF THE FLOW FIELD. ALSO SHOWN RELATIVE SIZE OF NOZZLE AND COLLECTION PROBES AND THAT OF THE HOT WIRE PROBE

Figure 3-10. OPTICAL LAYOUT OF THE LDV SYSTEM FOR MEASURING COAL PARTICLE VELOCITIES IN THE NEAR FORWARD LIGHT SCATTERING MODE

Figure 3-11. BLOCK DIAGRAM OF VELOCIMETER ELECTRONICS

The low noise, high gain (1-100K) amplifier, PAR model 225, is used to process the input signal from the photo diode. The low frequency components are filtered such that the 6 db rolloff is at 300 Hz. and the high end is at 100 KHz. Gain is typically set at 20K.

The heart of the system is a spectrum analyzer (HP 141T with HP8556A Low Frequency section and 8552B I.F. section) which scans the input signal through a narrow range frequency window. Hence, the frequency domain is obtained by the "sweep filter" technique.

The additional equipment in use is for calibration and data recording. This includes a 3K Precision Manufacturing signal generator Model E310B, which is used to provide a reference signal to the spectrum analyzer. The signal serves as a constant marker for orientation as well as calibration. By changing the input frequency the linearity of the plotter can be checked. The frequency of the signal generator is also checked against a cycle/time count on a Tektronix 556 oscilloscope.

A Sawtooth Buffer Amplifier (HP 467A) is used to clamp the sawtooth to zero at the beginning of the sweep by the spectrum analyzer. The input of the buffer accepts a voltage divided signal from the 300 volts output waveform of the scope.

A D.C. Power supply (model HP6248A) provides the constant voltage drive to the spectrum analyzer. The dc level also displaces the frequency as a function of the x position on both the x-y plotter and the CRT display in the spectrum analyzer. In this fashion the analyzer and the plotter can be made to agree in the scan width (the x dimension).

A Tektronix 556 dual channel oscilloscope monitors the signal from the pin diode via an amplifier stage and further provides the external sawtooth voltage to drive the spectrum analyzer and the x-y plotter.

Finally, the frequency domain signal is recorded on an x-y plotter (HP 7044A) through a dampening rc filter "L" section.

The data analysis follows the conventional fringe model (e.g., see [36]) which is shown in Figure 3-12.

Figure 3-12. ENLARGED CROSS-SECTIONAL VIEWS OF THE BEAM CROSSOVER REGION

The fringe spacing is

$$D_f = \frac{\lambda}{2 \sin \frac{\theta}{2}}$$

where λ is the laser beam wavelength (0.6328 μ for the present He-Ne laser), and half the angle between the beams is $\frac{\theta}{2} = \tan^{-1} \left(\frac{\text{half beam spacing}}{\text{distance to beams crossover}} \right)$.

The scattered light intensity is modulated at a frequency f_D which is related to the particle velocity by the relationship

$$f_D = \frac{v}{D_f} = \frac{2v}{\lambda} \sin \frac{\theta}{2}.$$

As an example, for beam spacing of 1 cm, and 249 cm distance to beam crossing, the half angle is

$$\frac{\theta}{2} = \arctan \frac{0.5}{249} = 0.115^\circ,$$

and the fringe spacing is

$$D_f = 157.6 \mu\text{m}.$$

For particle velocity of 3 meters/sec the Doppler frequency is

$$f_D = 19.04 \text{ kHz}.$$

The coal particles used for this study were in the size range of 40-50 μm which is much smaller than the fringe spacing.

The results of this study indicated that the particles were moving at a velocity higher than that of the gas. This happened since the particles were introduced through the inner tube (see Figure 3-7) at a high muzzle velocity and their time of flight was shorter than the relaxation time (see Page 3-5) required for accommodation to the gas velocity. This result is important for the analysis of the results of the hot tests.

The Laser Facility. The chemical Hydrogen Fluorine (HF) laser facility uses an electrical arc to heat He and to partially dissociate SF_6 gas to provide atomic fluorine. The hot gas mixture is accelerated through a supersonic nozzle array. This nozzle array consists of 36 two-dimensional supersonic nozzles of area ratio 15.5 through which the atomic fluorine and helium diluent flow. Separating each of the nozzles is a sonic fuel injection slit. The fluorine-helium nozzles and fuel injection slits have typical exit width of 3.7 and 0.05 mm (or 0.15 mm), respectively. The nozzle bank is 17.8 cm long and 2.5 cm high.

The jets exhaust into a rectangular cavity and the lasing axis is transverse to the flow direction. Two gold coated mirrors (98% reflectivity) one flat and one concave (3.7 m radius of curvature), are located in recessed enclosures which are purged with helium. Both mirrors are 10 cm high and 10 cm wide. The mirrors are water cooled and the temperature rise of the cooling water is used to determine closed-cavity power when lasing. A general view of the laser cavity with its top removed, the arc, and the nozzles is shown in Figure 3-13.

The power output of the laser is about 700 watts for more than 10 min operation with possible shorter runs with power output of 1000-1300 watts. The raw beam shape is a square about 2 cm x 2 cm. The beam is usually reshaped and focused to meet the requirements as described below.

Optical Train and Beam Shape. In order to meet the test requirements shown in Section 3.1.1, and to provide isotropic heating of the coal particles (i.e., simultaneous irradiation from several directions) a multiple pass beam is required.

As shown below, the temperature measurements require particle density of approximately $2.5 \times 10^3 \text{ cm}^{-3}$, a condition under which 90% of the beam penetrates through the stream of coal particles. Rather than dump the passing beam, it can be turned around and sent through the test cell, again 10% of the beam is absorbed. Theoretically this process can be repeated as many times as justified by the power available, as shown in Figure 3-14. Thus, if the power in the original beam is $P_0 = AI_0$, the power intercepted by the particles is $P_0(1 - e^{-\beta})$ and the remaining beam, of power $P_0 e^{-\beta}$,

Figure 3-13. THE HF CHEMICAL LASER CAVITY

Figure 3-14. TOP VIEW OF BEAM PATH

goes through the volume. Here

I_0 is the original beam intensity in units of power per area

A is the beam cross section area

and, $\beta = SNL$

where, S is the effective cross section of a particle, approximately equal to the projected area of an equivalent sphere. This assumption is close enough for particles with diameter much larger than the wave length N is the number density of particles in the volume, and L is the beam path length.

For small values of β the attenuation can be approximated by a series expansion as follows

$$e^{-\beta} \approx 1 - \beta,$$

The power losses on the turning mirrors are of the same order as in the coal stream. Thus the power of the beam approaching the second pass is $P_0 e^{-2\beta}$. The power intercepted is, as before, $P_0 e^{-2\beta}(1 - e^{-\beta})$ while the power emerging is $P_0 e^{-2\beta}(e^{-\beta})$ or $P_0 e^{-3\beta}$. Following the same logic, it can be shown that the total power intercepted during n passes of the beam is

$$P_{\text{tot}} = P_0(1 - e^{-\beta}) + P_0 e^{-2\beta}(1 - e^{-\beta}) + P_0 e^{-4\beta}(1 - e^{-\beta}) + \dots$$

$$+ P_0 e^{-2(n-1)\beta}(1 - e^{-\beta}) = P_0 \frac{1 - (e^{-2\beta})^n}{1 + e^{-\beta}}.$$

Further, using the series expansion for small β , in the limit of a large number of passes, the intercepted power is

$$P_{\text{tot}} = \frac{P_0}{2}$$

$\lim_{n \rightarrow \infty}$

This result is expected since in each pass half the energy removed from the beam is absorbed in the particle stream and half in the optical system.

In the present experiment the beam passed through the test cell six times. Thus, the total power absorbed by the stream of coal particles is

$$P_{\text{total}} = 0.367 P_0.$$

Only 36.7% of the available power is intercepted by the particles.

From a different point of view, this arrangement would correspond to irradiation of the coal stream by six beams of power P_0 , $P_0 e^{-2\beta}$, $P_0 e^{-4\beta}$, ... etc. The total incident power for $\beta = .1$ and $n = 6$ is

$$P_{\text{tot},i} = P_0 \frac{1 - e^{-2n\beta}}{1 - e^{-2\beta}} = 3.855 P_0.$$

and the absorbed power is

$$P_{\text{tot}} = P_{\text{tot},i} (1 - e^{-\beta}) = 0.367 P_0.$$

In terms of radiative intensity incident upon the coal particles

$$I_{\text{total}} = P_{\text{tot},i}/A = 3.855 I_0.$$

This result can also be obtained from the absorbed power by dividing P_{tot} by the number of particles and the cross section of a particle i.e.,

$$I_{\text{tot}} = P_{\text{tot}}/nS.$$

Using $n = NAL$,

$$I_{\text{tot}} = P_{\text{tot}}/NLSA = P_{\text{tot}}/A\beta$$

Actually, $\beta = 1 - e^{-\beta}$, and therefore, as before

$$I_{\text{tot}} = \frac{0.367 P_0}{(1 - e^{-\beta})A} = 3.855 I_0.$$

In order to meet the requirements of the variable intensity (exponential) beam as discussed in Section 3.1.1, an approach similar to the one discussed above can be taken. The beam can be "folded" and sent back and forth across the test section. The only difference is that for the present case the beam is focused in one plane so that its cross section area decreases from one pass to the next. If all these beams are aligned so that their bottom edges coincide, a step type intensity increase is obtained along the coal particle path. The original beam of power P_0 and area $A_0 = 1 \text{ cm} \times 1 \text{ cm}$, for instance, is focused so that in the second pass the cross section is only $A_1 = 1 \text{ cm} \times \alpha \text{ cm}$ where $0 < \alpha < 1$. The power of the second beam is $P_1 = P_0 e^{-2\beta}$ so that the intensity is $I_1 = P_1/A_1 = I_0 (e^{-2\beta}/\alpha)$. Thus, a particle moving through the test cell enters first a field of intensity I_0 and after moving a distance of $(1 - \alpha)$ it enters a field of intensity $I_0 + i_1$. The third fold of the beam is only $1 \text{ cm} \times \alpha^2 \text{ cm}$ in cross section and it contributes additional intensity of $I_2 = I_0 (e^{-2\beta}/\alpha)^2$ and so forth. If α is selected such that $\alpha = e^{-2\beta}$, the radiation field grows in increments of I_0 since $I_1 = I_2 = I_3 = \dots = I_0$. For $\beta = 0.1$ this requires $\alpha = 0.8$ or a 20% reduction in the beam cross section is required between the passes.

It should be noted that the total power absorbed in that case is the same as in the case of a uniform intensity field, i.e., 36.7% of the available power if six passes are selected. The difference is in the distribution of power; more of it is absorbed toward the lower section of the test cell as described schematically in Figure 3-15.

Beam shaping requirements are the following:

- 1) A square cross section beam of an initial dimension about $1 \text{ cm} \times 1 \text{ cm}$ with a uniform intensity distribution
- 2) Coherence length of the order required for six passes (due to the size of the optical elements, the beam is folded in approximately 20 cm sections at a time, i.e., a coherent length of more than 120 cm is required).

Figure 3-15. CUMULATIVE POWER DENSITY FOR SIX PASSES OF A BEAM FOCUSED IN THE y DIRECTION.

The practical problem in shaping the HF laser beam arises from the nonuniformity of the laser which operates at several modes. Thus focusing of the beam for one mode does not necessarily provide a focused beam in the other modes. Further, it turns out that the beam as it comes out of the laser cavity does not have a uniform intensity distribution but may have one or more "hot" spots.

Laborious attempts to implement the multiple pass technique has proven only partly successful. Due to time constraints the technique was abandoned in favor of a single pass beam. Although test results reported in succeeding sections indicate that a single beam may do the job. It is felt that from the standpoint of energy utilization and experimental perfection the former technique is preferred. That is true provided that the extra difficulties, in terms of alignment of the optical train, and beam shaping can be overcome.

Particle Temperature Measurement Using Three Color Pyrometer. The temperature of the particles in the beam is determined by using an optical pyrometer to measure thermal emission at three different wavelengths. For coal particles the emissivity should be nearly unity at wavelengths between 0.6 and 2.0 μm , which is the range most suitable for optical pyrometry in the 800-2500 K range. The ratio of emission at two different wavelengths in the 0.6-2.0 μm interval is a strong function of temperature, and is also proportional to the spectral emissivity ratio, which will be nearly unity. Thus the ratio of emission in two spectral pass bands can be used to determine the temperature. A third radiometric channel is desirable as a check on the accuracy of the technique.

An optical diagram of the three-color pyrometer is shown in Figure 3-16 and the pyrometer is shown in Figure 3-17. The data reduction and a quantitative analysis of the temperature measuring technique is given below.

To determine minimum particle temperatures measurable by this technique assume we use an optical system which collects radiation from a rectangular column 5 mm high (the laser beam diameter) and $x = 0.5$ mm wide in the flow (x) direction. The narrower width in the flow direction will provide spatial resolution. The collected solid angle of radiation will be assumed to be

1. Field lens (150 mm f.l.)
2. Aperture
3. Chopper
4. Lens (44 mm f.l.)
5. 8. & 12. Lenses
6. 9. & 13. Detectors
7. 10. & 11. Color filters
14. Beam splitter

Figure 3-16. THREE-COLOR PYROMETER; OPTICAL DIAGRAM.

Figure 3-17. THREE COLOR OPTICAL PYROMETER
(165363-80-24 A)

$$\Omega_{\text{coll}} = \frac{1}{2} \left(\frac{2\Delta x}{d_{\text{beam}}} \right) = 0.1 \text{ steradian}$$

where the $1/2$ assumes an $f/2$ collector lens aperture and the $2\Delta x/d_{\text{beam}}$ limitation keeps the x dimension of the collected ray bundle comparable to the desired spatial resolution Δx .

We further assume that each radiometric channel has a bandwidth $\Delta\lambda_i$ equal to 10% of the center wavelength $\bar{\lambda}$. The collected power is then

$$P_{\lambda} = c_{\lambda} \frac{\pi^2}{4} d_p^2 n_p \cdot d_{\text{beam}} \cdot \frac{2hc^2 \cdot \Delta\lambda \cdot \eta_{\text{opt}} \cdot \Omega_{\text{coll}} \cdot 0.1 d_{\text{beam}}^2}{\lambda^5 [\exp(\frac{hc}{\lambda kT}) - 1]}$$

where ϵ_{λ} is the spectral emissivity, n_p is the particle number density, η_{opt} is the collection efficiency of the optical system, d_{beam} is the laser beam diameter and d_p is the particle diameter. The largest value of n_p that will be selected is that for which

$$\frac{\pi}{4} (n_p)_{\text{max}} d_p^2 d_{\text{beam}} \approx 0.1,$$

since this will still permit 90% of the laser light to penetrate the stream of coal particles, and will allow 90% of the emitted radiation to pass out of the stream. Assuming $d_p = 100 \mu\text{m} = 10^{-2} \text{ cm}$, and $d_{\text{beam}} = 0.5 \text{ cm}$, we obtain

$$(n_p)_{\text{max}} \approx 2.5 \times 10^3 \text{ cm}^{-3}$$

Figure 3-18 shows plots of the collectable power p as a function of λ for various values of the particle temperature, based upon the assumptions that $(\pi/4 \cdot n_p \cdot d_p^2 \cdot d_{\text{beam}}) = 0.1$, $\Delta\lambda = 0.1\lambda$, $\eta_{\text{opt}} = 0.1$, $\Omega_{\text{coll}} = 0.1$, and $d_{\text{beam}} = 5 \text{ mm}$.

Figure 3-18. COLLECTED POWER AT DETECTOR (P_{λ}) AND DETECTOR NOISE-EQUIVALENT POWER. N.E.P. VS. RADIOMETER WAVELENGTH, FOR THE INSTRUMENT VIEWING COAL PARTICLE EMISSION.

P_{λ} CURVES ARE SHOWN FOR PARTICLE TEMPERATURES OF 600, 800, 1000, AND 1300 K. MEASUREMENTS ARE FEASIBLE WHERE P_{λ} EXCEEDS N.E.P. BY $\sim 10\times$ OR MORE. AN ELECTRONIC BANDPASS OF 10 HZ IS ASSUMED FOR THE N.E.P. ESTIMATES.

Also shown in Figure 3-18 are calculated values of the noise-equivalent power (N.E.P.) which is the radiant power at the detector required to provide a signal-to-noise ratio of unity. Curves are shown for an uncooled Si photodiode and a photoconductive PbS detector operated at 193K. A detector element size of 3 mm and an electronic measurement bandpass of 10 Hz (sufficient for a 0.1 sec time constant) are assumed in the N.E.P. calculation.

Figure 3-18 illustrates that particle temperature measurements can be made at temperatures above 800 K using radiometer channels appropriately selected wavelength intervals in the 0.6-2.0 μ m interval. Operation at longer wavelengths is undesirable because the measured intensities become relatively insensitive to temperature, thereby increasing errors due to calibration uncertainty and background thermal radiation drift.

Selection of Coal Type. Three coals were originally selected for the experiment. Two coals from the Penn. State University Coal Bank, a high volatile PSOC 358 and a low volatile PSOC 632 both of the Bituminous rank. The third coal was a Montana Rosebud, the same coal used in the 20 MW_T pulverized coal burning experiment described in Section 5 of this report. Properties of these coals are summarized in Table 3-2. The table gives the global composition of the coals, the specific composition of the various size cuts may differ. Other than statistical variations which are manifested in the analyses of the various samples, it is believed that breakup during the pulverization of the coal occurs in a preferential manner such that the composition of the various cuts is not the same as that of the original coal. The composition of the specific samples utilized in each experiments will be reported along with that of the processed coal. The coals were sifted using standard Tyler sieves.

Table 3-2. SUMMARY OF DATA FOR COAL IN THE FREE FLIGHT BURNING TEST.

COAL AND RANK	PSOC-632 LOW VOL. (APPALACHIAN, PENNSYLVANIA)	PSOC-358 HVA (APPALACHIAN, KENTUCKY)	MONTANA ROSEBUD
<u>Proximate Analysis (as rec'd)</u>			
moisture	3.45	1.23	15.87
ash	12.78	5.06	9.48
V.M.	15.78	32.90	33.81
F.C.	67.99	60.81	40.84
<u>Ultimate Analysis (as rec'd)</u> (Excludes Moisture)			
ash	12.78	5.06	9.48
carbon	75.08	81.18	56.30
hydrogen	3.58	5.13	3.87
nitrogen	1.16	1.28	0.70
total sulfur	0.78	0.56	0.74
oxygen (diff.)	3.17	5.56	13.01

Table 3-2. SUMMARY OF DATA FOR COAL IN THE FREE FLIGHT BURNING TEST (Continued).

COAL AND RANK	PSOC-632, LOW VOL. (APPALACHIAN, PENNSYLVANIA)	PSOC-358 HVA (APPALACHIAN, KENTUCKY)	MONTANA ROSEBUD
Atomic Ratio O:C	0.0250	0.0500	0.0211
Atomic Ratio H:C	0.5731	0.7585	0.8240
Calorific Value (as Rec'd)	12797	14475	9556
<u>Major Mineral Analysis</u>			
SiO ₂	47.8	57.5	42.87
Al ₂ O ₃	34.7	28.5	16.17
TiO ₂	2.50	1.92	0.86
Fe ₂ O ₃	13.3	4.58	4.69
MgO	0.23	0.70	4.27
CaO	0.72	1.10	16.02
Na ₂ O	0.17	1.14	0.43
K ₂ O	0.94	2.48	0.42
P ₂ O ₅	0.11	0.10	0.28
SO ₃	0.55	0.80	13.29
Ash Fusion Temp. (°F)-Liquid	2700	2700	T ₂₅₀ =2370°F

3.1.3 Results and Discussion

The notes in this section describe the chronological development of the test technique. Many of the observations contributed to a better understanding of the process of in-flight heating of coal particles by laser radiation as well as of the coal pyrolysis process. Some of the observations were unexpected but in retrospect could be explained in terms of the analyses carried out in preceeding sections and by the application of simple engineering considerations.

The experimental approach undertaken in this program is unique and innovative, and a great portion of the effort went into the initial development and further refinement of the technique. At this time, although the final results are presented, it is clear that further refinement of the technique is required. This subject is discussed in some detail in the recommendations section. From a purist's point of view it may be said, thus, that the work is still incomplete.

3.1.3.1 Some Notes on Observations During the Free Flight Laser Pyrolysis Test

In the first few attempts to pyrolyze the pulverized coal by a laser beam in an N₂ atmosphere, the beam was arranged to make six passes through the test cell and then instead of dumping the beam it was turned back, by another flat mirror, to return through the same path. Thus, the beam traveled twelve times through the test cell. In order to keep the beam collimated, focusing elements were inserted in the path as needed. It should be mentioned that the HF beam is in the IR wavelength and a parallel HeNe beam (visible, red) was utilized for the alignment of the optical train. To check the final alignment with the HF beam, plastic "burn" targets were inserted one at a time at various positions along the beam path and from the burn pattern it was possible to determine whether the beam was properly aligned.

With a total laser power between 400 and 700 watts and coal particle stream of a few grams per minute, nothing could be seen but occasional sparks within the path of the beam but outside the test cell. These sparks could be a result of heat up of particles which were carried away from the main stream and exposed to the laser radiation for a longer period of time.

Although nothing else was observed visually, this does not mean that the particles were not heated up. It is known that in order for the thermal radiation to be in the visible range, the emitting body has to be quite hot and so it is possible that the particle temperature was not high enough. However, the expected particle temperature was high enough that visible radiation was expected so that an explanation was needed.

At this point it was decided to purge the complete test chamber (a box of about 150 cm x 60 cm x 60 cm) with dry N_2 to reduce possible absorption of the HF beam by humidity in the air. Then the beam power was measured before and after passage through the stream of coal particles. In this power test, very little attenuation was observed.

These two phenomena, the low heating of the particles and the small attenuation of the beam, are explained if the particle velocity is much higher than the expected velocity. The following calculation demonstrates this point.

The beam attenuation was measured at two flow rates of coal ($\dot{m}_p$), 0.25 and 6.0 gm/min, particle size (d_p) was about 50 μ , and stream of coal was about 0.5 cm in diameter.

The number density of the particles is

$$N = \frac{\dot{m}_p}{\rho_p \frac{\pi d_p^3}{6} A V_p},$$

where A is the cross section area of the particle stream and V_p is the particle velocity.

If the particles emerge from the inner nozzle tube and do not slow down to the gas velocity then

$$V_p \approx 4.8 \text{ m/sec}.$$

Using the above data the following results can be shown:

at $\dot{m}_p = 0.25 \text{ gm/min}$, $N \approx 5200 \text{ cm}^{-3}$
 and
 at $\dot{m}_p = 6.0 \text{ gm/min}$, $N \approx 1.26 \times 10^4 \text{ cm}^{-3}$.

The beam attenuation in a single pass is

$$\frac{I}{I_0} = e^{-NSL},$$

where S is the effective extinction cross section assumed to be equal to the geometric cross section of the particle. Hence,

$\frac{I}{I_0} = 0.995$ for $\dot{m}_p = 0.25 \text{ gm/min}$,
 and
 $\frac{I}{I_0} = 0.882$ for $\dot{m}_p = 6.0 \text{ gm/min}$.

Considering that the cross section of the beam and that of the stream of particles were in the same range, the edges of the beam are not attenuated by as much as the center of the beam (the optical depth approaches zero close to the edge of the particle stream). Further, if there is some misalignment or if the particle stream is nonstationary, the attenuation is even lower than that calculated above. Thus, the fact that only a little attenuation is observed can be explained.

The equations given in Section 3.1.1 can be used to estimate the particle temperature as follows.

$$\Delta T_p = \frac{\alpha d_p I}{8 k_g} (1 - e^{-t/\tau})$$

where

$$\tau = \frac{\rho_p c_p d_p^2}{12 k_g},$$

and for N_2 , at 300 K,

$$k_g = 63.9 \times 10^{-6} \frac{\text{cal}}{\text{cm sec K}} .$$

Thus, for

$$I = 500 \text{ watt/cm}^2 ,$$

the following is obtained:

$$\tau = 10.2 \times 10^{-3} \text{ sec}$$

$$t = \frac{L}{v_p} = \frac{1}{480} = 2.08 \times 10^{-3}$$

$$\frac{\alpha d_p I}{8 k_g} = 1052 \text{ K}$$

and

$$\Delta T_p = 195^\circ \text{K} .$$

Hence, particle temperatures of the order of 500 K should be anticipated and thus the thermal radiation is indeed very faint.

From this analysis it is clear that in order to achieve higher particle temperatures there are several possible routes. First, particle velocity should be reduced, which would increase the residence time of the particle in the beam. Second, the thermal conductivity of the gas could be changed by changing the carrier gas; this should have a strong effect on the final temperature as can be seen from the formulae. Third, particle size may be changed. Last, the laser intensity can be changed, although the freedom to increase the intensity is limited by the available power and by the optical system.

The solution to the problem was achieved by a combination of all of the above techniques. Several carrier gases were utilized in consecutive tests; their thermal conductivities are listed in Table 3-3 taken from [37].

Table 3-3. THERMAL CONDUCTIVITY OF SELECTED GASES, CAL/CM SEC K.

TEMPERATURE, K	N ₂	Ar	Ne	SF ₆	Kr	Xe	He
300	63.9×10^{-6}	42.7×10^{-5}	116.2×10^{-6}	33.5×10^{-6}	22.5×10^{-6}	13.1×10^{-6}	363.2×10^{-6}
1000	158.9×10^{-6}	97.9×10^{-6}	254.0×10^{-6}	135.5×10^{-6}	57.0×10^{-6}	35.3×10^{-6}	789.6×10^{-6}
2000	272.6×10^{-6}	153.6×10^{-5}	397.2×10^{-6}	225.9×10^{-6}	90.3×10^{-6}	56.6×10^{-6}	1234.8×10^{-6}
molecular weight	28.0	40.0	20.2	146.1	83.8	131.3	4.0

Pyrolysis in SF₆. The first breakthrough occurred on the first test run using SF₆ as a carrier and a diluent gas. At low temperatures SF₆ is an inert gas with a thermal conductivity about one half that of nitrogen. The problem, though, is that at higher particle temperature the coal may react with the gas.

A calculation, similar to the one performed above for the case of nitrogen as a carrier gas, is performed for the following conditions in SF₆ gas:

$$d_p = 42\mu,$$

$$I = 700 \text{ Watt/cm}^2,$$

$$k_g = 33.5 \times 10^{-6},$$

$$\text{and } V_p \approx 220 \text{ cm/sec.}$$

The results are

$$\tau = 13.7 \times 10^{-3} \text{ sec,}$$

$$t = 4.5 \times 10^{-3} \text{ sec,}$$

$$T_f = 2387 \text{ K,}$$

$$\text{and } \Delta T_p = 668 \text{ K.}$$

Hence, particle temperature of close to 1000 K is expected so that in this case some radiation in the visible range should be observed. The actual observations during one such test are shown schematically in Figure 3-19. Here, a single pass of a focused beam intersects the coal stream in SF₆ environment. The figure shows several distinct regions. (1) is the cold stream of coal particles, (2) is the region in which the coal particles are heated up by the laser radiation; during the experiment this region was glowing very bright in the yellow-white emission. (3) in this region it was possible to observe a stream of glowing, single particles moving down into the collection tubes. Region (4) is a very incandescent zone which actually filled the complete path of the laser beam on both sides of the particle stream. It is thought that this very luminous radiation is a result of emission from low molecular weight hydrocarbon (HC) gases and vaporized tars which evolved from the coal and were irradiated by the

Figure 3-19. LASER PYROLYSIS OF COAL IN SF_6 GAS. (SEE TEXT)

laser beam. Finally, a faint blue glow was observed in region (5) which surrounded the beam path and the coal stream. Since SF_6 is an oxidizer it is believed that the blue emission was a result of the combustion of the HC in this gas.

Another phenomenon which was observed during such runs was that the stream of coal did not flow downwards in the same manner as it had without irradiation. With irradiation the stream was observed to spread out and much of the coal actually missed the suction tubes. In addition, as time elapsed, there was a monotonic drop in the power reaching the meter across the pyrolysis zone.

The above observation is explained as follows. When a portion of the coal volatilizes, a significant increase occurs in the volumetric flow rate through the system due to the extra gaseous HC evolved in the process. For instance, the density ratio between the solid coal and methane at ambient conditions is about 2000. If only 10% of the coal, flowing at 1 gm/min, is converted into methane, the increase in volume is about $(0.1/1.25)2000 = 160$ cc/min, a significant increase in the gaseous flow rate. Now, since the suction tubes flow generally is matched with the delivery flow, the extra gases are not collected, and actually disrupt the smooth flow of the coal and the carrier gas. In addition, these HC gases are not removed rapidly enough from the path of the laser beam resulting in strong absorption of the laser radiation. The absorption increases with time, as the concentration of the HC gases increases as evident by the power meter output. The laser radiation couples with the molecules causing excitation in the vibrational-rotational modes, and the incandescent emission in the path of the beam is believed to be due to the return of the HC molecules to their ground state. It is not clear, however, whether this emission is in a continuum or a discrete spectra. Further, the emission from the HC gas also interferes with the operation of the optical pyrometer which operates in the near IR range.

Table 3-4 summarizes the chemical analyses done on the coal pyrolyzed in SF_6 at a laser radiation power of about 300 Watts.

Table 3-4. CHEMICAL ANALYSIS OF A MONTANA ROSEBUD PULVERIZED COAL, PYROLYZED AT $P_0 = 300$ WATTS, IN SF_6 , % WT.

ELEMENTS*	VIRGIN COAL (Sample 5)	(45-53 μ) PYROLYZED COAL (Sample 3)	(38-45 μ) PYROLYZED COAL (Sample 14)
C	52.72	51.62	51.21
H	4.25	3.88	3.15
N	0.62	0.79	0.85
S	1.47	0.97	1.78
F	0.049	4.36	N/A
atomic ratio H:C	0.9674	0.9020	0.7381
Loss on Ignition %	80.12	83.17	72.77
Si	3.8%	2.80%	3.6%
Fe	2.3	2.20	5.0
Al	1.5	1.20	1.5
Zn	0.24	0.45	0.39
Ca	0.86	0.085	1.2
B	0.013	0.015	0.011
Cu	0.024	0.18	0.013
Mn	0.060	0.067	0.069
Ni	0.0028	0.0035	0.0072
Pb	0.0058	0.029	0.0069
Cr	0.0088	0.0053	0.010
Ti	0.030	0.040	0.069
Mg	0.80	1.20	3.60

*Other trace elements not reported here.

The analysis of the organic elements was done following the ASTM standards (carbon and hydrogen - ASTM D3178, sulfur - D3177, nitrogen - D3179). The loss-on-ignition value indicates the percent of ash left after a complete combustion of a sample in air at about 500°C. A loss on ignition value lower than that of the virgin coal would indicate that during the pyrolysis some of the organic matter (C, H, etc.) was removed from the coal and the ash content is higher. The analysis of the major and the trace elements in the ash was done by a semiquantitative emission spectroscopy technique, and the entries in the table indicate percent in total sample.

Several observations can be made. First, there is a decrease in the atomic ratio H:C in the pyrolyzed coal which indicates that low molecular weight HC gases evolved during the pyrolysis. These gases are usually richer, if not saturated, in hydrogen. Second, as indicated in the table, the loss on ignition in one case is larger and in the other case is lower than that of the virgin coal. This observation gave rise to the hypothesis that during rapid heating and pyrolysis some inorganic matter vaporizes off the coal particles. Another mechanism of inorganic matter loss is by ejection of subparticles by the evolving gases. This amounts to breaking up small chunks of the original particle as in the case of "sparking coal" (a phenomenon which occurs with some coals even at low heating rates, when the volatile gases mechanically carry solid material away from the surface).

The fact that the inorganic material is vaporized was later verified by collecting and analyzing condensed tars and vapors all of which were found to contain ash elements similar to those found in the coal. The technique used to identify the elements in the ash may not be very accurate in an absolute sense, but it is sufficient for comparison between samples. Such a comparison indicates that enrichment in some elements while deficiency in others occur during the pyrolysis process. This may be attributed to a preferential vaporization of some of the elements. The main conclusion from this observation is, however, that an inorganic element (e.g., the trace element) cannot serve in a reliable way as a tracer for the determination of the degree of volatilization.

Finally, a comment is necessary in regards to the carrier gas. Obviously, aside from its low thermal conductivity, SF_6 is not a good choice for this kind of testing since the pyrolysis behavior of the coal could have been affected by the presence of SF_6 in the system. SF_6 was only used to check the effect of thermal conductivity of the carrier gas. That there was some reaction between the volatile matter and the SF_6 was already indicated by the blue flame observed in the experiment. This was further substantiated by the pungent odors attributed either to sulfur or to ozone and by the marked enrichment in fluorine observed in the pyrolyzed coal. The next series of tests were run in Xe atmosphere. Xenon has a thermal conductivity lower than both N_2 or SF_6 , the only problem is associated with its high cost.

Pyrolysis in Xe. For Xe the blue flame, which had been visible in the SF_6 test, disappeared. Also, no odor of sulfur or other chemicals was sensed. Typical pyrolysis results for a PSOC-632 coal in Xe atmosphere are shown in Table 3-5.

One difference between this test and previous ones may be attributed to the type of coal. The PSOC-632 coal is low in volatile matter and the amount of gases evolved was lower than before. Therefore, the luminous zone did not extend far from the particle stream. In later tests, however, at a high laser power density the same coal released as much volatiles as the other coals. Further, in the case of the smaller particles, the table indicates that both the H:C ratio and the loss on ignition number decreased. This result is consistent with the release of low molecular weight HC gases. However, no consistent trend can be seen in the analysis of the elements contained in the ash. Enrichment is observed in the case of Si, Fe and Ti but with a deficiency in Al. As before, enrichment in the elements would indicate a release of organic matter only. However deficiency in some elements indicates that there is a selective vaporization of some of those elements. Since the oxides of the metals have a very high melting point (typical fusion temperature of Al_2O_3 is 2300 K, MgO -3080 K, and SiO_2 2000 K) it is not clear whether a reaction takes place in which the oxides are reduced to the pure elements which then vaporize at a lower temperature.

A further analysis of the case reported in the latter table indicates that the calculated final temperature of the small and the large particles

Table 3-5. CHEMICAL ANALYSIS OF A LOW VOLATILE PSOC-632
PULVERIZED COAL PYROLYZED IN Xe.

PARTICLE SIZE LASER POWER, WATT	38 - 45 μ 300		53 - 63 μ 300	
ELEMENTS*	VIRGIN COAL (Sample 20)	PYROLYZED COAL (Sample 19)	VIRGIN COAL (Sample 25)	PYROLYZED COAL (Sample 24)
C	77.93	75.94	78.05	78.11
H	3.78	3.61	3.78	3.74
N	1.17	1.04	1.12	1.27
S	1.12	1.89	1.37	1.45
atomic ratio H:C	0.5821	0.5705	0.5812	0.5746
Loss on Ignition %	90.15	87.48	90.09	90.22
Si	2.2%	2.9%	2.0%	1.9%
Fe	1.3	2.6	1.5	1.7
Al	1.5	1.1	1.6	1.5
Mg	0.034	0.017	0.019	0.017
Ca	0.058	0.061	0.056	0.067
B	0.00026	0.00070	0.00047	0.00061
Cu	0.0016	0.0060	0.0018	0.0034
Mn	0.0043	0.011	0.010	0.0045
Ni	0.0019	0.0049	0.0013	0.0020
Pb	0.0010	0.0032	0.0031	0.0033
Cr	0.0040	0.0073	0.0029	0.0037
Ti	0.089	0.11	0.16	0.12

*Other trace elements not reported here.

is 1225 K and 1552 K, respectively. The pyrometer readings for the latter case are in the range between 1130 to 1540 K. A part of this pyrometer output in which the three channels have been recorded is reproduced in Figure 3-20. The fluctuations in the signal indicate variations in the number density of the particles and not fluctuations in temperature. This is so since all three channels fluctuate in phase. The number density fluctuations may be attributed to the cyclic feeding of coal by the screw auger in the feeder. Finally, Figure 3-21 shows the luminescence from the pyrolysis zone during a typical test run in Xe atmosphere.

Pyrolysis in Ar. In the next series of tests, Ar replaced the Xe atmosphere. Laser power was about 500 watts and the incandescent zone within the particle stream appeared to be the brightest observed so far. The pyrometer output from a test in Ar with 90 to 106 μm PSOC-632 coal is shown in Figure 3-22. The three channels of the pyrometer are shown as well as a fourth channel monitoring the total remaining power in the laser beam past the pyrolysis zone. The original power of the beam, 500 watt, was kept constant. Hence the observed attenuation corresponds to the absorption of the beam by both the particles and the gaseous HC. It can be seen that the absorption increases with time and it is believed that the increase in volatiles concentration in the beam path is causing this phenomenon. From the chart, the total absorption is about 50-75 watts. Calculations of the absorption by only the particle stream can be performed as follows.

The particle flow rate is 3 g/min, average diameter is 98 μm and the velocity is about 200 cm/sec. The diameter of the particle stream is estimated at about 0.5 cm, thus the number density of the particle is

$$N = \frac{\dot{m}_p}{\rho_p \frac{\pi d_p^2}{6} \times V_p \times A} = 1926 \text{ cm}^{-3}.$$

The power absorbed therefore is

$$p = P_0 (1 - e^{-NSL}) = 35 \text{ watts},$$

Figure 3-21. TYPICAL LUMINOSITY IN THE PYROLYSIS ZONE
DURING A LASER PYROLYSIS TEST
(LASER BEAM APPROACHES FROM LEFT).

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Figure 3-22. TEMPERATURE & LASER POWER MEASUREMENTS DURING COAL PYROLYSIS EXPERIMENT 40-106 μ , PSOC-632 COAL.

where S was taken to be equal to the cross section of a single particle, and L is the path length in the coal stream, about 0.5 cm (at the center of the stream).

If the above calculation is correct, then the observed absorption in excess of 35 Watts has to be due to the presence of volatiles and vapors in the beam path. It should be noted that the vapors could be visually observed and that they had the appearance of white-yellow smoke.

It would be interesting to compare the particle temperature as read by the pyrometer to an independent estimate of the temperature rise. In fact, two such independent estimates can be made, one based on the laser beam absorption and the other based upon the laser power density input and the convective cooling, as was done several times before.

Assuming that the power absorbed in the coal causes a direct temperature rise (no heat loss by convection) according to

$$P = \dot{m} C_p \Delta T,$$

the expected temperature rise is

$$\Delta T = \frac{35}{\frac{3}{60} \cdot 0.25 \times 4.187} = 670 \text{ K.}$$

Hence, the particles temperature is about 970 K. This temperature seems to be low if the intense luminosity observed during the experiment originated from thermal radiation. However, as mentioned earlier, it is possible that molecular absorption/emissions by the volatiles was involved.

An estimate of the particle temperature rise can also be obtained from the relationship derived earlier, namely

$$\Delta T_p = \frac{\alpha_d I}{8k_g} \left(1 - e^{-t/\rho C_p d_p^2/12 k_g} \right).$$

Here $t \approx 66.2$ msec, and

$$I = 500/\frac{\pi}{4} (0.7)^2 = 1300 \text{ Watt/cm}^2.$$

Thus

$$\Delta T_p = 509.8 \text{ K,}$$

which is not much different from the number derived above. Unfortunately, these temperatures also do not correspond to the values obtained from the pyrometer chart. The values calculated from the chart are in the range of 1420 - 1520 K. However, the temperature readings, using any two of the three pyrometer channels, have a variance as large as 10% associated with them. The discrepancy can be understood if, as already mentioned, the molecular emission overlaps or coincides with any of the wavelength used in the pyrometer. It is well known that HC gases have absorption spectra in the near IR, this spectra is associated with low energy vibrational/rotational transitions. If the visible emission during the experiment is also associated with these gases then it is possible that the range between 0.8 to 1.1 μm is within the emission bands of the gases, influencing the pyrometer readings.

In light of the discrepancy in the determination of the temperatures it remains to examine what happened to the coal in passing through the laser beam. Scanning electron micrographs of the coal are shown in Figure 3-23. Shown in (a), the virgin coal, the main features of which are the angular shape of the particles and their uniformity in size. In (b) and (c) the pyrolyzed coal is shown. The two main features observed in (a) have changed (although among the many particles a few appear to be totally unchanged), particles are much smaller and their surface appears more rounded. Also, large pores can be observed in the surface and many of the particles are spherical (see in c).

Definitely, the particles underwent a dramatic transformation. Although the temperature history during that process is not clear, this dramatic change is also reflected in the chemical analysis of the samples as shown in Table 3-6. The two different samples of pyrolyzed coal in the table correspond to different times during the same experiment, where sample 56 is of the coal which was pyrolyzed last.

The most significant result in the table is the dramatic decrease in the H:C ratio. As before, this signifies a release of gases rich in hydrogen such as low molecular weight HC. However, the loss on ignition value for 56 also indicates that a large volume of inorganic matter has been vaporized as well. In sample 51 this is not the case and the ratio between organic and inorganic matter decreased dramatically. However, the

Figure 3-23(a): 90-106 μm , PSOC-635, VIRGIN COAL.

Figure 3-23(b): 90-106 μ , PSOC-635, PYROLYZED COAL.
3-62

Figure 3-23(c). 90-106 μ , PSOC-635 PYROLIZED COAL.
3-63

Table 3-6. CHEMICAL ANALYSIS OF 90-106 μ , PSOC-632 COAL,
I = 1300 WATT/CM², Ar ATMOSPHERE.

ELEMENT	VIRGIN COAL (Sample 55)	PYROLYZED COAL (Sample 56)	PYROLYZED COAL (Sample 51)
C	77.35	80.80	83.43
H	4.03	2.87	3.54
N	1.12	1.00	1.12
S	1.46	1.06	0.91
Atomic Ratio H:C	0.6252	0.4262	0.5092
Loss on Ignition%	90.15	91.20	54.51
Si	2.55	2.80	1.30
Fe	1.10	0.41	0.66
Al	1.30	0.92	0.57
Mg	0.015	0.011	0.023
Ca	0.071	0.14	0.016
R	0.00054	0.0014	0.0011
Cu	0.0046	0.0071	0.0057
Mn	0.0025	0.0011	0.0027
Ni	0.0011	0.0015	0.059
Pb	0.0039	---	---
Cr	0.0016	0.0011	0.015
Ti	0.092	0.048	0.039

composition of the ash in sample 51 is unlike that of the virgin coal. Again, a selective vaporization could be the responsible mechanism.

Other Effects. Other interesting or unusual effects have been observed in many experiments and will be reported below. One effect is associated with the condensation of vapors on cold surfaces. At the end of test runs in which a large volume of "smoke" had been observed these condensed tars could be found on all the metallic surfaces. The appearance of these condensed vapors was not unlike typical soot "strings". Occasionally during an experiment these vapors would condense on the rim of the collection probe or the rim of the supply nozzle. The material would then build up into the laser beam path. Once in the path of the beam it would heat up and glow in an intense incandescient emission. The laser beam would "burn" through this buildup and soon a new one would form. The duration of exposure to the beam would be sufficient, however, to revaporize part of this matter. These events would repeat at a rate of several times per minute and could be clearly observed in a high speed motion picture taken during such a test. Figure 3-24 is a SEM showing the structure of these condensed tars under various magnifications up to 5000. The structure of this material is similar to that of a sand castle which is built by dropping water droplets containing some sand on top of each other. This structure is clearly not a pileup of the coal particles themselves, it is the buildup of tar droplets which solidified immediately upon contact with the surface or with other droplets.

The chemical composition of the matter shown in Figure 3-24 is tabulated in Tables 3-7 and 3-8 as samples 58 and 73. Both these samples have a very low H:C ratio and for that reason were termed as graphitized coal or tar. The loss on ignition of sample 73 is close to 100 percent indicating that the material consists primarily of carbon and that most of the ash has been vaporized out of it. By contrast, sample 58 has a lower loss on ignition value and an unusually high Si content.

Sample 70 is of condensed vapors which were collected off various cold surfaces in the test setup. These vapors did not condense within the path of the laser beam but may have been exposed to the beam radiation and perhaps vaporized as they evolved from the coal particles. Again, the high Si content is noteworthy although no apparent explanation can be found.

Figure 3-24. CONDENSED TARs IN LASER PYROLYSIS TEST
OF 38-45 μm , PSOC-635 COAL

Table 3-7. CHEMICAL ANALYSIS OF GRAPHITIZED TAR. ORIGINAL COAL
38-45 μ , PSOC-632, I = 1300 WATT/CM², Ar ATMOSPHERE.

ELEMENT	VIRGIN COAL (Sample 63)	GRAPHITIZED COAL (Sample 58)
C	76.75	80.64
H	3.93	1.02
N	1.10	2.40
S	1.46	1.59
Atomic Ratio H:C	0.6145	0.1518
Loss on Ignition%	90.20	87.33
Si	2.2	3.7%
Fe	1.3	1.1
Al	1.5	1.4
Mg	0.017	0.013
Ca	0.062	0.14
B	0.0005	0.0010
Cu	0.0025	0.0045
Mn	0.0076	0.0062
Ni	0.0030	0.0037
Pb	--	--
Cr	0.0045	0.0050
Ti	0.11	0.079

Table 3-8. CHEMICAL ANALYSIS OF CONDENSED TARs AND GRAPHITIZED TARs.
 38-45 μ , PSOC-632 COAL, I = 1300 WATT/CM², Ar ATMOSPHERE
 (THE VIRGIN COAL IS THE SAME ONE SHOWN IN TABLE 3-7 SAMPLE 63)

ELEMENT	CONDENSED TARs (Sample 70)	GRAPHITIZED TARs (Sample 73)
C	77.48	88.00
H	2.47	1.43
N	3.50	0.79
S	N.D.	1.05
Atomic Ratio H:C	0.3825	0.1950
Loss on Ignition %	86.62	98.59
Si	3.5%	0.39%
Fe	1.4	0.12
Al	1.8	0.18
Mg	0.0058	0.0043
Ca	0.13	0.018
B	0.0012	0.0005
Cu	0.0025	0.00031
Mn	0.0066	0.00074
Ni	0.0034	0.00031
Pb	--	--
Cr	0.0037	0.00023
Ti	0.086	0.012
N.D. - Not detected

During the experiment reported in Table 3-8, temperature on the order of 2500 K was read by the pyrometer. A portion of the pyrometer chart is reproduced in Figure 3-25. In this chart, as before, the fluctuations are attributed to the number density of the particles in the stream which varied perhaps due to the cyclic nature of the coal feeder operation. These cycles can be observed in both the temperature readings and in the laser power attenuation trace.

A calculation of the number density of the particles for this case yields

$$N \cong 2.63 \times 10^4 \text{ cm}^{-3}.$$

The absorbed power of the beam is therefore about 16.63% or about 83.15 watts. A simple energy balance for this case yields a final temperature of about 1900 K only. The discrepancy again is perhaps attributed to the absorption/emission by vaporized tars.

In another test using the high volatile PSOC-358 coal, the filter element through which the gases were removed from the test cell, was observed to be coated with some yellow-brown matter. It is believed that low molecular weight HC gases would pass through the filter (0.45 μm pores) but that higher molecular weight vapors or tars would be condensed on it. Due to the small size of the sample the only analysis that could be done on the filter was the emission spectroscopy. The findings are summarized in Table 3-9. It is of interest to note the high ratio of Si, Fe and Al in this sample.

Table 3-9. CHEMICAL ANALYSIS OF CONDENSED VAPORS ON A FILTER ELEMENT
(INORGANIC MATTER ONLY)

(Sample 81)			
Si	18%	Cu	0.10
Fe	5.8	Na	16.0
Al	6.2	Ti	0.79
Mn	0.15	Cr	0.19
Mg	0.46

Figure 3-26. FLUORESCENT X-RAY SPECTRUM.

Figure 3-27. FLUORESCENT X-RAY SPECTRUM.

Figure 3-28. LASER PYROLYSIS EXPERIMENT GRAPHITIZED PARTICLES,
 38-45 μ , PSOC-358 COAL.
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Table 3-10. CHEMICAL ANALYSIS OF A 38-45 μ , PSOC-358 COAL,
I = 1300 WATT/CM², Ar ATMOSPHERE.

SAMPLE	VIRGIN COAL (Sample 92)	GRAPHITIZED COAL (Sample 85)
C	80.57	81.44
H	4.60	2.95
N	1.23	2.01
S	0.77	0.77
Atomic Ratio H:C	0.6851	0.4347
Loss on Ignition %	95.68	96.41
Si	1.2	1.2
Fe	0.19	0.20
Al	0.59	0.31
Mg	0.011	0.0066
Ca	0.044	0.018
B	0.00074	0.00077
Cu	0.0012	0.00042
Mn	0.0026	0.0012
Ni	0.0014	--
Pb	0.0016	--
Cr	0.0018	0.00049
Ti	0.052	0.022

A fluorescent X-Ray analysis of the same filter element, shown in Figure 3-26, identifies the same elements as shown in the above table. For comparison purposes another X-Ray spectrum of the original coal is shown in Figure 3-27.

Finally, a dramatic picture of the graphitized matter in another test using the PSOC-358 coal can be seen in Figure 3-28. The material seems to be composed of hollow shells, as if the inner matter has vaporized and only the outer shell was left. The elemental composition of this matter is shown in Table 3-10.

3.1.4 Summary of Results

In-flight laser pyrolysis of coal particles was performed using various coals and different particle sizes. Total laser power typically ranged between 300 to 500 watts. The beam was usually focused using 100 or 200 mm focal length CaF_2 lenses. The waist diameter of the beam was about 7 mm providing a power density in the range from 0.78 to 1.3 KWatt/ cm^2 . Particle flow rate through the beam was adjustable between zero to about 10 gm/min, and the particle velocity typically was about 2 meters/sec. The particle stream had a diameter of about 0.5 cm, thus the range of number density of the particles for these conditions was between about 6500 to 70,000 cm^{-3} . In order to prevent the recondensation of tars on the particles, the stream of pyrolyzed particles, the carrier gas and the evolved tars and hydrocarbon gases passed through a swirl particle separator located at the bottom of a collection probe. The collection probe system consisted of two concentric tubes so that particles which passed through the center of the laser beam, were collected separately from those particles falling through the edges of the beam. The latter particles may have been subjected to lower intensities due to the Gaussian nature of the beam.

The coal and various products of the pyrolysis experiment were analyzed for their organic matter composition (carbon, hydrogen, nitrogen and sulfur), and their ash composition (% ash, major metals and trace elements). The various samples were studied visually under various magnifications using a Scanning Electron Microscope (SEM) and X-Ray spectrum was used to identify composition of specific features.

During a typical test run the temperature was recorded using a three color pyrometer. The laser beam transmission through the test cell was also monitored so that the total power absorbed by the particles and the volatile matter could be monitored.

The complete test matrix, showing the various coals, the particle size and the type of atmosphere in the various experiments is given in Table 3-11 in which most of the tests were repeated several times.

Table 3-11. TEST MATRIX

COAL TYPE PARTICLE SIZE	MONTANA ROSEBUD	PSOC-632	PSOC-358
< 38 μ	- - -	- -	-
38-45 μ	N ₂ , SF ₆ , Ar	Xe, Ar	Ar
45-53 μ	- SF ₆ -	- -	-
53-63 μ	- - -	Xe -	-
63-75 μ	- - -	- -	-
75-90 μ	- - -	Xe -	-
90-106 μ	- - Ar	- Ar	Ar

It was established very definitely that the volatile matter (light HC gases or vaporized tars) absorbs the incident laser radiation which has a wave length of 2.7 μ m. It is unknown, at this point, which specific compounds are responsible for this absorption. A characteristic infrared group frequencies Table [38] indicates that the hydrogen stretching region extends between wavenumbers of 3700 to 2700 cm^{-1} or 2.7 to 3.7 μ m. Absorption peaks in the region of 3700 to 3100 cm^{-1} (2.7 to 3.2 μ m) are ordinarily due to various O-H and N-H stretching vibration. Hence various alcohol groups could be involved. However, a detailed study is needed for a positive identification of the absorption mechanism. Further, from the three color pyrometer readings it seems that some emission in the near IR can be traced to these volatiles. No doubts exist about emission in the visible range as shown earlier in photographs (e.g., Figure 3-21).

Hence the readings of the pyrometer are composed of the total of the thermal radiation (black body type) of the coal particles and the gaseous emission. This fact may be important in the case of industrial flames where IR radiation is an inherent feature. The coupling between this radiation and the volatile matter surrounding the coal particles may have an important impact upon the combustion analyses and modeling.

The observed discrepancy between the measured and the computed temperatures may be attributed to the phenomena described above. Further, the gases may selectively absorb the radiation emitted by the particles and that may cause a discrepancy between the various pyrometer channels. And finally, due to the nonuniformity in the laser power density, some particles may be heated more than others and may shift the pyrometer reading toward the higher temperature.

Calculated and measured particle temperatures are in the range between 1500 to 2500K, typical heating rates are therefore in the range between 3.4×10^5 to 6.29×10^5 K/sec. Under these conditions it was shown that the devolatilization process may cause a dramatic reduction in the H:C ratio meaning that the evolved matter is nearly saturated in hydrogen relative to the coal. Further, in the process, the ash in the coal or the inorganic elements are carried away in proportions similar to their original composition. It is believed that the metals are vaporized after being reduced from the oxide form. Another possible mechanism of ash elements removal is through break-up of the original particle or the removal of small pieces thereof by the evolving gases. It was observed that during the rapid heating, some particles acquire a horizontal velocity usually away from the direction of the laser beam approach. The rocket effect is caused when a relatively large volume of gases is released by the particle through a small opening in its surface. The softest surface area on the particle which yields first is perhaps on the side heated by the beam. Thus the particles are trajected in the opposite direction. Some "rocketing" particles may be seen in Figure 3-29. It is possible that during such a violent release of gases, the particle may actually break-up with submicron particles formed. These subparticles have a composition similar to that of the pulverized coal.

Some of the vaporized matter including the tars, were observed to condense into submicron particles upon contact with the ambient atmosphere

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Figure 3-29. LASER PYROLYSIS OF COAL, ROCKET EFFECT DUE TO
RELEASE OF VOLATILES (LASER BEAM FROM LEFT TO RIGHT)

and usually would appear to the eye as white/gray smoke which filled the test chamber. The chemical analyses shows that basically all the elements which can be found in the original coal could also be found in the condensed vapors. Further, when these vapors condensed in a position that would keep them in the laser beam path (e.g., on some solid surfaces), the vaporization process would continue. More ash would vaporize and more tars and light HC gases evolved. The final solid product would be graphitized matter (of a very low H:C ratio), whose structure may resemble empty shells or cemospheres.

From this discussion it is also clear that the number of experiments carried out is not sufficient to characterize the pyrolysis process. The purpose of many of the tests was to examine the system, the technique and its capabilities. Various unexpected difficulties will have to be overcome before the full potential of the technique can be utilized. The results shown so far indicate that this technique may outdo all other rapid pyrolysis techniques by merits of its wide range of parametric variations and precise control of these test parameters. The recommended refinements are discussed in the following section.

3.1.5 Recommendations for Future Work

Some critical issues in this technique are (a) the accurate determination of particle velocity and the ability to control this velocity and (b) the exact determination of the laser power density profile. Other issues of slightly less importance are the rapid removal of the volatiles from the test cell, the improved spatial resolution of the pyrometer and the determination of available "windows" in the emission bands by the HC gases. Also improved diagnostics for the determination of the volatiles composition utilizing a gas chromatograph and a mass spectrometer may help in resolving the reactions and kinetics of the pyrolysis process. Finally, other lasers may be utilized in which the beam shaping and optical requirements are easier for the experimentalist. These issues are discussed in the following sections.

In regards to the particle velocity, this may be the easiest issue to correct. The particle feeder should be replaced with one that doesn't operate intermittently. A particle feeder operating on the principle of elutriation may be best. It is recommended to avoid long lines between the feeder and the test cell since these require high velocities to avoid plugging by the coal particles. When high velocity is used it is not easy to reduce the velocity without the spreading of the jet into a large diameter.

The second issue mentioned was the determination of the laser power density profile. This is a simple task which is routinely performed in any laser study. The task of getting a beam with a specified profile may be more difficult, though. Beam shaping and optical requirements depend on the wavelength of the particular laser, the quality of the beam, and the total energy involved.

Further, the experimental setup should be designed in such a way that all or most of the volatile matter can be rapidly removed from the test cell. These are two reasons for this. First, the tars may recondense on the coal particles and influence the outcome of the study. Second, there is a definite overlap between the laser irradiation and the absorption spectra of the volatiles, as well as between the thermal radiation by the particles and the absorption of the volatiles. Both of these effects are disturbing to the proper conduct of the experiment. Finally, the increase in volume of gases flowing in the system affects the flow field and thus the particle velocity.

Due to the interaction between the volatiles and the laser radiation, the gaseous spectrum may overlap some of the pyrometer channels, so that the temperature reading may be misleading. It is necessary, therefore, to study the emission spectra of the evolved gases and to identify "windows" in which the thermal radiation from the particles is not obscured by the gaseous emission. This can best be done using a proper monochromator or other optical spectrometers. This study should be done prior to the selection of the pyrometer wavelengths.

Finally, the spatial resolution of the pyrometer should be improved or the particle heating distance be increased. This will allow the experimental determination of the temperature history of a particle. This information, combined with other diagnostics will provide data in regards to kinetics and mechanisms of volatilization. Latent heat of vaporization at various stages of the process may be determined as well. This information may be very important for modeling and scaling of combustion hardware.

A system of a gas chromatograph and a mass spectrometer utilized in conjunction with microprobe sampling may provide useful information in

regards to the mechanisms and kinetics of pyrolysis. Also, the fate of fuel bound nitrogen and sulfur and the mechanisms of pollutant formation may be determined. Further, the determination of the fate of the ash elements during rapid heating has an important impact on the design and operation of coal burning equipment.

The last recommendation deals with the determination of the degree of volatilization. It has been shown that trace elements cannot be used as traces for the purpose of determining the relative degree of volatilization since these elements themselves may vaporize. Therefore, the total mass participating in the experiment, whether solid, liquid or gas, should be collected and analyzed to yield a total mass balance. An accurate bookkeeping of the fate of various species is needed as well. It is perhaps this task which makes the design of the experiment radically different from the present system in which an open test cell is utilized. However, recall that an open test cell has advantages of its own, for instance, it does not need windows for the laser beam, thus no cooling is needed, and beam losses are minimized.

3.2 EFFECTS OF PARTICLE SHAPE ON AERODYNAMIC DRAG AND COMBUSTION

3.2.1 Objectives and Engineering Issues

In attempting to model combustor fluid dynamics an important question has arisen regarding whether nonspherical coal particle shape effects may be a significant factor in enhancing volume burning in the combustor. That is, is it possible that coal particles, sized according to traditional sifting techniques, can behave as either much larger or smaller particles due to extremes in shape? This raises the distinction between the physical size of a particle and its effective size. The literature suggests a number of possible ways to calculate the effective size of nonspherical particles. For example,

- (1) Sieve diameter - The width of the minimum square aperture through which the particle will pass. This will be referred to later as the particle's physical size.
- (2) Volume diameter, d_v - Diameter of a sphere having the same volume as the particle where

$$V = \pi/6 d_v^3.$$

- (3) Drag diameter, d_d - Diameter of a sphere having the same resistance to motion as the particle in a fluid of the same viscosity and at the same velocity. For $Re < 0.2$ (and approximately up to 1.0) $F_D = 3\pi \mu V d_d$.
- (4) Stokes' diameter, d_{ST} - Diameter of a sphere free-falling in the regime $Re < 0.2$, at the same velocity as the particle. Therefore, the drag diameter and Stokes' diameter are the same for free fall at these Reynolds numbers. In general, $d_{ST}^2 = (d_v^3)/d_d$.

In principle, the third definition of effective diameter is most appropriate for modeling combustor fluid dynamics; however, at low Reynolds numbers it is convenient to determine the effective diameters of the particles at their terminal velocities according to definition four. Back-of-the-envelope calculations have shown that in the combustor, slip velocities may be large enough that the Reynolds number is no longer $O(1)$. Still, this approximation may be valid sometimes and, as will be seen later, yields valuable information about particle fluid dynamics. Hereafter, all references to particle drag size will indicate the Stokes' diameter. Particle physical size will be the size obtained

by sifting the coal sample. In the remainder of this section, the methods used to determine the Stokes' diameter are discussed. Results are presented in which physical size and drag size are compared. Conclusions regarding the impact of these results on combustor models are then presented.

3.2.2 Experimental Approaches

In preliminary tests, particles were dropped in a 1.7 meter plexi-glas tube. The time elapsed between the instant of release and the moment light was scattered by the particles as they intercepted a laser beam across the bottom of the tube was recorded. By noting both the first and last points at which light was scattered by the particles as they crossed the laser's path, a range of Stokes' sizes for the sample could be calculated. Although quite simple in principle, these tests were immediately complicated by the presence of dust in the air which often intercepted the laser path before or after the fallen particles. Also, it was difficult to uniformly start the flow of particles in the tube without imparting some undesirable initial momentum to them. Although it might have been possible to devise a better system utilizing quartz crystal microbalances at the base of the tube to sense arrival of particles, this would have represented a few orders of magnitude increase in both expense and set-up time. For these reasons, an alternative approach to determine effective sphere size was sought.

A survey of the literature indicated that the micromerograph is an instrument designed to determine the Stokes' diameter of a powder sample. The only requirements are that the density of the sample be known and the effective size be between 1 and 250 microns, although better results are obtained for samples between 2 and 70 microns. The micromerograph (U.S. manufacturer - Val-Dell Co., Norristown, PA) is a sedimentation balance which uses nitrogen as the working gas. A blast of nitrogen at high pressure forces the sample through the region between two adjustable cones, causing the agglomerated particles to separate, and into the sedimentation column. This column is made of aluminum and has an inside diameter of 3.5 inches and is 85 inches long. At the base of the column is a null-seeking servo-electronic balance whose current output is proportional to the accumulated weight of sample on the pan. The accumulated weight versus time curve is recorded on a strip chart. With the help of

a template supplied by the manufacturer which incorporates Stokes' law, this curve can be translated into the standard format of "particle effective sphere diameter" versus "cumulative weight percent larger than".

There are, however, some subtleties involved in correctly interpreting the micromerograph test results. For example, the template used to convert the data to a particle size distribution uses Stokes' drag law. Strictly speaking this law is accurate for $Re = \rho_f V D / \mu < 0.2$. Using this value, the definition of Re_d , and the fact that the terminal velocity at low Reynolds numbers is given by $V_{ST} = \rho_s g D^2 / 18 \mu$ (neglecting buoyancy and where subscript "s" implies the solid, "f" the fluid), the critical value of Stokes' diameter above which Stokes' law should not be used becomes:

$$D^3|_{\text{critical}} = \frac{3.6 \mu^2}{\rho_s \rho_f g}$$

For coal particles settling in nitrogen:

$$\rho_s \approx 1.4 \text{ gm/cm}^3$$

$$\rho_f = 1.1 \times 10^{-3} \text{ gm/cm}^3 \quad (1 \text{ atm, } 25^\circ\text{C})$$

$$\mu = 0.64 \text{ gm/hr-cm} \quad (1 \text{ atm, } 25^\circ\text{C})$$

so that $D|_{\text{critical}} = 42 \mu\text{m}$. Davies [39] notes that for $Re = 0.83$ ($D|_{\text{critical}} = 68 \mu\text{m}$), Stokes' law underpredicts the effective size by 10%. White [40] has developed an empirical equation for the drag coefficient of a sphere which is accurate to within ± 10 percent for Reynolds numbers up to 2×10^5 . This equation was used to determine the difference between the effective sphere sizes when using Stokes' drag law instead of White's equation. For example, for known particle density, gas density and viscosity a given terminal velocity can be used to compare the calculated effective sphere size as determined by the micromerograph to the correct value (different when $Re > 0.2$). Some values have been tabulated in Table 3-12. Above $Re = 0.2$ the micromerograph underestimates the effective sphere sizes by the amounts shown in Table 3-12. The effect of this trend on the data will be discussed later.

Table 3-12. COMPARISON OF EFFECTIVE SPHERE SIZES.

V_{terminal}	D_{Stokes}	D_{White}	$\left[\frac{D_{\text{Stokes}} - D_{\text{White}}}{D_{\text{White}}} \right] \times 100\%$	$Re_{D_{\text{White}}}^*$
7.4 cm/sec	45 μm	45 μm	0%	0.2
17.0 cm/sec	68 μm	72 μm	-6%	0.8
37.0 cm/sec	100 μm	114 μm	-12%	2.6
230.0 cm/sec	250 μm	500 μm	-50%	71.0

Another point open to interpretation is whether or not the fraction of the test sample that is blown to the wall as the micromerograph is fired is a representative or selective sampling of the total. Allen [41] indicates it is probably selective, fine particles being more readily attracted to the walls. Therefore for samples of predominantly small particles the results from the micromerograph should be accepted with caution.

The deagglomerator is intended to break clumps of particles into their constituents, however there is some question about whether, in addition, particles are fragmented. There is some evidence that fragmenting can be prevented. The usual test procedure is to successively test samples at higher deagglomerating pressures. Initially, increasing the pressure shifts the entire particle size distribution toward smaller particles. When fragmenting does occur due to higher pressures and more forceful contact of particles with the walls of the deagglomerator, the particle size distribution suddenly changes shape to indicate the sample is almost monodisperse. Then, the pressure is decreased and the sample run again to obtain useable test results. In this way, fragmenting by the deagglomerator is supposed to be avoided.

The above discussion sheds light on possible problems with interpreting micromerograph test results. Overall, the instrument is well suited for determining particle size distributions. The instrument is easily run without the need for highly trained operators and results are

*Using $\rho_p = 1.4 \text{ gm/cm}^3$.

repeatable to within 3 percent. Also, the manufacturer indicates that uncertainties as to whether representative or selective portions of the sample cling to the tube walls and whether samples fragment in the deagglomerator would be dispelled by re-testing a sample that had collected at the tube bottom.

For completeness, other methods of particle size analysis are discussed here.

- (a) Tyler Standard Sieves - Available in a series of mesh sizes, these sieves are often used to separate samples into smaller size groups using a shaker to agitate the sieves. Problems are sometimes encountered with plugging of the sieve openings (blinding) or with non-uniform openings in woven-wire screens. These problems have been addressed respectively, by the development of a shaker in which an oscillating vertical column of air gently keeps the sample in motion (sonic sifter) and by the manufacture of micromesh sieves, in which variations in opening size are markedly reduced.
- (b) Coulter Counter (a.k.a. Sedigraph) - This instrument operates on the electrical sensing zone method of particle size determination. Particles are suspended in an electrolyte and then counted and sized as they pass through an orifice with immersed electrodes on each side. The resistance changes as the particles pass through, producing voltage pulses proportional to particle volume. Problems occur when two or more particles pass through together, known as coincidence. Depending on pore size, the Coulter counter may determine envelope volume instead of true volume, leading to overestimations of particle size. In comparison to the micromerograph, the Coulter counter is less versatile since a compatible dispersing liquid must be determined for each different material. For the micromerograph, since gas is used as the sedimentation fluid, there are no complications of this kind.

3.2.3 Results and Discussion

Montana Rosebud coal was pulverized and centrifugally separated into three size groups (Vortec Corp., Compton, CA). Prior to sending samples of this coal for analysis on the micromerograph (Val-Dell Co., Norristown, PA) the density was determined by the Liquid Pycnometer Method (analysis by Micron Data Laboratories, Mission Viejo, CA). The results are presented in Table 3-13. The maximum difference between these values is less than 6%. The density used in all of the micromerograph test results was 1.20 gm/cm^3 since these tests were performed before the actual densities

had been determined. Later, the effect on the data of using this value instead of the correct one will be discussed.

Table 3-13. DENSITY OF COAL SAMPLES.

COAL MESH SIZE	DENSITY (gm/cm ³)
100% - 10 mesh, 0% - 100 mesh (150 μ m - 2000 μ m)	1.4222
75 $\pm$ 5% - 200 mesh (75 $\pm$ 5% by weight < 75 μ m)	1.3512
100% - 325 mesh (< 45 μ m)	1.3725

Coal Physical Size. Since the goal of these tests is to compare physical size distributions obtained from sifting to drag size, obtained from the micromerograph, coal was sifted at TRW with special care. Typically, seven Tyler screens were mounted on a shaker with a small amount (about 50 grams) of coal, and shaken for at least one hour. At that time the screens were emptied, cleaned with a wire brush and compressed air, and the process repeated with more unsifted coal.

Since surface moisture could cause clumping of coal particles, samples were baked before sifting and further analysis. The three coal size groups were baked in an oven at 100°C for 24 hours. The resulting percentage loss in weight of the samples is tabulated below.

<u>SAMPLE*</u>	<u>WEIGHT LOSS</u>
100% - 10 M	20.4%
75% - 200 M	18.3%
100% - 325 M	9.2%

Proximate analysis of these coals was also performed (Commercial Testing and Engineering Company, Chicago, IL). The test results indicated that the moisture contents were:

*These abbreviated sample identifications will be used hereafter. The full identification is presented in the table showing coal densities.

<u>SAMPLE</u>	<u>MOISTURE CONTENT</u>
100% - 10 M	17.53%
75% - 200 M	15.01%
100% - 325 M	13.70%

Allowing for differences between the two analyses in the magnitude of the moisture content (probably due to the coals exposure to different environmental humidity conditions), the trends are the same. The larger coal contains more moisture. After baking, the samples are considered to be dry coal in which clumping due to surface moisture has been eliminated. Hereafter, unless otherwise noted on the graphs, the coal that has been analyzed has already been oven baked to remove moisture.

Some samples were also sent out to be separated on the sonic sifter. Two examples of the results obtained for physical size from the TRW Tyler sieves and the sonic sifter are shown in Figures 3-30 and 3-31. Note that although there are differences between the two distributions for both the 75% - 200 M and 100% - 10 M coals, it will be shown later that they are not large enough to alter the conclusions drawn when comparing physical size distribution (either one) to drag size distribution. Since there was little difference in the two distributions more confidence in the TRW sifting technique developed.

In Figure 3-32 is shown the sonic sifter result for unbaked 75% - 200 M coal. Comparison to Figure 3-31 in which the sonic sifter result for baked coal appears shows that baking coal does little to change the physical size distribution. However, previous distributions for baked and unbaked samples obtained in-house (using Tyler sieves) did indicate a shift in the distribution toward smaller sizes for baked coal. This indicates that baking may help to deagglomerate coal clumps and that the sonic sifter is capable of breaking these clumps whether or not the coal is baked.

Problems were encountered in trying to obtain a size distribution for the 100% - 325 M coal since Tyler sieves smaller than 38 μ m are not available. A sample was sent out to be analyzed on the sonic sifter (which uses micromesh sieves), however two problems prevented the distribution from

Figure 3-30. PHYSICAL SIZE DISTRIBUTIONS FOR 100%-10M COAL

Figure 3-31. PHYSICAL SIZE DISTRIBUTIONS FOR 75%-200M COAL

Figure 3-32. SONIC SIFTER DISTRIBUTION FOR BAKED AND UNBAKED 75%-200M COAL

being completed. First, for this very fine coal, blinding of the sieves occurred frequently. Also, the oscillating column of air intended to prevent blinding caused particles to move toward and adhere to the sieve walls. Since more than 25% of the sample ended up on the walls the test results were not useable. For these reasons, a physical size distribution for this coal is not available.

Coal Physical Size vs. Drag Size. Micromerograph size distributions were obtained for baked coal samples from all three size groups. These distributions were then plotted with the physical size distributions obtained using TRW Tyler sieves (100% - 10 M, 75% - 200 M). These graphs are shown in Figures 3-33, 3-34, and 3-35.

For the 100% - 10 M coal, seen in Figure 3-33, there is an obvious shift in the distribution toward smaller particle sizes when comparing physical and drag size. Although the TRW Tyler physical size distribution was used here, comparison to Figure 3-30 shows that the two physical size distributions are not different enough to alter the appearance of the large shift in Figure 3-33. Since the micromerograph determines Stokes' diameter, this indicates that a significant fraction of the coal behaves as spheres of smaller diameter than the actual particles. (Since the actual particles are not spherical, their "diameter" represents a dimension in one direction only. For example, if the particles are oblate spheroids, the diameter represents either the major or minor dimension.) In contrast to the large coal, the 75% - 200 M does not show as marked a shift in particle size, although there is some difference between the two distributions. As above, if the sonic sifter size distribution for this coal had been used instead, the same conclusions would be drawn. For the smallest coal, 100% - 325 M, Figure 3-35 shows the drag size distribution. Although no physical size distribution is available for comparison, since about 70% of the sample has an equivalent sphere diameter of less than 12 microns the drag size distribution for this coal too is probably shifted to smaller sizes.

Earlier it was shown that for particle sizes of 100 μ m and larger the micromerograph underestimates effective sphere sizes by greater than 10%. In analyzing the drag size distributions for the three coal samples it is apparent that only the 100% - 10 M data is strongly affected by that

Figure 3-33. SIZE DISTRIBUTIONS COMPARED FOR 100%-10M COAL

Figure 3-34. SIZE DISTRIBUTIONS COMPARED FOR 75%-200M COAL

3-95

Figure 3-35. DRAG SIZE DISTRIBUTION FOR 100%-325M COAL

finding. One effect of correcting this data would be to expand the limits of any particular subgroup in the distribution (larger than 45 μm) to larger diameters. In this case it could happen that some of the sample would behave as spheres of larger diameter than the physical size limit of the sample. However, Figure 3-33 shows that the major difference between the two size distributions would still be the huge percentage of the sample that behaves as spheres of a smaller diameter.

In point of fact, the micromerograph distributions were obtained for an assumed coal density of 1.2 gm/cm³. The actual densities were found to be slightly higher (see Table 3-13). It can be shown that the relation between effective sphere size and density as used by the micromerograph is

$$d_1 \sqrt{\rho_1} = d_2 \sqrt{\rho_2} = \text{constant}$$

so that if $\rho_1 = 1.2$ and $\rho_2 = 1.4$, then d_2 will be .93 d_1 . Therefore, the actual drag sizes are 7% lower than indicated in the last figures. This makes the difference between the two size distributions that much more apparent.

During the course of this test program, the manufacturer was asked to calibrate the micromerograph and report any inconsistencies to us. This was done using National Bureau of Standards spherical glass beads, $\rho = 2.6$ gm/cm³, between 3 and 30 microns in diameter. The calibration indicated operation was normal. Also, an independent calibration done on an instrument at the Jet Propulsion Laboratory (Pasadena, CA) indicated, similarly, there were no machine calibration problems.

In order to guarantee that the reason the size distributions were shifted was not due to, perhaps, taking a "more crushed" sample from each coal size group, some of the 75% - 200 M coal was sifted into narrow subgroups and sent for micromerograph analysis. The results of these analyses are shown in Figures 3-36 and 3-37. Here, again, it is clear that the drag size is significantly smaller than the physical size. This eliminates doubts about the possibility of having obtained samples of the coal groups that were not statistically representative of the whole.

Earlier it was noted that the fine particles of a sample might be collected on the wall during a micromerograph test. Corrections for this

Figure 3-36. DRAG SIZE DISTRIBUTION FOR 200-230 MESH
(63-75µm), 75%-200M COAL

Figure 3-37. DRAG SIZE DISTRIBUTION FOR 140-170 MESH (90-106µm),
75%-200M COAL

effect would yield a larger percentage of small particles in the distribution, further enhancing the differences between physical and drag size distributions.

It is important to note that if a significant fraction of a coal sample behaves as spheres of smaller diameter in a low Reynolds number flow, combustor operation will be affected. For example, if particles behave as small spheres they will spend more time in the volume before being centrifuged to the wall. This may result in a lower amount of captured slag. Later, the effect of particle size on particle burnout will be discussed.

Rosin-Rammler Correlation. The significance of the effect of varied effective particle size on the combustor burning models can only be evaluated by quantifying the shift in size. The Rosin-Rammler correlation has been developed from data that indicated coal tends to break in a predictable manner. Once fit to size distribution data, the correlation may be used as a continuous function which indicates the percentage by weight of particles larger than any size, x , that is,

$$R = 100 \exp \left[- (x/x_0)^n \right]$$

where,

R = cumulative weight percent oversize

x = particle size.

This correlation was fit to both physical and drag size distributions for the three coal groups.

The value of x_0 gives the particle size for which 36.8% of the particles are larger so that as the number of small particles increases, x_0 decreases. The exponent, n , is an indication of the dispersion of sizes around x_0 . A low value indicates a wide size distribution. Figure 3-38 shows a plot of the raw data and the Rosin-Rammler fit to that data for the 75% - 200 M coal. The actual values of x_0 and n for three size groups of baked coal are tabulated in Table 3-14. In some cases, there is a large percent difference between the values of x_0 for two size distributions. This indicates it may be important to identify the drag characteristics of a sized coal sample. Later it will be shown how differences in effective particle radius may strongly affect the performance of a cyclone combustor.

75 ± 5 - 200 MESH MONTANA ROSEBUD (BAKED)

KEY

- PHYSICAL SIZE
- △ DRAG SIZE
- ROSIN-RAMMLER ($\log\text{-}\log \frac{100}{R}$ VS. $\log X$)
(PHYSICAL SIZE)
- ROSIN-RAMMLER
(DRAG SIZE)

OTHER CASES

100-10 M	PHYSICAL SIZE	$r = 0.950$
	DRAG SIZE	$r = 0.993$
100-325 M	PHYSICAL SIZE (NOT AVAILABLE)	
	DRAG SIZE	$r = 0.990$

Figure 3-38. ROSIN-RAMMLER CORRELATION OF THE SIZE DISTRIBUTION DATA

Table 3-14. ROSIN-RAMMLER CORRELATION OF THE SIZE DISTRIBUTIONS.

COAL SIZE	DISTRIBUTION	$x_o (\mu m)$	$\left[\frac{x_o/drag - x_o/physical}{x_o/physical} \right] \times 100\%$	n
100% - 10 M	physical drag	449.8 212.4	-52.8	2.69 1.20
75% - 200 M	physical drag	51.0 44.2	-13.3	1.31 1.09
100% - 325 M	physical drag	* 17.3	*	* 1.71

Particle Shape-Nonspherical Coal Particle Drag. Previous results (micromerograph and physical size distributions) indicate particle shape plays an important role in determining the drag characteristics (effective radius) of coal particles. It is interesting to try to determine what shapes must be present in order to yield the observed differences between physical and size distributions obtained previously.

The micromerograph determines the effective sphere radius of coal particles by using Stokes' law. By assuming the particles are disk or cylinder shaped, the aspect ratio can be determined. For example, disks (oblate spheroids) may fall either broadside or edgewise in the flow. According to Lamb [42], for both cases the effective sphere size can be found, i.e., the sphere which would fall at the same rate in a Stokes flow. The two disks and their equivalent spheres are shown below.

disk broadside

disk edgewise

equivalent sphere

equivalent sphere

*Recall that the physical size distribution for this sample could not be obtained.

Note that the values of equivalent sphere radius apply only in the limit of thin disks, i.e., $t/R \ll 1$. Circular cylinders could also be treated as limiting cases of prolate ellipsoids.

Since particle trajectory is governed by the weight to drag ratio, and since the equivalent sphere has the same value of this ratio (by definition), the aspect ratio for the two disks can be found, as below.

$$\left. \frac{\text{weight}}{\text{drag}} \right|_{\text{equivalent sphere}} = \frac{2}{9} \frac{\rho g r^2}{\mu u}$$

$$\left. \frac{\text{weight}}{\text{drag}} \right|_{\text{disk-edgewise}} = \frac{\pi}{12} \frac{\rho g R t}{\mu u}$$

$$\left. \frac{\text{weight}}{\text{drag}} \right|_{\text{disk-broadside}} = \frac{\pi}{8} \frac{\rho g R t}{\mu u}$$

where,

ρ = particle density

u = particle relative velocity

μ = gas viscosity

r = equivalent sphere radius

R = ellipsoid major radius

Therefore,

for disks broadside, $t/R = 8/3\pi(r/R)^2$

for disks edgewise, $t/R = 16/9\pi(r/R)^2$.

Therefore, once the equivalent sphere radius and physical size of a coal particle are known, the shape of that particle may be assumed and its required aspect ratio calculated. Note, however, that for disks falling edgewise the average physical size from sifting corresponds to the thickness t . The equation above may be used to solve for R , and then t/R . In both cases, the equivalent sphere diameter is smaller than the ellipsoid major diameter. Contrary to this, cylinder-like particles act like spheres of larger diameter than the cylinder.

Samples of 75% - 200 M coal were sifted into two narrow size groups - 63-75 μm and 90-106 μm . The average physical size of the coal particles in these two groups was 69 μm and 98 μm , respectively. Then, using the micromerograph size distributions for each of these coals, the average drag size for each of several size ranges was found. Using these values for $\bar{r}$ and $\bar{R}$, the required aspect ratio could be calculated using the above formulas. The results are shown in Figures 3-39 and 3-40. The figures show only a small percentage of the sample behaved as larger spheres and, therefore, the particles were probably not cylinder-like. By modeling the small spheres as disks falling broadside* the aspect ratios were calculated and are indicated near the base of each size group. For the smaller sizes, the low aspect ratios indicate that the particles would be coal flakes.

Impact Upon Combustor Performance. The expected burning characteristics for the three coal size groups chosen for testing at the 20 MW_T level are shown in Figure 3-41. The curves predict there will be exclusively volume burning for the fine coal (100% - 325 M) and perhaps also for the 75% - 200 M coal, and a mix between volume burning and wall burning for the coarse coal (100% - 10 M). The burnout curve for the 75% - 200 M sample applies for either the physical or drag size distribution since they are quite similar (see Figure 3-33). In Section 5 the actual test results are presented.

For comparison a typical 200 Mesh coal physical size distribution (Figure 2-1) for ball mill ground coal has been used to obtain the burnout curve labeled "Typical 200 M". Note that this coal does not burn in the volume as readily as the other 200 Mesh sample, which has been centrifugally ground, a process believed to produce more fine particles.

In Figure 3-42 are the burnout curves for two 200 Mesh (ball mill ground) coal samples taken from the Rosebud seam at different times. Although samples 1 and 2 had less than 10% by weight of particles less than 40 μm according to the physical size distribution, their drag size

*In the Stokes regime, Davies [39] reports that irregularly shaped particles will fall with a random orientation, as will elliptical laminae, disks, parallelograms, etc. Therefore, the choice of disks falling broadside versus edgewise was purely arbitrary.

Figure 3-39. ASPECT RATIOS FOR DISK-SHAPED PARTICLES OF 200-230 MESH, 75%-200M COAL

Figure 3-40. ASPECT RATIOS FOR DISK-SHAPED PARTICLES OF 140-170 MESH, 75%-200M COAL

Figure 3-41. MASS BURNOUT AS A FUNCTION OF COMBUSTOR RADIUS FOR DIFFERENT COAL SIZE DISTRIBUTIONS

Figure 3-42. MASS BURNOUT AS A FUNCTION OF COMBUSTOR RADIUS FOR TWO 200 MESH (BALL MILL GROUND) SAMPLES.

distributions indicated there was 44% and 68% by weight of sample in this group, respectively. The figure shows that for a particular coal sample there is a marked difference depending upon whether the physical or drag size distribution for the coal is used in the model. Therefore, the net effect of particles behaving as much smaller spheres is to cause a noticeably more rapid burnout of the injected coal in the volume. Unless this factor is taken into account in the combustor design, the slag capture may be less than satisfactory. Note also that the burnout curves for the two physical size distributions are similar to that for the typical 200 Mesh coal of Figure 3-41. However, the drag size distributions indicate about 50% burnout by $R/R_{\max} = 0.4$ for this ball mill ground coal whereas for the centrifugally ground coal of Figure 3-40 this occurs much earlier, at about $R/R_{\max} = 0.2$, due to the larger percentage of fine particles.

In summary, particle shape effects may be strong enough to shift the entire size distribution so that burning and combustor performance will be altered. In order to model the performance correctly, the drag size distribution, which accounts for irregularly shaped particles, must be used in the design calculations.

4. WALL BURNING

4.1 OBJECTIVES AND ENGINEERING CONSIDERATIONS

An analysis of the dynamics of coal particles in a pulverized coal cyclone combustor indicates that under certain conditions a significant portion of the burning may take place on the walls of the combustor rather than in free flight. The principal conditions which determine the combustion mode (wall vs. free flight) are the coal size distribution, the flow pattern in the combustor and the geometry. Trajectory calculations shown in the analysis section 2 indicate that wall combustion is plausible given the appropriate conditions. In that case, a mechanism must exist by which the oxygen in the core of the combustor is transported to the walls to permit an efficient coal burnout.

Indeed, cyclone combustors appear to be very efficient, and typically carbon burnout in excess of 99% is achieved. Wall burning analytical models, in which combustion is assumed to be controlled by turbulent diffusion of oxygen across the boundary layer at the wall, do not predict such a complete combustion, however. It is well known that recirculation zones and reversed flow regimes which arise in swirling flows enhance the mixing processes and hence increase the burning rate. When the combustion takes place on the wall, however, such flow patterns are likely to differ from those commonly observed. Another enhancement mechanism which may increase the oxygen transport to the wall is that of a gaseous thermal centrifuge. The phenomena occurs when the hot, low density burned gases adjacent to the walls are buoyed away from the combustion zone toward the axis of the combustor under a gravity field as high as 5000 g*. The radial inflow is balanced by a radial outflow of the relatively cold, high density unburned gases which are centrifuged from the core toward the walls, supplying the required oxygen for the combustion on the walls.

A qualitative experimental study of the buoyancy effect had been completed under a TRW IR&D program in which a cold flow simulator was utilized. The low density burned gas at the walls was simulated by the introduction of a low molecular weight gas at the walls of the combustor

*Unstable stratification akin to Rayleigh instability.

simulator. Flow field visualization technique was achieved through laser induced fluorescence of finely dispersed particulates seeded in the core flow. Results, recorded on high speed still and cine photographs, indicated the presence of such a buoyancy effect [43].

In addition, an analytical study has shown that the buoyancy effect combined with wall roughness could provide the enhancement in mixing required for a complete carbon burnout [12].

Recall that a cyclone combustor is not necessarily a wall combustor; however, analysis (Section 2) indicate that for some conditions wall combustion dominates. Thus, the analysis and experimental study which follow are intended to explore the enhancement mechanisms for those cases in which the combustion does occur primarily on the walls.

The key to designing a valid experiment in which a cold flow model replaces the actual combustion hardware is in the correct simulation. In the case of a scaled down model the geometrical similarity needs to be preserved. In addition, the basic assumption underlying any cold flow model is that the chemical reaction rates are faster than the rates observed in a particular combustion device. Hence, the chemical reaction is not the controlling mechanism; rather, the limitations are due to the physical processes such as mixing and diffusion. In that case the problem in combustion may be treated from the fluid flow standpoint. Flow simulation is obtained, therefore, by preserving the values of some parameters or dimensionless groups. In some cases it is not possible to preserve, at the same time, the values of all the parameters and a judicious decision is needed for selecting the important ones [44].

In the present investigation a cold flow model has been utilized to study the enhanced mixing or mass transport phenomena through a heat transport experiment. The analogy between heat and mass transfer is well known and can, therefore, be exploited in order to simplify the simulation.

4.2 EXPERIMENTAL SETUP

The apparatus consists of a 1/4 scale cold flow model of a 6 MW pulverized coal cyclone combustor. A general schematic of the system is shown in Figure 4-1 and the simulator itself can be seen photographed in

Figure 4-1. WALL COMBUSTION SIMULATOR FLOW DIAGRAM

Figure 4-2. A 10 cm (4 in) in diameter copper pipe, 37.6 cm (14.7 in) long simulates the combustor. The pipe is wrapped in a tight pitch coil made out of an 0.38 cm (1/8 in) O.D., copper tubing which is soldered to the pipe to ensure a good contact. Air may enter the simulator either tangentially through a swirl generator head or axially. In the case of an axial inlet flow, the swirl head is removed and a straight section is attached instead. This section is a commercially available laminar flow element (LFE) about 15.2 cm (6 in) in diameter containing a section of capillary tubes across which a pressure drop is measured to yield the gas flow rate. Following the capillary section there is a contoured contraction down to 10 cm (4 in). In the case of a tangential inlet, a swirl head is used which consists of 10 adjustable area inlet nozzles. The blades, shown in Figure 4-3, can be closed or opened to effect the tangential inlet velocity. The gas enters without any axial velocity. It should be mentioned, though, that the actual combustor has only one tangential flow inlet, which makes the flow field more complicated. The outlet of the simulator can be either an axial or a tangential flow direction section. Finally, a baffle plate having an exit port about 2 cm in diameter can be inserted at the end of the simulator pipe in front of the exit section. The baffle plate simulates the slag baffle in the actual combustor.

The circulation of hot or cold liquid in the coil sets the wall temperature above or below the temperature of the gas flowing inside the simulator. The extent of heat transfer between the gas and the liquid can be determined by calorimetric calculations once the flow rates of the gas and the liquid are known and their respective temperature changes are measured. The effect of buoyancy on the experiment is eliminated when the wall is cold relative to the gas, providing stable stratification.

The apparatus is connected to a large vacuum pump (485 CFM capacity) and the flow of air is controlled by a manual 6" pinch valve. Air flow rate is measured by means of the laminar flow element (LFE). (When the swirl head is used, the LFE is connected upstream of the swirl head.) The pressure drop across an LFE can be shown to be directly proportional to the volumetric flow rate,

$$\Delta P = CQ,$$

where,

$$C = \frac{128 \mu L}{\pi D^4} C_D$$

Figure 4-2. COMBUSTOR SIMULATOR HEAT TRANSFER EXPERIMENT

Figure 4-3. VARIABLE AREA INLET GUIDE VANES IN THE SWIRL HEAD CONFIGURATION OF COMBUSTOR SIMULATOR.

and where C_D is a calibration factor. The measurement of the pressure and temperature of the incoming air allows the determination of the mass flow rate.

The flow rate of the cooling/heating liquid is measured by means of a positive displacement flow meter (PDF) which produces an analog signal (voltage) directly proportional to the volumetric flow rate of the liquid. The liquid in this experiment was a 50-50 mixture of water and ethylene glycol for which the properties (density, specific heat, thermal conductivity and viscosity) are available as a function of temperature.

In some of the early experiments, the circulating liquid was directly heated/cooled in a constant temperature bath (CTB) as shown in Figure 4-1. In later tests the liquid circulated in a closed system and was heated or cooled in a coil immersed in the CTB. To avoid contamination of the fluid by the liquid pump, shown in Figure 4-1, the pump was removed and the fluid was driven by a gas pressure. The CTB has a cooling capacity which varies between 100 and 300 watts depending on the both temperature and a constant heating capacity of about 750 Watts. The operating range of the CTB is between -30°C to 150°C with stability better than $\pm 0.1^{\circ}\text{C}$.

The following temperatures have been measured with standard thermocouples: liquid temperature at entrance and exit from the coil, copper pipe wall temperature at inlet and at exit, and air temperature at inlet. The temperature of the air at the exit was found to be nonuniform, that is, some stratification existed at the exit which made a single temperature measurement meaningless for calorimetric purposes. A mixing cup temperature was therefore of more interest. Several attempts were made to mix the gas at the exit by various techniques - 1) inserting a nozzle which forced the gas to pass through a small opening, 2) using a bluff body at the center to create recirculation, and finally 3) installing a small fan in the exit duct. In some cases an improvement was noticed, however, a concern was raised in regards to the effect of these devices on the flow field in the simulator. Eventually these devices were removed and the bulk temperature of the air at the exit was calculated via the energy balance

$$\Delta q_{\text{liquid}} = -\Delta q_{\text{air}},$$

or

$$\dot{m}_l C_{pl} \Delta T_l = -\dot{m}_g C_{pg} \Delta T_g$$

For the cold wall tests dry N_2 gas was used rather than air since there is a possibility that condensation of humidity on the walls might affect the heat transfer.

The test procedure which was followed in all the tests allowed for the establishment of a steady state condition where all flow rates and temperatures had stabilized. Data was taken under those conditions.

The similarity parameters between the actual combustor and the simulator were the Reynolds number, swirl number, length to diameter ratio, and the ratio of density at the wall to the density in the core (determines the buoyancy effect).

4.3 RESULTS AND DISCUSSION

The test data are summarized in Tables 4-1 and 4-2 giving the various operating conditions and measured data. The simulator was operated under two basic "heat exchanger" configurations, parallel flow and counter flow. The temperature variations along the apparatus are shown schematically in Figure 4-4. The nomenclature in the figure is such that the air always enters at the inlet (designated i) and leaves at the exit (designated x) while the liquid may enter at either the inlet or the exit side of the simulator. Usually, only the end point temperatures were measured. In some cases, however, wall and liquid temperature were also measured at the mid-point or at half length. These measurements have shown that the temperature does not vary linearly along the length; rather it changes at a high rate between the mid-point and the liquid entrance point, and at a lower rate between the mid-point and the liquid exit point.

Of the two configurations tested the simplest case to analyze was the axial gas flow one. This case is similar to the classical problem of heat transfer in the entrance region of a pipe except that complications exist due to the specific entrance configuration. Some background discussion may be useful here.

Table 4-1. Simulator Test Data (no swirl)

AXIAL INFLOW (no swirl)

TEST #	FLOW ⁽¹⁾	WALL ⁽²⁾	$\dot{m}_l$	$\dot{m}_g$	$\Delta T_l^{(3)}$	$\Delta T_w^{(4)}$	$\Delta T_i^{(5)}$	$\Delta T_x^{(6)}$	T_{gi}
			g/sec	g/sec	°C	°C	°C	°C	°C
111	↑↑	h	2.13	114.01	-30.42	-20.9	8.12	0.76	24.0
112	↑↑	h	1.981	187.8	-36.5	-23.7	10.73	0.51	24.0
113	↑↑	h	1.235	60.35	-43.5	-20.0	14.1	0.51	24.0
114	↑↑	h	2.43	60.35	-23.6	-18.22	6.6	1.2	24.0
115	↑↑	c	0.596	26.83	11.74	5.75	-6.39	-0.40	24.0
116	↑↑	c	0.596	29.51	-16.26	-10.06	-0.65	-6.30	24.0
117	↑↑	c	0.596	16.10	-13.83	-9.45	-0.17	-4.55	24.0
118	↑↑	h	1.193	26.83	26.31	22.23	0.97	5.05	24.0

(1) ↑↑ - parallel flow

↑↑ - counter flow

(2) h - hot wall

c - cold wall

(3) $\Delta T_l = (T_{\text{exit}} - T_{\text{inlet}})$ liquid(4) $\Delta T_w = (T_{\text{exit}} - T_{\text{inlet}})$ wall(5) $\Delta T_i = (T_{\text{liquid}} - T_{\text{wall}})$ inlet(6) $\Delta T_x = (T_{\text{liquid}} - T_{\text{wall}})$ exit

Table 4-2. Simulator Test Data (swirl)

WITH SWIRL

TEST #	FLOW	WALL	$\dot{m}_\ell, \text{g/sec}$	$\dot{m}_g, \text{g/sec}$	$\Delta T_{\ell i}, ^\circ\text{C}$	$\Delta T_w, ^\circ\text{C}$	$\Delta T_i, ^\circ\text{C}$	$\Delta T_x, ^\circ\text{C}$	T_{gi}	
42	↑↑	c	0.48	9.65	18	8.1	-10.1	-0.2	18.9	core gas: dry N ₂
44	↑↓	c	0.52	9.39	-16.5	-14.9	-2.4	-4.0	20.4	
46	↑↓	c	0.64	22.28	-20.5	-16.5	-0.25	-4.5	20.0	
47	↑↓	c	0.48	24.95	-17.27	-11.4	-2.09	-10.34	17.68	
48	↑↓	c	0.48	21.46	-25.35	-14.50	-0.35	-10.85	19.92	
49	↑↓	c	0.48	9.07	-24.76	-15.87	-0.62	-9.5	20.7	"
52	↑↓	h	1.12	9.39	36.85	30.75	0.5	5.1	25.0	core gas: air
53	↑↓	h	1.12	26.82	48.10	40.8	2.41	11.67	24.5	"
54	↑↓	h	0.83	75.11	50.9	34.5	0.92	18.0	23.8	"
104	↑↓	h	0.990	71.22	54.30	48.47	1.46	7.30	25.8	"

See footnotes in Table 4-1.

Figure 4-4. HEAT TRANSFER EXPERIMENT; BASIC FLOW CONFIGURATIONS AND AXIAL TEMPERATURE VARIATIONS:

- (a) Cold wall parallel flow
- (b) Cold wall counter flow
- (c) Hot wall parallel flow
- (d) Hot wall counter flow

The problems of flow and of heat transfer at the entrance region to pipes ($L/D < 60$) has been given much attention in the literature. The classical "Graetz Problem" [45] yields an analytical solution to laminar flow heat transfer in that region. An extension of that solution carried to higher order terms was given more recently [46]. Reference [47] discusses a numerical solution to laminar flow for the case of uniform velocity and temperature profiles at the inlet to the pipe. This reference assumes that the development of the velocity profile in the entrance region follows the one given in Reference [48]. Solutions are given for a constant wall temperature and for a constant heat flux. An extension of the heat transfer problem which includes the radial component of velocity in the hydrodynamic boundary layer is given in [49]. Experimental studies in laminar flow were reported elsewhere [50,51]. Turbulent flow conditions have been investigated in [52-54].

The main feature of the heat transfer at the entrance region to pipes is that the thermal boundary layer starts to grow from zero thickness. At the point of zero thickness the heat transfer coefficient is infinitely large. The heat transfer coefficient gradually decreases until a limiting value is reached which corresponds to a fully developed pipe flow in which the thermal boundary layer is fully developed. The heat transfer coefficient in the case of a hydrodynamic boundary layer which is not yet developed at the point at which the thermal boundary layer begins, is higher than that in the case that the hydrodynamic layer is fully developed at that point.

For a pipe entrance $\delta/R \ll 1$, thus the flow is in many aspects similar to flow over a flat plate. This similarity can be seen in Figure 4-5 in which predicted values of the heat transfer coefficient based on the aforementioned references are plotted both for the entrance region to a pipe and for a flat plate. For laminar flow conditions, the Graetz solution is given for the limiting case of a uniform velocity profile. The flat plate solution for a fully developed hydrodynamic layer using the Pohlhausen velocity profile and the Leveque parabolic profile approximation are also shown. Another solution according to Schlichting [55] is shown along with two solutions by Deissler. One for a fully developed velocity profile and the other for a uniform velocity and temperature profiles at the inlet.

Figure 4-5. COMPARISON BETWEEN THE MEAN HEAT TRANSFER COEFFICIENT BASED ON LENGTH FOR VARIOUS FLOW CONFIGURATIONS. $L/D=3.76$, PRANDTL NUMBER 0.71 AND REYNOLDS NUMBER BASED ON LENGTH.

All of these solutions were derived from the published work by converting to a Reynolds number based on length, for a ratio $L/D = 3.76$, and for a Prandtl number 0.71.

It should be noted, however, that the actual heat transfer may be higher than that predicted by the various theories if the flow conditions deviate from the well-behaved flow prescribed in the analyses. Various degrees of augmentation of the heat transfer are expected if, for instance, the flow separates at the entrance to the pipe, or in the case of free stream turbulence or acoustic disturbances [56]. The calculation of the coefficient of heat transfer may further be complicated if axial conduction of heat exists in the pipe wall. This may well be the case very close to the inlet where theoretically the coefficient is infinitely large. The presence of a temperature gradient in the pipe walls is a sufficient driver to set such an axial heat flow.

Various attempts were made in the present investigation to correlate the experimental data. The effect of a variable heat transfer coefficient as well as the effects of axial conduction were taken into account. However, due to available experimental data, such as accurate wall temperature distribution, various assumptions were required in order to proceed with the analyses. A somewhat simplified analysis is shown in the following sections. This analysis does not require more information than that available from the experiment. The numerical results of this simplified analysis are not very different from those obtained by the other techniques. The simplicity of this solution makes it the most attractive.

The local heat balance between the pipe wall and the air can be written as

$$h_g (T_{gi} - T_w) \pi D dx = \pm \dot{m}_l C_p dT_l,$$

where the thermal potential is the difference between the local wall temperature (T_w) and the free stream temperature (T_{gi}) of the gas. The $\pm$ sign on the right hand side refers to parallel or counter flow of the liquid.

Similarly, the local heat balance between the pipe and the liquid can be written as

$$\alpha h_{\ell} (T_w - T_{\ell}) \pi D dx = \pm \dot{m}_{\ell} C_p dT_{\ell}.$$

Here α is a correction factor relating the surface area ratio between the liquid carrying coil and that of the pipe.

Adding these two equations, yields a differential equation expressing the liquid temperature

$$T_{gi} - T_{\ell} = \pm \frac{\dot{m}_{\ell} C_p}{\pi D U} \frac{dT_{\ell}}{dx},$$

where
$$\frac{1}{U} = \frac{1}{h_y} + \frac{1}{\alpha h_{\ell}}.$$

The boundary condition may, for instance, be the inlet temperature of the liquid, i.e., at $x = 0$, $T_{\ell} = T_{\ell i}$.

The solution to the equation using the boundary condition is

$$T_{\ell} - T_{gi} = (T_{\ell i} - T_{gi}) \exp \left[\mp \frac{\pi D U}{\dot{m}_{\ell} C_p} x \right].$$

Using this solution in the equation of heat balance between the wall and the liquid, yields a solution to the wall temperature distribution

$$T_w - T_{gi} = (T_{\ell i} - T_{gi}) \left(1 - \frac{U}{\alpha h_{\ell}} \right) \exp \left[\mp \frac{\pi D U}{\dot{m}_{\ell} C_p} x \right].$$

With the aid of the liquid temperature distribution, this equation may be rewritten as

$$T_w - T_{gi} = (T_{\ell} - T_{gi}) \left(1 - \frac{U}{\alpha h_{\ell}} \right).$$

From here, using the definition of U , it can be shown that

$$1 + \frac{h_g}{\alpha h_{\ell}} = \frac{T_{\ell} - T_{gi}}{T_w - T_{gi}}$$

It should be noted that the above expression, relating the ratio between the heat transfer on the gas side to that on the liquid side, may be evaluated at any point along the pipe (e.g. the inlet or the exit).

In order to present the equation in a more familiar form, the equation for the liquid temperature distribution is rewritten and evaluated at the end point (exit),

$$\frac{T_{lx} - T_{gi}}{T_{li} - T_{gi}} = \exp \left[\mp \frac{\pi D U}{\dot{m}_l C_p} L \right],$$

or

$$\ln \left[\frac{T_{lx} - T_{gi}}{T_{li} - T_{gi}} \right] = \mp \frac{\pi D L U}{\dot{m}_l C_p}.$$

Using the definition of U, the right hand side may be written as

$$\frac{\pi D L U}{\dot{m}_l C_p} = \frac{\pi D L}{\dot{m}_l C_p} \frac{h_g}{\left[1 + \frac{h_g}{\alpha h_l} \right]}.$$

Next, the global heat balance, which expresses the overall heat exchange between the liquid and the gas, is written

$$-\dot{m}_g C_{pg} (T_{gx} - T_{gi}) = \pm \dot{m}_l C_p (T_{lx} - T_{li})$$

Where T_{gx} is a mixing cup temperature of the gas at the exit.

With the last two equations, one may write

$$\ln \left[\frac{T_{lx} - T_{gi}}{T_{li} - T_{gi}} \right] = \frac{\pi D L}{\dot{m}_g C_{pg}} \frac{(T_{gx} - T_{gi})}{(T_{lx} - T_{li})} \frac{h_g}{\left[1 + \frac{h_g}{\alpha h_l} \right]}.$$

By definition, the heat transfer coefficient, or the Stanton number is

$$C_H = \frac{h}{\rho C_p V} = \frac{h}{\frac{\dot{m}}{A} C_p}$$

where A is the flow cross section area.

Hence

$$C_H = \frac{h_g A}{\dot{m}_g C_{pg}} = \frac{\ln \left[\frac{T_{lx} - T_{gi}}{T_{li} - T_{gi}} \right]}{\left[\frac{T_{lx} - T_{li}}{T_{gx} - T_{gi}} \right] \left[1 + \frac{hg}{\alpha h_\ell} \right]}$$

where

$$1 + \frac{hg}{\alpha h_\ell} = \frac{T_\ell - T_{gi}}{T_w - T_{gi}}$$

evaluated at either end of the pipe.

Data from the simulator experiments have been correlated using the above equations as shown in Figure 4-6. From the cross section area between the inlet guide vanes it is estimated that the ratio between the resultant velocity to the axial velocity (q/u) in the simulator is close to 7.5. The data for the swirl test seems to be bounded by the lines of $q/u = 6$ and $q/u = 12$. These lines were computed using the analysis presented in Section 2-2. The "no swirl" data is scattered around the $q/u = 1.0$ line which is the line for turbulent flow at the entrance region to a pipe taken from figure 4-5.

Two main conclusions can be drawn. First, there is no difference between the hot and the cold wall cases. As shown in section 2-2, the criterion under which a buoyancy effect is important is the Monin-Obukov length. For the temperatures employed in these experiments, the Monin-Obukov length has been shown to be large compared to the simulator diameter or the boundary layer thickness. Under these conditions buoyancy effect is small as the data indicates.

Figure 4-6. STANTON NUMBER VS. REYNOLDS NUMBER BASED ON LENGTH.

The other important effect shown is the significance of swirl. Swirl definitely increases the heat transfer coefficient and by analogy, the mass transfer. This result is in agreement with the analysis.

Finally, the results of this experiment pointed out the correct approach for the analysis of the heat transfer in a cyclone combustor. Specifically, the boundary layer growth, being independent of the azimuthal direction, dominated by the Reynolds number based on the resultant velocity rather than the axial velocity of the flow. This approach provides a better correlation with the data and it has a direct impact upon the combustor performance analysis.

4.4 RECOMMENDATIONS

The one subject not covered so far by the simulator experiment is that of wall roughness. It remains to be shown that wall roughness may significantly affect the heat transfer as predicted by an earlier analysis [12]. It is recommended to use the same experimental set up with various degrees of wall roughness (measured as equivalent sand height) for measurements of the heat transfer. Basically, the roughness promotes turbulence on a large scale. The large scale turbulence is the primary mechanism responsible for heat transfer.

Another subject which was not explicitly shown is the effect of buoyancy. Although the roughness effect may be larger by order of magnitude, the buoyancy effect may still be important in promoting mass and energy transfer in large combustion hardware. Extremely large temperature difference between the wall and the flowing medium in the simulator is needed to demonstrate this effect. That may be accomplished however, by resistance heating of the walls or by using cryogenics for wall cooling.

It is believed that both experiments, that of wall roughness and that of buoyancy, have an importance beyond the academic interest and may influence cyclone combustor modeling.

5. COAL COMBUSTOR TESTS

5.1 OBJECTIVES AND ENGINEERING CONSIDERATIONS

The primary objective of the program was to test a large scale 20 MW thermal combustor to assess combustor performance in the approximate limits of volume burning and wall burning. The data is expected to provide inputs to the modeling effort to provide scaling laws for building larger, more expensive hardware. Burning coal particle trajectory calculations were made in helping to arrive at the test conditions and in specifying coal parameters. Special emphasis was placed on testing 100% - 325 M ($d < 43 \mu\text{m}$) and 100% - 10 M, 0% - 100 M ($150 < d < 2000 \mu\text{m}$) coals for which predominantly volume burning and wall burning, respectively, were anticipated. Montana Rosebud coal, currently specified by DoE for testing MHD pulverized coal combustor hardware, was used in this test series (Section 5.2.4).

Performance was evaluated on the basis of combustor pressure and temperature, percent carbon burnout, and slag capture. According to predictions, it was anticipated that the fine coal would burn completely in the volume, exhibit high carbon burnout, but have poor slag capture. On the other hand, the coarse coal should burn partly in the volume but predominantly at the wall. From earlier studies [12] and the wall heat transfer studies presented here (Section 4), it is concluded that entrainment of the air from the core into the boundary layer is rapid enough to provide complete combustion at the wall. In this regard, if it is assumed that chemical kinetic processes are not limiting combustion, then it is believed that burning at the wall is complete.

5.2 HARDWARE AND TEST CONDITIONS

5.2.1 Combustor Configuration

The 20 MW coal combustor was designed and fabricated under a Department of Energy contract to develop a high pressure pulverized coal combustor capable of producing exhaust gases having the proper temperature, electrical conductivity and uniformity required for magnetohydrodynamic (MHD) power generation. An isometric view of the 20 MW combustor is shown in Figure 5-1. This combustor was designed for two stage operation but is capable of performing as a single stage device.

Figure 5-1. 20 MW THERMAL COMBUSTOR.

All the combustor internal walls are water cooled bare metal walls, with slag retention pins distributed across the internal surface. A double-wall construction is used throughout to provide the necessary cooling water passages. The outer wall serves as the pressure shell and the inner liner serves as the water jacket.

The slagging stage combustor section is a cylinder approximately 23 inches in diameter and 60 inches long and includes the volute section which has an axial length of approximately 9 inches. The slag baffle orifice is 12 inches in diameter and is designed as an integral part of the volute section.

In the first or slagging stage, air is injected into the section tangent to the combustor wall and normal to the combustor axis. A single-point, variable-area air inlet control system is used to achieve the required control on air inlet velocity.

The coal injector is located on the combustor axis in the head end assembly, and pulverized coal is injected into the combustion chamber as a conical sheet for effective mixing. The coal injector is designed to permit axial position changes as well as injection velocity changes.

The combustor is designed to operate with a bare metal wall and without the use of refractory insulation for thermal control. Mechanical slag retention pins are used on the combustor walls to initiate rapid slag buildup, to hold the slag to the walls and to maintain a uniform slag layer. Test results indicate that the slag layer thickness varies as a function of operating conditions.

Coal and slag particles are centrifuged to the wall due to the swirling flow in the combustor. The aerodynamic shear force on the wall causes the slag to flow along the wall and into the slag tank entrance. Slag particles too small to be centrifuged to the wall, and those which vaporize in the combustor flow out of the combustor, but are captured in the wet scrubber which follows the combustor.

5.2.2 Test Set Up

During tests #075 through #077, the second stage hardware required for MHD test conditions were installed. This second stage extension

included an inlet transition section, oxidizer injector ring and Performance Evaluation Module (PEM) which accounted for an additional 22 inches in length having a cross-sectional area of 30.93 in². The throat was attached to the PEM and for this series of tests the throat cross-sectional area was 12.6 in². This test set-up has been shown in Figure 5-2.

The test configuration was altered for the second series of tests #109 and #110 by removal of the second stage hardware and attachment of the throat directly onto the volute exit. This throat section was larger than that previously used with a cross-sectional area of 16.0 in². This test set-up is shown in Figure 5-1. See Figure 5-3 for combustor dimensions.

5.2.3 Combustor Pinhole Camera

As part of this program, a pinhole video camera was developed to observe combustion phenomena in various regions of the combustor. Because there is so little information on the combustion gas and slag flow patterns within the combustor it was intended to gain insight in these areas. Real time video coverage of the tests provided information on slag motion along the walls, into the slag tank, and on ignition characteristics of the coal sheet emanating from the coal injection pintle.

The details of the design and a sequence of pictures recorded are contained in Appendix A.

5.2.4 Coal Preparation and Analysis of Coal and Slag

The raw coal (about 20 tons) was pulverized by an independent vendor* using a centrifugal impaction technique. Simultaneously the coal was segregated into three size cuts as follows:

- (a) 100% - 10 mesh, 0% - 100 mesh,
- (b) 75% - 200 mesh,
- and (c) 100% - 325 mesh.

Approximately 6.5 tons were produced in each size cut. The coal was then dried in air and shipped in sealed barrels to the test site. To facilitate in the interpretation of the test results, coal samples were taken for analyses as indicated below.

*Vortec Company, Compton, CA.

Figure 5-2. 20 MW THERMAL COMBUSTOR WITH PERFORMANCE EVALUATION MODULE (PEM).

Figure 5-3. COMBUSTOR DIMENSIONS (IN).

- (a) Coal - ultimate, proximate and mineral analysis.
- (b) Slag - carbon content, and mineral analysis.
- (c) Specific gravity of coal using the Liquid Pycnometer Method.
- (d) Visual analysis of slag and coal using Scanning Electron Microscopy.
- (e) Size distribution analysis.

To ensure a proper statistical sampling, each analyzed coal sample was assembled from representative quantities taken out of every barrel containing that specific coal.

The results of the chemical analyses are summarized in Tables 5-1, 5-2 and 5-3, corresponding to the coarse, medium and fine coals, respectively. The analyses of slag recovered in the slag tank (trap) and that from the scrubber are reported in the same tables.

The size distribution of the three coal size cuts and the Rosin-Rammler distribution coefficients were reported in Section 3, Figures 3-30, 3-31, 3-32 and 3-38. Burning features are shown in Figure 3-41.

5.2.5 Combustor Test Conditions

The nominal combustor test conditions are shown in Table 5-4. A 46-page detail Test Plan was also written and used by the test engineers in conducting the tests.

5.3 RESULTS AND CONCLUSIONS

5.3.1 Combustor Test Data

The combustor operating conditions and selected test data are shown in Table 5-5. The combustor was tested following an established test procedure whereby the various flow rates and combustor pressures were measured. Velocities were calculated from the measured flow rates, densities and areas. Further, the operation of the combustor at high pressure ensures a choked operation at the exhaust throat. This allows the combustion temperature to be calculated by use of the sonic formula for known flow area and measured pressure. The preheat temperature is measured by means of a thermocouple.

Table 5-1. COARSE COAL (100%-10 MESH, 0%-100 MESH) COAL SPEC. GRAV. = 1.4222 GM/CM³.

	VIRGIN COAL	SLAG FROM TANK	SLAG FROM SCRUBBER
<u>PROXIMATE ANALYSIS AS REC'D.</u>			
%Moisture	17.53		
%Ash	12.23		
%Volatile	31.14		
%Fixed Carbon	39.10		
	100.00		
Btu/lb	9029		
%Sulfur	1.14		
<u>ULTIMATE ANALYSIS AS REC'D.</u>			
%Moisture	17.53		
%Carbon	52.29		
%Hydrogen	3.71		
%Nitrogen	0.84		
%Chlorine	0.06		
%Sulfur	1.14		
%Ash	12.23		
%Oxygen (diff)	12.20		
	100.00		
<u>MINERAL ANALYSIS OF ASH</u> (Percent Weight Ignited Basis)			
Silica, SiO ₂	43.14	49.71	40.21
Alumina, Al ₂ O ₃	14.55	19.64	22.85
Titania, TiO ₂	0.72	0.73	1.32
Ferric Oxide, Fe ₂ O ₃	8.59	10.31	10.83
Lime, CaO	14.23	14.99	16.88
Magnesia, MgO	3.18	3.15	5.05
Potassium Oxide, K ₂ O	0.56	0.55	0.25
Sodium Oxide, Na ₂ O	0.39	0.24	0.34
Sulfur Trioxide, SO ₃	13.42	0.31	0.22
Phos. Pentoxide, P ₂ O ₅	0.16	0.05	0.05
Strontium Oxide, SrO	0.11		
Barium Oxide, BaO	0.77		
Manganese Oxide, Mn ₃ O ₄	0.18		
Undetermined	0.00	0.32	1.00
	100.00	100.00	100.00
Alkalies as Na ₂ O, Dry Coal Basis	0.11		
Silica Value	62.40		
Base:Acid Ratio	0.46		
T ₂₅₀ Temperature	2345°F		
Fouling Index	0.18		
Slagging Index	0.63		
%Carbon, Dry Basis		7.35	3.39

Table 5-2. MEDIUM COAL (75%-200 MESH) COAL SPEC. GRAV. = 1.3512 GM/CM³

	VIRGIN COAL	SLAG FROM TANK	SLAG FROM SCRUBBER
<u>PROXIMATE ANALYSIS AS REC'D.</u>			
%Moisture	15.87		
%Ash	9.48		
%Volatile	33.81		
%Fixed Carbon	40.84		
	<u>100.00</u>		
Btu/lb	9556		
%Sulfur	0.74		
<u>ULTIMATE ANALYSIS AS REC'D.</u>			
%Moisture	15.87		
%Carbon	56.30		
%Hydrogen	3.87		
%Nitrogen	0.70		
%Chlorine	0.03		
%Sulfur	0.74		
%Ash	9.48		
%Oxygen (diff)	13.01		
	<u>100.00</u>		
<u>MINERAL ANALYSIS OF ASH</u> (Percent Weight Ignited Basis)			
Silica, SiO ₂	42.87	55.01	37.79
Alumina, Al ₂ O ₃	16.17	17.31	16.31
Titania, TiO ₂	0.86	0.73	0.74
Ferric Oxide, Fe ₂ O ₃	4.69	6.79	23.17
Lime, CaO	16.02	14.54	15.19
Magnesia, MgO	4.27	3.11	4.03
Potassium Oxide, K ₂ O	0.42	0.60	0.66
Sodium Oxide, Na ₂ O	0.43	0.53	0.35
Sulfur Trioxide, SO ₃	13.29	0.19	0.67
Phos. Pentoxide, P ₂ O ₅	0.28	0.17	0.24
Strontium Oxide, SrO	0.17	0.09	0.10
Barium Oxide, BaO	0.31	0.62	0.48
Manganese Oxide, Mn ₃ O ₄	0.22	0.19	0.27
Undetermined	0.00	0.12	0.00
	<u>100.00</u>	<u>100.00</u>	<u>100.00</u>
Alkalies as Na ₂ O, Dry Coal Basis	0.08		
Silica Value	63.18		
Base:Acid Ratio	0.43		
T ₂₅₀ Temperature	2375°F		
Fouling Index	0.18		
Slagging Index	0.38		
%Carbon, Dry Basis		0.36	1.11

Table 5-3. FINE COAL (100%-325 MESH) COAL SPEC. GRAV. = 1.3725

	VIRGIN COAL	SLAG FROM TANK*	SLAG FROM SCRUBBER*
<u>PROXIMATE ANALYSIS AS REC'D.</u>			
%Moisture	13.70		
%Ash	13.51		
%Volatile	33.89		
%Fixed Carbon	38.90		
	<u>100.00</u>		
Btu/lb	9296		
%Sulfur	0.67		
<u>ULTIMATE ANALYSIS AS REC'D.</u>			
%Moisture	13.70		
%Carbon	54.45		
%Hydrogen	3.86		
%Nitrogen	0.81		
%Chlorine	0.08		
%Sulfur	0.67		
%Ash	13.51		
%Oxygen (diff)	12.92		
	<u>100.00</u>		
<u>MINERAL ANALYSIS OF ASH</u> (Percent Weight Ignited Basis)			
Silica, SiO ₂	43.79	51.18	46.79
Alumina, Al ₂ O ₃	24.61	18.92	24.01
Titania, TiO ₂	0.87	0.88	0.88
Ferric Oxide, Fe ₂ O ₃	4.68	9.51	6.07
Lime, CaO	10.86	14.80	16.08
Magnesia, MgO	3.21	2.60	3.75
Potassium Oxide, K ₂ O	0.68	0.47	0.33
Sodium Oxide, Na ₂ O	0.27	0.32	0.27
Sulfur Trioxide, SO ₃	10.21	0.14	0.14
Phos. Pentoxide, P ₂ O ₅	0.41	0.18	0.05
Strontium Oxide, SrO	0.10		
Barium Oxide, BaO	0.17		
Manganese Oxide, Mn ₃ O ₄	0.14		
Undetermined	0.00	1.00	1.63
	<u>100.00</u>	<u>100.00</u>	<u>100.00</u>
Alkalies as Na ₂ O, Dry Coal Basis	0.11		
Silica Value	70.02		
Base:Acid Ratio	0.28		
T ₂₅₀ Temperature	2570°F		
Fouling Index	0.08		
Slagging Index	0.22		
%Carbon, Dry Basis		1.29	0.13

*Additional analyses, and SEM of slag is given in Appendix C.

Table 5-4. NOMINAL COMBUSTOR TEST CONDITIONS.

- CONDITIONS:

- Power Level $P \approx 20 \text{ MW}_{\text{th}}$
- Chamber Pressure, $p_c = 6 \text{ atm}$
- Stoichiometry, $\phi \approx 1.0$
- Temperature, $T_c = 4000^\circ\text{F}$
- 3 Coal Sizes -- $0-325$; $75 \pm 5-200$; $0-100$, $100-10$
- Preheat, $T_{\text{ph}} = 2900^\circ\text{F}$

- PERFORMANCE MEASUREMENT:

- Chamber Pressure, p_c
- Chamber C^* Temperature, T_c^*
- Heat Transfer, Q_L
- Carbon Burnout, %
- Slag Capture, %
- Gas Composition CO , CO_2 , %

- DIAGNOSTICS:

- Pinhole Camera

Table 5-5. COMBUSTOR TEST DATA

TEST #	W _{AIR} lb/sec	V _{AIR} ft/sec	W _{COAL} lb/sec	V _{COAL} ft/sec	PERCENT SLAG RECOVERY		PCH psia	MM _T Btu/sec	Ø	% O ₂ by wt	T _{GAS} °F max
					SLAGGING STAGE	OVERALL					
075	4.65	177.5	.85	45.5	78.1%	92.7%	79	14116	.86	23.2	4682
076	4.65	130.7	.94	46.1	23.1%	43.0%	78	15080	.86	23.2	4589
077	4.64	180.0	.96	45.5	23.9%	48.8%	79	15140	.76	23.2	4645
109	4.65	208.0	.96	53.0	51.9%	94.8%	68	15570	.72	23.2	4656
110	4.65	375.0	1.00	53.7	45.7%	92.4%	67	16019	.70	23.2	4677

TEST #	PREHEAT °F	COAL CHARACTERISTICS			PERCENT HEAT LOSS		COMMENTS
		%H ₂ O	%ASH	MESH SIZE	SLAGGING STAGE	OVERALL	
075	2895	17.53	12.23	100	9.6	13.6	overall combustor slag coverage good, poor carbon burn out in slag in tank
076	2912	13.70	15.66	325	10.2	14.1	overall combustor slag coverage good black/glassy appearance-hotter than #075
077	2941	13.70	15.66	325	9.9	13.6	overall combustor slag coverage good black/glassy overall
109	2930	15.87	9.48	200	7.2	10.9	overall combustor slag coverage good, slag in head end region indicative of running cold
110	2900	15.87	9.48	200	7.7	11.1	same as #109

W_{AIR} = preheat air flowrate

Ø = stoichiometry (0 < 1, fuel rich)

V_{AIR} = preheat air velocity at inletT_{GAS} = calculated combustion temperatureW_{COAL} = coal flowrate%O₂ = in vitiated preheat airV_{COAL} = coal velocity at pintle exit

PCH = combustor pressure at headend

MM_T = thermal energy added to gas

Slag recovery is evaluated by weighing the slag captured in both the tank and the scrubber. Slag capture is reported as a percent of the total ash content of the coal for both the slagging stage (slag tank) and total system.

Heat loss as a percent of thermal input is obtained by calorimetry from the temperature rise of the cooling water.

Based on the data presented here and the analyses presented earlier, the combustor performance is evaluated next.

5.3.2 Data Interpretation and Analysis

5.3.2.1 Carbon Burnout

In this section, attention is directed toward two key features of combustor performance: carbon burnout and slag capture. It is intended that the data be used to guide the code development and to improve its predictive capability.

The first point to be addressed is carbon burnout. Tables 5-1 through 5-3 include a compilation of the coal and slag specifications and Table 5-5 contains combustor performance data, pressure and calculated temperature mentioned earlier. The two key indicators of carbon burnout are

- (1) Evidence of unburned carbon captured in the slag tank and scrubber and,
- (2) Measurements of combustor pressure.

One might expect a larger fraction of unburned carbon for the test operating with the coarse coal than for the fine coal tests. This is because a larger fraction of unburned coal is centrifuged to the wall when using coarse coal rather than fine coal. Recall that the pretest calculations predict that about 60% of the coal is swirled (heated but unburned) to the wall under nominal operating conditions (see Figure 3-41, 100% - 10 M).

The data shows that unburned carbon represented only 7% of the slag captured. This result can be expressed as a fraction of the coal flow rate by the following formula:

$$\frac{\dot{m}_{c \text{ slt}}}{\dot{m}_c} = \frac{\dot{m}_{c \text{ slt}}}{\dot{m}_{\text{slt}}} \times \frac{\dot{m}_{\text{slt}}}{\dot{m}_{\text{sl}}} \times \frac{\dot{m}_{\text{sl}}}{\dot{m}_c}$$

where

$\dot{m}_c$ = flow rate of coal

$\dot{m}_{c \text{ slt}}$ = flow rate of unburned carbon captured by the slag tank

$\dot{m}_{\text{sl}}$ = flow rate of total slag or ash (inorganic content of coal)

$\dot{m}_{\text{slt}}$ = flow rate of slag captured by slag tank.

By substituting measured values for these ratios for Test 75, from the various tables in this section, the loss of unburned carbon expressed as a fraction of the coal flow rate is

$$\frac{\dot{m}_{c \text{ slt}}}{\dot{m}_c} = 0.006.$$

Expressed as a fraction of carbon flow rate, a value of about .015 is obtained. Thus, it is observed that the amount of unburned carbon is quite small. Had this been a large fraction, some significant change in combustor pressure would have been observed between this case (Test 75) and the fine coal tests (76 and 77). For this fine coal, an order of magnitude more complete burnout was observed, i.e.,

$$\frac{\dot{m}_{c \text{ slt}}}{\dot{m}_c} = .0006.$$

For the fine coal in which combustion occurs almost entirely in the volume (see Section 5.3.2.2), the above result was expected. Considering the high performance of the combustor with coarse coal in which 60% of the combustion was predicted to occur at the wall, carbon burnout was still very good. This supports the hypothesis that wall burning in swirl burners is very efficient.

5.3.2.2 Slag Capture

The burning coal particle trajectory code (see Section 2) was used to calculate particle impact points for both coarse and fine coals, Figures 5-4 and 5-5, respectively. (Ancillary calculations of particle temperature, mass loss and time as a function of position are shown in Appendix B.) It was assumed that only the particles having trajectories which pass through the slag baffle (or orifice) are lost. Thus it is assumed for convenience that particles impacting the end wall become part of the wall slag layer which eventually ends up in the slag tank. The two figures show that these particles have burned out rather early in their trajectories so that only slag particles exist at the exit plane. From the particle drag size distributions and Figures 5-4 and 5-5, estimates have been made of the mass fraction of slag trapped. These estimates are 83 and 13% for the coarse and fine coals, respectively; 78 and 23%, respectively, were measured. Although reasonably good agreement is observed by way of the trend, not enough data are available to establish a correlation.

5.4 RECOMMENDATIONS

Because of the brevity of the current test series, some questions remain and others have arisen which could be answered or clarified by further testing. This testing should be conducted at large scale, 20-50 MW_T level as this approach appears to hold the most promise for improving our predictive capability for scaling to still larger hardware. Therefore it is recommended to conduct further tests, with adequate diagnostics, to accomplish the following:

- (1) Evaluate advanced concepts for providing better slag capture. The approach will be closely guided by past experience at TRW and elsewhere, systems requirements, and our analytical models.
- (2) Improve the pinhole camera diagnostics. Several small modifications are necessary to extend its performance:
 - a) convert from a black and white to a color vidicon,
 - b) build an entrainment design to eliminate the slag "bridging" problem, and (c) convert the receiver to accept a radiometer and monochromometer to measure total radiation and spectral content. An evaluation and implementation of this camera or another technique to measure particle dynamics and burning near the wall is needed.

Figure 5-4. BURNING COAL PARTICLE TRAJECTORIES FOR COARSE COAL, 0% - 100 MESH, 100% - 10 MESH.

Figure 5-5. BURNING COAL PARTICLE TRAJECTORIES FOR FINE COAL, 100% - 325 MESH.

- (3) Measure detailed gas and particle concentrations over various regions in the combustor having locally fuel rich and lean operation. An existing probe developed by TRW for this purpose, can be used. These data are needed to improve our understanding of the various combustion zones and to improve our model for the analysis.
- (4) Conduct simple tests under low ϕ (gasification) conditions to evaluate mixing-reaction concepts to yield high value products, to improve our understanding of these processes and to evaluate the validity of the extensions proposed in the analysis section.

Appendix A

COMBUSTOR PINHOLE CAMERA

1. INTRODUCTION

This section describes a camera which was developed to observe combustion phenomena inside a high pressure (6 atm) slagging, pulverized coal combustor. The instrument incorporates a conventional TV video camera, external light filters coupled to the camera automatic gain control (agc), and an aerodynamic-window pinhole assembly. The pinhole assembly is shown in Figures A-1 and A-2. The pinhole assembly is 12 cm long with a major diameter of 5 cm and a minor diameter of 2 cm. Installation of the instrument on the head end of the TRW MHD Pulverized Coal Combustor is shown in Figure A-3. The fields of view from the combustor headend are shown in Figure A-4. The concept and design of this pinhole assembly will be described in some detail.

Two key features of the pinhole are that no material (glass) windows contact the combustion gases and very little gas purge is necessary to keep the optical train clear of combustion debris. Conventional glass window ports with gas purges generally cannot be kept clean in this combustion environment for test periods beyond a few minutes. The use of low purge rates minimizes the local and global aerothermodynamic disturbances to the observed phenomena.

The dynamic range of the TV camera was extended by several orders of magnitude by using an external circular variable filter wheel coupled to the camera agc. This feature also provided signal saturation protection to the vidicon tube.

In the sections which follow, discussion of the design, operation and results of this instrument will be presented.

2. PINHOLE DESIGN

2.1 CONCEPTUAL DESIGN

The conceptual design of the pinhole camera is shown in Figure A-5. Nitrogen gas flowing through the pinhole (orifice) provides an aerodynamic window which keeps the optics clean and, of course, in a remote position

Figure A-1. PHOTOGRAPH OF PINHOLE ASSEMBLY--FRONT VIEW.

Figure A-2. PHOTOGRAPH OF PINHOLE ASSEMBLY--REAR VIEW.

Figure A-3. PINHOLE CAMERA INSTALLED ON HEADEND OF TRW COMBUSTOR.

Figure A-4. FIELD OF VIEW FROM PINHOLE PORTS IN HEADEND

relative to the combustion gases and particulate. The focussed geometry of the convergent nozzle provides a large momentum flux of purge at the orifice to repel particles without using large amounts of gases which might dilute or disturb the combustion processes.

These same purge gases help cool the pinhole assembly. Additional water cooling was also provided adjacent to the purge manifold. A set of transfer lenses is used to optimize the field of view and focus the pinhole at the lens plane of a recording camera or vidicon. Not shown here is an external filter which was adjusted automatically so as to limit saturation of the recording camera.

2.2 DESIGN REQUIREMENTS

At this stage, special emphasis was placed on providing pinhole hardware which could demonstrate concept feasibility rather than the subtleties of an optimum design. The subsequent operating performance of the device would serve to improve the instrument in a second generation design.

The following technical requirements were established in order to provide a basis for the pinhole design.

- (1) Provide a purge configuration to repel combustion particulate and gases, keep hole clear of slag, cool pinhole assembly, and minimize combustor flow disturbances.
- (2) Provide additional external filters to safely extend the dynamic range of the TV camera (vidicon). These filters are to be integrated into the existing agc for the camera.

2.3 PURGE CONSIDERATIONS

2.3.1 Repulsion of Combustion Particulate

The force balance on a decelerating nonburning particle whose motion is opposed by the purge flow is

$$m \frac{du}{dt} = -C_D \frac{1}{2} \rho_j (u - u_j)^2 .$$

The time to decelerate the particle to zero velocity (i.e., time to stop and thence begin to repel the particle) is

$$t = \frac{4}{3} \frac{\rho}{\rho_j} \frac{d}{C_D} \frac{\frac{u_o}{u_j}}{u_j \left(1 - \frac{u_o}{u_j}\right)}$$

where,

ρ, ρ_j = particle and jet densities

u_o, u_j = particle initial velocity and jet velocity

d = particle diameter

C_D = drag coefficient

Now for conditions here

$$\frac{\rho}{\rho_j} = 10^2$$

$$d = 50 \times 10^{-4} \text{ cm}$$

$$C_D \approx > 1$$

$$u_o = 1500 \text{ cm/sec}$$

$$u_j = 3 \times 10^4 \text{ cm/sec (assures sonic flow through pinhole)}$$

then,

$$t \leq 10^{-6} \text{ sec.}$$

The distance travelled after this short interval is

$$x = \frac{1}{2} u_o t$$

$$= 8 \times 10^{-4} \text{ cm}$$

which is less than the particle diameter. Thus the purge level required

to keep the pinhole sonic is more than adequate to stop combustion debris from entering the pinhole.

2.3.2 Cooling of Pinhole

The pinhole is cooled to some degree by the purge. The amount of cooling has been estimated as follows to determine an equilibrium temperature

of the copper pinhole. The heat balance is

$$Q_{in} = Q_{out} = \int q \cdot n \, dA_s$$

where,

$$q = h(T_w - T),$$

$$h = C_H \rho u c_p,$$

$$\text{and } \rho u = \dot{m}/A.$$

One obtains,

$$Q_{in} = \frac{2C_H c_p \dot{m}(T_w - T)}{\sin\theta} \int_{R_o}^{R_l} \frac{dR}{R}$$

and thus,

$$(T_w - T) = \frac{Q_{in} \sin\theta}{2C_H \dot{m} c_p \ln \frac{R_l}{R_o}}$$

For our conditions...

$$q_{in} = 50 \frac{\text{Btu}}{\text{ft}^2 \text{ sec}} \frac{\pi(.9)^2}{4 \times 144} \text{ ft}^2$$

$$\Theta = 15^\circ \text{ (Half Angle)}$$

$$C_H = 0.003 \text{ (Re} = 5 \times 10^5\text{)}$$

$$c_p = 0.25 \frac{\text{Btu}}{\text{lbm}^\circ\text{F}}$$

$$R_\ell = 7 \text{ mm}$$

$$R_o = 1 \text{ mm}$$

$$\dot{m} = 0.02 \text{ lbm/sec}$$

The temperature difference becomes

$$(T_w - T) = 1000^\circ\text{F}$$

To insure that the assembly operates at a lower wall temperature, a water coolant passage was added to the pinhole assembly to provide additional cooling.

2.3.3 Purge Level for Slag Rejection

Continuous molten slag flow on the wall of the combustor would cover the pinhole unless the purge were adjusted to keep it clear.

The slag density and velocity are assumed to have the following values

$$\rho_{sl} = 1.5 \text{ g/cc}$$

$$u_{sl} = 1 \text{ cm/sec}$$

The gas purge conditions already specified for the jet emerging from pinhole exit plane are

$$\rho_j = 1.2 \times 10^{-2} \text{ g/cc}$$

$$u_j = 3 \times 10^4 \text{ cm/sec}$$

The condition to be satisfied to separate the slag flow at the orifice, is indeed satisfied, i.e.,

$$\rho_j u_j^2 \gg \rho_{sl} u_{sl}^2$$

2.3.4 Decay of Purge Disturbance

Disturbances to the combustor flow by the purge gases near the pin-hole will now be estimated. Although the jet momentum flux to cross stream momentum flux ratio is quite large, $\rho_o u_o^2 / \rho_s u_s^2 = \lambda$ of several hundred, the ratio of forces, decays rapidly with jet length

$$\frac{\lambda d_o^2}{d_j^2} \sim \frac{1}{x^2}$$

This follows from two key features of the jet: (1) linear growth, $d_j \sim x$, and (2) constant total momentum flux, $\rho_o u_o^2 d_o^2$. Thus, not only does the jet velocity decay as $1/x^2$, but the jet is also turned away into the cross stream direction.

A correlation by Keffer and Baines [57] of jet penetration is shown in Field [58]. At large extent, one obtains

$$\frac{y}{d_o \lambda} = 5.5 \left(\frac{x}{d_o \lambda} \right)^{2.175}$$

where y and x are the distances from the orifice in the cross flow and downstream directions, respectively. From the above correlation, the jet is swept out of the pinhole line of sight by $y \sim 2 d_o$ at a downstream distance of $x \sim 10 d_o$. For this pinhole, $d_o = 2$ mm. Downstream disturbances should be small for $x > 2$ cm.

2.4 PINHOLE OPTICS

2.4.1 Spatial Resolution

The resolution of a pinhole camera is essentially determined by the aperture and the distance to the object. For a pinhole, the Rayleigh resolution, δ , is

$$\delta = 1.22 \lambda f\#$$

where

$$f\# = \frac{L}{d_o}$$

L is the objective distance, 100³ cm, and d_o the aperture diameter, 0.2 cm. Choosing the wavelength in the red (.6 microns) the resolution becomes

$$\delta = 1.22 (.6) 500 = 3.66 \text{ microns.}$$

Since we do not expect to see microscopic detail, such resolution is acceptable provided that an 0.2 cm aperture can be purged to keep the slag clear.

Next, field of view needs to be considered. The port body is a 6.6 cm length of tube with a diameter of 22.8 mm. The pipe aspect ratio limits the field of view. To solve this problem a set of field lenses is provided to realy the combustor pinhole aperture to coincidence at the iris (aperture) of the vidicon. This is shown in the optical scheme in Figure A-5.

The lens nearest the combustor aperture is located a focal length from the pinhole. This lense accepts semi-paraxial rays from the object within

PINHOLE CAMERA PORT CONCEPTUAL DESIGN

Figure A-5. CONCEPTUAL DESIGN OF PINHOLE CAMERA

the field of view and relays them through the lens to a focal point between the first and second lens. Because the rays are paraxial they are brought to a focus at a distance equal to the focal length of the lens. Note, however that the directions of the received rays from an extreme off axis angle are collimated somewhat parallel to the axis of the centerline of the system. All rays entering the pinhole are generally made to go parallel to the axis.

The second lens then takes the rays, collimated from the first lens, and converges them to an image of the combustor pinhole. Note that the rays passing through the image of the pinhole have now become paraxial because they have been taken from a place at the focal length of the second lens. Thus, lens #1 is located a focal length's distance from the pinhole. Lens #2 is separated from lens #1 by twice the focal length, and finally, the imaged pinhole is located at one focal length from lens #2 (assuming lens #1 and #2 are identical). This scheme then provides a wide field of view although it suffers a loss of resolution due to the pinhole. Although the camera is located external to the combustor wall, the camera focus is set for the distance from the combustor wall to the region of interest.

2.4.2 Combustor Radiation

Now, one must consider the available light from the interior of the combustor through the pinhole. At 1600°K the black body radiation (.8 emissivity) of the combustor walls is 29 watts/cm² over the spectrum of 0.4 to 15 microns. The peak radiation occurs at 1.8 microns at which the line power radiation is 10.4 watts/cm². The power radiated in the visible (vidicon range) is 0.4 microns to 0.8 microns and represents 0.4% of the total radiated power, or 116×10^{-3} watts/cm². The pinhole aperture is 2 mm in diameter, and the power, p_o , radiated through the hole into a 2π steradian hemisphere is calculated as:

$$p_o = \frac{116 \times 10^{-3} \text{ watts}}{\text{cm}^2} \times \frac{1 \text{ cm}^2}{100 \text{ mm}^2} \times \frac{\pi(2 \text{ mm})^2}{4} = 3.64 \times 10^{-3} \text{ watts.}$$

The power intercepted by the first field lens (P_{L1}) of the optical relay system is less than the 2π steradian field. P_o then must be proportioned as the ratio of the solid angle times a factor of two because

of the Lambertian power distribution.

$$P_{L1} = \frac{2A_{L1}}{(f.l.)^2} \times \frac{P_o}{2\pi} \frac{(133) \text{ mm}^2}{(25.4)^2 \text{ mm}^2} \times \frac{3.64 \times 10^{-3}}{3.14} = 243 \times 10^{-6} \text{ watts}$$

where,

A_L = area of first lens;

f.l. = focal length of first lens; its distance to the pinhole.

This is the power impingent on the first lens.

2.4.3 Power Losses Through the Optical Train

Figure A-6 is the block diagram of the optical system. The figure differs from Figure A-5 by the addition of an uncoated window. Exterior to the port assembly are neutral density filters, a TV camera lens, and the vidicon aperture window.

Taking into account the reflection losses through the uncoated and coated optical elements, the throughput is reduced. Assuming a 4% per surface loss on uncoated surfaces and a 2% per surface loss on the coated surfaces the losses are:

<u>Power Level (Fig. A-2)</u>		<u>Loss Thru Optical Element (per surface)</u>
$P_{L1} = 243 \times 10^{-6}$ watts	impingent on 1st lens	4%
$P_{L2} = 224 \times 10^{-6}$ watts	impingent on 2nd lens	2%
$P_W = 215 \times 10^{-6}$ watts	impingent on window	4%
$P_{ND} = 198 \times 10^{-6}$ watts	impingent on ND wheel	4%
$P_C = 190 \times 10^{-6}$ watts	impingent on Camera lens	2%
$P_V = 183 \times 10^{-6}$ watts	impingent on vidicon	2%

If the vidicon has a 25.4 mm dia window then the available illumination in watts/cm² is:

$$\frac{183 \times 10^{-6} \text{ watts}}{5.07 \text{ cm}^2} = 36.1 \times 10^{-6} \text{ watts/cm}^2.$$

A comparison can now be made between the available power and the power requirements of a color TV camera.

Television Parameters. TV camera sensitivities for color are typified by 200 ft candles (ft cd) at the mean to 20 ft cd at a minimum. Damage to the vidicon occurs at about 600 to 800 ft cd. If the mean of 200 ft cd is converted to lumens/cm² we have:

$$200 \text{ ft cd} \times \frac{1 \text{ lumen}}{1 \text{ ft cd ft}^2} \times \frac{1 \text{ ft}^2}{(30.5 \text{ cm})^2} = \frac{.215 \text{ lumens}}{\text{cm}^2}$$

To convert to watts use the conversion of 200 lumens/visible band = 1 watt, versus the standard conversion of 680 lumens/green line = 1 watt, to account for the power distribution over the visible range of the vidicon. To operate at nominal conditions the color camera requires

$$\frac{.215 \text{ lumens}}{\text{cm}^2} \times \frac{1 \text{ watt}}{200 \text{ lumens}} = 1.08 \times 10^{-3} \frac{\text{watts}}{\text{cm}^2}$$

Similar calculations have been made for a monocular TV camera and are presented in Table 1.

2.4.4 Camera Choice

The decision to use either the color or black and white TV cameras was governed by the results shown in Table A-1. Since the total available light to the camera is 36×10^{-6} watts/cm², only the black and white camera would receive enough light to register a proper picture on the monitor. The color camera, with a threshold of 48×10^{-6} watts/cm², is below the required light level and at best would just barely produce a picture. Therefore, the black and white system was used. (We noted in subsequent operation during an actual test that there was enough light for color operation. The conversion to the color vidicon should be straight forward.)

Table A-1. PHOTOELECTRIC PROPERTIES OF TV CAMERA

CAMERA	SPECTRAL RANGE	MEAN LUMINANCE SENSITIVITY	THRESHOLD LUMINANCE SENSITIVITY	TUBE TYPE	INSTALLATION & REMARKS
Black & White Javelin Model SC821	0.4-0.8 microns	20 ft-cd $108 \times 10^{-3} \frac{\text{watts}}{\text{cm}^2}$	5 ft-cd $2.69 \times 10^{-6} \frac{\text{watts}}{\text{cm}^2}$	vidicon (std)	Dimensionally smaller. Optical centerline is lower to Table surface. Uses existing 75 Ω coax. AGC is accessible.
Color JVC Model G-71	0.4-0.8 microns	190 ft-cd $1.02 \times 10^{-3} \frac{\text{watts}}{\text{cm}^2}$	9 ft-cd $48.3 \times 10^{-6} \frac{\text{watts}}{\text{cm}^2}$	vidicon with striped filter	Optical centerline & overall dimensions are larger than the B&W camera. Transmission line is a special coax (non standard to CTS). No AGC access.

2.5 ATTENUATOR ELECTRONICS

2.5.1 Concept of Operation

The pinhole camera television monitoring system has been discussed in section 2.4 with reference to the amount of visible radiation passing through the pinhole optics. A description of the method adopted to limit the visible radiation power levels received by the vidicon follows.

The specifications of the Javelin Model SC821 TV camera indicate that at a light power level of $2.69 \mu\text{w}/\text{cm}^2$ as usage will begin to be produced in the vidicon, damage to the vidicon occurs for levels one-thousand times greater than this. In order to extend the power range from one thousand to one million, a motor driven variable neutral density filter was added. The control for filtering is integrated into the existing agc* of the camera.

The neutral density filter wheel is a glass wheel whose transmission varies linearly from 60° to 300° . The region from 0° to 60° is uncoated and essentially 90% transmitted. At a maximum density the attenuation by the filter is 1000 or ND 3.0.**

Positioning of the ND filter sector for a given light flux is governed by the internal TV camera's agc system. The agc is the negative feedback voltage that normally controls the gain of the video amplifier within the TV camera. Zero feedback voltage means maximum sensitivity (gain) to detect a very dimly illuminated subject. Conversely at high intensity light levels the agc voltage will be maximum. The camera's gain is adjusted in order to present an optimum contrast range to the TV screen.

Attenuator Electronics Design and Operation. By placing the ND filter wheel between the camera lens and the pinhole window port the camera electronics will adjust itself for the best picture using both the internal agc and the external ND filter wheel simultaneously (see Figure A-6). The nominal agc voltage is referenced against a potentiometer

* automatic gain control

**ND 3.0 means attenuation by a factor of 10^{+3} using a Neutral Density filter.

Figure A-6. OPTICAL BLOCK DIAGRAM.

voltage to determine a residual error voltage. The potentiometer output wiper is mechanically referenced to the ND filter wheel. The polarity of the error voltage determines the direction of the rotation of the filter wheel by a servomotor. As the motor turns, both the potentiometer and the ND filter wheel move until a null is reached. Should the error voltage be so great (maximum light) as to not null, the motor will continue to turn the potentiometer until the limit switch is activated to remove the driving voltage. Only by reversing the error voltage will the motor be capable of rotation in the opposite direction. Reactivation of the motor drive is possible through the bypass function provided by the diode (D_4), shown in the electrical schematic in Figure A-7 and Table A-2.

Referring to the electrical schematic the function of the electronic components and the resulting mechanical motion will be described. When the camera is installed on the combustor and the combustor is not activated, the TV camera will see total darkness. In darkness the agc circuits do not generate any voltage; hence, the operational Amplifier A_1 (non inverting) senses zero volts and will likewise produce a zero error current. The follow-up potentiometer R_6 , which is connected to the ND filter wheel, will provide a positive bucking current. These opposing currents are summed at the junction of R_4 , and R_5 such that no current flows through R_7 . Current through R_7 will generate an error voltage which will be amplified by Q_2 (inverting) to drive the motor, M_1 , toward the direction which reduces the follow-up potentiometer voltage. Zero output voltage from the potentiometer corresponds to the minimum attenuation sector of the ND filter and the motor will stop since Q_2 will have no error signal to amplify.

Now, when the combustor is activated, a hot air preheat is established in the combustor. The camera will then see a gradual increase in light level to some nominal level.

The Buffer Amplifier, Q_1 will track the negative agc voltage as the light level increases (with increasing air temperature) providing a current through R_4 and R_7 . The negative error voltage generated across R_7 then drives Q_2 to provide the positive voltage and current necessary to drive the motor clockwise. This moves the ND filter wheel into a

Figure A-7. PINHOLE TV CAMERA ATTENUATOR SERVO ELECTRONICS

Table A-2. COMPONENTS

R_1, R_3	1.1K Ω	Resistor
R_2	12K Ω	Resistor
R_4, R_5, R_7, R_{12}	10K Ω	Resistor
R_6, R_{13}	1.0K Ω	Resistor
R_8	130K Ω	Resistor
R_9	43K Ω	Resistor
R_{10}, R_{11}	.5M Ω	Resistor
Q_1	741	Op Amp
Q_2	LH0021	Op Amp
C_1	3000 pf	Capacitors
D_1	IN4001	Diode
D_2, D_3	IN4001	Diodes
D_4	In4001	Diode
M_1	28VDC	25 rpm Max Globe (Surplus) Motor
SW_1		Limit Switch

higher density region causing the light level on the vidicon to drop slightly. Both the agc and the potentiometer follow-up currents will decrease toward each other at different rates. The agc is very fast in comparison to the repositioning response time of the ND wheel. Different slewing rates prevent hunting oscillations from occurring. There is also a factor of approximately 1/4 in the response time for the motor to respond to an increase in light as to a decrease in light. The protective fast attenuation of the light into the vidicon is accomplished with the selective feedback network R_8 , D_1 and R_9 . The diode, D_1 , blocks the positive feedback current allowing only R_8 to provide the greater gain through Q_2 . A negative polarity on the motor drive voltage allows R_9 (in parallel to R_8) to carry current thus reducing the gain of Q_2 amplifier. The overall gain of Q_2 is set with R_{12} .

Further, when coal is injected into the combustor, the camera sees another rise in light intensity. The agc voltage will rise to saturation in the negative direction. The amplifier Q_2 also saturates in the high gain (positive output) direction causing the motor to race to attenuate the sharp rise in light level. When the null is approached the inertia of the motor will cause a back electromotive force (e.m.f.) to be generated (inductive kick) as the drive signals are reduced. The back e.m.f. would normally overload the amplifier Q_2 and burn it out except that diodes D_2 and D_3 hold the voltages to the ± 15 volt supply. Should the light levels be sufficiently high as to cause the motor to reach the limit switch, the agc will continue to govern an acceptable video signal until the agc voltage itself saturates causing blooming of the TV picture. The limit switch SW_1 will disable the motor when the ND wheel has reached its maximum attenuation region over the camera lens. The diode, D_4 , across the limit switch, is arranged such that if the motor drive voltage is reversed, the diode provides electrical continuity.

3. RESULTS

3.1 CALIBRATION PHOTOGRAPH

A checkout photograph shown in Figure A-8 was taken through the pin-hole assembly. The pinhole was located 1 meter from an eye chart illuminated

by a 120 watt flood lamp. A five second exposure was required using Type 52 Polaroid film (ASA 400). The field of view observed is 37 cm which corresponds to a total angle of about 22°.

3.2 COMBUSTION VIDEOTAPES

The use of the pinhole camera, once installed in either the combustor headend or slag tank, was highly successful. In the headend, a clear picture of the slag motion on the walls was observed while only the preheater was in operation. When the coal flow was initiated obscuration of the pinhole occurred very rapidly (with 1 to 2 seconds) as the flow transients decayed. A very interesting coal ignition sequence was recorded while purging the coal pintle of the 325 Mesh coal used in one of the test series.

Six polaroid pictures taken from the video replay screen are recorded in Figure A-9. The picture quality resulting from this first attempt at transfer is disappointing, but this penalty is, of course, small compared to the benefit of having real-time video coverage of these combustion phenomena. Each photograph records a view taken from the headend toward the slag baffle. In photograph (a), only the 2900°F air preheater is in operation, the coal not yet being injected. The dark cylindrical object on the left side is the coal pintle, the light background, hot slag and the dark right side, the slag baffle. Slag motion on the wall is easily observed on the video tape. The white splotches on the slag baffle are actually protuberances of molten slag moving circumferentially by the air shearing forces. In photograph (b), a very small amount of coal has been injected while in (c), ignition has occurred and in (d), the flame has encompassed the perimeter of the coal sheet. In photograph (e) the flame front has advanced along the sheet toward the pintle and in (f) the flame appears to be attached to the pintle exit. After this sequence, the burning coal sheet appeared to be convected back toward the camera and headend of the combustor. Subsequent viewing was obscured by a uniform bright background, apparently that of a uniform volume of burning particles. Besides this problem, another one which limited viewing of the combustion processes, was that the slag motion built a "streamlined" bridge over the pinhole orifice, blocking the view but not plugging the orifice itself. This problem can probably be minimized by using an

PINHOLE CAMERA PHOTOGRAPH

37 cm

PINHOLE LOCATED 1 METER FROM EYE CHART.
5 SEC EXPOSURE TYPE 52 POLOROID (ASA 400)
CHART ILLUMINATED AT 1 METER WITH 120 WATT FLOOD LAMP.
SMALLEST LETTERS 5mm WIDE.

Figure A-8. PINHOLE CAMERA PHOTOGRAPH

(a)

(d)

(b)

(e)

(c)

(f)

Figure A-9. PHOTOGRAPHS OF VIDEO SEQUENCE OF COAL IGNITION AT INJECTION PINTLE.

entrainment rather than flux mounted pinhole assembly so that the slag can flow around, rather than over the device.

APPENDIX B

CALCULATED PARTICLE BURNOUT PATTERNS

The following figures show the coal particle burnout patterns for various combustor operating conditions and coal size distributions. The analytical model and assumptions were discussed in detail in Section 2. The following symbols were used throughout the figures unless otherwise indicated.

KEY

	<u>Symbol</u>	<u>$d_p, \mu m$</u>
1	⊕	15.5
2	△	34.5
3	+	41.5
4	x	49.0
5	◇	58.0
6	⊕	69.0
7	⌘	82.5
8	⌘	98.0
9	Y	203.0

**CALCULATED PARTICLE BURNOUT PATTERNS
FOR
COARSE COAL, 0% - 100 MESH, 100% - 10 MESH,
DRAG SIZE DISTRIBUTION**

Figure B-1: PARTICLE TEMPERATURE VERSUS RADIAL POSITION IN THE COMBUSTOR

Figure B-2: BURNOUT MASS FRACTION VERSUS RADIAL POSITION IN THE COMBUSTOR

Figure B-3: RADIAL POSITION VERSUS TIME

Figure B-1. PARTICLE TEMPERATURE VERSUS RADIAL POSITION IN THE COMBUSTOR

B-4

Figure B-2. BURNOUT MASS FRACTION VERSUS RADIAL POSITION IN THE COMBUSTOR

Figure B-3. RADIAL POSITION VERSUS TIME

**CALCULATED PARTICLE BURNOUT PATTERNS
FOR
75 $\pm$ 5% - 200 MESH, DRAG SIZE DISTRIBUTION**

Figure B-4: PARTICLE TRAJECTORIES

Figure B-5: TEMPERATURE VERSUS RADIAL POSITION

Figure B-6: BURNOUT MASS VERSUS RADIAL POSITION

Figure B-7: RADIAL POSITION VERSUS TIME

B-7

Figure B-4. PARTICLE TRAJECTORIES

Figure B-5. TEMPERATURE VERSUS RADIAL POSITION

B-6

Figure B-6. BURNOUT MASS VERSUS RADIAL POSITION

Figure B-7. RADIAL POSITION VERSUS TIME

**CALCULATED PARTICLE BURNOUT PATTERNS
FOR
FINE COAL, 100% - 325 MESH, DRAG SIZE DISTRIBUTION**

Figure B-8: TEMPERATURE VERSUS RADIAL POSITION

Figure B-9: BURNOUT MASS FRACTION VERSUS RADIAL POSITION

Figure B-10: RADIAL POSITION VERSUS TIME

B-12

Figure B-8. TEMPERATURE VERSUS RADIAL POSITION

B-13

Figure B-9. BURNOUT MASS FRACTION VERSUS RADIAL POSITION

Figure B-10. RADIAL POSITION VERSUS TIME

CALCULATED PARTICLE BURNOUT PATTERNS:

**EFFECT OF PREHEAT TEMPERATURE
(Normal 200 Mesh Coal)**

	1500 °F	2000 °F	2400 °F	2900 °F
Particle Trajectories	B-11	B-12	B-13	B-14
Burnout Versus Radial Position	B-15	B-16	B-17	B-18
Temperature Versus Radial Position	B-19	B-20	B-21	B-22
Radial Position Versus Time	B-23	B-24	B-25	B-26

Figure B-11.

Figure B-12.

Figure B-13.

Figure B-14.

B-18

Figure B-15.

61-8

Figure B-16.

B-20

Figure B-17.

B-21

Figure B-18.

B-22

Figure B-19.

Figure B-20.

B-24

Figure B-21.

Figure B-22.

Figure B-23.

Figure B-24.

Figure B-25.

Figure B-26.

Figure B-27. EFFECTS OF VOLATILIZATION EXTENT AND PREHEAT TEMPERATURE ON TOTAL MASS LOSS

Appendix C

COMBUSTOR TESTS SLAG ANALYSIS

The chemical analysis and carbon content of the slag from the tests was shown in Tables 5-1, 5-2, and 5-3.

Two forms of slag were usually observed in the slag tank. One, a glossy black material and the other, a gray refractory-like porous matter, were both very brittle. SEM's and x-ray spectrum of both these materials are shown in Figures C-1 to C-4. The slag in the scrubber was typically brown-yellow and the SEM and x-ray spectrum of it is shown in Figure C-5 and C-6.

Although there is a definite difference in appearance and consistency of these slags, the overall compositions are not that different. Small differences in composition may be seen in the mineral analysis, but the difference in appearance is attributed to different modes of formation.

Figure C-1. SLAG FROM TANK, REFRACTORY-LIKE POROUS MATTER
(FINE COAL TEST).

11-JUL-80 11:03:25 STANDBY
 RATE: 3553CPS TIME 56LSEC
 00-20KEV: 10EV/CH PRST 100CSEC
 A: SAMPLE#2 1641BB: SEAL INC.
 FS= 5418 MEM: A FS= 200
 |02 |04 |06 |08 |10

CURSOR (KEV)=05.20

EDAX

Figure C-2. X-RAY SPECTRUM OF POROUS SLAG IN TANK (FINE COAL TEST).

Figure C-3. SLAG FROM TANK, BLACK GLOSSY MATTER, (FINE COAL TEST).

11-JUL-80 10:31:36 STANDBY
 RATE: 1818CPS TIME 79LSEC
 00-20KEV: 10EV/CH PRST 100CSEC
 A: SAMPLE #3 1639B: SEAL INC.
 FS= 2398 MEM: A FS= 200
 |02 |04 |06 |08 |10

CURSOR (KEV)=05.20

EDAX

Figure C-4. X-RAY SPECTRUM OF SLAG FROM TANK, BLACK GLOSSY MATTER (FINE COAL TEST).

Figure C-5. SLAG FROM SCRUBBER (FINE COAL TEST).

11-JUL-80 10:16:44 STANDBY
 RATE: 144CPS TIME 96LSEC
 00-20KEV: 10EV/CH PRST 100CSEC
 A: SAMPLE #1 B: SEAL INC.
 FS= 494 MEM: A FS= 200
 |02 |04 |06 |08 |10

CURSOR (KEV)=05.20

EDAX

Figure C-6. X-RAY SPECTRUM OF SLAG FROM SCRUBBER
(FINE COAL TEST).

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