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**ADVANCED COMBUSTION SYSTEM FOR INDUSTRIAL BOILERS
PHASE II**

Quarterly Technical Progress Report

OCTOBER-DECEMBER 1990

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1.0 INTRODUCTION

The contract start date (for Phase I) was June 11, 1987. Contract completion date (for Phase II) is September 11, 1991.

This is the fifth quarterly report covering work on Phase II of the project. The period covered is October through December 1990.

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 gas as fuels for many industrial boilers.

The advanced coal combustion system concept includes the following components:

- a new burner for ultra fine coal fuels which could replace existing oil and/or gas burners
- a coal injector that could replace the oil gun in existing burners, as an alternative to complete replacement of the burner assembly
- a coal storage and dense phase coal feed system
- an automatic control system, based on computer control with feedback from low-cost combustion-quality transducers
- ash removal and particulate cleanup equipment.

The components of the advanced coal combustion system are shown schematically in Figure 1.1. Areas of contract activity are enclosed with dotted lines by the large rectangle.

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Fig. 1.1. Advanced Combustion System for Industrial Boilers

1.1 Phase I. Summary of Results

During Phase I of the project, a coal injector was designed, fabricated, and tested. It is a direct replacement for the oil gun in the original equipment of a 200 hp Cleaver-Brooks fire-tube boiler. The system was tested at coal-firing rates in the range of 2 to 6 million Btu's per hour, firing Upper Elkhorn No. 3 (eastern bituminous, "UE3") coal supplied by Energy International, Incorporated. For these tests, propane was used to preheat the boiler before initiation of coal firing. The propane flow was turned off after coal combustion was established. No combustion air preheat was used. During these tests, boiler efficiency was typically about 85 to 86 percent, while carbon conversion efficiency was approximately 94 percent. Concentrations of CO were less than 150 ppm. The NO_x emissions were less than 0.6 pounds per million Btu's.

Following a series of laser-illuminated cold-flow-visualization tests, a new burner also was designed, fabricated, and tested during Phase I. The arrangement is shown in Figure 1.2. It is a two-stage, swirl burner which fits in the space previously occupied by the original Cleaver-Brooks burner, and uses the existing section of refractory. Air flow can be regulated independently into each of the two stages. Additionally, the angle is adjustable for individual swirl blades.

Upper Elkhorn No. 3 ultra fine coal was used as the standard fuel for most UTSI-burner tests. Firing rates were in the range of 2 to 6 million Btu's per hour. Upper Elkhorn No. 3 coals were tested with three levels of ash. These were approximately 1.4%, 2.7%, and 4.8% ash, on an as-fired basis. The 2.7%-ash UE3 coal was used for

Figure 1.2 UTSI Phase I Replacement Burner

most tests because it exhibited a good balance between ash content and ash-fusion characteristics. The 2.7%-ash UE3 coal also served as a reference and established a baseline for performance. Additionally, a 1.3 float fraction of a western Eagle Butte subbituminous coal was used as the fourth ultra-fine test fuel. It contained 4.4% ash on an as-fired basis.

All four test coals were supplied by Energy International, Inc. with a mean particle size of about 10 mm and a top size of 44 mm. The coals were delivered to UTSI in plastic-lined, 55-gallon steel drums.

Propane was used to preheat the boiler before initiation of coal firing. The propane flow was turned off after coal combustion was established. No combustion air preheat was used with the UTSI burner. Boiler efficiency was approximately three percent higher with UE3 coal than in the previous test series with coal injectors, and typically was about 88 to 89 percent. Carbon conversion efficiency was approximately 97 to 99 percent for UE3 coals. A very high value of 99.9 percent carbon conversion was attained with the 4.4%-ash Eagle Butte coal. These results are about 3 to 6 percent higher than those measured when the UTSI coal injector was used in the Cleaver-Brooks burner.

Forty to sixty percent of the ASTM coal ash remained in the boiler. However, the deposits were powdery and easy to remove by increasing the fan speed after the conclusion of each combustion test. The increased air velocity quickly re-entrained and removed most of the previously-deposited ash.

Concentrations of CO were below 100 ppm. The NO_x emissions ranged from 1.2 to 1.3 pounds per million Btu's with the UE3 coals. With the Eagle Butte coal, a lower level of 0.86 pounds of NO_x per million Btu's was measured.

In addition to the burner-development activities, a system was designed, fabricated, tested, and used routinely for data acquisition and manual boiler/burner control. The system is based upon a dedicated micro-computer based on the Intel "286" cpu chip architecture using UTSI-developed software. **In Phase II this system will provide automation of system control and data acquisition.**

1.2 Initiation of Phase II

Phase II started on October 1, 1989.

The main objective of the current work is to move ahead from the primarily R&D oriented approach of Phase I toward commercialization of a complete coal-retrofit system.

In order to accomplish this, our plans include the following goals and activities.

Goals

- Decrease NO_x emissions to less than 0.7 lb/MBtu

Although the UTSI commercial fire-tube boiler is fired at 6 MBtu/hour and therefore is much smaller than steam generators usually subjected to NO_x regulations, we have based our goal upon the value specified in *Performance Standards for Commercial/Industrial/Institutional Steam Generation* for coal-fired boilers in the 100 MBtu/h to 200 MBtu/h range; a level of 0.6 lb NO_x/MBtu is specified for coal-fired electric utility steam generators larger

than 250 MBtu/hour by the *Performance Standards for Electric Utility Steam Generating Units Commencing After September 18, 1978*. As a supplemental goal, we will attempt to obtain this lower level of emissions with NO_x less than 0.6 lb/MBtu.

- Decrease particulate emissions to less than 0.6 lb/MBtu

This is based upon the current *UTSI site permit* issued by the state of Tennessee; otherwise, Tennessee particulate limit is 0.8 lb/MBtu for a 6 MBtu/h boiler such as the UTSI unit.

- Increase carbon burnout so all test coals exceed 99% efficiency at a firing rate of approximately 6 MBtu/h

This is based upon a *stated DOE goal*.

- Increase the turn-down ratio from the present 3:1 capability

This is based upon *extension of previous achievement* of the stated DOE goal of 3:1.

Planned Activities

- Investigate the effects on reducing NO_x emissions by deep-staging combustion air or reburning
- Add on-line cleaning capabilities for removal of powdery fireside deposits
- Add particulate-removal equipment to reduce stack emissions
- Develop higher efficiency three-stage burner
- Add air pre-heater and evaluate effects

- Add low-cost combustion-quality transducer for automated control of boiler efficiency
- Develop simple, reliable, and inexpensive on-line dense-phase flow-control capability with storage hopper operating at atmospheric pressure and suitable for reloading with coal at any time during extended periods of operation
- Automate the boiler control system
- Evaluate potential of bulk bags for receiving, storing, and unloading ultra fine coal
- Develop a commercially acceptable ultra-fine coal storage and dense-phase feed system
- Demonstrate performance of new three-stage burner
- Make an economic evaluation and develop a commercialization plan
- Demonstrate commercial feasibility of the integrated system with a 100-hour test operation

1.3 Phase II. Summary of Previous Results

Work in Phase II has concentrated on: a.) adapting a commercially available automotive oxygen sensor for use in the boiler control system; b.) developing a commercially oriented dense-phase coal transport system; c.) designing, fabricating, testing, and fine tuning an improved burner for better combustion efficiency; and d.) adding deep-air-staging capabilities to the new burner to decrease NO_x emissions to

slightly above 0.4 lb-NO_x/MBtu with ultra fine coal. This performance is considerably better than the DOE goal for Phase II work.

2.0 TECHNICAL PROGRESS IN PHASE II DURING OCTOBER-DECEMBER 1990

QUARTERLY SUMMARY:

During this quarter, work continued on development/improvement of the low-NO_x coal combustor for the boiler system. Reburning tests were conducted in the external, water-cooled test duct with a length of 15 feet using ultra fine coal with propane to reduce the NO_x levels to as low as 0.295 lb-NO_x/MBtu. Work also continued on design/construction of the new coal-feed system that will be used for the 100-hour demonstration test with the on-line refillable coal hopper operating in air at atmospheric pressure. Coal will be loaded into the hopper from bulk bags.

Initial testing of the UTSI boiler control and automation system was successful. Normally-pulverized coal with approximately 70% passing a number 200 sieve was burned in the external test duct. Initial flame-visualization tests were successful, and the burner was able to handle coal without being micronized to the ultra fine level.

Refractory was poured for a new combustor second-stage assembly. Subsequently, the combustor was installed inside the 200 hp fire-tube boiler.

2.1 Task 3: Integrated Combustion System Development

Quarterly activity details follow.

2.1.1 Procurement of Equipment for Coal Feed System

Construction, erection and painting of the new coal tank were completed. Load cells were installed. Work began on the final electrical connections. The arrangement

of the coal-supply system is shown in Figure 2.1. The UTSI burner will be connected directly to the outlet line from the auger which is shown at the lower right of Figure 2.1 as "coal feed to burner." Dense-phase coal-flow control is accomplished with the burner first-stage eductor via on-line changes in motive-air pressure and/or discharge-tank fluidizing rate.

2.1.2 Low-NO_x Burner Modification and Testing

The general configuration of the burner with deep air staging is shown schematically in Figure 2.2. It has a large insulated section which provides for a primary combustion zone operating under reducing conditions with controlled heat losses. Secondary air passes through an annular passage behind the insulation. The air enters at ambient temperature, cools the walls of the primary combustion zone, and heats as it moves through the annulus. Subsequently this deep-staged air enters the secondary combustion zone, flowing through multiple orifices and producing eight separate mixing jets.

During this quarter, a six-foot refractory length was used with several arrangements of the air mixing jets. As illustrated in Figure 2.2, the jets were either opposed (upper half of the figure, right side) or set at a 20° counter-swirl position (lower half of the figure, right side). In addition, the 20° counter swirl was tested in two variations. One of these used 45° counter-current flow (lower half of the figure, left side); the other had no counter-current flow (0°, as shown in the upper half of the figure, left side). The opposed jets were tested without counter flow.

The order of increasing mixing intensity was:

opposed----> 20° counter swirl (cs)-----> 20°cs/45° counter current (cc).

Figure 2.1 Atmospheric-Pressure Coal Loading/Storage System with Bin Discharger and Fluidizing Plenum

Figure 2.2 Configuration of the Air Jets for Deep Staging

Reburning tests were conducted in the external, fifteen-foot test duct. It simulates many of the characteristics of the boiler fire-tube. The duct is cooled by an external water spray. Combustion gases exhaust directly to the atmosphere. Preliminary testing in this duct makes observation of the flame much easier, and also makes the burner more accessible for modification.

Propane was injected at the center of the six-foot refractory length, as shown in Figure 2.3. Reburn air was added in one of two ways:

- through the burner primary and secondary air registers, or
- through reburn-air injectors located in the same plane as the propane injectors.

The test matrix for the various configurations examined during this reporting period is shown in Table 2.1. Ultra-fine Upper Elkhorn #3 coal with approximately 2.7 weight percent ash was used as the test coal. This continues to be the "standard" UTSL test coal. Jet angles for three deep-staged secondary air arrangements were tested along with two locations for adding propane-reburn air.

Figure 2.3 Location of Propane and Reburn-Air Injectors

**Table 2.1. Test Matrix for Reburn-Air Injection Locations During
Propane Reburning Measurements**

INTRODUCTION OF REBURN AIR	DEEP-STAGED SECONDARY COMBUSTION AIR JET ARRANGEMENT		
	OPPOSED JETS (0°cs/0°cc)	20°cs (20°cs/0°cc)	20°cs/45°cc (20°cs/45°cc)
WITH PRIMARY AND DEEP-STAGED SECONDARY AIR	✓	✓	✓
THROUGH REBURN AIR INJECTORS			✓

In addition to where the reburn-air was added and how the secondary air jets were configured, the quantity of propane relative to coal was evaluated. This relationship was expressed in terms of propane, as percent of total coal-plus-propane Btu input. Tests were conducted in the range of approximately 8 to 14 percent propane.

Another major operational variable was the air-to-fuel ratio in the primary combustion zone. This can be enumerated in terms of stoichiometry, and the symbol ϕ_P indicates the primary stoichiometric ratio (theoretical air/fuel) in this report. For this series of tests, values of ϕ_P were in the range of approximately 0.6 to 0.8. The total (or final) stoichiometric ratio, ϕ_T , was held near 1.15. The system is capable of operating with relatively low excess air, and ϕ_T of 1.1 is a stable condition.

Figure 2.4 is a composite view of individual NO_x test results from previous coal tests with opposed, 20°cs , and $20^\circ\text{cs}/45^\circ\text{cc}$ secondary air jet configurations. Emissions of NO_x are plotted vs. the primary stoichiometric ratio for the normal six-foot refractory configuration. This information is included for comparison with the new reburn data.

Figure 2.4. Summary of NO_x Emissions During Previous Coal-Only Tests With Data from All Secondary Air Jet Angles

Figure 2.5 shows reburn results for all tests conducted with reburn air introduced through the primary and secondary combustion-air registers. Deep-staged secondary air jets were configured with either opposed or 20°cs angles. Emissions of NO_x are plotted vs. the primary stoichiometric ratio for the six-foot refractory configuration. When the primary stoichiometric ratio, ϕ_p , is greater than 0.65, reburning lowered NO_x emissions by about 0.02 to 0.05 lb/MBtu for the same primary stoichiometry. However when ϕ_p was less than 0.65, no reduction in NO_x emissions was measured.

Figure 2.5. NO_x Emissions During Reburning Tests With Reburn Air Introduced Through Primary and Secondary Air Registers

Figure 2.6 shows reburn results with $\phi_p = 0.6$ with two locations for injection of propane-reburn air. Deep-staged secondary air jets were configured with 20°cs/45°cc angles. Emissions of NO_x are plotted vs. the quantity of propane used for reburning, expressed as percent of total Btu input, for the six-foot refractory configuration. When reburn air is introduced through the primary and secondary air registers, there is no reduction in NO_x emissions (dashed line). However, when the reburn air is

introduced through the reburn jets, a major decrease in NO_x emissions results! A low value of 0.295 lb NO_x/MBtu was achieved with 13.7% of the heat input from propane.

Figure 2.6. NO_x Emissions During Reburning Tests With $\phi_p = 0.6$

Figure 2.6 is significant because the primary stoichiometry was chosen for very low NO_x levels with coal-only. Any reduction in NO_x emissions from this level (very low for coal) is extremely important. The results show that operation below 0.3 lb NO_x/MBtu can be achieved with coal in a 200 hp fire tube boiler with the UTSI retrofit system. With

additional "fine tuning" of the present configuration combined with higher propane levels it is quite possible that the California standard of 0.2 lb NO_x/MBtu can be attained. For example, if the refractory length were to be extended by approximately two feet, it is highly probable that the level of 0.2 lb NO_x/MBtu would be achieved.

Propane reburning with deep air staging has produced the lowest NO_x emissions to date. **The low value of 0.295 lb NO_x/MBtu is far better than the contract goal of <0.7 lb/MBtu or the supplemental UTSI goal of <0.6 lb/MBtu.** It is expected that the carbon conversion efficiency would significantly exceed 99 percent when the burner is installed inside the Cleaver-Brooks 200 hp fire tube boiler.

2.1.3 Cold Start Burner Lightoff Demonstration

We demonstrated a cold start using coal with a small propane flame for a lighter. Refractory was not preheated before lighting the coal. Combustion air preheat (as always) was not used. The coal ignited immediately, and the propane lighter was turned off shortly after ignition. The coal-only flame was stable, and was slightly smoky only during the first 40 to 50 seconds. Coal flowrate was set at a low-to-medium load level for this experiment.

2.1.4 Pulverized Coal (70% -200 mesh) Burning Capability Demonstration

During December, we conducted a very successful combustion test (flame visualization) in the external duct using conventionally-pulverized coal (not the normal finely micronized particle size). The potential importance of the initial test using pulverized coal can be considered in several areas:

- *Fuel Options.* The multiple fuel capabilities of the advanced combustor could include natural gas, propane, number 2 oil, ultra fine (micronized) coal, and normal pulverized coal (typical output from pulverizers at a utility).
- *Fuel Costs.* If conventionally-pulverized coal could be used, the cost per million Btu's would be far more attractive for industrial applications.
- *Equipment Costs and Availability.* Existing, conventional pulverizers could be used to produce a commercial fuel.

2.1.5 Combustor Fabrication

In December, we poured refractory for a new combustor second-stage assembly for installation in the fire-tube boiler. Subsequently, the new combustor was installed inside the 200 hp fire-tube boiler.

2.2 Task 4: Project Management and Reporting

The September, October, and November 1990 monthly reports were issued. The January-March 1990, and the April-June 1990 Quarterly Technical Progress Reports were issued.

We prepared material for the PETC annual internal review and sent it to John Winslow.

3.0 WORK PLANNED FOR JANUARY-MARCH 1991

During the next quarter, work will continue on developing and measuring performance of the UTSI low-NO_x coal combustor for the boiler system. Work also will continue on completion and testing of the new coal feed system that will be used for the 100-hour demonstration test. Additional tests will be conducted with the UTSI boiler control and automation system

Fly ash particle size measurements will be made, relative to feasibility of use of cyclonic ash collector (cyclone sampler).

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