AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

A-3
2

DOE/PC/92176--T6

**THERMODYNAMIC PROPERTIES OF PULVERIZED COAL DURING
RAPID HEATING DEVOLATILIZATION PROCESSES**

QUARTERLY PROGRESS REPORT

October - December 1993

Prepared by

W.M. Proscia
J.D. Freihaut

United Technologies Research Center
411 Silver Lane
E. Hartford, CT 06108

For

U.S. Department of Energy
Pittsburgh Energy Technology Center

Contract No. DE-AC22-92PC92176

DOE Contracting Officer's Representative

Clifford A. Smith

March 1994

DISCLAIMER

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

RECEIVED
MARCH 1994
DOE/PC/92176--T6

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ds

CONTENTS

1.0 Executive Summary	1
2.0 Introduction and Overview of Technical Objectives	2
3.0 Task 5. Heat of Thermal Decomposition of Volatile Coal Samples.....	5
4.0 Task 8. Specific Heat Of Char Samples	8
5.0 Task 10. Morphological Characterization of Coal/Char Samples as a Function of Extent of Devolatilization.	10
6.0 Planned Activities	12
7.0 References	13

1.0 Executive Summary

Knowledge of the thermodynamic and morphological properties of coal associated with rapid heating decomposition pathways is essential to progress in coal utilization technology. Specifically, knowledge of the heat of devolatilization, surface area and density of coal as a function of rank characteristics, temperature and extent of devolatilization in the context of rapid heating conditions is required both, for the fundamental determination of kinetic parameters of coal devolatilization, and to refine existing devolatilization sub-models used in comprehensive coal combustion codes.

The objective of this research is to obtain data on the thermodynamic properties and morphology of coal under conditions of rapid heating. Specifically, the total heat of devolatilization, external surface area, BET surface area and true density will be measured for representative coal samples. In addition, for one coal, the contribution of each of the following components to the overall heat of devolatilization will be measured: the specific heat of coal/char during devolatilization, the heat of thermal decomposition of the coal, the specific heat capacity of tars, and the heat of vaporization of tars.

The heat of decomposition of a HVA bituminous coal (PSOC 1451D) as a function of extent of reaction has been determined by application of Hess's Law to microbomb calorimetry measurements of the devolatilization products. The resulting heat of decomposition is endothermic at low extents of reaction and increases to about 440 cal/g coincident with the completion of the release of primary tars. The heat of decomposition then decreases to essentially zero at the maximum extent of reaction. These data imply that early in the devolatilization process endothermic bond breaking reactions predominate whereas at large extents of reaction endothermic bond scission reactions and exothermic reactions are in approximate balance.

The specific heat of PSOC 1451D chars as a function of extent of reaction has been determined. Chars at appreciable extents of reaction are observed to have higher effective heat capacities than the parent coal. Structural changes during devolatilization, primarily bond breaking, result in increased degrees of freedom and correspondingly higher heat capacity. All four chars exhibit an endothermic peak near 200°C with the magnitude of the peak exhibiting the order 796°C > 895°C ~ 660°C > 507°C. The 660°C, 796°C and 895°C chars are cenospheres, while the 507°C char is not. The thin shell of the cenospheres present a smaller mass transfer resistance to tar evolution resulting in higher mass loss at low temperatures. The higher measured effective heat capacity is a consequence of the heat of vaporization required to evolve this tar mass.

Morphological characterization of char samples was initiated this quarter. True density measurements using helium pycnometry and total surface area measurements using CO₂ adsorption for both the Pittsburgh #8 and Lower Kittanning coal. Both coals show an increase in true density as a function of extent of reaction due to the release of hydrogen-rich volatiles. Surface areas are also observed to increase as a function of extent of reaction, in agreement with results for similar coals reported in the literature.

2.0 Introduction and Overview of Technical Objectives

Introduction

Knowledge of the thermodynamic and morphological properties of coal associated with rapid heating decomposition pathways is essential to progress in coal utilization technology. Specifically, knowledge of the heat of devolatilization, surface area and density of coal as a function of rank characteristics, temperature and extent of devolatilization in the context of rapid heating conditions is essential to the fundamental determination of kinetic parameters of coal devolatilization. These same properties are also needed to refine existing devolatilization sub-models utilized in large-scale modeling of coal combustion systems.

In many instances the kinetic analysis of rapid coal devolatilization data acquired in laboratory reactors depends on an assumed set of heat capacity, heat of devolatilization and particle morphology parameters. In other cases, attempts to measure particle temperatures during devolatilization (Refs. 1,2,3) lead to results that are not in agreement either with a priori determinations obtained with energy balance expressions using estimations of thermodynamic properties of coal found in the open literature or inert, carbon-based calibration standards used to calibrate the reactor system. Although it is not always clear if the discrepancies are due to inadequate thermodynamic properties of the particle during devolatilization, particle shape factors, inadequate emittance values or some combination of these factors, it is now apparent that independent determinations of these properties in heating conditions characteristic of disperse phase coal utilization technology is necessary. Moreover, since it is now well-established that the energy transfer rate between an environment and injected coal particles, significantly influences the observable devolatilization response time of the particles (Ref. 4), the independent determination of the specific heat and devolatilization heat of reaction of coal is necessary.

Objective

The objective of this research is to obtain data on the thermodynamic properties and morphology of coal under conditions of rapid heating. Specifically, the total heat of devolatilization, external surface area, BET surface area and true density will be measured for representative coal samples. The coal ranks to be investigated will include a high volatile A bituminous (PSOC 1451D) and a low volatile bituminous (PSOC 1516D). An anthracite (PSOC 1468) will be used as a non-volatile coal reference. In addition, for one coal, the contribution of each of the following components to the overall heat of devolatilization will be measured: the specific heat of coal/char during devolatilization, the heat of thermal decomposition of the coal, the specific heat capacity of tars, and the heat of vaporization of tars.

Project Tasks

The work required to complete the objectives of this investigation has been divided into eleven tasks. Each of these tasks is summarized below. The details of the technical approach have been described previously (Ref. 5).

Task 1 - Project Work Plan

UTRC shall provide the DOE with a detailed Project Plan within 30 days of contract initiation. Work on no other tasks shall proceed until written approval of this plan is obtained by UTRC from the DOE Project Manager. The Project Plan shall include a Management Plan, Milestone Schedule, Status Report, and Cost Plan.

Task 2 - Calibration of the Heated Grid Calorimeter

UTRC shall measure the specific heat of the non-volatile reference coal (anthracite, PSOC 1468) from 25° C to 800° C at heating rates of 1000° C/sec and lower in the heated grid (HG) device. The values will be established relative to NBS calorimeter standards for differential scanning calorimeter (DSC) and differential thermal analysis (DTA) samples. The sensitivity of the heated grid device for determining thermodynamic properties at high heating rates will be established before proceeding with Tasks 3-9.

Task 3 - Low Temperature Specific Heat Capacity of Volatile Coal Samples

UTRC shall measure the specific heat capacity for a minimum of one coal sample over the temperature range of 25° C to 300° C. The measurements will be conducted at heating rates of 1000° C/sec and lower in the UTRC HG.

Task 4 - Heat of Devolatilization of Volatile Coal Samples

UTRC shall measure the heat of devolatilization for a minimum of one coal sample over the temperature range of 25° C to 800° C using heating rates of 1000° C/sec in the calibrated HG. Devolatilization product characteristics will be determined to ensure the devolatilization pathway is that followed in the entrained flow reactor (EFR).

Task 5 - Heat of Thermal Decomposition of Volatile Coal Samples

UTRC shall measure, using the EFR and microbomb calorimeter (MBC), the heat of decomposition for a minimum of one coal sample by: (1) devolatilizing the coal in the EFR, (2) determining the char, tar and gas yields, (3) measuring the tar and char elemental compositions, (4) determining the heat of combustion of the char and tar products using the MBC, (5) estimating the heat of combustion of the gaseous products, and (6) using Hess's and Kirchoff's laws to derive the heat of decomposition.

Task 6 - Specific Heat and Heat of Fusion of Tars from Rapid Heating

UTRC shall measure the specific heat and heat of fusion of tar samples for a minimum of one coal sample over the temperature range from 25° C to 300° C using the HG and tar samples generated in the EFR.

Task 7 - Heat of Vaporization of Tars from Rapid Heating

UTRC shall measure the heat of vaporization of tar samples for a minimum of one coal sample over the temperature range from 300° C to 700° C using the HG and tar samples generated in the EFR.

Task 8 - Specific Heat of Char Samples

UTRC shall measure the specific heat of the coal/char as a function of extent of devolatilization and temperature for a minimum of one coal sample using partially devolatilized samples from the EFR and the HG.

Task 9 - Comparison of Directly Measured Heat of Devolatilization and Thermodynamic Function Determined Value

UTRC shall determine the heat of devolatilization for a minimum of one coal sample based on independent measurements of heat of decomposition (Task 5), specific heat and heat of fusion of tars (Task 6), heat of vaporization of tars (Task 7), and specific heat of coal/chars (Task 3 and Task 8). This value shall be compared and contrasted to the directly measured heat of devolatilization values from 25° C to 800° C obtained in Task 4.

Task 10 - Morphological Characterization of Coal/Char Samples as a Function of Extent of Devolatilization

UTRC shall characterize statistically representative samples of coal/char particles as a function of extent of devolatilization for a minimum of one coal sample. The characterization shall be with respect to combustion related reactivity parameters such as swelling and cenosphere development, CO₂ or O₂ surface areas, and helium (true) density.

Task 11 - Reporting

UTRC shall comply with all required reporting over the 18 month period of the contract.

3.0 Task 5. Heat of Thermal Decomposition of Volatile Coal Samples

The heat of decomposition will be determined by application of Hess's Law to measurements or estimates of the heat of combustion of the parent coals and each of the products of devolatilization. The complete sequence of steps required to determine the heat of decomposition is as follows:

- (1) devolatilize the coal in the EFR,
- (2) determine the char, tar and gas yields,
- (3) measure the tar and char elemental compositions,
- (4) determine the heat of combustion of the parent coal, char and tar products using a microbomb calorimeter (MBC),
- (5) estimate the heat of combustion of the gaseous products, and
- (6) using Hess's and Kirchoff's laws to derive the heat of decomposition.

Hess's Law states that the enthalpy change for a reaction is equal to the sum of enthalpy changes for individual reactions that can be added together to give the desired reaction. Thus adding,

results in the equivalent reaction:

Therefore, the heat of decomposition is given by:

$$\Delta H_{\text{dec}} = \Delta H_{\text{comb}}^{\text{coal}} - \sum f_{\text{coal}}^i \Delta H_{\text{comb}}^{\text{product}_i} ,$$

where f_{coal}^i is the mass fraction yield of the i^{th} product.

Results for a HVA bituminous coal (PSOC 1451D) as a function of extent of reaction are presented in Table I. The calculations are based on raw, uncorrected values for the heats of combustion of the parent coal and char samples determined in the microbomb calorimeter. The " ΔH_{char} " and " ΔH_{tar} " columns in the table are $f_{\text{coal}}^{\text{char}} \cdot \Delta H_{\text{comb}}^{\text{char}}$ and $f_{\text{coal}}^{\text{tar}} \cdot \Delta H_{\text{comb}}^{\text{tar}}$, respectively. The total gas yields are the sum of the five IR-active species quantified with the FT-IR: CH₄, C₂H₄, C₂H₂, CO, and CO₂ plus 1.62% H₂O. Other species such as benzene and hydrogen cyanide are observed only at low levels and can be neglected in this analysis. Since H₂O was not measured it is estimated as equal to the equilibrium moisture content of the coal. The heats of combustion of the char, tar and light gases are plotted cumulatively in Fig. 1 as a function of extent of reaction. Also shown is the heat of combustion of the parent coal and the heat of decomposition determined by difference. The resulting heat of decomposition is endothermic at low extents of reaction and increases to about 440 cal/g at the 660°C gas temperature condition. The heat of decomposition then decreases to essentially zero at the maximum extent of reaction. These data imply that early in the devolatilization process endothermic bond breaking reactions predominate whereas at large extents of reaction endothermic bond scission reactions and exothermic reactions are in approximate balance.

Table I

Heat of Decomposition of PSOC 1451D

GAS TEMP (C)	% MASS LOSS (raw)	CHAR (BTU/LB) (raw)	CHAR (kcal/g)	ΔH_{char} (kcal/g)	% TAR	TAR (BTU/LB)	TAR (kcal/g)	ΔH_{tar} (kcal/g)
Parent Coal	0	12554	6.9750	6.9750	0			
507	14.3	12602	7.0017	6.0004	11.65	15100	8.3896	0.9774
660	27.8	12895	7.1645	5.1727	24.55	15143	8.4135	2.0655
796	25.6	12208	6.7828	5.0464	21.85	15150	8.4173	1.8392
895	37.2	11294	6.2749	3.9407	33.18	14895	8.2757	2.7459
GAS TEMP (C)	% CH ₄	% C ₂ H ₄	% C ₂ H ₂	% CO	% CO ₂	TOTAL GAS YIELD (%)	$\Sigma(f \cdot \Delta H)_{gas}$ (kcal/g)	ΔH_{dec} (kcal/g)
507	0.89	0.05	0	0	0.09	2.65	0.1244	-0.1272
660	1.21	0.15	0.01	0	0.26	3.25	0.1802	-0.4434
796	1.6	0.18	0.04	0.2	0.11	3.75	0.2441	-0.1547
895	1.56	0.24	0.09	0.1	0.41	4.02	0.2496	0.0389
Heat Comb.: (kcal/g) (H ₂ O) liq.	13.30	12.04	11.95	2.42	0.00			

4.0 Task 8. Specific Heat Of Char Samples

The objective of this task is to measure the specific heat of coal/char as a function of extent of devolatilization. PSOC 1451D has been devolatilized in the EFR to various extents of reaction. The chemical characteristics of the resulting chars were described previously (Ref. 6). A series of heated grid experiments have been performed to determine the mass loss of these partially devolatilized char samples as a function of final temperature. The raw data and sigmoid curve fits are plotted in Fig. 2. The mass loss curves are needed to process the heated grid data to obtain heat capacity values. Next sets of three replicate heated grid runs for each char were performed. The raw data was analyzed using the new analysis method described in Ref. 7. The resulting effective heat capacity curves for each char are shown in Figs. 3-6. Also, shown in the figures are average heat capacities for each char sample calculated by performing a cubic spline fit for each replicate run and averaging. Note that for the 507°C and 796°C chars one of the three replicate runs was discarded since the results were anomalous. The run-to-run variability is within a 10-15% band around the average for each char.

The average heat capacities for the four chars are compared with that for the parent coal, graphite, and the Merrick model in Fig. 7. The heat capacity of the 507°C char tracks that of the parent coal up to about 500°C at which point the coal exhibits a much steeper rise in heat capacity due to its correspondingly steeper mass loss vs. temperature curve. The other chars are observed to have higher heat capacities than the parent coal. Structural changes during devolatilization, primarily bond breaking, result in increased degrees of freedom and correspondingly higher heat capacity. All four chars exhibit an endothermic peak near 200°C with the magnitude of the peak exhibiting the order 796°C > 895°C ~ 660°C > 507°C. The 660°C, 796°C and 895°C chars are cenospheres, while the 507°C char is not. The thin shell of the cenospheres present a smaller mass transfer resistance to tar evolution resulting in higher mass loss at low temperatures. The higher measured effective heat capacity is a consequence of the heat of vaporization required to evolve this tar mass.

The morphological characterization of the chars at the University of Pittsburgh is not yet completed. However, morphological data for PSOC 1451D coal and chars devolatilized in the SANDIA entrained flow reactor were obtained in a previous investigation (Ref. 8). That study used the next larger size cut of the DOE "D" coals, 106-125 μm , and operated the reactor at peak gas temperatures of 581°C, 760°C and 1006°C. The morphological characteristics of these chars (Table II) should be similar to those generated in the UTRC EFR at 507°C, 796°C and 895°C peak gas temperatures. The data show an order of magnitude decrease in sample thickness as the solid coal particle, with 115 μm dia., swells and forms a cenosphere, with 4 μm shell thickness. Such a large change in the characteristic dimension for mass transfer resistance supports the hypothesis above that the reduced mass transfer resistance of the cenosphere char particles results in higher mass loss and correspondingly higher effective heat capacity as a result of the heat of vaporization required to vaporize the tars.

TABLE II Morphology of PSOC 1451D Parent Coal and Chars

T_{gas} (C)	Swell- ing Ratio	Shell Thick- ness (μm)	Mass Loss (%)	ρ_p (g/cc)	ρ_s (g/cc)	Poro- sity (%)	N₂ BET S.A. (m²/g)	Pore Vol. (cc/g)
(coal)	-	-	-	0.67	1.46	53	4.2	0.8
581	-	-	15	0.25	1.30	80	1.8	2.3
760	1.50	4.3	30	0.12	1.10	90	4.0	6.5
1006	-	-	-	0.12	1.27	90	6.0	6.1

5.0 Task 10. Morphological Characterization of Coal/Char Samples as a Function of Extent of Devolatilization.

This task is being performed under subcontract to the University of Pittsburgh under the direction of Prof. George Klinzing. The overall objectives of this task are to characterize statistically representative samples of coal/char particles as a function of extent of devolatilization. The characterization shall be with respect to combustion related reactivity parameters such as swelling and cenosphere development, CO₂ or O₂ surface areas, and helium (true) density. Analysis of chars of Pittsburgh #8 coal and Lower Kittanning coal was started in the reporting period. The properties measured and the observations made are given below:

True Density

Helium pycnometer measurements of the density of char samples were performed as done earlier for the parent coal samples. Samples were weighed and put in a cell in the instrument. Degassing was done in situ at about 6-7 psi below atmospheric pressure for 2 hours at room temperature. Results obtained are given in Table III. The data for Pittsburgh #8 coal and chars is plotted in Figure 8. Error bars are included which are based on standard deviation. Figure 9 shows the data for Lower Kittanning coal. Pittsburgh #8 coal shows a consistent increase in the density as a function of extent of devolatilization. This is due to the expulsion of hydrogen-rich volatiles which are lighter, resulting in a higher density material being left behind. Lower Kittanning coal shows similar results except for a small initial decrease.

Total Surface Area

Total surface area was determined by using the ORR pore volume analyzer from Micromeritics corporation. Samples were degassed at 60°C and 10⁻⁴ torr for 15 hours. Carbon dioxide adsorption was carried out at 298 K at 4 different pressures. For each measurement about 15 minutes were allowed for pressure stabilization before adsorption. Thirty minutes were allowed for adsorption equilibrium to be established. Total surface area was then calculated using the Polyani-Dubinin equation. The results are given in Table IV followed by percent regression values for linear data fit in Table V. Graphical representation is made in Figure 10. Again owing to the same reason as mentioned above, the surface areas are observed to be increasing consistently. Surface areas for Pittsburgh #8 rise more steeply than for the Lower Kittanning coal due to the higher volatile content. The Lower Kittanning coal shows a small decrease initially and then increases steadily. The results are consistent with those for similar coals reported in the literature (Refs. 9-13).

Table III**True density of coal and chars**

Run#	Pittsburgh #8					Lower Kittanning				
	Coal	507C Char	660C Char	796C Char	895C Char	Coal	507C Char	660C Char	796C Char	895C Char
1	1.402	1.434	1.434	1.506	1.578	1.513	1.525	1.574	1.622	1.667
2	1.387	1.437	1.432	1.49	1.575	1.509	1.514	1.566	1.615	1.666
3	1.39	1.441	1.433	1.504	1.576	1.509	1.524	1.551	1.631	1.665
4	1.393	1.421	1.465	1.448	1.522	1.513	1.464	1.541	1.587	1.615
5			1.526	1.478			1.491			
6			1.538				1.501			
Mean	1.393	1.433	1.471	1.485	1.563	1.511	1.503	1.552	1.614	1.653
Std Dev.	0.006	0.007	0.045	0.024	0.027	0.002	0.023	0.018	0.019	0.026

Table IV**Total Surface Area for Coal and Chars (m²/gm)**

	Coal	507C Char	660C Char	796C Char	895C Char
Pittsburgh #8	87.34	99.15	141.87	191.67	195.2
L Kittanning	114.07	104.05	150.84	176.95	196.75

Table V**Percent Regression for Linear fit of Data using Polanyi-Dubinin Method
(for Surface Areas listed in Table IV)**

	Coal	507C Char	660C Char	796C Char	895C Char
Pittsburgh #8	99.94	99.99	99.77	99.84	99.99
L Kittanning	99.96	99.99	99.99	99.82	99.85

6.0 Planned Activities

Work on Task 6, Specific Heat of Tars and Task 7, Heat of Vaporization of Tars, will be completed. The Task 10 effort, Morphological Characterization of Coal/Char Samples as a Function of Extent of Devolatilization, will continue at the University of Pittsburgh. In particular, determination of bulk density will be carried out next for the char samples followed by pore volume distributions using the mercury porosimeter. Next, image analysis will be started for size distribution, shape and petrology.

7.0 References

1. Fletcher, T.H., *Combustion and Flame*, **78** (2), 223-236 (1989).
2. Best, P.E., et al., *Combustion and Flame*, **66**, 47-56 (1986).
3. Maloney, D.J., et al., *Combustion and Flame*, **84**, 210-220 (1991).
4. Freihaut, J.D., et al., *Combustion Properties of Micronized Coal*, Final Report, DE-AC22-80263, DOE, PETC (1989).
5. Proscia, W.M. and Freihaut, J.D., *Thermodynamic Properties Of Pulverized Coal During Rapid Heating Devolatilization Processes*, Quarterly Report for July-Sept., 1992, DE-AC22-92PC92176, DOE, PETC (1992).
6. Proscia, W.M. and Freihaut, J.D., *Thermodynamic Properties Of Pulverized Coal During Rapid Heating Devolatilization Processes*, Quarterly Report for Jan.-March, 1993, DE-AC22-92PC92176, DOE, PETC (1993).
7. Proscia, W.M. and Freihaut, J.D., *Thermodynamic Properties Of Pulverized Coal During Rapid Heating Devolatilization Processes*, Quarterly Report for July-Sept., 1993, DE-AC22-92PC92176, DOE, PETC (1993).
8. Seery, D.J., et al., *Kinetics of Coal Pyrolysis*, Final Report, DE-AC22-84PC70768, DOE PETC (1989).
9. Cameron, A. and Stacy, W. O., "Changes in the Pore Structure of Coke during Carbonization and Gasification, " *Australian Journal of Applied Science*, Vol. 9, (1958), pp. 283-302.
10. Cameron, A. and Stacy, W. O., "The Pore Structure of Chars and Cokes, " *Australian Journal of Applied Physics*, Vol. 10, (1959), pp. 449-457.
11. Chiche, P., Durif, S. and Pregermain, S., "Development of the Internal Surface Area of Coals during Carbonization, " *Fuel*, Vol. 44, (1965), pp. 5-28.
12. Toda, Y., "A Study by Density Measurement of Changes in Pore Structure of Coals with Heat Treatment: Part 1. Macropore Structure, " *Fuel*, Vol. 52, (1973), pp. 36-40.
13. Tsai, Ching-Yi and Scaroni, A. W., "The Structural Changes of Bituminous Coal Particles during the Initial Stages of Pulverized-Coal Combustion, " *Fuel*, Vol. 66, (1987), pp. 200-206.

HEAT OF DECOMPOSITION VS. EXTENT OF REACTION PSOC 1451D

Figure 1

MASS LOSS FROM PARTIALLY DEVOLATILIZED CHARS IN THE HEATED GRID APPARATUS

Figure 2

507 AVG

EFFECTIVE HEAT CAPACITY OF 507°C CHARS

Figure 3

660 AVG

EFFECTIVE HEAT CAPACITY OF 660°C CHARS

Figure 4

EFFECTIVE HEAT CAPACITY OF 796°C CHARS

Figure 5

895 AVG

EFFECTIVE HEAT CAPACITY OF 895°C CHARS

Figure 6

Figure 7

Figure 8

True density for Pittsburgh #8 coal and its chars.
The error bars correspond to one standard deviation.

Figure 9

True density for Lower Kittanning coal and its chars.
The error bars correspond to one standard deviation.

Figure 10

Total Surface Area of Coals and their chars
(obtained by Poyani-Dubin Method).

**DATE
FILMED**

6/22/94

END