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DR-1148-7

DOE/PC/40267-5
(DE85010673)

COMBUSTION CHARACTERIZATION OF COALS FOR INDUSTRIAL APPLICATIONS

Final Technical Report for the Period January 1, 1981—May 29, 1985

By
Nsakala ya Nsakala
Ramesh L. Patel
Tony C. Lao

March 1985

Work Performed Under Contract No. AC22-81PC40267

For
U. S. Department of Energy
Office of Fossil Energy
Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania

By
Combustion Engineering, Inc.
Kreisinger Development Laboratory
Windsor, Connecticut

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

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(DE85010673)
Distribution Category UC-90a

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ACKNOWLEDGEMENTS

The authors appreciatively acknowledge various people at Combustion Engineering, Inc., for their contributions to the success of this program. Messrs. Dana R. Raymond, Rudy A. Jackobek, and Donald J. Holeman conducted all the Drop Tube Furnace System tests. Ms. Lorraine S. Miemiec and Messrs. Gary M. Tessier, Stanley R. Bohdanowicz, Mark Mirolli, David Warpula, Bruce Griffith, Glen Miemiec, Venkateswara Garimella and Oscar K. Chow conducted all the Controlled Mixing History Furnace tests. Ms. Christine E. Thompson and Messrs. Gilbert L. Hale, David E. Gaughan, Kurt W. Johnson, Joseph R. Fliss, Robert M. Easton, Douglas Sharpe, Arnold L. Tyler, Karl A. Poglitsch, Norman C. Borggard, and Robert E. Seaberg provided all the fuels analyses. Messrs. John G. Cogoli and Kees A. Bueters provided the computer programs. Messrs. Richard W. Borio and Gary J. Goetz, in their respective capacities as Manager of Fuels Technology and Supervisor of Fuels Research, provided constructive review of the test procedures, data reduction techniques, and a general guidance of this program.

The financial support of this program by the Department of Energy, Pittsburgh Energy Technology Center, under contract No. DE-AC22-81PC40267, is appreciatively acknowledged.

ABSTRACT

In-depth fundamental information was obtained from a two-inch inner diameter laminar flow reactor referred to as the Drop Tube Furnace System (DTFS). This information consists of the following: (1) pyrolysis kinetic characteristics of four coals of various rank (Texas lignite, Montana subbituminous, Alabama high volatile bituminous, and Pennsylvania anthracite); and (2) combustion kinetic studies of chars produced from the foregoing parent coals. A number of standard ASTM and special in-house bench scale tests were also performed on the coals and chars prepared therefrom to characterize their physicochemical properties. The pilot scale (500,000 Btu/hr) Controlled Mixing History Furnace (CMHF) was used to determine the effect of staged combustion on NO_x emissions control from and overall combustion performance of the Alabama high volatile bituminous coal.

The quantitative fundamental data developed from this study indicate significant differences in coal/char chemical, physical, and reactivity characteristics, which should be useful to those interested in modeling coal combustion and pyrolysis processes. These results underscore the fact that coal selection is one of the keys governing a successful coal conversion/utilization process. The combustion kinetic information obtained on the high volatile bituminous coal has been used in conjunction with Combustion Engineering's proprietary mathematical models to predict the combustion performance of this coal in the Controlled Mixing History Furnace. Comparison of the predicted data with the experimental results shows a virtually one-to-one scale-up from the DTFS to the CMHF. These data should provide vital information to designers in the area of carbon burnout and NO_x reduction for large scale coal utilization applications.

CONTENTS

TABLES

FIGURES

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

Objective

The Department of Energy's intent in sponsoring this and other related programs is to foster increased usage of our vast domestic coal reserves. To effectively use coal in existing and new applications requires a more definitive, quantitative understanding of coal properties vs. performance. As such, the objective of this program was to provide detailed data on the combustion characteristics of coals by burning them in well controlled bench and pilot scale reactors. The data were subsequently used to develop the methodologies that most reliably characterize coals from a pyrolysis/combustion standpoint thereby permitting accurate performance predictions to be made.

Technical Approach

Four coals were selected for this study on the basis of a balanced consideration of rank, geological region, and a variety of chemical and physical characteristics. They include a Texas (Wilcox) lignite, a Montana (Rosebud) subbituminous, an Alabama (Black Creek) high volatile bituminous, and a Pennsylvania (Buck Mountain) anthracite.

Standard ASTM (American Society for Testing and Materials) procedures along with special bench scale tests, the Drop Tube Furnace System (DTFS), and Controlled Mixing History Furnace (CMHF) were employed in this program. Standard ASTM tests consisted of proximate, ultimate, and screen analyses, higher heating value, ash composition, ash fusibility temperatures, and Hardgrove Grindability Index. Special bench scale tests consisted of Micro-Proximate and Micro-Ultimate (H, C, N) Analyses, Flammability Index, Pore Surface Area and Thermo-Gravimetric (TGA) Reactivity.

The Perkin-Elmer TGS-2 System was used to determine both the micro-proximate analyses of coals and chars and the thermo-gravimetric combustion reactivities of DTFS-generated chars in air. The Perkin-Elmer 240 Elemental Analyzer was used to determine micro-ultimate analyses of coals and chars.

The Quantachrome Corporation Surface Area Analyzer was used to measure both the N_2 and CO_2 adsorptions under specific conditions. These adsorption data were subsequently used in conjunction with the Brunauer, Emmett, and Teller (BET) and Dubinin-Kaganer gas adsorption principles (1, 2) to calculate the N_2 and CO_2 specific pore surface areas of coals and chars. The Flammability Index Apparatus was used to determine relative ignition temperatures of coals in an oxygen atmosphere.

The electrically-heated Drop Tube Furnace System was used to determine the pyrolysis and combustion characteristics of coals and/or chars in the 1450-2650°F gas temperature range. The heating rates encountered in the DTFS are commensurate with those encountered in practical systems. The reaction histories were monitored by solid/gas sampling at various points along the DTFS reaction zone, which is two inches in inner diameter and sixteen inches in length.

The pilot scale Controlled Mixing History Furnace was used to determine the effect of staged combustion at 500,000 Btu/hr on NO_x emissions from and combustion performance of the Alabama high volatile bituminous coal.

The combustion kinetic information obtained on the Alabama high volatile bituminous coal was used in conjunction with a Combustion Engineering's proprietary mathematical model to predict the combustion performance of the Controlled Mixing History Furnace.

Results

DTFS pyrolysis of coals in nitrogen atmosphere in the 1450-2650°F temperature range and 0.05-0.8 sec. residence time range showed a clear dependence upon fuel property, temperature, and time. For example, for Texas lignite, at 0.2 sec. the pyrolysis weight loss increases from 16% to 51% as the temperature increases from 1450°F to 2650°F; and at 1450°F the pyrolysis weight loss increases from 3% to 34% as time increases from 0.05 to 0.8 sec. However, at 2650°F pyrolysis is virtually complete within 0.2 sec. for the lignite, subbituminous and high volatile bituminous coals.

Apparent activation energies (E) for the pyrolysis of coals are 7980, 4740, 7825, and 7755 cal/mole, respectively, for the lignite (ligA), subbituminous (subB), high volatile bituminous (hvAb), and anthracite. The corresponding frequency factors (k_0) are 50.8, 13.5, 32.5, and 38.7 $sec.^{-1}$

Fuel properties, temperature, and residence time had significant effects on char combustion in the DTFS. Combustion char reactivities were, in general, closely related to char pore structures.

Relative DTFS char reactivities were: Montana subbituminous (subB) > Texas lignite (ligA) > Alabama high volatile bituminous (hvAb) >> Pennsylvania anthracite. For example, in 0.03 O_2 atm at 2650°F and 0.5 sec. the combustion efficiencies are 93, 81, 74, and 13%, respectively, for the subB, ligA, hvAb, and anthracite chars. The respective total open pore volumes of these chars are 0.95, 0.68, 0.59, and 0.08 cm^3/g, indicating the important role played by pore structure during char combustion. These results show for example, that the low reactivity of the anthracite char is a result of inaccessibility of its microporous structure by oxygen during combustion.

Apparent activation energies (E) and frequency factors (A) for the combustion of chars in the DTFS showed significant sensitivities to the fuel nature and method of derivation. For example, using measured bulk gas temperatures gave E values of 21050, 26730, 23380, and 17990 cal/mole for ligA, subB, hvAb, and anthracite chars, respectively, with corresponding A values of 57, 593, 80, and 4.3 g/cm^2 sec. O_2 atm.; whereas using calculated particle surface temperatures gave corresponding E and A values of 20350, 25400, 22250 and 17840 cal/mole and 36, 271, 50, and 3.7 g/cm^2 sec. O_2 atm. Differences in kinetic parameters between the two methods are due to differences between corresponding gas and particle temperatures. Particle temperatures are greater than gas temperatures by 14 to 100°K. These differences are similar to those found by Field (3).

A comparison between the present results and selected literature results show that at 1600°K: (1) the surface reaction rate coefficient of Field's subB char (4) is greater than that of Smith and Tyler's semi-anthracite (5) by a factor approaching three orders of magnitude; (2) the surface reaction rate coefficient of this work's most reactive char (subB) is greater than that of this work's least reactive char (anthracite) by a factor of 6; and (3) while the surface reaction rate coefficient of this work's anthracite is less than a factor of two higher than that of Beer and co-workers' anthracite (6,7), it is almost two orders of magnitude higher than that of Smith and Tyler's semi-anthracite.

CMHF testing on the Alabama high volatile bituminous coal indicated that a judicious use of the staged combustion concept brought about drastic reductions in NO_x emissions without adversely affecting the overall fuel combustion. For example, at 20% excess air and 50% optimum primary stage stoichiometry, a 1.56 sec. primary stage residence time led to a 50% reduction in NO_x emissions (from 498 for the unstaged baseline case to 249 ppm @ 3% O_2). The overall fuel combustion efficiency under these circumstances was 98%. While a primary stage residence time of 1.56 sec. is actually impractical on a commercial scale, it is important to note that a substantial reduction in NO_x emissions occurred even only after a primary stage residence time of 0.5 sec. (a 21% NO_x reduction from 498 to 395 ppm).

Mathematical modeling studies on the CMHF combustion performance of the Alabama hvAb coal using DTFS kinetic data showed a good agreement between experimental and theoretical results, indicating a virtually one-to-one DTFS-to-CMHF scale-up. These results indicate that a properly refined model could be used to predict the combustion performance on a commercial scale.

CONCLUSIONS

The major conclusions that can be drawn from the results of this study are as follows.

- The pyrolysis of each coal is clearly dependent upon temperature and time. Higher temperatures and/or longer residence times yield higher pyrolysis weight losses. At 2650°F, however, pyrolysis is virtually complete within 0.2 sec. for the lignite, subbituminous and high volatile bituminous coals.
- The apparent activation energies (4.7-8.0 kcal/mole) encountered here are rather low. Information in the literature suggests that such low values are not necessarily indicative of a physical (i.e., heat and mass transfer) control of the pyrolysis process.

- Texas lignite, Montana subB, and Pennsylvania anthracite did not show any swelling by virtue of their chemical nature (they are thermosetting, i.e., they do not soften upon rapid heating). Alabama hvAb on the other hand swelled by 34% (this coal is thermoplastic, i.e., it softens upon rapid heating). The ligA and subB showed, respectively, 12% and 14% volatile matter enhancements over their ASTM volatile matter contents. The hvAb and anthracite showed no volatile matter enhancements. Volatile matter enhancements in dilute phase reactors are a result of the minimization of secondary, char-forming reactions.

- The open pore volumes of the lignite, subbituminous and high volatile bituminous coals increased by about one order of magnitude as a result of nearly complete pyrolysis. The microporous nature of the anthracite, on the other hand, is such that the increase in the open pore volume under comparable experimental conditions was less than 5%.

- Char combustion efficiencies vary significantly with fuel property, temperature and time. Combustion efficiencies show the following trend: Montana subB char > Texas lignite char > Alabama hvAb char >> Pennsylvania anthracite char. This is consistent with the open pore volume trends exhibited by these chars, indicating the important role played by the pore structure during combustion.

- The dependence of char combustion upon temperature and fuel property is depicted by the magnitudes of the kinetic parameters obtained. The apparent activation energies are: 21050, 26730, 23380, and 17990 cal/mole for the lignite, subbituminous, high volatile bituminous, and anthracite chars, respectively. The corresponding frequency factors are 57, 593, 80, and 4.3 g/cm^2 sec. O_2 atm.

- Differences in reactivities of chars derived from coals of various rank are due to actual differences in reactivities and/or differences in experimental conditions used by different investigators. These results clearly indicate that using kinetic parameters found in the literature for a particular modeling application can be risky, and, therefore, should be done with circumspection.

- CMHF test results showed that both primary stage stoichiometry and primary stage residence time are important parameters for controlling NO_x emissions. For the Alabama hvAb coal, a 50% NO_x reduction was achieved at a primary stage stoichiometry of 50% and primary stage residence time of 1.56 sec. The overall excess air and fuel fineness had small but significant influence on NO_x reduction.

- CMHF results indicate that a judicious use of staged combustion leads to an effective control of NO_x emissions without adversely affecting the overall fuel combustion efficiency. It is postulated that conditions in the neighborhoods of 50% primary stage stoichiometry and 0.5 sec. primary stage residence time are effective in significantly reducing NO_x emissions in commercial applications.

- Model simulation studies on the CMHF combustion performance of the Alabama high volatile bituminous coal, using the DTFS-derived kinetics, indicate a virtually one-to-one DTFS-to-CMHF scale-up. These findings indicate that a properly refined model can be used to predict the combustion performance on a commercial scale. C-E is, indeed, using this type of concept to predict carbon heat losses in utility and industrial boilers.

RECOMMENDATION

The wide diversity in physicochemical characteristics of American coals inevitably leads to wide differences in combustion performance of the same coals in practical systems. As such, more work needs to be done to characterize the reactivities of suites of coals so that their performance for particular applications may be better predicted. This is crucial for meeting the national goal of increased coal utilization with increased efficiency and drastically reduced pollutants emissions into the environment. Since the Department of Energy is on the correct course in supporting coal research and development programs in the area described here and in other areas as well, it simply is recommended that the DOE continue to do so without relenting. Specific recommendations follow.

- Expand the data base to include various coals with a potential commercial significance.
- Apply fundamental data for large scale performance predictions.

Section 1

INTRODUCTION

BACKGROUND

Pyrolysis Process

In essentially all coal utilization processes, the important first step is devolatilization in either the presence (combustion, gasification, liquefaction) or absence (coke making) of a reactive atmosphere. The devolatilization is normally caused by subjecting the coal to a thermal stress; that is, heating it.

The products of devolatilization are permanent gases, tars, light hydrocarbon gases and a solid residue (char). The specific composition of the products is a function of the nature of the parent coal and of how the pyrolysis* is performed. It is the coal properties and pyrolysis conditions that determine the degree to which primary and secondary reactions occur. Thus, alteration of the pyrolysis conditions, however mild, or a change in coal composition, due to mild oxidation for example, can markedly affect the yield and composition of the vapor phase components versus that of the solid residue.

For all processes other than coke making, it is generally desirable to maximize the yield of the vapor (or liquid) phase components and minimize the production of char. For a given coal, this can be achieved by conducting the pyrolysis in a dilute phase mode of operation (as compared to a fixed bed). This carries the attendant advantages of high heating rates and enhanced interaction between primary volatiles and the reacting atmosphere, thereby minimizing unwanted secondary char-forming reactions.

* The terms pyrolysis and devolatilization are often used interchangeably. Strictly speaking, however, pyrolysis refers to heating coal in an inert atmosphere while devolatilization occurs irrespective of atmosphere when coal is heated.

It is generally understood that the proximate volatile matter of a coal is not a quantitative indication of pyrolysis behavior under practical operating conditions (e.g., rapid heating, suspension firing) encountered in pulverized coal fired boilers.

Numerous investigators (8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18), and others not cited here, have conducted a variety of tests in dilute-phase and heated grid reactors to study the pyrolysis phenomenon on coals of various rank. This phenomenon is so complex that it still is not well understood. It is basically this understanding gap that provides the incentive for further investigation in this area.

Combustion Process

The combustion of pulverized coal is a complex process consisting of a number of overlapping steps including heating and ignition of the dust cloud, devolatilization and burnout of the carbonaceous residue. Initially, a cloud of relatively cool coal particles is heated by flame radiation and by mixing with recirculated hot combustion products. During this process the particles lose a small fraction of their volatile matter. A point is reached where further heating results in very rapid oxidation and ignition occurs. For a given coal, the temperature at which ignition occurs is not a fixed point, but is controlled by a Semenov heat balance (19) and may vary depending upon the type of furnace and its operating conditions.

After ignition occurs devolatilization proceeds at a rapid pace. Rapid devolatilization takes up approximately 10% of the time beyond ignition, the remainder of the time being required for char burnout. Studies have indicated that the volatile yields during the rapid heating rates (10^4 - 10^5°C/sec) characteristic of dispersed particles in coal flames may be significantly higher (by as much as 30%) than the yields observed during the slow heating rates of the ASTM proximate volatile matter analysis.

Occurring simultaneously with devolatilization (for the smaller particles) and requiring most of the combustion time is the process of char burnout. This is a multi-step process consisting of a number of physical and chemical steps. The slowest of the steps controls the rate of the overall process. First, oxygen is transported through a boundary layer to the particle surface. Next oxygen diffuses into the pores of the particle. Oxygen now must adsorb or chemically attach itself to the pore walls or, in the case of a slightly porous material, to the external surface. Oxygen next reacts with the char to form a carbon-oxygen complex. This complex must then desorb or chemically detach itself from either the pore wall or the external surface. Next the gaseous product formed by the complex desorption from the surfaces diffuses out of the pores and away from the particle. The rate determining step during char burnout is dependent upon temperature, particle size, porosity and pore size distribution.

Other aspects of the fuel that may influence the combustion rate include swelling, agglomerating tendency, and mineral matter. Swelling and agglomeration affect the nature of the pore structure of the residual char, thus influencing the burning characteristics of this char. The mineral matter, depending on its chemical nature and degree of dispersion in the coal matrix, may catalyze or hinder the chemical reactivity of the coal char.

Temperature exerts a considerable influence upon reaction rates. Diffusion controlled reaction rates increase with temperature to the 0.75 power and chemical controlled rates increase with temperature according to $\exp(-E/RT)$ or in some cases $T^{-1/2}\exp(-E/RT)$, where E is the activation energy, R is the gas constant and T is the absolute temperature.

Coal combustion phenomenon has also been investigated by numerous researchers (3, 4, 5, 6, 7, 20, 21, 22, 23) using various experimental techniques. These and other studies not cited here depict the extreme complexity of coal combustion phenomenon. More work needs to be done in order to enhance our understanding of this phenomenon.

OBJECTIVE AND TECHNICAL APPROACH

Objective

The Department of Energy's intent in sponsoring this and other related programs is to foster increased usage of our vast domestic coal reserves. To effectively use coal in existing and new applications requires a more definitive, quantitative understanding of coal properties vs. performance. As such, the objective of this program was to provide detailed data on the combustion characteristics of coals by burning them in well controlled bench and pilot scale reactors. The data were subsequently used to develop the methodologies that most reliably characterize coals from a pyrolysis/combustion standpoint thereby permitting accurate performance predictions to be made.

Technical Approach

Four coals were selected for this study on the basis of a balanced consideration of rank, geological region, and a variety of chemical and physical characteristics. They include a Texas (Wilcox) lignite, a Montana (Rosebud) subbituminous, an Alabama (Black Creek) high volatile bituminous, and a Pennsylvania (Buck Mountain) anthracite.

The study program was structured to cover the following milestones:

Fuels Characterization. Standard ASTM and special in-house techniques were used to provide various physical and chemical characteristics of the four parent coals and chars produced therefrom.

Drop Tube Furnace System (DTFS) Studies. This laminar flow, laboratory scale, reactor was used extensively to derive principally: (1) the pyrolysis kinetic parameters of closely size graded particles from each parent coal; and (2) the combustion kinetic parameters of closely size graded particles from each parent coal char.

Controlled Mixing History Furnace (CMHF) Studies. This pilot scale, plug-flow, reactor was fired at 500,000 Btu/hr to study the effects of the staged combustion concept on the NO_x emissions and overall combustion performance of the Alabama high volatile bituminous coal.

Mathematical Modeling. An in-house computer model was used to simulate the combustion performance of the Alabama high volatile bituminous coal in the CMHF using the kinetic information derived from this coal in the DTFS. The ultimate goal here was to develop a DTFS-to-CMHF combustion performance scale-up for this particular high volatile bituminous coal.

COMMERCIAL APPLICABILITY

Combustion Engineering, Inc., is now using the type of combustion performance simulation explained in this report on a commercial basis. In this respect, the combustion kinetic information derived from the Drop Tube Furnace System is used in conjunction with advanced proprietary computer models and extensive field data base to predict carbon heat losses in utility and industrial boilers. Carbon heat loss guarantees are being made on the basis of this technique. As such, this technique is of interest from both academic and practical standpoints.

Section 2
TECHNICAL APPROACH

SELECTION OF COALS

The selection of the four coals studied in this program was based on a balanced consideration of rank, geological region, ash contents, ash fusibility temperatures, and volatile matter contents. The sources of these four parent coals are (Table 2-1): (1) a Texas lignite from Wilcox seam; (2) a Montana subbituminous coal from Rosebud seam; (3) an Alabama high volatile bituminous coal from Black Creek seam; and (4) a Pennsylvania anthracite from Buck Mountain seam. The mines and counties of these coals are also identified in Table 2-1.

TABLE 2-1
SOURCES AND ASTM RANKS OF COALS

	SOURCES			ASTM RANK
SEAM	MINE	COUNTY	STATE	
Wilcox	Monticello	Titus	Texas	Lignite A (ligA)
Rosebud	Colstrip	Rosebud	Montana	Subbituminous B (subB)
Black Creek	Arkadelphia	Cullman	Alabama	High Volatile Bituminous A (hvAb)
Buck Mountain	Eckley	Luzerne	Pennsylvania	Anthracite (an)

BENCH SCALE STUDIES

Standard ASTM (American Society for Testing and Materials) and special in-house techniques were used to conduct the bench scale studies on the four coals identified above and chars prepared therefrom. The standard and special techniques are, respectively, identified and briefly described below.

ASTM Techniques

ASTM techniques were used to determine the proximate, ultimate, and screen analyses, higher heating values, and Hardgrove grindability indices of parent coals, and coal ash fusibility temperatures and compositions. The proximate, ultimate, and screen analyses of coal chars were also determined by ASTM techniques.

Special Techniques

Special in-house techniques were used to determine the following: (1) the Flammability Indices of the parent coals; (2) the micro-proximate analyses, particulate surface areas and densities, and thermo-gravimetric analyses of coal chars. These techniques are briefly described in the following sub-sections. The particle size distributions of coals and chars were determined using the dry screen analysis technique.

Flammability Index. The Flammability Index is a relative ignition temperature obtained by running tests under a given set of conditions in a specific apparatus. Briefly, testing involves firing 0.2 gram of 200x0 mesh fuel in an oxygen atmosphere through a preheated furnace. The temperature of the furnace is increased incrementally until a point is reached where the fuel will ignite. This temperature is called the Flammability Index. The value of the Flammability Index compared to other fuels indicates the ignition temperature/flame stability on a relative basis. This apparatus is described in Appendix A.

Micro-Proximate Analyses. The Perkin-Elmer TGS-2 System was used to determine the micro-proximate analyses of chars after it had been established that this apparatus yielded volatile matter results which were virtually indistinguishable from the corresponding ASTM proximate analyses. This method was used to save the Drop Tube Furnace System (DTFS) testing time since only milligrams of samples were required to determine their proximate analyses.

In this test procedure, a 4 to 6 mg sample is purged with nitrogen to remove oxygen traces. The moisture loss is obtained by heating in an inert atmosphere (nitrogen) to 105°C and holding for three minutes. Subsequently, the sample is heated at 100°C/min to 950°C and held at this temperature for five minutes to obtain volatile matter. After this, the temperature is lowered to 750°C and a switching valve is opened to introduce oxygen for the combustion of fixed carbon at this temperature. The residue represents the ash content. A sample plot of this analysis is shown in Figure 2-1. The TGS-2 equipment used for this analysis is described in Appendix A.

Specific Surface Areas and Densities. The principle of physical absorption of gases was used to determine specific surface areas of the coal and char samples. Data obtained from nitrogen and carbon dioxide absorptions at 77 and 298°K, respectively, in the Quantasorb Surface Area Analyzer (manufactured by Quantachrome Corporation) were used in conjunction with the Brunauer, Emmett, and Teller (BET), and Dubinin-Kaganer Equations (1, 2) to determine the BET (N_2) and CO_2 specific surface areas of the subject samples. The Surface Area Analyzer is described in Appendix A. The mercury porosimeter, and helium null pycnometer were used to determine, respectively, the "apparent" and "true" densities of the same coal and char samples.

Thermo-Gravimetric Analyses. The Perkin-Elmer TGS-2 System was also used to determine char combustion reactivity under isothermal conditions as follows. A 4 to 6 mg sample is placed in the TGS-2 System and heated in the presence of nitrogen at 50°C/min to 700°C. After stabilization at this temperature, air is introduced to burn off the fixed carbon. Percent weight of the unburned char and rate of weight loss are recorded on a strip chart as a function of time. These thermo-grams (Figure 2-2) are subsequently used to determine percent combustion efficiency of the char.

DROP TUBE FURNACE SYSTEM (DTFS) STUDIES

Facility/Test Procedure

The DTFS is comprised of a 1-inch diameter horizontal tube gas preheater and a 2-inch inner diameter vertical tube test furnace for providing controlled temperature conditions to study pyrolysis and/or combustion phenomena. This

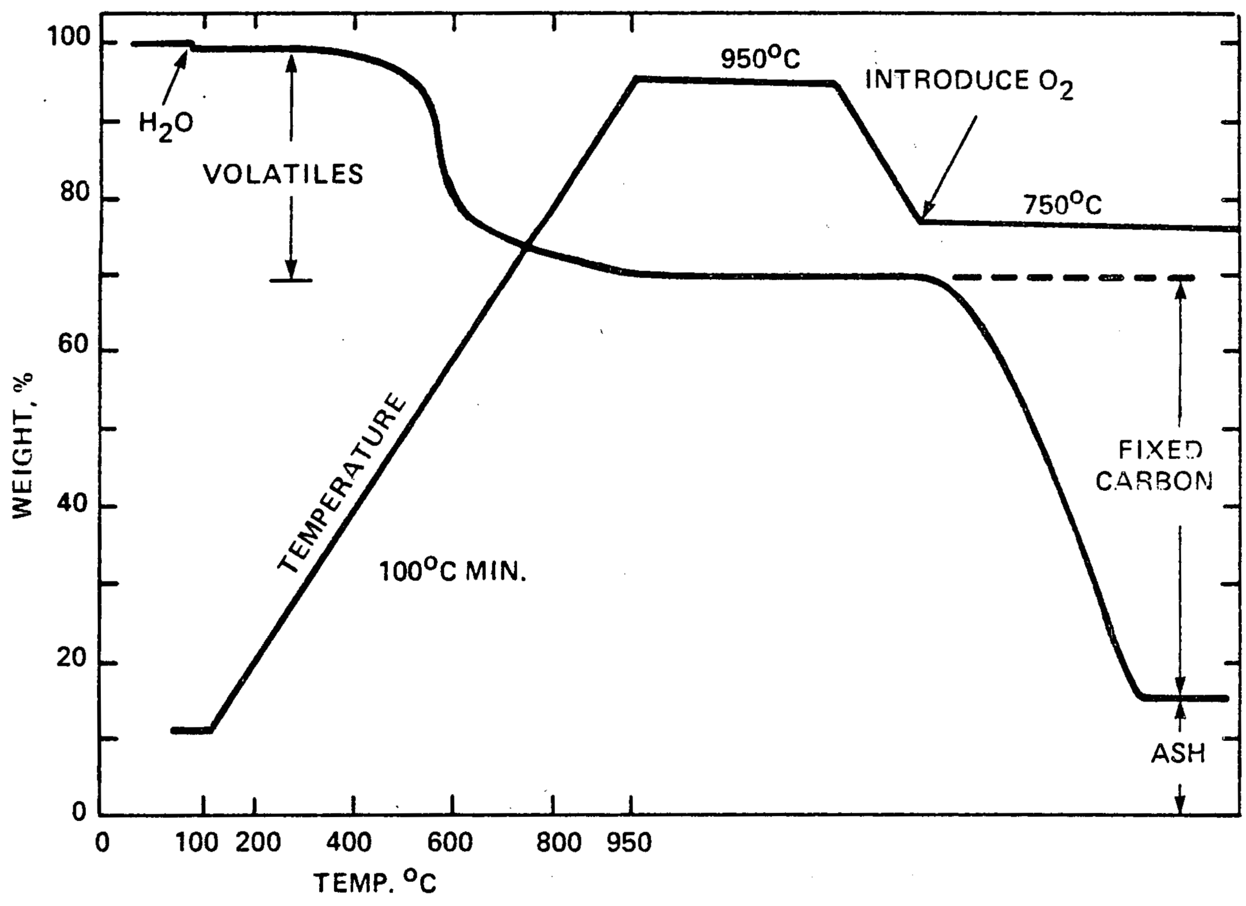

Figure 2-1 TYPICAL TGS-2 SYSTEM MICRO-PROXIMATE ANALYSIS OF COAL

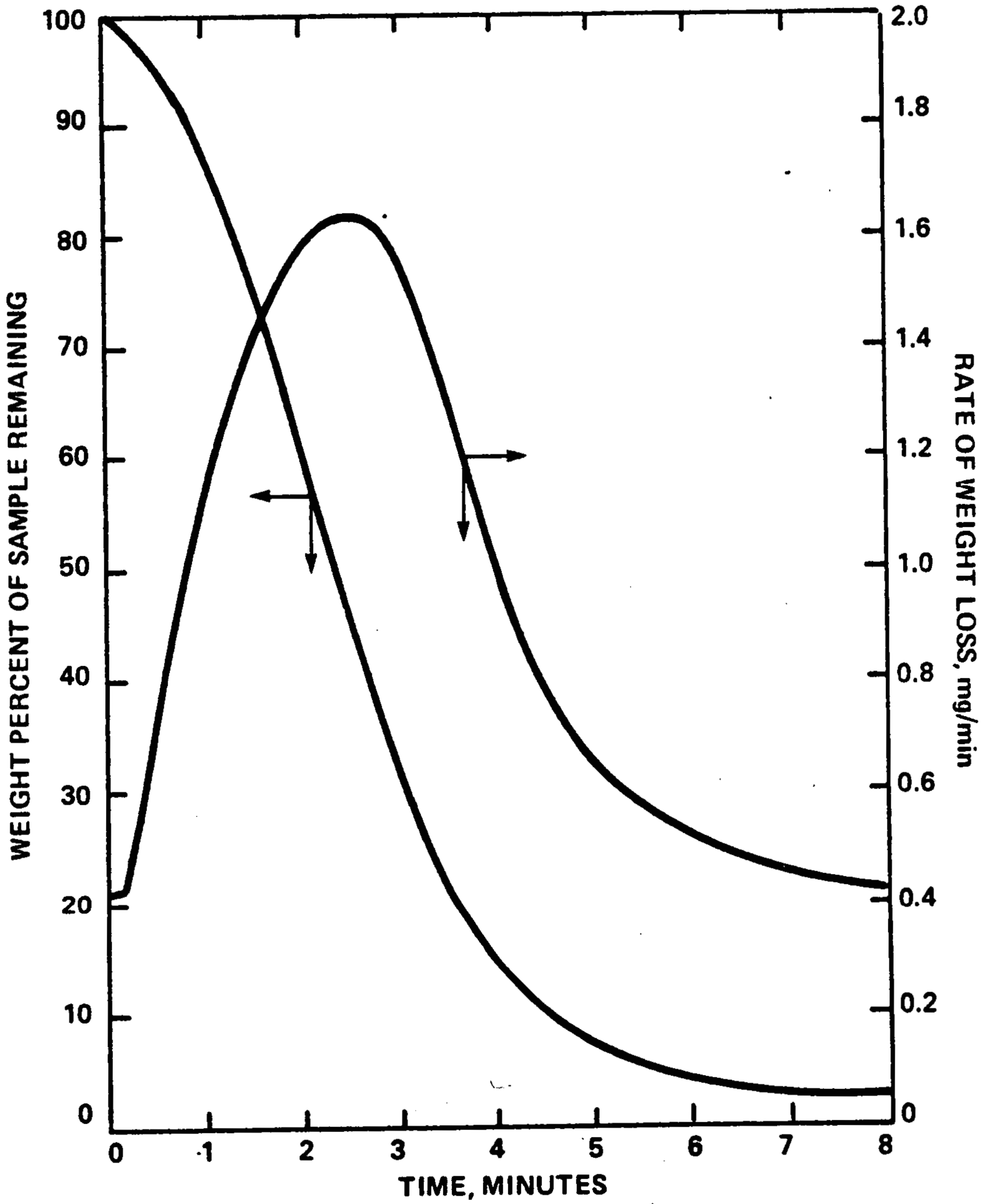

Figure 2-2 TYPICAL TGS-2 SYSTEM THERMOGRAM

entrained flow reactor is capable of heating reactant gases and reacting particulates to temperatures up to 2650°F (1730°K) and obtaining particle residence times up to about one second to simulate the rapid heating suspension firing conditions encountered in pulverized coal fired boilers.

The DTFS testing procedure entails the following: (1) feed the fuel at a precisely known rate (in the 0.055-0.095 g/min range) through a water-cooled injector into the test furnace reaction zone; (2) allow the fuel and its carrier gas (~ 150 cm^3/min) to rapidly mix with a preheated down-flowing secondary gas stream (12-16 l/min); (3) allow combustion and/or pyrolysis to occur for a specific time (dictated by the transit distance); (4) quench the reactions by aspirating the products in a water-cooled sampling probe; (5) separate the solids from the gaseous products in a filter medium; and (6) determine on-line NO_x, O_2, CO_2, and CO concentrations in the effluent gas stream. Details on the DTFS are given in Appendix A.

An ash tracer technique (10, 14) is used in conjunction with the proximate analyses of a given feed sample and the chars subsequently obtained from the test furnace to calculate the pyrolysis weight losses and/or combustion efficiencies as a function of selected operational parameters (temperature, residence time, fuel type, etc.).

Coal Pyrolysis Test Matrix

Five tests (Table 2-2) were run in the DTFS on each of the four subject coals sized to 200x400 mesh in nitrogen atmosphere in the 1450-2650°F (1060- 1730°K) temperature range and residence times ranging up to 0.8 sec. Data from this study were used to determine the pyrolysis efficiencies which were subsequently used to derive the global kinetic parameters (apparent activation energies and frequency factors) for the pyrolysis of these four coal samples.

Char Preparation

The chars on which the combustion kinetic parameters were determined (see next section) were prepared *a priori* in the DTFS. All the coal chars were prepared under strictly similar conditions so that differences in their physical and chemical characteristics were due solely to differences in the nature of their parent coals.

TABLE 2-2

TEST MATRIX FOR PYROLYSIS OF COALS IN THE DROP TUBE FURNACE SYSTEM (DTFS)

COAL	TEST NO.	SIZE (MESH)	REACTION MEDIUM (VOL. %)	GAS TEMPERATURE (°F)
	TML-I-1	200x400	100% N_2	1450
	TML-I-2	200x400	100% N_2	1600
TEXAS	TML-I-3	200x400	100% N_2	1900
LIGNITE	TML-I-5	200x400	100% N_2	2400
	TML-I-6	200x400	100% N_2	2650
	MRC-I-1	200x400	100% N_2	1450
	MRC-I-2	200x400	100% N_2	1600
MONTANA	MRC-I-3	200x400	100% N_2	1900
subB COAL	MRC-I-5	200x400	100% N_2	2400
	MRC-I-6	200x400	100% N_2	2650
	AAC-I-1	200x400	100% N_2	1450
	AAC-I-2	200x400	100% N_2	1600
ALABAMA	AAC-I-3	200x400	100% N_2	1900
hvAb COAL	AAC-I-5	200x400	100% N_2	2400
	AAC-I-6	200x400	100% N_2	2650
	PEA-I-2	200x400	100% N_2	1600
	PEA-I-3	200x400	100% N_2	1900
PENNSYLVANIA	PEA-I-4	200x400	100% N_2	2150
ANTHRACITE	PEA-I-5	200x400	100% N_2	2400
	PEA-I-6	200x400	100% N_2	2650

Because of feeding difficulties of the +50 mesh particles through an 18-gauge hypodermic tube, all the DTFS feed coals and chars were sized to -50 mesh. The preparation procedure involved the following: Coal was pulverized to a regular grind (∿70% through 200 mesh) and size graded to 50x0 mesh. All the oversize (+50 mesh) particles were re-ground to -50 mesh then added to the original 50x0 mesh fraction. This enhanced the degree of representativeness of the coal sample.

The regular grind (50x0 mesh) coal was pyrolyzed in the DTFS in the presence of nitrogen under the following conditions: (1) coal feed rate ≅ 1 g/min, (2) nitrogen flow rate ≅ 15 1/min; (3) heated reaction zone length* = 23 inches; and (4) temperature ≅ 2650°F. The resulting char was subsequently size graded to 200x400 mesh. Any oversize materials (i.e., >200 mesh) were re-ground and size graded to 200x400 mesh. This size cut was added to the first one to enhance the degree of representativeness of the test sample.

Char Combustion Test Matrix

Five tests (Table 2-3) were run in the DTFS on each of the four 200x400 mesh coal chars (prepared a priori as specified in the preceding section) in 0.03 O_2 atmosphere (in nitrogen balance) in the 1600-2650°F (1140-1730°K) temperature range and residence times ranging up to 0.85 sec. Data were used to determine the char combustion efficiencies, which were subsequently used to derive the global combustion kinetic parameters (apparent activation energies and frequency factors).

CONTROLLED MIXING HISTORY FURNACE (CMHF) STUDIES

Facility/Test Procedure

The pilot scale (500,000 Btu/hr) CMHF is based on the principle of plug-flow which resolves time into distance along the length of the furnace. It consists of a refractory-lined 1.5 foot inner diameter cylinder with an overall

* A fixed probe, fitted onto the bottom of the test furnace, was used during DTFS char preparation.

TABLE 2-3

TEST MATRIX FOR COMBUSTION OF
COAL CHARS IN THE DROP TUBE FURNACE SYSTEM (DTFS)

COAL	TEST NO.	SIZE (MESH)	REACTION MEDIUM (VOL. %)	GAS TEMPERATURE (°F)
TEXAS LIGNITE	TMLC-I-2	200x400	3% O_2/97% N_2	1600
	TMLC-I-3	200x400	3% O_2/97% N_2	1900
	TMLC-I-4	200x400	3% O_2/97% N_2	2150
	TMLC-I-5	200x400	3% O_2/97% N_2	2400
	TMLC-I-6	200x400	3% O_2/97% N_2	2650
MONTANA subB COAL	MRCC-I-2	200x400	3% O_2/97% N_2	1600
	MRCC-I-3	200x400	3% O_2/97% N_2	1900
	MRCC-I-4	200x400	3% O_2/97% N_2	2150
	MRCC-I-5	200x400	3% O_2/97% N_2	2400
	MRCC-I-6	200x400	3% O_2/97% N_2	2650
ALABAMA hvAb COAL	AACC-I-2	200x400	3% O_2/97% N_2	1600
	AACC-I-3	200x400	3% O_2/97% N_2	1900
	AACC-I-4	200x400	3% O_2/97% N_2	2150
	AACC-I-5	200x400	3% O_2/97% N_2	2400
	AACC-I-6	200x400	3% O_2/97% N_2	2650
PENNSYLVANIA ANTHRACITE	PEAC-I-2	200x400	3% O_2/97% N_2	1600
	PEAC-I-3	200x400	3% O_2/97% N_2	1900
	PEAC-I-4	200x400	3% O_2/97% N_2	2150
	PEAC-I-5	200x400	3% O_2/97% N_2	2400
	PEAC-I-6	200x400	3% O_2/97% N_2	2650

(1) Chars were prepared a priori in the DTFS in nitrogen gas at 2650°F.

height of 22.6 feet. A mixture of pulverized fuel and primary air is fired downward into the furnace from a single burner centrally located at the top of the furnace. The furnace consists of four zones--preheat, combustion, water-cooled, and after-burner--proceeding downward from the fuel admission point.

By sampling at different ports along the length of the furnace, it is possible to examine the carbon burnout and NO_x formation histories of a fuel. An ash tracer method is also used to determine the solids combustion efficiency as a function of operational parameters. Gaseous products aspirated in a sampling probe are analyzed on-line to determine NO_x, O_2, CO, and CO_2 concentrations. Details of this test facility are given in Appendix A.

Coal Combustion/NO_x Emissions Control Test Matrix. The test matrix for the CMHF study on the Alabama hvAb coal is given in Table 2-4. For all experimental runs, the secondary/tertiary air was preheated to 700°F to simulate field conditions. Fifteen tests were performed in four series to study the effect of (1) primary stage stoichiometry; (2) primary stage residence time; (3) overall excess air; and (4) fine grinding upon carbon burnout and NO_x formation. A firing rate of 0.5×10^6 Btu/hr (36 lb/hr) was used.

In the first test series, the primary stage air stoichiometry (Figure 2-3) was varied at 15, 30, 50, 60, 70, and 90% of theoretical air. The remaining air was introduced into ring 4 such that the overall excess air was maintained at 20%.

In the second test series, the optimum primary stage stoichiometry found in first series was maintained constant and the remaining air was introduced into rings 2, 3, and 5 in order to vary the primary stage residence time.

In the third series, the optimum values of the primary stage stoichiometry and primary stage residence time found in series 1 and 2, respectively, were maintained constant and the percentage of excess air was varied at 0, 10, 20, and 35%.

TABLE 2-4

TEST MATRIX FOR COMBUSTION OF ALABAMA HIGH VOLATILE BITUMINOUS COAL IN THE CONTROLLED MIXING HISTORY FURNACE (CMHF)

Test No.	Study Parameter	Coal Fineness	Primary Stage Stoichiometry	Secondary Air Ring No.	Overall Excess Air %
I-1	Primary	--------	15	1 and 4	20
I-2	Stage	↑	30	1 and 4	20
I-3	Stoichio-		50	1 and 4	20
I-4	metry		70	1 and 4	20
I-5			90	1 and 4	20
I-6		Regular Grind	60	1 and 4	20
II-1	Primary	(71% - 200 mesh)	-	1 and 1	20
II-2	Stage		50	1 and 2	20
II-3	Residence		50	1 and 3	20
II-4	Time		50	1 and 5	20
III-1	Overall		50	1 and 4	0
III-2	Excess		50	1 and 4	10
III-3	Air	↓	50	1 and 4	20
III-4		--------	50	1 and 4	35
IV-1	Coal Fineness	Fine Grind (87% - 200 mesh)	50	1 and 4	20

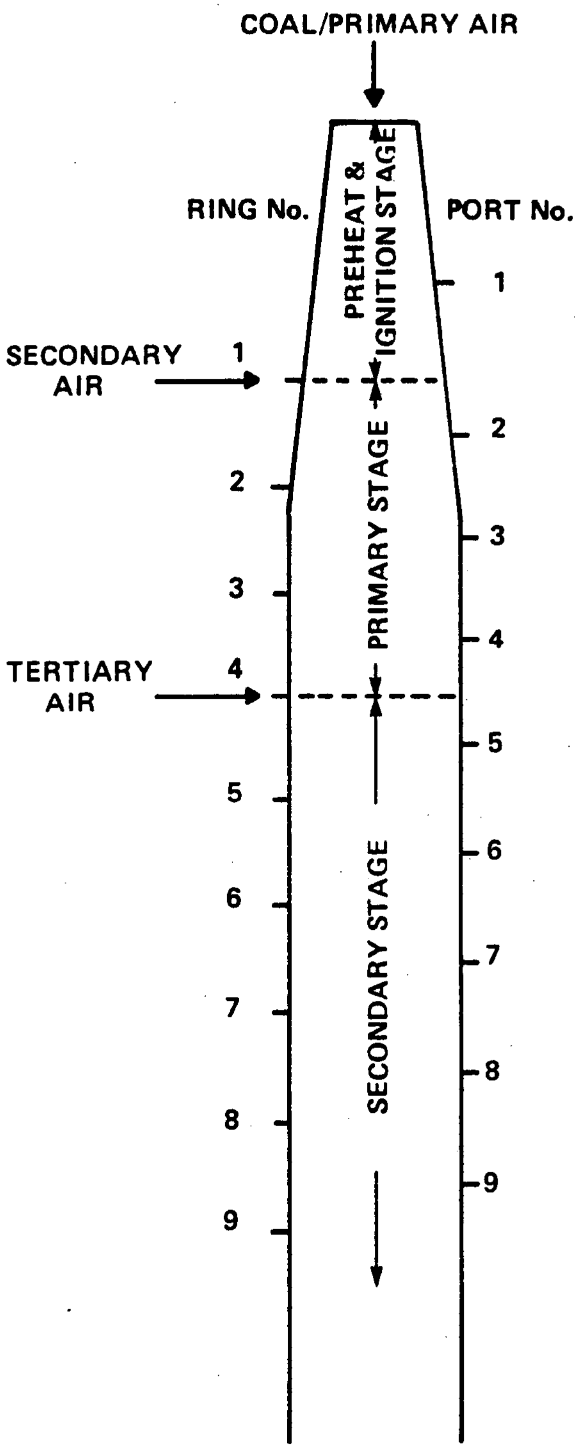

Figure 2-3 SCHEMATIC OF CONTROLLED MIXING HISTORY FURNACE DEFINING COMBUSTION STAGES

In the fourth series, a single test was carried out with fine coal grind (87% through 200 mesh compared to 71% through 200 mesh in series 1-3). In this test primary stage stoichiometry and tertiary air introduction level were maintained at optimum, and excess air was kept at 20%.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

The salient features of the DTFS data reduction program are (1) calculate the residence time of fuel particles as they flow down the test furnace reaction zone taking into account the reactant gas velocities as well as solid free fall velocities (24, 25); (2) calculate the combustion or pyrolysis efficiency by ash tracer method; (3) calculate the reaction kinetic parameters (apparent activation energy and frequency factor) for coal pyrolysis or char combustion; and (4) calculate particle surface temperatures during char combustion. A data reduction computer program, developed previously with in-house funding, was used to accomplish all these tasks. The calculation methods used here are briefly described below.

Ash Tracer Method

This method is predicated on the assumption that the ash does not undergo appreciable changes during coal combustion or pyrolysis. As such, the combustion or pyrolysis efficiency (η) can be calculated from the values of the ash contents in the feed sample and partially reacted char (collected at a given DTFS reaction zone position). This method is expressed in mathematical form (10, 14) as follows:

$$\eta = 100 \left[1 - (A_0/(100-A_0))((100-A')/A')\right] \qquad (2\text{-}1)$$

where A_0 and A' are the percent ash contents (expressed on a dry basis) of the feed sample and partially reacted char, respectively.

Coal Pyrolysis Kinetics

The derivation method used by Nsakala et al. (12, 14), Scaroni et al. (16), and Walker et al. (17) was also used here. That is, briefly:

$$C = C_0 \exp(-kt) \qquad (2\text{-}2)$$

where C_0 is the maximum obtainable weight loss under the prevailing conditions referred to as ΔW_∞, and C is the remaining pyrolyzable material weight at time t ($C = \Delta W_\infty - \Delta W$, where ΔW is the pyrolysis weight loss at time t), and k is a pyrolysis rate constant. Plugging these values into and manipulating Equation (2-2) yields

$$\ln (1-\Delta W/\Delta W_\infty) = -kt \qquad (2\text{-}3)$$

Plotting the left hand side of Equation (2-3) vs. t yields straight lines from which the k values can be obtained from the slopes of the least squares fits.

Now, the k values can be used in conjunction with a first order Arrhenius law to obtain

$$k = k_0 \exp (-E/RT) \qquad (2\text{-}4)$$

where k_0, E, R, and T are, respectively, the pyrolysis frequency factor, the apparent activation energy, the universal gas constant, and the reaction gas temperature.

Plotting ln k vs. 1/T yields straight lines from which the values of k_0 and E can be obtained from the intercepts and slopes of the least squares fits. The data illustrating this calculation procedure are given in Section 3 below.

Char Combustion Kinetics

Char combustion kinetic parameters were determined on the basis of Field's formulation given below (3, 4).

Overall Reaction Rate Coefficient. The overall reaction rate coefficient (K) is defined as the rate of carbon removal per unit external surface area per unit atmosphere partial pressure of oxygen in gas. That is

$$K = q/P_g \qquad (2\text{-}5)$$

where q is the rate of carbon removal per unit external surface area (g $cm^{-2} sec^{-1}$), and P_g is the partial pressure of oxygen in the gas (atm).

Reaction rate, q, is given by

$$q = (1/t)\int_0^B (1/S)\, dB \qquad (2\text{-}6)$$

where S is the surface area at burn-off level B per unit weight of moisture and ash-free char, and t is the residence time in the reaction zone. S is given by

$$S = 6U/X\rho \qquad (2\text{-}7)$$

where U (= 1-B) is the fraction of combustible char remaining unburnt, X is the mean weight particle diameter (cm), and ρ is the apparent density of char (g/cm^3, dry-ash-free basis).

Field found the following variation of surface area with burn-off assuming a shrinking core mechanism

$$S/S_0 = U^{2/3} \qquad (2\text{-}8)$$

where S_0 is the geometric surface area of the feed char. Goetz et al. (23) found previously in this laboratory that char combustion proceeded principally by a shrinking core mechanism.

Combining Eqs. (2-6) and (2-8) yields

$$q = (1/t)\int_1^U (-1/(S_0\, U^{2/3}))\, dU \qquad (2\text{-}9)$$

which, upon integrating between the limits, leads to

$$q = 3(1-U^{1/3})/S_0 t \qquad (2\text{-}10)$$

Substituting q in Eq. (2-5) from Eq. (2-10) yields

$$K = 3(1-U^{1/3})/(S_o t\ P_g) \tag{2-11}$$

Diffusional Reaction Rate Coefficient. Diffusional reaction rate coefficient (K_{DIFF}) is given by

$$K_{DIFF} = 24\ \emptyset\ D/\bar{X}\ R'T_g \tag{2-12}$$

where D is the binary diffusion coefficient of oxygen through the carrier gas (nitrogen) (cm^2/sec.), $\bar{X}$ is the mean weight particle diameter (cm), R' is the gas constant (82.06 atm. cm^3/mole °K), T_g is the gas temperature in the boundary layer (°K), and $\emptyset$ is the mechanism factor (defined as the ratio of moles of carbon consumed to moles of reactant gas transported to the surface). A value of $\emptyset$ equal to 2 was used (which assumes that CO is the primary combustion product which is subsequently oxidized to CO_2 in the boundary layer).

Surface Reaction Rate Coefficient. The overall reaction rate coefficient (K) is dependent on both the rate of transport of oxygen by diffusion to the particle surface (K_{DIFF}) and the rate of reaction of oxygen at the particle surface (K_S). This is represented mathematically as

$$1/K = 1/K_{DIFF} + 1/K_S \tag{2-13}$$

Eq. (2-13) can be rearranged to

$$K_S = K\ K_{DIFF}/(K_{DIFF} - K) \tag{2-14}$$

Eq. (2-14) was used throughout this work to calculate surface reaction rate coefficients during char combustion.

Apparent Activation Energy and Frequency Factor. The Arrhenius relation was used in conjunction with Eq. (2-14) to calculate the apparent activation energy (E) and frequency factor (A) for char combustion. That is

$$K_S = A \exp(-E/RT_g) \tag{2-15}$$

The values of E and A in Eq. (2-15) were determined for each char combustion from the slopes and intercepts of the least squares fits of ln K_S vs. $1/T_g$ plots. Results obtained from this work are illustrated in Section 3.

Particle Surface Temperature Calculation. The procedure used by Field (3) was followed here. This temperature is calculated from a thermal balance on the particle, equating the heat lost by conduction and radiation to the heat released at the particle surface.

Assuming that carbon monoxide is the primary product of char combustion (i.e., $\emptyset = 2$), the heat released at the surface is 2300 cal per gram of carbon burnt. And the rate of heat generation (H_g) per unit area is given by

$$H_g = 2300\ q \tag{2-16}$$

where q is the rate of carbon removal per unit area [Eq. (2-10)].

The rate of heat loss by conduction (H_c) is given by

$$H_c = 2\ \lambda(T_p - T_g)/X \tag{2-17}$$

where λ, T_p, T_g, and X are, respectively, the thermal conductivity of reactant gas (cal/cm. sec. °K), particle surface temperature (°K), measured bulk gas temperature (°K), and particle diameter (cm).

The rate of heat loss by radiation is given by

$$H_r = \varepsilon\sigma(T_p^4 - T_w^4) \tag{2-18}$$

where ε, σ, and T_w are, respectively, the emissivity of the surface (taken to be unity), the Stefan-Boltzmann constant (1.36×10^{-12} cal/cm. sec. °K), and the reactor wall temperature (°K).

The equilibrium particle temperature (T_p) is calculated from

$$H_g = H_c + H_r \tag{2-19}$$

Eq. (2-19) was solved by a previously developed computer program using a straightforward iterative method to give the particle temperature corresponding to each measurement of char combustion efficiency.

The T_p values obtained from this calculation were subsequently used in conjunction with the Arrhenius Eq. (2-15)--in this case $K_S = A \exp(-E/RT_p)$--to derive the char combustion kinetic parameters.

As such, two methods were used to derive the char combustion kinetic parameters in this study: (1) using the measured bulk gas temperatures (T_g); and (2) using the calculated particle surface temperatures (T_p). Results obtained from this study are illustrated in Section 3.

CONTROLLED MIXING HISTORY FURNACE DATA REDUCTION PROGRAM

A computer program formulated earlier with in-house funding was used to reduce the CMHF data resulting from each test.

The features of the program are (1) computation of the corrected gas temperatures; (2) calculation of the residence times of the combustion products from the mass flow data, furnace geometry, and the temperature profiles; (3) calculation of relevant variables at each sampling port such as combustion efficiency using the ash tracer technique, percent stoichiometry of the mixture, concentrations of NO and NO_x normalized to a theoretical 3% O_2, and fuel nitrogen fate calculated in terms of percent retention by char, percent conversion to NO, percent conversion to gas phase nitrogen species, and percent conversion to molecular nitrogen.

NO_x correction to 3% O_2 was made on the basis of the following relationship

$$[NO_x]_c = [(21 - 3)/(21 - O_2)][NO_x]_m \qquad (2\text{-}20)$$

where $[NO_x]_c$, $[NO_x]_m$, and O_2 are, respectively, the corrected NO_x, measured NO_x, and percent oxygen in the effluent gas stream during NO_x measurement.

The input to the program for each test consists of the following: mass flow rates of pulverized fuel and all the air streams; points of secondary air introduction; fuel composition; suction pyrometer data; gas analysis data; and the char and feed fuel composition data.

Section 3

RESULTS

CHARACTERISTICS OF COAL, CHAR, AND ASH SAMPLES

Coal Analyses

The analyses (Table 3-1) of the Montana Rosebud, Alabama Black Creek, and Pennsylvania Buck Mountain coals are consistent with their ASTM classifications of subbituminous B, high volatile A bituminous, and anthracite, respectively. Although the Texas lignite is classified as lignite A, its moist, mineral-free higher heating value is 8870 Btu/lb (not shown in Table 3-1), which is 570 Btu/lb higher than the top value (8300 Btu/lb) allowed for a lignite A (26). Consistent with some of the coal selection criteria applied in this study, these coals have widely varying volatile matter contents (4.1 - 53.6% on a dry-ash-free basis) and ash contents (2.1 - 18.0 lbs/10^6 Btu).

Hardgrove Grindability Indices

The Hardgrove grindability index (HGI) of the anthracite is 30, indicating that this coal is relatively hard to grind. The HGI of the other three coals vary from 40 to 58, indicating that these coals fall within the typically encountered range and that no problems regarding their pulverization should be encountered.

Flammability Indices

The flammability indices (Table 3-1) of the subject coals are 900°F, 980°F, 1110°F, and 1660°F, respectively, for the ligA, subB, hvAb, and anthracite. These results indicate that the first three coals ignite relatively easily and that they should not, under normal circumstances, present flame stability problems in pulverized coal fired boilers. The anthracite's value indicates that this coal is very difficult to ignite and that it would be expected to present flame stability problems in pulverized coal fired boilers.

Ash Analyses

Ash fusibility temperatures and compositions are also given in Table 3-1. Analyses of the Alabama and Pennsylvania coal ashes are typical of "Eastern"

TABLE 3-1
ANALYSES OF COALS

ANALYSIS	Texas (Wilcox) LigA AS RECEIVED	Texas (Wilcox) LigA DRY-ASH-FREE	Montana (Rosebud) subB AS RECEIVED	Montana (Rosebud) subB DRY-ASH-FREE	Alabama (Black Creek) hvAb AS RECEIVED	Alabama (Black Creek) hvAb DRY-ASH-FREE	Pennsylvania (Buck Mountain) anthracite AS RECEIVED	Pennsylvania (Buck Mountain) anthracite DRY-ASH-FREE
Proximate, Wt. Percent								
Moisture (Total)	21.2	--	23.9	--	3.6	--	5.7	--
Volatile Matter	34.7	53.6	30.7	45.0	37.7	40.3	3.5	4.1
Fixed Carbon	30.0	46.4	37.6	55.0	55.8	59.7	83.3	95.9
Ash	14.1	--	7.8	--	2.9	--	7.5	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Ultimate, Wt. Percent								
Moisture (Total)	21.2	--	23.9	--	3.6	--	5.7	--
Hydrogen	3.5	5.5	3.6	5.3	4.9	5.3	1.7	1.9
Carbon	45.6	70.5	51.6	75.5	78.5	84.0	82.7	95.3
Sulfur	0.6	0.9	0.7	1.0	0.7	0.7	0.4	0.5
Nitrogen	0.8	1.3	0.9	1.3	1.6	1.7	0.7	0.8
Oxygen (Diff.)	14.2	21.8	11.5	16.9	7.8	8.3	1.3	1.5
Ash	14.1	--	7.8	--	2.9	--	7.5	--
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Higher Heating Value, Btu/lb	7845	12130	8800	12880	13935	14910	12740	14675
Ash Loading, lbs/mm Btu	18.0	--	8.9	--	2.1	--	5.9	--
Flammability Index, °F	900	--	980	--	1110	--	1660	--
Hardgrove Grindability Index	48	--	53	--	40	--	30	--
Ash Fusibility (Red. Atm.), °F								
I.T.	2160	--	2150	--	2600	--	2700+	--
S.T.	2210	--	2180	--	2700+	--	2700+	--
H.T.	2250	--	2200	--	2700+	--	2700+	--
F.T.	2360	--	2280	--	2700+	--	2700+	--
ΔT (F.T. - I.T.)	200	--	130	--	+100	--	-	--
Ash Composition, Wt. Percent								
SiO_2	52.1	--	38.5	--	56.9	--	48.5	--
Al_2O_3	18.1	--	16.3	--	28.0	--	38.5	--
Fe_2O_3	3.5	--	4.9	--	8.1	--	4.2	--
CaO	12.4	--	18.5	--	1.1	--	0.3	--
MgO	2.3	--	3.3	--	0.6	--	0.4	--
Na_2O	0.3	--	0.3	--	0.6	--	0.3	--
K_2O	0.4	--	0.3	--	0.9	--	1.1	--
TiO_2	2.0	--	0.7	--	1.6	--	3.2	--
SO_3	8.2	--	15.0	--	1.7	--	0.8	--
Total	99.3	--	97.8	--	99.5	--	97.3	--

coal ashes in which the iron contents are greater than the sums of alkali and alkaline earth contents. Analyses of the Texas and Montana coal ashes are, on the other hand, typical of "Western" coal ashes, whereby the sums of alkali and alkaline earth contents are greater than the iron contents.

The Texas and Montana coal ashes have moderately high calcium contents (12.4% CaO and 18.5% CaO, respectively). Due to its fluxing tendency, this feature is probably largely responsible for these ashes' relatively low fusibility temperatures.

Char Characteristics

Analyses. Selected physicochemical characteristics of the DTFS-generated chars, subsequently sized to 200x400 mesh, are given in Table 3-2. It is important to note that all the chars are virtually volatile matter-free (1.4-3.5% residual volatile matters on a dry-ash-free basis). While the subB char has a dry-ash-free (daf) carbon content of 87%, the other three chars are 97-99% carbonaceous.

Pore Structures. The pore structure data on the four chars are also given in Table 3-2. These data show, for example, that the BET specific pore surface areas increase from 2.6 to 191 m^2/g (daf) as the rank of the parent coal decreases from anthracite to lignite. The CO_2 surface areas also follow a similar trend. It is however noteworthy that while the total open porosity of the anthracite char is only 13%, those of the other three chars are much higher and fall in the 51 to 66% range.

Particle Size Distributions. Dry sieve analysis was used to determine the particle size distributions of the 200x400 mesh chars. These data (Table 3-3) were analyzed by the Rosin-Rammler method (27) to determine the dispersion factors (n), fineness factors (X'), and mean weight particle sizes ($\bar{X}$). Results (Table 3-3) show a high degree of uniformity in particle size distributions between all four chars (the mean weight particle sizes fall in a narrow range of 54-56 μm). This close control of particle size distributions ensures that the differences in reactivities between the chars of interest are not due to differences in particle sizes.

TABLE 3-2

PHYSICOCHEMICAL CHARACTERISTICS OF 200x400 MESH DROP TUBE FURNACE SYSTEM - GENERATED CHARS

QUANTITY	TEXAS (WILCOX) ligA	MONTANA (ROSEBUD) subB	ALABAMA (BLACK CREEK) hvAb	PENNSYLVANIA (BUCK MOUNTAIN) anthracite
Proximate, Wt. %				
Volatile Matter	2.3(3.5)*	2.3(2.8)*	1.5(1.6)*	1.3(1.4)*
Fixed Carbon (Diff.)	64.3	80.3	94.6	92.1
Ash	31.2	14.9	3.9	5.9
Ultimate, Wt. %				
Hydrogen	0.3	0.3	0.3	0.2
Carbon	64.6(97.0)*	72.1(87.3)*	93.2(97.0)*	92.4(98.9)*
Sulfur	0.8	0.8	0.5	0.4
Nitrogen	0.5	0.5	1.0	0.4
Oxygen (Diff.)	0.4	8.9	1.1	0.0
Ash	31.2	14.9	3.9	5.9
S_{BET}, m^2/g, daf	191.3	89.9	16.4	2.6
S_{CO_2}, m^2/g, daf	210.9	162.9	16.3	1.6
ρ_{Hg}, g/cm^3, daf	0.79	0.69	0.86	1.62
ρ_{He}, g/cm^3, daf	1.71	2.01	1.75	1.86
V_T, cm^3/g	0.681	0.952	0.591	0.080
Θ, %	53.8	65.7	50.9	12.9

* Dry-Ash-Free Basis (daf)

$V_T = 1/\rho_{Hg} - 1/\rho_{He}$

$\Theta = [1 - \rho_{Hg}/\rho_{He}] \times 100$

TABLE 3-3

PARTICLE SIZE DISTRIBUTIONS FOR 200x400 MESH CHARS

SIEVE OPENING, X, μm	CUMULATIVE WEIGHT PERCENT GREATER THAN X			
	TEXAS ligA	MONTANA subB	ALABAMA hvAb	PENNSYLVANIA anthracite
63	23.4	28.0	24.3	33.4
53	48.4	52.2	51.2	47.1
45	79.1	82.5	80.9	86.5
38	99.8	98.5	96.3	97.7
ROSIN-RAMMLER PARAMETERS				
n	12.4	7.8	7.1	7.5
X' (μm)	69.5	60.0	58.0	60.0
$\bar{X}$ (μm)	55	56	54	56

n = Dispersion factor
X' = Fineness factor
$\bar{X}$ = Mean weight particle size

Thermo-Gravimetric Reactivities. Thermo-gravimetric burn-off curves in air at 700°C (1292°F) for the 200x400 mesh chars are given in Figure 3-1. The following reactivity trend emerges: ligA char ≅ subB char > hvAb char >> anthracite char. Both lignite and subbituminous chars are burned to completion in 8 minutes; at this point the high volatile bituminous and anthracite chars are burned to 90% and 30%, respectively.

These reactivity trends support the pore structure trends reported for the same chars. That is, generally, the higher the open porosity, the higher is the reactivity. These results show the important role played by the pore structure during char combustion.

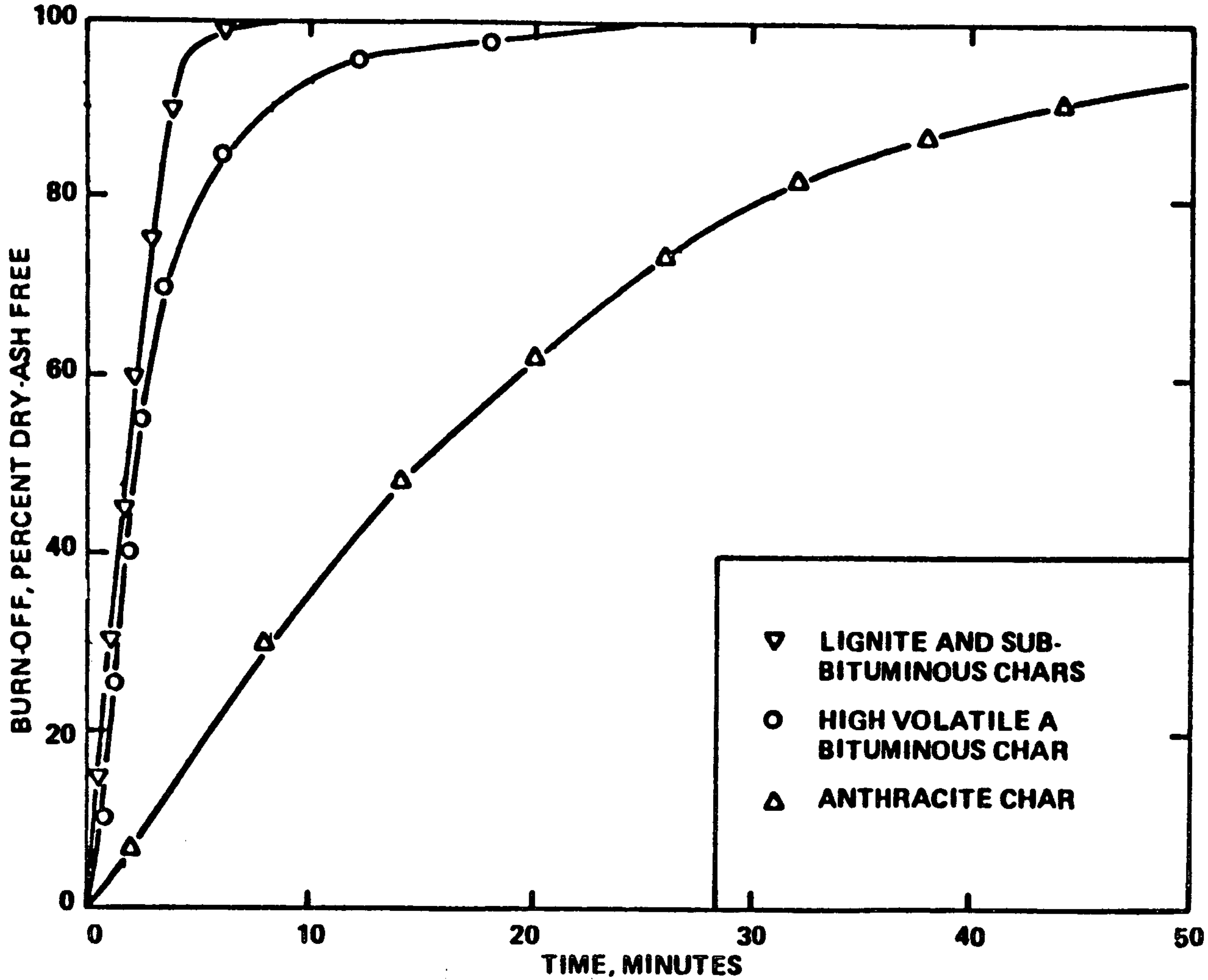

Figure 3-1 THERMO-GRAVIMETRIC BURN-OFF CURVES IN AIR AT 700°C (1292°F) FOR 200 x 400 MESH DTFS CHARS

PYROLYSIS AND/OR COMBUSTION OF COALS AND CHARS IN THE DROP TUBE FURNACE SYSTEM

Pyrolysis of Coals

The controls of the DTFS are designed to maintain the wall temperatures of the preheater and test furnace at certain values. These values dictate the ultimate gas temperature profiles in the reaction zone of the test furnace. A small suction pyrometer was used to measure the nitrogen gas temperatures.

Results are shown in Figure 3-2. Gas temperatures are seen to rise and level-off after a certain distance. The isothermal zone is located within the last eight to ten inches of the sixteen-inch reaction zone. These plateau temperatures are the ones that are referred to throughout this report. Example, T_6 = 2650°F indicates that the isothermal zone was at this temperature. All the temperature profiles used for obtaining coal pyrolysis kinetic data are given in Figure 3-2.

Volatile Yields and Swelling Characteristics. The 200x400 mesh size fraction of each parent coal was pyrolyzed in nitrogen atmosphere at 2650°F and the resulting char was collected at the 16-inch DTFS reaction zone. The objectives of this experiment were to determine: (1) the maximum obtainable volatile yields or pyrolysis weight losses (ΔW_∞) under the prevailing conditions; and (2) the Q-factor. The Q-factor is indicative of the volatile yield enhancements in dilute-phase, rapid heating applications, such as the DTFS, over ASTM volatile matter contents. This technique has been discussed by various authors (10, 14, 16, 17). The heating rates in the DTFS-type applications have been found to be on the order of 10^4°C/sec.

A regular commercial grind (∿70% - 200 mesh) of each parent coal was also pyrolyzed in the DTFS in nitrogen atmosphere at 2650°F. Resulting chars were collected at 4-, 8-, and 16-inch reaction zones. The swelling factor (α) of each coal was determined, based on previous in-house experience, as follows

$$\alpha = [(\bar{X}_4 + \bar{X}_8 + \bar{X}_{16})/3]/\bar{X}_o \qquad (3\text{-}1)$$

where $\bar{X}_4$, $\bar{X}_8$, $\bar{X}_{16}$ are respectively, the mean weight particle sizes of chars obtained at 4-, 8-, and 16-inch reaction zones, and $\bar{X}_o$ is the mean weight particle size of the feed coal.

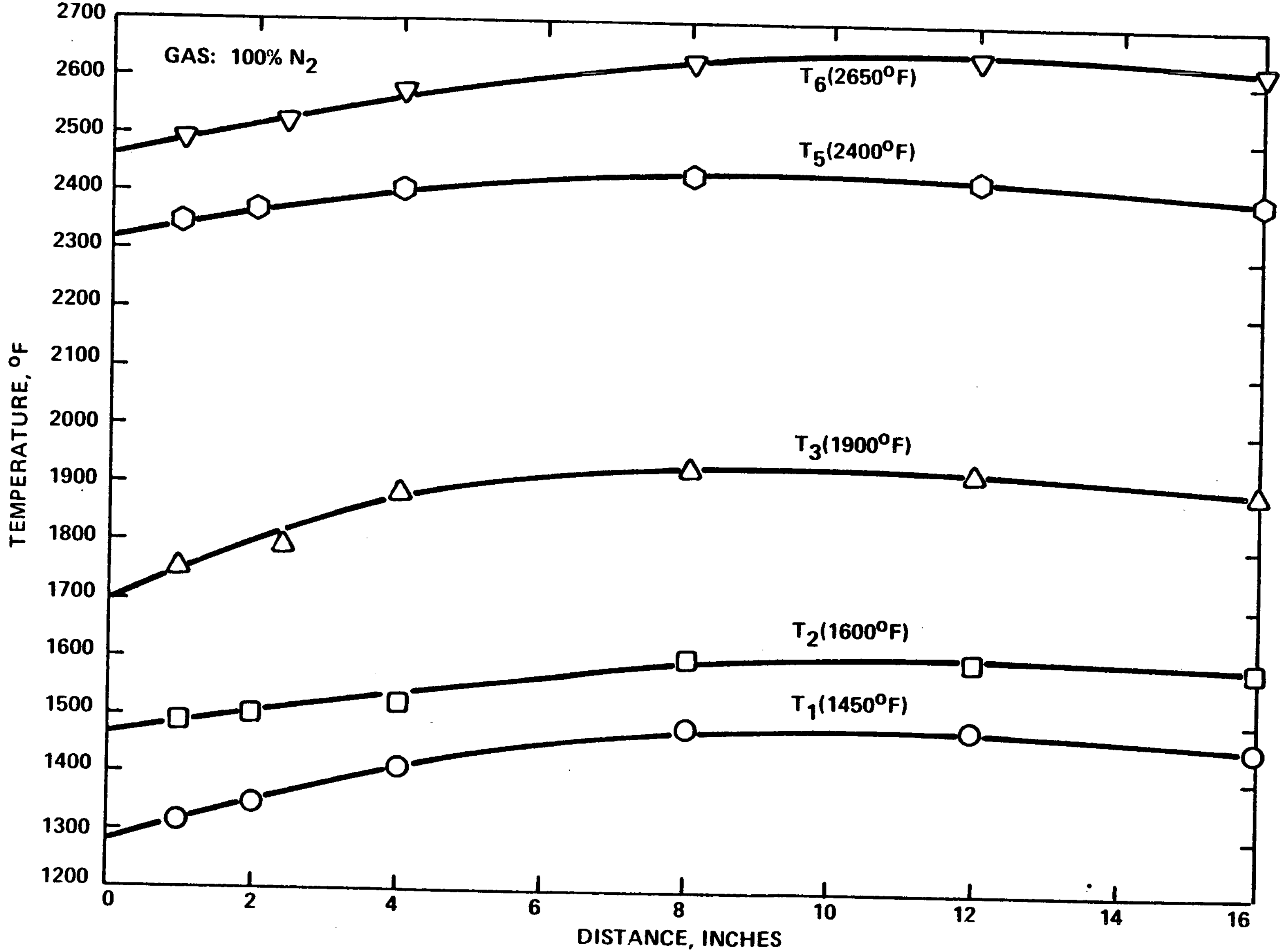

Figure 3-2 AXIAL NITROGEN GAS TEMPERATURE PROFILES IN THE DROP TUBE FURNACE SYSTEM REACTION ZONE

Results from this study (Table 3-4) indicate that:

- Texas lignite, Montana subB, and Pennsylvania anthracite did not show any swelling by virtue of their thermosetting nature. Alabama hvAb, which is thermoplastic, swelled by 34%.
- The ligA and subB showed, respectively, 12% and 14% volatile matter enhancements over their ASTM volatile matter contents. The hvAb and anthracite showed no volatile matter enhancements.
- The maximum pyrolysis weight losses obtainable under the prevailing DTFS test conditions are 58.5, 47.6, 38.2, and 4.9%, respectively, for the ligA, subB, hvAb, and anthracite.

All these pieces of information are very important, as will be seen later, in coal pyrolysis kinetic information derivations and coal combustion modeling studies.

TABLE 3-4

COAL VOLATILE YIELDS AND SWELLING CHARACTERISTICS

COAL	200x400 MESH			REG. GRIND (∿70%-200 MESH)		
	VM_{ASTM}	$(\Delta W_\infty)_{DTFS}$	Q-FACTOR	$\bar{X}_o$	$\bar{X}_c$	SWELLING FACTOR (α)
TEXAS lignite	53.0	58.5	1.12	64	65	1.0
MONTANA subB	45.9	47.6	1.14	58	56	1.0
ALABAMA hvAb	38.2	38.2	1.0	59	79	1.34
PENNSYLVANIA anthracite	4.9	4.9	1.0	64	63	1.0

$\bar{X}_c = (\bar{X}_4 + \bar{X}_8 + \bar{X}_{16})/3$

Effect of Temperature. Closely size graded (200x400 mesh, $\bar{X}$ = 53 - 56 μm) coal samples (Table 3-5) were pyrolyzed in the DTFS in nitrogen atmosphere at 1450, 1600, 1900, 2400, and 2650°F and residence times ranging up to 0.8 sec. as specified in Section 2 (Table 2-2).

Results on the effect of temperature and time on the pyrolysis weight loss are plotted in Figure 3-3. They show that:

- The pyrolysis of each coal is clearly dependent upon temperature and time. Higher temperatures and/or longer residence times yield higher pyrolysis weight losses. For example, for Texas lignite, at 0.2 sec. the pyrolysis weight loss increases from 16% to 51% as the temperature increases from 1450°F to 2650°F; and at 1450°F the pyrolysis weight loss increases from 3% to 34% as time increases from 0.05 to 0.8 sec.

- At 2650°F, however, pyrolysis is virtually complete within 0.2 sec. for the lignite, subbituminous and high volatile bituminous coals.

TABLE 3-5

PARTICLE SIZE DISTRIBUTIONS FOR 200x400 MESH COALS

	CUMULATIVE WEIGHT PERCENT GREATER THAN X			
SIEVE OPENING, X, μm	TEXAS ligA	MONTANA subB	ALABAMA hvAb	PENNSYLVANIA anthracite
63	32.2	31.8	26.0	28.4
53	55.9	54.8	49.0	51.7
45	81.4	82.8	75.5	78.0
38	96.6	98.8	94.1	95.6
ROSIN-RAMMLER PARAMETERS				
n	6.9	9.3	6.1	7.3
X' (μm)	59.5	58.0	57.9	57.0
$\bar{X}$ (μm)	56	55	54	53

n = Dispersion factor
X' = Fineness factor
$\bar{X}$ = Mean weight particle size

Effect of Fuel Properties. In order to compare the pyrolysis weight losses between coals, selected data in Figure 3-3 are re-plotted in Figure 3-4. These plots show comparatively the effects of temperature and time on the pyrolysis of the lignite, subbituminous, and high volatile bituminous coals.

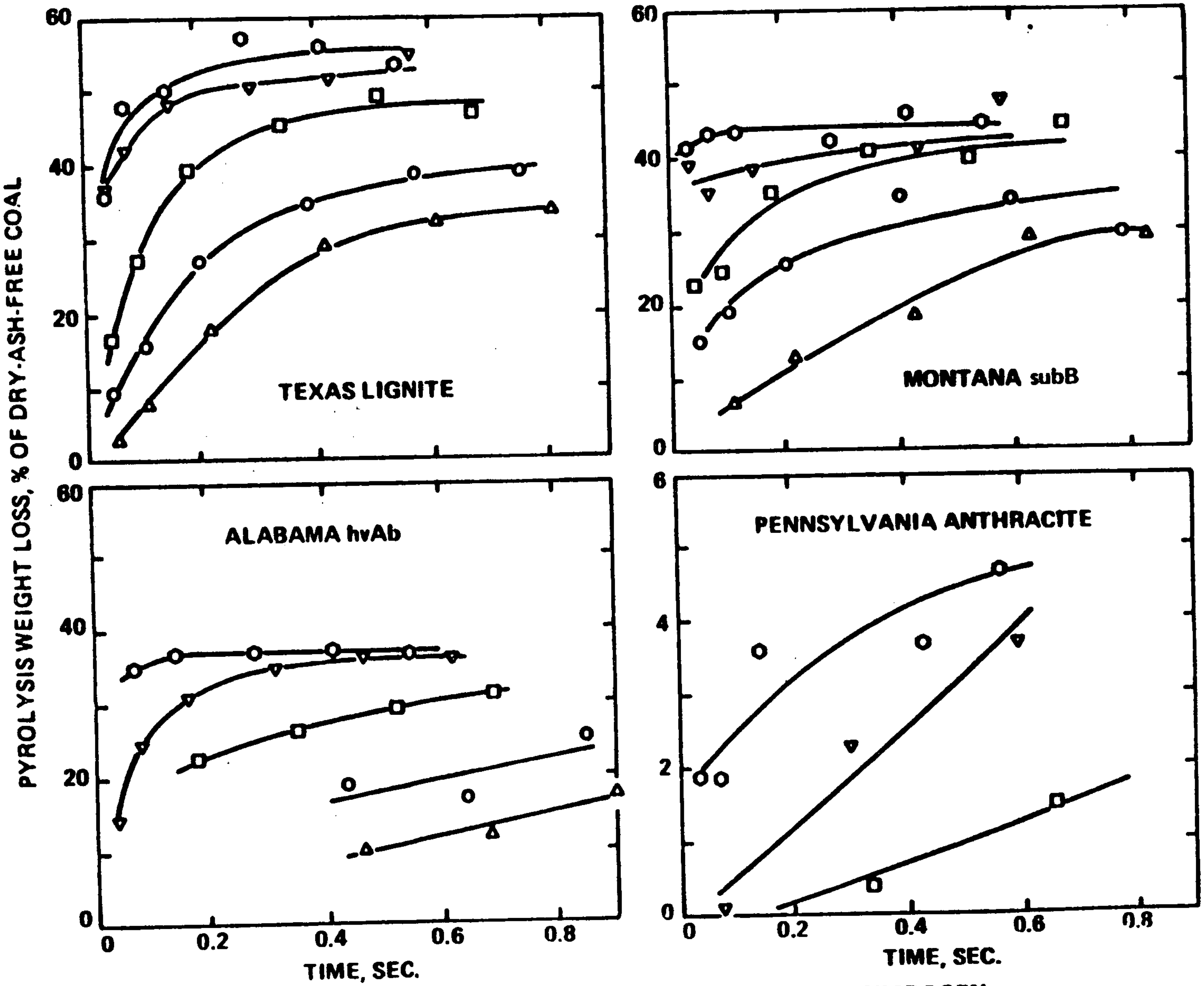

Figure 3-3 DTFS PYROLYSIS WEIGHT LOSSES OF 200 x 400 MESH COALS IN NITROGEN ATMOSPHERE AT VARIOUS TEMPERATURES (△ 1450°F, ○ 1600°F, □ 1900°F, ▽ 2400°F, ○ 2650°F)

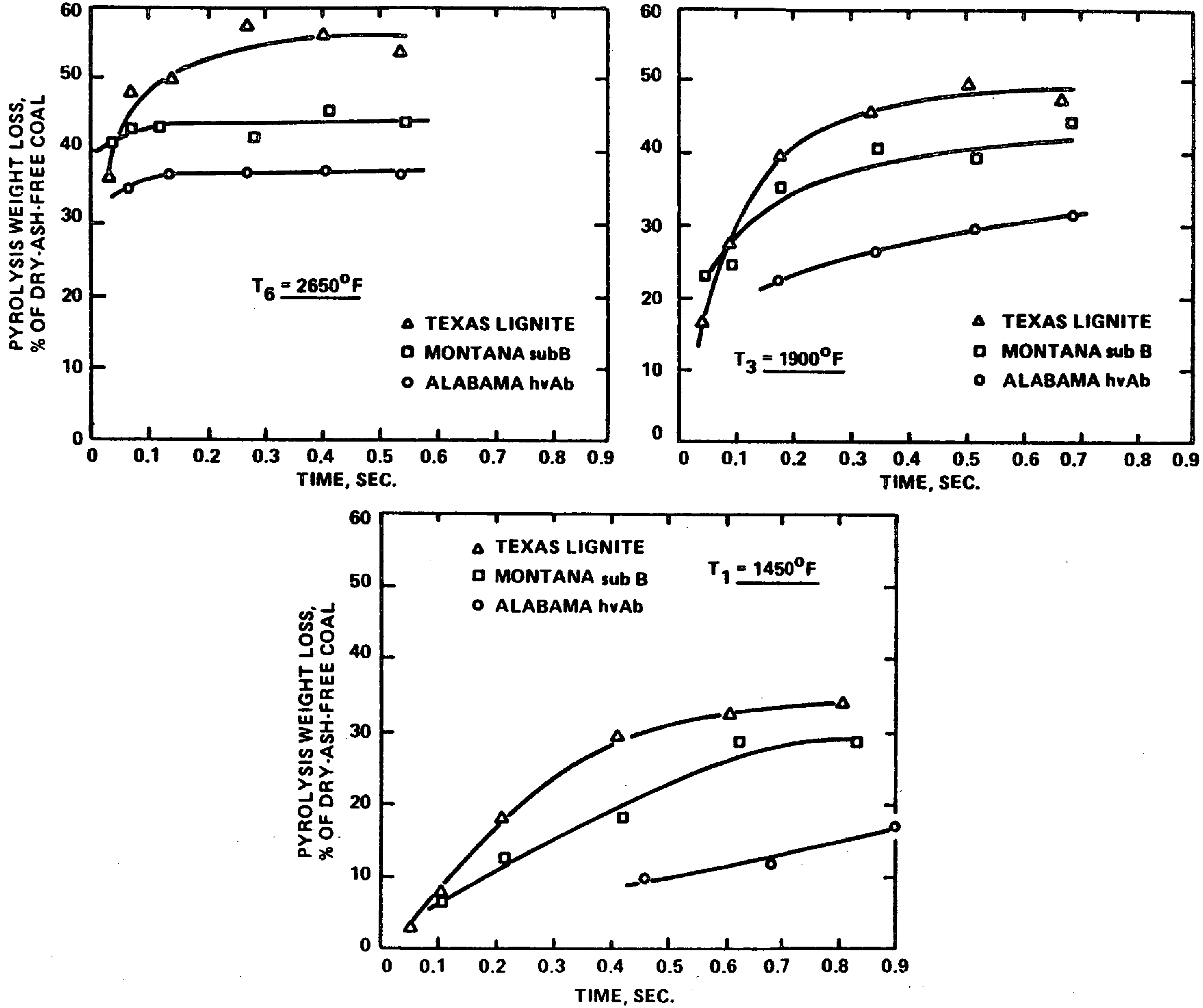

Figure 3-4 EFFECT OF FUEL TYPE ON DTFS PYROLYSIS WEIGHT LOSSES OF 200x 400 MESH COALS IN NITROGEN ATMOSPHERE AT VARIOUS TEMPERATURES

These results show that pyrolysis is dependent upon the nature of the parent coal. That is, at a given temperature and time, the higher the volatile matter in the parent coal the higher is the pyrolysis weight loss. Nevertheless, the rates of pyrolysis of these three coals are similar.

Kinetic Parameters. The pyrolysis weight loss curves in Figure 3-3 were used to derive the pyrolysis kinetic parameters of the subject coals in conjunction with the procedure outlined in Section 2 [Refer to Equations (2-2) to (2-4)].

Plots of $\ln(1 - \Delta W/\Delta W_\infty)$ vs. t yield straight lines (Figure 3-5) from which the pyrolysis constants k can be obtained from the slopes of the least squares fits.

In their relatively low temperature (923-1273°K range) pyrolysis studies, Badzioch and Hawksley (10), Nsakala et al. (14), and Scaroni et al. (16) found that the curves of the type given in Figure 3-5 radiated from a common origin whose time was greater than zero. They found this to be independent of coal, particle size, and temperature. They proposed that this time was associated with the rapid heat up time during which negligible pyrolysis occurred. No such consistent occurrence was encountered in the present pyrolysis study which was conducted at much higher temperatures (1060-1730°K). The implication here is that it cannot be stated in a general way that negligible pyrolysis takes place during the rapid heat up time. As such, the residence times reported here are total residence times; they entail no rapid heat up time corrections.

Now, the k values can be used in conjunction with a first order Arrhenius law to obtain the plots given in Figure 3-6. The apparent activation energies (E) and frequency factors (k_0) are derived from, respectively, the slopes and intercepts of the least squares fits of the straight lines given in Figure 3-6. Results are given in Table 3-6.

The apparent activation energies (4.7 - 8.0 kcal/mole) encountered here are rather low. Various investigators (10, 11, 13, 16, 17, 18) employing dilute-phase reactors similar to the present DTFS and the heated grid experiments

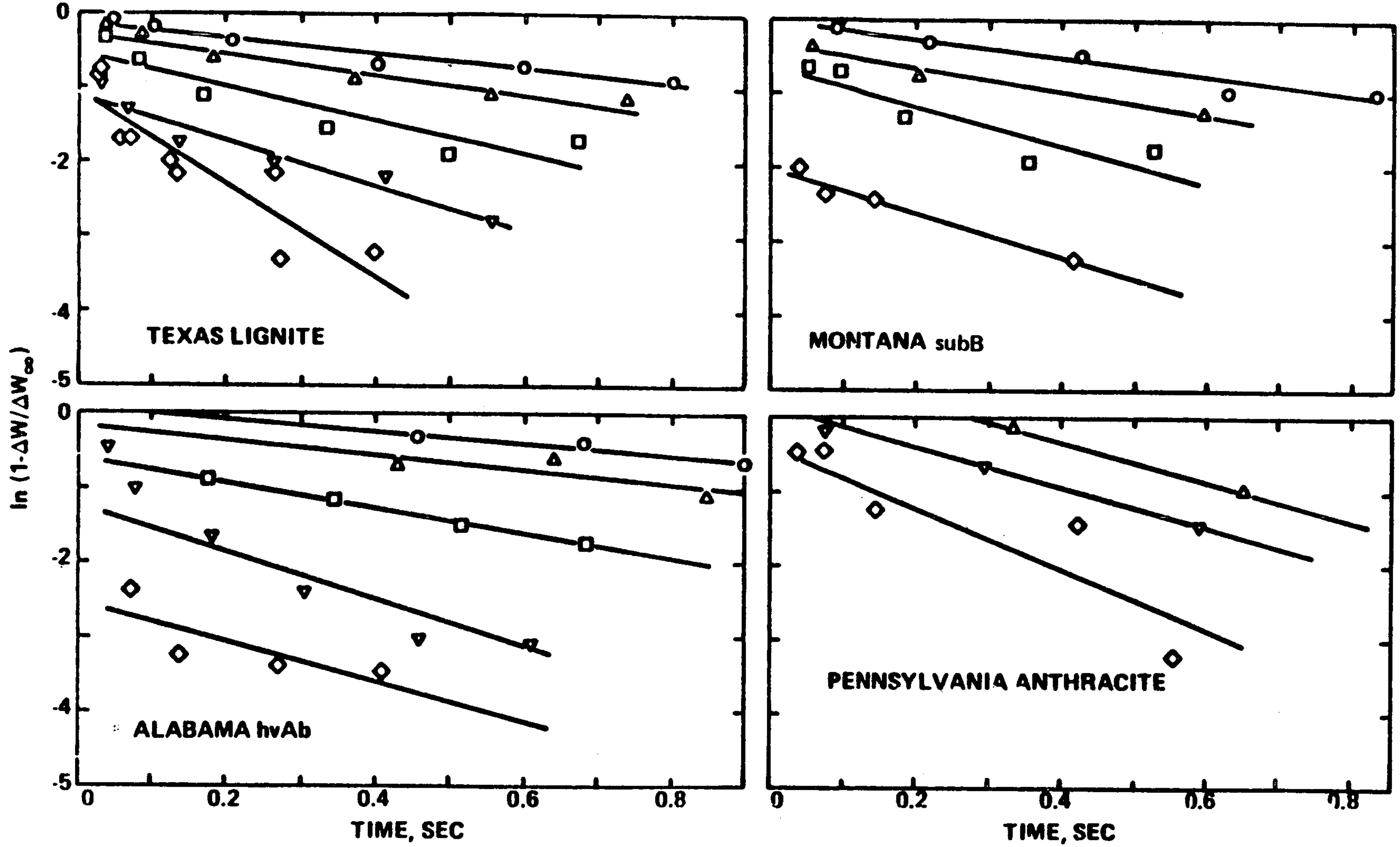

Figure 3-5 VARIATION OF ln $(1-\Delta W/\Delta W_{\infty})$ WITH DTFS RESIDENCE TIME FOR PYROLYSIS OF 200 x 400 MESH COALS IN INITROGEN ATMOSPHERE AT VARIOUS TEMPERATURES (○ 1450°F, △ 1600°F, □ 1900°F, ▽ 2400°F, ◇ 2650°F)

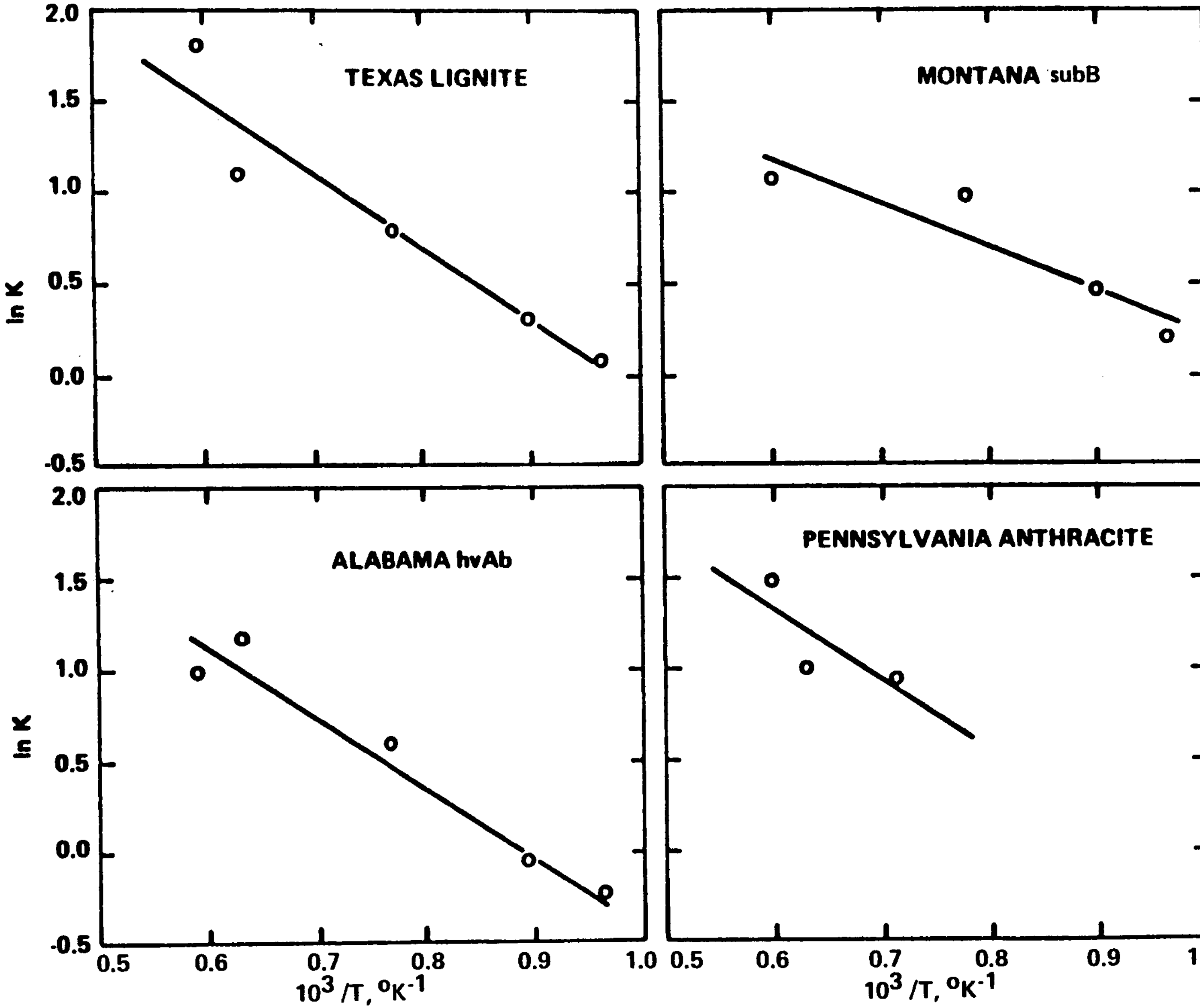

Figure 3-6 ARRHENIUS PLOTS FOR DTFS PYROLYSIS OF VARIOUS 200 x 400 MESH COALS

also encountered relatively low activation energies (generally less than 20 kcal/mole) for thermal decomposition of coals of various rank.

TABLE 3-6

KINETIC DATA FOR PYROLYSIS OF 200x400 MESH COALS IN NITROGEN ATMOSPHERE AND 1035-1690°K TEMPERATURE RANGE

COAL	AVERAGE TEMPERATURE (°K)	KINETIC PARAMETERS k	E	k_o	γ
	1035	1.101			
	1112	1.365			
TEXAS	1295	2.207	7980	50.8	-0.95
ligA	1585	3.017			
	1674	6.385			
	1036	0.194			
	1112	0.455			
MONTANA	1286	0.971	4740	13.5	-0.93
subB	1674	1.065			
	1038	0.710			
	1119	0.949			
ALABAMA	1301	1.166	7825	32.5	-0.98
hvAb	1583	3.191			
	1689	2.657			
	1405	2.552			
PENNSYLVANIA	1585	2.704	7755	38.7	-0.79
anthracite	1674	4.330			

k = Rate Constant, sec^{-1}
E = Activation Energy, cal/gmole
k_o = Frequency Factor, sec^{-1}
γ = Correlation Coefficient of ln k vs. 1/T

Since low activation energies are usually associated with heat and mass transfer effects, one may surmise that the present results indicate a physical rate control mechanism. The absence of particle size effects on the rate of pyrolysis was previously interpreted to mean an absence of heat and mass transfer effects. Anthony et al. (11, 13) provide a probable explanation in terms of a distribution of activation energies for the generation of different volatile species. They obtained activation energies of 10 and 48 kcal/mole, respectively, for single step and multi-step correlations. The implication is that for a complex process like pyrolysis, a low apparent activation energy may not necessarily be indicative of a physical rate control mechanism.

Development of Pore Structure During Pyrolysis of Coals. Selected pore structure parameters (BET and CO_2 specific surface areas, total open pore volumes and percent porosities) were followed as a function of coal pyrolysis weight loss under specific conditions.

The total open volumes (V_T) of the 200x400 mesh lignite, subbituminous, high volatile bituminous, and anthracite feed samples are 0.078, 0.071, 0.018, and 0.051 cm^3/g (daf), respectively (Tables 3-7 to 3-10). This lack of correlation of the total open porosities of coals with rank was previously shown by Gan et al. (28).

Results in Tables 3-7 to 3-10 indicate in general an opening of the pore structure as the pyrolysis weight loss increases (i.e., as more volatile species escape the coal matrix). A similar observation was made by Nsakala et al. (29) and Maloney (18). The development of the pore structure during coal pyrolysis is dependent upon the nature of the parent coal. In general, low rank coals by virtue of their thermosetting nature (i.e., they do not soften upon rapid heating) yield chars with higher open pore structures than high rank coals. The present results bear out this hypothesis. However, it should be noted that the rates of pore structure developments are similar for the lignite, subbituminous, and high volatile bituminous coals. The rate of the pore structure development for the anthracite is, on the other hand, much more sluggish than those of the other three coals due to its inherently closed nature. In summary:

- The total open pore volume of the lignite increases by more than one order of magnitude (from 0.078 to 0.980 cm^3/g) as the pyrolysis weight loss increases from 0% (feed sample) to 53% (2650°F @ 16-inch reaction zone). The corresponding increase in the BET surface area is from 3 to 117 m^2/g (dry-ash-free basis).

TABLE 3-7

CHARACTERISTICS OF TEXAS LIGNITE AND ITS DTFS 16-INCH PYROLYSIS CHARS

PARAMETER	CASE					
	Feed Coal (200x400 Mesh)	T_1(1450°F)	T_2(1600°F)	T_3(1900°F)	T_5(2400°F)	T_6(2650°F)
Pyrolysis Weight Loss, ΔW, % daf	0	34.2	39.2	47.4	54.8	53.0
Residual VM in Char, V_c, % daf	N/A	23.5	16.2	9.7	3.3	2.6
S_{BET}, m^2/g, dry	2.5	3.6	5.0	5.4	25.3	83.6
S_{BET}, m^2/g, daf	3.0	4.6	6.6	7.4	36.0	117.4
S_{CO_2}, m^2/g, dry	85	155	135	120	140	199
S_{CO_2}, m^2/g, daf	100	199	177	163	154	216
ρ_{Hg}, g/cm^3, dry	1.35	1.21	1.16	1.15	1.12	0.86
ρ_{Hg}, g/cm^3, daf	1.24	1.04	0.98	0.95	0.89	0.67
ρ_{He}, g/cm^3, dry	1.48	1.59	1.64	1.87	1.88	2.13
ρ_{He}, g/cm^3, daf	1.36	1.41	1.45	1.68	1.66	1.95
Open Pore Vol., V_T, cm^3/g	0.078	0.252	0.331	0.457	0.521	0.980
Open Porosity, θ, %	9.6	26.2	32.4	43.5	46.4	65.6

TABLE 3-8

CHARACTERISTICS OF MONTANA SUBBITUMINOUS COAL AND ITS PYROLYSIS CHARS OBTAINED FROM THE DTFS REACTION ZONE

PARAMETER	Feed Coal (200x400 Mesh)	T_1(1450°F) CASE						T_6(2650°F) CASE					
		REACTION ZONE LENGTH						REACTION ZONE LENGTH					
		1"	2"	4"	8"	12"	16"	1"	2"	4"	8"	12"	16"
Pyrolysis Time, τ, sec.	0	0.055	0.109	0.215	0.421	0.623	0.827	0.035	0.070	0.140	0.276	0.411	0.545
Pyrolysis Weight Loss; ΔW, % daf coal	0	-	6.4	12.6	18.3	29.1	29.2	41.3	43.2	43.4	41.8	45.7	44.2
Residual VM in Char, % daf coal	N/A	40.5	35.0	27.4	21.6	18.1	16.7	6.8	4.9	3.9	2.9	2.7	2.9
S_{BET}, m^2/g, dry	2.9	1.4	1.4	1.3	1.7	1.6	1.9	10.4	18.3	53	85	101	103
S_{BET}, m^2/g, daf	3.2	1.6	1.5	1.4	1.8	1.8	2.2	12.1	21.3	62	98	118	121
S_{CO_2}, m^2/g, dry	82	72	79	76	99	106	116	115	125	113	142	107	109
S_{CO_2}, m^2/g, daf	90	79	87	84	110	119	126	133	145	131	164	126	127
ρ_{Hg}, g/cm^3, dry	1.30	1.20	1.15	1.06	1.09	1.08	-	0.78	0.76	0.80	0.75	0.71	0.70
ρ_{Hg}, g/cm^3, daf	1.24	1.14	1.09	1.00	1.02	1.00	-	0.70	0.68	0.72	0.67	0.63	0.62
ρ_{He}, g/cm^3, dry	1.42	1.39	1.41	1.46	1.47	1.67	-	1.78	1.76	1.79	1.65	1.76	1.86
ρ_{He}, g/cm^3,daf	1.36	1.33	1.35	1.39	1.40	1.59	-	1.69	1.66	1.70	1.55	1.66	1.77
Open Pore Vol., V_T, cm^3/g	0.071	0.125	0.177	0.281	0.266	0.371	-	0.837	0.868	0.800	0.847	0.985	1.05
Open Porosity, θ, %	8.8	14.3	19.3	28.1	27.1	37.1	-	58.6	59.0	57.6	56.8	0.62	65.0

TABLE 3-9

CHARACTERISTICS OF ALABAMA HIGH VOLATILE BITUMINOUS COAL AND ITS DTFS 16-INCH PYROLYSIS CHARS

PARAMETER	CASE					
	Feed Coal (200x400 Mesh)	T_1(1450°F)	T_2(1600°F)	T_3(1900°F)	T_5(2400°F)	T_6(2650°F)
Pyrolysis Weight Loss, ΔW, % daf	0	17.8	25.3	31.4	36.4	36.7
Residual VM in Char, V_c, % daf	N/A	19.4	11.9	6.0	0.9	0.6
S_{BET}, m^2/g, dry	0.9	0.9	1.2	0.9	30.3	26.4
S_{BET}, m^2/g, daf	0.9	0.9	1.2	0.9	31.9	28.1
S_{CO_2}, m^2/g, dry	133	103	168	111	103	-
S_{CO_2}, m^2/g, daf	137	106	176	117	109	-
ρ_{Hg}, g/cm^3, dry	1.29	0.93	0.92	1.01	0.75	0.84
ρ_{Hg}, g/cm^3, daf	1.27	0.91	0.89	0.98	0.72	0.80
ρ_{He}, g/cm^3, dry	1.32	1.54	1.54	-	1.60	1.65
ρ_{He}, g/cm^3, daf	1.30	1.52	1.51	-	1.57	1.61
Open Pore Vol., V_T, cm^3/g	0.018	0.441	0.461	-	0.752	0.629
Open Porosity, θ, %	2.3	40.1	41.1	-	54.1	50.3

TABLE 3-10

CHARACTERISTICS OF PENNSYLVANIA ANTHRACITE AND
ITS DTFS 16-INCH PYROLYSIS CHARS

PARAMETER	CASE					
	Feed Coal (200x400 Mesh)	T_2(1600°F)	T_3(1900°F)	T_4(2150°F)	T_5(2400°F)	T_6(2650°F)
Pyrolysis Weight Loss, ΔW, % daf	0	-	-	1.5	3.7	4.7
Residual VM in Char, V_c, % daf		-	-	1.9	1.6	1.9
S_{BET}, m^2/g, dry	7.6	3.4	11.0	1.4	1.2	1.3
S_{BET}, m^2/g, daf	8.1	3.7	11.7	1.5	1.2	1.4
S_{CO_2}, m^2/g, dry	115	143	111	122	157	-
S_{CO_2}, m^2/g, daf	122	152	118	130	167	-
ρ_{Hg}, g/cm^3, dry	1.53	1.48	1.54	1.60	1.65	1.65
ρ_{Hg}, g/cm^3, daf	1.48	1.44	1.50	1.51	1.61	1.61
ρ_{He}, g/cm^3, dry	1.65	1.58	1.74	1.79	1.93	1.93
ρ_{He}, g/cm^3, daf	1.60	1.54	1.70	1.75	1.90	1.90
Open Pore Vol., V_T, cm^3/g	0.051	0.045	0.078	0.091	0.095	0.095
Open Porosity, θ, %	7.5	6.5	11.8	13.7	15.3	15.3

- The total open pore volume of the subbituminous coal increases also by more than one order of magnitude (from 0.071 to 1.05 cm^3/g) as the pyrolysis weight loss increases from 0% (feed sample) to 44% (2650°F @ 16-inch reaction zone). The corresponding increase in the BET surface area is from 3 to 121 m^2/g (dry-ash-free basis).

- The total open pore volume of the high volatile bituminous coal increases also by more than one order of magnitude (from 0.018 to 0.629 cm^3/g) as the pyrolysis weight loss increases from 0% (feed sample) to 37% (2650°F @ 16-inch reaction zone). The corresponding increase in the BET surface area is from 1 to 28 m^2/g (dry-ash-free basis).

- The total open pore volume of the anthracite, on the other hand, increases by less than a factor of 2 (from 0.051 to 0.095 cm^3/g) as the pyrolysis weight loss increases from 0% (feed sample) to a mere 4.7% (2650°F @ 16-inch reaction zone). The BET surface area, not showing enough sensitivity, actually decreases from 8 to 1.4 m^2/g (dry-ash-free basis).

Combustion of Chars

A small suction pyrometer was also used to measure the 3% O_2/97% N_2 gas medium (i.e., 0.03 O_2 atm.) temperatures.

Results are shown in Figure 3-7. Gas temperatures are seen to rise and level-off after a certain distance. The isothermal zone is located within the last eight to ten inches of the sixteen-inch reaction zone. These plateau temperatures are the ones that are referred to throughout this report. Example, T_6 = 2650°F indicates that the isothermal zone was at this temperature. These temperature profiles are consistent with those obtained similarly on the nitrogen atmosphere (Figure 3-2). These temperature profiles were used for obtaining char combustion kinetic data.

Effect of Temperature. The 200x400 mesh DTFS-generated chars were burned in the DTFS in 0.03 O_2 atm. (in nitrogen balance) at 1600, 1900, 2150, 2400, and 2650°F and residence times ranging up to 0.85 sec. as specified in Section 2 (Table 2-3).

Results on the effect of temperature and time on the combustion efficiencies of the four coal chars are given in Figure 3-8. They show that:

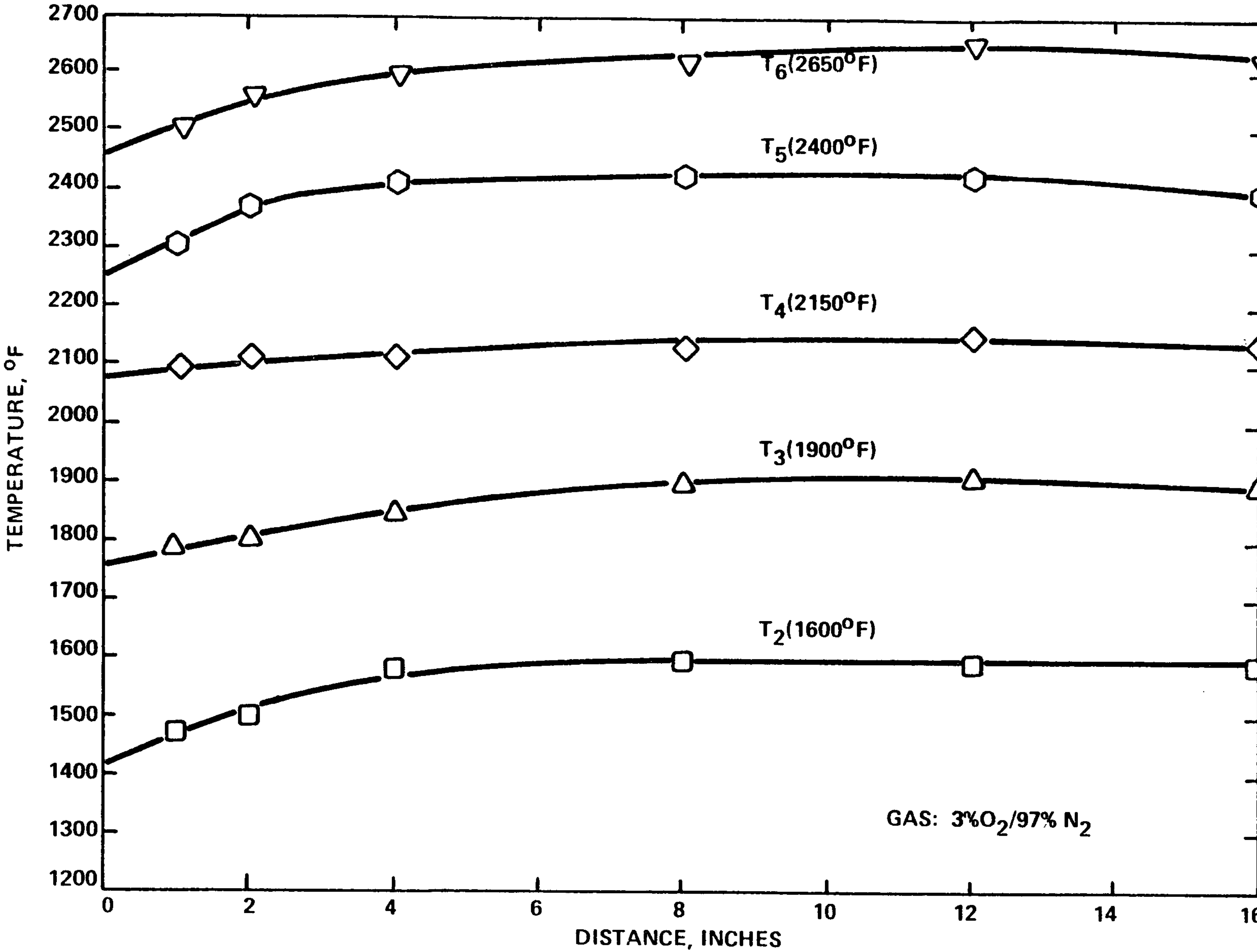

Figure 3-7 AXIAL 3%O_2/97% N_2 GAS TEMPERATURE PROFILES IN THE DROP TUBE FURNACE SYSTEMS REACTION ZONE

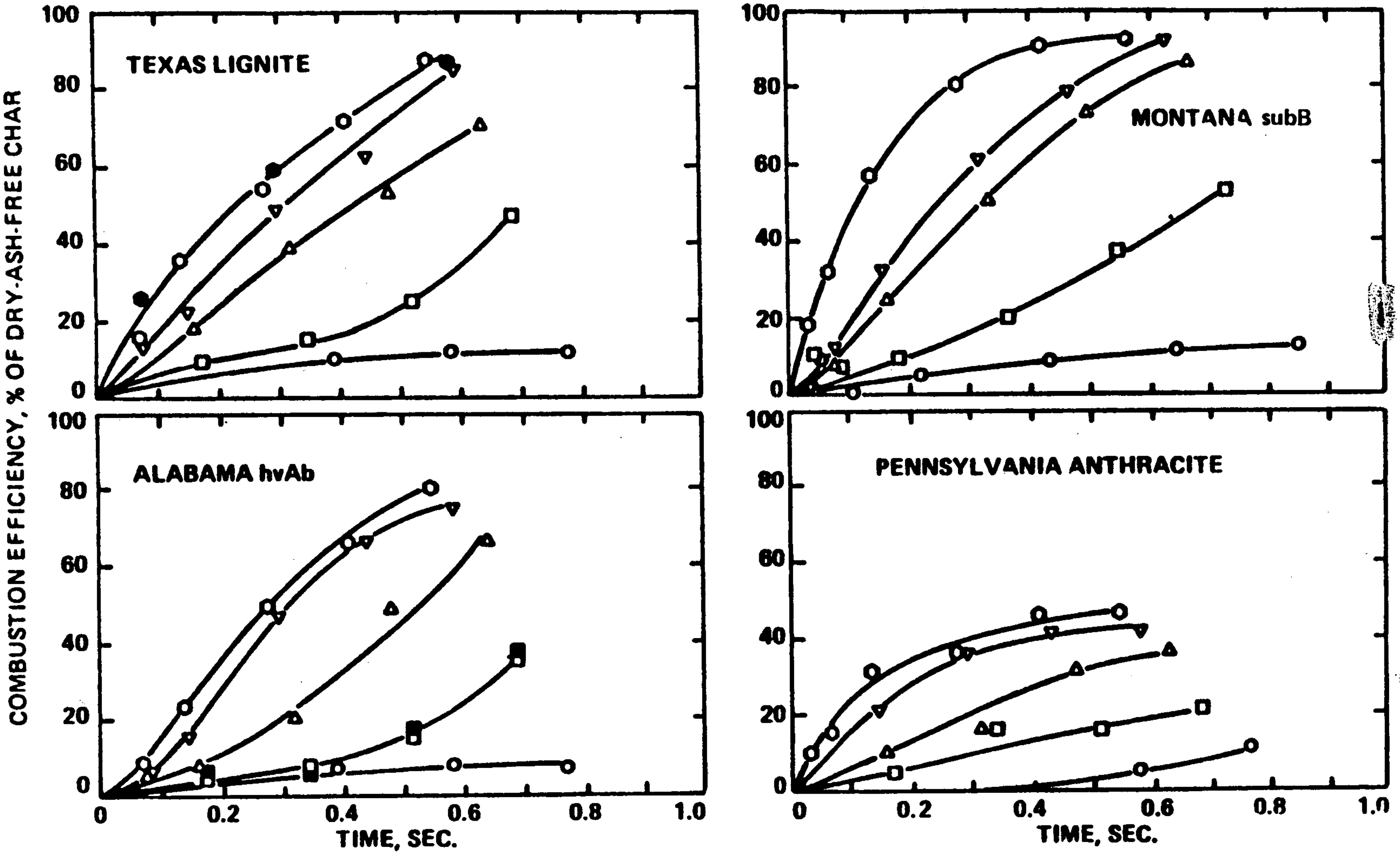

Figure 3-8 DTFS COMBUSTION EFFICIENCIES OF 200 x 400 MESH COAL CHARS IN 3% O_2 / 97% N_2 MEDIUM AT VARIOUS TEMPERATURES (○ 1600°F, □■ 1900°F, △ 2150°F, ▽ 2400°F, ○● 2650°F)

- Char combustion efficiencies vary significantly with temperature and time. For example, for Texas lignite, at 0.5 sec. the combustion efficiency increases from 11% to 82% as temperature increases from 1600°F to 2650°F; and at 2650°F the combustion efficiency increases from 28% to 82% as residence time increases from 0.1 to 0.5 sec.

- Combustion efficiencies show the following trend: Montana subB char > Texas lignite char > Alabama hvAb char >> Pennsylvania anthracite char.

Effect of Fuel Properties. To more clearly depict the differences in reactivities between the four chars, some of the data in Figure 3-8 are re-plotted in Figure 3-9. These results show that the reactivity trend given above holds at virtually all residence times for the 1600, 2150, and 2650°F cases. For example, at 0.5 sec. and 2650°F the combustion efficiencies are 93, 81, 74, and 13%, respectively, for the subB, ligA, hvAb, and anthracite chars. This trend is consistent with the trend observed for these chars total open pore volumes (0.95, 0.61, 0.59, and 0.08 cm^3/g, respectively), indicating the important role played by pore structure during char combustion. These results indicate, for example, that the low reactivity of the anthracite char is attributable to the fact that its predominantly micropore structure is inaccessible to oxygen during combustion.

It is noteworthy that combustion characteristics of Texas lignite, Montana subB and Alabama hvAb coal chars are such that none of the parent coal is expected to present any carbon heat loss problems if fired in a properly designed and operated pulverized coal fired boiler. The anthracite would, as would be expected, present severe carbon heat loss problems in a conventional pulverized coal fired boiler. Burning anthracite successfully would require relatively higher temperatures, longer residence times, and finer particles.

Kinetic Parameters. The char combustion efficiency curves given in Figure 3-8 were used in conjunction with the procedure detailed in Section 2 [Refer to Equations (2-5 to 2-15)] to derive the combustion kinetic parameters. Two methods were used in these derivations. The first method employed the measured bulk gas temperatures (T_g); whereas the second method employed the particle surface temperatures (T_p) calculated according to Equations (2-16 to 2-19).

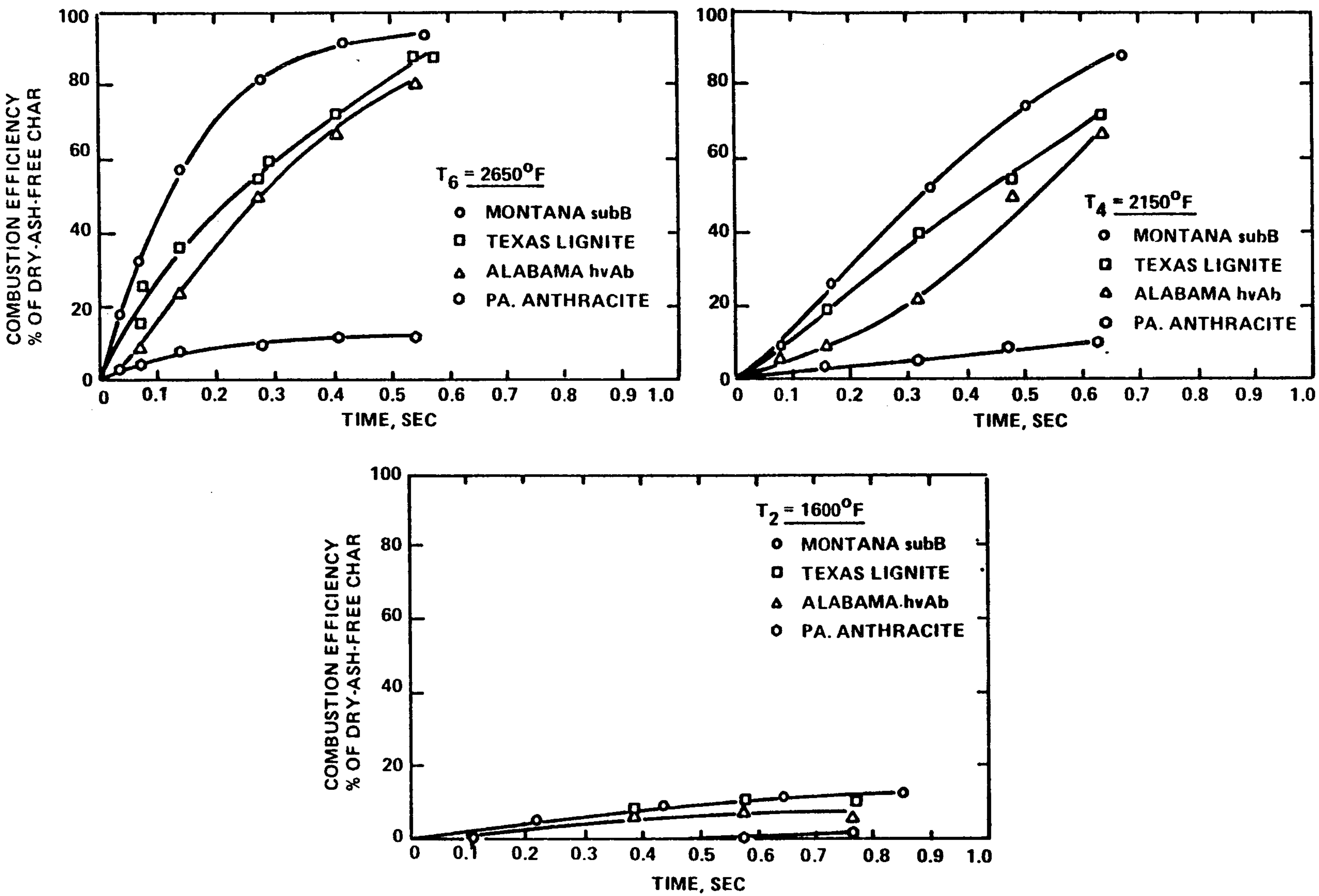

Figure 3-9 EFFECT OF FUEL TYPE ON DTFS COMBUSTION EFFICIENCIES OF 200 x 400 MESH COAL CHARS IN 3% O_2/97% N_2 MEDIUM AT VARIOUS TEMPERATURES

The Arrhenius plots of ln K_s vs. 1/T, where K_s is the surface reaction rate coefficient and T is either the gas or particle temperature, yielded straight lines (Figures 3-10 and 3-11). The apparent activation energies and frequency factors were then obtained from the slopes and intercepts of the least squares fits of these plots. Results are given in Tables 3-11 and 3-12. They show that:

- Method 1 (i.e., using measured bulk gas temperatures) gave apparent activation energies of 21050, 26730, 23320, and 17990 cal/mole, respectively, for the lignite, subbituminous, high volatile bituminous, and anthracite chars. The corresponding frequency factors were 57, 593, 80, and 4.3 g/cm^2 sec. O_2 atm.
- Method 2 (i.e., using calculated particle surface temperatures) gave corresponding apparent activation energies of 20350, 25400, 22550, and 17840 cal/mole, and frequency factors of 36, 271, 50, and 3.7 g/cm^2 sec. O_2 atm.
- Differences in kinetic parameters between the two methods are due to differences between corresponding gas and particle temperatures. Particle temperatures are greater than gas temperatures by 14 to 110°K. These differences are similar to those found by Field (3).

The impact of differences in kinetic parameters due to the choice of the method of derivation is depicted in Figure 3-12. This figure shows that while the impact on the very low reactivity and low temperature sensitivity anthracite char is negligibly small, it is very significant on the lignite char. Hence, it is very important to specify the method used for deriving particular combustion kinetic parameters.

Comparison with Literature Kinetic Data. Figure 3-13 compares the results of the present work obtained from Method 2 with some of the data encountered in the literature (4, 5, 6, 7, 30). These plots illustrate the great differences in reactivities that exist between chars derived from coals of various or even of similar rank range. These differences are due to actual differences in char reactivities and/or differences in experimental conditions used by different investigators. For examples, at 1600°K:

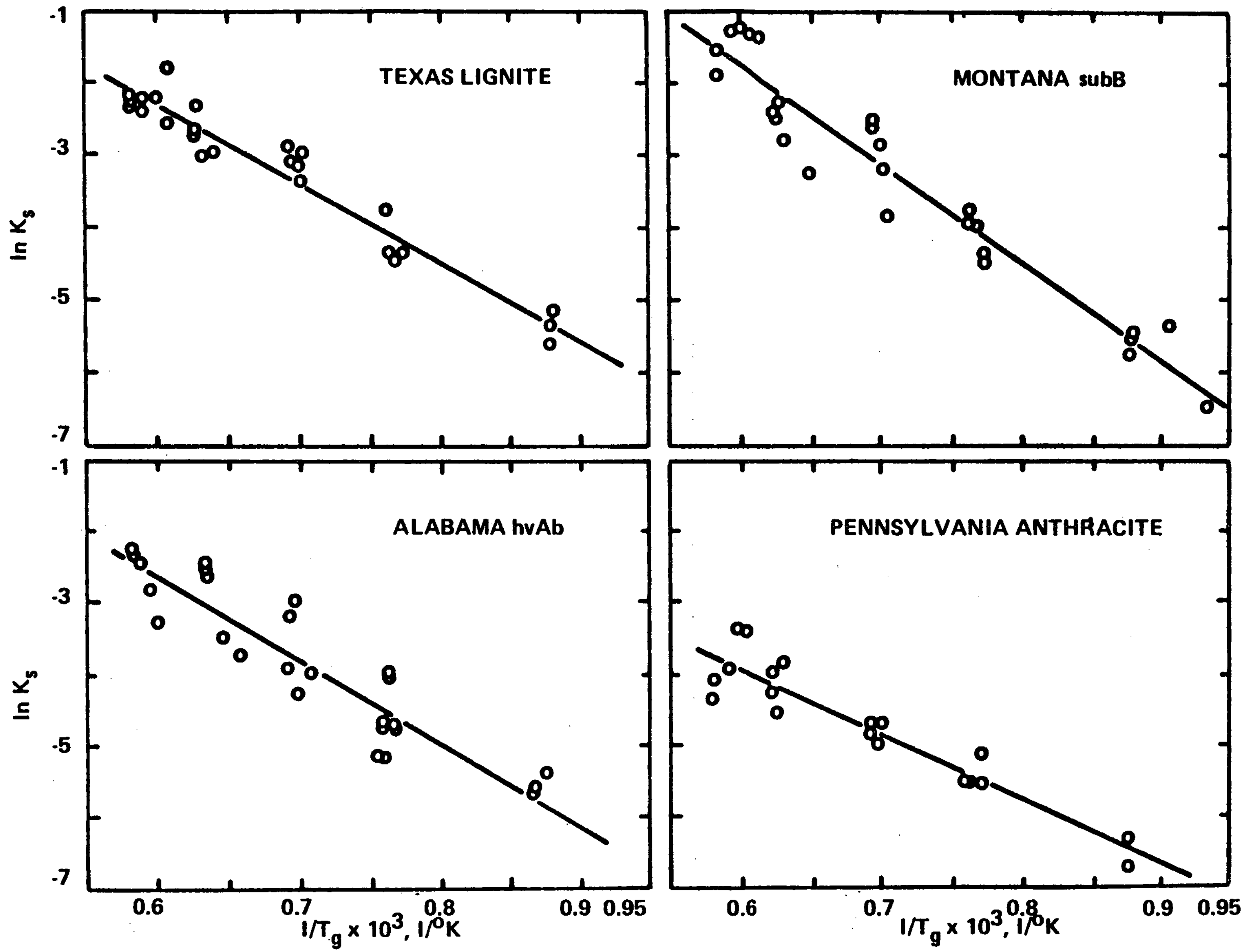

Figure 3-10 ARRHENIUS PLOTS FOR DTFS COMBUSTION OF VARIOUS 200 x 400 MESH COAL CHARS USING MEASURED BULK GAS TEMPERATURES

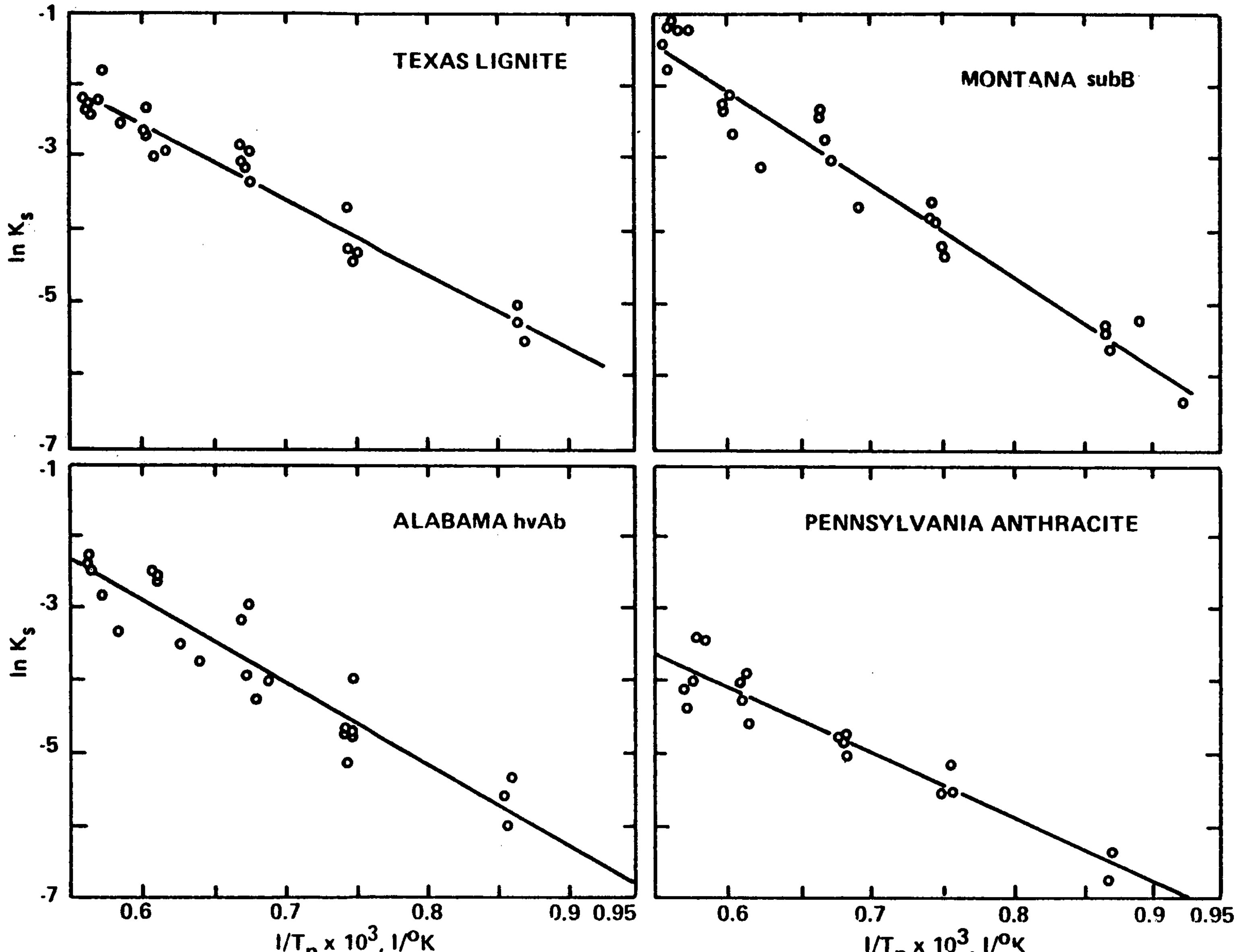

Figure 3-11 ARRHENIUS PLOTS FOR DTFS COMBUSTION OF VARIOUS 200 x 400 MESH COAL CHARS USING CALCULATED PARTICLE SURFACE TEMPERATURES

TABLE 3-11

KINETIC DATA FROM COMBUSTION OF 200x400 MESH LIGNITE AND SUBBITUMINOUS CHARS IN 0.03 OXYGEN ATMOSPHERE AND 1070-1800°K TEMPERATURE RANGE

TEXAS LIGNITE				MONTANA SUBBITUMINOUS			
METHOD 1		METHOD 2		METHOD 1		METHOD 2	
TEMP.	K_S	TEMP.	K_S	TEMP.	K_S	TEMP.	KS
1138	.00625	1160	.00625	1074	.00173	1090	.00175
1142	.00508	1159	.00507	1105	.00537	1128	.00540
1141	.00384	1154	.00384	1138	.00494	1159	.00496
1297	.01349	1331	.01348	1142	.00448	1159	.00449
1306	.01202	1338	.01202	1141	.00357	1154	.00357
1316	.01391	1344	.01390	1308	.02181	1345	.02178
1317	.02513	1347	.02510	1298	.01310	1332	.01310
1424	.05349	1484	.05328	1299	.01451	1333	.01450
1430	.03509	1483	.03501	1316	.02230	1349	.02228
1436	.04422	1490	.04409	1317	.02735	1347	.02732
1447	.04684	1496	.04671	1424	.02505	1468	.02501
1449	.05746	1496	.05728	1430	.04885	1489	.04868
1564	.05291	1624	.05273	1436	.06509	1497	.06477
1586	.04915	1645	.04901	1447	.08648	1507	.08594
1600	.07063	1663	.07032	1449	.09374	1505	.09315
1601	.06748	1658	.06723	1547	.04313	1604	.04302
1597	.09830	1656	.09773	1589	.06974	1656	.06941
1651	.07775	1722	.07735	1605	.09314	1675	.09254
1675	.11011	1759	.10919	1607	.10132	1672	.10066
1701	.08783	1775	.08733	1600	.11830	1661	.11744
1720	.09562	1785	.09510	1640	.29347	1749	.28475
1724	.11208	1787	.11139	1661	.29676	1771	.28804
1651	.16732	1746	.16488	1678	.33592	1783	.32496
1701	.10683	1777	.10606	1693	.31236	1794	.30365
1724	.10896	1784	.10834	1720	.23771	1804	.23361
				1725	.16665	1791	.16507

Kinetic Parameters (Texas Lignite)		Kinetic Parameters (Montana Subbituminous)	
E = 21050	E = 20350	E = 26730	E = 25400
A = 57	A = 35.6	A = 593	A = 271
γ = -0.967	γ = -0.972	γ = -0.965	γ = -0.972

Method 1 - Using Measured Bulk Gas Temperatures (T_g)
Method 2 - Using Calculated Particle Surface Temperature (T_p)
E = Activation Energy, cal/mole
A = Frequency Factor, g/cm^2-sec. O_2 atm.
γ = Correlation Coefficient of ln K_S vs. 1/T Plot
Temp. = °K

TABLE 3-12

KINETIC DATA FROM COMBUSTION OF 200x400 MESH
HIGH VOLATILE BITUMINOUS AND ANTHRACITE CHARS IN 0.03 OXYGEN
ATMOSPHERE AND 1070-1800°K TEMPERATURE RANGE

ALABAMA HIGH VOLATILE BITUMINOUS				PENNSYLVANIA ANTHRACITE			
METHOD 1		METHOD 2		METHOD 1		METHOD 2	
TEMP.	K_S	TEMP.	K_S	TEMP.	K_S	TEMP.	K_S
1146	.00459	1166	.00459	1142	.00122	1156	.00122
1157	.00363	1173	.00363	1141	.00183	1152	.00183
1158	.00237	1169	.00237	1298	.00406	1325	.00406
1310	.00848	1340	.00847	1299	.00605	1327	.00605
1322	.00570	1349	.00569	1316	.00401	1337	.00401
1322	.00870	1347	.00870	1317	.00401	1333	.00401
1315	.01879	1341	.01878	1430	.00918	1466	.00918
1310	.00887	1340	.00886	1436	.00683	1468	.00683
1322	.00571	1349	.00571	1447	.00906	1476	.00906
1322	.00947	1347	.00946	1449	.00797	1471	.00797
1315	.01861	1342	.01860	1589	.02111	1633	.02109
1416	.01803	1456	.01801	1605	.01841	1646	.01839
1434	.01391	1472	.01390	1607	.01422	1639	.01421
1447	.01964	1487	.01962	1600	.01052	1624	.01051
1447	.04148	1494	.04139	1661	.03289	1715	.03284
1441	.05186	1486	.05172	1678	.03404	1735	.03398
1525	.02335	1568	.02333	1693	.01905	1739	.01903
1552	.03021	1601	.03016	1720	.01642	1757	.01641
1580	.07046	1643	.07015	1725	.01239	1753	.01238
1586	.08264	1647	.08223				
1585	.07893	1637	.07861				
1665	.03622	1719	.03616				
1683	.05988	1750	.05967				
1704	.08357	1775	.08314				
1719	.09267	1782	.09221				
1724	.10183	1781	.10133				

Kinetic Parameters (Alabama High Volatile Bituminous)

Method 1	Method 2
E = 23320	E = 22550
A = 80	A = 50
γ = -0.922	γ = -0.926

Kinetic Parameters (Pennsylvania Anthracite)

Method 1	Method 2
E = 17990	E = 17840
A = 4.3	A = 3.7
γ = -0.939	γ = -0.948

Method 1 - Using Measured Bulk Gas Temperatures (T_g)
Method 2 - Using Calculated Particle Surface Temperatures (T_p)
E = Activation Energy, cal/mole
A = Frequency Factor, g/cm^2-sec. O_2 atm.
γ = Correlation Coefficient of ln K_S vs. 1/T Plot
Temp. = °K

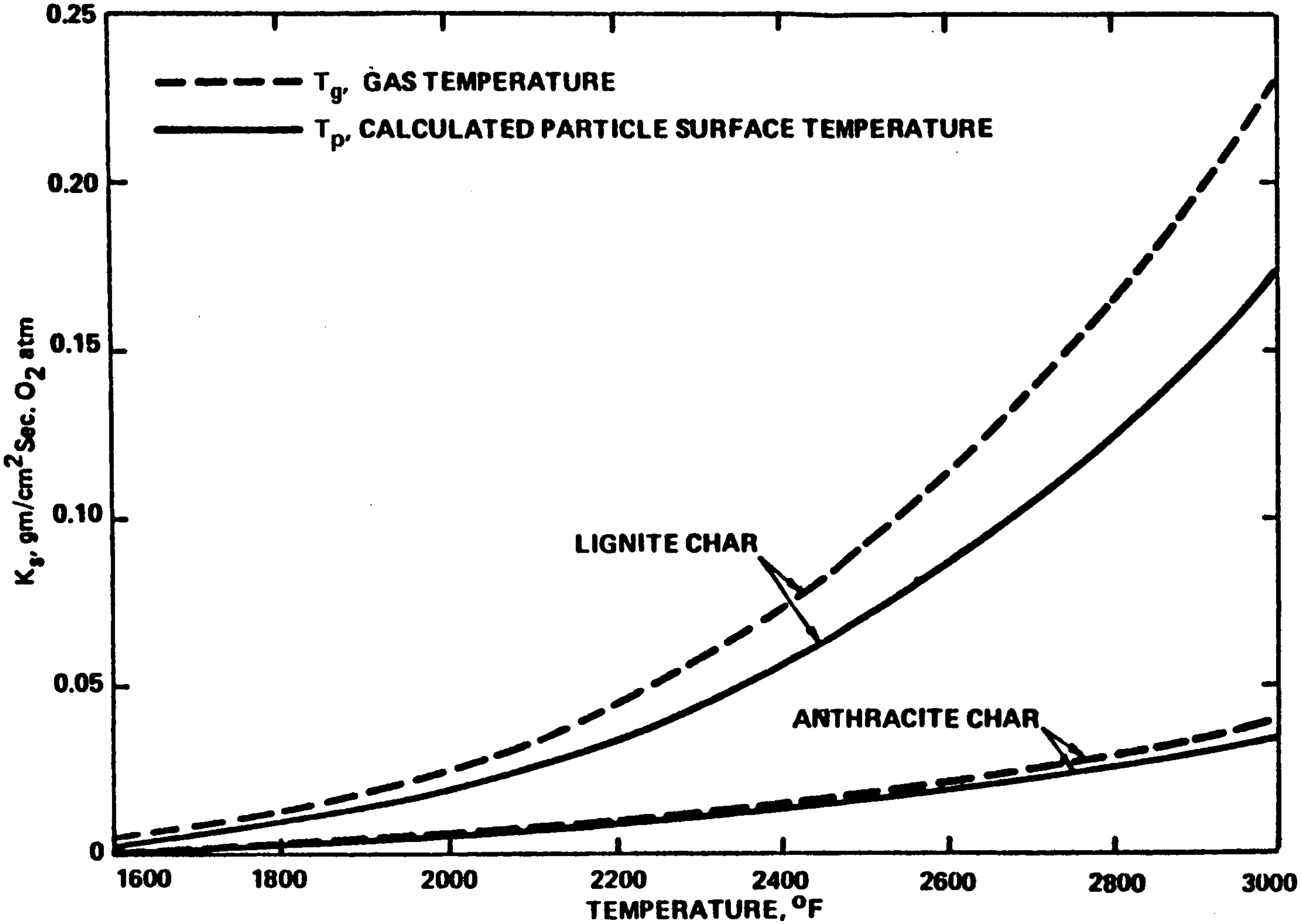

Figure 3-12 VARIATION OF COMBUSTION SURFACE REACTION RATE COEFFICIENT TEMPERATURE FOR TEXAS LIGNITE AND PENNSYLVANIA ANTHRACITE CHARS IN THE DTFS

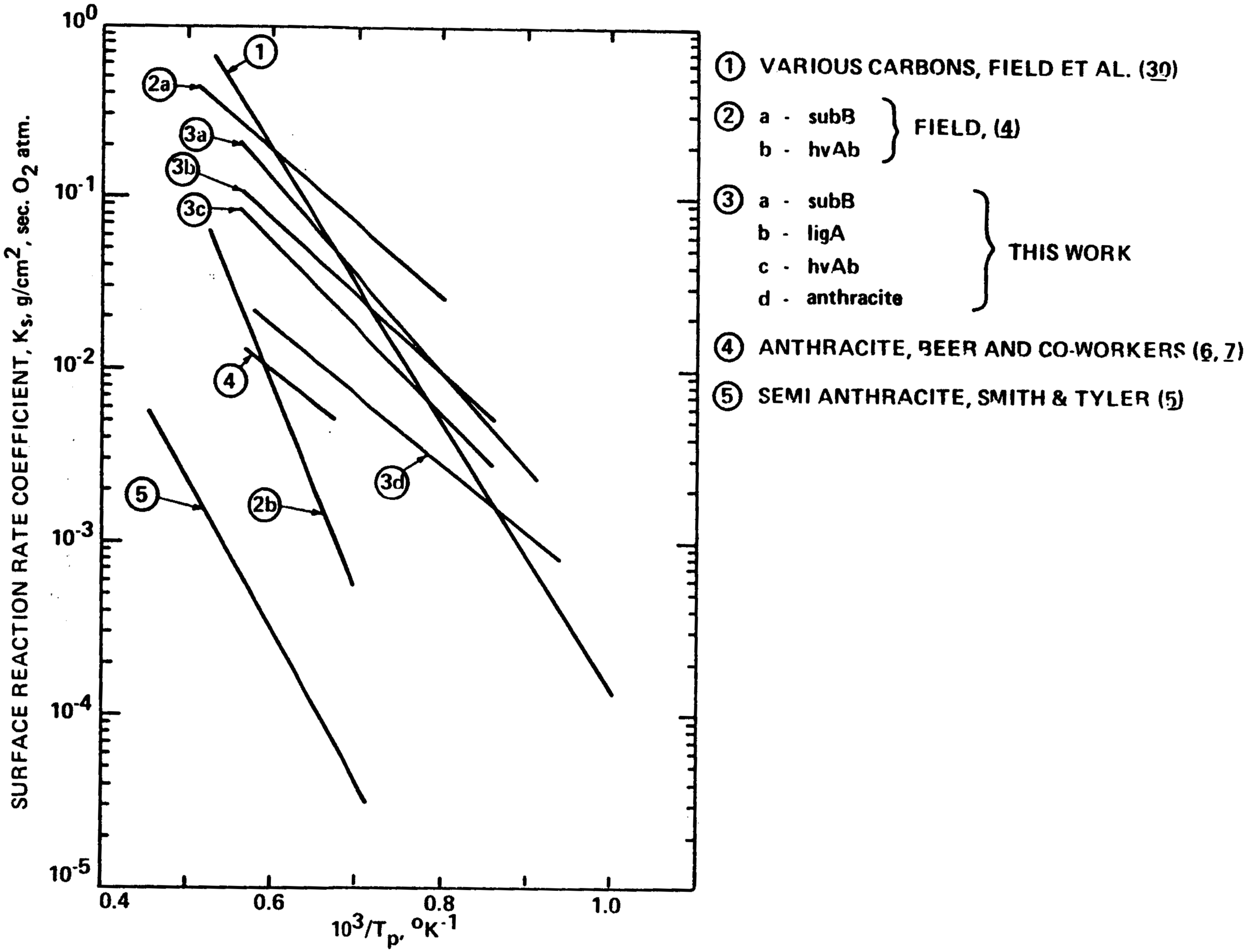

Figure 3-13 RELATIONSHIP BETWEEN SURFACE REACTIVITY COEFFICIENT AND SURFACE TEMPERATURE FOR PRESENT STUDY AND SOME LITERATURE DATA

- The surface reaction rate coefficient of Field's subB char (4) is greater than that of Smith and Tyler's semi-anthracite (5) by a factor approaching three orders of magnitude (820).

- The surface reaction rate coefficient of this work's most reactive char (subB) is greater than that of this work's least reactive char (anthracite) by a factor of 6.

- While the surface reaction rate coefficient of this work's anthracite is less than a factor of two higher than that of Beer and co-workers' anthracite (6, 7), it is almost two orders of magnitude higher than that of Smith and Tyler's semi-anthracite.

These results clearly indicate that using kinetic parameters found in the literature for a particular modeling application can be risky, and, therefore, should be done with circumspection.

The analytical data obtained from the DTFS studies are given in Appendix B.

COMBUSTION PERFORMANCE OF THE ALABAMA HIGH VOLATILE BITUMINOUS COAL IN THE CONTROLLED MIXING HISTORY FURNACE

The Alabama hvAb coal was fired in the pilot scale CMHF at 500,000 Btu/hr in order to evaluate the effect of staged combustion on NO_x emissions and overall combustion efficiencies.

Staged combustion was obtained in the CMHF as previously depicted in Figure 2-3. The preheating and ignition stage is located between the points of introduction of coal/primary air and secondary air. The primary stage is located between the points of introduction of secondary air and tertiary air. And the secondary stage is located downstream of the point of introduction of tertiary air.

The test matrix for this study has been discussed in Section 2 (Table 2-4). The analytical data obtained from the CMHF are given in Appendix C.

Effect of Staged Combustion on NO_x Emissions

Effect of Primary Stage Stoichiometry. Results indicate that staged combustion has a significant effect on overall CMHF NO_x emissions and that the primary stage stoichiometry is one of the most important parameters in controlling fuel-bound NO_x formation.

As the primary stage stoichiometry increases from 15 to 120% of the theoretical air required for complete combustion, the CMHF outlet NO_x level (corrected to 3% O_2) decreases gradually from 420 ppm to a lowest level of 282 ppm, then increases relatively fast to 498 ppm at 120% (Figure 3-14). These results can be explained in terms of the existence of an optimum stage stoichiometry (50% in this particular case) which provides an optimum amount of NO and intermediate nitrogen species (HCN, CN, NH_x, etc.) favoring NO to N_2 conversion in the primary stage.

The classical bowl-shaped curve depicted in Figure 3-14 is consistent with the CMHF results obtained previously in this laboratory (31) on a Wyoming subbituminous B coal, a Kentucky high volatile B bituminous coal, and two SRC (Solvent Refined Coal) samples (Figure 3-15).

Effect of Primary Stage Residence Time. The effect of primary stage residence time was determined at the optimum primary stage stoichiometry of 50%. Percent excess air was maintained at 20%, and the secondary air was introduced in ring 1. Primary stage residence time was changed by varying the level of tertiary air introduction from ring 1 to ring 5. Fuel feed rate and primary and secondary air flow rates were kept constant throughout the tests.

The effect of primary stage residence time on NO_x formation is illustrated in Figure 3-16. Changing the tertiary air introduction level from ring 1 to ring 5 resulted in an increase in primary stage residence time from 0 to 1.56 sec. This resulted in a 50% reduction in NO_x at the furnace outlet (from 498 to 249 ppm @ 3% O_2). It is observed that the outlet NO_x decreases very rapidly during the first second of the residence time indicating that primary stage residence time also has a significant influence on reducing NO_x emissions.

The decrease of NO_x with residence time is due to the fact that residence time enhances the NO to N_2 conversion in the sub-stoichiometric primary stage zone. The relatively flat portion of the curve at over one second suggests that the reactions of various nitrogen intermediate species (HCN, CN, NH_x, etc.) have reached a chemical thermo-dynamic equilibrium at the fuel-rich primary stage. Therefore, results indicate that even though the overall NO_x emissions may not be adversely affected by extending the primary stage residence time, a primary stage residence time of over 1.5 sec. is neither more effective nor necessary.

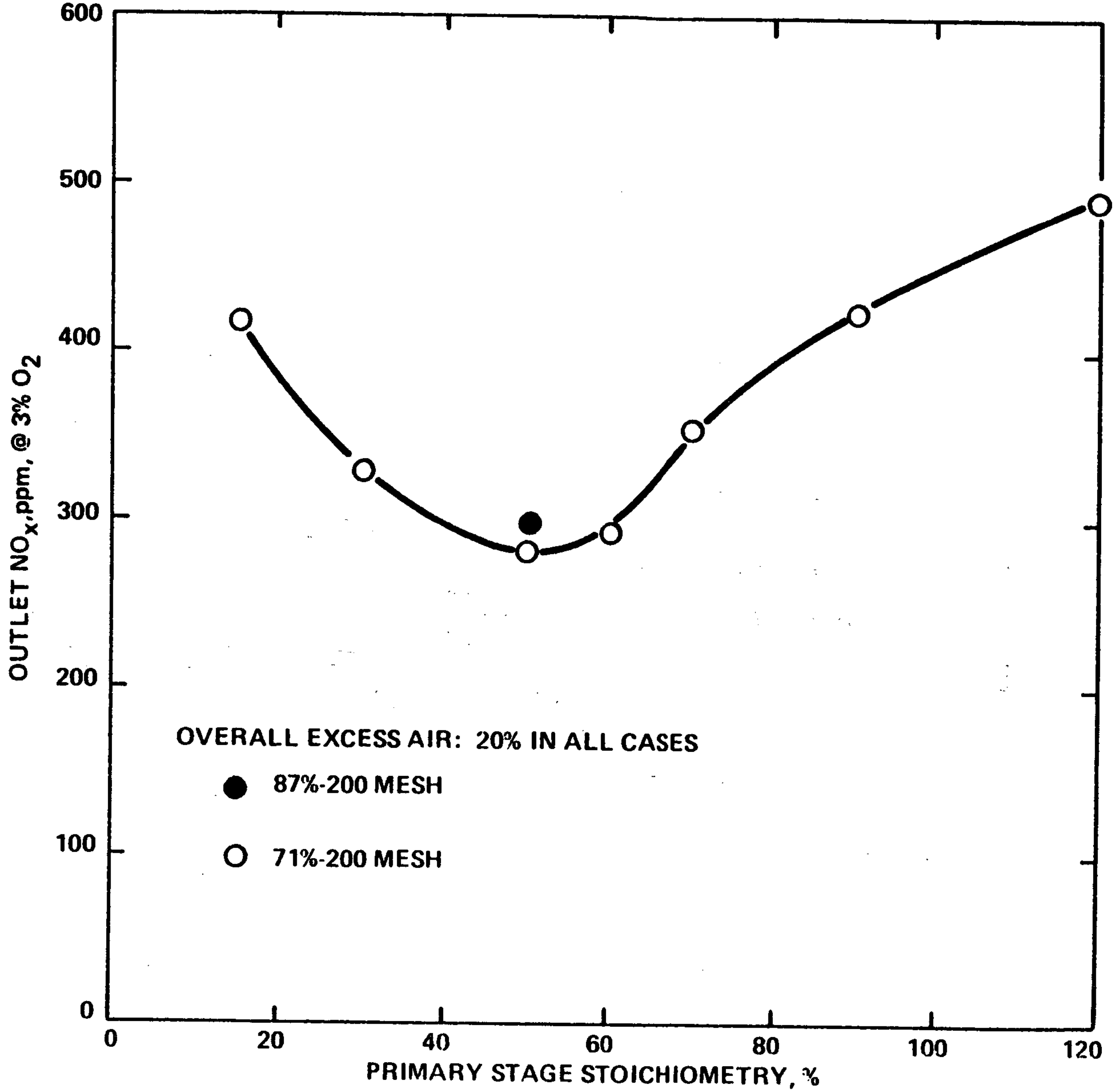

Figure 3-14 EFFECT OF PRIMARY STAGE STOICHIOMETRY ON CMHF NO_x EMISSIONS OF ALABAMA hvAb COAL

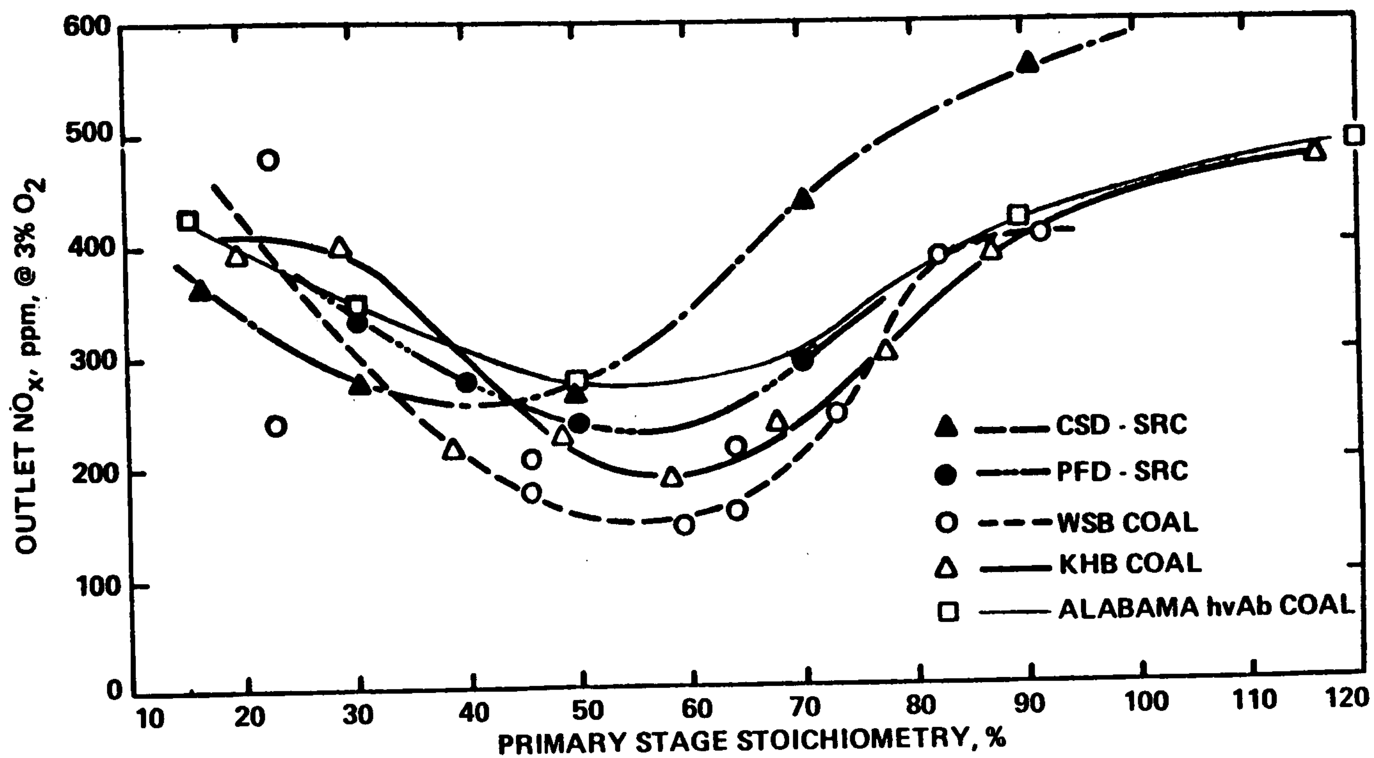

Figure 3-15 EFFECT OF PRIMARY STAGE STOICHIOMETRY ON CMHF NO_x EMISSIONS OF ALABAMA hvAb AND REFERENCE FUELS

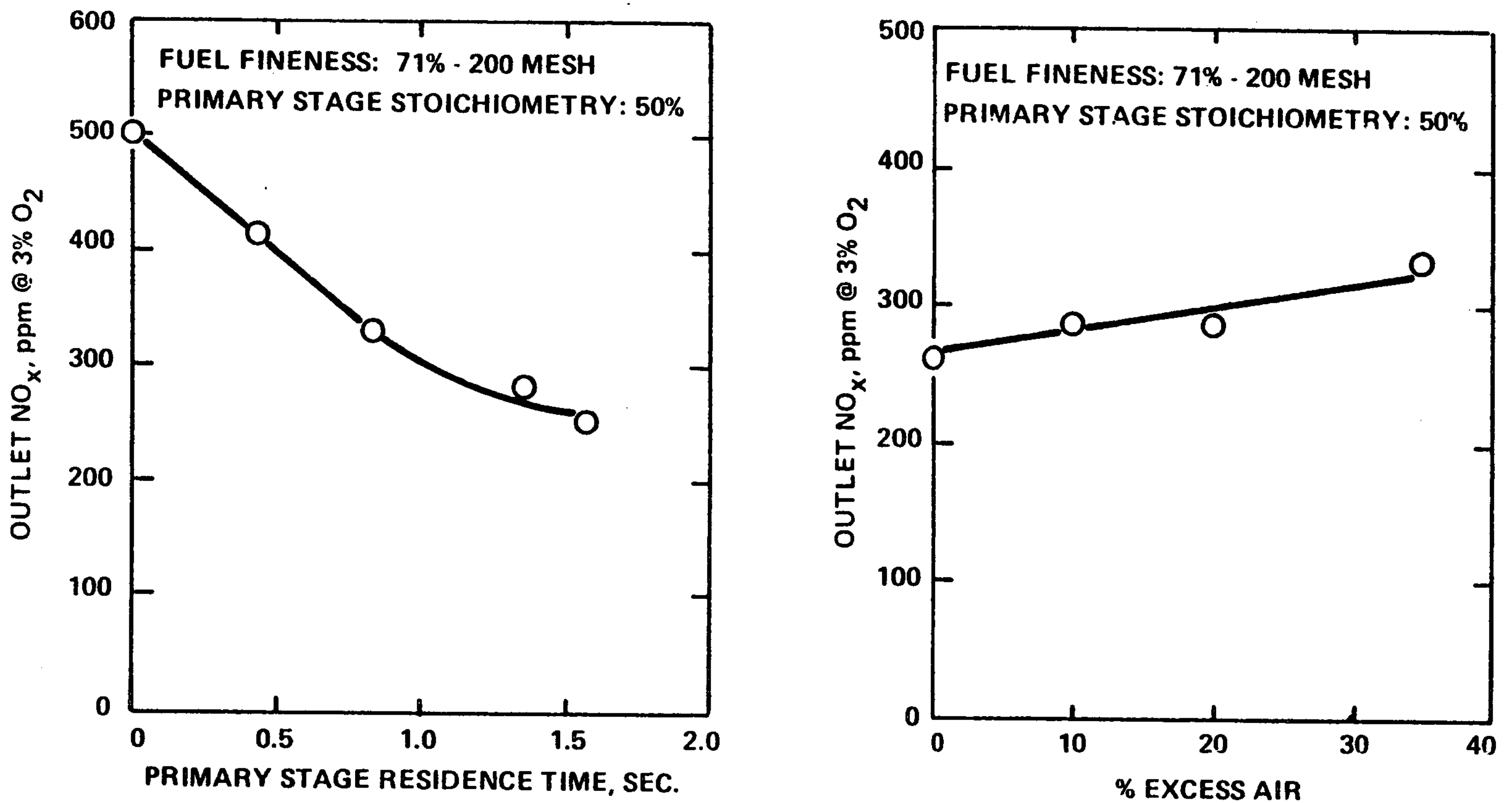

Figure 3-16 EFFECTS OF PRIMARY STAGE RESIDENCE TIME AND OVERALL EXCESS AIR ON CMHF NO_x EMISSIONS OF ALABAMA hvAb COAL

Effect of Excess Air. The effect of excess air on NO_x emissions at the outlet of the furnace is also shown in Figure 3-16. Results indicate that NO_x increases with increasing excess air. However, the rate of increase in NO_x is moderate. NO_x increases from 260 ppm to 330 ppm (@ 3% O_2) as excess air increases from 0 to 35%. This moderate increase is expected since all the tests were run under an optimum NO_x primary stage stoichiometry of 50%. A larger increase would be expected under a single stage combustion scheme.

Effect of Fuel Fineness. The outlet NO_x for the finer grind (87%-200 mesh) was 300 ppm as opposed to 282 ppm for the coarser grind (71%-200 mesh). Flame temperature was higher for the finer grind than for the coarser grind (2670°F vs. 2530°F peak temperature). Therefore, it is postulated that the 6% higher NO_x emissions for the finer grind than for the coarser grind is at least partly due to higher thermal NO_x contribution. Another explanation for higher NO_x for the finer grind than the coarser grind is its shorter primary stage residence time (1.26 vs. 1.45 sec., Table 3-13). All the outlet NO_x data discussed above are presented in Table 3-13.

Effect of Staged Combustion on Overall Combustion Efficiency.

The influence of staged combustion on the overall combustion efficiency was also examined. The same parameters studied above were studied here. That is: (1) primary stage stoichiometry; (2) primary stage residence time; (3) overall excess air level; and (4) fuel fineness.

Primary Stage Stoichiometry. Figure 3-17 is a plot of combustion efficiencies vs. furnace residence time. The curves indicate that after an average of 1.1 sec. of preheating and ignition time, the higher the primary stage stoichiometry, the faster the fuel burns, which is a consequence of higher availability of oxygen in the early stages of combustion. In all cases the overall combustion efficiencies reached about 97%, at the end of the reaction zone (port 9 elevation, Figure 2-3). The significance of these curves is that, regardless of the primary stage stoichiometry, the overall combustion efficiencies measured at the furnace outlet are virtually indistinguishable. This is principally due to the fact that total residence times (τ) in the CMHF are quite long (τ > 2.5 sec.).

TABLE 3-13

SUMMARY OF CMHF OUTLET NO_x EMISSIONS FROM ALABAMA hvAb COAL

TEST NO.	STUDY PARAMETER	STAGE STOICHIOMETRY (%) PRIMARY	STAGE STOICHIOMETRY (%) OVERALL	RESIDENCE TIME (SEC.) PRIMARY	RESIDENCE TIME (SEC.) OVERALL	TERTIARY AIR RING NO.	OUTLET NO_x (PPM @ 3% O_2)
I-1		15	120	3.48	430	1 & 4	417
I-2	PRIMARY	30	120	1.96	2.85	1 & 4	329
I-3	STAGE	50	120	1.45	2.36	1 & 4	282
I-4	STOICHIOMETRY	70	120	1.09	1.98	1 & 4	355
I-5		90	120	.80	1.65	1 & 4	428
I-6		60	120	1.66	2.55	1 & 4	294
II-1*		-	120	-	1.27	1 & 1	498
II-2	PRIMARY	50	120	0.43	1.67	1 & 2	413
II-3	STAGE	50	120	0.84	1.92	1 & 3	327
II-4	RESIDENCE TIME	50	120	1.56	2.27	1 & 5	249
III-1		50	100	1.25	2.22	1 & 4	260
III-2	OVERALL	50	110	1.28	2.28	1 & 4	287
III-3	EXCESS	40	120	1.57	2.40	1 & 4	325
III-4	AIR	50	135	1.16	1.91	1 & 4	343
IV-1	FUEL FINENESS	50	120	1.26	2.06	1 & 4	300

* Single Stage Baseline Test

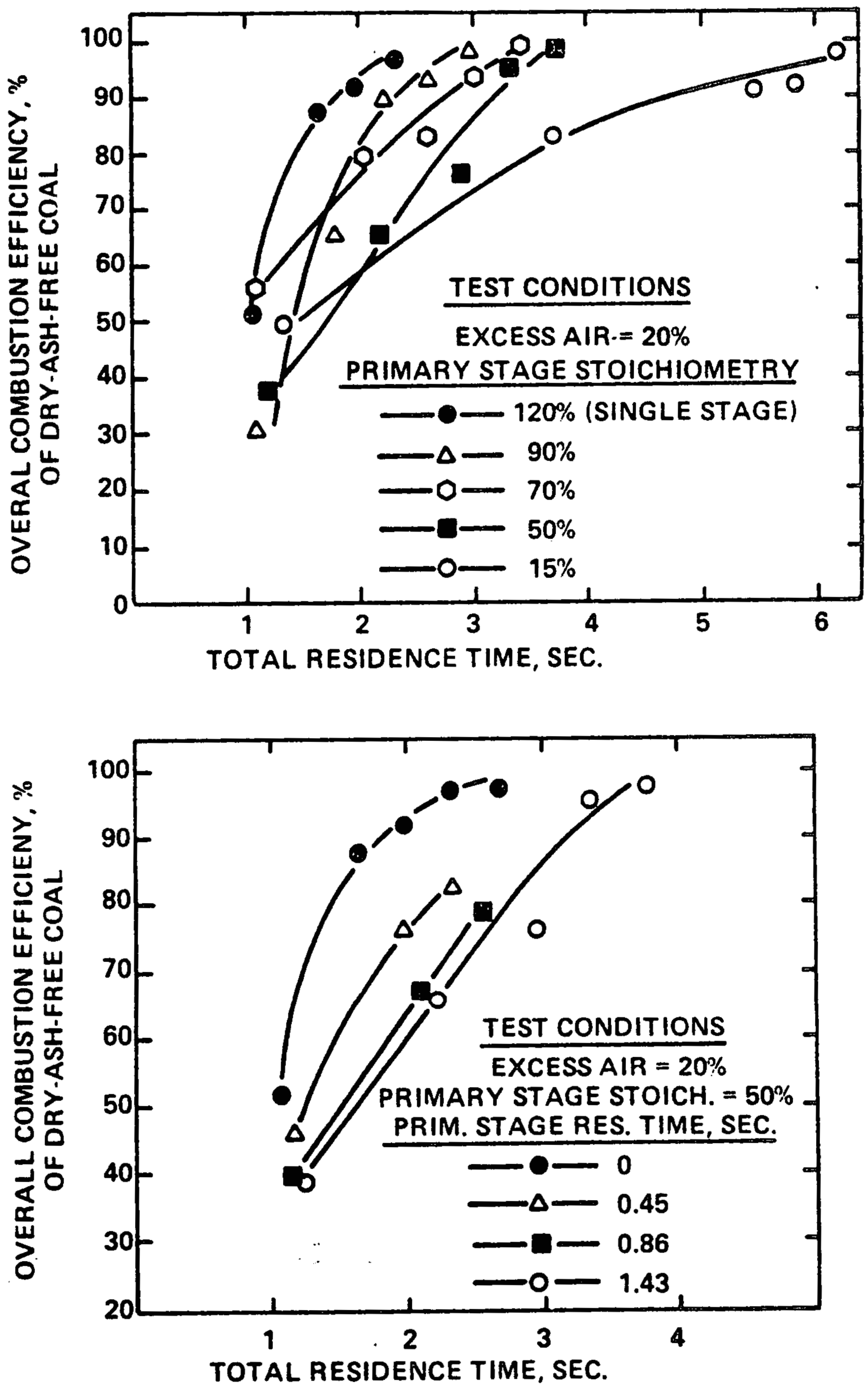

Figure 3-17 EFFECTS OF PRIMARY STAGE STOICHIOMETRY AND PRIMARY STAGE RESIDENCE TIME ON CMHF OVERALL COMBUSTION EFFICIENCY OF ALABAMA hvAb COAL

Primary Stage Residence Time. The combustion efficiencies are also plotted vs. residence time in Figure 3-17. The trend of the curves shows that increasing the fuel residence time in the fuel-rich primary zone delays the combustion process. However, at the end of the reaction zone (port 9 elevation), the overall combustion efficiencies are also virtually indistinguishable. This is understandable since the residue chars entering the CMHF secondary zone are subjected to a relatively long residence time (on the order of 0.7-1.0 sec.).

Overall Excess Air Level. The combustion efficiencies are plotted vs. residence time in Figure 3-18. While the results show that somewhat higher combustion efficiencies were obtained at the highest excess air level, there was, surprisingly, no consistent trend of combustion efficiency with excess air in the CMHF. The overall combustion efficiencies measured at the end of the CMHF reaction zone are unaffected by excess air (they are all in the 97-98% range).

Fuel Fineness. The influence of fuel fineness on combustion efficiency was examined using two grinds: (1) a 71% through 200 mesh, with a mean weight particle size ($\bar{X}$) of 62 μm; and (2) an 87% through 200 mesh, with a mean weight particle size of 45 μm. In each case, the tertiary air was introduced in ring 4 and the primary stage stoichiometry was kept constant at 50%. The percentage of excess air was maintained constant at 20%.

The combustion efficiencies are plotted vs. furnace residence time in Figure 3-18. Reducing the mean weight particle size by 27% (from 62 to 45 μm) enhances the early stage combustion efficiency by an average of ten percentage points. From a combustion efficiency standpoint, the advantage of fine grinding is, therefore, obvious. However, at the furnace outlet, the combustion efficiencies of both grinds are in the 97-98% range. This is understandable since the total residence times in the furnace are quite long ($\tau > 3$ sec.).

Concluding Remarks

Based on this pilot scale study on the Alabama hvAb coal, it can be concluded that a judicious use of staged combustion leads to an effective control of

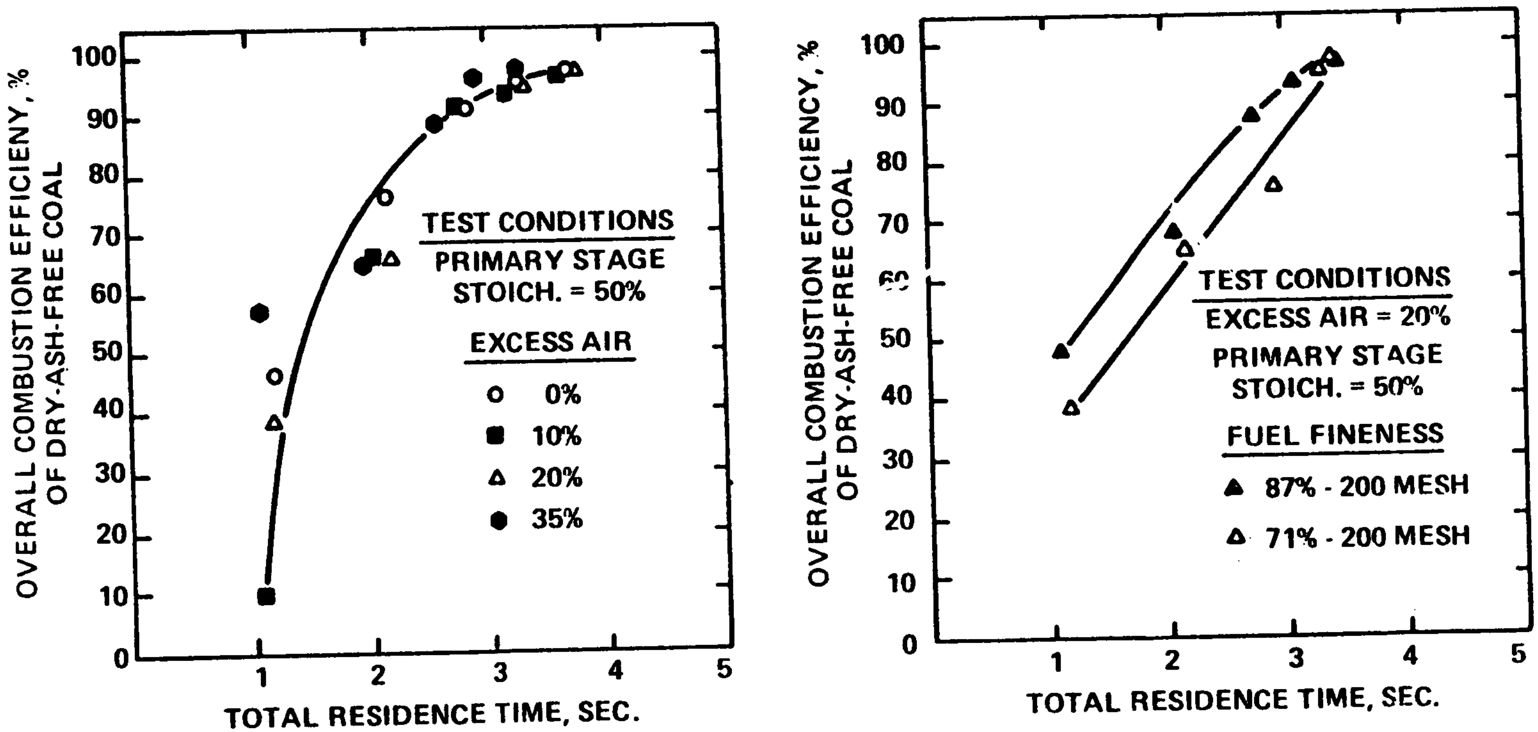

Figure 3-18 EFFECTS OF OVERALL EXCESS AIR AND FUEL FINENESS ON CMHF OVERALL COMBUSTION EFFICIENCY OF ALABAMA hvAb COAL

NO_x emissions without adversely affecting the overall fuel combustion efficiency. Specific conclusions follow.

- Both primary stage stoichiometry and primary stage residence time are very important parameters for controlling NO_x emissions. At 20% overall excess air: (1) an optimum primary stage stoichiometry of 50% of theoretical air, at a primary stage residence time of 1.45 sec. brought about a 43% reduction in NO_x compared to the unstaged baseline case (282 vs. 498 ppm); and (2) a primary stage residence time of 1.56 sec., at a primary stage stoichiometry of 50%, led to a 50% reduction in NO_x compared to the same unstaged baseline case (249 vs. 498 ppm).

- The effect of excess air on NO_x emissions under an optimum primary stage stoichiometry condition is moderate but significant. Increasing the excess air from 0 to 35%, while holding the primary stage stoichiometry constant at 50%, led to an increase in NO_x of 27% (330 vs. 260 ppm).

- The effect of fuel fineness on NO_x emissions under an optimum primary stage stoichiometry is small. Increasing the fineness from 71% to 87% through 200 mesh brought about an increase in NO_x emissions of only 6% (300 vs. 282 ppm). This small increase is believed to be due to higher thermal NO_x and/or shorter primary stage residence time.

- While parameters such as primary stage stoichiometry, primary stage residence time, and fuel fineness affect the Alabama hvAb coal throughout most of the combustion process, the combustion efficiencies tend to converge as residence times increase. This is principally due to the fact that the total residence times (τ) in the CMHF are quite long ($\tau > 2.5$ sec., the specific residence times being a function of CMHF operating conditions). The overall fuel combustion efficiencies at the furnace outlet are in all cases in the 97-98% range.

- While a primary stage residence time of 1.5 sec. is actually impractical on a commercial scale, it is important to note that a substantial reduction in NO_x occurs in the CMHF after a primary stage residence time of 0.5 sec. (a 21% reduction, from 498 to 395 ppm). And this 0.5 sec. primary stage residence time is commercially achievable.

Section 4

MATHEMATICAL MODELING: DTFS-TO-CMHF COMBUSTION PERFORMANCE SCALE-UP FOR ALABAMA hvAb COAL

The objective of this modeling effort was to establish a DTFS-to-CMHF scale-up and to examine the feasibility of using fundamental kinetic information for large scale combustion performance predictions.

Mathematical Model

As seen in Section 2, the combustion and NO_x characteristics of the Alabama hvAb coal were also determined in the CMHF at 500,000 Btu/hr firing rate. The DTFS-derived kinetic parameters of this coal char were used in conjunction with other coal data and an in-house mathematical model to simulate the CMHF combustion processes under various conditions. This mathematical model is essentially based upon the formulation of Field and co-workers (21), whereby the following differential equation is solved

$$du_j/dt = -S_j q_j \qquad (4\text{-}1)$$

where u_j, S_j, and q_j are, respectively, the weight of a particular residual char fraction at time t per unit initial weight of char, the geometric surface area of each particular fraction per unit weight of char and the rate of carbon removal per unit geometric surface area. Equation (4-1) assumes that the volatile matter is instantaneously released and burned. As such, the pyrolysis process is not modeled. It is noteworthy that the pyrolysis information presented in this report can be used in developing coal pyrolysis models for incorporation in overall combustion models.

The specific information needed to solve Equation (4-1) is given in Appendix D. The calculation approach is illustrated in Figure 4-1. The following information was input into the mathematical model: (1) particle size distribution (R) and apparent density (ρ_f) of the fuel; (2) temperature/time history

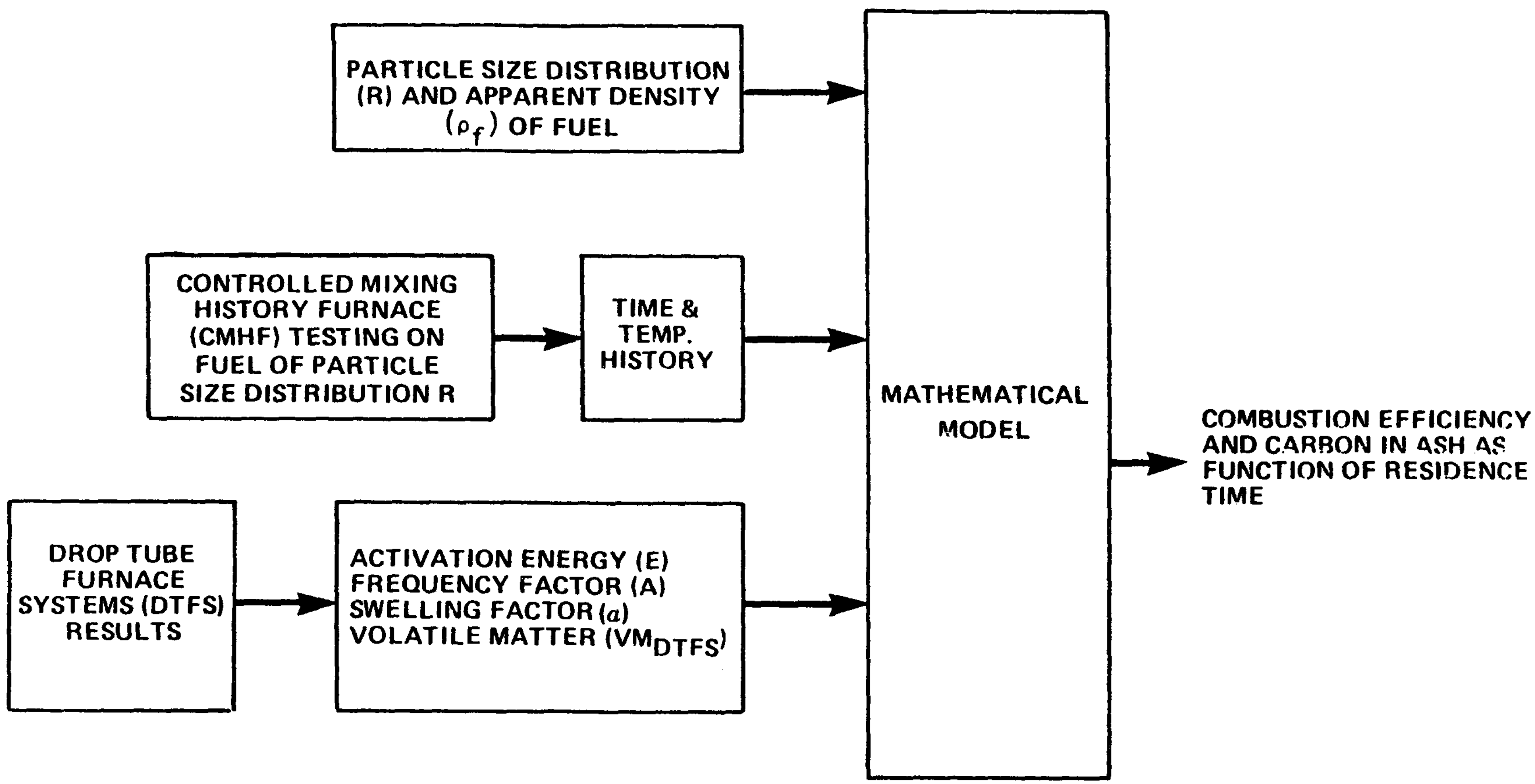

FIGURE 4-1 FLOW DIAGRAM FOR THE CMHF COMBUSTION PERFORMANCE MODEL SIMULATION

generated in the CMHF while burning the fuel having particle size distribution R; and (3) kinetic information [char activation energy (E) and frequency factor (A), and coal swelling factor (α) and volatile matter yield (VM_{DTFS})] obtained from the DTFS. A sample calculation -- showing input/output data -- is also given in Appendix D. The ultimate output is the combustion efficiency and carbon in ash as a function of residence time.

Results

Results from this simulation are presented in Figures 4-2 and 4-3. It should be noted that the simulation results are relevant only in the fuel lean region since the pyrolysis step is not modeled. As such, no simulation results are given here for the sub-stoichiometric region. It also should be noted that the simulation results represent actual runs without making any adjustments to the DTFS kinetic data.

Figure 4-2 shows two cases: (1) base line (no air staging, 20% excess air, commercial fuel grind); and (2) optimum NO_x reduction (50% primary stage stoichiometry, 20% excess air, fine grind). The agreement between experimental and simulated results is very good.

Figure 4-3 shows the baseline case along with three other staged combustion cases of variable excess air (10, 20, and 35%), burning the regular commercial grind. The agreements between experimental and simulated results for these staged combustion cases are not as good as those given in Figure 4-2. Nevertheless, it is noteworthy that the degrees of disagreement are not serious, especially given the fact that the computer model was run on the basis of unadjusted DTFS-derived kinetic data.

Concluding Remarks

These modeling studies show that a good agreement exists between theoretical and experimental results, indicating a virtually <u>one-to-one</u> DTFS-to-CMHF scale-up for the Alabama high volatile bituminous coal. C-E is using this type of technique for predicting carbon heat losses in utility and industrial boilers. This technique therefore can be used to screen potential coals for a given boiler application and is of great value.

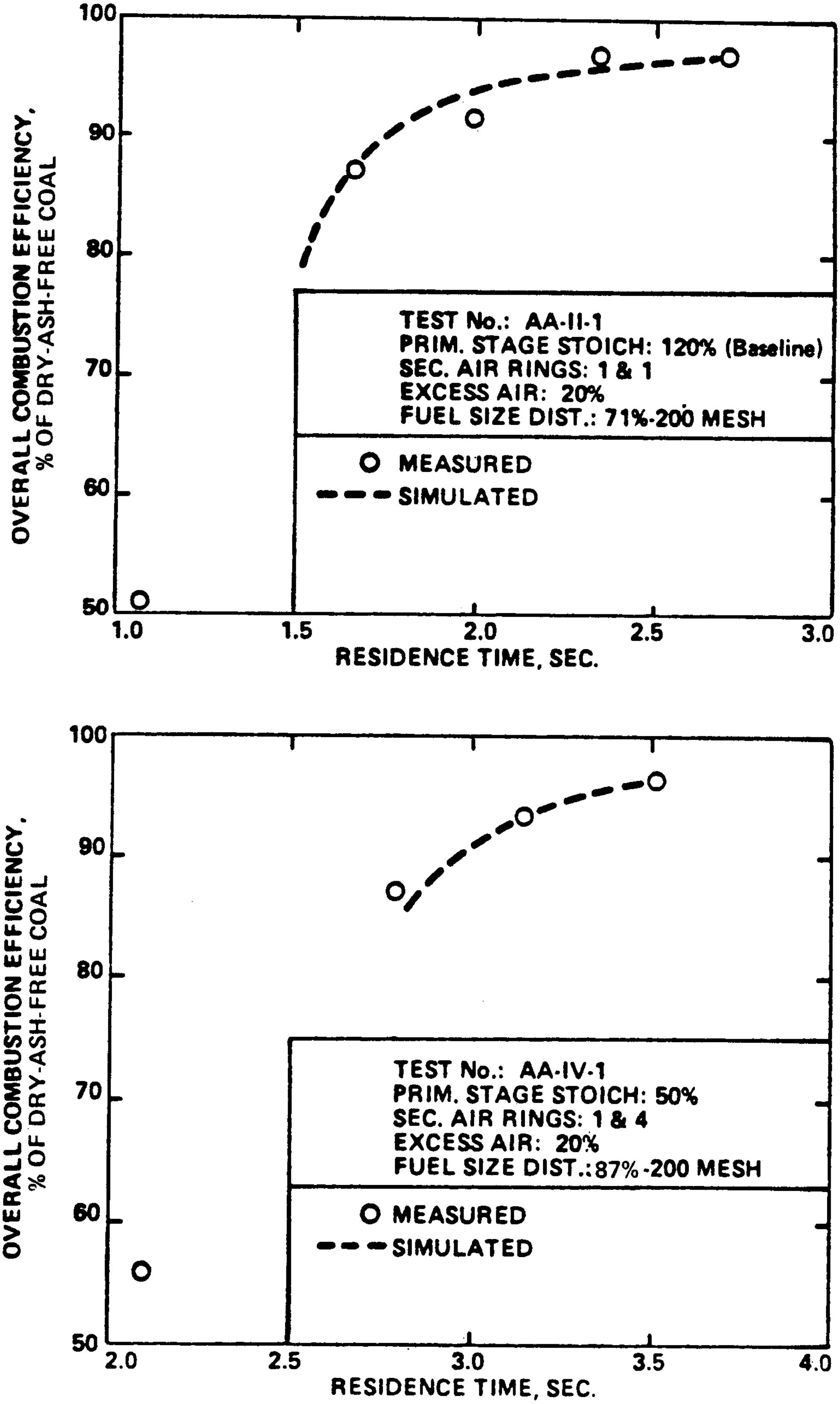

Figure 4-2 SIMULATED CMHF COMBUSTION PERFORMANCE FOR REGULAR AND FINE GRINDS OF ALABAMA hvAb COAL USING DTFS KINETIC INFORMATION

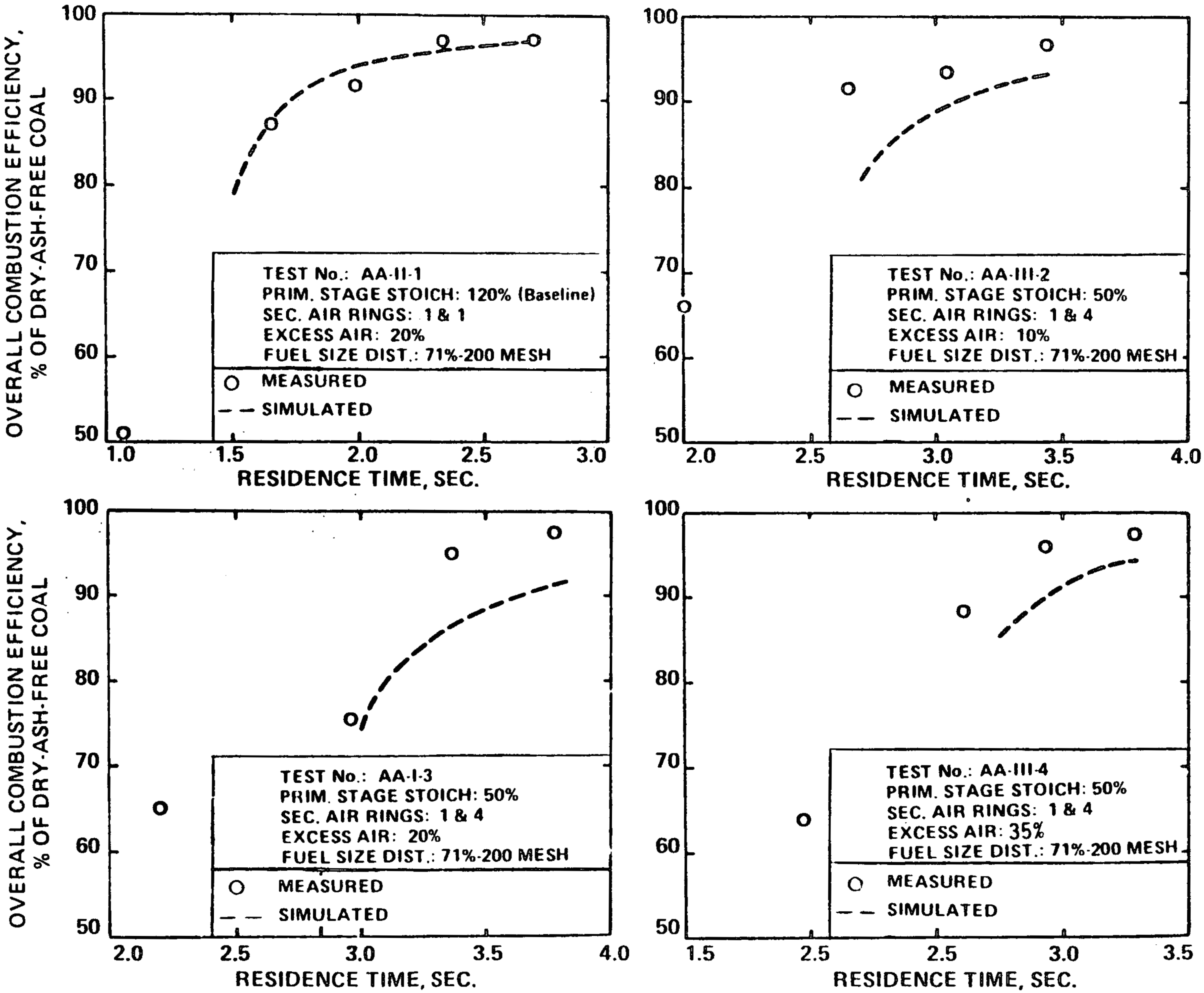

Figure 4-3 SIMULATED CMHF COMBUSTION PERFORMANCE FOR ALABAMA hvAb COAL AT VARIOUS EXCESS AIR LEVELS USING DTFS KINETIC INFORMATION

Section 5
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APPENDIX A
TEST FACILITIES

All the major test facilities used throughout this investigation are described below.

Flammability Index Apparatus

The Flammability Index Apparatus (Figure A-1) is a device used to determine the ignition temperatures of pulverized solid fuels under specific conditions. This apparatus was employed to measure the relative ignition temperatures of coals. About 0.2 g of sample sized to 200x0 mesh is placed in the sample holder. The furnace is preheated to a desired level, then a solenoid-operated valve is opened, allowing oxygen from a 2-liter storage reservoir to suspend and convey the sample through the furnace. If ignition does not occur, the procedure is repeated at higher temperatures, in 50°F increments, until ignition occurs. If ignition does occur in the first trial, then the procedure is repeated to determine the temperature below which ignition does not occur. In either case, fine tuning is necessary to further narrow the error margin. This ignition temperature is called the Flammability Index. The value of the Flammability Index compared to other fuels indicates the flame ignition temperature/stability on a relative basis.

TGS-2 Thermo-Gravimetric Analysis System

The Perkin-Elmer Model TGS-2 is a complete, second-generation system for accurately recording the weight loss or weight gain or rate of weight change of a sample as it is subjected to a precisely controlled temperature environment. It is a completely modular system consisting of the following independently packaged units: the Thermobalance Analyzer, the Electronic Balance Control, the Temperature (program) Microprocessor Controller, the Heater Control Unit, the First Derivative Computer (FDC), and the Recorder.

This apparatus uses a small solid sample to determine either its micro-proximate analysis using the general procedure established by the American Society for Testing and Materials (ASTM) or its thermo-gravimetric reactivity under

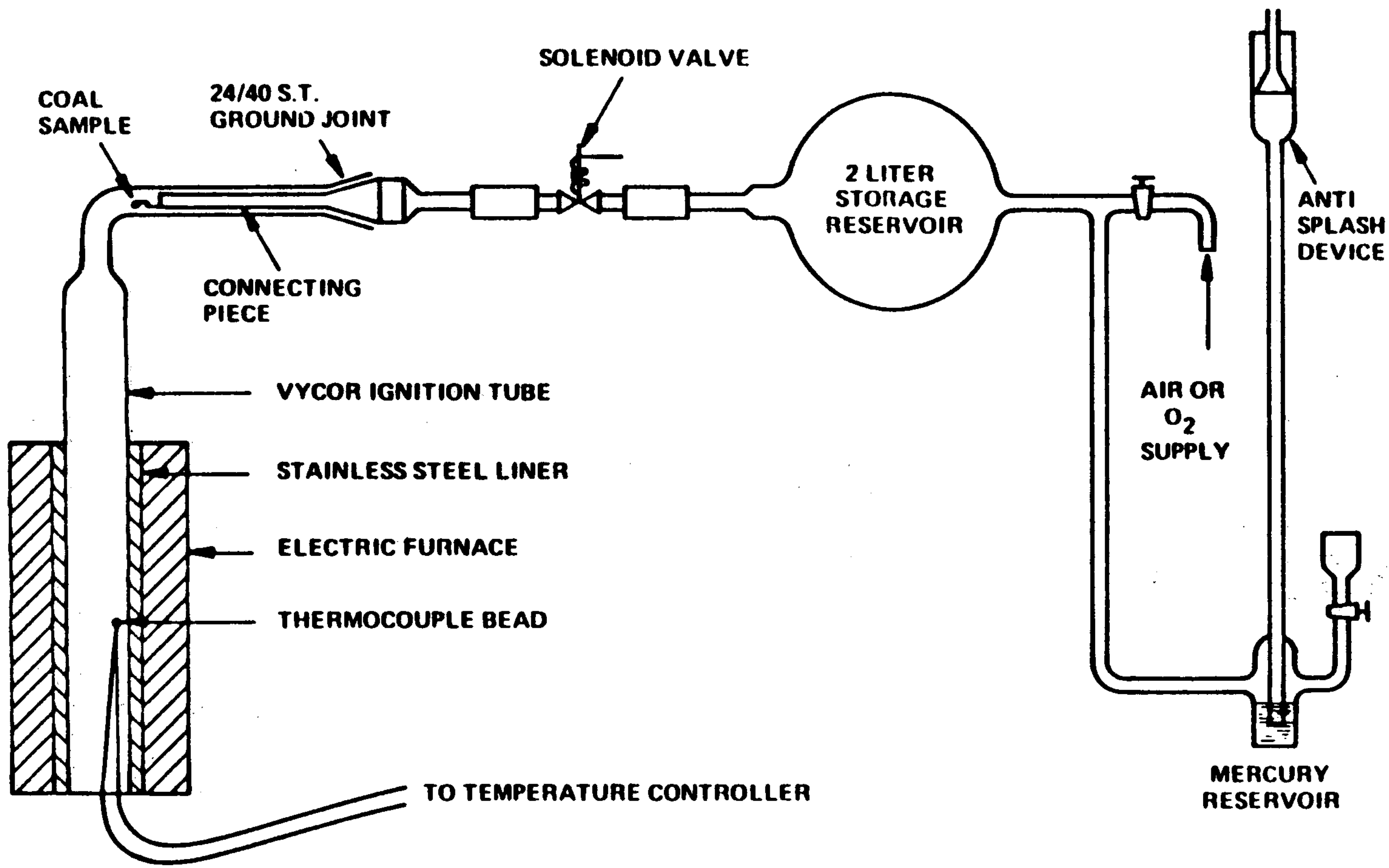


Figure A-1 SCHEMATIC OF FLAMMABILITY APPARATUS specific experimental conditions (heating rate, reaction medium, and reaction temperature).

The micro-proximate analysis is determined as follows. A 4-6 mg sample is purged with nitrogen to remove oxygen traces. The moisture loss is obtained by heating in nitrogen to 105°C and holding for three minutes. Subsequently, the sample is heated at 100°C/min to 950°C and held at this temperature for five minutes to obtain volatile matter. After this, the temperature is lowered to 750°C and a switching valve is used to introduce oxygen for the combustion of fixed carbon at this temperature. The residue represents the ash content.

The isothermal char reactivity test is determined as follows. A 4-6 mg sample of specific size grade is placed in the TGS-2 System and heated in the presence of nitrogen at 50°C/min to the reactivity temperature (700°C). After stabilization at this temperature, the reaction medium (air) is introduced. The percent weight of the unburned char and rate of weight loss are recorded on a strip chart as a function of time. These thermo-grams are subsequently used to determine the char combustion efficiency history and reactivity parameter (which indicates the maximum rate of weight loss per unit weight of the original sample in the TGS-2 System).

Quantasorb Surface Area Analyzer

The principle of operation of the Quantasorb Surface Area Analyzer involves passing a mixture of helium (used as a carrier) and adsorbate (N_2 or CO_2) through a U-shaped small cell containing the sample.* The amount of adsorbate physically adsorbed at various partial pressures on the sample (adsorbent) surface can then be used to calculate the sample's surface area.

* Outgassed in the Quantasorb at 200°C and one hour using nitrogen as the sweeping gas.

Adsorption and desorption occur when the sample is immersed into and then withdrawn from the liquid controlling the adsorption temperature. Liquid nitrogen and room temperature (25°C) water are used for nitrogen adsorption and desorption, respectively. Room temperature and hot (60°C) water are used for carbon dioxide adsorption and desorption, respectively. Changes in the ratio of helium to adsorbate in the flowing stream, due to adsorption and desorption, are sensed by a specially designed thermal conductivity detector. The signals delivered by the detector are nearly Gaussian in shape. The instantaneous signal height is proportional to the rate of adsorption or desorption and the total integrated area under the curve is proportional to the quantity of gas adsorbed. As such, the function of the Quantasorb Surface Area Analyzer is to measure the quantity of gas adsorbed at a given temperature and partial pressure.

A BET (Brunauer, Emmett, Teller) single point method was used in conjunction with N_2 adsorption at -196°C (-321°F) to determine the samples BET specific surface areas (1). A Dubinin-Kaganer method was used in conjunction with CO_2 adsorption at 25°C (77°F) to determine the samples' CO_2 specific surface area (2).

Drop Tube Furnace System (DTFS)

The Drop Tube Furnace System (Figure A-2) is comprised of a 1-inch inner diameter horizontal tube gas preheater and a 2-inch inner diameter vertical tube test furnace for providing controlled temperature conditions. Both tubes are electrically heated with silicon carbide elements (SiC) and are rated at 2800°F. The DTFS was used to study pyrolysis and combustion of coals and/or chars.

The principle of operation of the DTFS is as follows: Size graded fuel is introduced with a small amount of carrier gas into the hot reaction zone of the test furnace through a water-cooled fuel injector. A preheated secondary gas stream is introduced around the primary stream. Injection of fuel particles into the hot gas stream results in a rapid heating of the particles to the prevailing gas temperature (at a rate of the order of 10^4°C/sec)(10, 12, 16). Following the rapid heating period, pyrolysis and/or combustion of

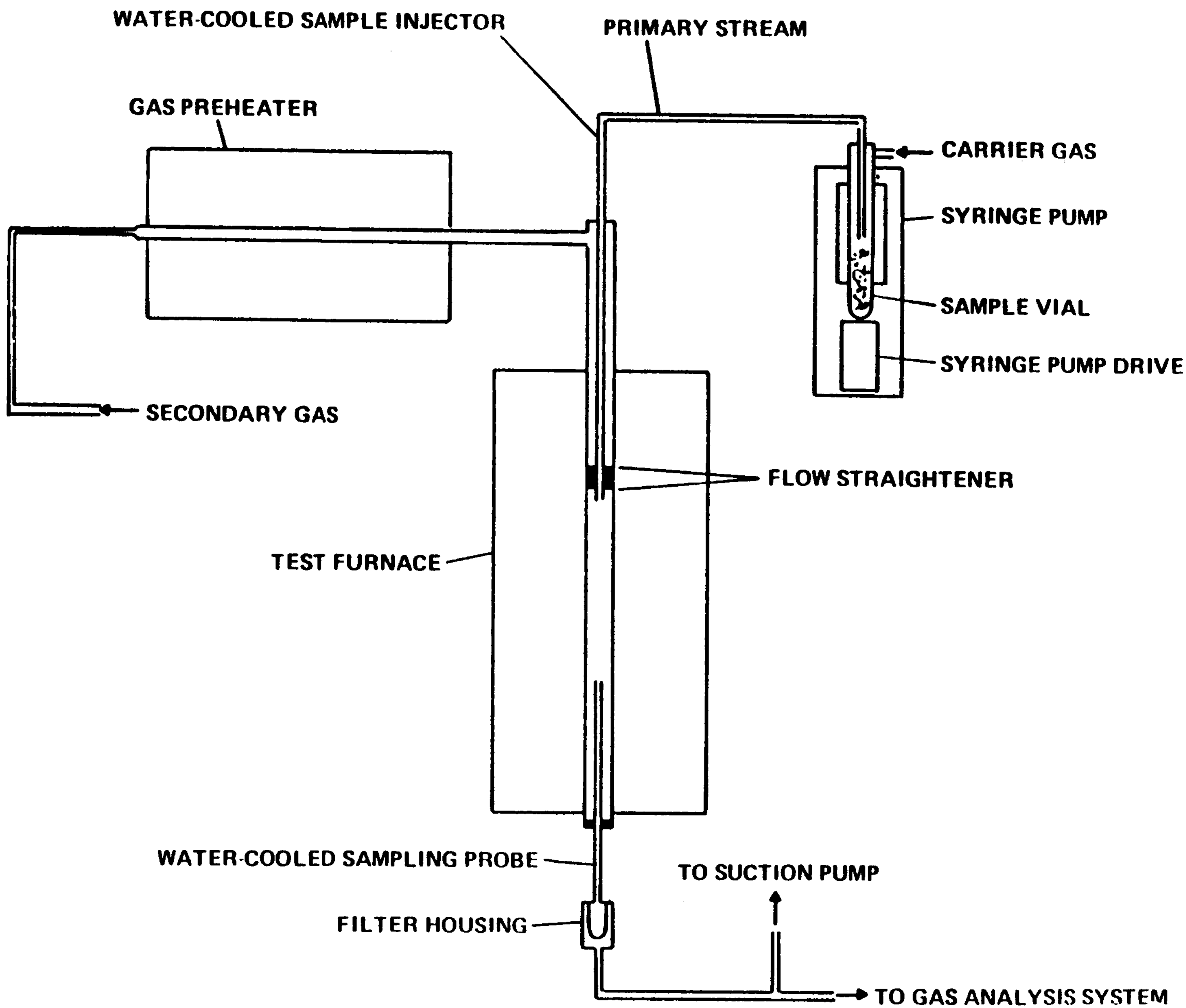


Figure A-2 SCHEMATIC OF THE COMBUSTION ENGINEERING DROP TUBE FURNACE SYSTEM particles occur for a specific time. Then all reactions are rapidly quenched. Solid products are separated from the gaseous products in a small filter housing, and an aliquot of the effluent gas sample is sent to a pre-calibrated Gas Analysis System.

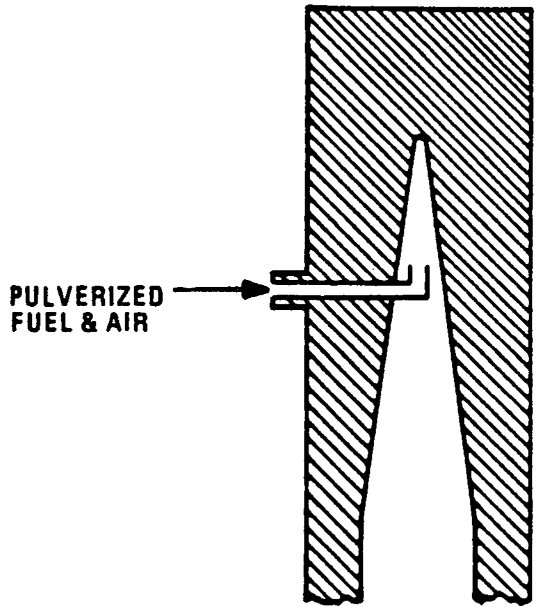
The solid products collected at various locations along the axis of the DTFS reaction zone can be analyzed to determine solid conversion efficiencies. An ash tracer method, which is based on the assumption that ash remains inert during either pyrolysis or combustion, is used to calculate the fuels' pyrolysis or combustion efficiencies. The aliquot of the effluent gas sample is analyzed on-line to determine NO_x, O_2, CO, and CO_2 concentrations.

Controlled Mixing History Furnace (CMHF)

The Controlled Mixing History Furnace is an important tool in examining pulverized fuel combustion fundamentals (Figure A-3). The CMHF consists of a refractory-lined 1.5 foot I.D. cylinder with an overall height of 22.6 feet. A mixture of pulverized fuel and primary air is fired downward into the furnace from a single burner centrally located at the top of the furnace. The furnace consists of four zones--preheat, combustion, water-cooled, and afterburner--proceeding downward from the fuel admission point.

Six gas-fired burners surround the preheat zone as a means of warm-up and assistance in ignition and flame stabilization if required. Provisions exist for the introduction of preheated secondary air (to about 700°F) at seven levels in the combustion zone (Figure A-3). This zone is equipped with nine sampling ports along its length so that the progress of the combustion reaction can be monitored by temperature, gas and solid analyses. The CMHF uses the concept of plug flow in which no axial mixing occurs and all reactants have an equal velocity and furnace residence time. The original burner (Figure A-3) is designed as a closed jet, conical in shape, to conform to gas expansion such that gas recirculation is avoided and a flat flame front is produced.

During the normal course of operation, raw fuel is pulverized in a bowl mill, collected by cyclone and bag filter collectors and stored in a hopper. The



SCHEMATIC OF CMHF BURNER

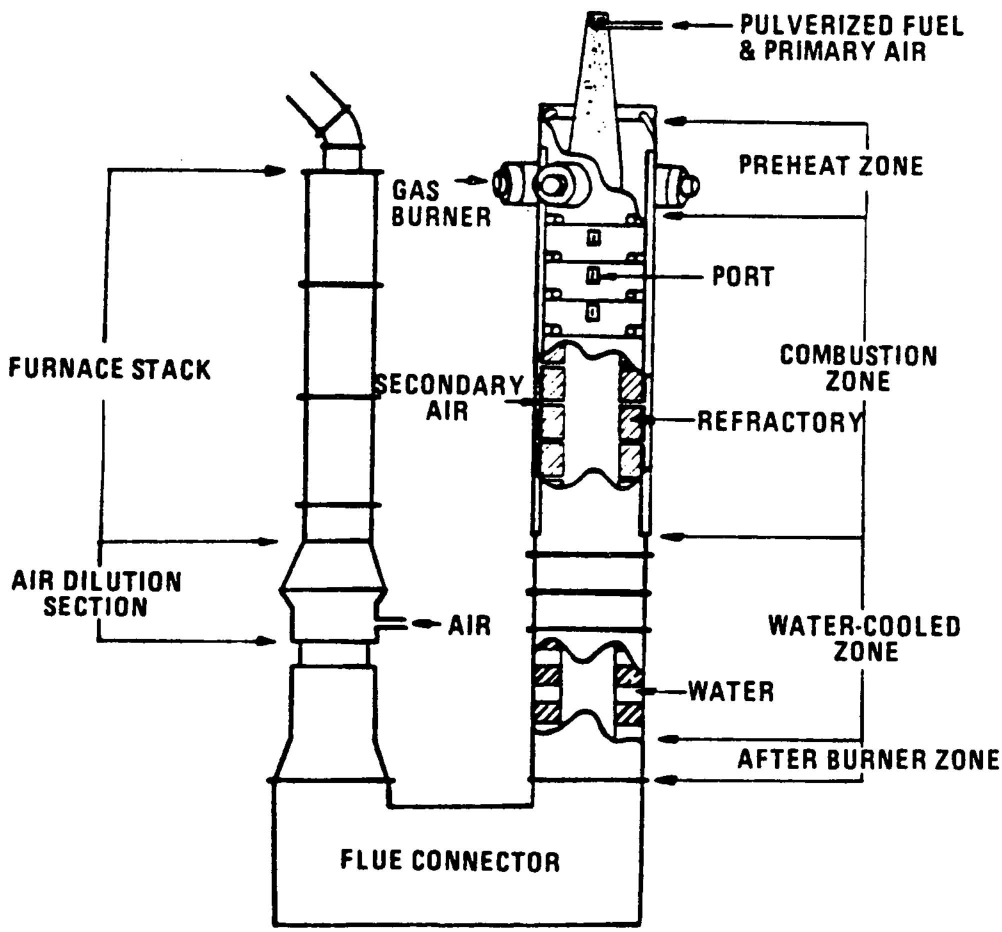


Figure A-3 CONTROLLED MIXING HISTORY FURNACE stored fuel is then gravimetrically fed into the CMHF where it undergoes combustion under controlled conditions. Unburned solids in the flue gas are collected by a cyclone collector (Figure A-4).

The solid products, which are collected in a water-cooled sampling probe along the axis of the CMHF combustion zone, are subjected to proximate and ultimate analyses. An ash tracer method is used to determine the solids conversion efficiencies as a function of operational parameters. Ultimate analyses give a measure of the fuel nitrogen conversion. Gaseous products aspirated in the sampling probe are sent to the Gas Analysis System for an on-line determination of NO_x, O_2, CO, and CO_2 concentrations.

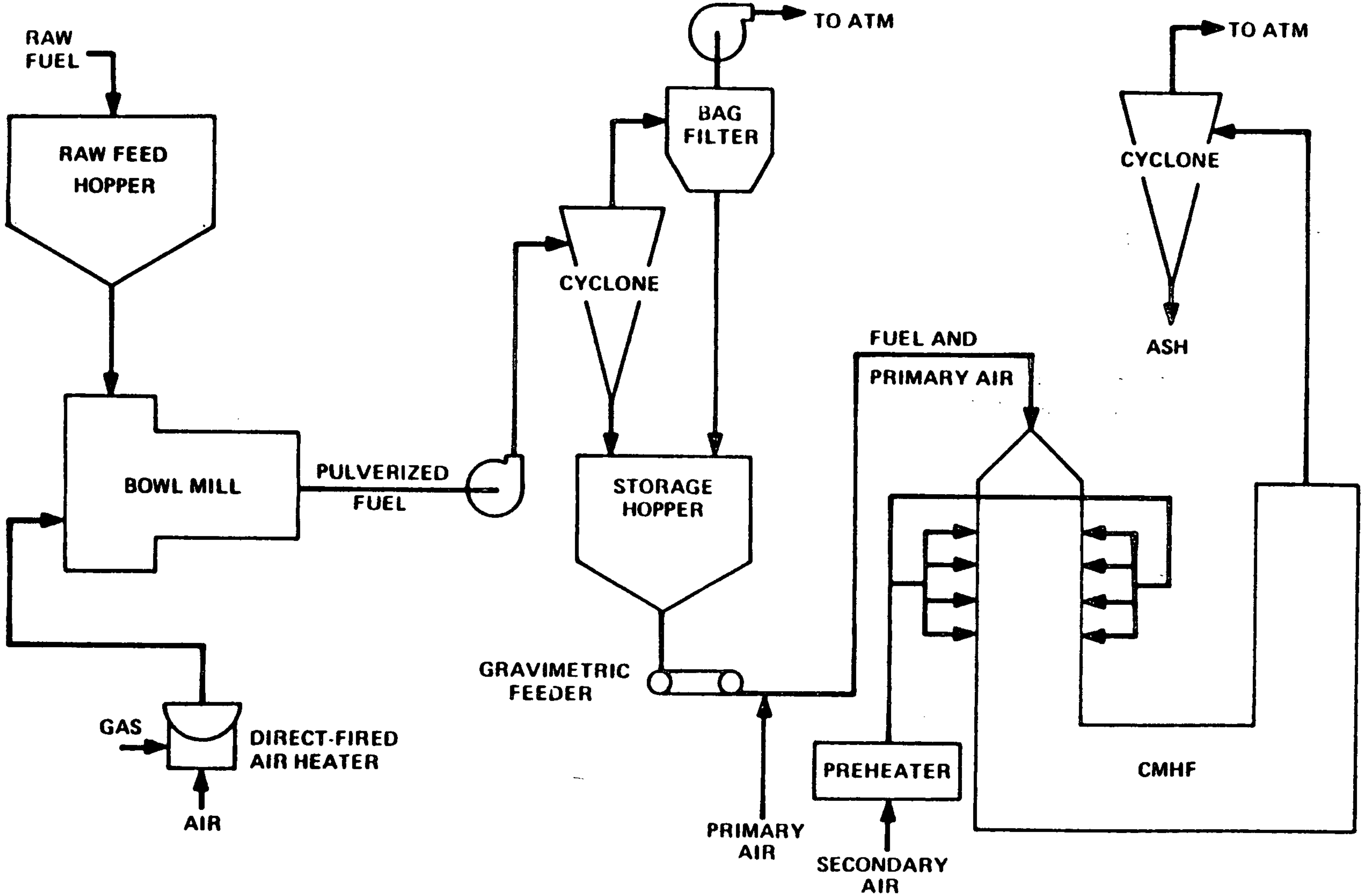


Figure A-4 CONTROLLED MIXING HISTORY FURNACE TEST FACILITY

APPENDIX B

DROP TUBE FURNACE SYSTEM TEST DATA

The computer printouts presented in this Appendix summarize the DTFS test data. Terms which may not be obvious are explained as follows:

TML = Texas Monticello Lignite

TMLC = Texas Monticello Lignite Char

MRC = Montana Rosebud Coal

MRCC = Montana Rosebud Coal Char

AAC = Alabama Arkadelphia Coal

AACC = Alabama Arkadelphia Coal Char

PEA = Pennsylvania Anthracite

PEAC = Pennsylvania Anthracite Char

K = Overall Reaction Rate Coefficient, g $cm^{-2}sec^{-1}atm^{-1}$

KS = Surface Reaction Rate Coefficient, g $cm^{-2}sec^{-1}atm^{-1}$

KDIFF = Diffusional Reaction Rate Coefficient, g $cm^{-2}sec^{-1}atm^{-1}$

Reynolds Number = $\rho vd/\eta$ where ρ, v, and η are the reactant gas density, velocity, and viscosity, respectively, and d is the reactor diameter. A Reynolds Number < 2200 indicates that the gas flow is in the laminar regime. This is the case for all the data presented here (Reynolds Numbers are in the 145-204 range).

NOTE: The values of K/K_{DIFF} approaching unity indicate a diffusion-controlled phenomenon. All K/K_{DIFF} < 0.7 were deleted when calculating surface reaction rate coefficients (KS).

DROP TUBE FUKNACE SYSTEM DATA REDUCTION PROGRAM

DATE :06/21/83
TEST NO.:TML-1-1
FUEL :200X400 MESH TEXAS LIGNITE COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .057
APPARENT DENSITY (GM/CC) = 1.25
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 15.3

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1305.	.2	17.0	0.	.100	0.000	0.
2.0	1332.	.3	17.7	0.	.100	0.000	0.
4.0	1381.	.1	19.5	0.	.100	.002	20.
8.0	1448.	1.7	21.6	0.	.100	.002	20.
12.0	1486.	.3	22.2	1.	0.000	.008	80.
16.0	1470.	5.2	22.0	3.	0.000	.016	160.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1305.	.053	3.1	5.84	41.96	204.
2.0	1332.	.106	7.8	5.80	42.62	202.
4.0	1381.	.208	18.0	5.72	43.78	199.
8.0	1448.	.408	29.4	5.62	45.36	196.
12.0	1496.	.604	30.5	5.57	46.27	194.
16.0	1470.	.801	34.2	5.59	45.40	195.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :06/22/83
TEST NO.:TML-1-2
FUEL :200X400 MESH TEXAS LIGNITE COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .058
APPARENT DENSITY (GM/CC) = 1.25
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 15.6

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1482.	1.4	17.7	0.	.100	.003	0.
2.0	1495.	1.5	18.8	0.	.100	.006	40.
4.0	1510.	1.8	21.0	1.	.100	.012	80.
8.0	1562.	1.2	23.1	2.	.100	.017	160.
12.0	1602.	.9	24.3	5.	0.000	.024	220.
16.0	1598.	4.7	23.5	7.	0.000	.030	240.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1482.	.048	9.1	5.57	46.97	197.
2.0	1495.	.097	15.7	5.56	47.27	197.
4.0	1510.	.192	26.9	5.53	47.64	196.
8.0	1562.	.379	34.8	5.46	48.89	194.
12.0	1602.	.563	38.8	5.41	49.86	192.
16.0	1598.	.747	39.2	5.42	49.76	192.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :6/23/83
TEST NO.:TNL-I-3
FUEL :200X400 MESH TEXAS LIGNITE COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .059
APPARENT DENSITY (GM/CC) = 1.25
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 15.3

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1795.	1.1	19.0	1.	.100	.003	30.
2.0	1810.	1.4	21.2	2.	.100	.011	110.
4.0	1855.	1.7	24.3	4.	.050	.020	200.
8.0	1915.	1.5	26.4	8.	0.000	.032	320.
12.0	1935.	1.5	27.8	11.	0.000	.040	400.
16.0	1917.	3.4	26.5	15.	0.000	.040	400.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1795.	.043	16.3	5.18	53.63	180.
2.0	1810.	.086	27.4	5.16	53.98	180.
4.0	1855.	.171	39.4	5.11	55.35	178.
8.0	1915.	.336	45.7	5.05	56.48	176.
12.0	1935.	.500	49.4	5.02	56.96	175.
16.0	1917.	.665	47.4	5.04	56.52	176.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :6/24/83
TEST NO.:TNL-I-5
FUEL :200X400 MESH TEXAS LIGNITE COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .058
APPARENT DENSITY (GM/CC) = 1.25
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 15.3

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2337.	0.0	23.8	8.	.100	.012	280.
2.0	2357.	0.0	25.5	8.	0.000	.024	400.
4.0	2389.	.4	27.6	16.	0.000	.045	500.
8.0	2421.	.5	28.5	21.	0.000	.057	560.
12.0	2435.	.4	29.1	23.	0.000	.057	600.
16.0	2419.	2.5	29.8	23.	0.000	.057	700.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2337.	.036	36.3	4.65	66.50	162.
2.0	2357.	.071	41.9	4.64	66.99	161.
4.0	2389.	.141	46.1	4.61	67.74	160.
8.0	2421.	.280	50.4	4.58	68.51	159.
12.0	2435.	.419	51.8	4.57	68.83	159.
16.0	2419.	.558	54.8	4.59	68.45	159.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :6/29/83
TEST NO.:TML-1-6R
FUEL :200X400 MESH TEXAS LIGNITE COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .055
APPARENT DENSITY (GM/CC) = 1.25
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 15.2

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2475.	3.7	23.2	9.	.100	.015	320.
2.0	2488.	2.8	28.0	16.	.100	.030	520.
4.0	2513.	1.7	29.2	28.	0.000	.047	580.
8.0	2580.	2.3	32.0	31.	0.000	.063	560.
12.0	2635.	4.0	31.0	29.	0.000	.060	700.
16.0	2635.	4.5	29.4	26.	0.000	.053	800.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2475.	.035	33.9	4.54	69.02	156.
2.0	2488.	.069	48.1	4.53	69.32	156.
4.0	2513.	.137	50.3	4.51	69.91	155.
8.0	2580.	.271	56.9	4.46	71.49	153.
12.0	2635.	.403	56.0	4.42	72.79	152.
16.0	2635.	.534	52.8	4.42	72.79	152.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :3/18/83
TEST NO.:AAL-1-1
FUEL :200X400 MESH ALABAMA COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .058
APPARENT DENSITY (GM/CC) = 1.30
AVE. PARTICLE DIA.(MICRON)= 54.0
GAS FEED RATE (L/MIN) = 13.5

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1340.	0.0	0.0	1.	.100	0.000	80.
2.0	1365.	0.0	0.0	2.	.050	0.000	60.
4.0	1401.	0.0	0.0	7.	.050	0.000	150.
8.0	1438.	0.0	3.2	7.	.050	0.000	130.
12.0	1456.	0.0	3.2	2.	.050	.003	130.
16.0	1455.	0.0	3.4	2.	.050	.006	130.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1340.	.059	0.0	5.60	37.72	178.
2.0	1365.	.117	0.0	5.56	38.24	176.
4.0	1401.	.231	0.0	5.50	39.00	175.
8.0	1438.	.456	10.2	5.45	39.76	173.
12.0	1456.	.679	12.0	5.43	40.14	172.
16.0	1455.	.902	17.8	5.43	40.13	172.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :3/22/83
TEST NO.:AAC-1-2
FUEL :200X400 MESH ALABAMA COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .057
APPARENT DENSITY (GM/CC) = 1.30
AVE. PARTICLE DIA.(MICRON)= 54.0
GAS FEED RATE (L/MIN) = 13.5

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1503.	0.0	0.0	6.	0.000	.000	160.
2.0	1516.	0.0	0.0	3.	0.000	.000	200.
4.0	1536.	0.0	0.0	8.	0.000	.000	160.
8.0	1577.	0.0	3.5	6.	0.000	.001	200.
12.0	1632.	0.0	3.4	2.	0.000	.001	100.
16.0	1598.	0.0	3.8	5.	0.000	.001	220.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1503.	.055	0.0	5.36	41.13	170.
2.0	1516.	.109	0.0	5.34	41.41	173.
4.0	1536.	.217	0.0	5.32	41.83	169.
8.0	1577.	.429	19.0	5.27	42.68	167.
12.0	1662.	.638	17.6	5.23	43.20	166.
16.0	1598.	.849	25.3	5.24	43.12	166.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :3/23/83
TEST NO.:AAC-1-3
FUEL :200X400 MESH ALABAMA COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .055
APPARENT DENSITY (GM/CC) = 1.30
AVE. PARTICLE DIA.(MICRON)= 54.0
GAS FEED RATE (L/MIN) = 14.9

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1835.	0.0	0.0	5.	.050	0.000	220.
2.0	1850.	0.0	0.0	3.	.050	0.000	100.
4.0	1875.	0.0	3.6	4.	.050	.000	160.
8.0	1903.	0.0	3.8	8.	.050	.000	280.
12.0	1918.	0.0	4.0	12.	.050	.001	400.
16.0	1912.	0.0	4.1	18.	.050	.002	400.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1935.	.044	0.0	4.96	53.08	174.
2.0	1850.	.087	0.0	4.95	53.43	173.
4.0	1875.	.174	2.5	4.92	54.01	172.
8.0	1903.	.344	26.1	4.89	54.64	171.
12.0	1918.	.514	29.4	4.88	54.99	171.
16.0	1912.	.684	31.4	4.88	54.85	171.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :13/24/83
TEST NO.:AAC-1-5
FUEL :200X400 MESH ALABAMA COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .059
APPARENT DENSITY (GM/CC) = 1.30
AVE. PARTICLE DIA.(MICRON)= 54.0
GAS FEED RATE (L/MIN) = 13.9

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2337.	0.0	3.3	2.	0.000	0.000	60.
2.0	2357.	0.0	3.7	3.	0.000	.002	260.
4.0	2389.	0.0	4.1	6.	0.000	.003	300.
8.0	2416.	0.0	4.3	40.	0.000	.003	600.
12.0	2425.	0.0	4.4	45.	0.000	.004	600.
16.0	2414.	0.0	4.4	42.	0.000	.002	700.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2337.	.039	14.2	4.50	60.51	147.
2.0	2357.	.078	24.6	4.48	60.96	147.
4.0	2389.	.155	30.8	4.46	61.64	146.
8.0	2416.	.307	34.7	4.44	62.21	145.
12.0	2425.	.459	36.3	4.43	62.42	145.
16.0	2414.	.612	36.4	4.44	62.18	145.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :13/29/83
TEST NO.:AAC-1-6
FUEL :200X400 MESH ALABAMA COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .055
APPARENT DENSITY (GM/CC) = 1.30
AVE. PARTICLE DIA.(MICRON)= 54.0
GAS FEED RATE (L/MIN) = 15.0

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2515.	0.0	0.0	4.	0.000	0.000	340.
2.0	2535.	0.0	4.3	5.	0.000	0.000	400.
4.0	2565.	0.0	4.4	20.	0.000	0.000	460.
8.0	2605.	0.0	4.4	35.	0.000	0.000	700.
12.0	2635.	0.0	4.4	30.	0.000	0.000	600.
16.0	2635.	0.0	4.4	35.	0.000	0.000	700.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2515.	.035	0.0	4.36	69.18	153.
2.0	2535.	.069	34.7	4.35	69.64	153.
4.0	2565.	.137	36.7	4.33	70.34	152.
8.0	2605.	.271	36.9	4.30	71.27	151.
12.0	2635.	.405	37.0	4.28	71.97	150.
16.0	2635.	.538	36.7	4.28	71.97	150.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :5/26/82
TEST NO.:MRL-1-1
FUEL :200X400 MONT. ROSEBUD COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .082
APPARENT DENSITY (GM/CC) = 1.21
AVE. PARTICLE DIA.(MICRON)= 55.0
GAS FEED RATE (L/MIN) = 14.9

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1305.	4.5	7.8	0.	0.000	0.000	20.
2.0	1332.	4.0	8.7	0.	0.000	0.000	50.
4.0	1381.	4.6	9.2	0.	0.000	0.000	120.
8.0	1448.	3.4	9.9	0.	0.000	0.000	180.
12.0	1486.	5.3	11.0	0.	0.000	0.000	200.
16.0	1470.	5.5	11.0	0.	0.000	0.000	230.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1305.	.055	0.0	5.47	40.81	198.
2.0	1332.	.107	6.4	5.42	41.45	197.
4.0	1381.	.215	12.6	5.35	42.58	194.
8.0	1448.	.421	18.3	5.26	44.12	191.
12.0	1486.	.623	29.1	5.21	45.00	189.
16.0	1470.	.827	29.2	5.23	44.64	189.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :5/27/82
TEST NO.:MRL-1-2
FUEL :200X400 MONT. ROSEBUD COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .081
APPARENT DENSITY (GM/CC) = 1.21
AVE. PARTICLE DIA.(MICRON)= 55.0
GAS FEED RATE (L/MIN) = 14.9

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1482.	1.6	9.7	0.	0.000	0.000	60.
2.0	1495.	2.1	10.1	0.	0.000	0.000	120.
4.0	1510.	4.7	10.6	0.	0.000	0.000	180.
8.0	1562.	2.0	12.2	0.	0.000	0.000	460.
12.0	1602.	2.4	12.1	0.	0.000	0.000	400.
16.0	1598.	1.5	11.5	0.	0.000	0.000	460.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1482.	.051	14.7	5.21	44.92	189.
2.0	1495.	.101	18.9	5.20	45.21	188.
4.0	1510.	.201	25.5	5.18	45.56	187.
8.0	1562.	.397	34.4	5.11	46.76	185.
12.0	1602.	.590	34.1	5.06	47.68	183.
16.0	1598.	.783	29.5	5.07	47.59	183.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :6/1/82
TEST NO.:MRC-1-3
FUEL :200X400 MONT. ROSE BUD COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .082
APPARENT DENSITY (GM/CC) = 1.21
AVE. PARTICLE DIA.(MICRON)= 55.0
GAS FEED RATE (L/MIN) = 14.9

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1739.	1.6	10.6	3.	.100	0.000	200.
2.0	1774.	1.6	10.8	3.	.100	0.000	270.
4.0	1841.	1.0	12.4	4.	.100	0.000	520.
8.0	1915.	.7	13.5	5.	.100	0.000	740.
12.0	1935.	.9	13.2	5.	.100	0.000	840.
16.0	1917.	2.3	14.0	5.	.100	0.000	760.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1739.	.044	22.8	4.87	50.86	176.
2.0	1774.	.091	24.4	4.83	51.66	175.
4.0	1841.	.178	34.9	4.76	53.21	172.
8.0	1915.	.349	40.7	4.69	54.93	170.
12.0	1935.	.516	39.3	4.67	55.39	169.
16.0	1917.	.688	44.3	4.68	54.97	170.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :8/18/82
TEST NO.:MRC-1-4A
FUEL :200X400 MONT. ROSEBUD COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .080
APPARENT DENSITY (GM/CC) = 1.21
AVE. PARTICLE DIA.(MICRON)= 55.0
GAS FEED RATE (L/MIN) = 14.5

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1997.	.3	8.2	1.	0.000	.012	40.
2.0	2036.	.6	11.5	4.	0.000	.030	200.
4.0	2045.	.2	12.6	9.	0.000	0.000	600.
8.0	2070.	.8	12.2	5.	0.000	.030	700.
12.0	2127.	1.2	12.8	6.	0.000	.030	650.
16.0	2142.	2.2	13.2	5.	0.000	.090	660.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1997.	.043	0.0	4.64	55.22	163.
2.0	2036.	.084	28.7	4.60	56.10	162.
4.0	2045.	.168	35.5	4.60	56.29	162.
8.0	2070.	.333	33.5	4.57	56.86	161.
12.0	2127.	.495	37.4	4.52	58.14	159.
16.0	2142.	.657	40.2	4.51	58.49	159.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :6/14/82
TEST NO.:MRC-1-5
FUEL :200X400 MONT. ROSEBUD COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .086
APPARENT DENSITY (GM/CC) = 1.21
AVE. PARTICLE DIA.(MICRON)= 55.0
GAS FEED RATE (L/MIN) = 14.9

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2337.	0.0	13.2	3.	0.000	0.000	840.
2.0	2357.	0.0	12.6	8.	0.000	.036	1080.
4.0	2389.	0.0	13.1	6.	0.000	.036	1320.
8.0	2421.	0.0	12.6	5.	0.000	.060	1500.
12.0	2435.	.1	13.6	0.	0.000	.080	1600.
16.0	2419.	.3	15.0	4.	0.000	.090	1700.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2337.	.037	38.7	4.35	64.68	157.
2.0	2357.	.073	35.3	4.34	65.16	157.
4.0	2389.	.146	38.1	4.31	65.88	156.
8.0	2421.	.289	35.3	4.29	66.64	155.
12.0	2435.	.432	40.8	4.28	66.95	155.
16.0	2419.	.575	47.4	4.29	66.58	155.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :6/17/82
TEST NO.:MRC-1-5R
FUEL :200X400 MONT. ROSEBUD COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .080
APPARENT DENSITY (GM/CC) = 1.21
AVE. PARTICLE DIA.(MICRON)= 55.0
GAS FEED RATE (L/MIN) = 14.5

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2337.	.8	10.7	3.	0.000	.018	200.
2.0	2357.	1.0	12.8	5.	0.000	.030	540.
4.0	2389.	.7	12.4	6.	0.000	.030	640.
8.0	2421.	1.3	12.5	15.	0.000	.060	800.
12.0	2435.	.7	13.7	11.	0.000	.030	850.
16.0	2419.	2.4	14.0	8.	0.000	.060	900.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2337.	.038	22.9	4.35	62.86	153.
2.0	2357.	.075	37.2	4.34	63.32	152.
4.0	2389.	.150	34.7	4.31	64.03	152.
8.0	2421.	.297	35.7	4.29	64.76	151.
12.0	2435.	.443	41.7	4.28	55.06	150.
16.0	2419.	.591	44.3	4.29	64.70	151.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :5/15/82
TEST NO.:MRC-1-6
FUEL :200X400 MONT. ROSEBUD COAL
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .086
APPARENT DENSITY (GM/CC) = 1.21
AVE. PARTICLE DIA.(MICRON)= 55.0
GAS FEED RATE (L/MIN) = 14.9

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2475.	6.6	12.8	7.	0.000	0.000	1040.
2.0	2488.	7.1	13.1	1.	0.000	0.000	1160.
4.0	2513.	6.7	13.2	9.	0.000	0.000	1440.
8.0	2580.	5.8	13.0	7.	0.000	0.000	1920.
12.0	2615.	5.1	13.9	5.	0.000	0.000	2200.
16.0	2635.	6.4	13.4	4.	0.000	0.000	2250.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2475.	.035	41.3	4.22	67.88	153.
2.0	2498.	.070	43.2	4.21	68.17	152.
4.0	2513.	.140	43.4	4.19	68.75	152.
8.0	2580.	.276	41.8	4.15	70.31	150.
12.0	2635.	.411	45.7	4.11	71.59	149.
16.0	2615.	.545	44.2	4.11	71.59	149.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :8/12/82
TEST NO.:PEA-1-4
FUEL :200X400 MESH ANTHRACITE
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .066
APPARENT DENSITY (GM/CC) = 1.45
AVE. PARTICLE DIA.(MICRON)= 53.0
GAS FEED RATE (L/MIN) = 14.5

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1997.	.2	5.9	0.	0.000	0.000	0.
2.0	2036.	.3	5.8	0.	0.000	0.000	0.
4.0	2345.	.1	5.8	0.	0.000	0.000	0.
8.0	2070.	.6	5.8	0.	0.000	0.000	0.
12.0	2127.	.3	5.8	0.	0.000	0.000	0.
16.0	2142.	0.0	5.9	0.	0.000	0.000	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1997.	.042	1.7	5.16	55.22	163.
2.0	2036.	.084	.0	5.11	56.10	162.
4.0	2045.	.166	0.0	5.11	56.29	162.
8.0	2070.	.331	.4	5.08	56.86	161.
12.0	2127.	.491	.0	5.03	58.14	159.
16.0	2142.	.651	1.5	5.01	58.49	159.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :8/13/82
TEST NO.:PEA-1-5
FUEL :200X400 MESH ANTHRACITE
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .066
APPARENT DENSITY (GM/CC) = 1.45
AVE. PARTICLE DIA.(MICRON)= 53.0
GAS FEED RATE (L/MIN) = 14.5

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2337.	.6	6.0	0.	.150	0.000	0.
2.0	2357.	.4	5.8	1.	.150	0.000	0.
4.0	2389.	.3	5.8	3.	.150	0.000	0.
8.0	2421.	.7	5.9	3.	.100	.030	0.
12.0	2435.	.9	5.8	4.	.100	.036	0.
16.0	2419.	2.1	5.9	4.	.100	.048	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2337.	.038	3.9	4.83	62.86	153.
2.0	2357.	.075	.1	4.82	63.32	152.
4.0	2389.	.149	.0	4.79	64.03	152.
8.0	2421.	.295	2.3	4.76	64.76	151.
12.0	2435.	.440	.7	4.75	65.06	150.
16.0	2419.	.587	3.7	4.77	64.70	151.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :8/16/82
TEST NO.:PEA-1-6
FUEL :200X400 MESH ANTHRACITE
GAS :100 PCT N2

FUEL FEED RATE (GM/MIN) = .065
APPARENT DENSITY (GM/CC) = 1.45
AVE. PARTICLE DIA.(MICRON)= 53.3
GAS FEED RATE (L/MIN) = 14.5

EXCESS O2 (PCT) = 0.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2475.	.4	5.9	0.	.500	0.000	0.
2.0	2488.	.4	5.9	3.	.500	0.000	0.
4.0	2513.	.3	6.0	4.	.500	0.000	0.
8.0	2580.	.6	6.1	3.	.150	.018	0.
12.0	2635.	.4	6.0	2.	.150	.024	0.
16.0	2635.	1.4	6.0	5.	.150	.024	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2475.	.036	1.9	4.72	65.97	149.
2.0	2488.	.072	1.9	4.71	66.25	149.
4.0	2513.	.143	3.6	4.69	66.81	148.
8.0	2580.	.282	5.6	4.64	68.33	147.
12.0	2635.	.419	3.7	4.60	69.57	145.
16.0	2635.	.556	4.7	4.60	69.57	145.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :7/6/83
TEST NO.:TMLC-1-2
FUEL :200X400 MESH TEXAS(MONTICELLO) LIGNITE C
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .063
APPARENT DENSITY (GM/CC) = .79
AVE. PARTICLE DIA.(MICRON)= 55.0
GAS FEED RATE (L/MIN) = 15.6

EXCESS O2 (PCT) = 459.8

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1528.	0.0	0.0	0.	3.050	0.000	0.
2.0	1543.	0.0	33.8	0.	3.050	.002	0.
4.0	1565.	0.0	34.4	0.	3.050	.002	0.
8.0	1589.	0.0	33.7	0.	3.050	.003	0.
12.0	1596.	0.0	34.2	1.	3.040	.006	20.
16.0	1594.	0.0	34.2	2.	3.000	.030	40.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1528.	.050	0.0	3.36	47.97	195.
2.0	1543.	.099	10.0	3.34	48.34	194.
4.0	1565.	.196	12.3	3.32	48.88	193.
8.0	1589.	.389	9.6	3.31	49.46	192.
12.0	1596.	.581	11.6	3.30	49.62	192.
16.0	1594.	.773	11.6	3.30	49.58	192.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	1528.	.050	0.00000	.17552	0.00000	0.000
2.0	1543.	.099	.02480	.17652	.02885	.141
4.0	1565.	.196	.01560	.17800	.01710	.088
8.0	1589.	.389	.00604	.17958	.00625	.034
12.0	1596.	.581	.00494	.18001	.00538	.027
16.0	1594.	.773	.00376	.17991	.00384	.021

DATE :7/7/83
TEST NO.:TMLC-1-3
FUEL :200X400 MESH TEXAS(MONTICELLO) LIGNITE C
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .060
APPARENT DENSITY (GM/CC) = .79
AVE. PARTICLE DIA.(MICRON)= 55.0
GAS FEED RATE (L/MIN) = 15.5

EXCESS O2 (PCT) = 485.9

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1845.	0.0	0.0	0.	0.000	0.000	0.
2.0	1860.	0.0	34.2	0.	3.000	.002	0.
4.0	1875.	0.0	33.5	0.	3.000	.003	0.
8.0	1892.	0.0	35.1	1.	2.950	.024	70.
12.0	1909.	0.0	37.8	4.	2.900	.090	200.
16.0	1911.	0.0	46.6	8.	2.750	.220	220.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1845.	.043	0.0	3.12	55.46	181.
2.0	1860.	.087	11.6	3.11	55.82	180.
4.0	1875.	.172	8.7	3.10	56.18	180.
8.0	1892.	.343	15.0	3.09	56.58	179.
12.0	1909.	.512	24.4	3.08	57.00	178.
16.0	1911.	.681	47.3	3.07	57.05	178.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SFC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	1845.	.043	0.00000	.19616	0.00000	0.000
2.0	1860.	.087	.03355	.19711	.04044	.170
4.0	1875.	.172	.01263	.19807	.01349	.064
8.0	1892.	.343	.01134	.19912	.01202	.057
12.0	1909.	.512	.01301	.20021	.01391	.065
16.0	1911.	.681	.02233	.20036	.02513	.111

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :7/8/83
TEST NO.:TMLC-1-4
FUEL :200X400 MESH TEXAS(MONTICELLO) LIGNITE C
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .061
APPARENT DENSITY (GM/CC) = .79
AVE. PARTICLE DIA.(MICRON)= 55.0
GAS FEED RATE (L/MIN) = 15.3

EXCESS O2 (PCT) = 470.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2080.	0.0	0.0	0.	0.000	0.000	0.
2.0	2103.	0.0	34.7	0.	3.000	.006	0.
4.0	2115.	0.0	36.0	2.	2.950	.030	100.
8.0	2125.	0.0	43.0	7.	2.850	.150	260.
12.0	2145.	0.0	49.8	10.	2.700	.300	200.
16.0	2149.	0.0	61.7	15.	2.600	.380	140.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2080.	.040	0.0	2.97	60.44	170.
2.0	2103.	.080	13.5	2.96	60.98	170.
4.0	2115.	.159	18.3	2.95	61.28	169.
8.0	2125.	.317	39.1	2.94	61.51	169.
12.0	2145.	.473	53.7	2.93	61.99	168.
16.0	2149.	.629	71.5	2.93	62.09	168.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2080.	.040	0.00000	.21097	0.00000	0.000
2.0	2103.	.080	.04273	.21237	.05349	.201
4.0	2115.	.159	.03013	.21315	.03509	.141
8.0	2125.	.317	.03664	.21377	.04422	.171
12.0	2145.	.473	.03846	.21501	.04684	.179
16.0	2149.	.629	.04536	.21526	.05746	.211

DATE :7/11/83
TEST NO.:TMLC-1-5
FUEL :200X400 MESH TEXAS(MONTICELLO) LIGNITE C
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .061
APPARENT DENSITY (GM/CC) = .79
AVE. PARTICLE DIA.(MICRON)= 55.0
GAS FEED RATE (L/MIN) = 14.9

EXCESS O2 (PCT) = 453.3

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2330.	0.0	0.0	0.	0.000	0.000	0.
2.0	2355.	0.0	34.5	1.	2.990	.010	35.
4.0	2395.	0.0	37.3	4.	2.970	.095	220.
8.0	2420.	0.0	47.5	10.	2.750	.280	196.
12.0	2423.	0.0	55.1	16.	2.650	.400	150.
16.0	2415.	0.0	76.5	18.	2.570	.480	100.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2330.	.038	0.0	2.84	64.66	158.
2.0	2355.	.075	12.7	2.82	65.24	158.
4.0	2395.	.149	22.7	2.80	66.16	156.
8.0	2420.	.295	49.2	2.79	66.75	156.
12.0	2423.	.441	62.8	2.79	66.82	156.
16.0	2415.	.587	85.9	2.79	66.63	156.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2330.	.039	0.00000	.22636	0.00000	0.000
2.0	2355.	.075	.04294	.22788	.05291	.188
4.0	2395.	.149	.04050	.23028	.04915	.176
8.0	2420.	.295	.05414	.23182	.07063	.234
12.0	2423.	.441	.05228	.23200	.06748	.225
16.0	2415.	.587	.06900	.23152	.09830	.298

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :7/1/83
TEST NO.:TMLC-1-6
FUEL :200X400 MESH TEXAS(MONTICELLO) LIGNITE C
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .059
APPARENT DENSITY (GM/CC) = .79
AVE. PARTICLE DIA.(MICRON)= 55.0
GAS FEED RATE (L/MIN) = 15.2

EXCESS O2 (PCT) = 485.8

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2493.	0.0	0.0	0.	0.000	0.000	0.
2.0	2513.	0.0	35.3	5.	2.950	.100	170.
4.0	2555.	0.0	41.7	9.	2.850	.135	300.
8.0	2603.	0.0	50.0	15.	2.810	.280	190.
12.0	2637.	0.0	61.7	21.	2.650	.320	120.
16.0	2643.	0.0	78.6	24.	2.610	.450	96.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2493.	.035	0.0	2.76	69.85	157.
2.0	2513.	.070	15.7	2.75	70.37	156.
4.0	2555.	.138	35.7	2.73	71.33	155.
8.0	2603.	.274	54.0	2.71	72.45	154.
12.0	2637.	.407	71.5	2.69	73.25	153.
16.0	2643.	.541	87.5	2.69	73.41	153.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2493.	.035	0.00000	.23618	0.00000	0.000
2.0	2513.	.070	.05657	.23738	.07775	.247
4.0	2555.	.138	.07547	.23992	.11011	.315
8.0	2603.	.274	.06450	.24275	.08783	.266
12.0	2637.	.407	.06876	.24477	.09562	.281
16.0	2643.	.541	.07692	.24515	.11208	.314

DATE :7/13/83
TEST NO.:TMLC-1-6A
FUEL :200X400 MESH TEXAS(MONTICELLO) LIGNITE C
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .061
APPARENT DENSITY (GM/CC) = .79
AVE. PARTICLE DIA.(MICRON)= 55.0
GAS FEED RATE (L/MIN) = 14.3

EXCESS O2 (PCT) = 433.2

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2493.	0.0	0.0	0.	0.000	0.000	0.
2.0	2513.	0.0	38.3	4.	2.850	.080	80.
4.0	2555.	0.0	0.0	0.	0.000	0.000	0.
8.0	2603.	0.0	52.9	16.	2.600	.410	50.
12.0	2637.	0.0	0.0	0.	0.000	0.000	0.
16.0	2643.	0.0	78.2	25.	2.490	.500	20.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2493.	.037	0.0	2.76	65.72	148.
2.0	2513.	.074	25.9	2.75	66.17	147.
4.0	2555.	.147	0.0	2.73	67.11	146.
8.0	2603.	.290	59.1	2.71	68.17	145.
12.0	2637.	.432	0.0	2.69	68.93	144.
16.0	2643.	.574	87.2	2.69	69.07	144.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2493.	.037	0.00000	.23618	0.00000	0.000
2.0	2513.	.074	.09814	.23738	.16732	.413
4.0	2555.	.147	0.00000	.23992	0.00000	0.000
8.0	2603.	.290	.07418	.24275	.10683	.306
12.0	2637.	.432	0.00000	.24477	0.00000	0.000
16.0	2643.	.574	.07543	.24515	.10896	.308

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :4/14/83
TEST NO.:AACC-1-5
FUEL :200X400 MESH CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .068
APPARENT DENSITY (GM/CC) = .86
AVE. PARTICLE DIA.(MICRON)= 54.0
GAS FEED RATE (L/MIN) = 15.3

EXCESS O2 (PCT) = 257.2

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2260.	0.0	0.0	0.	0.000	0.000	0.
2.0	2285.	0.0	4.2	1.	3.180	.008	60.
4.0	2335.	0.0	4.6	4.	3.100	.075	250.
8.0	2385.	0.0	7.1	25.	2.800	.400	200.
12.0	2395.	0.0	10.8	51.	2.650	.600	120.
16.0	2393.	0.0	14.4	50.	2.550	.700	60.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2260.	.038	0.0	3.00	64.52	164.
2.0	2285.	.075	6.4	2.99	65.11	163.
4.0	2335.	.148	15.1	2.96	66.30	162.
8.0	2385.	.293	47.2	2.94	67.48	160.
12.0	2395.	.436	66.5	2.93	67.72	160.
16.0	2393.	.580	75.9	2.93	67.66	160.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2260.	.038	0.00000	.22620	0.00000	0.000
2.0	2285.	.075	.02118	.22776	.02335	.093
4.0	2335.	.148	.02671	.23087	.03021	.116
8.0	2385.	.293	.05415	.23396	.07046	.231
12.0	2395.	.436	.06111	.23457	.08264	.261
16.0	2393.	.580	.05905	.23442	.07893	.252

DATE :4/14/83
TEST NO.:AACC-1-6
FUEL :200X400 MESH CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .068
APPARENT DENSITY (GM/CC) = .86
AVE. PARTICLE DIA.(MICRON)= 54.0
GAS FEED RATE (L/MIN) = 15.1

EXCESS O2 (PCT) = 253.2

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2520.	0.0	0.0	0.	0.000	0.000	0.
2.0	2538.	0.0	4.3	8.	3.150	.022	150.
4.0	2570.	0.0	5.1	16.	3.010	.160	290.
8.0	2608.	0.0	7.4	39.	2.750	.430	180.
12.0	2635.	0.0	10.9	55.	2.570	.610	110.
16.0	2643.	0.0	16.9	68.	2.450	.750	56.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2520.	.035	0.0	2.87	69.90	155.
2.0	2538.	.070	8.7	2.86	70.31	154.
4.0	2570.	.138	23.8	2.85	71.07	154.
8.0	2608.	.274	49.5	2.83	71.95	153.
12.0	2635.	.409	66.7	2.82	72.59	152.
16.0	2643.	.543	80.1	2.81	72.77	152.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2520.	.035	0.00000	.24223	0.00000	0.000
2.0	2538.	.070	.03153	.24330	.03622	.130
4.0	2570.	.138	.04813	.24528	.05988	.196
8.0	2608.	.274	.06248	.24755	.08357	.252
12.0	2635.	.409	.06755	.24921	.09267	.271
16.0	2643.	.543	.07233	.24966	.10183	.290

DRUP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :4/19/83
TEST NO.:AACC-1-3R
FUEL :200X400 MESH CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .073
APPARENT DENSITY (GM/CC) = .86
AVE. PARTICLE DIA.(MICRON)= 54.0
GAS FEED RATE (L/MIN) = 15.3

EXCESS O2 (PCT) = 231.2

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1845.	0.0	0.0	0.	0.000	0.000	0.
2.0	1865.	0.0	0.0	0.	0.000	0.000	0.
4.0	1898.	0.0	4.1	1.	3.150	.006	30.
8.0	1920.	0.0	4.2	1.	3.150	.020	80.
12.0	1920.	0.0	4.7	5.	3.035	.110	200.
16.0	1908.	0.0	6.0	17.	2.820	.325	180.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1845.	.044	0.0	3.26	54.71	178.
2.0	1865.	.087	0.0	3.25	55.18	177.
4.0	1898.	.173	5.9	3.22	55.95	176.
8.0	1920.	.343	7.6	3.21	56.49	175.
12.0	1920.	.514	17.2	3.21	56.48	175.
16.0	1908.	.685	36.9	3.22	56.20	176.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	1845.	.044	0.00000	.19979	0.00000	0.000
2.0	1865.	.087	0.00000	.20109	0.00000	0.000
4.0	1898.	.173	.00850	.20319	.00887	.042
8.0	1920.	.343	.00556	.20465	.00571	.027
12.0	1920.	.514	.00905	.20461	.00947	.044
16.0	1908.	.685	.01705	.20387	.01861	.084

DATE :4/13/83
TEST NO.:AACC-1-4
FUEL :200X400 MESH CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .067
APPARENT DENSITY (GM/CC) = .86
AVE. PARTICLE DIA.(MICRON)= 54.0
GAS FEED RATE (L/MIN) = 15.1

EXCESS O2 (PCT) = 258.5

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2075.	0.0	0.0	0.	0.000	0.000	0.
2.0	2090.	0.0	4.1	0.	3.210	.003	20.
4.0	2121.	0.0	4.2	0.	3.210	.030	40.
8.0	2145.	0.0	4.9	5.	3.070	.130	300.
12.0	2146.	0.0	7.4	26.	2.800	.420	170.
16.0	2135.	0.0	10.8	40.	2.650	.600	96.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2075.	.041	0.0	3.11	59.46	168.
2.0	2090.	.081	5.5	3.10	59.81	167.
4.0	2121.	.161	8.5	3.08	60.54	166.
8.0	2145.	.319	21.2	3.07	61.09	166.
12.0	2146.	.478	49.1	3.07	61.12	166.
16.0	2135.	.636	66.5	3.07	60.87	166.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2075.	.041	0.00000	.21456	0.00000	0.000
2.0	2090.	.081	.01663	.21551	.01803	.077
4.0	2121.	.161	.01307	.21748	.01391	.060
8.0	2145.	.319	.01802	.21896	.01464	.082
12.0	2146.	.474	.03488	.21905	.04148	.159
16.0	2135.	.636	.04191	.21836	.05186	.192

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE 14/12/83
TEST NO.:AACC-1-2
FUEL :200X400 MESH CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .069
APPARENT DENSITY (GM/CC) = .86
AVE. PARTICLE DIA.(MICRON)= 54.0
GAS FEED RATE (L/MIN) = 15.5

EXCESS O2 (PCT) = 256.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1536.	0.0	0.0	0.	0.000	0.000	0.
2.0	1546.	0.0	0.0	0.	3.100	0.000	0.
4.0	1573.	0.0	0.0	0.	3.100	.006	10.
8.0	1603.	0.0	4.2	1.	3.090	.014	40.
12.0	1623.	0.0	4.2	1.	3.080	.021	80.
16.0	1625.	0.0	4.2	1.	3.075	.014	60.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1536.	.050	0.0	3.50	47.86	194.
2.0	1546.	.099	0.0	3.49	48.10	193.
4.0	1573.	.196	0.0	3.47	48.75	192.
8.0	1603.	.388	6.8	3.44	49.47	190.
12.0	1623.	.578	8.0	3.43	49.94	189.
16.0	1625.	.769	7.0	3.43	50.00	189.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	1536.	.050	0.00000	.17931	0.00000	0.000
2.0	1546.	.099	0.00000	.17999	0.00000	0.000
4.0	1573.	.196	0.00000	.18180	0.00000	0.000
8.0	1603.	.388	.00448	.18381	.00459	.024
12.0	1623.	.578	.00356	.18514	.00363	.019
16.0	1625.	.769	.00234	.18531	.00237	.013

DATE 14/13/83
TEST NO.:AACC-1-3
FUEL :200X400 MESH CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .070
APPARENT DENSITY (GM/CC) = .86
AVE. PARTICLE DIA.(MICRON)= 54.0
GAS FEED RATE (L/MIN) = 15.3

EXCESS O2 (PCT) = 247.2

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1845.	0.0	0.0	0.	0.000	0.000	0.
2.0	1865.	0.0	0.0	0.	0.000	0.000	0.
4.0	1898.	0.0	4.1	0.	3.180	.063	40.
8.0	1920.	0.0	4.2	1.	3.120	.017	80.
12.0	1920.	0.0	4.6	5.	3.050	.090	220.
16.0	1908.	0.0	6.0	15.	2.750	.300	220.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1845.	.044	0.0	3.26	54.71	178.
2.0	1865.	.087	0.0	3.25	55.18	177.
4.0	1898.	.173	5.7	3.22	55.95	176.
8.0	1920.	.343	7.5	3.21	56.49	175.
12.0	1970.	.514	16.0	3.21	56.48	175.
16.0	1908.	.685	36.4	3.22	56.20	176.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	1845.	.044	0.00000	.19979	0.00000	0.000
2.0	1865.	.087	0.00000	.20109	0.00000	0.000
4.0	1898.	.173	.00814	.20319	.00848	.040
8.0	1920.	.343	.00554	.23465	.00570	.027
12.0	1920.	.514	.00834	.20461	.00870	.041
16.0	1906.	.685	.01721	.20387	.01879	.084

DATE :7/22/82
TEST NO.:MRCC-1-2R
FUEL :200X400 MONT. ROSEBUD CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .067
APPARENT DENSITY (GM/CC) = .70
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 14.2

EXCESS O2 (PCT) = 352.1

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1449.	0.0	16.6	0.	3.050	0.000	0.
2.0	1474.	0.0	15.4	0.	3.050	0.000	0.
4.0	1530.	0.0	16.0	0.	3.050	0.000	0.
8.0	1589.	0.0	16.6	0.	3.040	0.000	20.
12.0	1596.	0.0	17.1	0.	3.050	.048	40.
16.0	1594.	0.0	17.2	1.	3.020	.072	50.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1449.	.057	9.4	3.15	42.07	182.
2.0	1474.	.112	.9	3.12	42.62	181.
4.0	1530.	.220	5.3	3.08	43.86	178.
8.0	1589.	.431	9.4	3.04	45.17	176.
12.0	1596.	.641	12.5	3.03	45.31	175.
16.0	1594.	.852	13.2	3.03	45.20	175.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF (*GM./CM2.SEC.ATM.*)	KS (*GM./CM2.SEC.ATM.*)	K/KDIFF
1.0	1449.	.057	.03660	.16722	.04685	.219
2.0	1474.	.112	.00173	.16886	.00175	.010
4.0	1530.	.220	.00524	.17255	.00541	.030
8.0	1589.	.431	.00483	.17637	.00496	.027
12.0	1596.	.641	.00438	.17679	.00449	.025
16.0	1594.	.852	.00350	.17670	.00357	.020

DATE :7/21/82
TEST NO.:MRCC-1-3R
FUEL :200X400 MONT. ROSEBUD CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .069
APPARENT DENSITY (GM/CC) = .70
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 14.5

EXCESS O2 (PCT) = 348.3

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1864.	0.0	16.9	0.	3.000	0.000	0.
2.0	1845.	0.0	16.4	0.	3.000	0.000	0.
4.0	1877.	0.0	16.7	0.	3.010	.048	70.
8.0	1878.	0.0	18.5	4.	2.920	.210	220.
12.0	1909.	0.0	22.6	9.	2.650	.430	150.
16.0	1911.	0.0	28.2	14.	2.560	.660	120.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1864.	.046	11.3	2.85	52.31	168.
2.0	1845.	.092	8.0	2.43	53.00	167.
4.0	1877.	.183	10.0	2.84	52.59	168.
8.0	1878.	.367	20.5	2.84	52.61	168.
12.0	1909.	.548	38.2	2.83	53.32	167.
16.0	1911.	.728	54.1	2.82	53.37	167.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF (*GM./CM2.SEC.ATM.*)	KS (*GM./CM2.SEC.ATM.*)	K/KDIFF
1.0	1864.	.046	.05527	.19385	.07732	.285
2.0	1895.	.092	.01962	.19575	.02181	.100
4.0	1877.	.183	.01228	.19463	.01310	.063
8.0	1878.	.367	.01350	.19469	.01451	.069
12.0	1909.	.548	.02003	.19665	.02230	.102
16.0	1911.	.728	.02401	.19678	.02735	.122

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE 16/28/82
TEST NO. IMRCC-1-4
FUEL 1200X400 MONT. ROSEBUD CHAR
GAS 3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .072
APPARENT DENSITY (GM/CC) = .70
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 14.6

EXCESS O2 (PCT) = 332.5

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2080.	1.5	15.3	25.	3.000	.030	20.
2.0	2103.	1.5	16.2	16.	2.990	.120	140.
4.0	2115.	1.3	19.3	10.	2.800	.360	180.
8.0	2125.	.9	27.0	19.	2.560	.630	140.
12.0	2145.	2.0	40.1	23.	2.320	.900	600.
16.0	2149.	1.7	58.7	28.	2.300	1.050	220.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2080.	.042	1.9	2.73	57.57	162.
2.0	2103.	.084	8.4	2.72	58.08	161.
4.0	2115.	.167	25.8	2.71	58.36	161.
8.0	2125.	.333	51.8	2.71	58.59	161.
12.0	2145.	.498	74.0	2.69	59.04	160.
16.0	2149.	.662	87.8	2.69	59.13	160.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2080.	.042	.00989	.20721	.01038	.048
2.0	2103.	.084	.02236	.20858	.02505	.107
4.0	2115.	.167	.03961	.20934	.04885	.189
8.0	2125.	.333	.04968	.20995	.06509	.237
12.0	2145.	.498	.06135	.21117	.08648	.291
16.0	2149.	.662	.06494	.21141	.09374	.307

DATE 16/28/82
TEST NO. IMRCC-1-5
FUEL 1200X400 MONT. ROSEBUD CHAR
GAS 3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .070
APPARENT DENSITY (GM/CC) = .70
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 14.1

EXCESS O2 (PCT) = 329.7

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2280.	1.3	15.4	1.	3.150	.060	60.
2.0	2326.	1.5	16.9	5.	3.030	.150	120.
4.0	2401.	1.4	20.8	11.	2.850	.360	200.
8.0	2430.	.9	31.8	25.	2.660	.660	160.
12.0	2433.	1.8	45.9	28.	2.450	.840	300.
16.0	2420.	1.0	69.9	30.	2.340	.930	140.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2280.	.041	2.4	2.63	59.97	151.
2.0	2326.	.081	12.9	2.61	60.98	150.
4.0	2401.	.159	32.5	2.57	62.61	148.
8.0	2430.	.313	61.8	2.56	63.25	147.
12.0	2433.	.467	79.4	2.56	63.32	147.
16.0	2420.	.622	92.5	2.56	63.04	147.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2280.	.041	.01249	.21933	.01324	.057
2.0	2326.	.081	.03612	.22208	.04313	.163
4.0	2401.	.159	.05332	.22652	.06974	.235
8.0	2430.	.313	.06615	.22827	.09314	.290
12.0	2433.	.467	.07019	.22845	.10132	.307
16.0	2420.	.622	.07765	.22768	.11830	.342

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :6/15/82
TEST NO.:MRCC-1-6
FUEL :200X400 MONT. ROSEBUD CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .070
APPARENT DENSITY (GM/CC) = .70
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 14.9

EXCESS O2 (PCT) = 354.0

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2493.	2.9	17.6	5.	2.780	.240	200.
2.0	2531.	3.4	20.3	11.	2.550	.450	380.
4.0	2561.	3.9	28.4	25.	2.450	.600	200.
8.0	2588.	2.9	47.3	33.	2.200	.960	100.
12.0	2637.	2.3	64.6	38.	2.150	1.060	20.
16.0	2646.	1.5	70.6	35.	2.100	1.020	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2493.	.036	18.5	2.53	68.29	153.
2.0	2531.	.071	32.2	2.52	69.18	152.
4.0	2561.	.142	57.0	2.50	69.87	152.
8.0	2588.	.281	81.0	2.49	70.49	151.
12.0	2637.	.418	90.8	2.47	71.63	150.
16.0	2646.	.555	92.9	2.47	71.84	150.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2493.	.036	.12956	.23196	.29347	.559
2.0	2531.	.071	.13091	.23423	.29676	.559
4.0	2561.	.142	.13861	.23599	.33592	.587
8.0	2588.	.281	.13493	.23754	.31236	.568
12.0	2637.	.418	.11953	.24043	.23771	.497
16.0	2646.	.555	.09851	.24095	.16665	.409

DATE :6/12/82
TEST NO.:PEAC-1-2
FUEL :200X400 ANTHRACITE CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .073
APPARENT DENSITY (GM/CC) = 1.61
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 14.6

EXCESS O2 (PCT) = 220.4

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1449.	0.0	6.6	0.	3.100	0.000	0.
2.0	1474.	0.0	6.7	0.	3.100	0.000	0.
4.0	1530.	0.0	7.1	0.	3.100	0.000	0.
8.0	1589.	0.0	7.3	0.	3.100	0.000	0.
12.0	1596.	0.0	7.5	0.	3.100	0.000	0.
16.0	1594.	0.0	7.6	0.	3.100	0.000	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1449.	.051	0.0	7.22	43.25	187.
2.0	1474.	.101	0.0	7.17	43.82	186.
4.0	1530.	.198	0.0	7.07	45.10	183.
8.0	1589.	.388	0.0	6.97	46.44	181.
12.0	1596.	.578	1.4	6.96	46.59	180.
16.0	1594.	.768	2.8	6.96	46.55	180.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	1449.	.051	0.00000	.16722	0.00000	0.000
2.0	1474.	.101	0.00000	.16886	0.00000	0.000
4.0	1530.	.198	0.00000	.17255	0.00000	0.000
8.0	1589.	.388	0.00000	.17637	0.00000	0.000
12.0	1596.	.578	.00121	.17679	.00122	.007
16.0	1594.	.768	.00181	.17670	.00183	.010

DATE :7/13/82
TEST NO.:PEAC-I-3
FUEL :200X400 ANTHRACITE CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .073
APPARENT DENSITY (GM/CC) = 1.61
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 14.6

EXCESS O2 (PCT) = 220.4

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1864.	0.0	6.9	0.	3.200	0.000	0.
2.0	1895.	0.0	7.0	0.	3.200	0.000	0.
4.0	1877.	0.0	7.5	0.	3.200	0.000	0.
8.0	1878.	0.0	7.7	0.	3.200	0.000	0.
12.0	1909.	0.0	7.7	0.	3.200	0.000	10.
16.0	1911.	0.0	7.8	0.	3.180	0.000	20.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1864.	.043	0.0	6.55	52.67	170.
2.0	1895.	.086	0.0	6.51	53.36	168.
4.0	1877.	.171	1.4	6.53	52.95	169.
8.0	1878.	.342	4.2	6.53	52.98	169.
12.0	1909.	.511	4.2	6.49	53.69	168.
16.0	1911.	.679	5.5	6.49	53.74	168.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF (*GM./CM2.SEC.ATM.*)	KS (*GM./CM2.SEC.ATM.*)	K/KDIFF
1.0	1864.	.043	0.00000	.19385	0.00000	0.000
2.0	1895.	.086	0.00000	.19575	0.00000	0.000
4.0	1877.	.171	.00397	.19463	.00406	.020
8.0	1878.	.342	.00587	.19469	.00605	.030
12.0	1909.	.511	.00393	.19665	.00401	.020
16.0	1911.	.679	.00393	.19678	.00401	.020

DATE :7/13/82
TEST NO.:PEAC-I-4
FUEL :200X400 ANTHRACITE CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .073
APPARENT DENSITY (GM/CC) = 1.61
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 14.6

EXCESS O2 (PCT) = 220.4

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2080.	0.0	7.0	0.	3.100	0.000	0.
2.0	2103.	0.0	7.2	0.	3.100	0.000	0.
4.0	2115.	0.0	7.6	0.	3.100	0.000	0.
8.0	2125.	0.0	7.7	0.	3.080	.030	50.
12.0	2145.	0.0	8.0	2.	3.060	.076	90.
16.0	2149.	0.0	8.1	3.	3.010	.126	90.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2080.	.040	0.0	6.27	57.57	162.
2.0	2103.	.079	0.0	6.24	58.08	161.
4.0	2115.	.158	2.8	6.23	58.36	161.
8.0	2125.	.315	4.2	6.21	58.59	161.
12.0	2145.	.471	8.1	6.19	59.04	160.
16.0	2149.	.626	9.3	6.19	59.13	160.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF (*GM./CM2.SEC.ATM.*)	KS (*GM./CM2.SEC.ATM.*)	K/KDIFF
1.0	2080.	.040	0.00000	.20721	0.00000	0.000
2.0	2103.	.079	0.00000	.20858	0.00000	0.000
4.0	2115.	.158	.00880	.20934	.00918	.042
8.0	2125.	.315	.00661	.20995	.00683	.031
12.0	2145.	.471	.00869	.21117	.00906	.041
16.0	2149.	.626	.00768	.21141	.00797	.036

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :7/15/82
TEST NO.:PEAC-1-5
FUEL :200X400 ANTHRACITE CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .073
APPARENT DENSITY (GM/CC) = 1.61
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 14.6

EXCESS O2 (PCT) = 220.4

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2280.	0.0	7.0	0.	3.040	0.000	0.
2.0	2326.	0.0	7.0	0.	3.010	0.000	0.
4.0	2401.	0.0	7.8	0.	3.010	0.000	60.
8.0	2430.	0.0	8.1	2.	2.950	.090	120.
12.0	2433.	0.0	8.2	11.	2.850	.270	100.
16.0	2420.	0.0	8.2	8.	2.850	.300	100.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2280.	.037	0.0	6.04	62.10	156.
2.0	2326.	.074	0.0	5.99	63.14	155.
4.0	2401.	.146	5.5	5.91	64.83	153.
8.0	2430.	.288	9.3	5.88	65.50	152.
12.0	2433.	.430	10.5	5.88	65.57	152.
16.0	2420.	.573	10.5	5.89	65.27	152.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2280.	.037	0.00000	.21933	0.00000	0.000
2.0	2326.	.074	0.00000	.22208	0.00000	0.000
4.0	2401.	.146	.01931	.22652	.02111	.085
8.0	2430.	.288	.01763	.22827	.01841	.075
12.0	2433.	.430	.01339	.22845	.01422	.059
16.0	2420.	.573	.01005	.22768	.01052	.044

DATE :7/15/82
TEST NO.:PEAC-1-6
FUEL :200X400 ANTHRACITE CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .073
APPARENT DENSITY (GM/CC) = 1.61
AVE. PARTICLE DIA.(MICRON)= 56.0
GAS FEED RATE (L/MIN) = 14.6

EXCESS O2 (PCT) = 220.4

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2493.	0.0	7.6	0.	3.200	0.000	0.
2.0	2531.	0.0	7.7	0.	3.200	0.000	0.
4.0	2561.	0.0	8.0	2.	3.050	.060	80.
8.0	2588.	0.0	8.1	8.	3.000	.120	80.
12.0	2637.	0.0	8.3	14.	2.925	.240	100.
16.0	2646.	0.0	8.3	18.	2.875	.300	80.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2493.	.035	2.8	5.82	66.91	150.
2.0	2531.	.069	4.2	5.78	67.79	149.
4.0	2561.	.138	8.1	5.75	68.47	149.
8.0	2588.	.274	9.3	5.73	69.07	148.
12.0	2637.	.408	11.7	5.68	70.19	147.
16.0	2646.	.541	11.7	5.67	70.39	147.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2493.	.035	.03854	.23196	.04622	.166
2.0	2531.	.069	.02884	.23423	.03289	.123
4.0	2561.	.138	.02975	.23599	.03404	.126
8.0	2588.	.274	.01764	.23754	.01935	.074
12.0	2637.	.408	.01537	.24043	.01642	.064
16.0	2646.	.541	.01178	.24095	.01239	.049

APPENDIX C

CONTROLLED MIXING HISTORY FURNACE TEST DATA

The computer printouts presented in this appendix summarize the CMHF data obtained on the combustion/NO_x emissions characterization of the Alabama high volatile bituminous coal. Terms which may not be obvious are explained as follows:

NO = Percent fuel nitrogen converted to NO

XN = Percent fuel nitrogen converted to NO and intermediate nitrogen species

N_2 = Percent fuel nitrogen converted to molecular nitrogen

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CE/DOE COAL COMBUSTION PROGRAM

TYPE OF COAL ARKADELPHIA HVAB
TEST NO. AA-1-1
DATE 12/6/82

COAL FLOW RATE	(FF)	36.00 LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00 LB/HR
SECONDARY AIR FLOW RATE	(SA)	396.00 LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00 LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54 LB AIR/LB COAL
EXCESS AIR	(EXA)	19.38 PCT
FLUE GAS RECIRCULATION	(FGR)	0.00 PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIOMETRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVERSION EFF. PCT	CHAR N2 RETENTION EFF. PCT	NO ----FORMATION EFF. PCT	XN ----FORMATION EFF. PCT	N2 ----FORMATION EFF. PCT
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	NNE(I)
1	1.331	0.	15.02	2122.5	11.80	10.00	.01	210.10	420.20	49.34	58.50	1.43	2.87	38.63
2	2.555	0.	15.02	2054.7	0.00	0.00	.01	182.23	364.46	66.04	36.53	1.39	2.79	60.68
3	3.711	0.	15.02	1987.0	13.00	10.00	.01	154.36	308.72	82.70	14.55	1.27	2.53	82.92
4	4.884	396.	15.02	2297.1	0.00	0.00	3.91	247.44	352.73	86.66	12.47	1.68	2.39	85.10
5	5.513	0.	119.38	2607.3	10.50	.03	7.80	395.45	422.73	90.59	10.39	11.59	12.39	77.22
6	5.690	0.	119.38	2568.5	0.00	0.00	6.28	397.28	409.51	90.70	9.49	12.99	13.39	77.12
7	5.870	0.	119.38	2529.8	13.20	.01	4.75	398.77	398.77	90.90	8.59	14.39	14.39	77.02
8	6.053	0.	119.38	2468.8	0.00	0.00	4.68	396.94	407.96	93.95	6.90	14.42	14.82	78.28
9	6.239	0.	119.38	2407.9	13.00	.01	4.60	395.12	417.07	97.00	5.21	14.45	15.25	79.54

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CE/DOE COAL COMBUSTION PROGRAM

TYPE OF.COAL ARKADELPHIA HVAB
TEST NO. AA-1-2
DATE 12/7/82

COAL FLOW RATE	(FF)	36.00 LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00 LB/HR
SECONDARY AIR FLOW RATE	(SA)	396.00 LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00 LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54 LB AIR/LB COAL
EXCESS AIR	(EXA)	19.38 PCT
FLUE GAS RECIRCULATION	(FGR)	0.00 PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIOMETRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVERSION EFF. PCT	CHAR N2 RETENTION EFF. PCT	NO FORMATION EFF. PCT	XN FORMATION EFF. PCT	N2 FORMATION EFF. PCT
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	NNE(I)
1	1.295	57.	15.02	2227.4	9.80	5.30	.01	21.44	124.34	35.87	56.88	.15	.85	42.28
2	2.043	0.	30.04	2431.5	0.00	0.00	.01	62.17	105.05	43.55	40.94	.77	1.30	57.76
3	2.649	0.	30.04	2635.5	13.40	3.40	.01	102.91	85.76	51.24	25.00	1.30	1.09	73.91
4	3.297	339.	30.04	2518.2	0.00	0.00	1.26	168.65	154.98	60.66	26.37	2.06	1.89	71.74
5	3.726	0.	119.38	2400.9	12.20	.20	2.50	243.24	233.51	70.09	27.74	9.85	9.45	62.80
6	3.921	0.	119.38	2323.2	0.00	0.00	2.75	263.84	256.44	65.18	33.22	10.50	10.20	56.58
7	4.122	0.	119.38	2245.4	11.00	.10	3.00	285.00	280.00	60.26	38.69	11.15	10.95	50.36
8	4.324	0.	119.38	2293.5	0.00	0.00	2.60	283.70	283.70	68.60	30.39	11.41	11.41	58.20
9	4.522	0.	119.38	2341.5	13.00	.20	2.20	282.45	287.23	76.94	22.09	11.68	11.87	66.04

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CE/DOE COAL COMBUSTION PROGRAM

TYPE OF.COAL ARKADELPHIA HVAB
TEST NO. AA-1-3
DATE 12/8/82

COAL FLOW RATE	(FF)	36.00 LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00 LB/HR
SECONDARY AIR FLOW RATE	(SA)	381.00 LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00 LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54 LB AIR/LB COAL
EXCESS AIR	(EXA)	15.43 PCT
FLUE GAS RECIRCULATION	(FGR)	0.00 PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIOMETRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVERSION EFF. PCT	CHAR N2 RETENTION EFF. PCT	NO FORMATION EFF. PCT	XN FORMATION EFF. PCT	N2 FORMATION EFF. PCT
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	NNE(I)
1	1.206	127.	15.02	2531.3	9.60	10.00	.01	30.30	733.21	38.92	46.43	.23	5.00	48.57
2	1.802	0.	48.59	2470.5	0.00	0.00	.01	68.60	430.92	52.19	35.63	1.33	8.38	55.99
3	2.201	0.	48.59	2409.7	11.00	10.00	.01	102.91	128.63	65.45	24.83	2.05	2.56	72.61
4	2.640	254.	48.59	2427.6	0.00	0.00	2.51	101.12	160.58	70.57	22.26	2.49	2.84	74.90
5	2.955	0.	115.43	2445.5	12.70	0.00	5.00	191.25	202.50	75.69	19.70	6.51	6.89	73.41
6	3.153	0.	115.43	2337.6	0.00	0.00	8.50	212.73	218.18	85.35	13.82	7.52	7.71	78.47
7	3.357	0.	115.43	2229.7	13.40	0.00	4.00	232.94	232.94	95.02	7.90	8.54	8.50	83.52
8	3.562	0.	115.43	2268.9	0.00	0.00	4.25	236.42	236.42	96.34	3.97	8.55	8.55	87.48
9	3.765	0.	115.43	2308.1	13.00	0.00	4.50	240.00	240.00	97.77	0.00	8.56	8.56	91.44

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CE/DOE COAL COMBUSTION PROGRAM

TYPE OF.COAL ARKADELPHIA HVAB
TEST NO. AA-I-4
DATE 12/8/82

COAL FLOW RATE	(FF)	36.00	LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00	LB/HR
SECONDARY AIR FLOW RATE	(SA)	395.30	LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00	LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54	LB AIR/LB COAL
EXCESS AIR	(EXA)	19.19	PCT
FLUE GAS RECIRCULATION	(FGR)	0.00	PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIOMETRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVERSION EFF. PCT	CHAR N2 RETENTION EFF. PCT	NO FORMATION EFF. PCT	XN FORMATION EFF. PCT	N2 FORMATION EFF. PCT
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	NNE(I)
1	1.191	207.	15.02	2497.3	2.80	7.50	.01	343.02	407.34	55.70	45.61	2.34	2.78	51.61
2	1.747	0.	69.65	2326.2	0.00	0.00	.01	332.30	396.62	67.47	29.93	9.19	10.97	59.09
3	2.049	0.	69.65	2155.2	11.50	.03	.01	321.58	385.90	79.24	14.25	9.02	10.82	74.92
4	2.388	188.	69.65	2214.0	0.00	0.00	1.76	264.22	318.00	80.82	16.43	6.81	8.19	75.38
5	2.656	0.	119.19	2272.8	9.40	.01	3.50	195.43	236.57	82.40	18.61	7.54	9.12	72.27
6	2.854	0.	119.19	2302.9	0.00	0.00	2.93	243.98	253.94	87.56	14.50	9.75	10.15	75.35
7	3.049	0.	119.19	2333.1	11.80	.01	2.35	289.54	270.24	92.72	10.39	11.99	11.19	78.43
8	3.247	0.	119.19	2227.3	0.00	0.00	4.08	311.08	308.42	95.44	7.41	11.71	11.61	80.98
9	3.451	0.	119.19	2121.6	12.00	0.00	5.80	337.50	355.26	98.16	4.43	11.43	12.03	83.54

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CE/DOE COAL COMBUSTION PROGRAM

TYPE OF COAL ARKADELPHIA HVAB
TEST NO. AA-I-5
DATE 12/9/82

COAL FLOW RATE	(FF)	36.00	LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00	LB/HR
SECONDARY AIR FLOW RATE	(SA)	396.00	LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00	LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54	LB AIR/LB COAL
EXCESS AIR	(EXA)	19.38	PCT
FLUE GAS RECIRCULATION	(FGR)	0.00	PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIO METRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVER-SION EFF. PCT	CHAR N2 RETENTION EFF. PCT	NO ---FORMATION EFF. PCT	XN ---FORMATION EFF. PCT	N2 ---FORMATION EFF. PCT
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	NNE(I)
1	1.110	283.	15.02	2671.2	11.50	5.50	.01	261.55	317.29	30.31	43.92	1.78	2.16	53.92
2	1.599	0.	89.60	2689.0	0.00	0.00	2.68	329.22	366.07	47.68	33.40	9.86	10.96	55.64
3	1.807	0.	89.60	2706.9	13.80	.50	5.36	420.01	431.52	65.04	22.89	10.92	11.22	65.90
4	2.039	113.	89.60	2575.0	0.00	0.00	6.28	382.10	406.56	77.25	17.88	9.45	10.06	72.06
5	2.251	0.	119.38	2443.1	11.50	.06	7.20	339.13	378.26	89.45	12.87	10.38	11.58	75.55
6	2.438	0.	119.38	2446.0	0.00	0.00	6.10	344.30	404.70	91.00	10.74	11.39	13.39	75.87
7	2.624	0.	119.38	2448.9	13.00	.30	5.00	348.75	427.50	92.55	8.62	12.40	15.21	76.18
8	2.811	0.	119.38	2393.8	0.00	0.00	4.38	311.28	384.36	95.16	6.70	11.53	14.23	79.07
9	3.002	0.	119.38	2338.7	15.00	.06	3.75	276.52	344.35	97.77	4.78	10.64	13.25	81.97

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CE/DOE COAL COMBUSTION PROGRAM

TYPE OF.COAL ARKADELPHIA HVAB
TEST NO. AA-1-6
DATE 12/9/82

COAL FLOW RATE	(FF)	36.00	LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00	LB/HR
SECONDARY AIR FLOW RATE	(SA)	389.00	LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00	LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54	LB AIR/LB COAL
EXCESS AIR	(EXA)	17.53	PCT
FLUE GAS RECIRCULATION	(FGR)	0.00	PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIOMETRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVERSION EFF. PCT	CHAR N2 RETENTION EFF. PCT	NO -----FORMATION EFF. PCT	XN -----FORMATION EFF. PCT	N2 -----FORMATION EFF. PCT
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	NNE(I)
1	1.563	166.	15.02	1321.0	0.00	0.00	.47	35.08	36.33	13.57	85.71	.23	.24	14.04
2	2.479	0.	58.77	1517.1	0.00	0.00	.94	71.77	74.33	27.14	71.43	1.53	1.59	26.98
3	2.964	0.	58.77	1713.1	0.00	0.00	1.40	110.20	114.13	40.71	57.14	2.35	2.43	40.43
4	3.446	223.	58.77	1909.2	0.00	0.00	1.86	150.48	155.86	54.27	42.86	3.19	3.30	53.84
5	3.784	0.	117.53	2105.2	0.00	0.00	2.32	192.76	199.65	67.84	28.57	7.75	8.02	63.41
6	3.993	0.	117.53	2301.3	0.00	0.00	2.79	237.20	245.67	81.41	14.29	9.39	9.72	75.99
7	4.186	0.	117.53	2497.3	14.00	.15	3.25	283.94	294.08	94.98	0.00	11.06	11.45	88.55
8	4.374	0.	117.53	2429.0	0.00	0.00	3.33	285.15	290.24	78.08	21.58	10.93	11.12	67.30
9	4.569	0.	117.53	2360.8	14.00	0.00	3.40	286.36	286.36	61.18	43.16	10.79	10.79	46.04

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CL/DOE COAL COMBUSTION PROGRAM

TYPE OF.COAL ARKADELPHIA HVAB
TEST NO. AA-11-1
DATE 12/9/82

COAL FLOW RATE	(FF)	36.00 LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00 LB/HR
SECONDARY AIR FLOW RATE	(SA)	396.00 LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00 LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54 LB AIR/LB COAL
EXCESS AIR	(EXA)	19.38 PCT
FLUE GAS RECIRCULATION	(FGR)	0.00 PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIO METRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVER-SION EFF. PCT	CHAR N2 REJENTION EFF. PCT	NO -----FORMATION EFF. PCT	XN FORMATION EFF. PCT	N2 FORMATION----- EFF. PCT
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	NNE(I)
1	1.068	396.	15.02	2882.9	11.80	10.00	.01	347.31	441.64	51.13	50.00	2.37	3.01	46.99
2	1.504	0.	119.38	2876.3	0.00	0.00	2.60	388.90	479.40	69.18	31.58	15.64	19.29	49.14
3	1.651	0.	119.38	2869.7	12.00	.01	5.19	444.13	529.54	87.23	13.15	15.55	18.54	68.31
4	1.816	0.	119.38	2789.1	0.00	0.00	5.05	456.97	524.66	89.41	12.69	16.17	18.57	68.74
5	1.985	0.	119.38	2708.5	15.00	.02	4.90	469.57	519.88	91.58	12.24	16.79	18.59	69.17
6	2.157	0.	119.38	2632.2	0.00	0.00	4.60	466.46	507.62	94.20	9.34	17.03	18.53	72.13
7	2.334	0.	119.38	2556.0	14.40	.02	4.30	463.47	495.81	96.82	6.44	17.26	18.46	75.10
8	2.516	0.	119.38	2461.9	0.00	0.00	4.15	454.01	496.74	96.83	6.95	17.06	18.66	74.38
9	2.703	0.	119.38	2367.9	13.60	.02	4.00	444.71	497.65	96.84	7.47	16.86	18.86	73.67

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CE/DOE COAL COMBUSTION PROGRAM

TYPE OF COAL ARKADELPHIA HVAB
TEST NO. AA-11-2
DATE 12/10/82

COAL FLOW RATE	(FF)	36.00	LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00	LB/HR
SECONDARY AIR FLOW RATE	(SA)	360.00	LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00	LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54	LB AIR/LB COAL
EXCESS AIR	(EXA)	9.89	PCT
FLUE GAS RECIRCULATION	(FGR)	0.00	PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIOMETRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVERSION EFF. PCT	CHAR N2 RETENTION EFF. PCT	NO	XN	N2
												------FORMATION EFF. PCT		------
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	NNE(I)
1	1.157	120.	15.02	2515.5	10.60	0.00	.01	80.04	300.14	39.05	42.56	.55	2.04	55.40
2	1.742	240.	46.64	2712.1	0.00	0.00	2.10	177.81	304.81	62.45	27.92	3.05	5.23	66.85
3	1.970	0.	109.89	2908.8	14.10	.01	4.20	299.93	310.64	85.86	13.29	10.30	10.67	76.04
4	2.147	0.	109.89	2821.6	0.00	0.00	4.50	321.78	329.96	84.23	15.81	10.84	11.12	73.08
5	2.329	0.	109.89	2734.4	13.40	0.00	4.80	344.44	350.00	82.61	18.33	11.38	11.56	70.11
6	2.517	0.	109.89	2629.7	0.00	0.00	4.60	340.24	345.73	79.43	21.23	11.35	11.53	67.23
7	2.712	0.	109.89	2525.1	13.60	0.00	4.40	336.14	341.57	76.25	24.13	11.32	11.51	64.36
8	2.912	0.	109.89	2473.2	0.00	0.00	4.42	363.69	377.26	77.09	24.10	12.25	12.70	63.19
9	3.115	0.	109.89	2421.4	13.50	1.00	4.44	391.30	413.04	77.94	24.07	13.17	13.90	62.03

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CE/DOE COAL COMBUSTION PROGRAM

TYPE OF.COAL ARKADELPHIA HVAB
TEST NO. AA-II-3
DATE 12/10/82

COAL FLOW RATE	(FF)	36.00 LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00 LB/HR
SECONDARY AIR FLOW RATE	(SA)	366.00 LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00 LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54 LB AIR/LB COAL
EXCESS AIR	(EXA)	11.47 PCT
FLUE GAS RECIRCULATION	(FGR)	0.00 PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIO METRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVER-SION EFF. PCT	CHAR N2 RETENTION EFF. PCT	NO FORMATION EFF. PCT	XN FORMATION EFF. PCT	N2 FORMATION EFF. PCT
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	NNE(I)
1	1.155	126.	15.02	2580.6	11.20	10.00	.01	171.51	394.47	45.71	38.03	1.17	2.69	59.28
2	1.733	0.	48.23	2641.3	0.00	0.00	.01	145.78	287.28	56.08	32.19	2.83	5.58	62.22
3	2.103	240.	48.23	2702.0	13.00	10.00	.01	120.06	180.09	66.46	26.35'	2.37	3.56	70.09
4	2.380	0.	111.47	2677.2	0.00	0.00	2.41	237.16	256.52	70.00	27.31	9.03	9.77	62.93
5	2.568	0.	111.47	2652.4	13.50	1.50	4.80	388.89	355.56	73.55	28.26	12.94	11.83	59.91
6	2.759	0.	111.47	2561.8	0.00	0.00	4.65	346.79	335.78	70.15	30.60	11.61	11.24	58.16
7	2.956	0.	111.47	2471.1	13.00	.12	4.50	305.45	316.36	66.75	32.94	10.29	10.66	56.40
8	3.158	0.	111.47	2446.3	0.00	0.00	4.50	302.73	321.82	68.71	33.11	10.22	10.86	56.03
9	3.361	0.	111.47	2421.4	13.60	.01	4.50	300.00	327.27	70.68	33.28	10.14	11.06	55.65

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CE/DOE COAL COMBUSTION PROGRAM

TYPE OF.COAL ARKADELPHIA HVAB
TEST NO. AA-11-4
DATE 12/10/82

COAL FLOW RATE	(FF)	36.00 LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00 LB/HR
SECONDARY AIR FLOW RATE	(SA)	366.00 LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00 LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54 LB AIR/LB COAL
EXCESS AIR	(EXA)	11.47 PCT
FLUE GAS RECIRCULATION	(FGR)	0.00 PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIO METRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVER-SION EFF. PCT	CHAR N2 RETENTION EFF. PCT	NO ----FORMATION EFF. PCT----	XN	N2
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	NNE(I)
1	1.082	126.	15.02	2889.8	10.00	10.00	.01	21.44	68.60	70.38	31.71	.15	.47	67.83
2	1.605	0.	48.23	2889.7	0.00	0.00	.01	70.75	141.50	74.86	28.08	1.42	2.84	69.09
3	1.942	0.	48.23	2889.7	12.00	10.00	.01	120.06	214.39	79.34	24.45	2.43	4.33	71.22
4	2.320	0.	48.23	2776.0	0.00	0.00	.61	136.80	211.82	83.85	18.34	2.70	4.19	77.47
5	2.708	240.	48.23	2662.3	13.80	.14	1.20	154.55	209.09	88.37	12.23	2.99	4.04	83.73
6	3.005	0.	111.47	2509.9	0.00	0.00	2.10	192.86	226.19	90.86	10.98	7.58	8.89	80.13
7	3.204	0.	111.47	2357.4	13.40	.01	3.00	235.00	245.00	93.36	9.73	8.82	9.19	81.08
8	3.410	0.	111.47	2326.1	0.00	0.00	3.15	231.93	247.[illegible]5	95.67	7.47	8.64	9.21	83.33
9	3.617	0.	111.47	2294.7	14.00	0.00	3.30	228.81	249.15	97.99	5.20	8.47	9.22	85.57

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CE/DOE COAL COMBUSTION PROGRAM

TYPE OF.COAL ARKADELPHIA HVAB
TEST NO. AAIII-1
DATE 12/13/82

COAL FLOW RATE	(FF)	36.00 LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00 LB/HR
SECONDARY AIR FLOW RATE	(SA)	319.00 LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00 LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54 LB AIR/LB COAL
EXCESS AIR	(EXA)	-.91 PCT
FLUE GAS RECIRCULATION	(FGR)	0.00 PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIOMETRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVERSION EFF. PCT	CHAR N2 RETENTION EFF. PCT	NO FORMATION EFF. PCT	XN FORMATION EFF. PCT	N2 FORMATION EFF. PCT
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	NNE(I)
1	1.202	131.	15.02	2433.3	14.00	7.70	.01	31.44	480.23	46.62	34.57	.21	3.26	62.16
2	1.799	0.	49.54	2568.1	0.00	0.00	.01	62.89	291.57	61.44	25.41	1.26	5.85	68.74
3	2.161	0.	49.54	2702.9	17.60	3.30	.01	94.33	102.91	76.25	16.25	1.94	2.11	81.64
4	2.552	188.	49.54	2622.6	0.00	0.00	2.81	150.87	158.29	83.60	13.52	2.72	2.85	83.63
5	2.858	0.	99.09	2542.3	13.60	.15	5.60	227.92	233.77	90.94	10.79	6.53	6.70	82.52
6	3.073	0.	99.09	2560.8	0.00	0.00	4.25	239.10	241.79	93.33	8.80	7.47	7.55	83.64
7	3.285	0.	99.09	2579.3	17.20	.30	2.90	248.62	248.62	95.72	6.82	8.41	8.41	84.77
8	3.500	0.	99.09	2479.9	0.00	0.00	2.10	238.10	254.76	96.57	5.84	8.41	9.00	85.15
9	3.722	0.	99.09	2380.5	16.00	.50	1.30	228.43	260.41	97.41	4.87	8.42	9.60	85.54

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CC/DOE COAL COMBUSTION PROGRAM

TYPE UF.COAL ARKADELPHIA HVBB
TEST NO. AA111-2
DATE 12/14/82

COAL FLOW RATE	(FF)	36.00 LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00 LB/HR
SECONDARY AIR FLOW RATE	(SA)	360.00 LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00 LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54 LB AIR/LB COAL
EXCESS AIR	(EXA)	9.89 PCT
FLUE GAS RECIRCULATION	(FGR)	0.00 PCT

PORT NO. (I)	CUM. RESIDENCE TIME, SEC. TT(I)	SEC. AIR RING LB/HR S(I)	STOICHIO METRY PS(I)	CORRECTED GAS TEMP F. CT(I)	CO2 PCT CO2(I)	CO PCT CO(I)	O2 PCT O2(I)	NO@3 PCT-O2 PPM NO3(I)	NOX@3 PCT-O2 PPM NX3(I)	CONVER-SION EFF. PCT CE(I)	CHAR N2 RETENTION EFF. PCT NRE(I)	NO -----FORMATION EFF. PCT----- NOE(I)	XN NSE(I)	N2 NNE(I)
1	1.104	131.	15.02	2840.6	13.00	9.50	6.09	38.22	168.98	9.15	63.84	.18	.82	35.34
2	1.644	0.	49.54	2858.6	0.00	0.00	3.05	63.50	117.82	37.74	48.17	1.05	1.95	49.88
3	1.989	0.	49.54	2876.7	17.80	3.70	.01	81.47	81.47	66.33	32.50	1.65	1.65	65.85
4	2.366	229.	49.54	2751.3	0.00	0.00	2.88	124.17	126.66	78.94	22.03	2.21	2.26	75.71
5	2.654	0.	109.89	2625.9	14.60	.04	5.75	182.95	188.85	91.56	11.56	5.73	5.91	82.53
6	2.844	0.	109.89	2612.3	0.00	0.00	3.98	203.52	206.17	92.62	9.94	7.12	7.21	82.85
7	3.034	0.	109.89	2598.7	17.40	0.00	2.20	220.21	220.21	93.68	8.32	8.51	8.51	83.17
8	3.229	0.	109.89	2476.9	0.00	0.00	2.50	252.49	252.97	95.20	7.08	9.62	9.64	83.28
9	3.432	0.	109.89	2355.0	16.50	.04	2.80	285.82	286.81	96.73	5.84	10.72	10.76	83.40

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CE/DOE COAL COMBUSTION PROGRAM

TYPE OF.COAL ARKADELPHIA HVAB
TEST NO. AAIII-3
DATE 12/14/82

COAL FLOW RATE	(FF)	36.00 LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00 LB/HR
SECONDARY AIR FLOW RATE	(SA)	396.00 LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00 LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54 LB AIR/LB COAL
EXCESS AIR	(EXA)	19.38 PCT
FLUE GAS RECIRCULATION	(FGR)	0.00 PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIO METRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVER-SION EFF. PCT	CHAR N2 RETENTION EFF. PCT	NO FORMATION EFF. PCT	XN FORMATION EFF. PCT	N2 FORMATION EFF. PCT
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	MNE(I)
1	1.257	94.	15.02	2283.8	10.00	3.80	1.05	171.45	406.07	12.29	67.24	1.11	2.63	30.13
2	1.937	0.	39.79	2456.0	0.00	0.00	.53	101.13	325.38	28.20	72.74	1.53	4.91	22.35
3	2.418	0.	39.79	2628.3	13.50	4.30	.01	34.30	248.69	44.11	78.24	.55	3.98	17.78
4	2.920	302.	39.79	2678.6	0.00	0.00	2.96	139.65	274.31	54.12	58.24	1.96	3.85	37.91
5	3.255	0.	119.38	2728.9	12.90	.05	5.90	286.09	309.93	64.13	38.24	9.41	10.20	51.57
6	3.431	0.	119.38	2614.9	0.00	0.00	4.65	308.26	324.77	64.54	40.63	10.98	11.57	47.80
7	3.614	0.	119.38	2500.9	15.70	.03	3.40	327.27	337.50	64.96	43.01	12.56	12.95	44.04
8	3.803	0.	119.38	2397.8	0.00	0.00	3.05	323.40	330.92	68.77	37.38	12.69	12.98	49.63
9	3.999	0.	119.38	2294.7	15.50	.01	2.70	319.67	324.59	72.58	31.75	12.82	13.02	55.23

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CE/DOE COAL COMBUSTION PROGRAM

TYPE OF.COAL ARKADELPHIA, HVAB
TEST NO. AAIII-4
DATE 12/14/82

COAL FLOW RATE	(FF)	36.00 LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00 LB/HR
SECONDARY AIR FLOW RATE	(SA)	452.80 LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00 LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54 LB AIR/LB COAL
EXCESS AIR	(EXA)	34.35 PCT
FLUE GAS RECIRCULATION	(FGR)	0.00 PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIO METRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVER-SION EFF. PCT	CHAR N2 RETENTION EFF. PCT	NO -----FORMATION EFF. PCT	XN -----FORMATION EFF. PCT	N2 -----FORMATION EFF. PCT
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	NNE(I)
1	1.108	132.	15.02	2877.[illegible]	11.40	3.20	.01	137.21	17.15	57.17	35.05	.94	.12	64.83
2	1.631	0.	49.75	2877.5	0.00	0.00	.01	92.19	12.86	60.78	43.06	1.86	.26	56.60
3	1.967	0.	49.75	2877.7	11.40	4.40	.01	47.17	8.58	64.39	51.07	.96	.17	48.75
4	2.342	321.	49.75	2755.9	0.00	0.00	3.86	144.36	131.23	76.44	31.68	2.44	2.22	66.09
5	2.612	0.	134.35	2634.0	11.20	.01	7.70	297.74	324.81	88.48	12.30	9.83	10.72	76.98
6	2.772	0.	134.35	2514.3	0.00	0.00	6.45	309.28	340.21	92.36	8.52	11.20	12.32	79.17
7	2.937	0.	134.35	2394.5	13.40	.00	5.20	318.99	353.16	96.24	4.73	12.57	13.92	81.35
8	3.109	0.	134.35	2337.7	0.00	0.00	5.50	322.26	348.39	96.94	5.01	12.46	13.47	81.51
9	3.281	0.	134.35	2280.9	13.00	0.00	5.80	325.66	343.42	97.65	5.29	12.36	13.03	81.68

CMHF DATA REDUCTION PROGRAM
PROJECT NUMBER 900436
CE/DOE COAL COMBUSTION PROGRAM

TYPE OF.COAL ARKADELPHIA HVAB
TEST NO. AAIV-1
DATE 12/16/82

COAL FLOW RATE	(FF)	36.00 LB/HR
PRIMARY AIR FLOW RATE	(TA+SCA)	57.00 LB/HR
SECONDARY AIR FLOW RATE	(SA)	396.00 LB/HR
FLUE GAS RECIRCULATION	(GRG+GRA)	0.00 LB/HR
THEORITICAL AIR REQUIRED	(THA)	10.54 LB AIR/LB COAL
EXCESS AIR	(EXA)	19.38 PCT
FLUE GAS RECIRCULATION	(FGR)	0.00 PCT

PORT NO.	CUM. RESIDENCE TIME, SEC.	SEC. AIR RING LB/HR	STOICHIO METRY	CORRECTED GAS TEMP F.	CO2 PCT	CO PCT	O2 PCT	NO@3 PCT-O2 PPM	NOX@3 PCT-O2 PPM	CONVER-SION EFF. PCT	CHAR N2 RETENTION EFF. PCT	NO -----FORMATION EFF. PCT	XN FORMATION EFF. PCT	N2 FORMATION-----EFF. PCT
(I)	TT(I)	S(I)	PS(I)	CT(I)	CO2(I)	CO(I)	O2(I)	NO3(I)	NX3(I)	CE(I)	NRE(I)	NOE(I)	NSE(I)	NNE(I)
1	1.147	132.	15.02	2546.4	11.00	10.00	.01	25.73	197.24	47.79	44.01	.18	1.35	54.64
2	1.726	0.	49.81	2598.0	0.00	0.00	.01	45.02	180.09	51.75	34.83	.90	3.58	61.58
3	2.096	0.	49.81	2649.7	12.40	10.00	.01	64.32	162.93	55.70	25.66	1.29	3.26	71.08
4	2.495	264.	49.81	2658.8	0.00	0.00	2.46	140.74	211.11	71.48	19.40	2.55	3.83	76.76
5	2.782	0.	119.38	2668.0	14.00	.04	4.90	240.37	273.91	87.25	13.15	8.57	9.77	77.08
6	2.956	0.	119.38	2616.4	0.00	0.00	3.95	232.26	292.96	90.35	10.26	8.79	11.09	78.66
7	3.134	0.	119.38	2564.7	16.00	.04	3.00	225.00	310.00	93.45	7.36	9.01	12.41	80.23
8	3.313	0.	119.38	2518.2	0.00	0.00	3.00	257.50	305.00	94.97	5.39	10.32	12.23	82.39
9	3.496	0.	119.38	2471.7	16.00	.01	3.00	290.00	300.00	96.49	3.42	11.64	12.04	84.55

APPENDIX D

CHAR COMBUSTION MODEL

The computer model, formulated to simulate plug flow char combustion in the CMHF, was based on mathematical expressions derived by Field and co-workers at BCURA (21). This particular model was chosen because the laminar-flow DTFS satisfies the plug-flow requirements whereby the reaction products are time-resolved along the furnace distance.

This model is versatile enough to take into account certain parameter changes, such as the percentage of excess O_2, anisothermal temperature profile in the reaction zone, particle size distributions, and reaction mechanism factor. Reaction rates are governed by diffusional and surface reaction rate coefficients, depending on particle size and temperature.

The basic model formulation is as follows. First, a definition of symbols is given.

y_j	=	initial diameter of coal particles
x_j	=	diameter of char particles after devolatilization
α	=	swelling factor
w_j	=	fraction of unburned char at any particular time
Σw_j	=	1.0
u_j	=	weight of residual char at any particular time per unit initial weight of char
U	=	Σu_j where U is unburned char in whole suspension.

The rate of change of weight fraction u_j is given by:

$$du_j/dt = -S_j q_j \qquad \text{(D-1)}$$

where S_j = geometric surface area of each particular fraction per unit weight of initial char, (cm^2/g), and

q_j = rate of carbon removal per unit surface area, (g/cm^2 sec.)

Assuming spherical particles

$$S_j = (6\, w_j \alpha^2)/(C_f \rho_f y_f) \qquad \text{(D-2)}$$

where C_f is a fraction of moisture and ash-free fuel after devolatilization
ρ_f is apparent density of moisture and ash-free fuel, (g/cm^3)

$$q_j = [P_g(U)]/(1/K_{DIFF} + 1/K_S) \qquad \text{(D-3)}$$

K_{DIFF} is diffusional reaction rate coefficient, $(g/cm^2$ sec. atm.), and

$$K_{DIFF} = (24\, \emptyset\, D)/(R'Tx_j) \qquad \text{(D-4)}$$

where $\emptyset$ is mechanism factor, defined as the ratio of moles of carbon consumed to moles of reactant gas transported to the surface.

R' is gas constant, $(82.06$ atm cm^3/mole °K)
T is gas temperature, (°K)
D is binary diffusion coefficient at 1 atm. for O_2-N_2 medium, $(cm^2$/sec)
K_s is surface reaction rate coefficient, $(g/cm^2$ sec. atm.)

$$K_S = A \exp(-E/RT) \qquad \text{(D-5)}$$

where E is activation energy, (cal/mole)
R is gas constant, (1.986 cal/mole °K)
A is frequency factor, $(g/cm^2$ sec. atm.)
$P_g(U)$ is a function of oxygen concentration

$$P_g(U) = [(c\, U + e)/(1 + e)]\, (P_o) \qquad \text{(D-6)}$$

$$\text{where } c = \frac{O_2 \text{ required to burn char from raw fuel}}{O_2 \text{ required to burn raw fuel}}$$

e is excess oxygen
P_o is initial partial pressure of O_2 in combustion medium.

Assuming constant particle density and burning from the outside, this leads to the final equation form:

$$du_j/dt = -[(u_j/w_j)^{2/3} S_j P_g(U)]/[(u_j/w_j)^{1/3}/K_{DIFF} + 1/K_S] \qquad \text{(D-7)}$$

Equation (D-7) represents a series of differential equations for all particle sizes for each fraction. The only variables are time, particle size distribution of each fraction, oxygen concentration, and the physical properties of the fuel.

A sample of a typical run is given below (Table D-1).

<u>Input</u>

1. Particle size distribution of commercial regular grind (∿ 70%-200% mesh) having a Rosin-Rammler dispersion index of 0.936. The representation of such a distribution by 10 mono-size fractions is shown in the computer output.

2. Swelling factor (α): 1.34

3. Apparent density (ρ_f): 1.30 g/cm^3 (dry-ash-free basis).

4. Fraction of moisture and ash-free char remaining after devolatilization (C_f): 0.618

5. Temperature Profile (see output).

6. Excess O_2: 0.20

7. O_2 Partial Pressure (P_o): 0.21 atm

8. Mechanism Factor (Ø): 2.0

9. Activation Energy (E): 23320.0 cal/mole

10. Frequency Factor (A): 80.0 g/cm^2-sec-atm.

11. Combustion Mode: Shrinking core

<u>Output</u>

The terms used in the output are explained as follows:

PSAD:	Particle size diameter, (cm)
KDIFF:	Diffusional reaction rate coefficient, (g/cm^2 sec atm.)
SI:	Particle geometric surface area, (cm^2/g)
WF:	Fractional weight in each size cut
PARTICLES:	Number of particles

Values of the above terms are the average values per size fraction

KS:	Surface reaction rate coefficient, (g/cm^2 sec. atm.)
CC:	Percent carbon in the char

SIZE FRACTION OF CHAR BURNED OFF: An "o" indicates incompleteness of combustion of a given size fraction. A "numerical value" indicates completeness of combustion of a given size fraction.

TABLE D-1

TEST NO.:AA-11-1
FUEL:ARKADELPHIA ALABAMA
GAS:AIR--MEASURED FUEL DENSITY

PSAD	KDIFF	S1	WF	PARTICLES
.0030	.4726	3181.51	.5338	.6885E+08
.0090	.1575	465.55	.2343	.1119E+07
.0151	.0945	126.12	.1142	.1178E+06
.0211	.0675	48.87	.0574	.2158E+05
.0271	.0525	19.46	.0294	.5199E+04
.0332	.0430	8.26	.0152	.1477E+04
.0392	.0364	3.66	.0080	.4685E+03
.0452	.0315	1.67	.0042	.1610E+03
.0513	.0278	.78	.0022	.5876E+02
.0573	.0249	.38	.0012	.2249E+02

KS	CC
.143285	95.22

TIME(SEC)	FRACTION OF CHAR UNBURNED	PARTIAL PRESSURE OF OXYGEN	TEMPERATURE (DEG K)	TOTAL COMBUSTION EFFICIENCY	SIZE FRACTION OF CHAR BURNED OFF	PCT. C IN ASH
1.4341	.8189	.1260	1855.6	49.39	0 0 0 0 0 0 0 0 0 0	94.23
1.4373	.6898	.1115	1855.5	57.37	0 0 0 0 0 0 0 0 0 0	93.22
1.4404	.5946	.1009	1855.4	63.24	0 0 0 0 0 0 0 0 0 0	92.22
1.4435	.5235	.0929	1855.3	67.65	0 0 0 0 0 0 0 0 0 0	91.25
1.4466	.4692	.0868	1855.2	71.00	0 0 0 0 0 0 0 0 0 0	90.34
1.4498	.4276	.0821	1855.1	73.57	0 0 0 0 0 0 0 0 0 0	89.50
1.4529	.3958	.0785	1855.0	75.54	0 0 0 0 0 0 0 0 0 0	88.75
1.4560	.3714	.0756	1854.9	77.05	0 0 0 0 0 0 0 0 0 0	88.10
1.4591	.3531	.0737	1854.8	78.18	0 0 0 0 0 0 0 0 0 0	87.55
1.4623	.3394	.0722	1854.7	79.0[illegible]	0 0 0 0 0 0 0 0 0 0	87.1[illegible]
1.4654	.3299	.0711	1854.6	79.61	1 0 0 0 0 0 0 0 0 0	8[illegible]
1.4685	.3216	.0702	1854.5	80.11	1 0 0 0 0 0 0 0 0 0	86.51
1.4716	.3140	.0693	1854.4	80.59	1 0 0 0 0 0 0 0 0 0	86.22
1.4748	.3065	.0685	1854.3	81.06	1 0 0 0 0 0 0 0 0 0	85.93
1.4779	.2991	.0677	1854.2	81.51	1 0 0 0 0 0 0 0 0 0	85.63
1.4810	.2920	.0669	1854.1	81.95	1 0 0 0 0 0 0 0 0 0	85.34
1.4841	.2852	.0661	1854.0	82.38	1 0 0 0 0 0 0 0 0 0	85.05
1.4873	.2785	.0654	1853.9	82.79	1 0 0 0 0 0 0 0 0 0	84.73
1.4904	.2720	.0646	1853.8	83.19	1 0 0 0 0 0 0 0 0 0	84.42
1.4935	.2657	.0639	1853.7	83.58	1 0 0 0 0 0 0 0 0 0	84.11
1.4966	.2596	.0632	1853.7	83.95	1 0 0 0 0 0 0 0 0 0	83.80
1.4998	.2537	.0626	1853.6	84.32	1 0 0 0 0 0 0 0 0 0	83.49
1.5029	.2480	.0619	1853.5	84.67	1 0 0 0 0 0 0 0 0 0	83.17
1.5060	.2425	.0613	1853.4	85.02	1 0 0 0 0 0 0 0 0 0	82.85
1.5091	.2371	.0607	1853.3	85.35	1 0 0 0 0 0 0 0 0 0	82.53
1.5123	.2319	.0601	1853.2	85.67	1 0 0 0 0 0 0 0 0 0	82.21
1.5154	.2268	.0596	1853.1	85.98	1 0 0 0 0 0 0 0 0 0	81.88
1.5216	.2170	.0585	1853.1	86.59	1 0 0 0 0 0 0 0 0 0	81.21
1.5279	.2077	.0574	1852.9	87.16	1 0 0 0 0 0 0 0 0 0	80.54
1.5341	.1991	.0564	1852.8	87.70	1 0 0 0 0 0 0 0 0 0	79.86
1.5404	.1909	.0555	1852.7	88.20	1 0 0 0 0 0 0 0 0 0	79.18
1.5466	.1833	.0547	1852.5	88.67	1 0 0 0 0 0 0 0 0 0	78.50
1.5529	.1761	.0539	1852.4	89.12	1 0 0 0 0 0 0 0 0 0	77.82
1.5591	.1693	.0531	1852.2	89.54	1 0 0 0 0 0 0 0 0 0	77.14
1.5654	.1630	.0524	1852.1	89.93	1 0 0 0 0 0 0 0 0 0	76.46
1.5716	.1571	.0517	1851.9	90.29	1 0 0 0 0 0 0 0 0 0	75.79
1.5779	.1515	.0511	1851.8	90.63	1 0 0 0 0 0 0 0 0 0	75.12
1.5841	.1463	.0505	1851.7	90.96	1 0 0 0 0 0 0 0 0 0	74.46
1.5966	.1366	.0494	1851.5	91.56	1 0 0 0 0 0 0 0 0 0	73.14
1.6091	.1283	.0485	1851.2	92.07	1 0 0 0 0 0 0 0 0 0	71.87
1.6216	.1210	.0477	1850.9	92.52	1 0 0 0 0 0 0 0 0 0	70.69
1.6341	.1149	.0470	1850.7	92.90	1 0 0 0 0 0 0 0 0 0	69.60
1.6591	.1053	.0459	1850.4	93.49	1 2 0 0 0 0 0 0 0 0	67.72
1.6841	.0976	.0450	1847.8	93.97	1 2 0 0 0 0 0 0 0 0	66.03
1.7091	.0905	.0443	1841.0	94.41	1 2 0 0 0 0 0 0 0 0	64.33
1.7341	.0841	.0435	1834.1	94.80	1 2 0 0 0 0 0 0 0 0	62.62
1.7591	.0782	.0429	1827.3	95.17	1 2 0 0 0 0 0 0 0 0	60.91
1.7841	.0729	.0423	1820.5	95.50	1 2 0 0 0 0 0 0 0 0	59.21
1.8341	.0632	.0412	1813.7	96.10	1 2 0 0 0 0 0 0 0 0	55.73
1.8841	.0554	.0403	1800.2	96.58	1 2 0 0 0 0 0 0 0 0	52.45
1.9341	.0491	.0396	1787.1	96.96	1 2 0 0 0 0 0 0 0 0	49.47
1.9841	.0443	.0391	1773.9	97.26	1 2 0 0 0 0 0 0 0 0	46.89
2.0341	.0406	.0387	1760.8	97.48	1 2 3 0 0 0 0 0 0 0	44.84
2.0841	.0378	.0383	1748.3	97.66	1 2 3 0 0 0 0 0 0 0	42.97
2.1341	.0351	.0380	1735.9	97.83	1 2 3 0 0 0 0 0 0 0	41.15
2.1841	.0326	.0378	1723.5	97.98	1 2 3 0 0 0 0 0 0 0	39.39
2.2341	.0304	.0375	1711.3	98.12	1 2 3 0 0 0 0 0 0 0	37.69
2.2841	.0283	.0373	1699.4	98.25	1 2 3 0 0 0 0 0 0 0	36.07
2.3341	.0265	.0371	1687.5	98.36	1 2 3 0 0 0 0 0 0 0	34.52
2.3841	.0246	.0369	1675.5	98.47	1 2 3 0 0 0 0 0 0 0	33.06
2.4341	.0233	.0367	1661.2	98.56	1 2 3 0 0 0 0 0 0 0	31.69
2.4841	.0219	.0366	1646.8	98.64	1 2 3 0 0 0 0 0 0 0	30.42
2.5341	.0207	.0364	1632.5	98.72	1 2 3 0 0 0 0 0 0 0	29.25
2.5841	.0197	.0363	1618.2	98.78	1 2 3 0 0 0 0 0 0 0	28.16
2.6341	.0187	.0362	1604.0	98.84	1 2 3 0 0 0 0 0 0 0	27.16
2.6841	.0179	.0361	1589.8	98.90	1 2 3 0 0 0 0 0 0 0	26.24
2.7341	.0171	.0360	1575.6	98.94	1 2 3 0 0 0 0 0 0 0	25.40

END OF PROBLEM

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