DRAFT DOE/PC/79653--T9

Advanced Combustion System for Industrial Boilers

Quarterly Technical Progress Report

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Prepared By:

Richard C. Attig
John P. Foote
William P. Millard
Roy J. Schulz
Charles L. Wagoner

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1.0 EXECUTIVE SUMMARY

The contract start date was June 11, 1987. Contract completion date is September 11, 1990. This is the second quarterly report. Highlights of activities during the period of August 1 through October 31, 1987 are the subject of this report.

The purpose of this project is to develop an advanced coal-combustion system for industrial boilers. With the new combustion system, coal could be used to replace oil and possibly gas as fuel for many industrial boilers.

The advanced combustion system is comprised of several parts:

* a new burner-design concept for coal fuels, developed from the familiar gas turbine combustor-can designs that have proven efficient, reliable, durable, and safe for the combustion of liquid fuel oils,
* a coal storage and dense-phase feed system for injecting clean, ultrafine pulverized coal into the burner at a low velocity, and
* an automatic control system based on feedback from low-cost automotive combustion-quality transducers.

A cold flow model of an initial phase of the new burner design and the associated laser flow-visualization techniques were developed during this quarter. A series of modifications of the initial cold flow model will be tested to establish details of design for the new burner. Also a 200 hp firetube boiler has been installed and tested using number 2 oil as a fuel. This boiler will be used for future combustion testing with the new burner and ultrafine pulverized coal. Additionally an ultrafine-coal injector has been designed which will be evaluated separately as a replacement for the oil gun in the firetube boiler. Two tons of deep-cleaned, ultrafine coal were received for initial tests with the coal injector.

2.0 INTRODUCTION

In the United States, the use of coal dominates the market for steam generation. However, almost all of it is used in utility and large industrial boilers where the final coal preparation, i.e. crushing and/or grinding, is done on site. The development of coal slurry and ultrafine cleaned coal fuels provides an opportunity for increased use of coal in smaller boilers, heaters and other applications. Coal preparation and handling at the utilization site can be minimized or eliminated. In some respects feeding can be made somewhat similar to feeding oil, which is a major fuel in this market.

Ultrafine coal has an excellent potential for efficient and clean burning in small combustion chambers. However, successful utilization of dry ultrafine coal will require advancing the technology of controlled coal feeding and coal combustion at low rates of coal flow.

The objective of the DOE contract with The University of Tennessee Space Institute (UTSI) is to develop and test an advanced coal combustion system for boilers used in industrial applications. The combustion system will be sized to meet the thermal input range of $6x10^6$ Btu/hr and other performance goals identified in Section 1.3.1 of PRDA #DE-RA22-86PC90259. An optional phase will include scale up to a thermal input of about $30x10^6$ Btu/hr. The combustion system proposed will have several features including: a) dense phase transport of dry, ultrafine coal using a carrier gas such as CO_2, N_2, combustible gas, etc., b) a novel burner design adapted from commercial gas turbine practice, and designed to facilitate flexible introduction of air for controlled combustion and, c) a computer based control system to permit combustion of the ultrafine coals, which have significantly wider variation in properties than No. 2 fuel oil or natural gas typically used in these applications. The new burner design is related to gas turbine combustor configuration by the techniques used to stage combustion, and control combustion temperature through the use of staged, tangential inflow (swirl). Similar systems developed for gas turbines are efficient and compact for combustion of fuel oil sprays. We believe this design has a potential for commercial applications. The UTSI design provides for staged air introduction with swirl control. The program is being supported by limited cold flow modeling.

The program consists of four tasks:

1) Cold flow modeling to visually evaluate burner gas flow fields to provide input into experimental burner efforts.

2) Small scale burner tests (~ 6×10^6 Btu/hr) to establish operating and performance characteristics of the base design, to optimize the design, and to evaluate several coals over a range of conditions. A dense phase coal feed system will be developed. A control system will also be developed in this task.

3) Design, fabricate and evaluate a combustor system firing into a larger fire tube industrial boiler (~ 30×10^6 Btu/hr), using the results of the modeling and small scale burner tests (optional phase).

4) The final task consists of project management and reporting activities.

3.0 EQUIPMENT DESCRIPTION

3.1 Task 1: Cold Flow Modeling

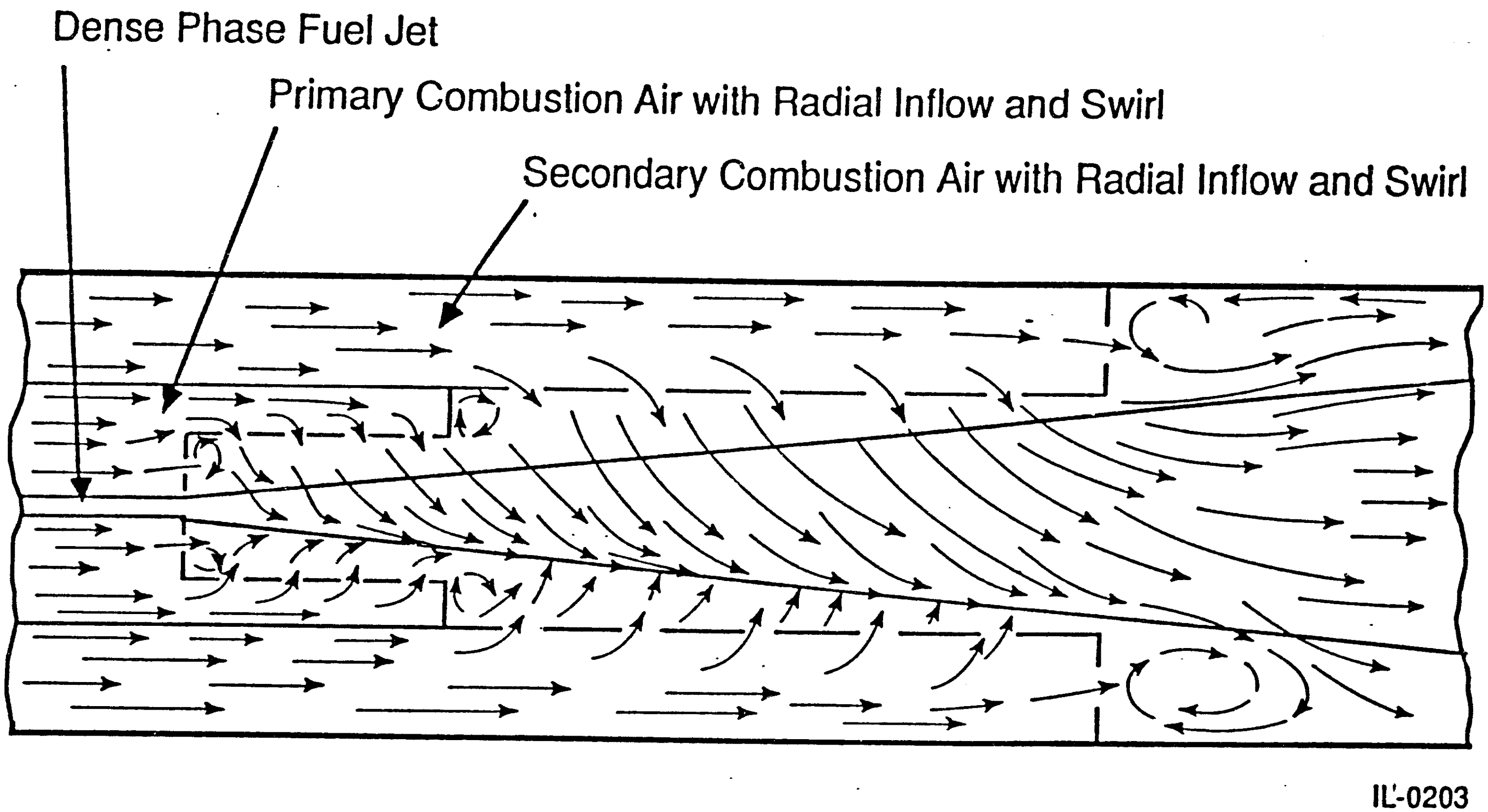
The major objective of this study is to develop a new coal-fired burner design for application to thermal input ranges of 2-6x10^6 Btu/hr and optionally, up to 30x10^6 Btu/hr. A relatively simple burner, based on the coal-fired injector used in an MHD combustor has been designed and will be tested as a replacement for the oil gun in the Cleaver-Brooks burner. The air distribution system will be left intact.

A second design, based on a turbine combustor-can concept will also be developed. The concept is shown schematically on Figure 3.1.1. This concept will be cold-flow modeled, using an acrylic plastic model, initially with three stages for introducing combustion air flow. The model will be operated while varying the air injection geometry, flow rates and velocities, while visually observing the model performance through use of dyes and other visual techniques.

A cold flow model of the combustor-can has been developed. Figure 3.1.2 shows a schematic of the burner sections and the tank into which the model burner exhausts. The burner sections shown are extended; the real burner and the final model configuration are expected to have much shorter segments.

3.2 Task 2: Small Scale Burner Development

A Cleaver-Brooks boiler will serve as a site for the future test series during development of the small-scale advanced coal burner. Figure 3.2.1 illustrates a typical configuration for Cleaver-Brooks boilers. A 200 hp boiler with a similar configuration has been installed during this quarterly period at The Energy Conversion Facility of UTSI. Figure 3.2.2 is a photograph showing the current status of the UTSI facility. Details of the Cleaver-Brooks boiler were presented in the first quarterly report.



Schematic Illustrating the Time-Average Structure of the Fuel Jet Mixing and Burning Flow Field in the UTSI Pulverized Coal Burner Design.

Figure 3.1.1

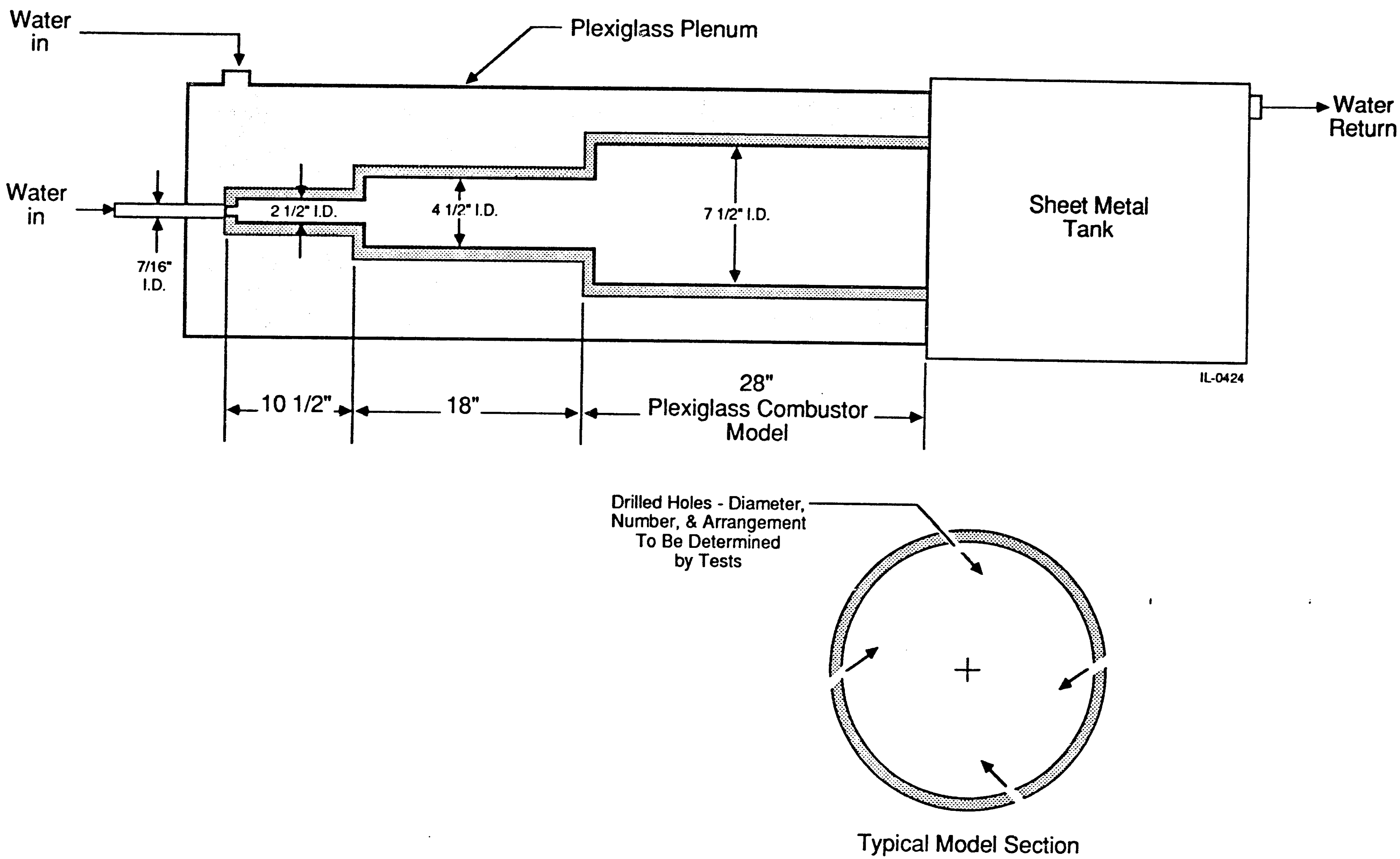


Figure 3.1.2 General Arrangement of UTSI Coal-Flow Burner Model

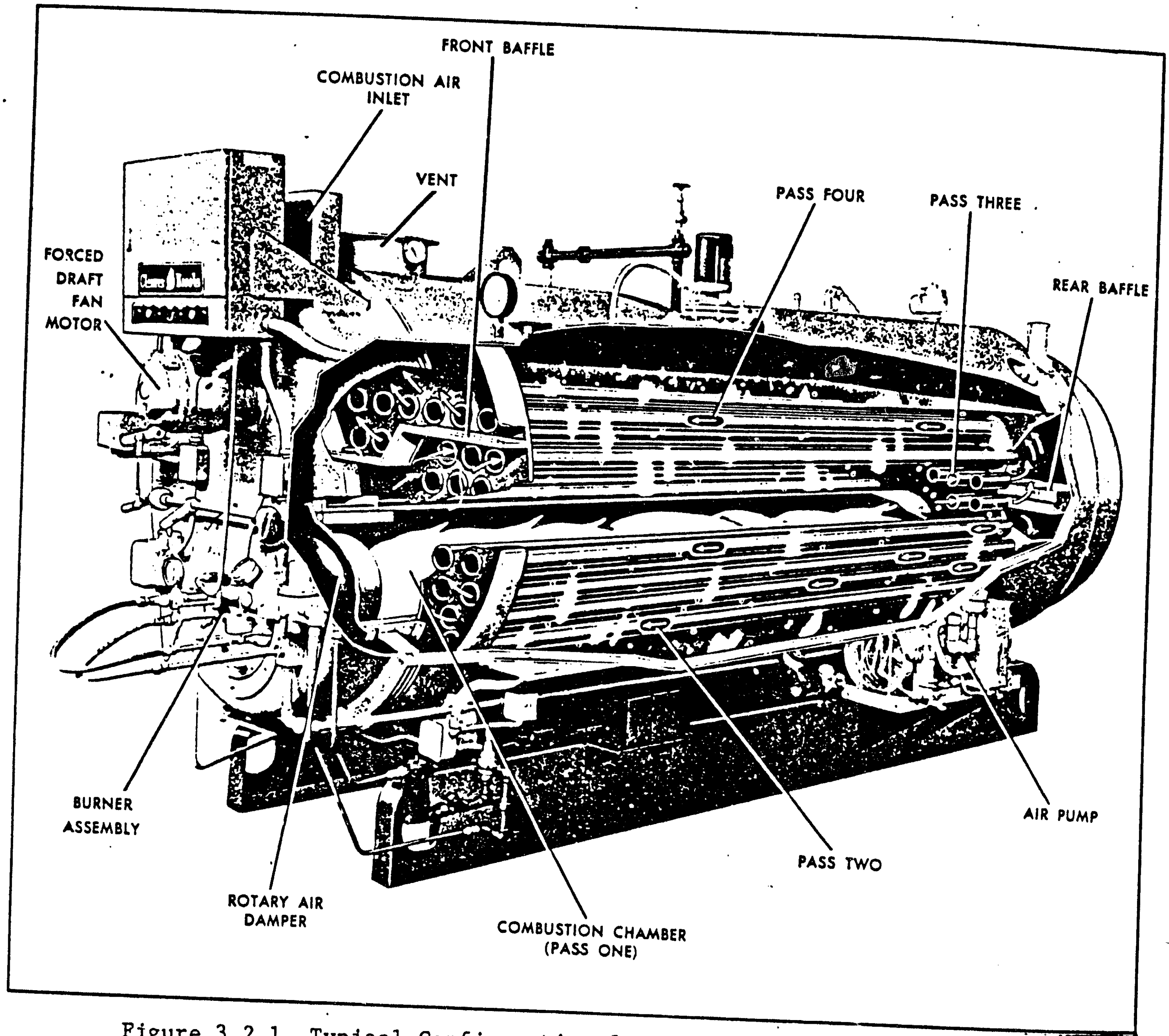


Figure 3.2.1 Typical Configuration for Cleaver-Brooks Firetube Boilers

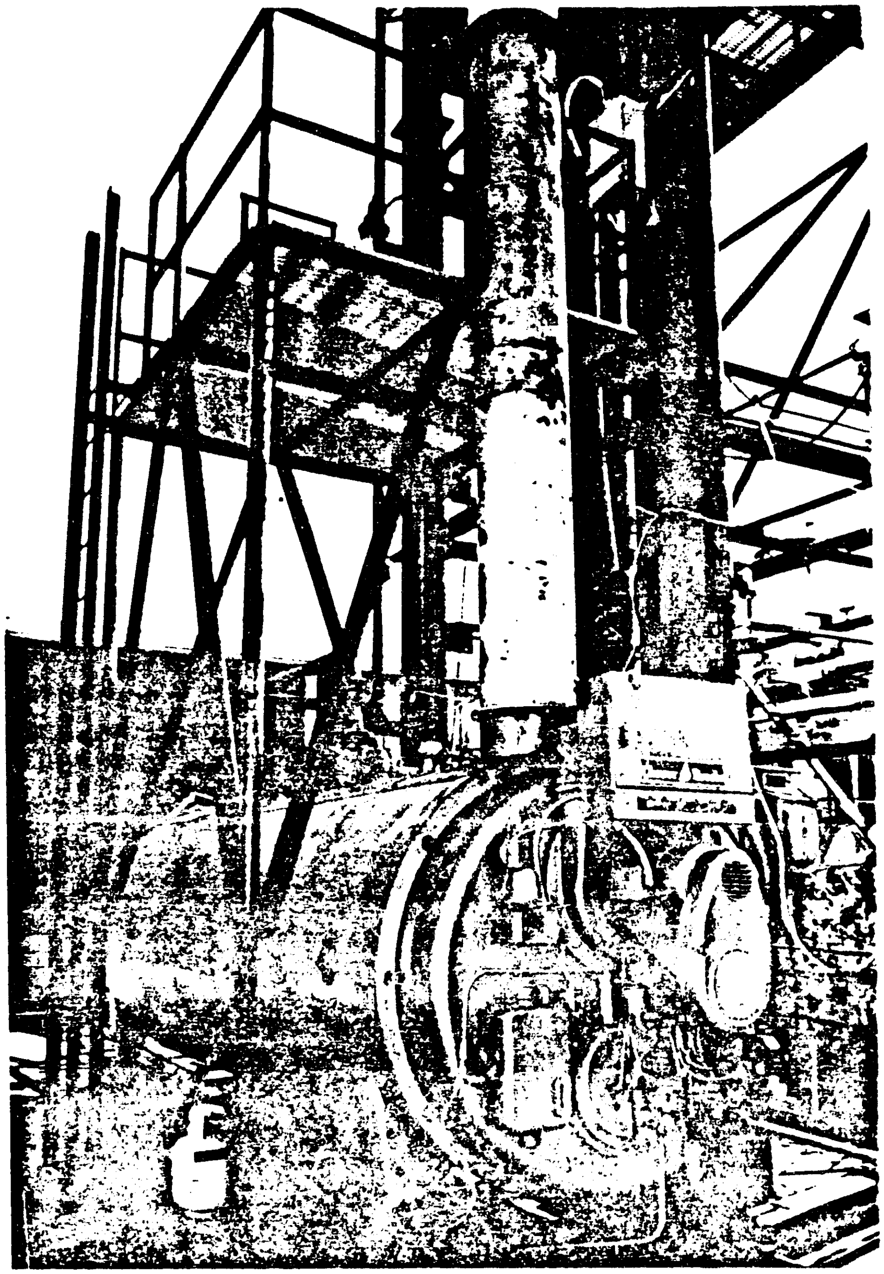


Figure 3.2.2 200 HP Cleaver-Brooks Firetube Boiler Installed at UTSI Test Site

4.0 RESULTS

4.1 Task 1: Cold Flow Modeling

The design of the cold flow model and the flow circuit in which it is installed, were completed. Components for fabricating the model and flow circuit were purchased. This includes plexiglas (R) tubing, aluminum plate, valves and flowmeters, screws, bolts, glue, and other sealants. The model and the flow circuit were fabricated as shown schematically in Figure 3.1.2, and in the photographs in Figures 4.1.1, 4.1.2, and 4.1.3. An argon laser was selected for flow visualization and was installed, aligned and used to illuminate the flow. A fluorescent dye was selected and its feed and injection system were designed and fabricated. The dye is stimulated by a sheet laser beam in the experiments. The dye was added to the central jet-like stream that simulates the fuel flow. This illumination shows the central jet's location in the burner section, and its spreading or mixing rate. Also, the fluctuations and stability of the jet flow are closely observable when testing.

Flow rates were determined for the model burner testing, and preliminary estimates were made of the swirl required. Swirl ports were put into the first burner section. Preliminary flows were established in order to become familiar with model burner flow system behavior.

Cold flow testing was performed with the first (smallest diameter) burner section connected directly to the tank. The experiments are designed to determine how swirl flow, distributed along the length of the burner section, will stabilize the fuel jet on the centerline of the system and control its mixing rate. The first experiments showed that the length of the first section will be about 1 to 1-1/2 diameters in length. Further experiments are planned in order to determine the best distribution (length-wise) for the

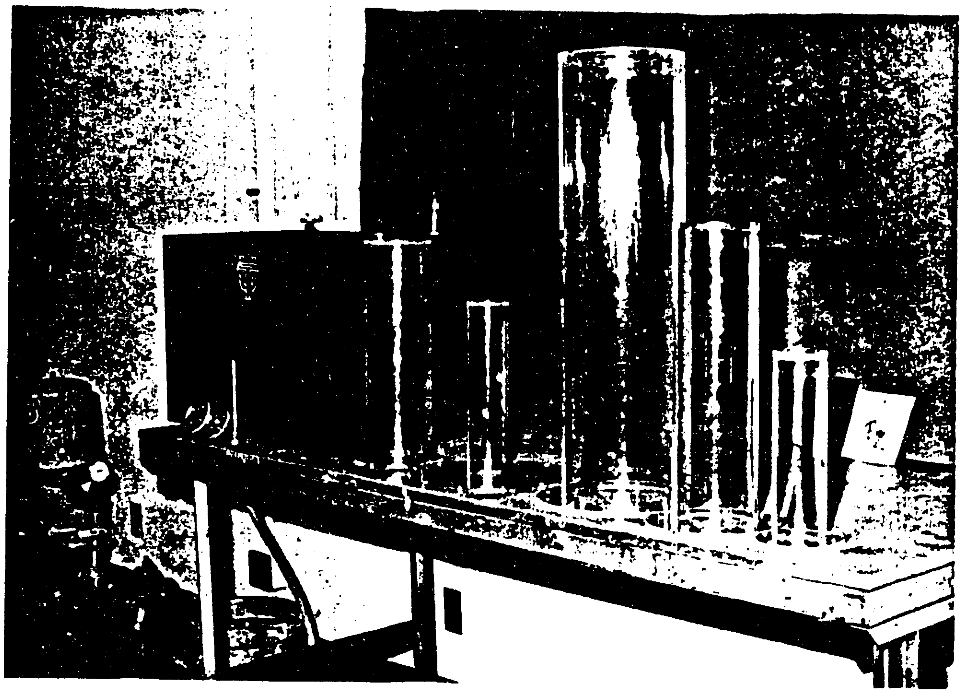


Figure 4.1.1 Individual Components of Cold Flow Visualization Model of UTSI Burner

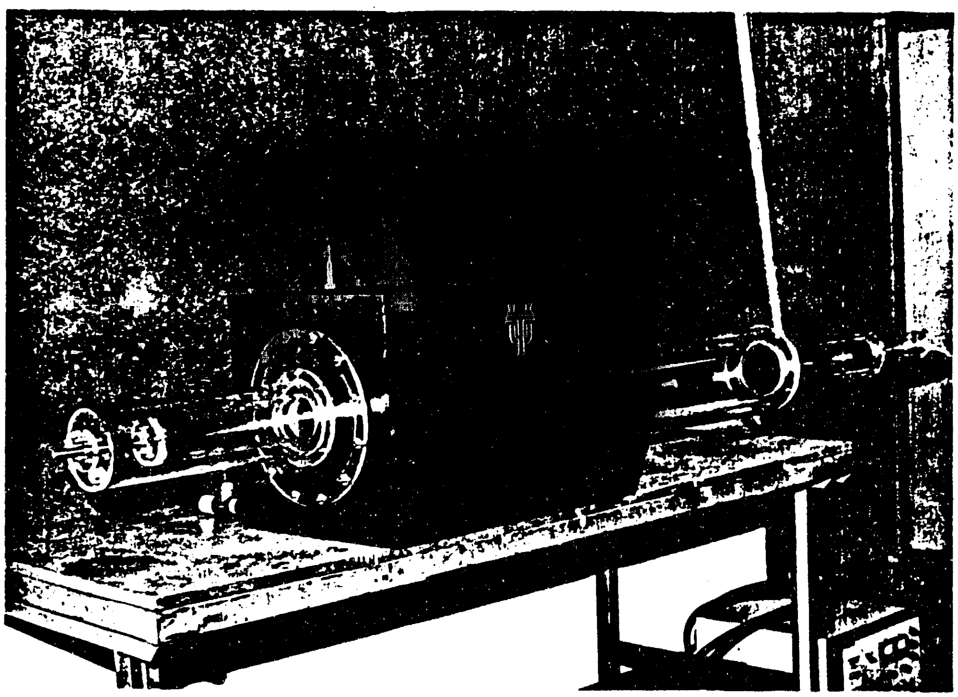


Figure 4.1.2 Assembled Cold Flow Visualization Model; Separate First-Stage Section on Left Side of Discharge Tank, and Complete Three-Stage Burner Assembly on Right

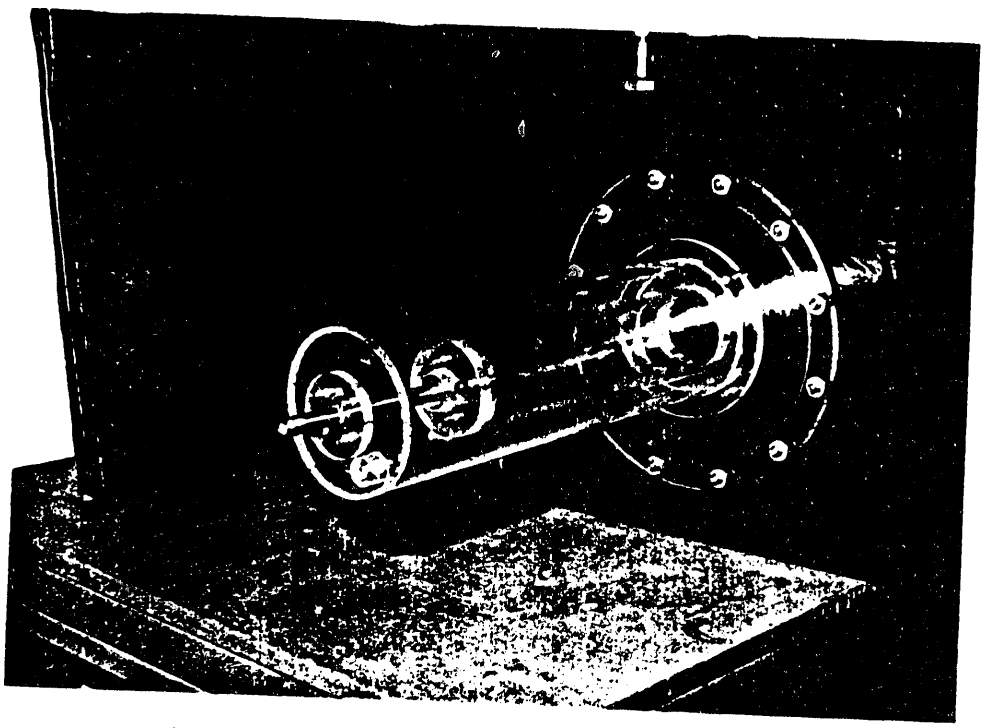


Figure 4.1.3 Close View of Separate First-Stage Section of Cold-Flow Burner Model

swirl flow. This will include the input swirl flow tangential velocity and direction. The distribution found must also satisfy the stoichometry requirements of the staged combustion burner design. Once the detailed operating design for the first section is determined, the second burner segment will be attached and cold flow modeling will be used to confirm its design and operating characteristics. The need for a third burner segment also will be determined. At that point, the prototype hot flow burner design can be confirmed.

4.2 Task 2: Small Scale Burner Development

Initial design specifications were developed for a coal injector for the 200 hp boiler, based on the UTSI MHD burner concept. The injector has been designed and released for fabrication. The coal injector will be tested as a possible direct substitution for the present commercial oil-gun assembly. This activity is being conducted in parallel with work on the advanced industrial burner. The latter is based on gas turbine combustor-can concepts.

Procurement and installation activities were completed for the basic support systems for the 200 hp boiler, including the stack sampling platform. Four thermocouples were installed to monitor temperature of combustion gases in the gas turn-around areas near the aft and forward end-bells of the boiler. The unit was operated with number 2 oil fuel at firing rates from two to six million Btu's per hour with approximately fifteen percent excess air. Gas temperatures were measured near the outlet of the main firetube with a high-velocity aspirating thermocouple probe (HVT). The results are shown in Figure 4.2.1 and show the dependence of gas temperature upon firing rate.

Flame length was observed to be strongly influenced by operating at different levels of excess air. Test levels of excess air were between approximately 50% and 14% with the number 2 oil fuel. The flame was very short at the higher levels of excess air; conversely, the flame extended

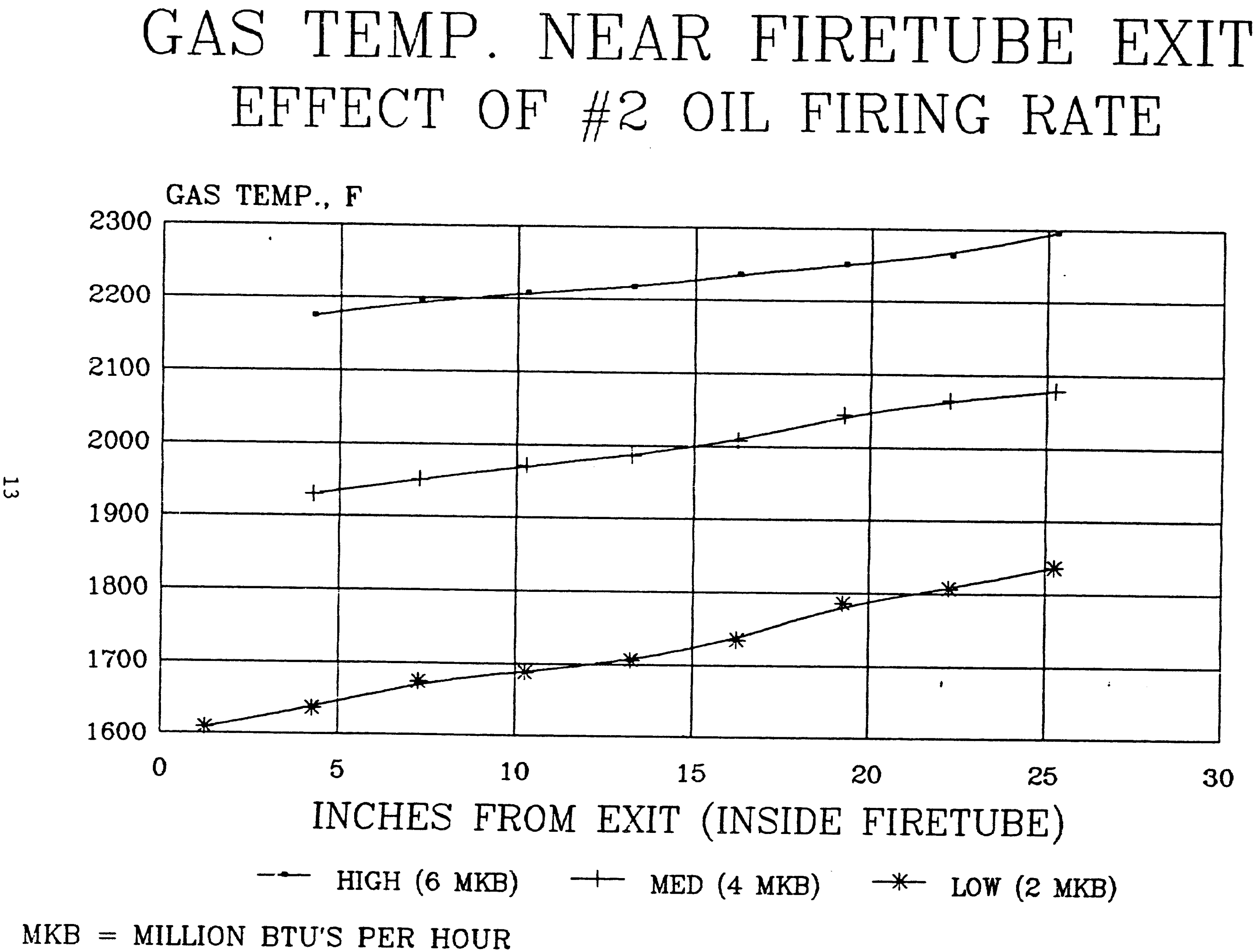


Figure 4.2.1 Measured HVT Gas Temperatures in Boiler Near Firetube Exit for Three Oil-Firing Rates

nearly to the full length of the firetube at the lowest levels. Low excess air is desirable to minimize NOx production and to maximize boiler efficiency. It is probable that even the small change in excess air from approximately 15% to 14% produced the effect shown in Figure 4.2.2.

Installation of advanced boiler instrumentation and development of methods for accomplishing the first operation with coal are progressing. Work continued on the design specifications for a dense-phase transport system to deliver ultrafine coal from the main storage bin to the advanced industrial burner. A search for suitable commercially-available equipment has not been successful to date. Modification of existing UTSI equipment may be the route chosen if commercial equipment is not found.

Several vendors were contacted to identify and procure a suitable coriolis meter for measurement of coal mass-flow rates. A request for bids was released for the coriolis meter.

Two tons of deep-cleaned, micronized coal were ordered from Energy International, Inc. (EI) and received at UTSI for initial tests with the coal injector. The parent coal bed is Upper Elkhorn #3. It is found in West Virginia, Virginia, Kentucky, and Tennessee. Original estimated reserves are 13,204,151,148 tons. Table 4.2.1 contains the deep-cleaned coal analyses which were made by Dravo Engineering for EI, and the results were forwarded to UTSI. Figures 4.2.3 and 4.2.4 show UTSI plots of the Dravo data for particle size and particle volume distributions, respectively. The coal was reported to have a mean volume diameter of 11.8 micrometers.

Slag viscosity was calculated from the Dravo data for ash composition by UTSI personnel using a procedure published by W. T. Reid (1). The calculated viscosity-temperature relationship is shown in Figure 4.2.5.

Bids are being sought for equipment to fire propane fuel. This will be

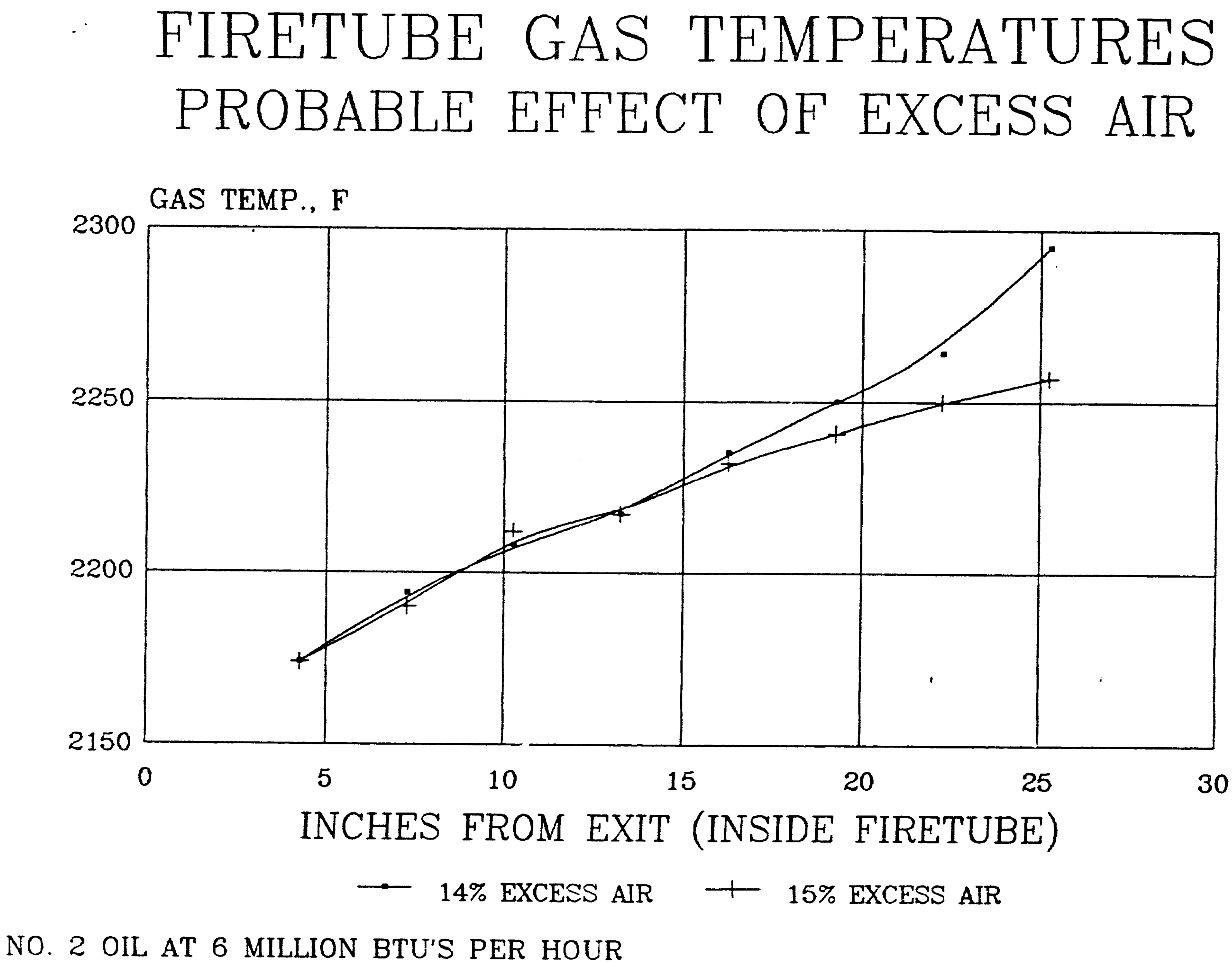


Figure 4.2.2 Probable Effect on Flame Length of Small Change in Excess-Air Level (Measured via HVT Gas Temperatures During Six Million Btu/hr Oil Test-Firing)

Table 4.2.1
Analyses of Deep-Cleaned Ultrafine Coal Sample
as Reported by Dravo Engineering, Inc.

COAL I.D. UE3-158-MCO-S

DESCRIPTION: Upper Elkhorn #3 Seam - Deep Cleaned Dry Micronized Coal for UTSI

PROXIMATE:

MOISTURE	1.06%
VOLATILE MATTER	37.79%
FIXED CARBON	60.81%
ASH	1.40%
SULFUR	0.64%
BTU/LB	15013

ASH CHEMISTRY:

SiO_2	39.79%
Al_2O_3	29.20%
TiO_2	2.24%
Fe_2O_3	16.41%
CaO	3.56%
MgO	0.76%
K_2O	1.18%
Na_2O	1.70%
SO_3	2.42%
P_2O_5	0.32%
SrO	0.45%
BaO	0.43%
Mn_2O_4	0.03%
BASE ACID RATIO	0.33%
T-250 TEMP.	2505°F

ULTIMATE:

CARBON	82.79%
HYDROGEN	5.23%
NITROGEN	1.64%

ASH FUSION:	REDUCING	OXIDIZING
INITIAL	2270°F	2490°F
SOFTENING	2380°F	2580°F
FLUID	2485°F	2670°F

FREE SWELLING INDEX: 7.5

HARDGROVE GRINDABILITY: NA

SULFUR FORMS:

PYRITIC	0.05%
SULFATE	0.01%
ORGANIC (DIFF)	0.58%

UTSI Addendum:

With the exception of the moisture value, data for the proximate, ultimate, higher heating value, and sulfur forms are reported on the dry basis. The base/acid ratio is 0.33 (not 0.33% as reported above).

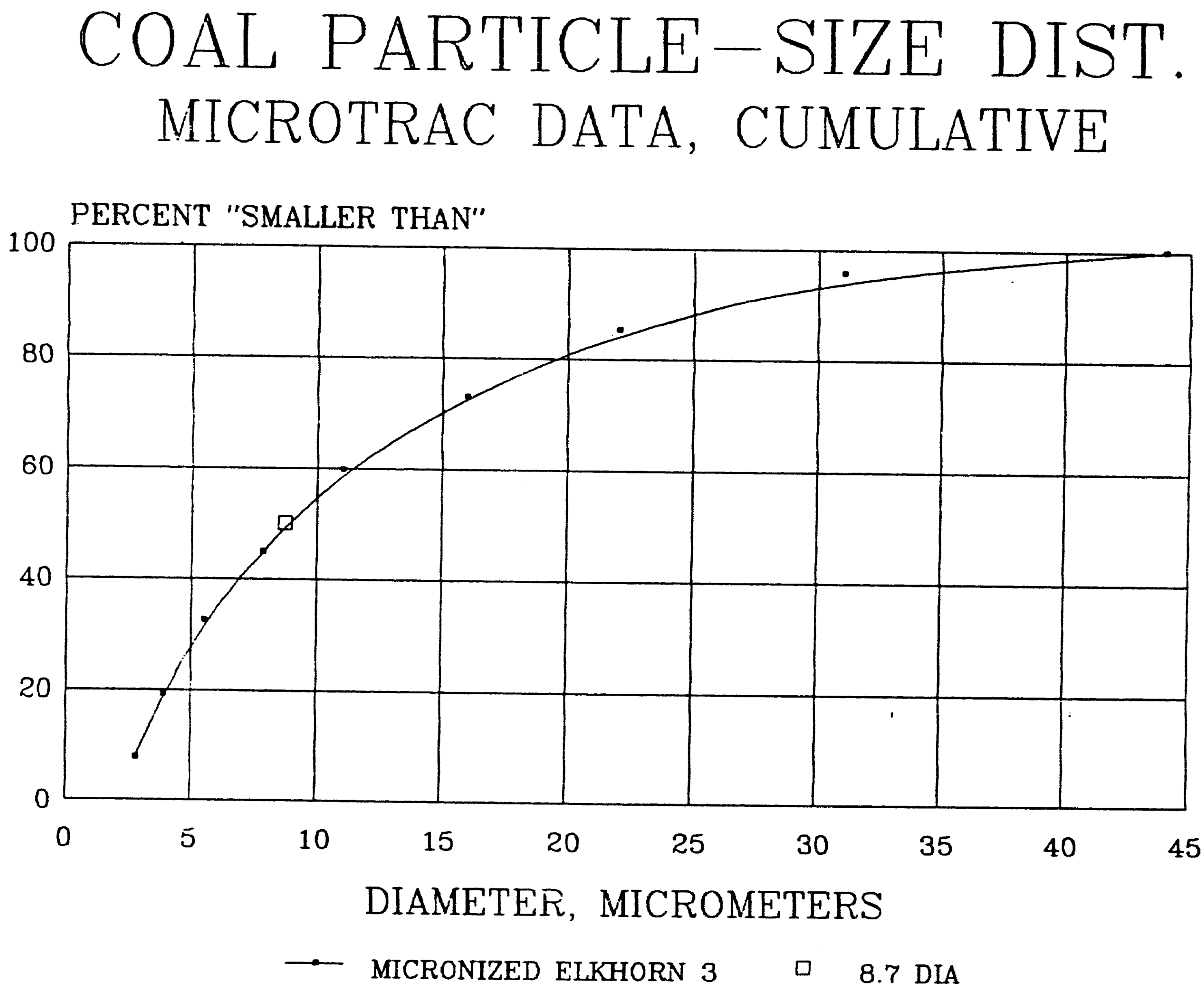


Figure 4.2.3 Particle-Size Distribution for Deep-Cleaned Ultrafine Coal (Cumulative Microtrac Data)

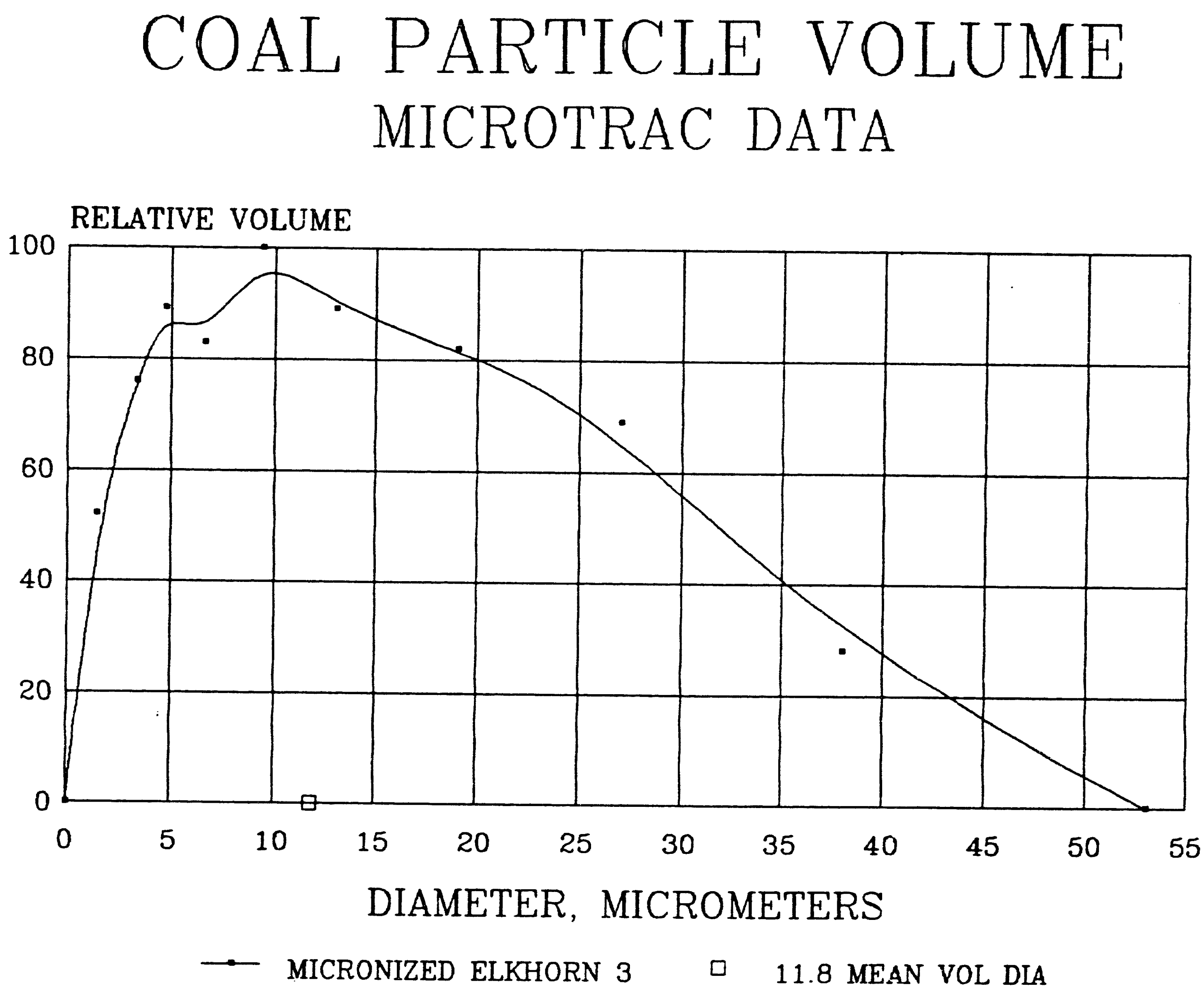


Figure 4.2.4 Particle-Volume Distribution for Deep-Cleaned Ultrafine Coal (Microtrac Data)

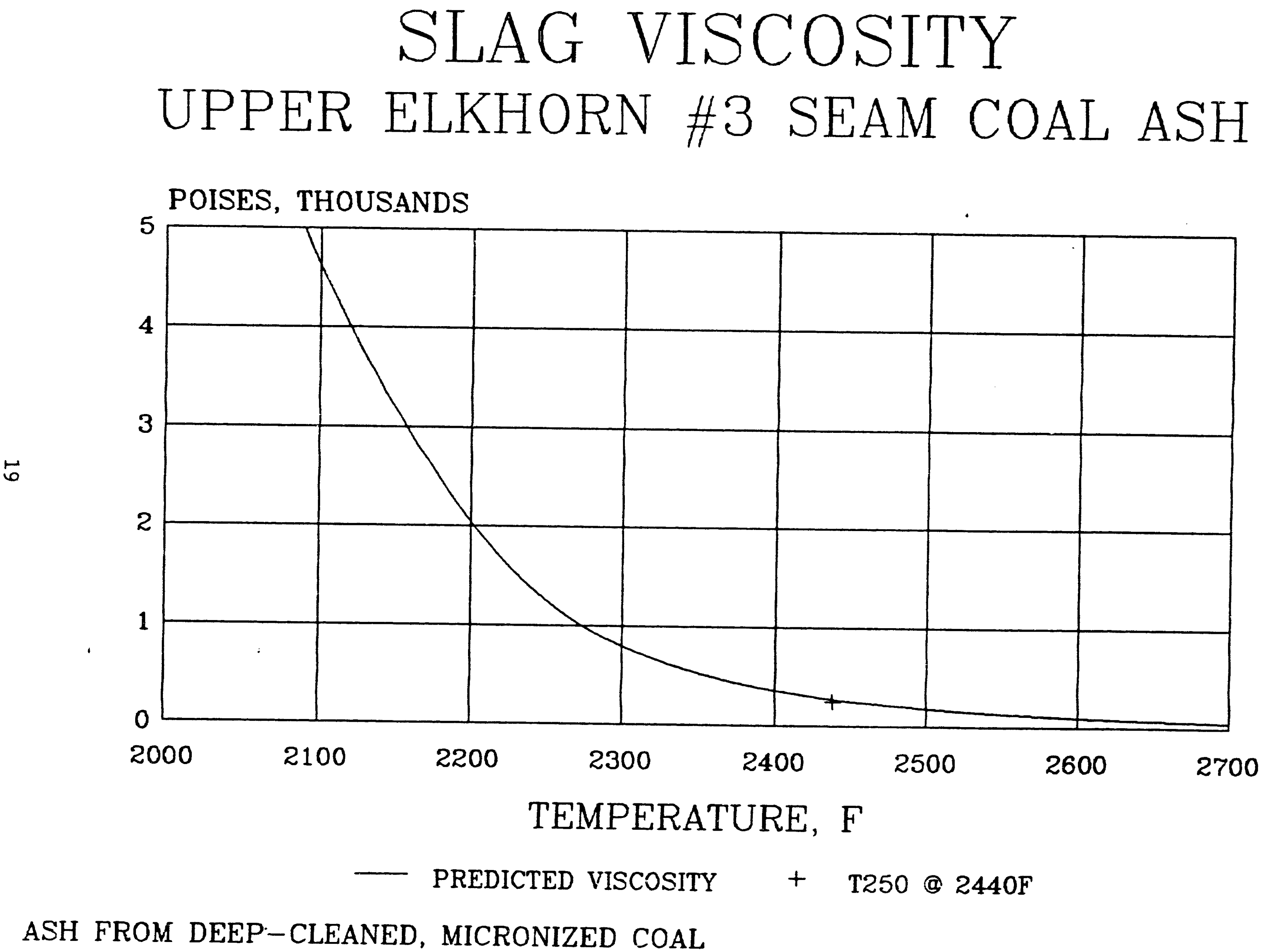


Figure 4.2.5 Predicted Slag Viscosity for Laboratory-Prepared Ash from Deep-Cleaned Ultrafine Coal

very useful for warm-up and ignition activities during later coal tests.

4.3 Task 4: Project Management & Reporting

A draft of the Management Plan was completed and transmitted to DOE. It included the Milestone Schedule and Status Report, Cost Plan, and Labor Plan.

Project management software was ordered and received. This will provide an additional aid for project planning, control, and reporting. The software is being used to integrate project details and examine critical-path relationships of planned activities. As a result, future changes can be incorporated if they occur, and their individual or combined effects can quickly be evaluated. Appropriate management action can then be identified and initiated more efficiently.

The first quarterly report was issued, covering June and July, 1987. Also, monthly reports were issued.

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1 Reid W T, "Microcomputer Calculation of the Viscosity of Coal-Ash Slags," ASME Paper No. 85-JPGC-Pwr-46, Joint ASME/IEEE Power Generation Conference, Milwaukee, Wisconsin; October 20-24, 1985.

5.0 DISCUSSION

The ash fusion temperatures shown in Table 4.2.1 are lower than the minimum levels desired by UTSI personnel. Additionally, the temperature of 2440°F for 250 poise as predicted in Figure 4.2.5 is 65 degrees lower than the value of 2505°F reported by Dravo Engineering in Table 4.2.1. This could increase formation of the type of fireside deposits that are difficult to remove.

In order to evaluate this situation more closely, information was examined from Figures 4.2.1 and 4.2.5. It can be seen in Figure 4.2.5 that coal-ash particles are predicted to be in the form of sticky, semi-molten glass (less than 5000 poises) at temperatures above 2100°F. (Note that calculations of viscosity above the 250 poise level can encounter significant error with ash compositions where an abrupt freezing point is exhibited. If the ash from the deep-cleaned Upper Elkhorn coal were to produce this effect, a predicted temperature of 2200-2300°F might be more accurate for the 5000 poise level). Figure 4.2.1 shows that HVT gas temperature measurements for oil firing at six million Btu's per hour were in the range from 2175°F to 2295°F near the outlet of the firetube. If coal firing were to produce gas temperatures similar to those measured for the number 2 oil, the viscosity of the coal-ash particles entrained in the combustion gas might be represented by the curve shown in Figure 5.1. This curve represents our "best calculated guess" at this time using the viscosity/temperature relationship from Figure 4.2.5. This figure supports the concept that the ash-deposition characteristics for this sample of deep-cleaned coal may be marginal.

Although the degree of uncertainty of the viscosity prediction presented in Figure 5.1 has not been established, it probably is more accurate than an evaluation based upon measured ash-fusion temperatures. As pointed out in

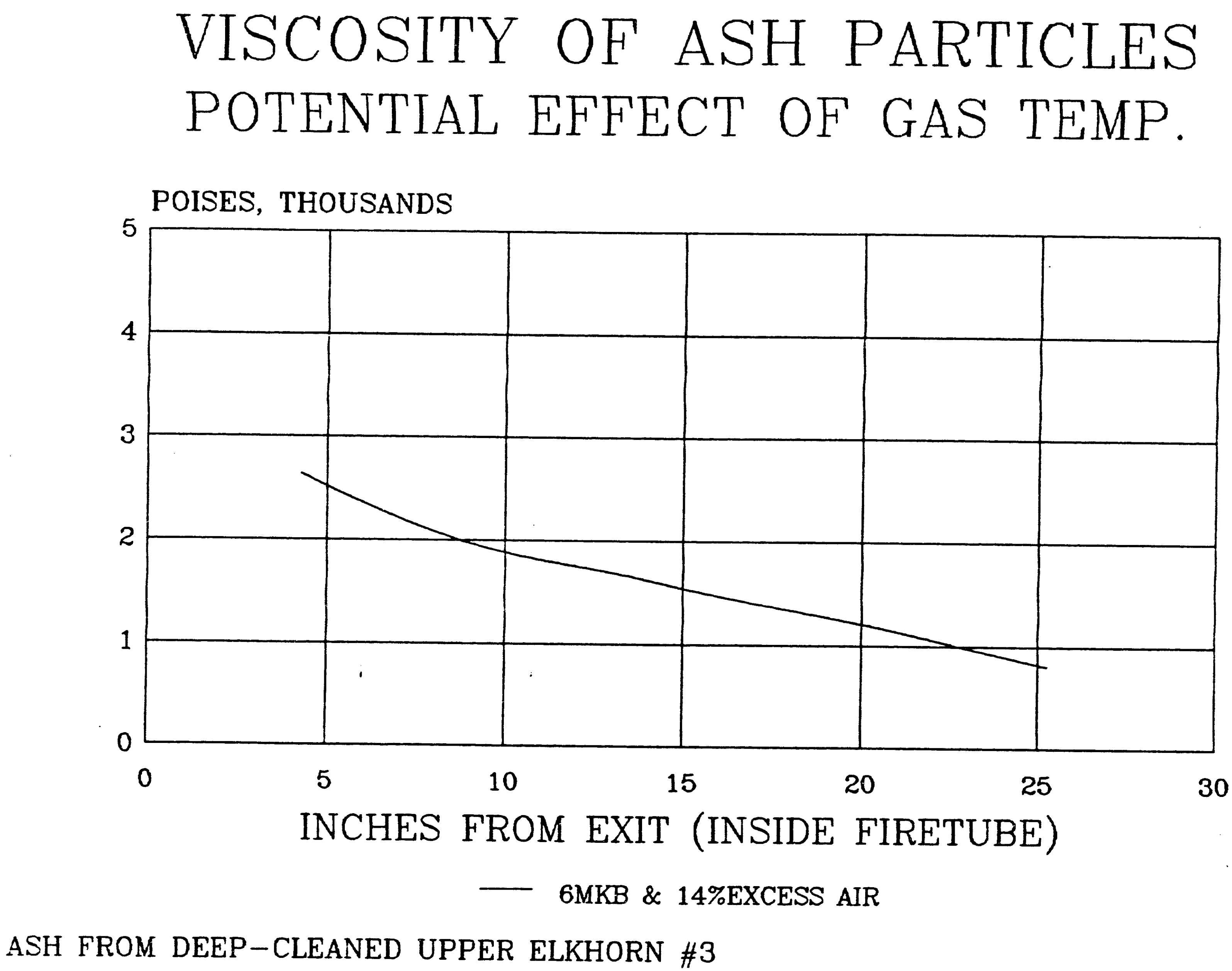

Figure 5.1 Potential for Sticky Coal-Ash Particles in Boiler Near Firetube Exit (Estimated via Predicted Viscosity <5000 Poises, Measured Gas Temperatures, and Probable Flame Length)

publications by Attig and Duzy (2), and Wagoner (3), (4), measured viscosity curves can extend into temperature ranges considerably below initial deformation temperatures measured with ASTM ash-fusion techniques.

Measured ash-fusion temperatures often are not closely related to measured viscosities. One of the reasons for this disparity is that ash-fusion temperatures are measured while slowly and continuously heating a sample of individual, heterogeneous, sulfated, loosely-cohering ash particles previously formed from a coal sample during a slow, relatively low-temperature ashing procedure in an electric furnace. Conversely, viscosity measurements typically are made during very slow, stepwise cooling of a molten slag which is essentially sulfate-free. The melt typically behaves as a glass for eastern U.S.A. coal ashes. With an air atmosphere, the degree of sulfation and oxidation within the melt is predominately determined by (equilibrium) thermodynamics.

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2 Attig R C and Duzy A F, "Coal Ash Deposition Studies and Application to Boiler Design," presented at the American Power Conference, April 1969, and published as B&W paper No. BR-899/TP9-4.

3 Wagoner C L, "Slag Viscosity," presented to Coal Gasification Modeling Workshop, Entrained-Flow Gasification/Combustion Session, January 20, 1982 and condensation published in the Proceedings, DOE/METC/82-24, UC-90c, pp. 314-319, July 1982.

4 Wagoner C L, "Comments on the Paper by W. T. Reid," Progress in Energy and Combustion Science, Volume 10, No. 2: Coal Combustion and Applications -- A Special Issue prepared by the DOE Coal Combustion and Applications Working Group, pp. 170-172, 1984.

The degree of sulfation of ASTM ash particles prepared for fusion measurements partially depends on low temperature thermodynamic equilibrium which favors sulfation, and partially depends on variations permitted by the ASTM procedure in details of individual laboratory ashing techniques such as heating-rate linearity, location of coal samples inside the furnace, air circulation patterns and flow rates within the ashing furnace, etc.

An additional point to consider when evaluating the accuracy of any predictions based upon laboratory analyses is that the size and composition of the individual particles of ASTM ash probably do not directly represent those ash particles actually entrained in combustion gas when the coal is combusted.

6.0 CONCLUSIONS

Flow visualization using a cold flow model with dye stimulated by a laser is a valuable technique for obtaining necessary design input for the advanced burner.

Because the boiler operated smoothly during the shakedown tests with oil firing after a few minor start-up problems were solved, we feel it can be an excellent test bed for the planned coal-combustion testing.

Gas-temperature measurements (HVT) will be useful for quantifying flame length and effects produced by changes in firing rates and levels of excess air.

The deep-cleaned, ultrafine coal sample of Upper Elkhorn Number 3 has marginal ash-fusion characteristics. Predicted slag viscosity data when combined with HVT measurements also indicate the potential for ash stickiness. Although the quantity of ash is low, the probability is significant that semi-molten ash particles will exit the firetube. This coal sample could promote unwanted fireside deposition of ash.

Use of project management software has improved accuracy in identification, planning, and scheduling of critical-path activities.

7.0 RECOMMENDATIONS

No changes to the technical approach are suggested.

END

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