**Establishment of an Environmental Control Technology Laboratory
with a Circulating Fluidized-Bed Combustion System**

Quarterly Technical Progress Report

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ABSTARCT

The purpose of this report is to summarize the progress made on the project “Establishment of an Environmental Control Technology Laboratory with a Circulating Fluidized-Bed Combustion (CFBC) System” in this quarter (September - December of 2003). The main tasks in this quarter consisted of the following four parts. First, all documents for managing this project have been prepared and sent to the Office of Project Management at the US Department of Energy’s (DOE’s) National Energy Technology Laboratory (NETL). Second, plans for the renovation of space for a new combustion laboratory for the CFBC system has progressed smoothly. Third, considerable progress in the design of the CFBC system has been made. Finally, a lab-scale simulated fluidized-bed combustion facility has been set up in order to make some fundamental investigations of the co-firing of coal with waste materials in the next quarter. Proposed work for the next quarter has been outlined in this report.

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ACRONYMS AND ABBREVIATIONS

CFBC	Circulating Fluidized-Bed Combustion
Cl ₂	Chlorine
CuO	Copper Oxide
CuSO ₄	Copper Sulfate
DOE	Department of Energy
ECTL	Environmental Control Technology Laboratory
EHE	External Heat Exchanger
ESP	Electrostatic Precipitator
FBC	Fluidized-Bed Combustion
HCl	Hydrochloric
HHV	High Heat Value
I.D.	Inside Diameter
MFC	Mass Flow Controller
NETL	National Energy Technology Laboratory
NO _x	Nitrogen Oxides
O.D.	Outside Diameter
PID	Proportional, Integral, Derivative
RDF	Refuse-Derived Fuel
SO ₂	Sulfur Dioxide
SO _x	Sulfur Oxides
U.S.	the United States

EXECUTIVE SUMMARY

The primary objective of this project is to establish an Environmental Control Technology Laboratory using a circulating fluidized-bed combustion (CFBC) system for investigating and controlling air pollutant emissions and provide a thorough understanding of combustion related air pollutant emissions in the United States. Therefore, the key part of this project is to design and construct a multi-purpose CFBC system, and to conduct an experimental investigation of its capabilities. In the first quarter of this project, the work primarily focused on the designing of the CFBC facility, and renovation of the new combustion laboratory where this CFBC facility will be constructed.

The purpose of this report is to summarize the progress made on this project in the first quarter. The main accomplishments of the research during this reporting period include the following parts. (1) Management documents prepared and finalized. The project management plan for 2004 fiscal year has been prepared. This plan established the milestones that are expected to be achieved in each quarter. The estimated expenditures for this project in the 2004 Fiscal Year have also been included in this plan. In Hazardous Substance Plan, the potential waste materials generated from this project have been listed and described. The corresponding EPA codes for these hazardous substances have been given. The possible methods used to treat these materials have also been provided in this plan. (2) Current situation on renovating the space for the new combustion laboratory. Renovation of the new combustion lab has been moved forward on schedule. The design of the combustor building housing the CFBC facility has been finished. (3) Progress on designing of the CFBC facility. Based on the collected information and experience of the Materials Characterization Center with various applications, Plan B, called the Stainless Steel Structure, will most likely be chosen for this CFBC facility. The potential problems for this plan have been discussed in this report, and the solutions to solve these problems have been provided and described also. (4) a lab-scale simulated fluidized-bed combustion (FBC) facility which has been setup in MCC Combustion Lab. Before 0.6MWth CFBC facility is built completely, a series of

fundamental researches on the formation of pollutants, such as organic compounds – PAHs, PCDD/Fs from the combustion or pyrolysis of biomass or refuse-derived fuels (RDF) with high sulfur coal, will be studied. Meanwhile, the occurrence and release of heavy metals, such as mercury, arsenic, and selenium, from the combustion of biomass or refuse-derived fuels (RDF) with high sulfur coal will also be investigated on this lab-scale simulated fluidized-bed combustion facility. Finally, the outline of work to be performed in the next quarter is introduced briefly.

EXPERIMENTAL

Renovation of the Space for the New Combustion Laboratory

In this quarter, work was concentrated on two tasks. Task one is the renovation of an existing building for the development of the Combustion Laboratory. Task two is the construction of a new steel frame building, which borders the combustion laboratory, to house and support the bench-scale (0.6 MW_{th}) CFBC system. In cooperation with the architects, the Combustion Laboratory room sizes, layout, equipment and all utilities have been identified and specified. Additionally, room size and height to house and support the bench-scale combustor, as well as, all utilities have been determined. During this period, conferences with the architects were held in which many details of room layout, utilities, ventilation, lighting, as well as structural details of the new combustor building were better defined. Specific details needed for completion of the architectural design were identified and are in the process of being reported to the architect.

Since the CFBC system will be housed in a newly constructed building, it will derive many support functions from the attached Combustion Laboratory facility. For example, electric power service equipment and the combustion air compressors will be housed in rooms of the newly renovated Combustion Laboratory. Also fuel preparation, storage and analysis will take place in different rooms of the Combustion Laboratory facility. Figure 1 shows the layout of this new combustion lab. Additionally, the combustor control room, service shop, and some facilities for flue gas analysis will be located in the Combustion Laboratory. Therefore, the combustor building construction and combustion laboratory renovation features that are dictated by combustor

requirements have been given to the architect for consideration and development. Initial design and construction activities consist of identifying the size of electric service components, both for the combustor operation and fuel preparation equipment, including associated dust control equipment. The overall design calls for a cooling water supply and outdoor heat rejection equipment, building ventilation and space allocation for flue gas handling equipment, such as electrostatic precipitators (ESP), bag house/fabric particulate filters, and induced draft fans. Floor cut-outs for the main combustor riser, fuel bunkers, fuel feeders, and ash return downcomer have been developed. These activities include as follows:

Figure 1. Layout of the New Combustion Laboratory

- Determine size (foot-print) of main components of combustor.
- Determine floor space size and allocation for the Combustion Laboratory and combustor building, including the height of the combustor building.
- Establish heat rejection facility size and location, operating temperature, and tentative design type.
- Calculate the size of utility services, such as electric power, natural gas, and compressed air.

- Design ventilation, heating, and air conditioning requirements for the Combustion Laboratory and the combustor building.
- Assist and consult with the architects upon selection of contractors for renovation of the space for the Combustion Laboratory and construction of the combustor building. The CFBC Room is 30 ft. x 48 ft. for only the first level, equal in height to the renovated Combustion Laboratory height. The part of the CFBC Room above this level is only 30 ft. x 30 ft.

Bench-scale 0.6 MW_{th} CFBC Facility

(a). Design Parameters of the CFBC Facility

The main design parameters of the CFBC facility are listed in Table 1.

Table 1. Design Parameters of the CFBC Facility.

Parameter	Unit	Value
CFBC Thermal Input	MW _{th}	0.6
Inside Diameter of Dense Zone	inch	12
Gas Velocity in Dense Zone	ft/s	24.57
Inside Diameter of Dilute Zone	inch	15.25
Gas Velocity in Dilute Zone	ft/s	22.40
Effective Combustion Height	feet	64.5
Fraction of Primary Air		0.7
Heat of Design Fuel – Kentucky High Sulfur Coal (~4% Sulfur Content)	Btu/lb (HHV)	11,650
Coal Feed Rate	lb/h	176
Average Diameter of Bed Materials	inch	0.0315
Gas Residence Time in Dense Zone	s	~0.5
Gas Residence Time in Dilute Zone	s	~2.5
Solid Recirculation Ratio		30
Bed Temperature in Dense Zone	°F	1562
Combustor Operating Pressure	psia	Atmospheric pressure

The thermal input of this CFBC facility is 0.6 MW, the overall bed height is 67.5 feet, which includes a 3-foot high wind box, an 11.5-foot high dense zone, and a 53-foot high dilute zone. The inside diameter of the dense zone is 12 inches, and the inside diameter of the dilute zone is 15.25 inches. This arrangement allows a certain amount of secondary air to be supplied into the combustor in order to control emission and combustion. A reducer is used to connect these two different size sections together. The design fuel is a Kentucky, high-sulfur bituminous coal which contains about 4 % sulfur in weight. To reach the goal of uniform bed temperature, the maximum temperature difference along the bed height will be controlled within 90°F. This CFBC facility will operate at atmospheric pressure.

Figure 2. CFBC Plan A Segment.

(b). Structure Plan of the CFBC Facility

From the beginning, two plans with different structures for the riser of the CFBC system have been considered. Plan A is called a Carbon Steel Structure. Figure 2 shows a

demonstration element of Plan A. Refractory and insulation lining is installed inside the carbon steel pipes. Plan B is called a Stainless Steel Structure. Two semi-cylindrical insulation materials are wrapped outside the stainless steel pipe. Figure 3 illustrates a demonstration element of Plan B. Because of the direct contact of the alloy with the high temperature flue gas and particles, the Type 310 stainless steel will be employed for Plan B.

The comparisons between these two structures are shown in Table 2. The advantages of Plan A are low capital cost and small thermal expansion. The main disadvantage is that the use of refractory materials makes it a heavy structure. Spallation of the refractory materials is another concern. For Plan B, the main benefits are possible multi-purpose applications and light weight. The major concerns are expense and thermal expansion.

Figure 3. CFBC Plan B Segment.

Table 2. Comparisons Between Plans A and B for the CFBC Structure.

	Plan A	Plan B
Description	<ul style="list-style-type: none"> • Carbon steel pipes and flanges as outside-shell • Refractory and insulation lining inside the carbon steel pipes 	<ul style="list-style-type: none"> • Type 310 stainless steel pipes and flanges • Light semi-cylindrical insulation materials wrapped outside the pipes
Advantages	<ul style="list-style-type: none"> • Low capital cost • Low thermal expansion of carbon steel pipes due to low surface temperature • Refractory and insulation can be repaired after corrosion and erosion. 	<ul style="list-style-type: none"> • Light weight • Beneficial to the multi-purposes applications, such as gasification and investigation of particle attrition during the combustion. • Flexible arrangement of heat exchange surfaces.
Disadvantages	<ul style="list-style-type: none"> • Easy leakage between two sections. • Difficult arrangement of the heat exchange tubes • Heavy weight • Spallation of refractory. 	<ul style="list-style-type: none"> • High cost • High thermal expansion of Type 310 stainless steel pipes due to the high temperature. • To avoid corrosion and erosion, the ceramic coating on inside surface is needed.

Installation of the Lab-Scale Simulated FBC Facility

Before the 0.6 MW_{th} CFBC facility is built completely, some fundamental studies will be investigated on a lab-scale simulated FBC facility. First, the mechanisms for the formation of pollutants, such as organic compounds – PAHs as well as PCDD/Fs

Figure 4. Schematic of the CFBC System.

from the combustion and pyrolysis of biomass and refuse-derived fuels (RDF) with high sulfur coal will be studied. Second, the occurrence and release of heavy metals, such as mercury, arsenic, and selenium, from the combustion of biomass and refuse-derived fuels (RDF) with high sulfur coal will be investigated. The results obtained from the lab-scale simulated FBC facility will be helpful for carrying out future experiments with the bench-scale CFBC facility.

(a). Installation of a Lab-Scale Simulated FBC Facility

A lab-scale simulated FBC facility has been remodeled and installed. Figure 5 is the schematic of this lab-scale FBC facility. The main body of this FBC is made of stainless steel pipe. Its inside diameter is 50 mm, and its effective bed height is 700 mm. The electric heaters (total four electric heating bars) are used to heat the FBC to the desired temperature from the outside. Heat loss is kept to a minimum by wrapping refractory and insulation materials outside the electric heaters. The compressed air regulated by a regulator is supplied into this FBC through the bottom windbox and gas distributor. Coal is fed continuously into the FBC by a screw feeder. The feed rate can vary from 100 to 200 g/h. The average particle size is about 0.5 mm. The bed temperature will be controlled around 800-900°C. The flue gas exiting from the top of the FBC is cleaned by a cyclone and cooled by a cooler, then sent to a flue gas analyzer to measure its composition.

(b). Preparation of Control and Measurement Instruments

In order to monitor the combustion temperature inside the bed, a thermocouple (1/8 inch O.D.) is inserted into the FBC from the top cover. A Proportional, Integral, and Derivative (PID) controller is used to control the heat bars to heat the bed to the desired temperature. After the compressed air is regulated by a pressure regulator, a mass flow controller (MFC) is employed to control and monitor the air flowrate entering the lab-scale FBC facility. The fuel is fed into the lab-scale FBC through a mini-screw feeder. The feeding rate can be controlled by adjusting the rotation speed of a DC motor. After cooling and cleaning, flue gas exiting from this FBC is led into a flue gas analyzer to

determine the gas compositions. A Semi-Continuous Emission Monitor (SCEM) is used to detect the mercury emission from the lab-scale FBC on-line.

Figure 5. Schematic of the 50 mm I.D. Lab-Scale FBC Facility.

RESULTS AND DISCUSSION

Project Management and Planning

Based on the requirements of the Cooperative Agreement, the following plans have been submitted:

- a. Project Management Plan for the 2004 Fiscal Year. This plan established the milestones that are expected to be achieved in each quarter. The estimated expenditures for this project in the 2004 Fiscal Year have also been included in this plan.
- b. Hazardous Substance Plan. In this plan, the potential waste materials generated from this project have been listed and described. The corresponding EPA codes for these hazardous substances have been given. The possible methods used to treat these materials have also been provided in this plan.

An internal Staffing Plan and a Project Management Plan have been developed to manage this project effectively. In these plans, the total tasks for designing and constructing the CFBC system are summarized, and the manpower needed to accomplish these tasks has been estimated. Every task is assigned to a particular individual who is responsible for meeting the requested schedule.

Collection of Information for Designing 0.6MW_{th} CFBC Facility

The CFBC facility is also expected to be used to develop other advanced combustion technologies, such as the oxygen-enhanced combustion and solid-fuel chemical looping combustion. With minor modifications in the future, Plan B is the most likely structure for these purposes. However, before reaching this decision, problems such as thermal expansion, corrosion and erosion must be solved. Several organizations that have experience with using stainless steel pipes to build CFBC systems have been and will continue to be consulted. These organizations include the Korean Institute of Energy Research, Southeastern University in China, the National Energy Technology Laboratory (NETL), Tsinghua University in China, and Southern Company in Alabama. Several issues have been addressed, such as deformation in the horizontal direction and the twist of stainless steel pipes, and the support and suspension of the CFBC system.

Design of the CFBC Facility

Based on the collected information and experience of the Materials Characterization Center with various applications, Plan B, called the Stainless Steel Structure, will most likely be chosen. For resistance to the high temperature operating environment, Type 310 stainless steel pipes and flanges will be used to build this CFBC. Figure 3 shows the schematic drawing of this CFBC facility. To control the gas velocities in the dense and dilute zones, the inside diameter of the dense zone is 12 inch, while the inside diameter of the dilute zone is 15.25 inch. The wall thickness of the stainless steel pipes is 0.375 inch. The outside of the Type 310 stainless steel riser is wrapped with 5 inch thick insulation materials to keep the heat loss to a minimum. The riser of the CFBC consists of 12 elements of such stainless steel pipes, with each element of 5 foot long. The bottom section is a 3-foot high windbox where the air enters the CFBC system. A water-cooling air distributor will be used for the facility. An 18-inch high reducer connects the dense zone (I.D. 12 inches) with the dilute zone (I.D. 15.25 inches). To control the bed temperature, the water-cooling jackets are arranged outside pipes of several elements to absorb the heat from the CFBC. Secondary air nozzles will be deployed in three layers along the CFBC riser in the dilute zone for investigating stage combustion. A primary cyclone with a water-cooling surface is connected with the combustor exit at the top of CFBC riser. To reach a high ratio of solids circulation, a secondary cyclone is also used. The solids separated from the gas stream by cyclones fall along the standpipe, which is made of stainless steel pipes (I.D. 5.047 inch). After cooling down in an external heat exchanger (EHE), these solids are fed into the dense zone of the CFBC by a non-mechanical valve. The fuels and limestone are fed into the CFBC by a series of augers, three feeding ports are located in three different levels, so it will be convenient to change the feeding location based on the characteristics of fuels. Two discharge ports will be used to withdraw fuel and limestone residues. One is at the bottom for bed ash, another is at the EHE for fly ash disposal. Sight glasses are arranged along the bed height for convenient observation. Pressure and thermocouple ports are located along the bed height also.

Solutions to Potential Problems in Designing 0.6MW_{th} CFBC Facility

Thermal Expansion: Based on the information collected from other organizations and subsequent calculations, thermal expansion must be taken into account due to the significant changes in the temperature in the process of start-up, operation, and shut-down of the CFBC facility. In the current design, the riser of the CFBC is divided into three sections. The bottom section, including the wind box, is 24.5-feet high. This section will be hung from the platform which the fuel augers sit on. Therefore, this section expands downward freely. The middle section, which is 20 feet long, sits on that platform. The weights of the middle section and bottom section are supported by this platform. The thermal expansion of this section goes upward with the increase in temperature. The 20 feet high top section with the cyclones will be hung from the uppermost support frame. So the top section expands downward. Between the middle and top sections, there is a 3 feet high expansion joint to compensate the upward expansion of the middle section and the downward expansion of the top section. Such arrangements make the thermal expansion of each section small enough to be handled and avoid deformation (creeping and rupture) caused by adding the total weight of the CFBC to an element. To prevent deformation and twist in the horizontal direction, three wheels fixed to the building supports, running in tracks attached to the riser of the CFBC, will be provided at each location. Several locations are arranged along the bed height. Therefore, the riser of the CFBC can only move in the vertical direction, deformation and twist in the horizontal direction are eliminated. The outside cooling jacket deployed at the bottom element of the middle section and the top element of the bottom section is the second part to prevent from deforming.

Heat Transfer: Bed temperature is one of the critical operating parameters of the CFBC system. Several methods are used to control the bed temperature. First, an external heat exchanger is located in the solid recirculation loop. The high temperature solids from cyclones are cooled down in this heat exchanger, then fed into the dense zone of the CFBC. The recirculated solids temperature can be controlled by adjusting the heat absorbed through the heat exchange tubes. Second, there are stainless steel pipe elements on the CFBC riser, one is just above the support platform and another is just below the heat exchange channels outside the stainless steel pipes. The heat exchange channels are

welded with the outside surface of each stainless steel pipe vertical, the total of 36 channels are divided into three groups. The flow rate of cooling water entering each group can be regulated independently, so the heat absorbed from the CFBC can be adjusted by shutting down one or two groups. Another reason to arrange the water-cooling heat exchange surfaces on these two sections is to reduce the temperature of the stainless steel pipe, further, to avoid the decrease of the strength of the stainless steel pipe significantly with the increase of the temperature. Finally, the primary cyclone with the water cooled heat exchange surface provides an extra measure for controlling the bed temperature. This heat exchange surface has similar construction with that used on the stainless steel pipe of the CFBC riser.

Corrosion and Erosion: Corrosion and erosion were taken into account during the design of this CFBC system, because corrosion and erosion are issues often met in the operation of the CFBC facility. In order to avoid serious erosion, a relative low gas velocity will be controlled in each zone. Since two-stage combustion will be employed in this CFBC system, the inside diameter of the dilute zone is enlarged from 12 inches in the dense zone to 15.25 inches in order to reduce the effect on the gas velocity due to the input of secondary air. To enhance the lifetime of the stainless steel pipes, the inside surface of several stainless steel pipe sections where the worst corrosion and erosion could take place will be coated with special materials. These places are the dense zone, the transition zone between the dense zone and the dilute zone, and the exit area of CFBC's riser. The coating layer (about 100 μm thick) not only can protect the inside surface from corrosion and erosion, but also can reduce the temperature of the stainless steel pipes. Based on NETL's experience, the erosion could become worse if the riser exit were close to the top cover of the CFBC's riser. In this design, the riser exit is located 1 foot below the top cover of the CFBC's riser to reduce erosion caused by the flow direction change and turbulence of gas stream carried solids. The primary cyclone also experiences serious erosion, particularly in its inlet area, due to the high velocity of the gas stream with high concentration of solids and high temperature in that area. The primary cyclone consists of two sections. The first section is the inlet part with the inside surface coating, and the second section includes the main straight part with the water-cooled heat exchange surface and cone part with the dip leg. Such design allows

replacing the first section easily and economically in case this section is damaged by erosion.

CONCLUSION

In the first quarter of this project, progress on the following tasks has been made:

- ◆ Designs and plans for renovating space for the New Combustion Laboratory have been finished, and the design and construction work is going forward on schedule.
- ◆ The design plan for the CFBC system has been finalized based on the information collected. Heat balance and heat transfer calculations have been made, and some key assembly parts have been designed in detail.
- ◆ Preparation work has been done for some fundamental research on a simulated FBC system.

FUTURE WORK

In the next quarter, work will be focused on the following areas:

- (1). Continue Construction of the New Combustion Laboratory.

Construction contracts for both tasks will be awarded and the renovation of the space for the Combustion Laboratory will begin. Construction of the new combustor building will start in the next quarter. The internal arrangement in this building will be considered, and the platform used for supporting the CFBC system will be designed in detail.

- (2). Parts design for the CFBC

Based on the drawings of the CFBC system and key assembly parts, all component parts of the CFBC system will be designed and drawn in detail, in order for manufacturer to process these parts.

- (3). Order the materials and equipment needed for the CFBC

Materials needed for constructing this CFBC facility will be purchased from suppliers. These materials include stainless steel pipes, flanges, insulation materials, bolts

and nuts, gaskets, and so on. Equipment required by this CFBC system will be ordered also in next quarter. They are a forced draft fan, an induced draft fan, augers for fuel and limestone feeding, water pumps and motors. At the same time, the manufacturers will be chosen for welding, coating and drilling the stainless steel pipes and flanges.

(4). Start Experiments on the Lab-Scale Simulated FBC Facility.

The following experiments will be conducted on this lab-scale simulated FBC facility in the next quarter:

- a. Investigation of conditions for oxidation of hydro chloride (HCl) to chlorine (Cl_2) (Deacon reaction) in a flue gas atmosphere. The effects of reaction temperature, hydrogen chloride, and oxygen concentrations in the flue gas, reaction time, and catalysts in fly ash on the formation of molecular chlorine will be studied with simulated FBC flue gas and operating conditions.
- b. Study of reaction conditions for copper oxide (CuO), oxygen (O_2) and sulfur dioxide (SO_2) to form copper sulfate (CuSO_4). The conditions for the formation of CuSO_4 (catalyst) will be determined. Also, the influence of limestone on formation of CuSO_4 will be investigated experimentally.

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