

SUBTASK 3.12 – OXYGEN-FIRED CFBC

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ABSTRACT

Traditionally, air is used as the source of oxygen for firing a combustion system. A fully oxygen-fired circulating fluidized-bed combustion (CFBC) system would result in the production of a flue gas stream consisting of mostly carbon dioxide and water. The concentrated carbon dioxide stream would be available for sequestering or other purposes. Temperatures in an oxygen-blown CFBC system would be controlled by a combination of flue gas recycle, solids recirculation, and by appropriately sizing and locating the amount of heat-transfer surface required.

Flue gas recycle provides the additional gas required for adequate fluidization and circulation of solids replacing the nitrogen that would be present in an air-blown system. The amount of flue gas recycle will determine how much of the remaining heat from the coal combustion will have to be removed. If the amount of flue gas recycle required by increasing solids recirculation and oxygen staging is limited, introducing the pure oxygen at multiple locations in the combustor to result in a more even temperature profile should result in a more compact system, thus reducing initial capital costs for construction. The overall efficiency of the process should be greater than that of an air-blown system since less fuel is required for the creation of the same amount of energy.

The Energy & Environmental Research Center (EERC) is in a unique position to advance this technology. It has a world-class CFBC pilot plant, has experience with firing a wide range of fuels in our air-fired CFBC pilot plant, has prior experience with oxygen-firing a slagging furnace system in a pulverized coal-fired mode with a bituminous coal, and has all of the components required for oxygen-firing right next to the CFBC pilot plant already in place.

An engineering study was performed to identify methods, an overall appropriate configuration, and an operating strategy for a fully oxygen-fired CFBC pilot plant by 1) developing a plan to optimize the amount of flue gas recycle required to control bed temperature; 2) determining how to best utilize the heat-transfer surfaces in a CFBC pilot plant, such as increased external bed surface, to more beneficially use increased solids recycle; 3) identifying appropriate methods for staged addition of the oxygen/recycled flue gas streams to maintain a good temperature profile in the combustor; and 4) determining the level of effort required to convert the EERC CFBC pilot plant to one that is oxygen-blown. The EERC additionally used its experience to consider what would be required for firing a wide range of fuels from biomass to low-rank coals to high-rank coals and petroleum cokes.

These proposed modifications will be performed based upon obtaining the required funding.

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EXECUTIVE SUMMARY

A study was performed to assess the conversion of the existing Energy & Environmental Research Center (EERC) pilot-scale circulating fluidized-bed combustor to a fully oxygen-blown system in a cost-effective manner. With the combination of pure oxygen addition and flue gas recirculation, a product gas stream very high in the concentration of carbon dioxide could be produced that could be beneficially used in another process or more easily sequestered. Another objective for oxygen-firing would be to significantly increase the overall process efficiency by increasing fuel throughput and by improving heat transfer. The EERC has the majority of the key components on-site to accomplish the modification in a cost-effective manner. It is estimated that \$199,000 in 2006 dollars would be required for equipment and modifications to accomplish this conversion. The proposed modifications will be performed based upon obtaining the required funding.

Significant modifications would include:

- Plumbing modifications to existing oxygen infrastructure
- Purchase of additional induced draft fan for flue gas recycle
- Installation of existing quench water scrubber to remove water vapor from a portion of the recycle flue gas
- Plumbing to install the induced draft fan and quench the water scrubber
- Installation of refractory in the primary cyclone to improve cyclone efficiency
- Modifications to install additional oxygen injection ports in the combustor
- Instrumentation required to measure and control flue gas and recycle gas flows in the system

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RESULTS AND DISCUSSION

Figure 1 is a schematic showing the present configuration of the Energy & Environmental Research Center (EERC) circulating fluidized-bed combustor (CFBC) pilot plant. Figure 2 shows the planned configuration for the EERC CFBC pilot plant modified for oxygen-blown operation. Figure 3 has cross-sectional views of all the refractory-lined components of the EERC CFBC modified for oxygen-blown operation.

Flue Gas Recycle Optimization

It was planned to optimize the amount of flue gas recycled to improve process efficiency. Calculations as well as experience with previous oxygen-blown combustion show that the required flue gas recycle would be dictated by a combination of the oxygen addition rate along with the firing rate to arrive at the desired operational velocity and excess air/oxygen level for a given amount of heat-transfer surface. Therefore, it is not likely that flue gas recycle could be optimized in any manner that would be beneficial to the process. Flue gas recycle should be considered as a dependent test variable instead of a control test variable. Appendix A describes and presents information on a spreadsheet developed to allow estimation of fuel and makeup O₂ requirements (mass and volume) for firing the EERC CFBC in a fully oxygen-blown mode of operation.

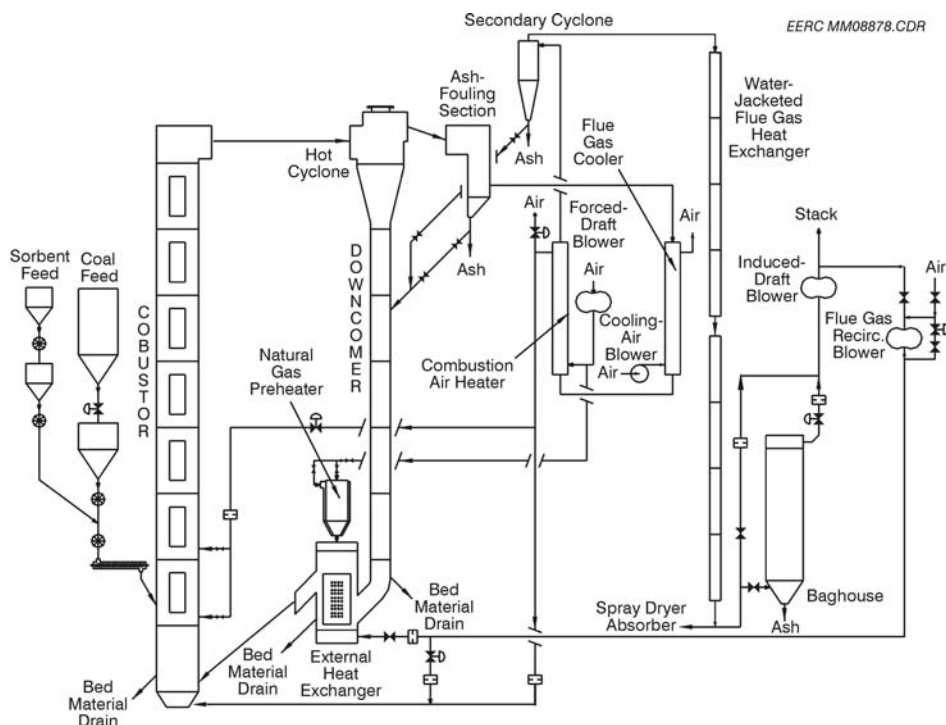


Figure 1. Existing EERC air-blown CFBC pilot plant.

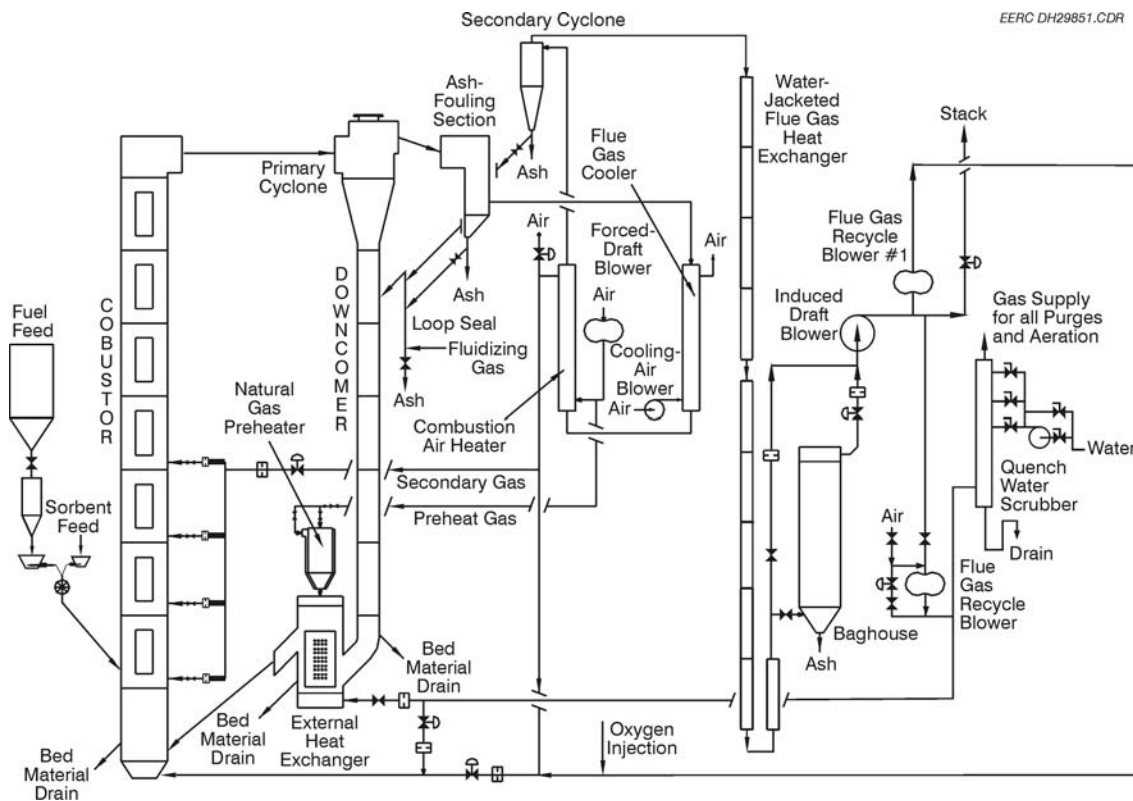


Figure 2. Proposed EERC O₂ CFBC pilot plant.

Staged Oxygen Addition

It would be possible to add oxygen to the recycled flue gas in a single location and then split the flow between the primary and secondary fluidizing gas. The addition of oxygen (not shown in Figure 2) at multiple elevations, with the added capability of controlling the oxygen concentration at these locations, could have some potential benefits. A more controlled staging oxygen addition would allow for better temperature control to potentially reduce localized hot spots in the lower portion where the oxygen would normally be introduced for the complete combustion of the coal. It could possibly result in some reduction of the emissions of nitrogen oxides and sulfur dioxides by better controlling temperature profiles in the combustor. Testing would be required to verify if there are potential benefits of increasing the number of oxygen injection locations as opposed to having simply a single location for oxygen addition prior to where the primary and secondary gas streams split. The CFBC pilot plant could be reconfigured using some of the existing 3-inch manual gate valves from the second level of secondary air addition. Two additional penetrations could be made into the combustor for this evaluation. The existing pipe manifold would have to be modified. Orifices with differential pressure gauges would be installed as a cost-effective method of manually measuring the flow rates at the different levels. Total secondary gas flow would still be measured by the existing system, providing an input to the data acquisition system. Additional small diameter plumbing would be required from the existing four oxygen mass flow meters.

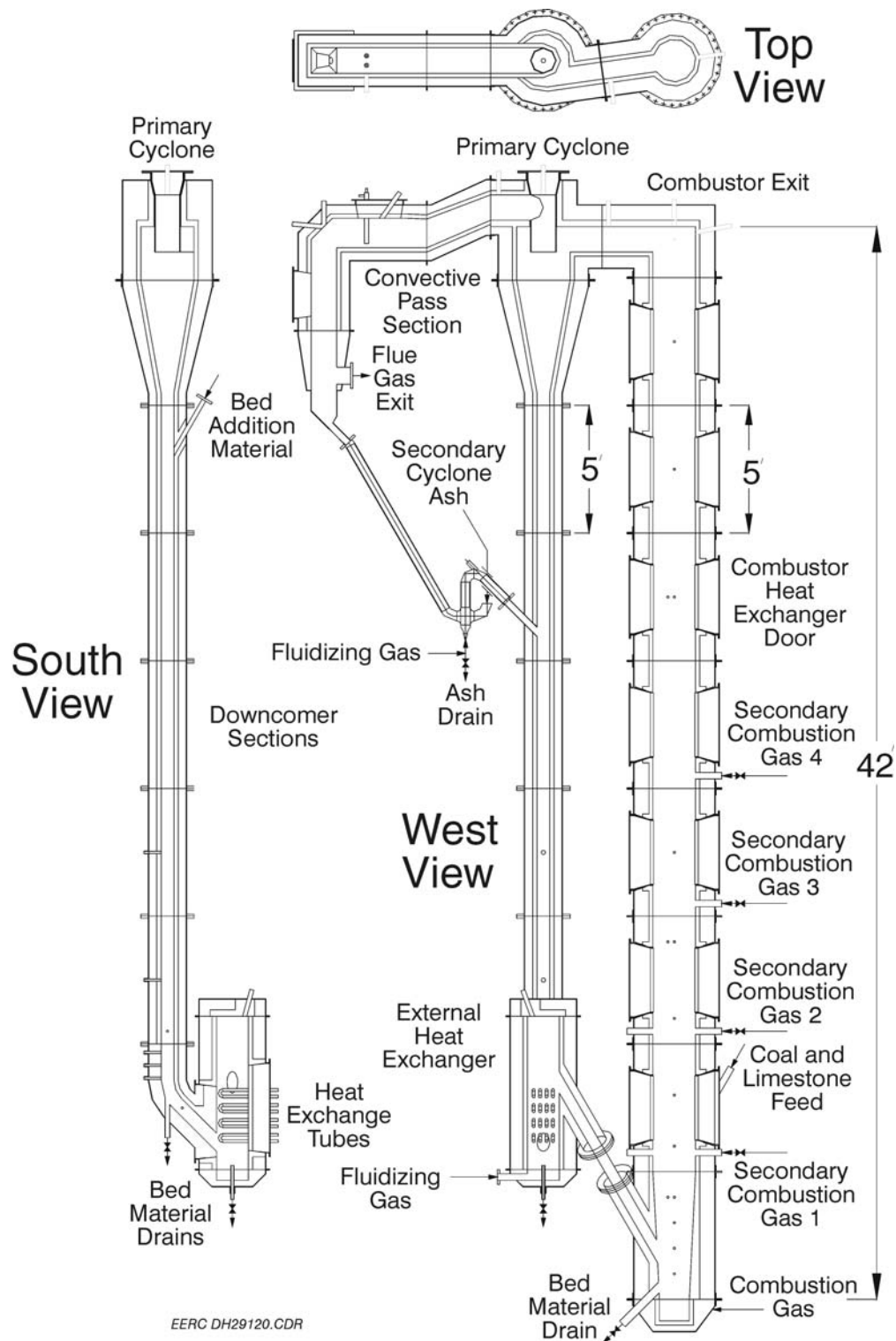


Figure 3. Cross-sectional view of the proposed EERC O₂ CFBC pilot plant.

Solids Recirculation

Recirculation rate is affected by the overall inventory of solids present, by the collection efficiency of the collection device capturing the solids, and by the system for returning the solids. Currently, hot solids (1450°–1650°F) are collected by the primary cyclone where they flow into the downcomer. The return portion of this system is well suited for the collection of these solids for recirculation and would not have to be modified. The collection efficiency of the primary cyclone could potentially be improved by a change in the geometry of the entrance duct into the cyclone. The entrance duct was purposely oversized so that a portion of the entrained solids impact the vortex finder, in an attempt to detune this cyclone and collect a size distribution of solids more representative of what would be collected in a full-scale system. This actually allowed more solids to pass through the primary cyclone than expected. A secondary cyclone added downstream of the ash fouling section collects a significant portion of the ash and bed material that pass through the primary cyclone. The solids collected by the secondary cyclone can be, in any combination, recirculated back to the downcomer or drained to a barrel.

Modification of the primary cyclone would consist of adding 2 inches of refractory to its entrance, which would change the inlet width from 8 inches to 6 inches. This would increase the entrance velocity by 25 percent, and more significantly, the inlet stream would not impact the vortex finder. This should significantly improve collection efficiency while resulting in a slight increase of the pressure drop across the cyclone. The goal would be to have the size distribution of solids captured by the primary cyclone be more comparable to a full-scale CFBC. The quantity of solids having to be recirculated back from the secondary cyclone would then be significantly reduced or eliminated.

Currently, a small amount of downstream solids (900°–1100°F) drop out and are collected at the exit of the convective pass section. These solids and those collected by the secondary cyclone (500°–600°F) are dropped in the upper portion of the downcomer through a series of valves and pipe sections, acting as small lock hopper sections. While reasonably good success has been achieved with this system, it potentially limits recirculation rates and does not provide a steady stream of solids because it is a batch/continuous instead of a continuous feed system. The valves in this system have to be cycled frequently to keep the solids moving, resulting in significant maintenance requirements to keep them operational. The valves in the higher-temperature regions are particularly subject to leakage of gas and solids.

A recirculation loop seal would eliminate the two valves for cycling the hot solids from the convective pass section and eliminate one of the valves required for recirculating secondary cyclone solids. The option of periodically diverting solids from the secondary cyclone to a barrel if the overall solids recirculation rate becomes too high would still be retained as an important operational function. This would require that the top two valves for the secondary cyclone remain in place. These two valves are not cycled as often and are not subjected to the higher-temperature solids.

Moisture Removal From Recycled Flue Gas

During air-blown operation, air is used for downcomer aeration, for coal feed injection gas, and for all of the pressure tap purges. Additional fluidizing gas would also be required for the solids going through the solids recirculation loop seal. If air is used, the nitrogen in the air would significantly dilute the carbon dioxide concentration of the product gas produced by this process. Recycled flue gas can potentially be used in place of air to eliminate nitrogen contamination of the product gas. Moisture in the flue gas would have to be removed from the recycled flue gas used in these locations so that it would not condense out in any flowmeters or in the coal feed system, potentially plugging it up. Moisture can be removed by use of either a water scrubber or condenser. An existing water quench scrubbing system from the EERC slagging furnace system (SFS) is planned to be used for use to remove the moisture from the recycled flue gas being used for aeration or as a coal feed assist. This quench system has already been successfully used for oxygen-firing with the SFS. The amount of flue gas recycled requiring scrubbing has been calculated to be less than what was required for the SFS, so this scrubber will allow for some excess capacity and is well suited for this application. Since it will have to be run at a higher pressure, it will be modified by increasing the length of the water seal leg at the bottom of the scrubber.

Flue Gas Recycle Fan Upgrades

For this process it is more efficient and allows for better operational control to have a second fan or blower dedicated to flue gas recirculation in addition to an induced-draft (ID) fan or blower. The existing flue gas recirculation blower is not adequate to handle all of the flow required. It is proposed here that a new variable speed centrifugal fan be purchased to be used as an ID fan. Then the existing ID blower would be converted to a flue gas recirculation blower (now identified as flue gas recirculation Blower 2) where it would supply the primary and secondary gas to the combustor. The existing flue gas recirculation blower (now identified as flue gas recirculation Blower 1) would still be retained to supply fluidizing flue gas to the external heat exchanger and would also supply the flue gas to the water quench scrubber system. It would be beneficial to retain this blower since it can supply a higher-pressure gas up to 6 psig, compared to 2 psig for Blower 2. Blower 1 would still be used to supply fluidizing air to the external heat exchanger when operating in the air-blown mode.

Heat-Transfer Surface Area

Initial evaluations and reviews of the past heat transfer test data for this system indicated that no additional heat-transfer surface would be required for this modification. There was originally designed a conservatively large amount of heat surface area available between the water-cooled door panels in the combustor and the tubes in the external heat exchanger that would be adequate for a wide range of test fuels. In the combustor, two more cooling panels could be added, if required. New panels would have to be fabricated for this installation. While possible, it would be difficult and expensive to modify the external heat exchanger for installation of additional heat exchange area. Presently, it is not planned to add additional heat transfer area for this testing.

Oxygen Supply and Metering

An on-site oxygen storage system is present at the EERC. A series of four mass flowmeters arranged in a parallel flow configuration are used for oxygen-blown operation on the EERC transport reactor development unit (TRDU) gasifier located immediately adjacent to the EERC CFBC system. These flowmeters can supply an amount of oxygen greater than would be required for firing the EERC CFBC in a fully oxygen-blown configuration. New oxygen-ready tubing, fittings, and valves to tie into the existing TRDU oxygen system would have to be purchased. It is planned to inject oxygen immediately prior to where the fluidizing gas supply pipe splits into the primary and secondary gas flow. Potentially, the flow nozzle used for the SFS could be used to disperse oxygen into the flue gas, or a flow nozzle of similar design could be fabricated for installation at this location. The capability also exists to split these flows for injection at multiple locations, as discussed earlier in this report.

Fuel and Sorbent Feed System

The existing solid fuel feed and sorbent feed system would have to be modified to eliminate the requirement for high-pressure air. An existing loss-in-weight K-Tron feeder previously used for biomass feed on the SFS is planned to be incorporated into the system to provide more accurate feed rates and to allow the use of recycled flue gas to be more easily incorporated. The auger that currently conveys coal or other solid fuels from the feeder to the combustor would be replaced with a pneumatic feed system. It is likely that one of the existing rotary valves will still be required to isolate the hot combustor gases from the solid fuel and sorbent feeders.

Additional Upgrades

There are, additionally, some key system components requiring upgrade or replacement to successfully complete this testing. The existing distributor plate was designed to operate over a very wide range of operating conditions up to a maximum superficial gas velocity of 23 ft/sec. Typically, operation has been within a superficial gas velocity ranging from 12 to 19 ft/sec. A new plate with fewer nozzles is planned that will provide good flow distribution while significantly reducing the amount of backsifting of solids into the combustor plenum. The existing exit flue gas orifice plate needs to be replaced with either a V-cone or venturi meter to provide a reliable measurement of the total flue gas. The existing data acquisition/control system is marginally adequate and due for replacement.

It is expected that the start-up procedure during the initial stages of heatup would be fairly similar to air-blown operation. The existing natural gas-fired burner in an air-blown mode can be used to preheat the system. During start-up, all the flue gas would go to the stack. When transitioning to or operating in an oxygen-blown mode, much less flow will go up the stack. A control valve will have to be installed at the entrance to the stack to result in some back pressure to eliminate the possibility of drawing air back through the stack with the flue gas recirculation blowers.

Cost Estimates

The estimated cost of completing this conversion is \$199,000 in 2006 dollars for equipment (\$81,000), supplies (\$4000) and labor (\$114,000).

Equipment required for this modification including estimated costs are as follows:

- ID blower (\$15,000)
- Pipe, valves, and small flow meters (\$21,000)
 - Large-diameter (2–8 inches) pipe, flanges, and fittings
 - Small-diameter (< 2-inch) pipe, tubing, fittings, and valves
 - Structural steel
 - Oxygen-ready pipe, tubing, and fittings
 - ▶ Large diameter valves
 - ▶ 4-inch control valve – primary combustion air
 - ▶ 6-inch manual valve – isolate exiting combustion air bypass line
 - ▶ 2-inch control valve – external heat-exchanger flow control
 - ▶ 8-inch control valve – stack flow control
 - Rotameter style flowmeters
 - ▶ 0–10 scfm – downcomer aeration – one
 - ▶ 0–20 scfm – coal feed venturi – one
 - ▶ 0–20 scfm – coal feed balance gas – one
 - ▶ 0–10 scfm – solids recirculation loop seal – one
 - ▶ 0–60 scfh – solids recirculation loop seal – two
- Instrumentation (\$45,000)
 - 6-inch V-cone – flue gas flow measurement
 - Oxygen sensors – two
 - Data acquisition control hardware/software
 - Electrical speed controller – FGR1 blower
 - Electrical speed controller – FGR2 blower

CONCLUSION

It is possible to convert the EERC air-blown CFBC pilot plant into an oxygen-blown system for the estimated cost of \$199,000 in 2006 dollars. It would then be capable of firing fuel in either a fully oxygen-blown configuration, a partial oxygen-blown system, or as still an air-blown system. This proposed modification will be performed if the required funding is obtained.

In summary, it is recommended that to complete the overall task of successfully converting the EERC CFBC pilot plant over to a system with 100% oxygen-firing capability, the following activities would be required:

- Modify the primary cyclone entrance
- Install new ID fan
- Install speed controllers on FGR1 and FGR2 blowers
- Modify flue gas pipe system to new ID fan
- Modify pipe from new ID fan to the stack
- Modify pipe run from FGR2 blower to the combustor primary and secondary gas supply
- Modify pipe run from new ID blower to FGR1 blower
- Relocate and install quench water scrubber
- Install pipe run from FGR1 blower to quench water scrubber and to the external heat exchanger
- Install new (V-cone, flow nozzle, or venture) flue gas measurement device
- Install solids recirculation loop seal system
- Modify and install new coal and limestone feed system
- Install pipe and tubing runs from quench water scrubber to purges, downcomer aeration, solids recirculation loop seal system, and coal and limestone feeder system
- Install oxygen feed system, including new tubing, valves, and fittings from existing TRDU oxygen mass flowmeters to CFBC
- Install oxygen sensors in the primary and secondary gas supply

- Construct and install new combustor distributor plate
- Install new data acquisition system

APPENDIX A

DEVELOPMENT OF A MASS BALANCE SPREADSHEET FOR AIR- AND OXYGEN-FIRING OF THE EERC CIRCULATING FLUID-BED COMBUSTOR

DEVELOPMENT OF A MASS BALANCE SPREADSHEET FOR AIR- AND OXYGEN-FIRING OF THE EERC CIRCULATING FLUID-BED COMBUSTOR

BACKGROUND

An Excel spreadsheet was developed to allow estimation of fuel and makeup O₂ requirements (mass and volume) for firing the EERC circulating fluid-bed combustor in an oxyfuel mode. In addition, the model allows estimation of the CO₂ concentration and mass rate for the flue gas that is vented from the system and can be used to estimate inputs and outputs for enriched O₂ (> 21% total input) firing. The model is based on a configuration utilizing flue gas recycle as a means of temperature control and fluidization within the combustor.

Inputs to the spreadsheet model include firing rate (Btu/hr), fuel type, percent excess O₂ in the flue gas, and volume rate of moisture-free flue gas (required for purges and fuel feed assist). A manual input, trial-and-error solution of the percentage of flue gas as recycle is required to close the balance. The spreadsheet user has the ability to select from four coal types, including Center lignite, Black Thunder subbituminous, Blacksville bituminous, and Salt Creek bituminous. Data available for each fuel include ultimate analysis, ash and moisture content, and higher heating value. User-defined fuel properties can also be input.

Outputs from the spreadsheet model include the percent O₂ in the recycle flue gas (after oxidant makeup) and volume rates of wet recycle flue gas and makeup O₂. The spreadsheet model also includes similar estimating capability for once-through air firing of the combustor. The balance results present mass rates for solid, liquid, and gas streams into and out of the combustor. For the gas stream exiting the combustor, the spreadsheet also estimates the molar and volumetric flow rates as well as the composition (volume basis) and molecular weight. With respect to the oxyfuel mode with flue gas recirculation, the spreadsheet model also presents the mass, molar, and volumetric flow rates for the recycle gas and the CO₂-rich vent gas.

Table A-1 presents a comparative summary of inputs and outputs when utilizing the air- and oxygen-firing mode. Table A-2 presents example results from the spreadsheet for the utilization of Center lignite as the fuel input. In the example presented, the mass rate of flue gas exiting the combustor is relatively unchanged although N₂ has been largely replaced by CO₂ and H₂O. The oxyfuel mode shows the significant potential to utilize this technology for producing CO₂-rich, sequestration-ready stream. The results also show that other trace effluents, such as SO₂, will be enriched through the recycle process. No attempt has been made to estimate the in-bed sulfur capture efficiency or the utilization rate of in-bed SO₂ sorbents.

Table A-1. Comparison of Inputs for Air-Firing Compared to Oxygen-Firing

	Air-Firing	Oxygen-Firing w/ Gas Recycle
Flue Gas, lb/hr	3081	944
Flue Gas, ft ³ /hr	40,320	11,550
H ₂ O, vol%	14.1	49.1
CO ₂ , vol% dry	16.1	94.9
N ₂ , vol% dry	80.3	0.6
O ₂ , vol% dry	3.55	3.93 [*]
SO ₂ , ppm dry	964	5700
Recycle Gas, lb/hr	NA	2193

^{*} Balance performed by keeping O₂ concentration at 2 vol% in the wet combustor flue gas.

Table A-2. Spreadsheet Example of Inputs and Calculations

Inputs											
Coal Type	Center Lignite										
Heat Input	3,000,000	Btu/hr	Input								
Coal	428	lb/hr	Calculated								
Relative Humidity		%	Input	Not currently used							
Air Temperature	70	F	Input	Not currently used							
Excess Air	20	vol or wt%	Input	2675.2	lb/hr Air	623.3	lb/hr O ₂	2229.4	0% Excess Air	lb/hr Air	519.4
Excess O ₂	3.75	vol or wt%	Input	(vary to obtain desired concentration of O ₂ in stack gas)							
Recycle Rate	69.9	vol or wt%	Adjust	to achieve desired O ₂ concentration in total recycle gas stream							
O ₂ in Recycle Gas	21.0	vol%	Calculated	(assuming split among dry and wet recycle gas)							
Dry Recycle Gas	0	scfm	Input	(for aeration, EHX, downcomer fluffing, purges, loop seal, feed assist)							
Wet Recycle Gas	447	scfm	Calculated	(for PA and SA)							
Makeup O ₂	108	scfm	Calculated								
Air Firing			In (lbs/hr)			Out (lbs/hr)			Gas Out Combustor and Stack		
			Solid	Gas	Total	Solid	Gas	Total	(lbs/hr)	(lb-moles/hr)	(sft ³ /hr)
H ₂ O			150.94				269.50		269.50	14.97	5675
H			13.17								
C			176.56								
N			2.44								
S			2.82								
O			59.58								
Ash			22.20			22.20					
Air				2675.22							
CO ₂							647.39		647.39	14.71	5576
SO ₂							5.64		5.64	0.0881	33.4
N ₂							2054.31		2054.31	73.37	27,807
O ₂							103.89		103.89	3.25	1230
Total			427.72	2675.22	3102.94	22.20	3080.73	3102.93	3080.73	106.39	40321
O ₂ -Firing with Flue Gas Recycle			In (lbs/hr)			Out (lbs/hr)			Gas Out Stack		
			Solid	Gas	Liquid	Total	Solid	Gas	Total	(lbs/hr)	(lb-moles/hr)
H ₂ O			150.94					895.36		269.50	14.97
H			13.17								
C			176.56								
N			2.44								
S			2.82								
O			59.58								
Ash			22.20				22.20				
Dry Recycle Gas				0.0							
Wet Recycle Gas				2193.3							
Makeup Water					0.0						
CO ₂							2150.80		647.39	14.71	5576
SO ₂							18.74		5.64	0.0881	33.4
N ₂							8.10		2.44	0.09	33
O ₂				545.41			64.71		19.48	0.61	231
Total			427.72	2738.66	0.00	3166.38	22.20	3137.72	3159.91	944.45	30.47

Continued...

Table A-2. Spreadsheet Example of Inputs and Calculations (continued)

O ₂ -Firing with Flue Gas Recycle	Gas Out Combustor					Wet Recycle Gas			Dry Recycle Gas to EHX, Purge			Wet Recycle Gas to PA, SA
	(lbs/hr)	(lb-moles/hr)	(sft ³ /hr)	(lbs/hr)	(lb-moles/hr)	(sft ³ /hr)	(lbs/hr)	(lb-moles/hr)	(sft ³ /hr)	(lbs/hr)	(lb-moles/hr)	(sft ³ /hr)
H ₂ O	895.36	49.74	18,852	625.86	34.77	13,178	0.00	0.00	0	625.86	34.77	13178
H												
C												
N												
S												
O												
Ash												
Dry Recycle Gas												
Wet Recycle Gas												
Makeup Water												
CO ₂	2150.80	48.88	18,526	1503.41	34.17	12,950	0.00	0.00	0	1503.41	34.17	12950
SO ₂	18.74	0.2925	110.9	13.10	0.2045	77.5	0.00	0.00	0	13.09	0.20	77
N ₂	8.10	0.29	110	5.66	0.20	77	0.00	0.00	0	5.66	0.20	77
O ₂	64.71	2.02	766	45.24	1.41	536	0.00	0.00	0	45.24	1.41	536
Total	3137.72	101.23	38,366	2193.26	70.76	26,817	0.00	0.00	0	2193.25	70.76	26,817.49