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EERC Pilot-Scale CFBC Evaluation Facility Project CFB Test Results

Topical Report
Task 1

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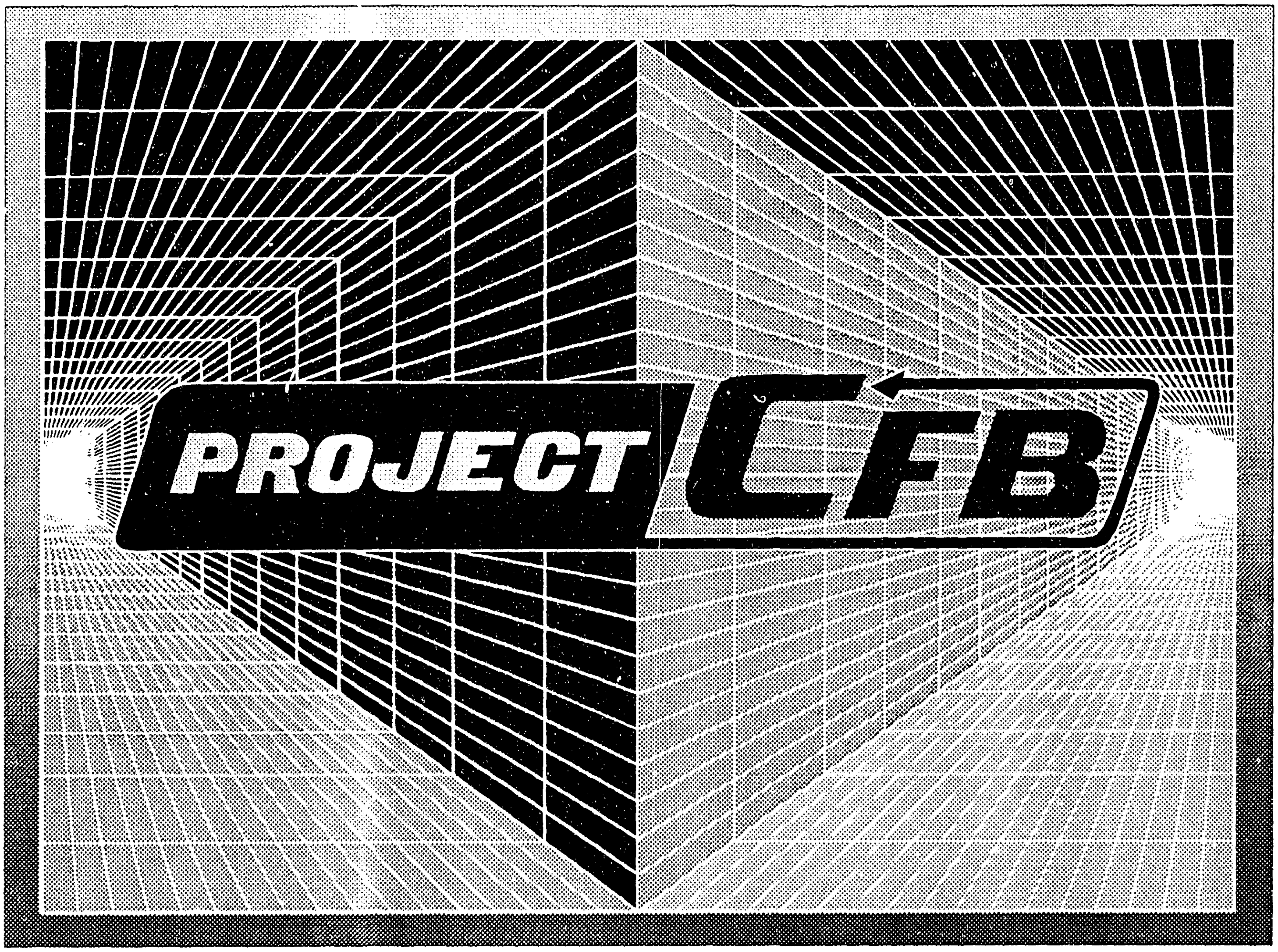

Project CFB Sponsors

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- North Dakota Lignite Research Council
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PROJECT CIRCULATING FLUIDIZED-BED

ABSTRACT

Project CFB was initiated at the University of North Dakota Energy and Environmental Research Center (EERC) in May 1988. Specific goals of the project were to 1) construct a circulating fluidized-bed combustor (CFBC) facility representative of the major boiler vendors' designs with the capability of producing scalable data, 2) develop a database for use in making future evaluations of CFBC technology, and 3) provide a facility for evaluating fuels, free of vendor bias, for use in the energy industry. Five coals were test-burned in the 1-MWth unit: North Dakota and Asian lignites, a Wyoming subbituminous, and Colorado and Pennsylvania bituminous coals. A total of 54 steady-state test periods were conducted, with the key test parameters being the average combustor temperature, excess air, superficial gas velocity, calcium-to-sulfur molar ratio, and the primary air-to-secondary air split.

The sulfur capture for a coal fired in a CFBC is primarily dependent upon the total alkali-to-sulfur ratio. The required alkali-to-sulfur ratio for 90% sulfur retention ranged from 1.4 to 4.9, depending upon coal type. While an alkali-to-sulfur ratio of 4.9 was required to meet 90% sulfur retention for the Salt Creek coal versus 1.4 for the Asian lignite, the total amount of sorbent addition required is much less for the Salt Creek coal, 4.2 pound sorbent per million Btu coal input, versus 62 pound/million Btu for the Asian lignite. The bituminous coals tested show optimal sulfur capture at combustor temperatures of approximately 1550°F, with low-rank coals having optimal sulfur capture approximately 100°F lower.

NO_x and N_2O emissions from the CFBC are highly coal dependent. The total amount of NO_x emitted, as well as the rate at which it changes with changes in combustor temperatures, varies with coal type. The rate of change is smallest with the lignites and largest with the bituminous coals. NO_x emissions also increase with increasing excess air and sorbent add rates. N_2O emissions increased as the rank changed from subbituminous to lignite to bituminous. The distribution of the nitrogen between the volatiles and the fixed carbon appears to be the most important fuel property affecting N_2O emissions. N_2O emissions show the opposite trend as NO_x, decreasing with increasing temperature and sorbent add rate, and a similar trend as NO_x for excess air.

Overall collection efficiency of solids in the main cyclone ranged from 93.8% to 99.9% and was adequate to maintain solids circulation for all the coals tested. For some tests, a secondary cyclone was employed to recycle some of the fine ash escaping the primary cyclone. The recycle of this material increased the recirculation rates. Recirculation rates decreased with decreasing velocity and bed inventory. Results indicated that for design of a full-scale system using low-ash, low-sulfur fuels, recycle from a secondary cyclone/multiclone or baghouse would be recommended to maintain bed inventory.

During testing with the North Dakota lignite, which contains 4% sodium in the ash, some bed material particle growth was observed, but did not lead to severe agglomeration. A fuel with slightly higher sodium or potassium could result in agglomeration problems. The fuels with high concentrations of organically bound calcium also showed potential to foul downstream convective and reheat sections of a boiler, indicating provisions for

adequate soot-blower coverage should be considered. The combination of high ash and high sulfur in the Asian lignite resulted in very large quantities of solid waste. For the other coals tested, the amount of solid waste generated increased with the amount of ash in the coal and the amount of limestone added.

Combustion efficiency for the two lignites and the subbituminous coal approached 100% over the entire range of temperatures tested. The combustion efficiencies for the Salt Creek bituminous coal ranged from 97% to 99%, while the combustion efficiencies for the Blacksville bituminous coal ranged from 90% to 97%. These differences are due to the higher reactivity of the char for the lower-rank coals and the higher volatile content of these coals in relation to the fixed carbon. Recycle from a secondary cyclone system or baghouse would improve the combustion efficiency for the bituminous coals. Combustion efficiency also increased with increased excess air.

Testing was conducted to compare the performance of the EERC CFBC with both a utility-scale plant and a vendor-operated pilot plant using the same coal and limestone. The 110-MW_e CFBC at the Colorado Ute Nucla Station has been successfully operating for the last several years and testing has been performed in cooperation with Electric Power Research Institute (EPRI). EPRI and Pyropower have also participated in testing in a pilot-scale CFBC in San Diego, California. Emissions of SO_2, NO_x, and CO and the measured combustion efficiencies and heat flux for the three units were similar. Based upon this comparison and supported by the information presented in the following report, the EERC 1-MW_{th} pilot-scale CFBC not only meets the original design objectives of Project CFB, but also provides data scalable to a full-scale unit. This unit, therefore, provides the energy industry a powerful tool for obtaining engineering design and environmental permitting data prior to building a new unit or switching fuels in an existing unit.

ACKNOWLEDGMENTS

The EERC would like to acknowledge the efforts of Bob Midleton, now retired from the Otter Tail Power Company, for being the prime motivator in initiating Project CFB. We are grateful for the valuable input supplied by Stan Selle of Northwest Research, Inc., Michael Johnson, formerly with the EERC, and Nanak Grewal of the University of North Dakota Mechanical Engineering Department, during the design and construction period.

The authors would like to strongly acknowledge the efforts of Butch Riske and his operations staff at the EERC whose dedication and craftsmanship made on-site construction possible, the EERC machine shop personnel for their excellent workmanship during fabrication of the pilot plant components, Rick Fox and Jim Aarestad of the EERC instrument shop for their tireless efforts involved in completing the instrumentation of the unit in a timely manner, Tom Stokke for his efforts in getting the data acquisition and control system up and running, and Jim Larsien whose input and efforts always result in a more successful, efficiently constructed and functional piece of test equipment.

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EXECUTIVE SUMMARY

INTRODUCTION

Project CFB was initiated in May 1988 at the University of North Dakota Energy and Environmental Research Center (EERC) under funding provided from the U.S. Department of Energy, the Empire State Electric Energy Research Corporation, Northern States Power Company, the Electric Power Research Institute (EPRI), Otter Tail Power Company, ARCO Coal Company, TU Electric, Consolidated Edison of New York, Premier Refractories and Chemicals, and the North Dakota Lignite Research Council. The overall goal of the project was to provide a technical basis for assessing the economic and environmental feasibility of circulating fluidized-bed combustion (CFBC) technology, focusing on the effects of system configuration and coal properties on performance. Specific goals of the project were to 1) construct a CFBC facility representative of the major boiler vendors' designs with the capability of producing scalable data, 2) develop a database for use in making future evaluations of CFBC technology, and 3) provide a facility free of vendor bias for use in the energy industry. Five coals have been test-burned in the unit: a North Dakota lignite, an Asian lignite, a Wyoming subbituminous, a Colorado bituminous, and a Pennsylvania bituminous. As expected, varying coal qualities did impact the overall performance of the CFBC.

The impact of coal quality on overall operability was assessed by comparing recirculation rates, the primary cyclone collector performance, bottom ash vs. fly ash split, and the size distribution of the circulating material resulting from burning the five different coals. Emissions are significantly impacted by coal quality. The following were evaluated: SO_2 emissions and limestone utilization; NO_x, N_2O, and CO emissions; fly ash collectability; and solid waste generation. Thermal performance changes resulting from varying coal quality were assessed by comparing heat-transfer coefficients and heat flux, combustion efficiency, and overall boiler efficiency. A summary of the effects of coal properties on CFBC performance is presented in Table ES-1.

BASIS OF CFBC COMPARISON–EQUIPMENT USED AND TEST CONDITIONS

A schematic of the pilot-scale CFBC used in these studies is shown in Figure ES-1. The combustor has an internal diameter of 20 inches and is 42 feet tall. The combustor is refractory-lined with twelve heat exchange panels located throughout seven of the combustor sections to control and adjust heat removal to match the heat duty of any fuel and/or operating conditions. The typical full-load thermal input of the unit is approximately 1 MWth. A 25-inch refractory-lined cyclone is used to collect and recirculate the solids through a combination loop seal and external heat exchanger. Solids flow through the external heat exchanger at all times, but water flow to the cooling coils can be shut off to effectively take the heat removal function of the external heat exchanger off-line.

Fuel and sorbent are metered separately through rotary valves, mixed, and fed by gravity into the combustor. Combustion air is preheated to approximately 600°F and split between primary and secondary air. Secondary air can be fed into the combustor at 6' or 11' above the distributor plate. Flue gas leaving the combustor passes across a convective fouling section that simulates the leading edge of a convective pass. Solids

TABLE ES-1

Effects of Coal Properties on CFBC System Design and Performance

Coal Property	Effect on System Requirements and Design	Effect on System Thermal Performance	Effect on System Environmental Performance
Heating Value	Determines size of feed subsystem, combustor, particulate collection equipment, and convective pass.	Efficiency impacted by moisture and ash content (see below).	Size of particulate collection devices (baghouse or ESP).
Moisture Content	Can impact feed system design and capacity and size of convective pass.	Higher moisture lowers thermal efficiency.	Very high moisture can increase CO emissions due to afterburning.
Ash Content	Determines size and type of particulate control subsystem and size of ash-handling subsystems.	Higher ash lowers thermal efficiency via heat losses from hot solids removal.	Size of particulate collection devices.
Volatiles/Fixed Carbon Content	Impacts fuel feed method.	Lower combustion efficiency for fuels with low V/FC content.	None, with proper design.
Sulfur Content[a]	Determines required capacity of sorbent subsystem and ash-handling subsystem.	Higher sulfur can lower thermal efficiency via heat losses from added solids for SO_x control (see ash content above).	None, or proportional,[b] if site and system size regulated. Determines SO_2 emissions (in conjunction with alkaline ash) if uncontrolled.
Nitrogen Content	None, with common designs and typical regulations.[c]	None, with common designs.[c]	Impacts NO_x emissions.
Chlorine Content	Can impact selection of materials for cool end components. May cause higher corrosion rates for in-bed tubes.	Typically none. Very high chlorides can lower thermal efficiency by requiring operation at higher exhaust temperatures.	Impacts HCl emissions.
Calcium Content of the Ash	Can reduce size of sorbent subsystem.	Typically none.	Higher ash calcium levels lower uncontrolled SO_x emissions.
Sodium and Potassium Content of the Ash	High sodium can dictate fouling prevention measures and allowance for agglomeration (e.g., soot blowing, frequent bed draining, aeration of downcomer).	Higher sodium can lower thermal efficiency due to tube fouling and heat losses from more frequent hot solids removal.	Higher sodium lowers uncontrolled SO_x emissions. Sodium tends to reduce fly ash resistivity for ESP performance improvement, may also enhance fabric filter performance.
Ash Fusibility	Low fusion temperatures can impact design, due to allowance for fouling and agglomeration potential.	Lower fusion temperatures impact thermal efficiency in the same way as higher sodium.	Typically none.

[a] The forms of sulfur can have an impact, with high pyrite content requiring longer gas residence time in the bed. The result may be increased operating pressure and blower capacity.

[b] Sulfur content can determine SO_x emissions, depending on which regulation applies (e.g., New Source Performance Standards (NSPS) regulations stipulate fractional removals).

[c] For low-NO_x regulations, a staged combustion or postcombustion NH_3-based suppression design may be required. Staged combustion designs can have higher CO emissions. Postcombustion NO_x suppression subsystems can lower the thermal efficiency slightly and do emit NH_3.

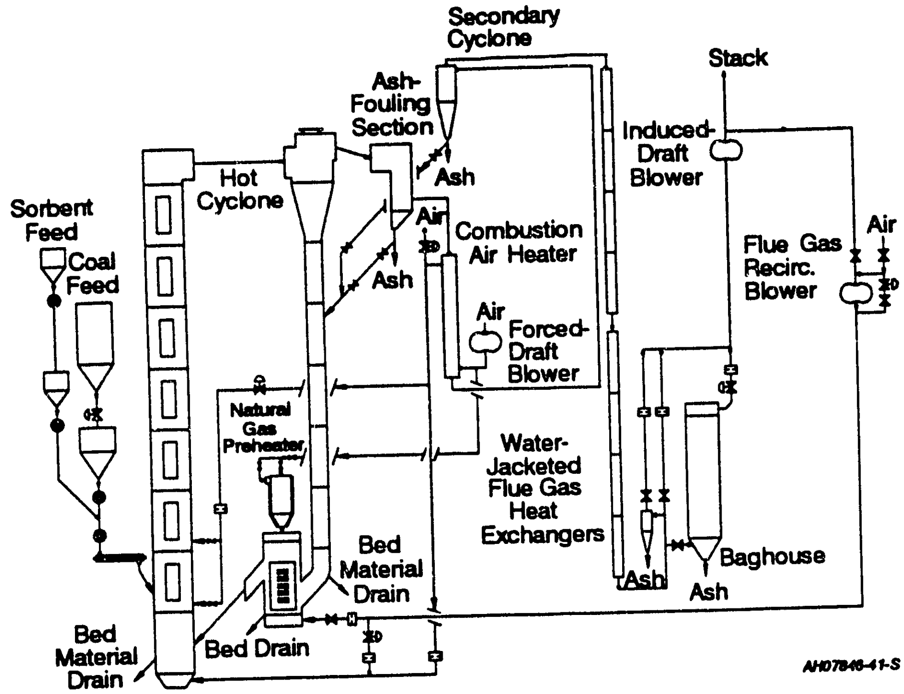

Figure ES-1. Schematic of EERC 1-MWth CFBC pilot plant.

collected in an 18-inch stainless steel secondary cyclone can either be returned to the combustor or collected to a barrel. The flue gas is then cooled by a series of water-cooled heat exchangers before entering a pulse-jet baghouse.

The data that follow summarize 54 steady-state tests performed over the following range of conditions:

Combustor Temperature, °F	1185 - 1698
Excess Air, %	9 - 125
Velocity, ft/sec	9 - 19
Ca/S, molar ratio	0 - 5.6
Primary Air, % total air	45 - 92
Load, %	50 - 100 (+)

Properties of the coals used are presented in Table ES-2.

UNIT VALIDATION

The 110-MWe CFBC at the Colorado Ute Nucla Station has been successfully operating for the last several years. As it is one of the demonstration plants supported by EPRI, EPRI was able to assemble a large database characterizing the performance of this unit. In addition, EPRI and Pyropower participated in pilot plant testing in a pilot-scale CFBC in San Diego, California. The EERC obtained samples of the same coal and limestone used by those organizations and has operated its CFBC under similar operating conditions. This has provided the opportunity to compare the performance of the EERC CFBC with both a utility-scale plant and a vendor-operated pilot plant.

TABLE ES-2

Analyses of Coals Used in the EERC Comparative Study

	Salt Creek	Center Lignite	Asian Lignite	Blacksville	Black Thunder
Proximate Analysis, as-received, wt%					
Moisture	7.7	37.1	17.0	2.9	27.6
Volatile Matter	31.0	29.0	37.4	35.1	33.2
Fixed Carbon	42.7	28.9	7.6	53.8	34.6
Ash	18.6	5.1	38.0	8.2	4.6
Ultimate Analysis, as-received, wt%					
Carbon	58.8	40.9	25.0	74.4	49.9
Hydrogen	5.0	7.0	4.3	5.3	6.6
Nitrogen	1.1	0.5	0.7	1.3	0.6
Sulfur	0.4	0.7	6.1	2.4	0.3
Oxygen	16.0	45.8	26.1	8.4	38.0
Ash	18.6	5.1	38.0	8.2	4.6
Ash Composition, as oxides, wt%					
Calcium, CaO	1.5	22.6	19.9	5.6	24.4
Magnesium, MgO	1.5	10.2	3.3	1.2	7.9
Sodium, Na_2O	0.2	3.7	0.3	0.7	0.5
Silica, SiO_2	59.9	14.5	30.6	43.6	28.5
Aluminum, Al_2O_3	30.9	9.7	12.4	22.7	16.4
Ferric, Fe_2O_3	3.0	16.1	13.7	16.6	6.4
Titanium, TiO_2	1.1	0.3	0.2	0.7	1.4
Phosphorous, P_2O_5	0.4	0.7	0.5	0.4	1.3
Potassium, K_2O	1.0	0.4	1.1	1.7	0.9
Sulfur, SO_3	1.0	[illegible]1.9	18.1	6.8	12.4
High Heating Value, as-received, Btu/lb	10,274	6,939	3,898	13,274	8,650

To simulate full-scale operation, the size distribution of the recirculating material and the fly ash from the pilot plant must be similar to that of a full-scale system. Figure ES-2 shows that the fly ash generated from the three units is similar. Operation of the system at typical full-scale conditions provides scalable heat flux and emissions data. Average heat flux in the combustor ranged from 18,200 Btu/hr-ft^2 at 55% load to 26,000 Btu/hr-ft^2 at 88% load and 32,600 Btu/hr-ft^2 at full load. The measured heat flux from the Nucla Station averaged 22,300 Btu/hr-ft^2 at half load and 32,800 Btu/hr-ft^2 at full load. Bed temperature distribution in the combustor for all full load tests was uniform over the entire length of the EERC combustor and was similar to that observed at the San Diego pilot plant.

Emissions of SO_2, NO_x, and CO among the three units were also similar. Sulfur retention for the three units is shown in Figure ES-3, with NO_x shown in Figure ES-4. Some NO_x emissions from the EERC combustor were high and reflect high excess air test conditions. Figure ES-5 compares N_2O emissions, and shows higher emissions from the EERC CFBC as compared to the Nucla Station. This trend is consistent with observations made by other researchers and is probably due to wall effects and other features associated with the smaller scale. The measured combustion efficiencies, shown in Figure ES-6, were comparable for the three units.

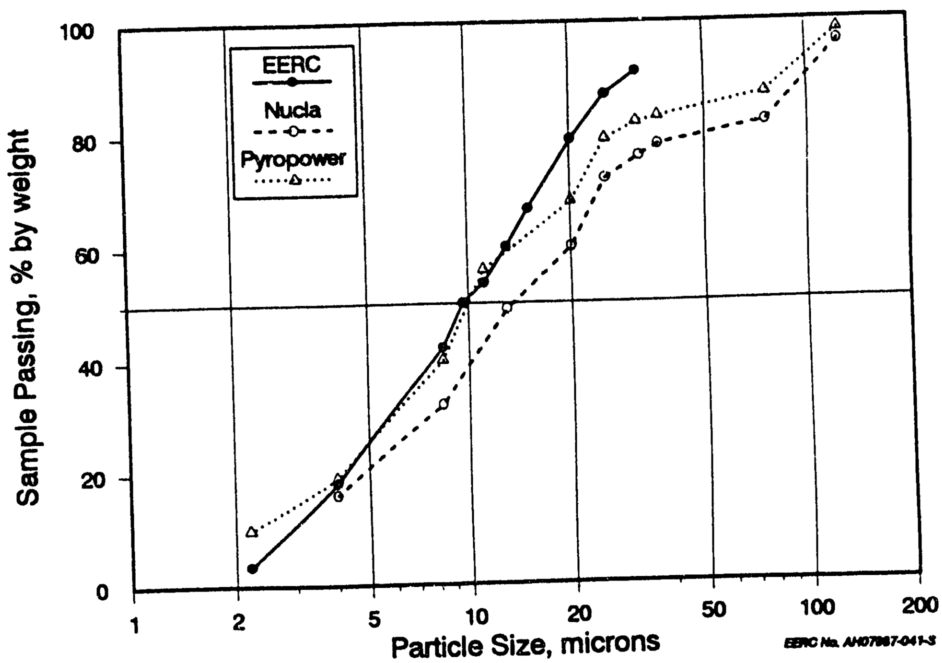

Figure ES-2. Size distribution of baghouse ash from the Nucla Power Station and the Pyropower and EERC pilot plants.

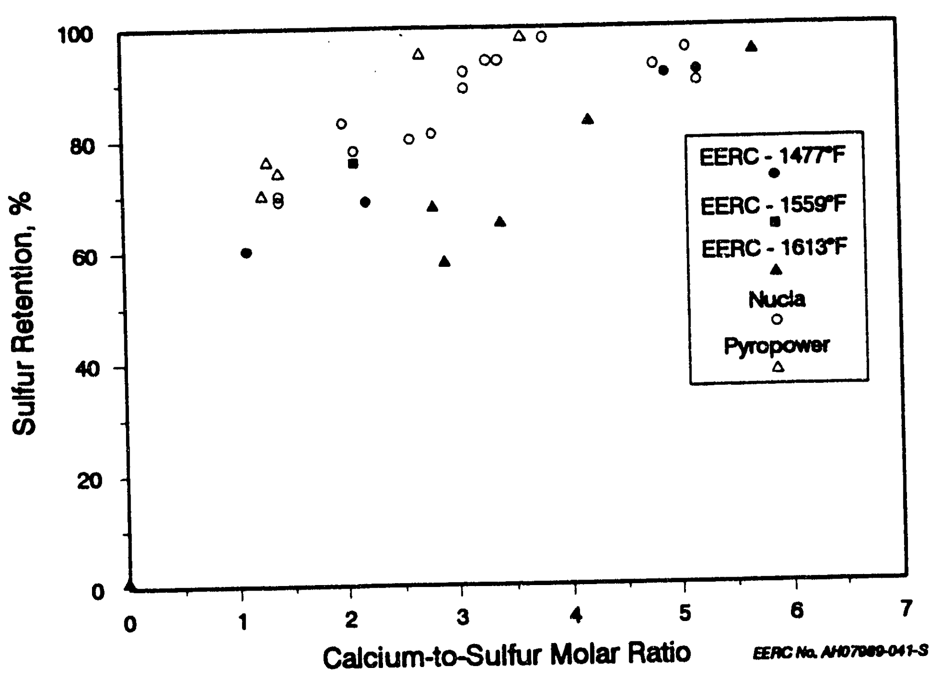

Figure ES-3. SO_2 retention as a function of calcium-to-sulfur ratio for the Nucla Power Station and the Pyropower and EERC pilot plants.

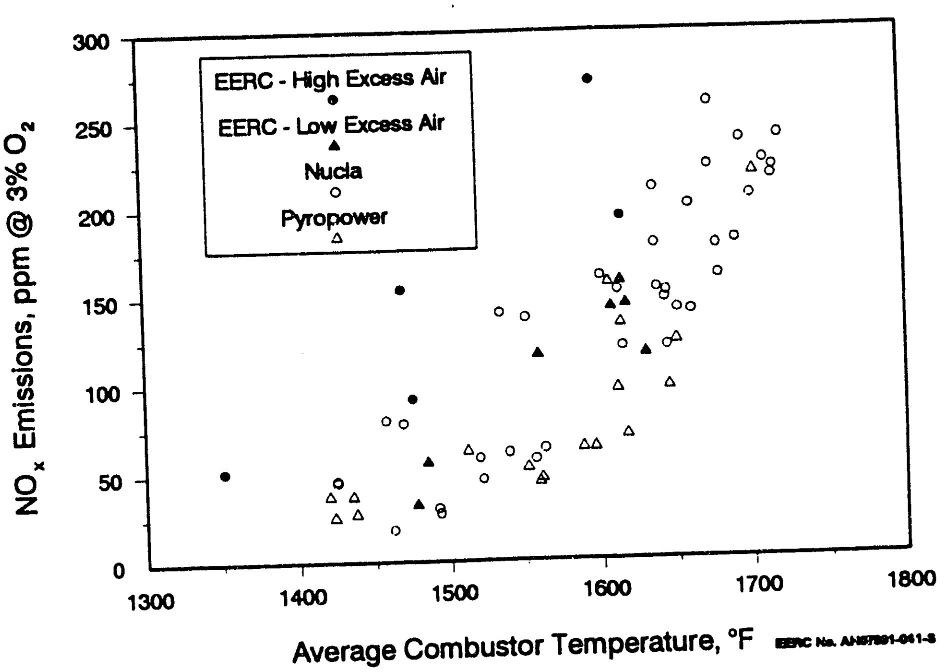

Figure ES-4. NO_x emissions as a function of temperature for the Nucla Power Station and the Pyropower and EERC pilot plants.

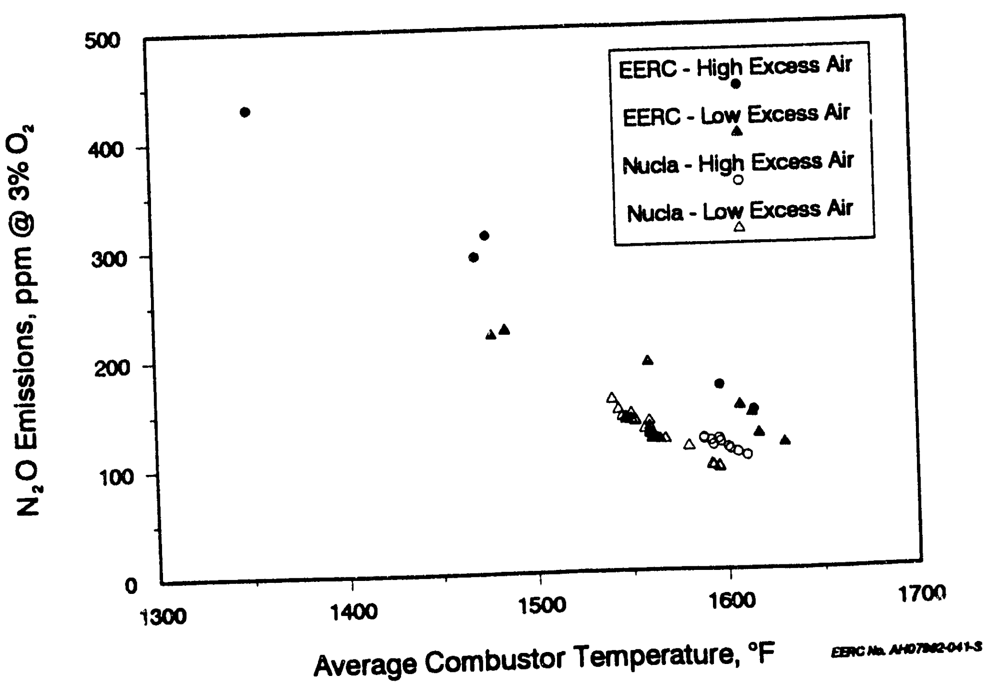

Figure ES-5. N_2O emissions as a function of temperature and excess air for the Nucla Power Station and the EERC pilot plant.

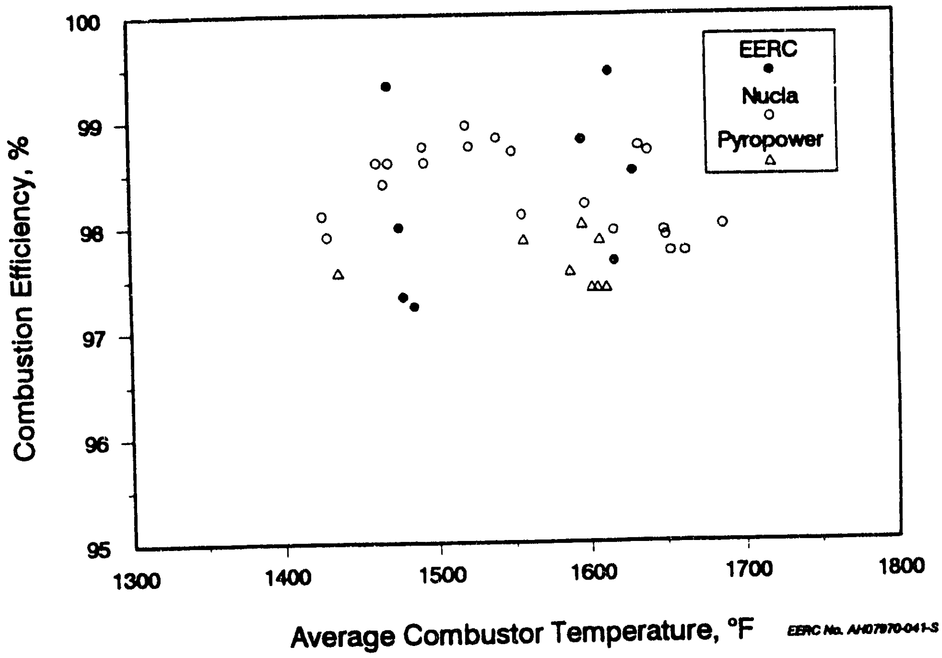

Figure ES-6. Combustion efficiency as a function of temperature for the Nucla Power Station and the Pyropower and EERC pilot plant.

Based on this comparison and supported by the information presented in this report, EERC personnel feel confident that the EERC 1-MWth pilot-scale CFBC meets the original design objectives of Project CFB and has a system that can provide data scalable to full-scale units.

THERMAL PERFORMANCE

Heat Flux

Because of the action of the circulating solids, the CFBC typically operates with a high heat flux. The heat flux for full-load conditions ranged from about 25,000 to 35,000 Btu/hr-ft^2. The heat flux increased with increasing temperature and velocity, but was generally independent of fuel type. Fuel type may indirectly affect heat flux, to a small degree, by its effects on recirculation rates and particle-size distributions.

Combustion Efficiency

Figure ES-7 presents combustion efficiency for the five test coals as a function of combustor temperature. All tests included on the graph were performed at 20% excess air, 16-ft/sec velocity, 60% primary air, and a Ca/S add rate to achieve 90% sulfur retention. The combustion efficiency for the two lignites and the subbituminous coal approached 100% over the entire range of temperatures tested. The combustion efficiencies for the Salt Creek bituminous coal ranged from 97% to 99%, while the

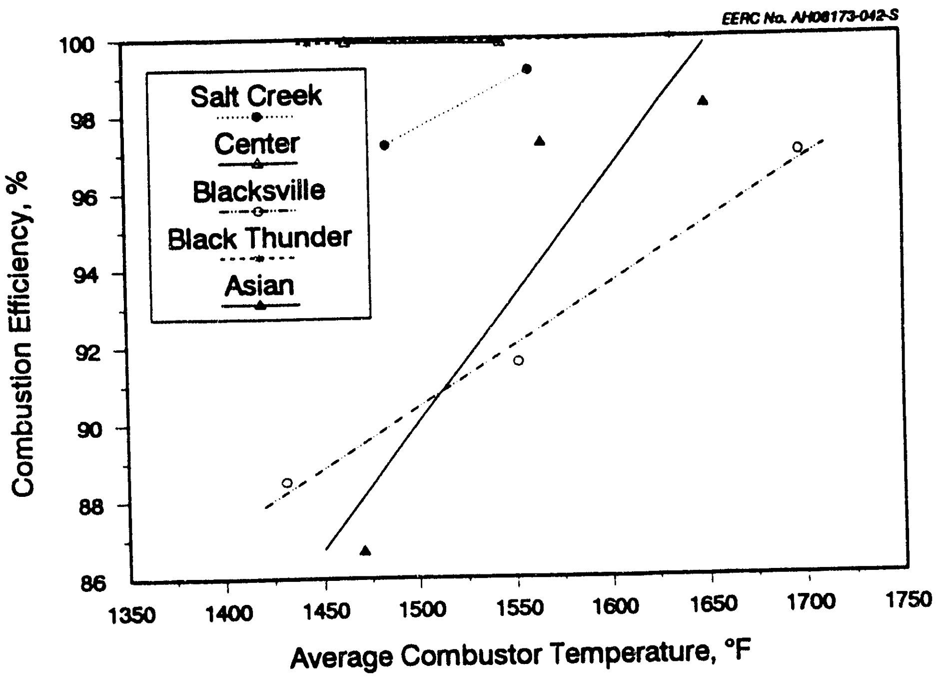

Figure ES-7. Combustion efficiency at 25% excess air and 16-ft/sec velocity as a function of temperature.

combustion efficiencies for the Blacksville bituminous coal ranged from 90% to 97%. These differences are due to the higher reactivity of the char for the lower-rank coals and the higher volatile content of these coals in relation to the fixed carbon. Recycle from a secondary cyclone system or baghouse would improve the combustion efficiency for the bituminous coals. Combustion efficiency also increased with increases in excess air.

Boiler Efficiency

The overall boiler efficiency is affected by a number of other parameters in addition to the carbon burnout of the fuel. Since low-rank coals typically contain higher levels of moisture than do bituminous coals, more heat is required (lost) during the combustion of low-rank coals to vaporize the extra moisture. When operating at a specific temperature and excess air, the high-moisture fuels generate increased mass flows through the system per delivered Btu than low-moisture fuels, resulting in a higher fraction of the energy being recovered in the downstream convective heat recovery unit. Figure ES-8 shows that, for the coals tested, the amount of energy generated ending up in the flue gas varied from 65% for the very moist Asian lignite to 43% for the relatively dry Blacksville bituminous. The shift of energy back to the convective pass results in a reduction of boiler efficiency due to greater stack losses for the high-moisture coals. Other losses in boiler efficiency result from the conversion of fuel hydrogen to water, unrecoverable heat from the discharge of ash and spent sorbent, and the calcination of the raw sorbent. A boiler efficiency credit is given for the sulfation of the sorbent, as this process produces usable heat.

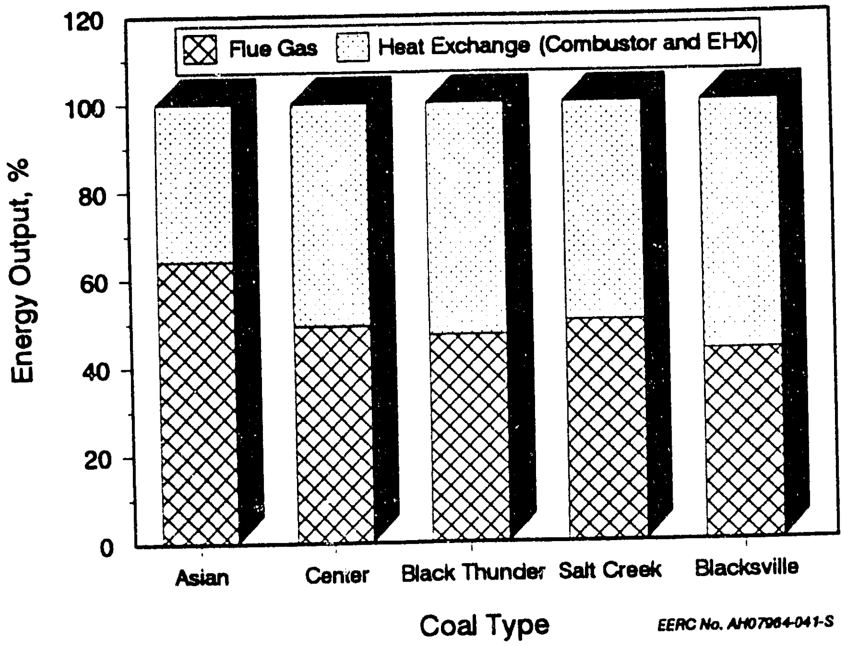

Figure ES-8. Heat split between combustor and flue gas as a function of coal type.

Boiler efficiency losses for the baseline cases with no sorbent addition are shown in Figure ES-9. Table ES-3 presents a similar comparison for 90% sulfur capture at baseline conditions. The combined losses due to the moisture and hydrogen in the fuel (evaporation and unrecovered sensible heat in the flue gas) range from a high of 13.5 for the Asian lignite to a low of 6.7 for the Blacksville bituminous. Heat losses due to ash and spent sorbent are much lower and depend upon the total ash content of the coal relative to its heating values and sorbent requirements needed to meet New Source Performance Standards (NSPS). These losses amounted to 6.9% for the high-sulfur, high-ash Asian lignite and ranged from 0.2% to 1% for the other coals tested. The total efficiency losses ranged from 10.5% for the Salt Creek bituminous to 22.4% for the Asian lignite. It is interesting to note that the Center lignite and the Black Thunder subbituminous both had higher boiler efficiencies than the Blacksville bituminous coal, due primarily to their high carbon burnout.

ENVIRONMENTAL PERFORMANCE

Emissions from a CFBC operating on a given fuel can generally be controlled using proper system design and operation. While system requirements are dependent upon coal properties, the actual emissions are dependent upon the system design and operation. It is currently possible to meet all present and proposed national standards with state-of-the-art CFBC technology.

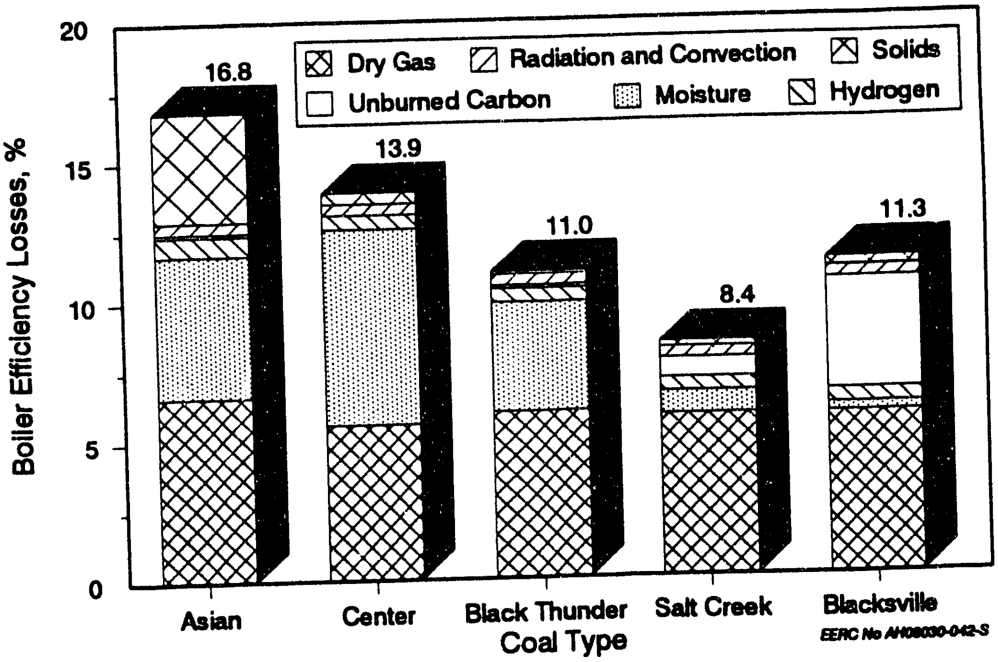

Figure ES-9. Boiler efficiency losses with no limestone addition at 1550°F (1607°F for Salt Creek), 26% excess air, 16-ft/sec velocity as a function of coal type.

TABLE ES-3

Boiler Efficiency Losses for Test Coals at 90% Sulfur Retention and 1550°F Combustor Temperature

Coal Type[1]:	TL	CL	BT	SC	BV
Dry Gas	7.1	5.6	5.7	5.5	5.9
Water in Fuel	5.6	3.6	3.9	0.9	0.3
Combustion of Fuel Hydrogen	0.8	0.7	0.5	0.4	0.5
Unburned Carbon	2.1	0.0	0.1	2.1	6.0
Calcination/Sulfation Solids	-0.5	0.3	0.1	0.3	0.0
Discharged Solids	6.9	0.5	0.2	0.9	1.0
Radiation and Convection	0.4	0.4	0.4	0.4	0.4
Total Losses	22.4	11.1	10.9	10.5	14.1
Boiler Efficiency	77.6	88.9	89.1	89.5	85.9

[1] TL = Asian lignite, CL = Center lignite, BT = Black Thunder subbituminous, SC = Salt Creek bituminous, BV = Blacksville bituminous.

Sulfur Emissions and Limestone Performance

While firing coals in a CFBC, the amount of sulfur capture is primarily determined by the total alkali-to-sulfur ratio. The alkali is provided by the mineral matter and cations contained within the coal and any added sorbent. The forms of alkali in the coal and combustor operating conditions, primarily temperature, are also important. Once the coal and sorbent properties are known, system design and operating specifications can be set to achieve the required level of sulfur capture, such as mandated by NSPS.

In specifying design and operating conditions for the CFBC, it is critical to know how much sorbent addition is required to meet applicable emissions standards. This can vary greatly with coal and sorbent types. For example, the data in Figure ES-10 show that, to retain 90% sulfur, the required alkali-to-sulfur ratio ranges from 1.4 to 4.9, depending upon coal type. Looking only at the alkali-to-sulfur ratio, however, can be misleading. For example, although an alkali-to-sulfur ratio of 4.9 is required to meet 90% sulfur retention for the Salt Creek coal versus 1.4 for the Asian lignite, the total amount of sorbent addition required is much less for the Salt Creek coal. A sorbent add rate of 4.2 pounds per million Btu of Salt Creek coal input is required, versus 62 pounds per million Btu of Asian lignite, due to differences in the level of sulfur and the alkali in the coal. The add rates of sorbent for the other coals tested in relation to varying levels of sulfur retention are presented in Figure ES-11.

The optimum bed temperature resulting in maximum sulfur capture varies somewhat with coal type. The bituminous coals tested show optimal sulfur capture at combustor temperatures of approximately 1550°F. The low-rank coals tested, however, exhibit optimal temperature for sulfur capture approximately 100°F lower. This is partially due to the coal structure and the forms and relationships of the sulfur and the alkali in the coal itself.

The source and size of limestone can also have an impact on sulfur capture. As a part of the test series discussed in this report, two different limestones were tested while burning the Blacksville bituminous coal. Limestone size was also a test parameter. Using a coarse limestone (-20 mesh), 40% of the calcium in the limestone was utilized for sulfur capture. A fine limestone (-40 mesh) of the same type resulted in a sorbent utilization of only 29%. A second limestone (Colorado Ute) of fine particle size (-40 mesh) showed similar performance, with approximately 29% utilization. To capture 70% of the sulfur, alkali-to-sulfur ratios of 1.8 for the coarse limestone and 2.3 for the two fine limestones tested would be required. In this case, the reactivities of the two limestones were similar. While the smaller-sized limestone had a greater surface-to-volume ratio, which would be expected to result in more efficient sulfur capture, the poorer utilization was probably the result of shorter sorbent residence time in the combustor. Cyclone collection efficiencies decrease with decreasing particle size, and smaller sorbent particles may leave the system without being recirculated. For limestones with different reactivities, the add rates can also vary as a function of limestone type. Results obtained on the impact of limestone size and type on other parameters are shown in Figure ES-12.

Nitrogen Oxide Emissions

Regulated nitrogen oxide emissions currently include NO and NO_2, collectively termed NO_x emissions. NO_x emissions from the CFBC are highly coal dependent. Figure ES-13 compares NO_x emissions for the five test coals as a function of temperature. These different NO_x levels are caused by inherent differences in the nitrogen in the coals. The nitrogen in the bituminous coals is released as CN, while the lower-rank coals release more of their nitrogen as NH_3. The distribution of nitrogen between the volatiles and the fixed carbon also varies significantly between coal ranks and is partially responsible for the trends shown in Figure ES-13. Not only does the total amount of NO_x emitted vary with coal type, the rate of NO_x emissions with changes in operating temperature also varies with coal type. The rate of change is the smallest with the lignites and the greatest with the bituminous coals. Therefore, the lignites are higher emitters of NO_x

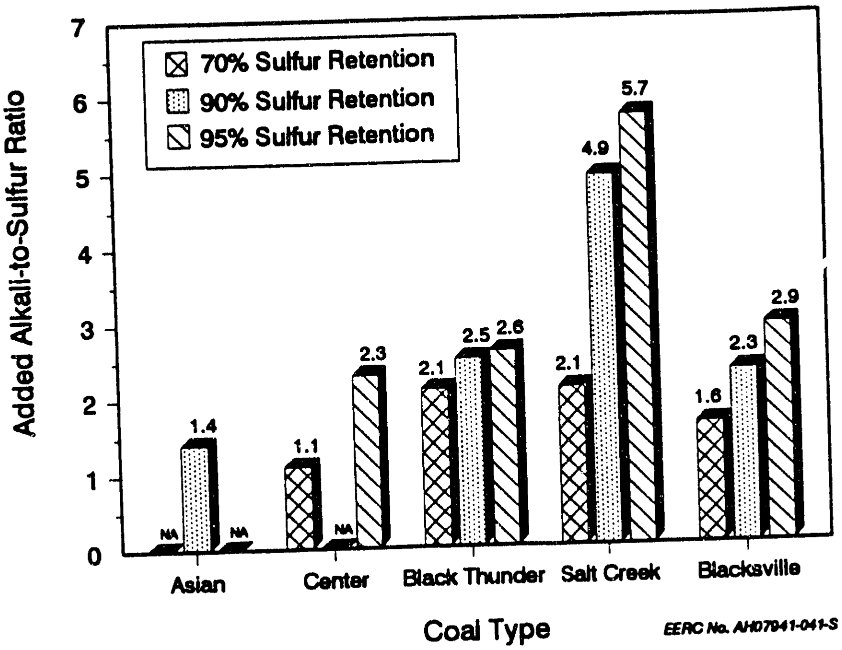

Figure ES-10. Added alkali-to-sulfur ratio required for increasing sulfur capture at 1550°F as a function of coal type.

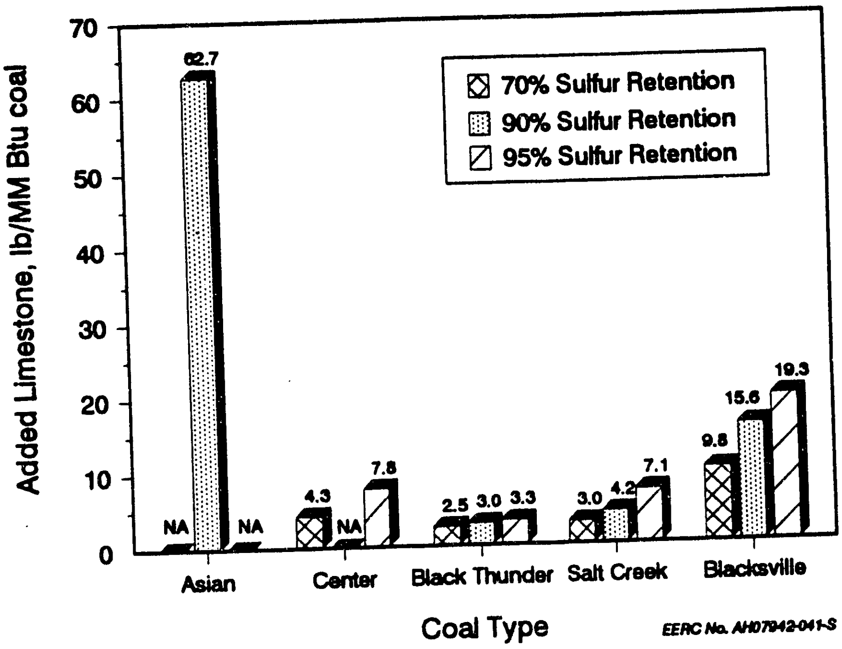

Figure ES-11. Added limestone required for increasing sulfur capture at 1550°F as a function of coal type.

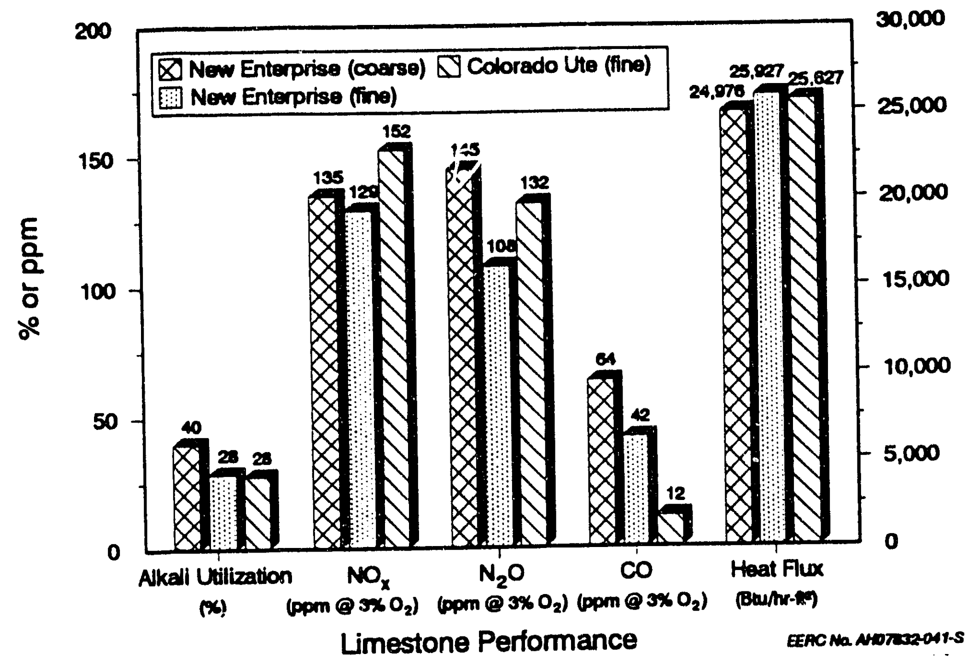

Figure ES-12. CFBC performance as a function of limestone size and type.

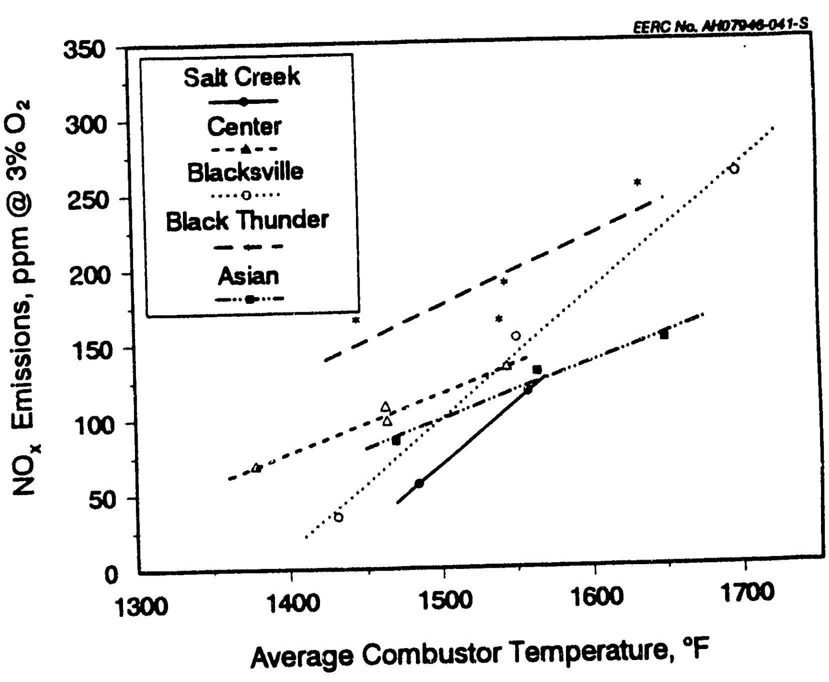

Figure ES-13. NO_x emissions at 20%-25% excess air, 16-ft/sec velocity, and 1.5-2.5 alkali-to-sulfur ratio as a function of combustor temperature.

than the bituminous coals at lower temperatures (1450°F), but emit less NO_x at higher temperatures. NO_x emissions also increase with increasing excess air and sorbent add rates.

Recently, relatively high emissions of nitrous oxide (N_2O) have been measured from CFBCs. Although these are currently not regulated, they may become important in the future. N_2O emissions are even more dependent upon fuel properties than NO_x. The trends noted during this study were increasing emissions of N_2O as the rank changed from subbituminous to lignite to bituminous. These trends are shown in Figure ES-14. The distribution of the nitrogen between the volatiles and the fixed carbon appears to be the most important fuel property affecting N_2O emissions. N_2O emissions show the opposite trend as NO_x, decreasing with increasing temperature and sorbent add rate, and a similar trend as NO_x for excess air.

Fly Ash Collectability

To provide an indication of the impacts of coal properties on fly ash collectability, dust loadings before and after the baghouse were performed. The dust loading into the baghouse for the high-ash, high-sulfur Asian lignite was the highest for the coals tested, at 2.13 grains/scf. Dust loadings for the other coals ranged from 0.60 to 0.90 grains/scf. For all of the coals, collection efficiencies using woven fiberglass bags in a pulse-jet baghouse were above 99.9%.

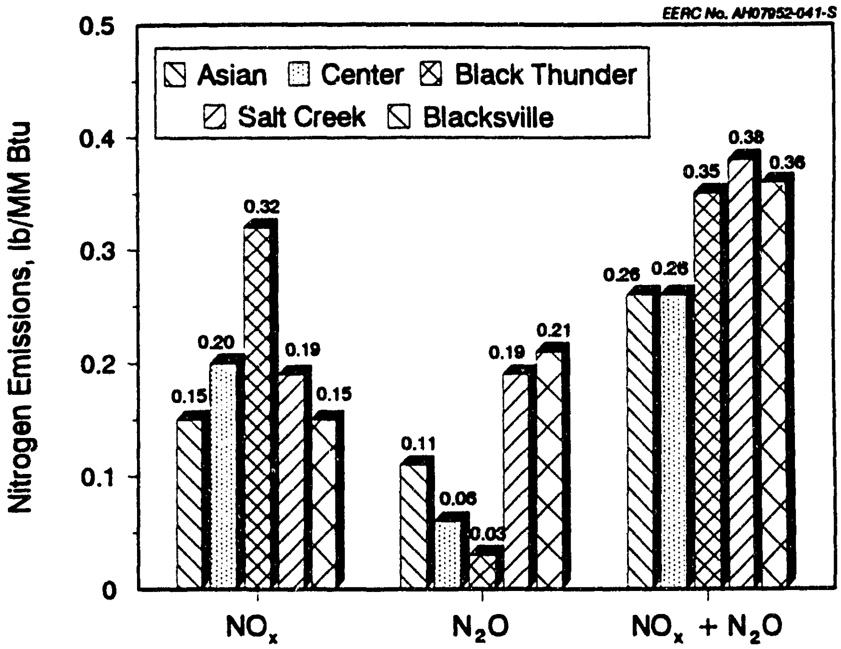

Figure ES-14. NO_x and N_2O emissions with no limestone addition at 1550°F, 26% excess air, and 16-ft/sec velocity as a function of coal type.

Solid Waste Generation

An important aspect of the design of the CFBC is sizing of the solids handling systems. From an operational standpoint, disposal of the solid wastes (coal ash and spent sorbent) becomes a very important economical consideration. The amount of solids generated is very dependent upon coal properties, as shown in Figure ES-15. The combination of high ash and high sulfur in the Asian lignite results in very large quantities of solid waste. For the other coals tested, the amount of solid waste generated increased with the amount of ash in the coal and the amount of limestone added. The two bituminous coals generated more solid wastes than the two low-rank coals. Limestone requirements are highest for high-sulfur, low-alkali coals and increase with increasing sulfur capture. The baseline and 70% retention tests for the Salt Creek run were performed at different temperatures than the other tests. This shift away from the optimum temperature for sulfur capture resulted in higher solid waste generation for these tests.

OPERATIONAL PERFORMANCE

There are several different aspects of the CFBC operation that are of concern. These include primary cyclone performance, solids recirculation rates or mass flux in the combustor, size distribution of the circulating solids, refractory wear, and deposition and agglomeration of ash. Many of these are determined primarily by system design and by the sizing of the feedstocks of fuel and sorbent. The properties of the fuel and its ash can also have an impact on operational performance.

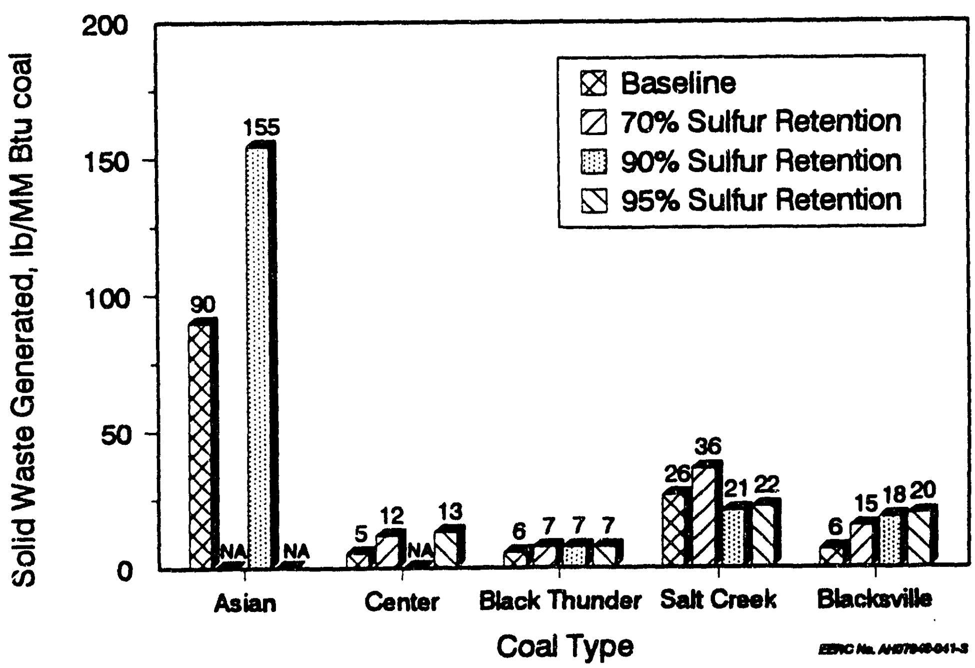

Figure ES-15. Solid waste generated at increasing levels of sulfur retention as a function of coal type.

Solids Performance

For the five coals tested, cyclone efficiency appeared to be primarily a function of operating conditions. Cyclone efficiency is defined as one minus the fly ash discharge rate divided by the recirculation rate. Cyclone efficiency is used here to collectively describe total system efficiency for capture of solids using a primary, and sometimes a secondary, collection device for solids recirculation. Solids capture is influenced by the collector geometry, as well as operational parameters including the combustor gas velocity and fuel and limestone properties.

Cyclone efficiencies ranged from a low of 93.8% with the Asian lignite to 99.9% with Black Thunder bituminous. For testing conducted with Center, Black Thunder, and Salt Creek fuels, secondary cyclone ash was recycled to maintain adequate bed inventory and recirculation rates. These three coals had relatively low coal ash and sulfur contents, resulting in low quantities of solids available for recirculation. Additionally, the size of the limestone used for Salt Creek testing was relatively small, making it difficult to keep in the system. The Blacksville bituminous was a low-ash coal, but required relatively high limestone feed rates due to its high sulfur content, and subsequently no secondary cyclone recycle was required to maintain sufficient bed inventory. Although the cyclone efficiencies for the Asian lignite (low Btu, high ash, and high sulfur) were significantly lower than for the other four test coals, no secondary cyclone recycle was required to maintain adequate bed inventory at all operating conditions.

In no case did additional bed material need to be added to maintain bed inventory. However, for the Black Thunder coal, which is very low in sulfur and ash, the only bed drain that was used during the tests was for sampling. This indicates that a system with a cyclone efficiency less than that of this pilot plant would not have been able to maintain bed inventory for this coal. For the other coals, the amount of ash in the coal and the added sorbent were sufficient to continually build bed inventory, requiring sizable bed drain. For design of a full-scale system using low-ash, low-sulfur fuels, recycle from a secondary cyclone/multiclone or baghouse would be recommended.

Recirculation rates and mass flux were primarily determined by operating parameters and were not directly affected by fuel type. Recirculation rates decreased with velocity and bed inventory. The recycle of secondary cyclone solids increased the recirculation rates. Recycle of secondary cyclone material would not be necessary to maintain high recirculation when burning high-sulfur coals, due to the large amount of limestone being added to the system, or when burning high-ash coals. Therefore, coal properties can indirectly have an impact on recirculation rates and mass flux by requiring recycle of ash from a secondary collection system.

One aspect of system operation that is directly impacted by fuel ash properties is agglomeration and deposition. The North Dakota lignite has a relatively high sodium level in the ash (4%). During the tests, particle growth was observed, but did not lead to severe agglomeration. However, a fuel with a slightly higher sodium or potassium level would likely result in agglomeration problems. The fuels with high concentrations of organically bound calcium also showed the potential for fouling in the convective and reheat sections of a boiler. A very hard, fine-grained calcium sulfate-based deposit formed on the ash-fouling probes and the primary flue gas heat exchanger during the tests with the Asian and North Dakota lignites. Therefore, a prudent design for fuels similar to these would include adequate soot-blower coverage.

IMPACT OF LOAD CONTROL METHOD

Two different operational procedures were used to simulate load reduction for CFB systems: one with and one without an external heat exchanger. Boiler efficiencies decreased when load was decreased by either of the methods. Operation with an external heat exchanger resulted in little change in operating temperature over the load range tested while those tests that simulated operation without an external heat exchanger had decreasing temperatures as the load decreased. The impacts of the load control method were directly related to these temperature differences.

No clear trend was evident to show how sulfur dioxide emissions are affected for either method of load control. For operation without an external heat exchanger, NO_x emissions tended to decrease, while N_2O and CO emissions increased, as load was decreased. These followed expected trends based on changes in temperature and excess air. For testing simulating operation with an external heat exchanger, NO_x emissions increased slightly due to increases in excess air, while N_2O and CO emissions were mostly unaffected as load was reduced, as these emissions are less sensitive to changes in excess air.

Combustor efficiencies were not affected for the reduced load testing for the more reactive lignites. Reducing load using either method appeared to improve combustion efficiency for the bituminous coals. This could have been due to the decreased operational velocities that accompanied the load reduction, resulting in less carbon blowing out of the system. Heat transfer coefficients and heat flux showed a decreasing trend with decreasing load.

PROJECT CFB TEST RESULTS

1.0 INTRODUCTION

Project CFB was initiated in May of 1988 to establish an independent CFBC test facility for the generation of comprehensive, reliable, and accessible data for utility and industrial applications. Otter Tail Power Company approached the EERC and played a key role in providing the impetus to get the project going. Sponsorship was sought from private companies and organizations and government agencies. Sponsors that agreed to participate include:

- ARCO Coal Company.
- Consolidated Edison of New York.
- Electric Power Research Institute (EPRI).
- Empire State Electric Energy Research Corporation (ESEERCO).
- North Dakota Lignite Research Council.
- Northern States Power Company (NSP).
- Otter Tail Power Company.
- Premier Refractories and Chemicals.
- TU Electric.
- U.S. Department of Energy (DOE).

Additionally, as the project proceeded, the EERC contributed internal funds to help see the project through to completion.

1.1 Project Objectives

Specific objectives of the project were:

- Obtain and compile available information about CFBs to provide a centralized resource for use by both EERC staff and sponsoring organizations of Project CFB.

- Within the constraints of the available budget and the available space for installation at the EERC, design a CFBC pilot plant system of a generic nature to provide data to assess the combustion of various coals over a wide range of operational conditions with and without the use of an external heat exchanger. The pilot plant should be representative of the major boiler vendor designs.

- Complete construction of the CFBC pilot plant system in the available EERC facilities.

- Perform shakedown of the pilot plant to ensure that the overall system is in operational status, provides data of high integrity, and is scalable to a full-scale system.

- The original goal was to perform parametric testing on two coals, an eastern bituminous coal with moderately high sulfur content (3%-5%) and a western coal with a high alkaline ash content (greater than 5%). Based upon further input from the sponsors, plus additional contributions from the DOE, NSP, EPRI, ARCO, and the Center North Dakota mine, it was decided to test four coals: Salt Creek bituminous coal used at the Nucla Power Generating Station, Center lignite supplied by BNI Coal, Ltd., Blacksville bituminous coal supplied by

ESEERCO, and Black Thunder subbituminous coal supplied by ARCO Coal Company from the Powder River Basin. An Asian lignite tested in the CFB was also included in this report for comparison to the other coals tested, even though it was conducted as a contract separate from Project CFB.

- Complete a final report detailing the results of all parametric testing for the five different coals.

1.2 Coal and Limestone Properties

Proximate and ultimate analyses of the coal and x-ray fluorescence analyses of the coal ash and limestone were performed. Results of the coal and limestone analyses for each run were averaged and are presented in Table 1-1.

1.3 Test Matrices

Table 1-2 is a comprehensive listing of all of the tests performed during Project CFB. The matrices show the target values for the test variables used during operation of the CFB on the five test coals. The following parameters were investigated during this program:

- Coal type
- Limestone type
- Limestone size
- Combustor temperature
- Superficial gas velocity
- Excess air level
- Primary-to-secondary combustion air split
- Secondary combustion air injection height
- Calcium-to-sulfur ratio/sulfur retention
- Load
- Load control method

1.4 Organization of Report

The report contains the following sections:

1.0 Introduction

2.0 Description of Facilities

3.0 Impacts of Coal and Limestone Properties on Operational Performance

4.0 Comparison to Full Scale

5.0 Summary and Conclusions

6.0 References

Appendices

TABLE 1-1

Coal and Limestone Analyses

	Salt Creek	Center Lignite	Asian Lignite	Blacksville	Black Thunder
Average Coal Analyses					
Proximate Analysis, as-received, wt%					
Moisture	7.7	37.1	17.0	2.9	27.6
Volatile Matter	31.0	29.0	37.4	35.1	33.2
Fixed Carbon	42.7	28.9	7.6	53.8	34.6
Ash	18.6	5.1	38.0	8.2	4.6
Ultimate Analysis, as-received, wt%					
Carbon	58.8	40.9	25.0	74.4	49.9
Hydrogen	5.0	7.0	4.3	5.3	6.6
Nitrogen	1.1	0.5	0.7	1.3	0.6
Sulfur	0.4	0.7	6.1	2.4	0.3
Oxygen	16.0	45.8	26.1	8.4	38.0
Ash	18.6	5.1	38.0	8.2	4.6
Ash Composition, as oxides, wt%					
Calcium, CaO	1.5	22.6	19.9	5.6	24.4
Magnesium, MgO	1.5	10.2	3.3	1.2	7.9
Sodium, Na_2O	0.2	3.7	0.3	0.7	0.5
Silica, SiO_2	59.9	14.5	30.6	43.6	28.5
Aluminum, Al_2O_3	30.9	9.7	12.4	22.7	16.4
Ferric, Fe_2O_3	3.0	16.1	13.7	16.6	6.4
Titanium, TiO_2	1.1	0.3	0.2	0.7	1.4
Phosphorous, P_2O_5	0.4	0.7	0.5	0.4	1.3
Potassium, K_2O	1.0	0.4	1.1	1.7	0.9
Sulfur, SO_3	1.0	21.9	18.1	6.8	12.4
High Heating Value, moisture-free, Btu/lb	11,131	11,071	4,698	13,670	11,941
High Heating Value, as-received, Btu/lb	10,274	6,939	3,898	13,274	8,650
Average Limestone Analyses, as oxides, %					
Silica	2.62	3.45	1.75	2.96	2.96
Aluminum	0.38	0.61	0.00	0.78	0.78
Iron	0.31	0.36	0.25	0.42	0.42
Titanium	0.02	0.03	0.03	0.03	0.03
Calcium	54.05	51.35	54.26	51.77	51.77
Magnesium	0.00	3.01	0.61	2.77	2.77
Sulfur	0.17	0.27	0.06	0.21	0.21
Sodium	0.00	0.07	0.26	0.06	0.06
Potassium	0.00	0.52	0.15	0.32	0.32

Section 2.0 contains an overview of the EERC CFBC test facility; the EERC coal and limestone preparation facility and procedures; the CFBC flue gas components, which were regularly monitored, and the equipment used for on-line analysis; the equipment and procedures used for analysis of solid samples taken during each run (coal, limestone, and various ash streams); and a brief description of the advanced electron microscopy equipment used for in-depth ash analysis.

The ways in which coal and limestone properties affect CFBC performance are discussed in Section 3.0 in terms of overall operability of the system, flue gas emissions, and thermal performance for the tests performed on the EERC pilot plant.

TABLE 1-2

Test Matrices

Coal Type Test Number	Average Combustor Temperature (°F)	Load (%)	Sulfur Retention (%) or Ca/S	PA/SA[1]	Flue Gas Velocity (ft/s)	Excess Air (%)
Salt Creek						
1	1616	100	0.54	54:46	16.0	20
2	1616	100	2.04	54:46	16.0	20
3	–[2]	75	2.04	56:44	–[2]	20
4	–[2]	50	2.04	–[2]	–[2]	30
5	1475	100	1.54	70:30	16.0	45
6	1475	100	1.54	50:50	16.0	15
7	1625	100	1.54	70:30	16.0	15
8	1625	100	1.54	50:50	16.0	45
9	1625	100	3.54	70:30	16.0	45
10	1625	100	3.54	50:50	16.0	15
11	1475	100	3.54	70:30	16.0	15
12	1475	100	3.54	50:50	16.0	45
Center Lignite						
0	1550	100	No ls[3] feed	60:40	16.0	25
1	1550	100	70%	60:40	16.0	25
2	–[2]	75	70%	60:40	16.0	–[2]
3	–[2]	50	70%	60:40	16.0	–[2]
4	1550	50	70%	60:40	16.0	25
5	1550	75	70%	60:40	16.0	25
6	1550	100	50%	60:40	16.0	25
7	1550	100	70%	60:40	16.0	25
8	1475	100	70%	60:40	16.0	25
9	1400	100	70%	60:40	16.0	25
10	1475	100	70%	60:40	16.0	25
Asian Lignite						
1	1550	100	90%	60:40	18.5	20
2	1450	100	same Ca/S as 1	60:40	18.5(–)	20
3	1650	100	same Ca/S as 1	60:40	18.5(+)	20
4	1550	100	No ls feed	60:40	18.5	20
Black Thunder						
1	1550	100	No ls feed	60:40	16.0	25
2	1550	100	90%	60:40	16.0	25
3	1450	100	same Ca/S as 2	60:40	15.2	25
4	1550	100	same Ca/S as 2	60:40	16.0	5
5	1550	100	70%	60:40	16.0	25
7	1550	75	same Ca/S as 2	80:20	12.0	25
8	1550	100	same Ca/S as 2	60:40	16.0	45
9	1650	100	same Ca/S as 2	60:40	16.8	25

[1] Primary-to-secondary combustion air split.
[2] Varied as needed to maintain the desired load.
[3] Limestone.

continued...

Table 1-2 (continued)

Coal Type Test Number	Average Combustor Temperature (°F)	Load (%)	Sulfur Retention (%) or Ca/S	PA/SA[1]	Flue Gas Velocity (ft/s)	Excess Air (%)
Blacksville						
1	1550	100	No ls feed	60:40	16.0	25
2	1550	100	90%	60:40	16.0	25
3	1425	100	same Ca/S as 2	60:40	15.0[4]	25
4	1550	100	same Ca/S as 2	70:30	19.0	15
5	1550	100	same Ca/S as 2	50:50	19.0	45
6	1675	100	same Ca/S as 2	60:40	17.0[4]	25
7	1550	100	same Ca/S as 2	50:50	13.0	15
8	1550	100	same Ca/S as 2	70:30	13.0	45
9	1550	75	same Ca/S as 2	80:20	12.0[4]	25
10	1550	50	same Ca/S as 2	100:0	8.0[4]	25
11	1000[4]	50	same Ca/S as 2	100:0[4]	13.2[4]	>100[4]
12	1400[4]	75	same Ca/S as 2	100:0[4]	13.8[4]	50[4]
12A	1400[4]	75	same Ca/S as 2	60:40	13.8[4]	50[4]
13	1550	100	95%	60:40	16.0	25
14[5]	1550	100	same Ca/S as 2	60:40	16.0	25
15	1550	100	70%	60:40	16.0	25
16[6]	1550	100	same Ca/S as 2	60:40	16.0	25
17[7]	1550	100	same Ca/S as 2	60:40	16.0	25
18	1550	100	No ls feed	60:40	16.0	25

[1] Primary-to-secondary combustion air split.
[4] Estimated value.
[5] Secondary air introduced into the combustor at level 3.
[6] Fine limestone.
[7] Salt Creek limestone.

Section 4.0 compares the test results from operation on one of the test coals (Colorado Salt Creek bituminous) to the results of test burns performed on two other CFB systems: a vendor-operated pilot plant, and a full-scale unit, both operated on the same type of coal and limestone, to determine the scalability of data from the EERC pilot plant.

The results of testing for Project CFB are summarized, and conclusions are set forth in Section 5.0. A list of references is given in Section 6.0.

The appendices contain separate sections for each particular test run which outline specific procedures and results for each coal tested. The appendices also contain a section which details the design and construction of the EERC pilot-scale CFBC, and modifications which were made to the system as testing progressed. The final appendix lists calculations used during operation of the pilot plant and during data reduction.

2.0 DESCRIPTION OF FACILITIES

2.1 1-MWth CFBC Test Facility

A schematic of the overall CFBC system in its latest configuration (as of January 1, 1992) is shown in Figure 2-1. The overall system is divided into the following subsystems:

- Combustion Air System
- Flue Gas System
- Flue Gas Recirculation System
- Ash-Fouling Section
- Coal and Sorbent System
- Combustor
- Solids Recirculation System
- Natural Gas-Fired Preheater
- Combustor Heat Exchange System
- External Heat Exchange System
- Flue Gas Cooling Water System

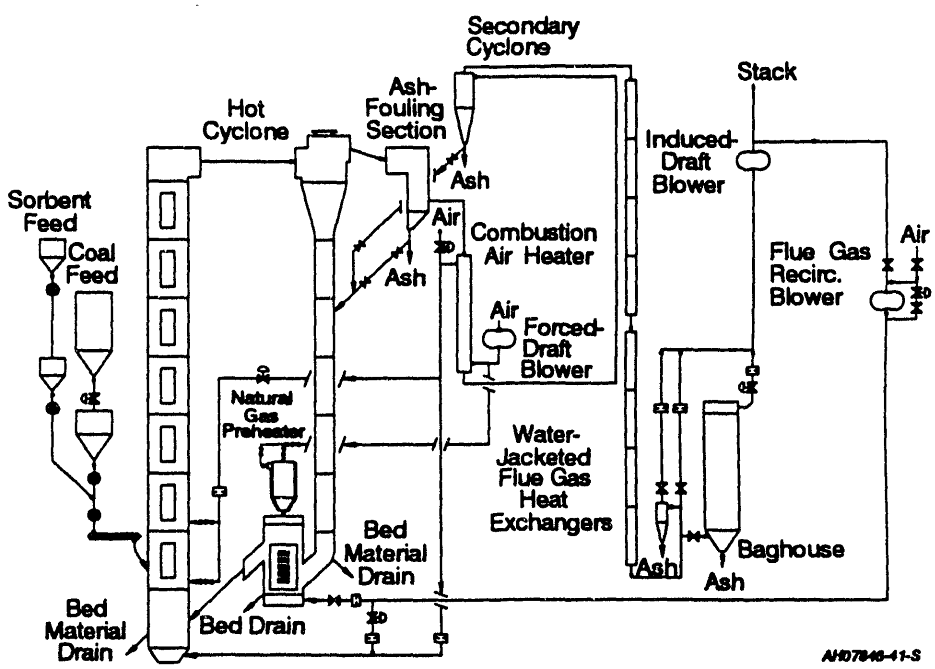

Figure 2-1. Schematic of CFB pilot plant.

A forced-draft blower supplies combustion air and secondary air to the combustor. The combustion air heater is a shell and tube heat exchanger that uses hot flue gas to preheat the combustion air before it enters the combustor. Total combustion air flow is controlled by the amount of bypass through the combustion air bypass valve located directly after the combustion air heat exchanger. The secondary combustion air control valve determines the ratio of the amount of combustion air which enters the test furnace above the distributor plate to the amount of combustion air introduced into the combustor plenum below the distributor plate. The secondary combustion air can be introduced through manifolds at two different levels, located 5'9" and 10'6" above the distributor plate in Sections 2 and 3, respectively, of the combustor. There are four 3-inch manual gate valves at each level used to select where overfire air is introduced into the combustor. Secondary air addition was through Section 2 during all tests with the exception of Test 14 of the Blacksville run.

Flue gas exits the top of the combustor, then flows through a refractory-lined primary cyclone with an inside diameter of 25 inches, the ash-fouling section, the combustion air heater, an 18-inch stainless steel secondary cyclone, eight water-jacketed flue gas heat exchangers, and through either the flue gas bypass, the baghouse, or partially through a 10-inch stainless steel cyclone. Temperatures and pressures are monitored throughout the flue gas system. Flue gas is drawn through the induced-draft (ID) blower where it enters a stack for release to the atmosphere. The ID blower speed is regulated with an electronic speed controller to maintain a zero-pressure balance point in the primary cyclone.

The flue gas recirculation blower is used to supply either air or flue gas to the external heat exchanger (EHX) and to supply flue gas to the combustor for flue gas recirculation testing. Manual gate valves located upstream of the blower allow either air or flue gas to enter the blower. Air was used as the EHX fluidizing gas during all testing.

Primary and secondary combustion air, flue gas recirculation, and flue gas flow rates are measured using orifice plates. Instrumentation is interfaced with the data acquisition/control system to record and display the flow rates. Orifice differential and static pressures are also monitored with magnehelic pressure gages.

The ash-fouling section is located at the exit of the primary cyclone. Two air-cooled stainless steel probes that are maintained at 1000°F are present in the ash-fouling section to detect potential ash deposition or slagging. There are provisions for the installation of six additional probes further downstream for a better indication of ash fouling that could occur in the convective pass tube bundle in a CFB boiler. A hopper attached to the base of the ash-fouling section collects ash which drops out of the flue gas stream due to an abrupt change in the direction of flue gas flow. The ash-fouling hopper is connected to the downcomer by a 4-inch stainless steel pipe for ash recirculation. Two pneumatically actuated gate valves are present in the return piping to prevent the bypass of flue gas back from the downcomer.

Coal is delivered to the combustor via two hoppers. The storage hopper has a capacity of about 3000 pounds of coal, which is transferred to a permanent feed hopper in 600-pound increments. A gate valve is used to recharge the coal feed hopper. The coal feed hopper is suspended from a load cell; approximate coal feed rates are calculated from the weight loss of the hopper over time. At the bottom of the weigh hopper, a rotary valve connected to an electronic speed controller is used to regulate the coal feed rate. The original sorbent feed system was identical to the coal feed system in most respects, but was sized somewhat smaller. The only significant differences between the two feed systems, other than overall size, are the capacity of the movable sorbent storage hoppers (1000 pounds) and the method of transferring material from the storage hopper to the feed hopper. A rotary valve is used for bulk sorbent transfer, whereas a pneumatically actuated gate valve is used for coal transfer. A completely different sorbent feed system was used for the final Blacksville bituminous test which required the addition of limestone (Test 17) and the entire Black Thunder subbituminous run. Limestone was fed directly into the sorbent rotary valve through a screw feeder which has a variable-speed screw and self-contained charge hopper. Limestone calibrations were performed manually every few hours, and/or every time the feed rate was adjusted. The charge hopper was filled by hand as needed with preweighed volumes of limestone. The sorbent rotary valve that the limestone was fed into also served as a partial seal against back pressure from the combustor. The coal and sorbent feed into a common pipe, which is equipped with another rotary valve to isolate the feed systems from system pressure in the combustor. The coal/limestone mixture drops into a 3-inch horizontal auger that conveys it to the combustor. At this point, the mixture drops downward through a 3-inch pipe and feeds by gravity with air assist into the combustor.

The combustor is a series of refractory-lined sections bolted together. All refractory used was castable and was supplied by Premier Refractories and Chemicals, Inc. Each combustor section contains 2 inches of hard-face abrasion-resistant refractory, type AR-153® VC, used in combination with 7 inches of insulating refractory. Type 304 stainless steel fibers were incorporated into all of the hard-face refractory cast into the system for increased toughness and shock resistance. The bottom two sections of the combustor contain LITE WATE® 58 LI insulating refractory which is designed for use under reducing conditions. The remaining combustor sections were insulated with CER LITE™ 50 which is formulated for use in oxidizing atmospheres. The bottom plenum section contains the primary combustion air entrance and a bed material drain. The solids recirculation return from the external heat exchanger flows to the first combustor section (Section 1). A removable stainless steel nozzle distributor plate is installed between the plenum and first combustor section. The next seven sections (Sections 2-8) each have two doorways on opposite sides for the installation of either blank refractory doors or heat exchanger panels. At this time, twelve of the possible fourteen heat exchanger panels are installed in the combustor: two each in Sections 2, 3, 4, 7, and 8, and one each in Sections 5 and 6. Section 2 contains the entrance for gravity feed of coal and sorbent and the first set of secondary combustion air ports. Section 3 has the second set of four secondary combustion air ports. Section 9, the combustor exit, connects to the primary refractory-lined cyclone. Thermocouples and pressure taps are present in all of the combustor sections. All pressure taps are continuously purged to keep them open for accurate pressure measurements.

The refractory-lined components of the solids recirculation system include the primary cyclone, the downcomer sections, and the external heat exchanger (EHX). CER LITE™ 50 was used as insulating refractory for all of these components. AR-153® VC hard-face abrasion-resistant refractory was used in the barrel section of the cyclone. FSC-9™ VC was selected as the hard-face refractory for the remainder of the solids recirculation components because of its greater resistance to the thermal shock which occurs in this portion of the system while maintaining its abrasion resistance. Solids that are captured by the primary cyclone drop into the downcomer and travel downward into the EHX. Thermocouples monitor the temperature at the entrance and exit of the primary cyclone. Additional solids that drop out in the ash-fouling section hopper and that are collected by the secondary cyclone can be either added back into the downcomer or collected separately.

The EHX has a plenum section into which either air or flue gas can be introduced. A removable stainless steel nozzle distributor plate is installed between the plenum and the main body of the EHX. The natural gas-fired preheater, described later, is attached to the top section of the EHX. Sixteen U-shaped stainless steel water-cooled heat exchanger tubes are installed in a removable refractory-lined door in the EHX. There are thermocouples and pressure taps distributed along the sections of the downcomer and in the external heat exchanger.

The natural gas-fired burner is bolted on top of the preheater and fires downward. The preheater combustion chamber is constructed with inner and outer stainless steel shells. To maintain an acceptable operational temperature on the inside surface of the preheater, air is circulated through a baffled cooling jacket. Cooling air enters at the top of the preheater and flows downward where it combines with the combustion gases at the bottom of the preheater transition cone. Preheater combustion air and the cooling jacket air are supplied by the forced-draft blower. A butterfly valve in the 4-inch supply line from the FD blower to the preheater and a gate valve between the preheater and the EHX isolate the preheat system when it is not being used. There are two additional butterfly valves in the combustion air and cooling air lines to the preheater for control purposes. There are also orifice plates in each line with magnehelics to monitor the flow rates. Gas flows to the natural gas burner and pilot burner are controlled with flowmeters located in the control room. There is a flame safety system located in the control room to shut off the flow of natural gas to the preheater if 1) a flame is not present in the preheater, 2) combustion air is not being supplied to the preheater or cooling jacket, or 3) the combustion air pressure is greater than the natural gas pressure supplied to the preheater.

The rate of water flow to the combustor heat exchangers (CHX) is measured individually for each door by flowmeters and controlled by globe valves installed above the flowmeters in the CHX panel boards. Total flow is measured with an in-line turbine flowmeter, which includes a bypass to allow for maintenance or repair during operation. An air system is connected to the inlet manifolds of each of the heat exchange panels. Air is used to cool the heat exchanger panels down during operation prior to the introduction of water. Each inlet manifold has a selector switch to allow for the proper distribution of either air or water through the manifold into the heat exchanger tubes of the panels.

There are sixteen heat exchange coils installed in the external heat exchanger door. Each U-shaped heat exchanger is constructed out of 1-inch stainless steel pipe with ½-inch stainless steel tubing at each end. Each of eight circuits has a flowmeter and flow control valve mounted in a panel board to monitor and control the flow of water. Total flow is measured with an in-line turbine flowmeter, installed with a bypass to allow for maintenance or repair during operation. There are eight different EHX heat exchanger circuits, two using a single tube, four with two tubes in series, and two with three heat exchanger tubes connected in series. There is a thermocouple located in the exit of each circuit to measure the exit water temperature.

2.2 Coal and Limestone Preparation

The coal and limestone were prepared in the solids preparation system shown in Figure 2-2. Crushing was performed with a Williams hammer-mill crusher. The material exited the crusher and was conveyed to a vibrating screen. Various screens were used during classification of the coals and limestones, with oversized material returned to the crusher.

The sized coal was routed into standby 2-ton capacity totes. The coal was then transferred as needed by forklift and crane to storage hoppers having net capacities of approximately 3000 pounds. The crushed and classified limestone was placed into two 1000-pound capacity storage hoppers. Any remaining prepared limestone was placed into 55-gallon drums and held in storage.

2.3 Flue Gas Emissions Monitoring

Flue gas composition was monitored continuously throughout the runs. The results of these analyses were recorded in the data acquisition system, as well as displayed in the control room. The flue gas was sampled at a location just prior to the baghouse (Sample Line A); in addition, a flue gas sample was taken at the primary cyclone exit (Sample Line B). SO_2, O_2, CO_2, CO, NO_x, and N_2O were measured at the first location; only SO_2 and O_2 emissions were measured at the second location. The duplication provides a method to ensure that no major leaks exist in the combustion air heater. Table 2-1 shows the instrument and technique used for each flue gas component analysis. The flue gas system analyzers were calibrated at least three times a day.

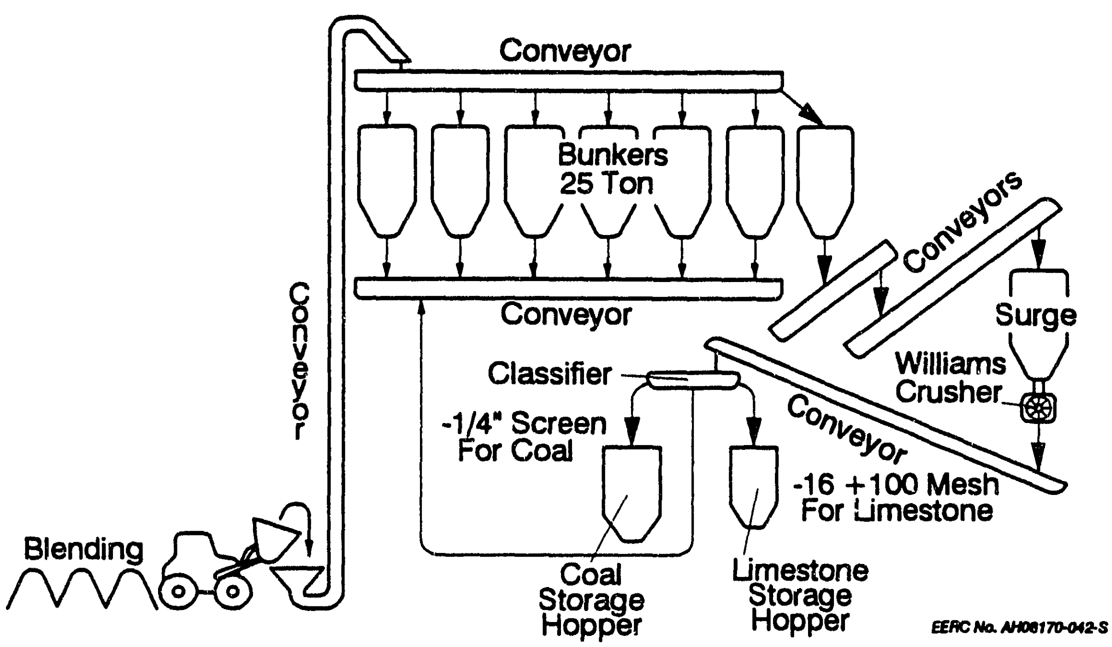

Figure 2-2. Schematic of solids preparation system.

TABLE 2-1

Flue Gas Analytical Instrumentation

Gas Component	Analyzer	Detection Technique
O_2	Beckman Model 755	Paramagnetic
SO_2	Dupont Model 400	Photometric Light Absorption
NO_x	Thermo-Electron Series 10	Chemiluminescent in a Photomultiplier Tube
N_2O	Siemens Ultramat 5E	Infrared
CO, CO_2	Beckman Model 865	Infrared

2.4 Analytical Equipment and Procedures

The following equipment and procedures were used for the analysis of coal, fly ash, limestone, and bed material samples:

- Proximate analysis was performed to determine moisture, ash, volatile matter, and fixed carbon levels of the coal. Moisture, ash, and volatile contents were determined with a Fischer 490 coal analyzer. Fixed carbon was calculated by subtracting the sum of the percentage moisture, ash, and volatile matter from 100%.

- Ultimate analysis was performed to determine the carbon, hydrogen, nitrogen, sulfur, ash, and oxygen content of the coal. A Perkin-Elmer Model 240 elemental analyzer was used to determine CHN concentrations. Total sulfur content was determined with a Fischer sulfur analyzer. Ash was determined as described above in the proximate analysis. Oxygen was calculated by subtracting from 100% the sum of percentages of moisture and the other components of the ultimate analysis.

- Heating (calorific) value of the coal was measured by ASTM Method D 2015-77 using a Parr adiabatic calorimeter and master controller.

- Particle-size distributions of the coal, limestone, bed material, downcomer material, secondary cyclone ash, and baghouse ash were determined by sieve analysis according to ASTM Method D 410-38 utilizing U.S. standard screens. Malvern (particle-size distribution by laser light scattering), wet sieve, and Coulter Counter analyses were also performed on the ash and limestone as needed for comparative purposes.

- Major mineral oxides (Al, Si, Na, Mg, Ca, P, K, Fe, Ti, and S) were determined by x-ray fluorescence using a Kevex 0700 x-ray spectrometer.

- The amount of carbonate (uncalcined limestone) in ash samples was determined by ASTM Method D 1756-62.

2.5 Scanning Electron Microscopy

Various solids samples were analyzed using scanning electron microscopy (SEM) with the Noran automated digital electron microscope (ADEM). The ADEM has the capacity for imaging and photography at magnifications ranging from 10 to 80,000. It is linked to a personal computer to allow for data manipulation.

3.0 IMPACTS OF COAL AND LIMESTONE PROPERTIES ON OPERATIONAL PERFORMANCE

Coals are ranked based on established ASTM guidelines according to their heating value, amount of volatiles, and fixed carbon content. The low-rank coals are characterized as having low heating value, high volatile content, and high moisture. Conversely, high-rank coals are characterized by high heating values and a high fixed carbon content. Generally speaking, the reactivity of the coal increases with decreasing rank.

The quantity and nature of the ash can vary widely and is more a function of the region of the country and the geological conditions under which the coal was formed rather than a function of rank. Many western U.S. coal ashes have relatively high alkaline contents as compared to their eastern counterparts; however, many of the coals in the Southwest have several of the same ash components as do typical eastern coals. Sulfur content, another critical coal property, is also more dependent upon location rather than rank, although most eastern coals have higher sulfur levels than do western coals. Therefore, it is critical to compare operational performance based on individual coal parameters independent of rank.

The EERC has built up an extensive database characterizing the performance of five coals under Project CFB. Detailed analysis of the coal composition and size are presented in Appendices A through E of this report. A list of the coals tested, along with their properties, was presented in Table 1-1. Figure 3-1 is a comparison of the average size distribution of the coals tested. Abbreviations of the coals used in this paper are CL--Center lignite, TL--Asian lignite, BT--Black Thunder subbituminous, SC--Salt Creek bituminous, and BV--Blacksville bituminous.

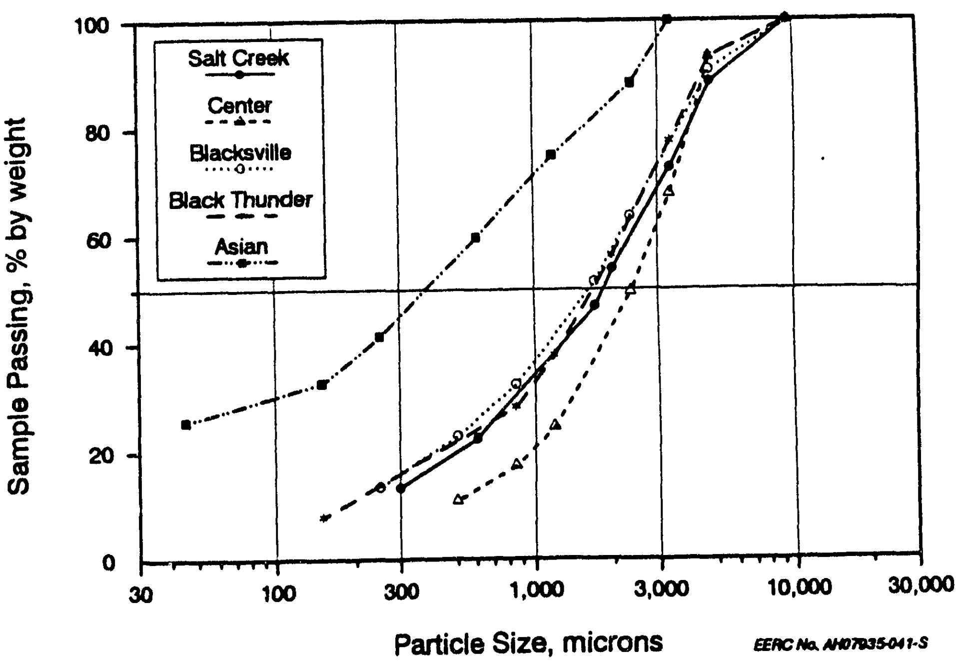

Figure 3-1. Comparison of average coal size distributions.

Table 3-1 shows a comprehensive list of selected critical test parameters that affect CFB performance along with a list of the critical operational performance results that were routinely determined for the test matrices conducted with the five different coals at the EERC. With the exception of replacement of the particulate collection device with a cyclone, the system geometry remained constant during all five test matrices. The operational test parameters selected for testing included average bed temperature, load (defined as a percentage of the coal feed rate at baseline conditions), either the calcium-to-sulfur ratio or sulfur retention, the primary/secondary combustion air split, superficial gas velocity, and excess air. Heat-transfer surface was varied as required to maintain the desired load. One test period during Blacksville testing was also performed at a different level of secondary air addition. The use of solids recycle from the secondary cyclone is an additional variable that was considered during examination of test results.

TABLE 3-1

Identification of EERC Test Parameters and Operational Results

Critical Operational Test Parameters	
Coal Size Distribution	Superficial Gas Velocity
Coal Composition	Excess Air
Limestone Size Distribution	Recycle of Secondary Cyclone Solids
Limestone Composition	Secondary Air Addition
Average Bed Temperature	Heat-Transfer Surface
Load	- Combustor
Ca/S Ratio or Sulfur Retention	- External Heat Exchanger
Primary/Secondary Combustion Air Split	
Critical Operational Performance Results	
Combustor Bed Material	Coal Feed Rate
- Size Distribution	Limestone Feed Rate
- Composition	Combustor Temp. Distribution
- Quantity	Combustor Pressure Distribution
Downcomer Material	Downcomer Temp. Distribution
- Size Distribution	Downcomer Pressure Distribution
- Composition	Recirculation Rate
- Quantity	Solids Collection Efficiency
Secondary Cyclone Ash	Limestone Utilization
- Size Distribution	Sulfur Retention or Ca/S Ratio
- Composition	SO_2 Emissions
- Quantity	NO_x Emissions
Baghouse Ash	N_2O Emissions
- Size Distribution	CO Emissions
- Composition	Combustion Efficiency
- Quantity	Heat Transfer

Three of the five test matrices (Blacksville bituminous, Black Thunder subbituminous, and Center lignite) were conducted with the New Enterprise limestone to, as much as possible, eliminate limestone selection from affecting test results. The first test matrix was with the Salt Creek subbituminous coal and limestone that were used for testing at the Colorado-Ute Nucla full-scale CFB electrical generating station. This test matrix addressed scalability of the EERC CFB pilot plant test results to the full-scale results from Nucla. Both the coal and limestone used for the Asian lignite test were from the same region. Table 1-1 has the average composition of the limestones utilized for each of the five test matrices, while Figure 3-2 shows the average limestone size distributions.

3.1 Overall Operability

3.1.1 Bed Material Size Distribution and Recirculation Rates

The bed material size distribution and recirculation rates are dependent upon the coal and limestone properties, operational parameters like superficial gas velocity and primary-to-secondary air split, and the performance of the particulate collection device used. During all of the first test matrix with Salt Creek bituminous coal, and through most of the second test matrix with Center lignite, an impaction-type collection device (the Chevron impactors) was used to capture solids for recirculation, along with a secondary cyclone to enhance overall solids collection efficiency. For the remaining test matrices, the primary cyclone was used both with and without secondary cyclone ash recycle for additional solids recirculation. Collection configurations are summarized in Table 3-2. Chevron impactor configurations are identified in Appendix F.

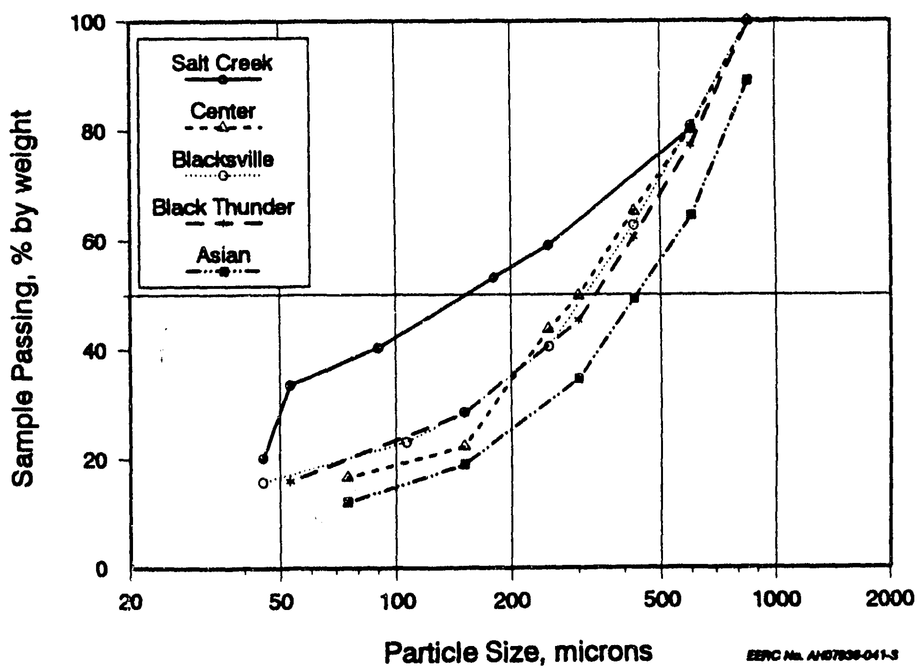

Figure 3-2. Average limestone size distributions.

TABLE 3-2

Solids Recirculation Configurations Utilized
During Parametric CFB Pilot Plant Testing

Test Identification	Primary Collection Device	Secondary Collection Device
Salt Creek Tests 1-12	Chevron Impactors - Configuration #1	18" Stainless Steel Cyclone
Center Tests 0-6	Chevron Impactors - Configuration #2	18" Stainless Steel Cyclone
Center Tests 7-10	25" Refractory Cyclone	18" Stainless Steel Cyclone
Blacksville Tests 1-18	25" Refractory Cyclone	None
Black Thunder Test 1	25" Refractory Cyclone	None
Black Thunder Tests 2-9	25" Refractory Cyclone	18" Stainless Steel Cyclone
Asian Tests 1-4	25" Refractory Cyclone	None

Figures 3-3 and 3-4 show the size distribution of the bed material sampled from the combustor and the bed material collected from the downcomer, respectively, from a representative test period from each of the five test matrices completed.

Addition of secondary combustion air is normally through Section 2 of the combustor, 5.75 feet above the distributor plate. To keep the solids fluidized in the bottom of the combustor, Section 1 is tapered, starting with an inside diameter of 14 inches at the bottom and increasing to 20 inches at the top. The remaining combustor sections above Section 1 all have a 20-inch inside diameter. During Test 14 with the Blacksville coal, secondary air addition was through Section 3 at a height of 10.5 feet above the distributor plate. This created a low-velocity region in combustor Section 2, allowing less solids to be carried up to Section 3, resulting in decreased solids recirculation compared to other Blacksville tests conducted at equivalent operating conditions.

One of the most significant factors affecting solids recirculation was whether or not the secondary cyclone was used to recirculate additional fines back into the system. For testing with the Blacksville bituminous coal and with the Asian lignite, it was not necessary to utilize secondary cyclone ash recycle. For the other low-ash, low-sulfur coals, secondary cyclone ash recycle was used to maintain solids inventory in the combustor. These tests tended to have lower recirculation rates compared to the Black Thunder subbituminous and Salt Creek bituminous tests. An exception to this trend was the Center lignite testing which had low recirculation rates even though secondary cyclone ash recycle was utilized. It appears that the cohesive ash properties, possibly due to the high sodium in the coal, might have resulted in reduced solids recirculation rates. It appears that solids recirculation is somewhat related to coal ash properties. It would take

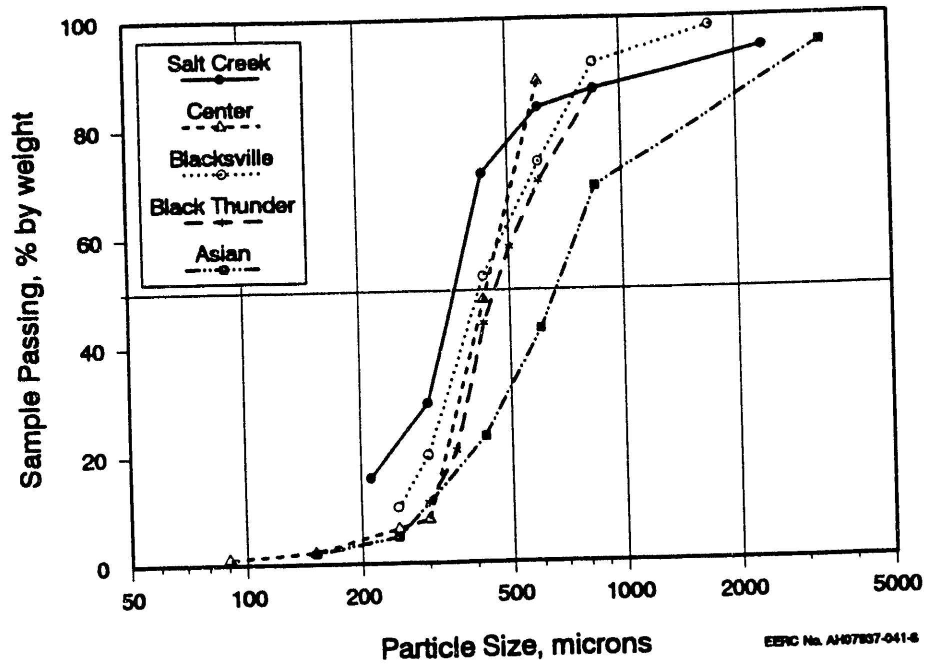

Figure 3-3. Size distributions of bed material sampled from combustor.

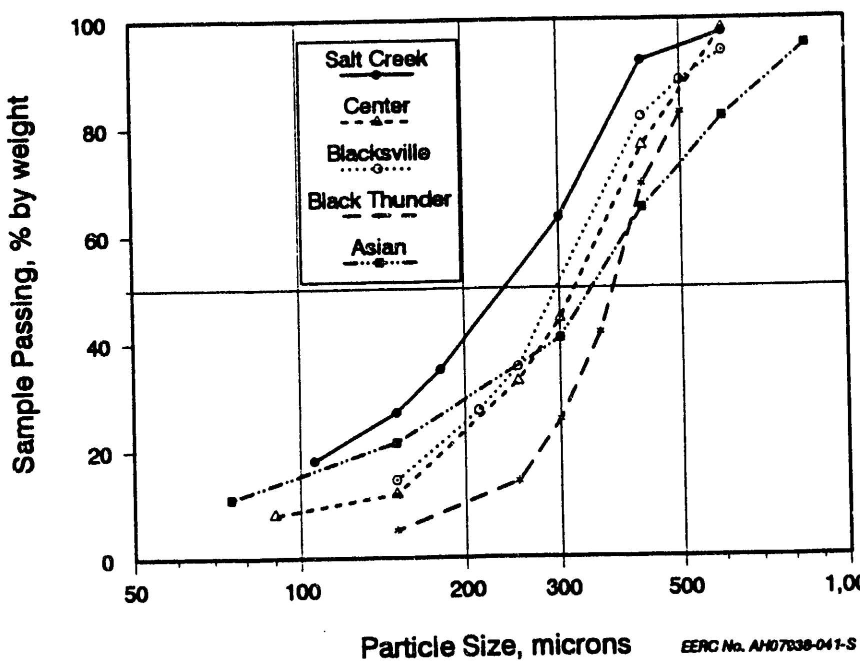

Figure 3-4. Size distributions of bed material sampled from downcomer.

a more specifically designed test matrix to better define the extent that coal properties affect solids recirculation. A carefully designed system, which would allow the reinjection of multicyclone or baghouse ash back into the recirculation loop, could likely be used to more closely control recirculation rates. Therefore, more efficient operation, in terms of heat transfer and emissions, could be obtained in the event that a fuel other than the design coal was to be used.

Figure 3-5 shows recirculation rate as a function of load. To decrease load, the superficial gas velocity is decreased along with the coal feed rate, which results in decreased solids recirculation. It can also be seen from these data that the Center, Black Thunder, and Salt Creek tests which employed secondary cyclone recycle resulted in increased solids recirculation rates.

3.1.2 Cyclone Efficiency

Cyclone efficiency is defined as one minus the fly ash discharge rate divided by the recirculation rate. Cyclone efficiency is used here to collectively describe total system efficiency for the capture of solids using a primary, and a secondary (if recycled), collection device for solids recirculation. Solids capture is determined by the collector geometry as well as operational parameters, including the combustor velocity and fuel and limestone properties. The collector configuration used for all five test coals was previously identified in Table 3-2. Adequate recirculation rates were maintained by some combination of high cyclone efficiency and a high input of solids into the system.

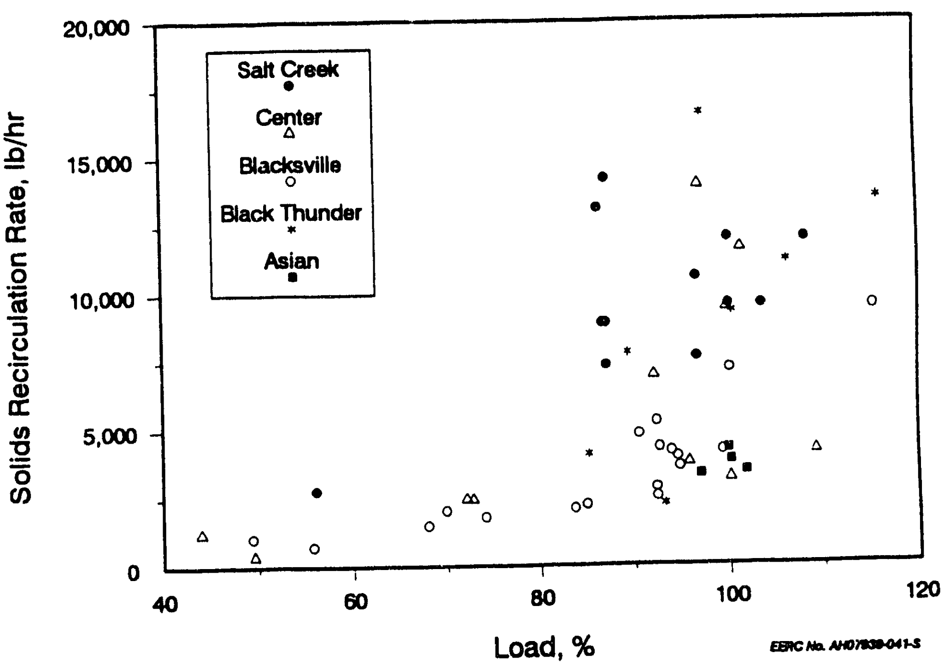

Figure 3-5. Recirculation rate as a function of load.

Cyclone efficiencies ranged from a low of 93.8% with the Asian lignite to 99.9% with Black Thunder bituminous. For testing conducted with Center, Black Thunder, and Salt Creek fuels, secondary cyclone recycle was used to maintain adequate bed inventory and recirculation rates. These three coals had relatively low coal ash and sulfur content, resulting in low quantities of solids available for recirculation. Additionally, the size of the limestone used for Salt Creek testing was relatively small, making it difficult to keep in the system. The Blacksville bituminous was a low-ash coal, but required relatively high limestone feed rates due to its high sulfur content, and subsequently no secondary cyclone recycle was required to maintain sufficient bed inventory. Although the cyclone efficiencies for the Asian lignite were significantly lower than for the other four test coals, no secondary cyclone recycle was required to maintain adequate bed inventories due to the high solids input of sorbent and the low-Btu, high-sulfur, high-ash fuel.

3.1.3 Solid Waste Generation

An important aspect of the design of the CFBC is sizing of the solids-handling systems. From an operational standpoint, disposal of the solid wastes (coal ash and spent sorbent) becomes a very important economical consideration. The amount of solids generated is highly dependent upon coal properties, as shown in Figure 3-6. The combination of high ash and high sulfur in the Asian lignite results in very large quantities of solid waste. For the other coals tested, the amount of solid waste generated increased with the amount of ash in the coal and the amount of limestone added. The two bituminous coals generated more solid wastes than the two low-rank coals. Sorbent addition rates are highest for high-sulfur, low-alkaline-ash coals and increase with increasing sulfur capture requirements. In designing the CFBC solids-handling system and determining waste disposal requirements, it is important to design for the highest solid waste generating fuel, otherwise derating will be required due to the inability to handle the large volume of wastes generated from these fuels.

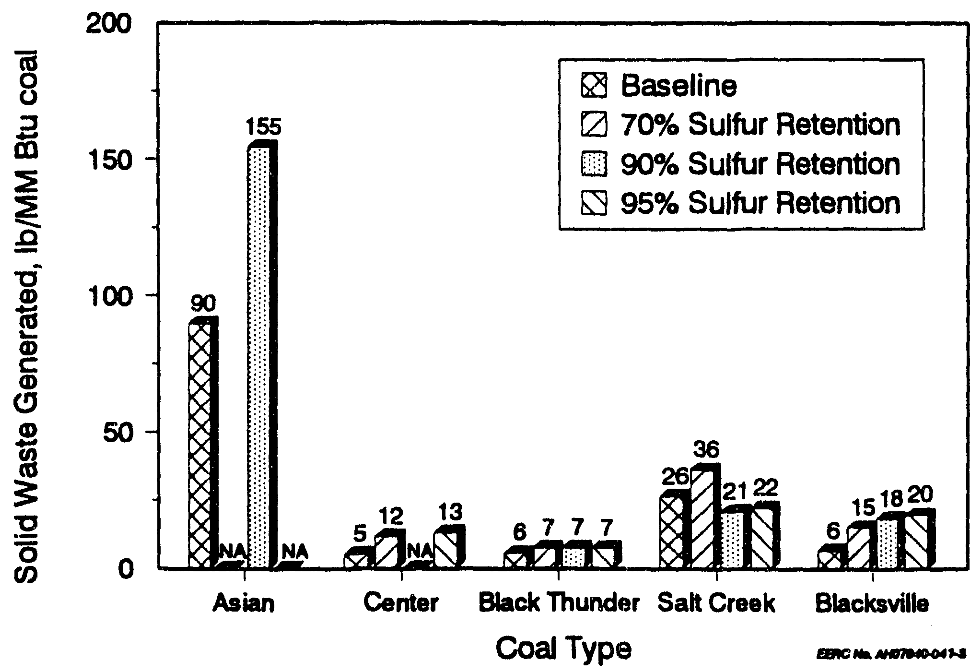

Figure 3-6. Solid waste generation as a function of coal property.

3.1.4 Agglomeration and Ash Deposition

One aspect of system operation that is directly impacted by fuel ash properties is agglomeration and deposition. The Center lignite has a relatively high sodium level in the ash (4%). During the tests, particle growth was observed, but did not lead to severe agglomeration. However, a fuel with slightly higher levels of sodium or potassium would likely result in problems due to agglomeration. Fuels with high levels of organically bound calcium have been shown to have the potential to cause problems with fouling in the convective and reheat sections of a boiler. A very hard, fine-grained calcium sulfate-based deposit formed on the ash-fouling probes and the primary flue gas heat exchanger during the tests with the Asian and Center lignites. Therefore, a prudent design for fuels similar to these would include adequate soot-blower coverage. More complete discussions of the agglomeration and deposition potential of the lignites can be found in Appendices B and E.

3.1.5 Corrosion and Erosion of System Components

While there was no specific testing performed to examine the corrosion and erosion of the CFBC components for the coals tested, it is possible to offer some subjective observations based upon visual inspections. Discussion is limited here to the refractory and metal surfaces exposed to hot flue gases and circulating bed material in the combustor, primary cyclone, downcomer, and external heat exchanger. Metal surfaces include the combustor heat exchangers, the heat exchange tubes (type 304 stainless steel) in the external heat exchanger, the primary cyclone vortex finder (¼-inch-thick type 310 stainless steel), and the thermocouple thermowells (⅜-inch schedule 80 type 310 stainless steel pipe).

The combined shakedown and testing performed for Project CFB resulted in more than 1000 hours of operation over a wide range of conditions. The refractory has been subjected to numerous heating cycles during start-ups, process upsets, and shutdowns. There have also been short-duration temperature excursions in the combustor to over 2000°F. To date, the refractory has required no maintenance of any sort and has shown absolutely no signs of any erosive or corrosive deterioration.

Regions where erosion is most likely to occur in the EERC CFBC system are in the combustor and primary cyclone. An unknown amount of internal circulation occurs in the combustor, and the entrance to the primary cyclone is subjected to the continuous flow of high-velocity (approximately 60 ft/sec) and high-temperature solids from the combustor. Some limited erosion to a patch of about one foot square has occurred inside the primary cyclone barrel where the bed material enters and makes its first turn. Typically a thin layer of ash is deposited on uncooled refractory and metal surfaces in the combustor and primary cyclone. Visual inspections following each run revealed the ash had eroded off at the cyclone entrance without causing any noticeable damage to the refractory surface.

All thermocouples (type K with a ⅜-inch-diameter type 304 stainless steel sheath) located in the high-temperature refractory-lined regions of the system are inserted into type 310 stainless steel thermowells to provide additional protection. No evidence of any significant corrosion or erosion to the thermocouple thermowells has been noted, including those in the combustor. Combustor heat exchangers are almost totally recessed inside the refractory walls of the combustor to protect them from erosion. No measurable erosion has been detected for any of the exposed surfaces of the combustor heat exchangers. As would be expected, no indication was found of any erosion of the heat exchange tubes and thermocouples located in the EHX since these components are exposed to low-velocity (1 to 2 ft/sec) bubbling solids. The vortex finder in the primary cyclone has survived the harsh conditions to which it has been subjected without any noticeable corrosion or erosion.

3.2 Emissions

3.2.1 SO_2 Emissions and Limestone Utilization

A comparison of sulfur emissions and sorbent performance is presented in Table 3-3. Sorbent performance is addressed as a function of sulfur capture ranging from 70% up to 95%. The amount of sulfur capture is mainly determined by the total alkali-to-sulfur ratio. Total alkali is provided by the inherent alkali, mineral matter and cations contained within the coal, and the added alkali supplied by sorbent addition. For all of the tests, limestone was the sorbent which was used to supply added alkali in the form of calcium.

Figure 3-7 shows the added alkali-to-sulfur ratio required for 70%, 90%, and 95% sulfur capture for the various coals tested. To retain 90% of the sulfur present in the coal, the required alkali-to-sulfur ratio ranged from 1.4 to 4.9 depending upon the coal type. However, looking only at the alkali-to-sulfur ratio is misleading. For example, although an alkali-to-sulfur ratio of 4.9 is required to meet 90% sulfur retention for the Salt Creek coal versus 1.4 for the Asian lignite, the total amount of sorbent addition required is much less for the Salt Creek coal. A sorbent add rate of 4.2 lb/MM Btu of Salt Creek coal input is required versus 62 lb/MM Btu of Asian lignite, due to differences in the level of sulfur and the alkali in the coal. Figure 3-8 presents the required limestone addition rates in relation to varying levels of sulfur capture for the five coals tested.

The optimum bed temperature resulting in maximum sulfur capture varies somewhat with coal type (Figures 3-9 and 3-10). The bituminous coals tested at the EERC show optimal sulfur capture at combustor temperatures of approximately 1550°F. Most of the low-rank coals tested, however, exhibited optimal temperature for sulfur capture approximately 100°F lower. This is partially due to the coal structure and the forms and relationships of the sulfur and the alkali in the coal itself.

The source and size of limestone can also have an impact on sulfur capture. Two different limestones were tested while burning the Blacksville bituminous coal, as well as two different limestone sizes. Using a coarse limestone (-20 mesh), 40% of the calcium in the limestone was utilized for sulfur capture. A fine limestone (-40 mesh) of the same type resulted in a sorbent utilization of only 29%. A second type of limestone (Colorado Ute) of fine particle size (-40 mesh) showed similar performance, with approximately 29% utilization. To capture 70% of the sulfur, alkali-to-sulfur ratios of 1.8 for the coarse limestone and 2.3 for the two fine limestones tested would be required. In this case, the reactivities of the two limestones were similar. While the smaller-sized limestone had a greater surface-to-volume ratio, which would be expected to result in more efficient sulfur capture, the poorer utilization was probably the result of shorter sorbent residence time in the combustor. Cyclone collection efficiencies decrease with decreasing particle size, and smaller sorbent particles may leave the system without being recirculated. For

TABLE 3-3
Comparison of Sulfur Emissions and Sorbent Performance

Coal Type	Asian	Center	Black Thunder	Salt Creek	Blacksville
Total Sulfur, %	5.9	0.58	0.3	0.45	2.4
Inherent Alkali/Sulfur Ratio	0.63	0.9	2.1	0.3	0.1
Inherent Sulfur Capture, %	70	23	3	2	14
Inherent Alkali Utilization, %	112	26	1.4	3	64
Optimum Temperature for Sulfur Capture, °F	1565	1375	1456	1520	1530
70% Sulfur Capture					
Test Number	–[1]	CL5	BT5	SC3	BV15
Added Ca/S	–[1]	1.1	2.1	2.1	1.6
Added Sorbent, lb/MM Btu[2]	–[1]	4.3	2.5	3.0	9.8
Utilization, %	–[1]	39	31	36	43
90% Sulfur Capture					
Test Number	TL1	–[1]	BT2	SC11	BV2
Added Ca/S	1.4	–[1]	2.5	4.9	2.3
Added Sorbent, lb/MM Btu	62.7	–[1]	3.0	4.2	15.6
Utilization, %	63	–[1]	31	19	39
95% Sulfur Capture					
Test Number	–[1]	CL8	BT8	SC9	BV13
Added Ca/S	–[1]	2.3	2.6	5.7	2.9
Added Sorbent, lb/MM Btu	–[1]	7.8	3.3	7.1	19.3
Utilization, %	–[1]	35	37	17	32

[1] No tests were performed at 1550°F and a corresponding sulfur capture.
[2] Pounds sorbent added per million Btu coal input.

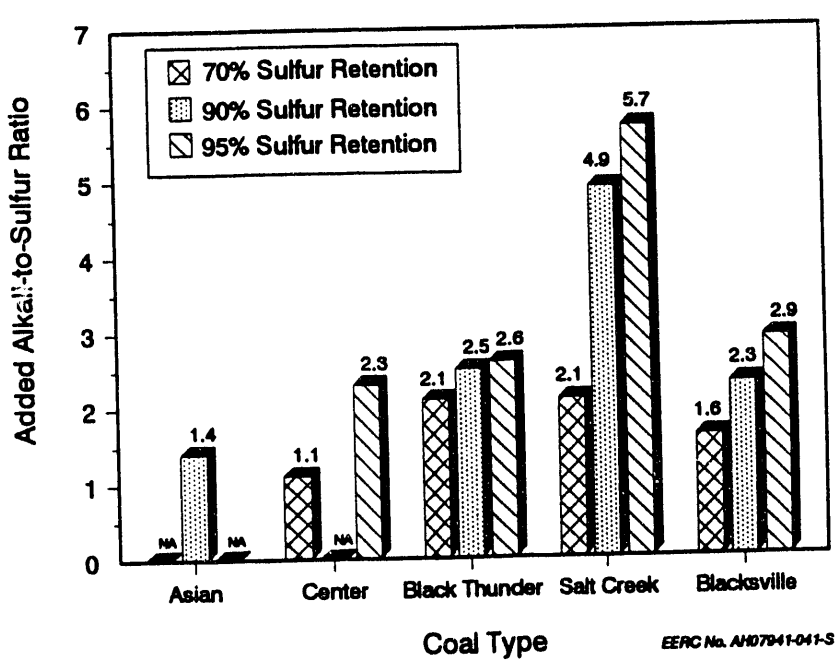

Figure 3-7. Added alkali-to-sulfur ratio required for increasing sulfur capture at ~1550°F as a function of coal type.

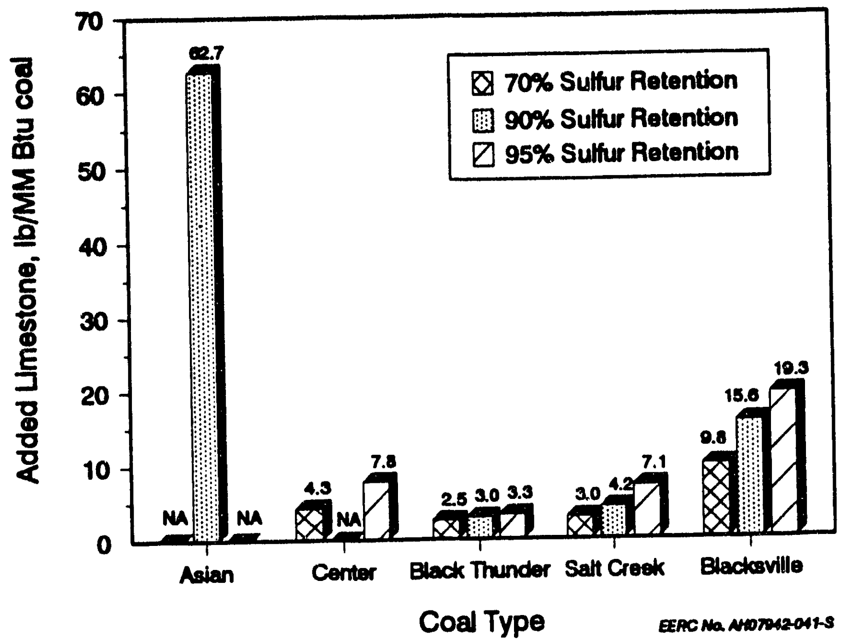

Figure 3-8. Added limestone required for increasing sulfur capture at ~1550°F as a function of coal type.

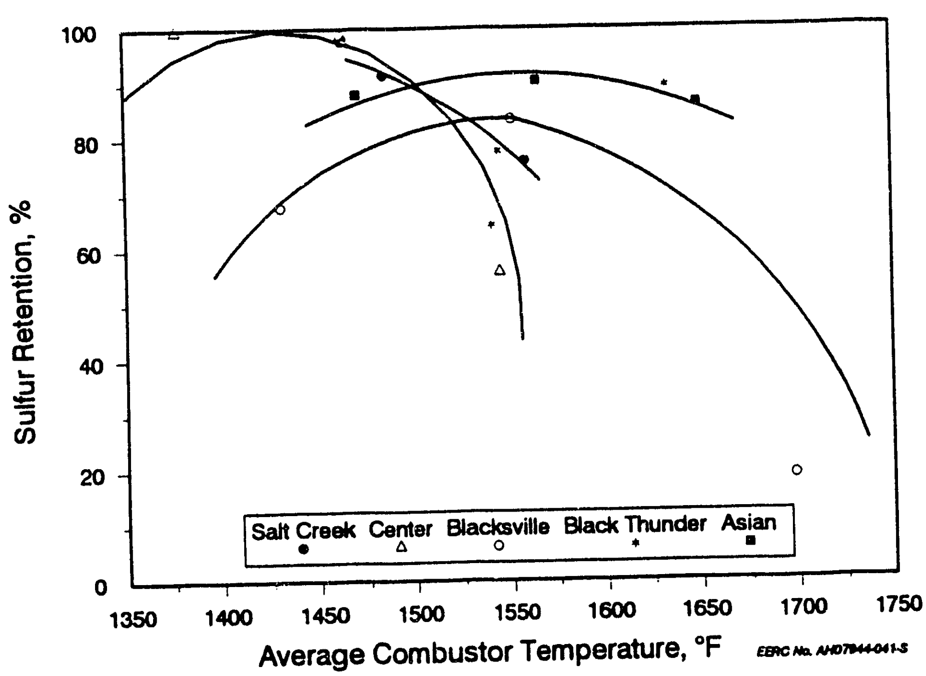

Figure 3-9. Sulfur retention as a function of average combustor temperature, showing the optimum temperature for maximum sulfur capture for each coal.

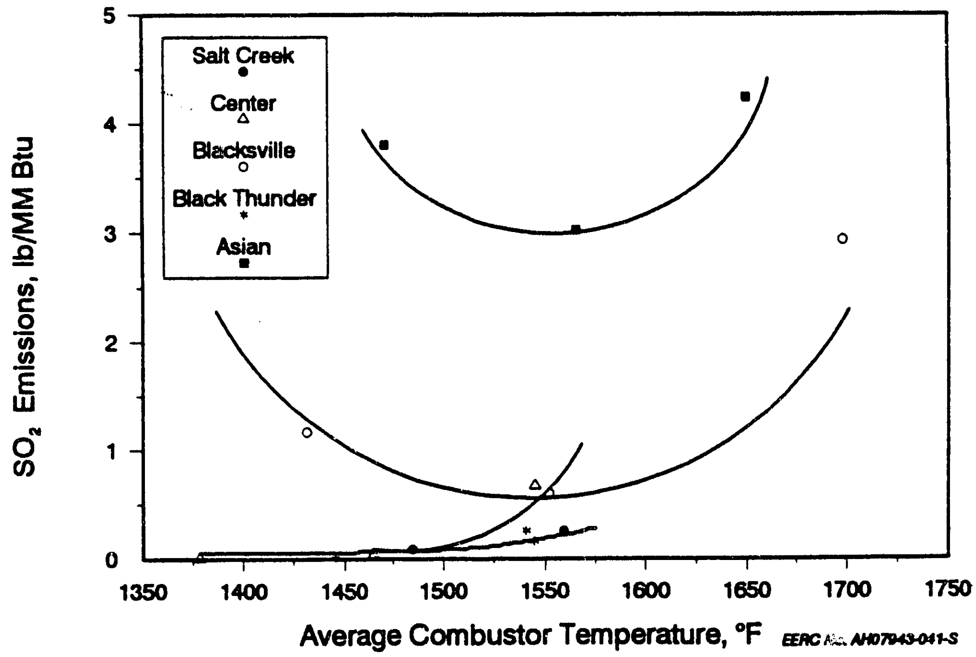

Figure 3-10. SO_2 emissions as a function of average combustor temperature, showing the optimum temperature for maximum sulfur capture for each coal.

limestones with different reactivities, the add rates can also vary as a function of limestone type. Results obtained on the impact of limestone size and type on other parameters are shown in Figure 3-11.

The coal properties that most affect the required amount of added alkali are total sulfur and inherent alkali present in the coal (indicated in Table 3-3 by the inherent alkali-to-sulfur ratio). Some generalizations on expected sulfur capture behavior as it relates to coal properties can be made based upon the testing performed. As the sulfur content of the coal increases, more limestone will be required, but utilization of the available calcium in the limestone will be higher due to the higher driving force supplied by the greater concentration of SO_2 in the combustor. The combination of a low-sulfur coal and a low inherent alkali-to-sulfur ratio will require sorbent addition at a low feed rate, but because of the diminished driving force within the combustor due to low SO_2 concentrations, the additional alkali-to-sulfur ratio required will be high. For a given amount of sulfur in the coal, as the inherent alkali-to-sulfur ratio increases, less added limestone will be required due to the increased capture of sulfur by the alkali inherent to the coal ash. Overall calcium utilization as a function of added calcium-to-sulfur ratio is shown in Figure 3-12.

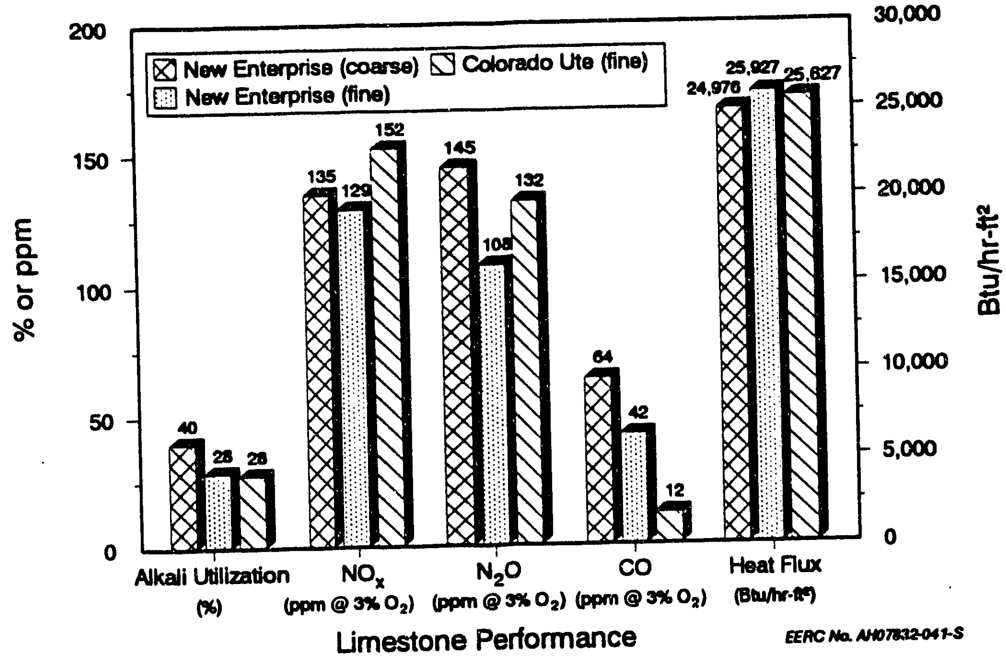

Figure 3-11. CFBC performance as a function of limestone size and type.

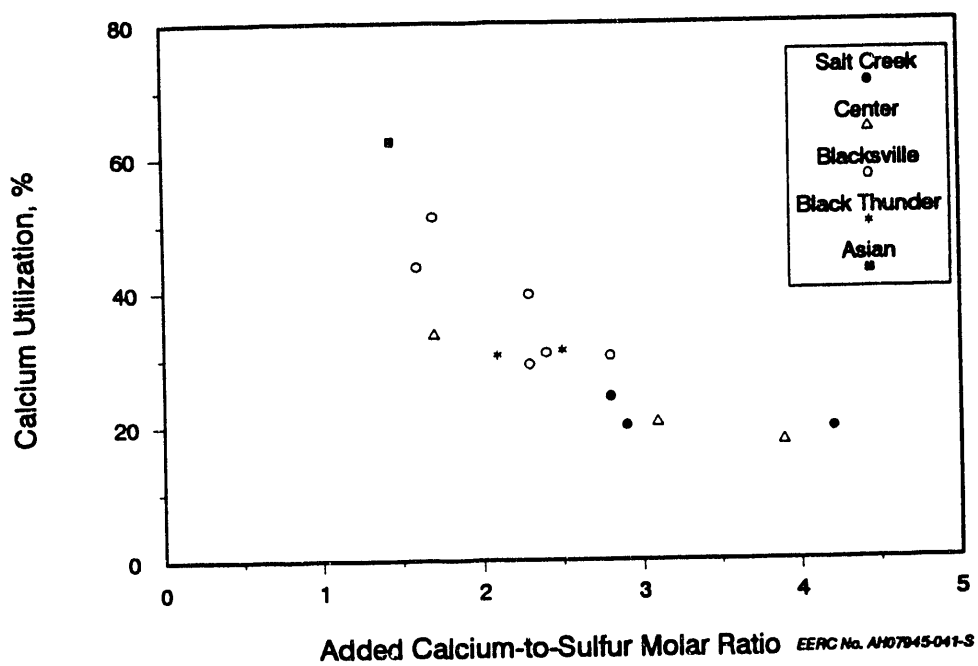

Figure 3-12. Calcium utilization as a function of added calcium-to-sulfur ratio.

3.2.2 Nitrogen Oxide Emissions

Regulated nitrogen oxide emissions currently include NO and NO_2, collectively termed NO_x emissions. NO_x emissions from the CFBC are highly coal dependent. Table 3-4 summarizes nitrogen emissions data for all five of the coals tested. Figures 3-13 and 3-14 compare NO_x emissions for the five test coals as a function of temperature. The different NO_x levels are caused by inherent differences in the nitrogen in the coals. The nitrogen in the bituminous coals is released as CN, while the lower-rank coals release more of their nitrogen as NH_3. The distribution of nitrogen between the volatiles and the fixed carbon also varies significantly between coal ranks and is partially responsible for the trends shown in Figures 3-13 and 3-14. Not only does the total amount of NO_x emitted vary with coal type, the rate at which the NO_x emissions increase when temperature increases also varies with coal type. The rate of change is the smallest with the lignites and the greatest with the bituminous coals. Therefore, the lignites are higher emitters of NO_x than the bituminous coals at lower temperatures (1450°F), but emit less NO_x at higher temperatures. NO_x emissions also increase with increasing excess air and sorbent add rates.

TABLE 3-4

Nitrogen Emissions

Coal:	Asian	Center	Black Thunder	Salt Creek	Blacksville
Fuel Nitrogen					
as-received, %	0.7	0.5	0.6	1.2	1.3
lb/MM Btu	1.38	0.76	0.72	1.12	1.02
Baseline Case, No Limestone					
Test Number	TL4	CL0	BT1	SC1	BV1
Average Combustor Temperature, °F	1564	1526	1575	1607	1558
Emissions, ppm					
NO_x	105	141	248	142	121
N_2O	81	48	25	150	168
NO_x+N_2O	186	189	273	292	289
Emissions, lb/MM Btu					
NO_x	0.15	0.20	0.32	0.19	0.15
N_2O	0.11	0.06	0.03	0.19	0.21
NO_x+N_2O	0.26	0.26	0.35	0.38	0.36
Conversion of Fuel Nitrogen, %					
NO_x	3.45	7.23	14.05	4.84	3.87
N_2O	5.29	4.90	2.83	10.20	11.91
NO_x+N_2O	8.74	12.13	16.88	15.04	15.78
Full Load, 90% Sulfur Capture					
Test Number	TL1	CL1	BT2	SC11	BV2
Average Combustor Temperature, °F	1565	1554	1547	1485	1544
Emissions, ppm					
NO_x	130	202	189	56	94
N_2O	59	22	44	223	145
NO_x+N_2O	189	224	233	279	239
Emissions, lb/MM Btu					
NO_x	0.18	0.27	0.24	0.29	0.11
N_2O	0.08	0.03	0.06	0.29	0.16
NO_x+N_2O	0.26	0.30	0.30	0.58	0.27
Conversion of Fuel Nitrogen, %					
NO_x	4.24	10.26	10.73	2.10	3.23
N_2O	3.84	2.25	4.63	16.40	10.28
NO_x+N_2O	8.08	12.51	15.36	18.50	13.51

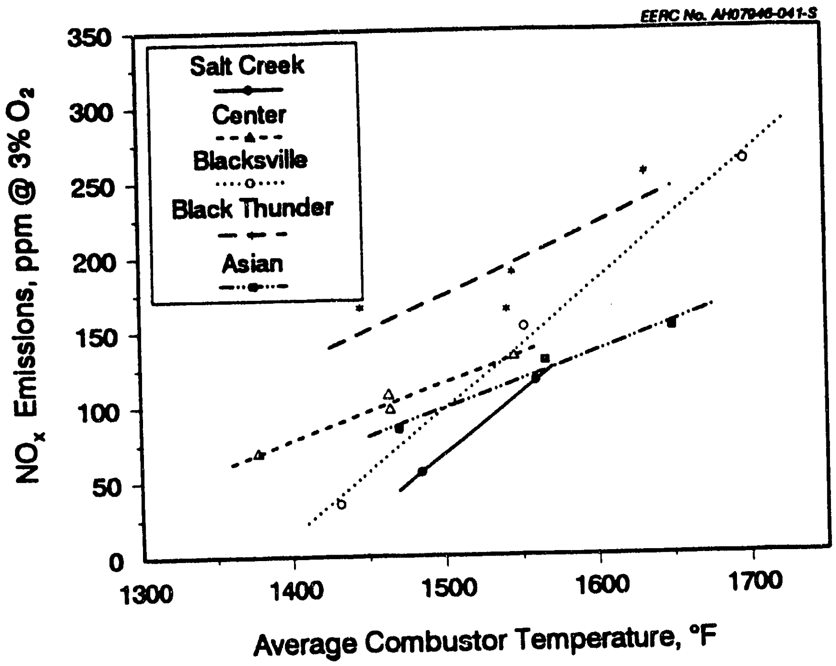

Figure 3-13. NO_x emissions in ppm at 20%-25% excess air, 16-ft/sec velocity, and 1.5-2.5 alkali-to-sulfur ratio as a function of combustor temperature.

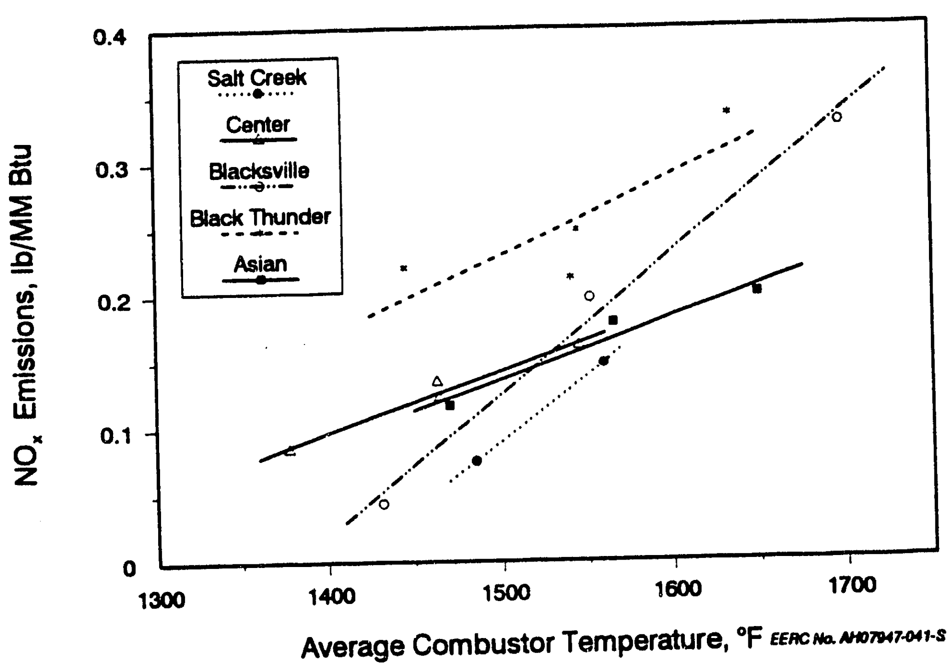

Figure 3-14. NO_x emission in lb/MM Btu at 20%-25% excess air, 16-ft/sec velocity, and 1.5-2.5 alkali-to-sulfur ratio as a function of combustor temperature.

Figure 3-15 compares NO_x emissions as a function of excess air for four different coals (no excess air tests were performed during the Asian lignite run). In all cases, NO_x emissions increased with increasing amounts of excess air. Figure 3-16, showing NO_x emissions as a function of primary-to-secondary air split, illustrates a typical trend on how the staging of combustion air affects NO_x emissions. Secondary air is introduced at about 5.5 feet above the distributor plate level. As the percentage of the total combustion air supplied through the distributor plate increased, increasing the amount of oxygen in the bottom of the combustor, the NO_x emissions correspondingly increased.

The effect of increasing limestone addition on NO_x emissions is shown in Figure 3-17. With the exception of the Black Thunder subbituminous coal, nitrogen oxide emissions increased with increasing limestone feed rates for the various ranks of coals tested. The opposite trend that occurred during Black Thunder testing cannot be explained at this time. However, it is believed to be a real trend.

New analytical techniques have recently made it possible to measure flue gas nitrous oxide (N_2O) levels. N_2O emissions from pulverized coal-fired systems are typically less than 10 ppm, while those from FBCs range from 25 to 150 ppm for most fuels on full-scale units. Although N_2O emissions are currently not regulated, they may become important in the future. The trends noted during this study were increasing emissions of N_2O as the rank changed from subbituminous to lignite to bituminous. These trends are shown in Figures 3-18 and 3-19. Similar trends have been noted on full-scale units. However, the N_2O emissions from full-scale systems are lower than those measured from the pilot scale. This has been attributed to increased wall effects inherent to small-scale systems. N_2O emissions are even more dependent on fuel properties than NO_x. The distribution of the nitrogen between the volatiles and the fixed carbon appears to be the most important fuel property affecting N_2O emissions.

N_2O emissions follow a trend opposite to that of NO_x, decreasing with increasing temperature (Figures 3-20) and sorbent add rate (Figures 3-21 and 3-22), and a similar trend as NO_x for excess air (Figure 3-23). No clear relationship between N_2O emissions and primary-to-secondary air split was evident from the results of testing (Figure 3-24). A strong interaction exists between N_2O emissions and temperature and excess air, as shown in Figures 3-20 and 3-23. Temperature has a stronger effect on N_2O emissions at lower excess air levels, while excess air has a much stronger effect at lower temperatures.

The percent conversion of fuel-bound nitrogen to NO_x and N_2O is illustrated in Figure 3-25. This assumes that only the fuel-bound nitrogen is converted and that nitrogen introduced with the combustion air is not converted at the comparatively low operational temperature typical in CFBs. Total nitrogen oxide emissions tend to increase as the rank of the coal increases.

N_2O emissions tend to decrease with increasing temperature, while NO_x usually will increase with increasing temperature, no matter what the coal rank is. No apparent consistent trend exists for total nitrogen oxide emissions, NO_x plus N_2O, as a function of average combustion temperature for the different ranks of coals tested, as shown in Figure 3-26.

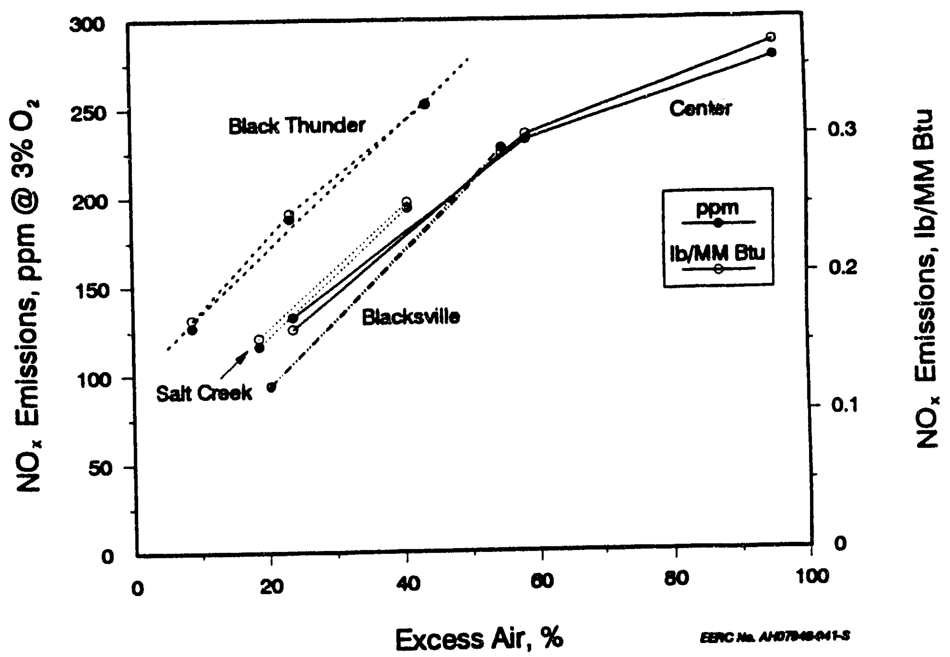

Figure 3-15. NO_x emissions at ~1550°F (1623° for Salt Creek) as a function of excess air.

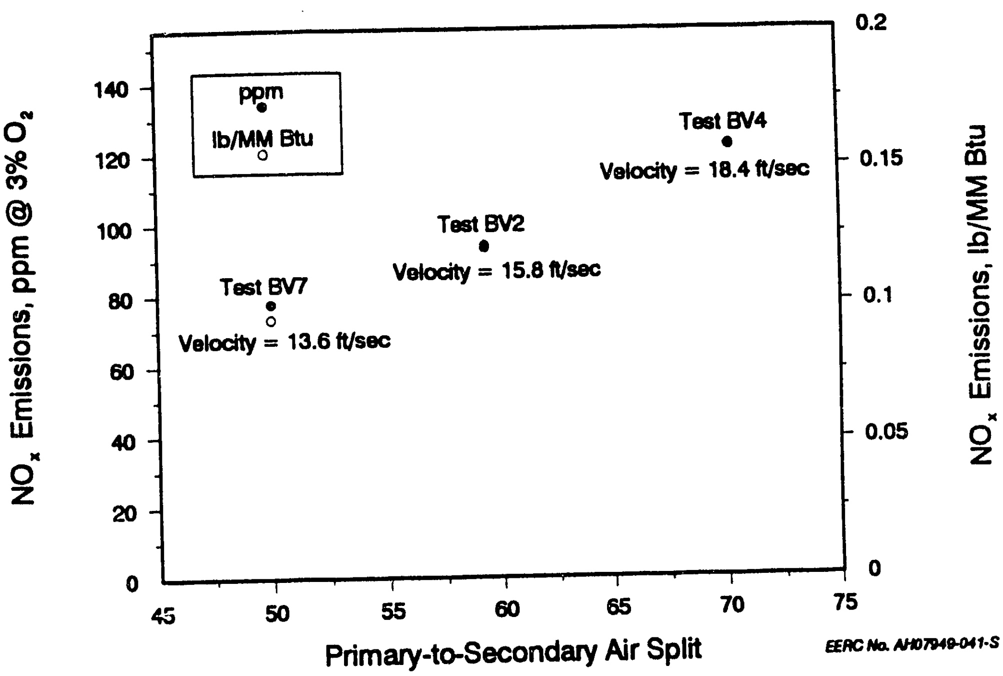

Figure 3-16. NO_x emissions for Blacksville coal at ~1550°F and 20% excess air as a function of primary-to-secondary air split.

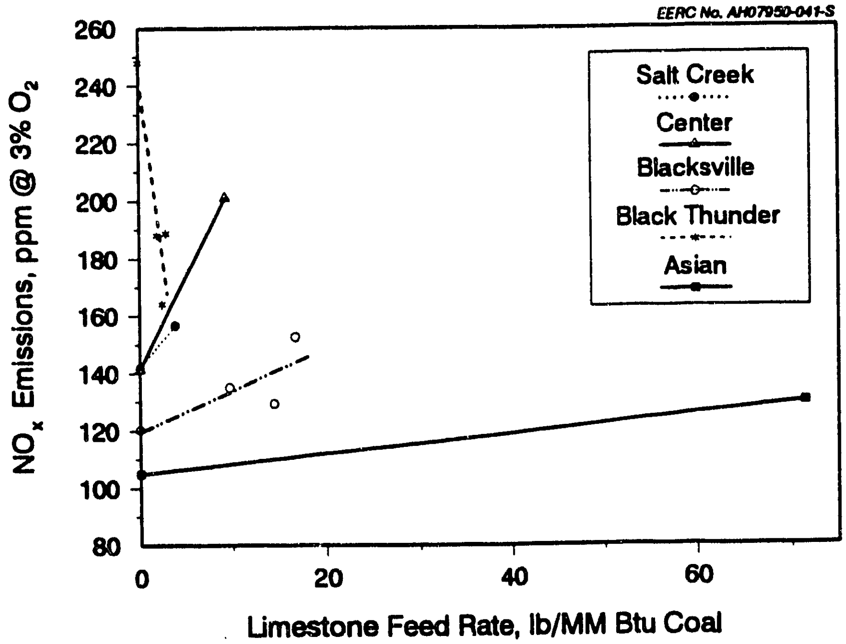

Figure 3-17. NO_x emissions at ~1550°F (1610° for Salt Creek), 16-ft/sec velocity, and 25% excess air as a function of limestone feed rate.

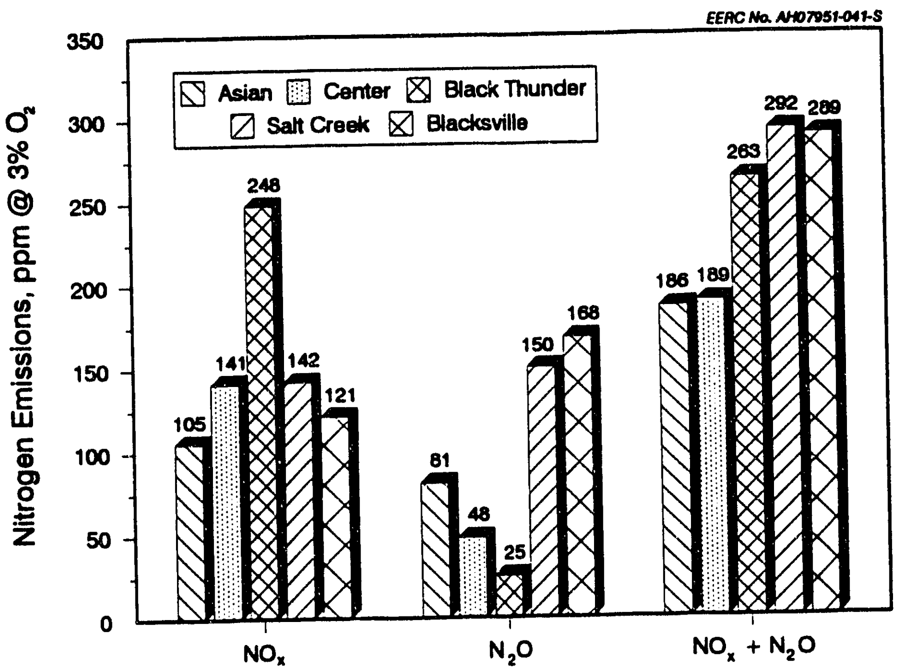

Figure 3-18. Nitrogen emissions (ppm) at ~1550°F, 16-ft/sec velocity, and 21%-34% excess air as a function of coal type.

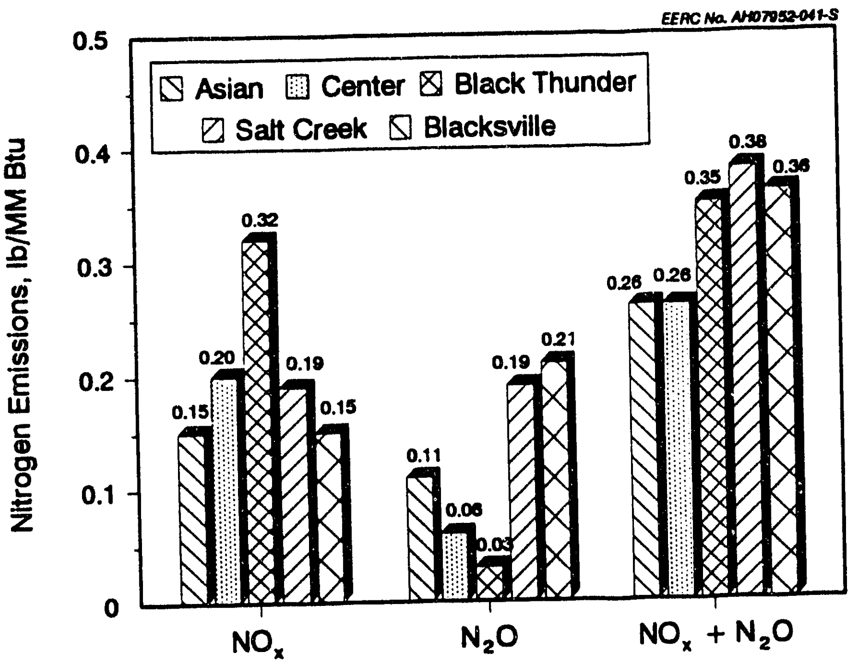

Figure 3-19. Nitrogen emissions (lb/MM Btu) at ~1550°F, 16-ft/sec velocity, and 21%-34% excess air as a function of coal type.

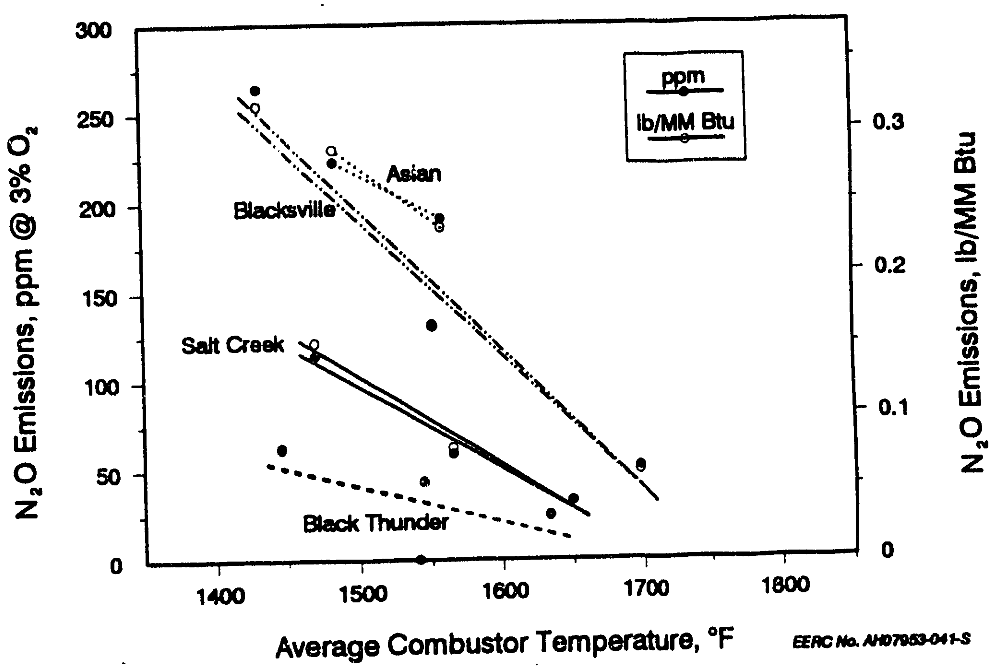

Figure 3-20. N_2O emissions as a function of average combustor temperature, at 16-ft/sec velocity and 21%-34% excess air.

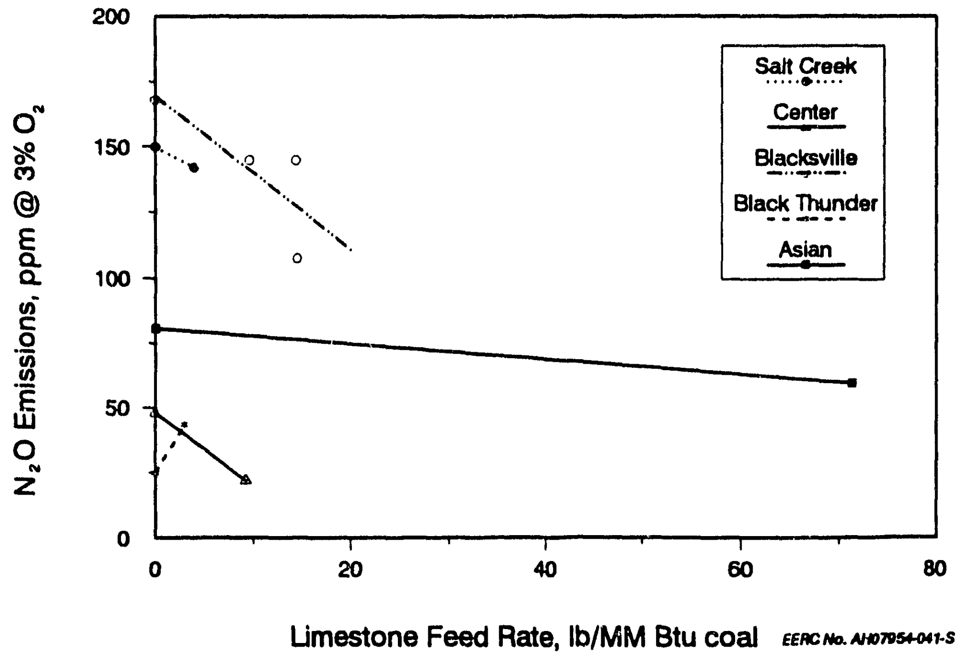

Figure 3-21. N_2O emissions as a function of sorbent add rate at ~1550°F, 16-ft/sec velocity, and 21%-34% excess air.

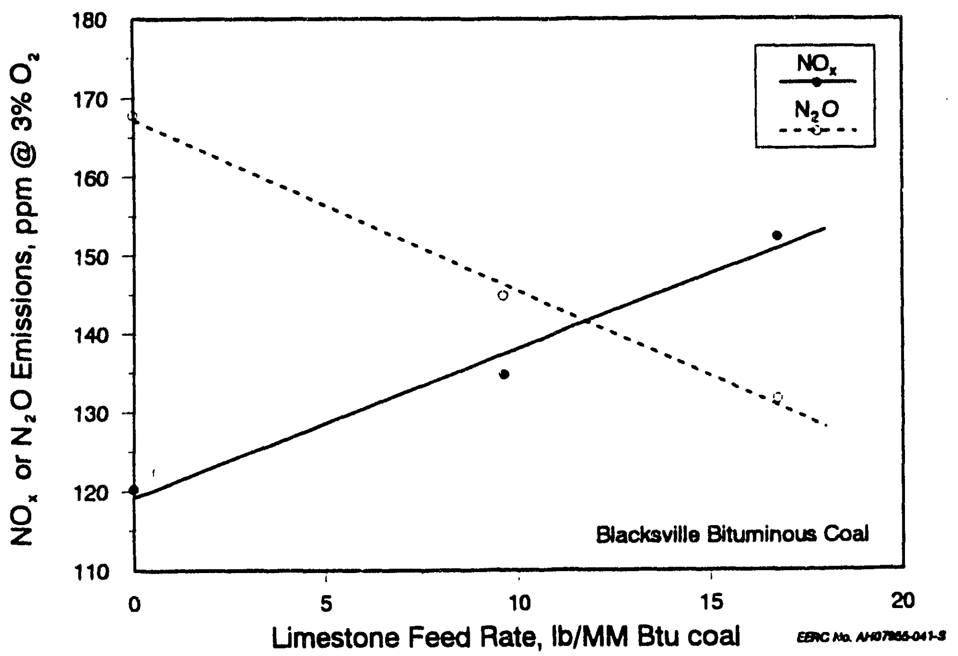

Figure 3-22. N_2O and NO_x emissions for Blacksville coal at ~1550°F, 16-ft/sec velocity, and 29% excess air as a function of sorbent add rate.

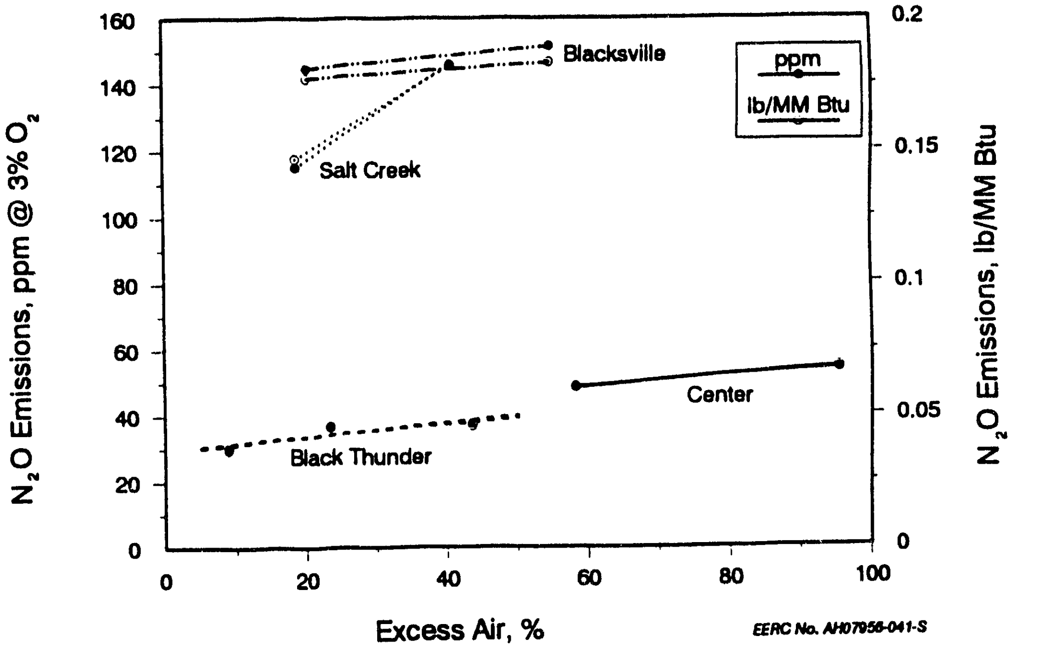

Figure 3-23. N_2O emissions at ~1550°F (1623°F for Salt Creek) as a function of excess air.

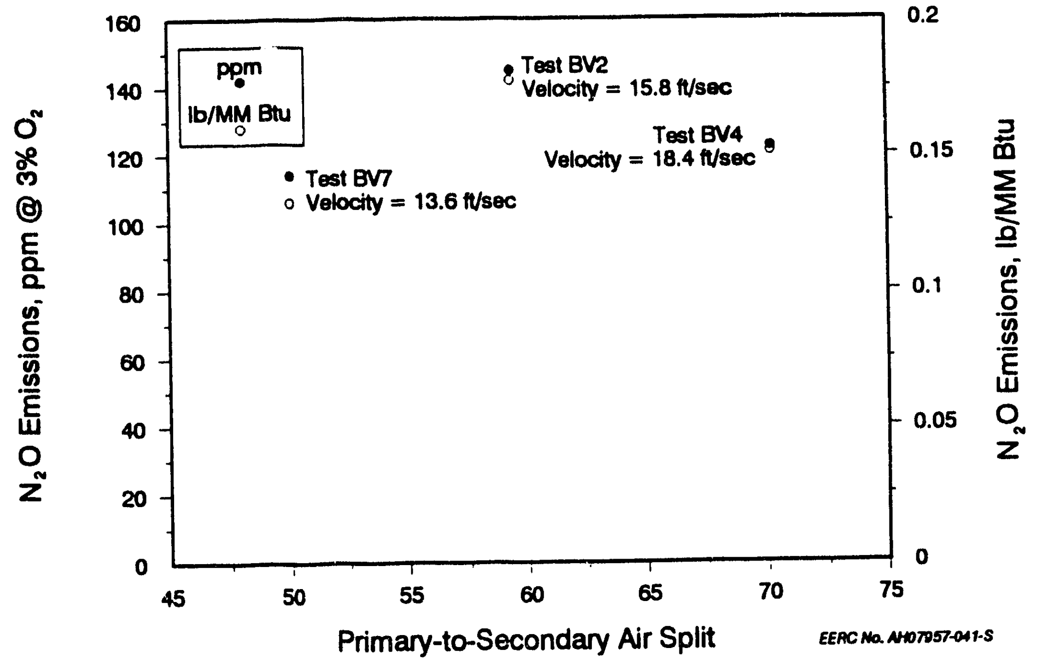

Figure 3-24. N_2O emissions for Blacksville coal at ~1550°F and 20% excess air as a function of primary-to-secondary combustion air split.

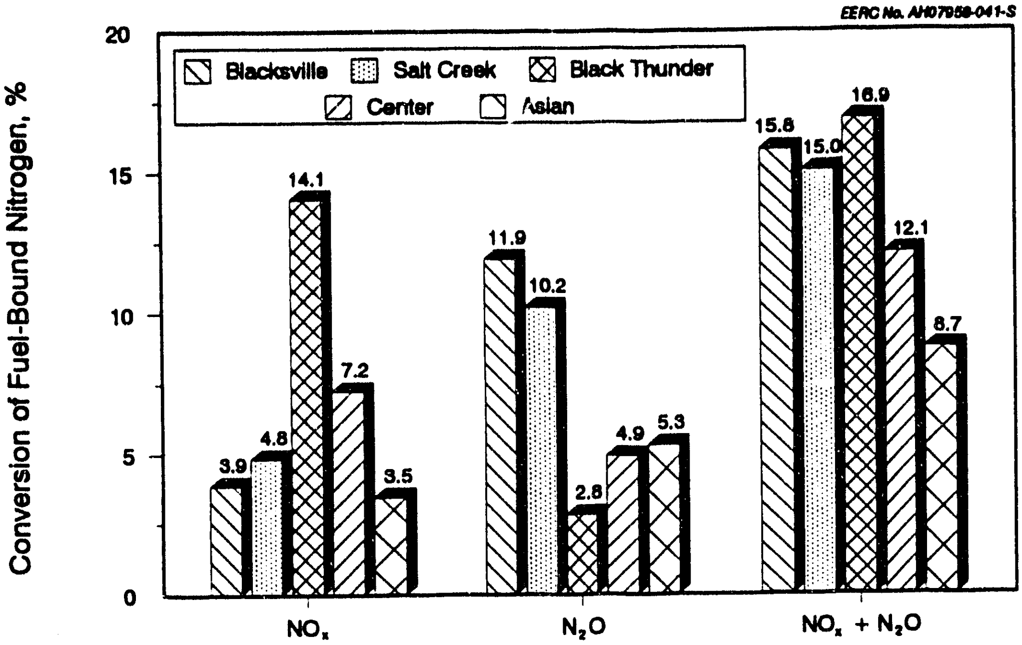

Figure 3-25. Percent conversion of fuel-bound nitrogen to NO_x and N_2O at ~1550°F, 16-ft/sec velocity, and 21%-34% excess air as a function of coal type.

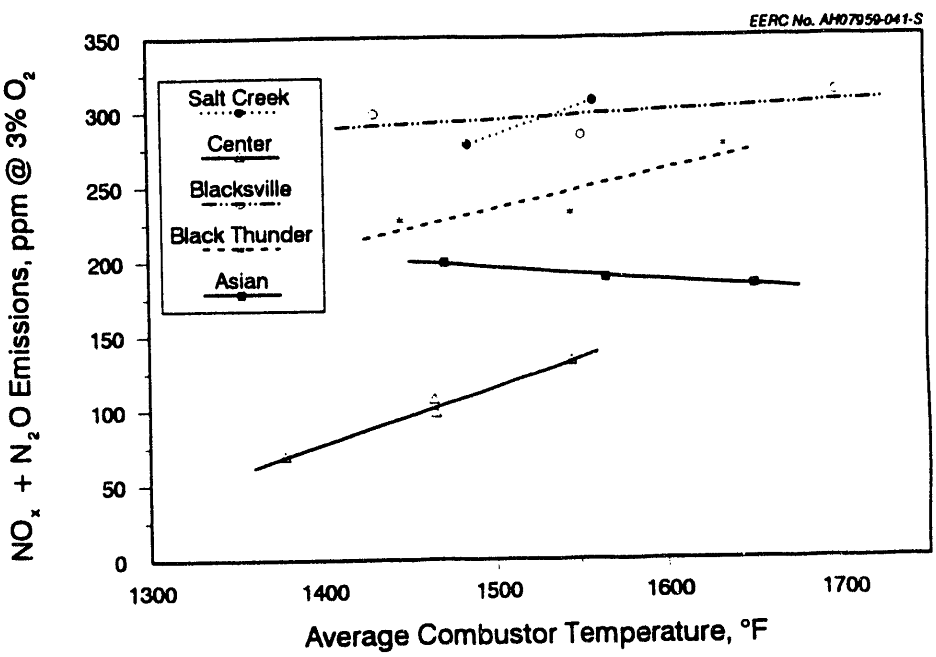

Figure 3-26. Total nitrogen oxide emissions at 16-ft/sec velocity and 17%-31% excess air as a function of average combustor temperature.

3.2.3 Carbon Monoxide Emissions

Carbon monoxide (CO) emissions are the result of incomplete conversion of the coal carbon to carbon dioxide. CO emissions tend to decrease with increasing temperature for all ranks of coal (Figure 3-27). As shown in Figure 3-28, CO emissions also decrease as excess air increases for all ranks of coal tested. Both of these conditions, higher temperatures and higher concentrations of oxygen, favor more complete conversion of the coal carbon to carbon dioxide.

3.2.4 Fly Ash Collectability

The ash formed from the combustion of coal and the sorbent added for sulfur control will either be removed as fly ash or bottom ash. The quantity of fly ash generated will primarily be a function of the quantity of ash and sulfur in the coal and the collection efficiency of the primary cyclone. Coal with higher ash and higher sulfur will typically generate more fly ash. The amount of the coal ash ending up as fly ash will also, to a lesser extent, be a function of the size of coal and sorbent and the friability of the sorbent, with finer grinds and friable sorbents generating a higher percentage of fly ash than bottom ash.

To provide an indication of the impact of coal properties on fly ash collectability, dust loadings before and after the baghouse were performed. The dust loading into the baghouse for the high-ash, high-sulfur Asian lignite was the highest for the coals tested, at 2.13 grains/scf. Dust loadings for the other coals ranged from 0.60 to 0.90 grains/scf. For all of the coals, collection efficiencies using woven fiberglass bags in a pulse-jet baghouse were above 99.9%. Table 3-5 summarizes the secondary cyclone and baghouse particulate loadings and removal efficiencies.

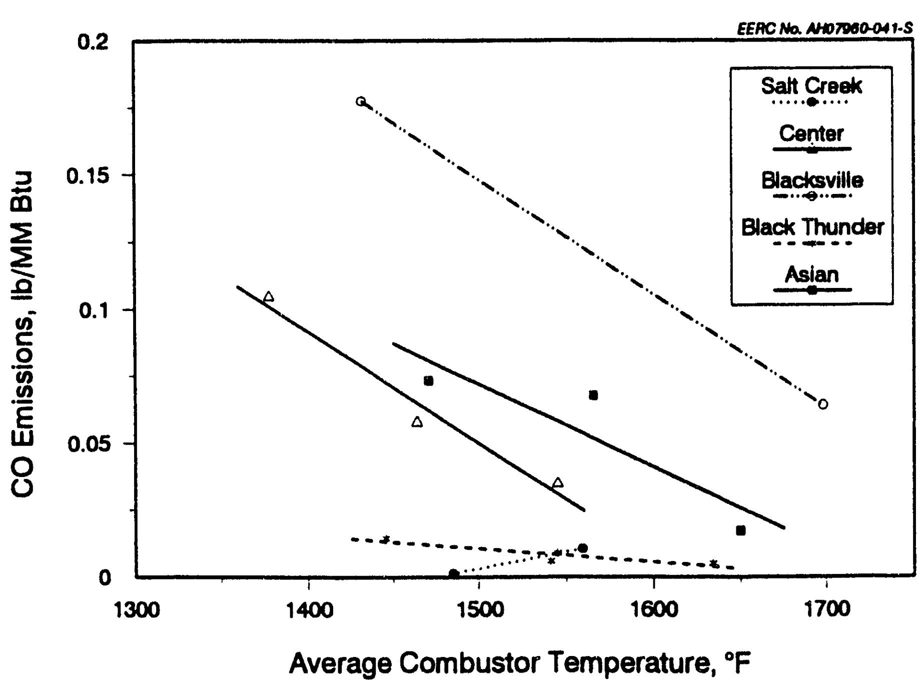

Figure 3-27. CO emissions at 16-ft/sec velocity and 17%-31% excess air as a function of average combustor temperature.

TABLE 3-5

Secondary Cyclone and Baghouse Particulate Loading/Removal Efficiencies

Test Number	Secondary Cyclone Inlet gr/scf	Secondary Cyclone Outlet gr/scf	Baghouse Inlet gr/scf	Baghouse Outlet gr/scf	Secondary Cyclone Inlet lb/hr	Secondary Cyclone Outlet lb/hr	Baghouse Inlet lb/hr	Baghouse Outlet lb/hr	Efficiencies, % Secondary Cyclone	Efficiencies, % Baghouse
CL1-0291	69.23	0.901	0.901	0.00035	299.35	4.96	4.96	0.0019	98.70	99.96
CL3[1]	28.91	0.261	0.261	0.00007	146.62	1.32	1.32	0.0004	99.10	99.97
TL1	114.67	4.263	4.263	NS[3]	614.60	26.99	26.99	NS	96.28	NA[4]
TL2	35.07	2.132	2.132	0.00161	201.46	11.66	11.66	0.0090	93.92	99.92
BV1	NS	0.604	0.604	0.00050	NS	3.57	3.57	0.0027	NA	99.92
BT1[2]	NS	0.854	0.854	0.00000	NS	5.13	5.13	0.0000	NA	100.00

[1] Two of the three baghouse outlet dust-loading sample filters lost weight. No visible dust on either filter.
[2] Small amount of baghouse outlet sample filter stuck to support screen, removed and weighed as much as possible.
[3] Not sampled.
[4] Not avilable.

3.3 Thermal Performance

3.3.1 Heat Flux and Heat-Transfer Coefficients

Table 3-6 compares the heat fluxes measured for the five different coals tested at the EERC. It has been attempted to limit comparison to similar conditions of average bed temperature, excess air level, superficial gas velocity, and the primary-to-secondary combustion air split. The as-tested higher heating value is included in the table as an indicator of the coal rank. The average size of the recirculated bed material is indicated by the d_{50} (average size of the material).

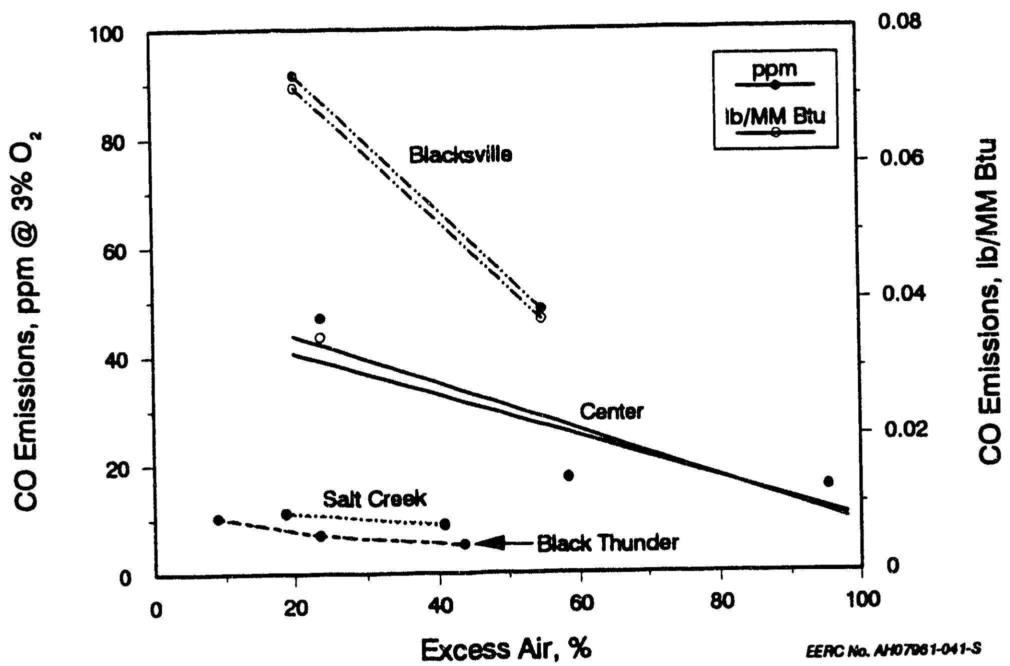

Figure 3-28. CO emissions at ~1550°F (1623°F for Salt Creek) as a function of excess air.

TABLE 3-6

Comparison of Heat Fluxes

Combustor									
Test	HHV, Btu/lb	Recirculaiton Rate, lb/hr	Bed Temperature, °F	SGV, ft/sec	Excess Air, %	PA/SA Split	Bed Mat. d_{50}, µm	HT Coefficient Btu/hr-ft²-°F	Heat Flux, Btu/hr-ft²
CL6	6,900	3,800	1,570	16.5	22.1	60/40	410*	16.5	23,900
TL1	3,800	3,800	1,565	16.6	24.4	60/40	668	16.9	24,000
BV16	13,300	4,200	1,572	15.9	21.7	60/40	503	17.9	25,900
BT5	8,700	9,300	1,541	15.9	22.5	60/40	440*	23.6	33,100
SC2	10,000	12,000	1,613	16.6	21.5	46/54	361	22.3	32,700

External Heat Exchanger							
Test	HHV, Btu/lb	Recirc. Rate, lb/hr	Bed Temp.,°F	SGV, ft/sec	Downcomer d_{50}, µm	HT Coeff. Btu/hr-ft²-°F	Heat Flux, Btu/hr-ft²
CL6	6,900	3,800	1,077	1.7	300*	68.8	65,700
TL1	3,800	3,800	1,289	1.7	348	58.1	66,300
BV16	13,300	4,200	1,137	2.0	343	71.4	73,100
BT5	8,700	9,300	1,339	1.8	315*	81.9	96,700
SC2	10,000	12,000	1,435	2.2	210	98.7	127,900

* Estimated size based on several test periods.

The most important factor affecting heat flux was the recirculation rate. The heat flux increased with increasing solids recirculation rates. This would be expected since solid densities are higher at correspondingly higher recirculation rates, and at higher solid densities there is more material to radiate and conduct heat to heat-transfer surfaces.

Because of the action of the circulating solids, CFBCs operate with a relatively high heat flux. The heat flux for full load conditions typically ranged from about 24,000 to 33,000 Btu/hr-ft². The heat flux increased with increasing temperature and velocity. As would be expected, the combustor heat-transfer coefficients followed the same trends as did the heat fluxes when comparing results obtained with the different coals tested (Table 3-6).

3.3.2 Combustion Efficiency

In comparing the properties of common solid fuels, the lignitic and subbituminous coals fall between the high fixed carbon content and heating value of the higher-rank fossil fuels and the more reactive high-volatile content biomass fuels. Reactivity of the low-rank coals is related to porosity and surface area, volatiles-to-fixed carbon ratio, partially oxygenated organic structure, and catalytic effects of metallic cations within the coal structure. Thus lower-rank coals will burn more completely and more rapidly than will a bituminous coal under similar operating conditions. Higher reactivity gives greater combustion efficiency, as measured by carbon conversion.

Figure 3-29 presents combustion efficiency for the five test coals as a function of combustor temperature. All tests were performed at equivalent conditions of approximately 20% excess air, 16-ft/sec velocity, 60% primary combustion air, and a limestone feed rate to achieve 90% sulfur retention. The combustion efficiencies for two lignites and the subbituminous coals approached 100% over the entire range of temperatures tested. The combustion efficiencies for the Salt Creek bituminous coal ranged from 97% to 99%, while the combustion efficiencies for the Blacksville bituminous coal ranged from 90% to 97%. These differences are primarily due to the higher reactivity of the char for the lower-rank coals and the higher volatile content of these coals in relation to the fixed carbon. Combustion efficiencies for the Blacksville testing were also low because no secondary cyclone ash was recirculated. The combustion efficiencies obtained during the Asian lignite testing were not as significantly affected by not recirculating secondary cyclone ash.

Figure 3-30 shows combustion efficiency as a function of excess air for testing conducted at 1538°F. The Blacksville and Salt Creek bituminous coals showed improved combustion efficiency as the level of excess air increased. Lower-ranked coals had high combustion efficiencies, so increased levels of excess air had little or no effect.

3.3.3 Boiler Efficiency

Boiler efficiency for each test point was calculated using a modified ASME PTC 4.1 as recommended by EPRI (4) and assuming a 300°F stack gas exit temperature and a 0.4% loss due to radiative and convective losses. Operational parameters that affect boiler efficiency include the coal moisture and total solids (coal ash and limestone) input into the

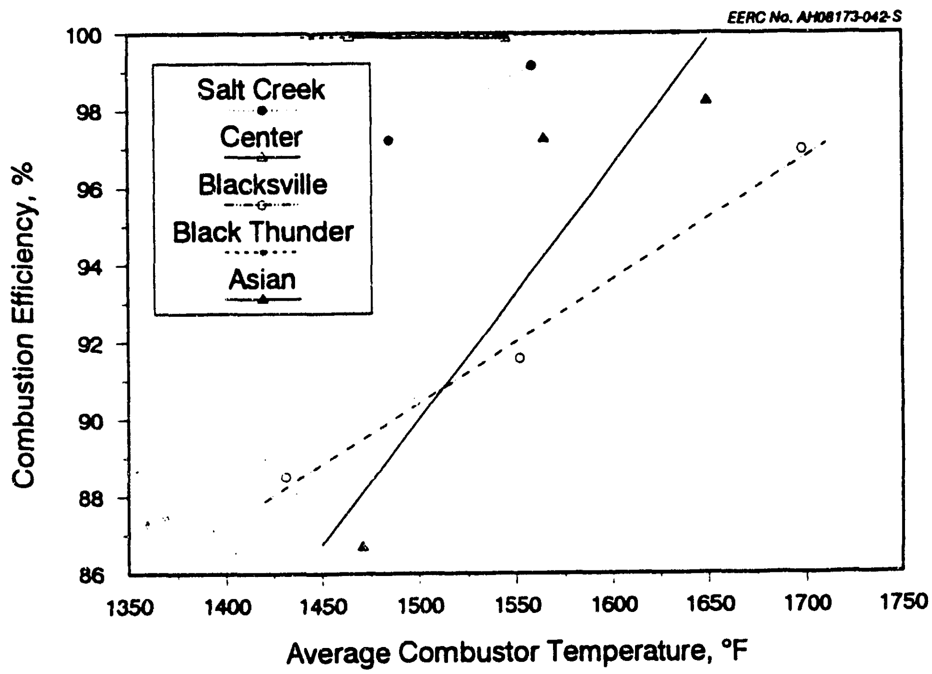

Figure 3-29. Combustion efficiency at 16-ft/sec velocity and 17%-31% excess air as a function of average combustor temperature.

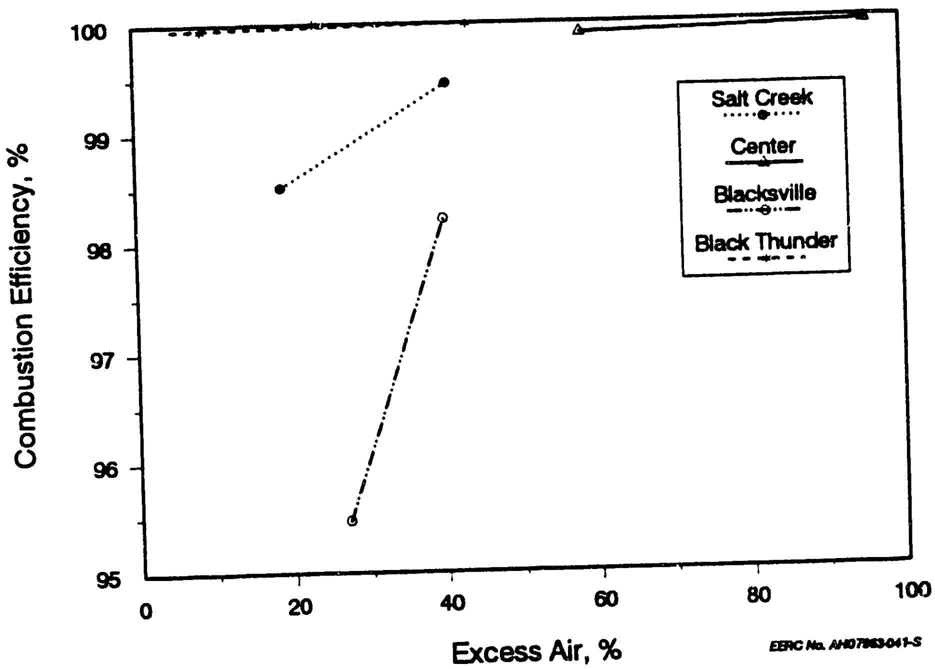

Figure 3-30. Combustion efficiency at ~1550°F (1623°F for Salt Creek) as a function of excess air.

system, excess air, secondary cyclone capture and recirculation of the fly ash downstream of the primary particulate collection device (usually a cyclone), and the operational combustor temperature. Operational changes that will result in improved boiler efficiency include those that decrease the amounts of mass flow (primarily gases and, less significantly, the solids) exiting the cyclone and those that increase levels of carbon burnout of the fuel.

Low-rank coals that typically contain higher levels of moisture than do bituminous coals will result in lower boiler efficiencies. The low-rank fuels require more energy during combustion to vaporize the additional moisture. When operating at a specific temperature and excess air level, the high-moisture fuels generate increased mass flows through the system per delivered Btu than lower-moisture fuels, resulting in a higher fraction of the energy being recovered in the lower-efficiency downstream convective heat recovery unit. Figure 3-31 shows that, for the coals tested, the amount of energy generated that ended up in the flue gas varied from 65% for the very moist Asian lignite to 43% for the relatively dry Blacksville bituminous. The shift of energy back to the convective pass results in a reduction of boiler efficiency due to greater stack losses for the high-moisture coals. Other losses in boiler efficiency result from the conversion of fuel hydrogen to water, unrecoverable heat from the discharge of ash and spent sorbent, and the calcination of the raw sorbent. A boiler efficiency credit is given for the sulfation of the sorbent, as this process produces usable heat.

Boiler efficiency losses for the baseline cases with and without limestone addition are presented in Table 3-7 and Figure 3-32. Critical operational data are also included for each test condition. The combined losses due to the moisture and hydrogen in the fuel

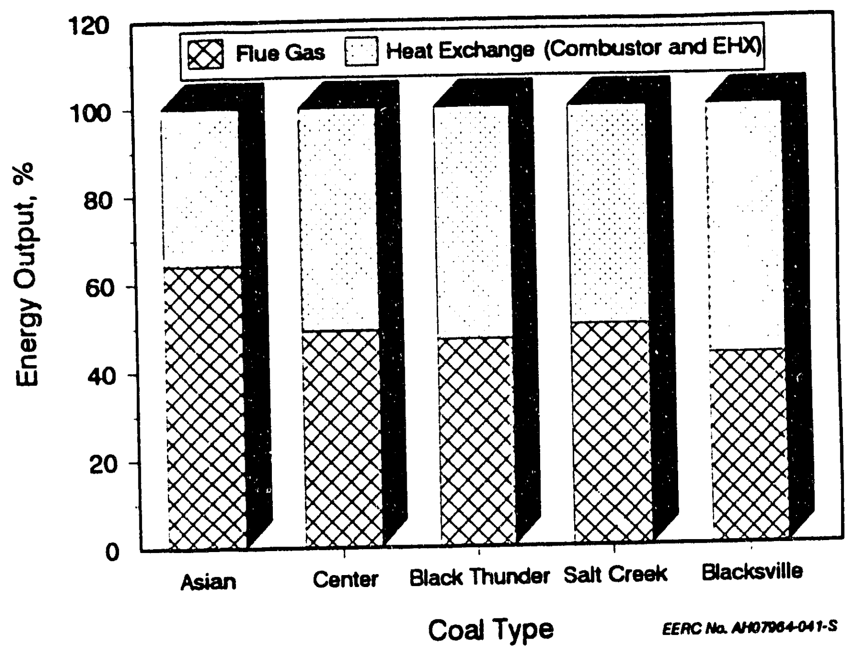

Figure 3-31. Energy generation at ~1550°F, 16-ft/sec velocity, and 21%-34% excess air as a function of coal type.

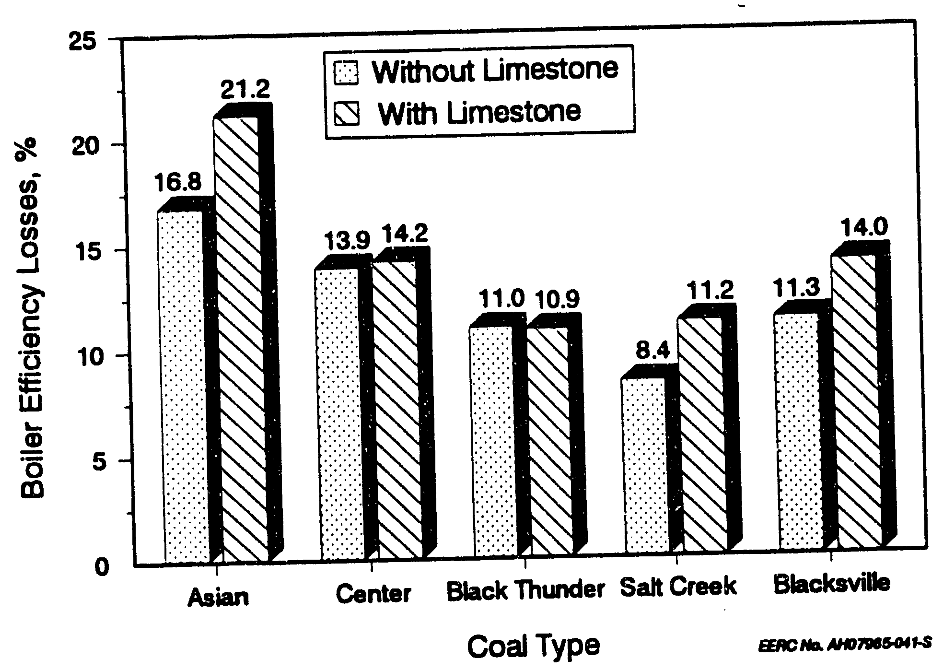

Figure 3-32. Boiler efficiency losses with and without limestone at 1550°F (1610°F for Salt Creek), 16-ft/sec velocity, and 20%-34% excess air as a function of coal type.

(evaporation and unrecovered sensible heat in the flue gas) range from a high of 6.6% for the Asian lignite, to a low of 0.8% for the Blacksville bituminous. Heat losses due to ash and spent sorbent are much lower and depend upon the total ash content of the coal relative to its heating values and sorbent requirements needed to meet the required sulfur capture. These losses amounted to 6.8% for the high-sulfur, high-ash Asian lignite and ranged from 0.2% to 1.4% for the other coals tested. The total efficiency losses ranged from 8.4% for the Salt Creek bituminous to 21.2% for the Asian lignite. Both Center lignite and Black Thunder subbituminous had higher boiler efficiencies than the Blacksville bituminous coal, due primarily to their high carbon burnout. Carbon combustion efficiency for the Blacksville coal could be improved with secondary ash recycle from the baghouse or other mechanical collector.

A system designed for a high-moisture fuel would require a larger fuel feed system to generate the same amount of steam and/or electricity as a unit designed for a low-moisture fuel. Downstream heat recovery equipment would have to be larger for higher-moisture fuels to account for the higher flue gas flow rates. Units designed for bituminous coals would likely be required to utilize ash recycle from a secondary cyclone system or baghouse to obtain acceptable levels of carbon burnout, while burnout of the more reactive low-rank coals are acceptable without secondary recycle.

3.3.4 Impact of Load Control Method

Low-load tests were performed with the Center lignite, Salt Creek bituminous, and Blacksville bituminous. Load was determined for each test by dividing the coal feed rate by the coal feed rate of the full-load baseline (with limestone) test for that coal type. Two different operational procedures were used to simulate load reduction. In the first, full-load heat-transfer surface was held constant, and combustor temperature decreased with load. In the second, average combustor temperature was held constant (the same as full-load baseline testing) by removing heat-transfer surface in the combustor and the external heat exchanger as load was reduced. In both cases, air flow rates were reduced, resulting in lower superficial gas velocities than during the full-load tests. Excess air was allowed to increase as load decreased. As a result, combustion air flow rates did not decrease in proportion to the coal feed rate, permitting operation at slightly higher velocities in the combustor to ensure adequate solids recirculation rates during the reduced-load tests.

Tables 3-8 and 3-9 present data on how reduced load, using constant heat-transfer surface and constant temperature, respectively, affected emissions and other operational results. Full load operation (100%) is compared to operation at approximately 75% and 50% for three coals in Table 3-8, and for two coals in Table 3-9.

The combined effects of temperature, velocity, excess air, and calcium-to-sulfur ratio make it difficult to identify any clear trends relating how sulfur capture was affected by either load reduction method. For operation with constant heat-transfer surface, NO_x emissions tended to decrease and N_2O and CO emissions to increase as load decreased. These trends were expected, based on changes in temperature and excess air. For the constant temperature tests, NO_x emissions increased slightly due to increases in excess air, while N_2O and CO emissions were mostly unaffected as load was reduced, as these flue gas components are less sensitive to changes in excess air level.

TABLE 3-7

Baseline Boiler Efficiency Data

Baseline Case Without Limestone Addition					
Coal:	TL4	CL0	BT1	SC1	BV1
Operational Conditions					
Load, %	92	112	90	97	94
Avg. Comb. Temp., °F	1564	1526	1573	1607	1558
SGV, ft/sec	16.1	14.6	16.1	16.7	16.1
Excess Air, %	26.6	22.0	33.8	20.8	28.3
Sulfur Retention, %	70.1	23.2	2.9	0.9	7.1
Solids Recirc., lb/hr	3450	4160	2250	7660	4170
Comb. HXs on-line	7	8	10	8	12
EHX HXs on-line	8	9	9	4	7
Boiler Efficiency Losses, %					
Dry Gas[1]	6.6	5.4	6.0	5.8	5.8
Water in Fuel[1]	5.1	6.7	3.9	0.8	0.3
Combustion of Fuel Hydrogen[1]	0.7	0.5	0.5	0.5	0.5
Unburned Carbon	0.1	0.0	0.3	0.7	4.0
Calcination/Sulfation	--	--	--	--	--
Radiation & Convection[2]	0.4	0.4	0.4	0.4	0.4
Discharged Solids	3.9	0.4	0.3	0.2	0.3
Total	16.8	13.4	11.4	8.4	11.3
Boiler Efficiency, %	83.2	86.5	88.6	91.6	88.7

Baseline Case With Limestone Addition					
Coal:	TL1	CL1	BT2	SC2	BV2
Operational Conditions					
Load, %	100	100	100	100	100
Avg. Comb. Temp., °F	1565	1554	1545	1607	1544
SGV, ft/sec	16.8	14.1	16.1	16.6	15.8
Excess Air, %	24.4	25.7	26.7	21.5	20.4
Sulfur Retention, %	90.3	67.5	77.7	67.7	90.1
Solids Recirc., lb/hr	3830	3170	10270	12050	7220
Comb. HXs on-line	4	7	10	8	12
EHX HXs on-line	7	6	8	3	7
Boiler Efficiency Losses, %					
Dry Gas[1]	7.1	5.7	5.7	5.9	5.9
Water in Fuel[1]	5.6	6.3	3.9	0.9	0.3
Combustion of Fuel Hydrogen[1]	0.8	0.5	0.5	0.5	0.5
Unburned Carbon	2.1	0.1	0.1	2.0	6.0
Calcination/Sulfation	-0.5	0.4	0.1	0.1	0.0
Radiation & Convection[2]	0.4	0.4	0.4	0.4	0.4
Discharged Solids	6.9	0.4	0.2	1.4	1.0
Total	22.4	13.8	10.9	11.2	14.1
Boiler Efficiency, %	77.6	86.2	89.1	88.8	85.9

[1] Assumes stack gas exit temperature = 300°F

[2] Assumes radiative and convective losses = 0.4%

TABLE 3-8

Impact of Load Reduction Using Constant Heat-Transfer Surface Between Tests

Test Number:	CL1	CL2	CL3	BV2	BV12	BV11	SC2	SC3	SC4
Operational Conditions									
Load, %	100	74	50	100	74	49	100	87	56
Avg. Comb. Temp., °F	1554	1375	1185	1544	1473	1390	1607	1559	1351
SGV, ft/sec	14.1	11.3	9.5	15.8	12.4	9.1	16.6	14.2	10.3
Excess Air, %	25.7	56.7	100.0	20.4	33.5	51.1	21.5	23.4	54.2
Sulfur Retention, %	67.5	84.8	93.9	90.1	91.4	90.1	67.7	75.9	67.8
Solids Recirc., lb/hr	3170	3170	1220	7220	1780	1060	12050	8920	2780
Total Calcium-to-Sulfur	4.0	2.6	1.2	2.4	2.3	2.6	3.2	2.5	2.9
Calcium Utilization, %	17.0	32.9	76.0	37.1	40.3	32.3	21.5	30.8	23.8
Comb. HXs on-line	7	7	7	12	12	12	8	9	8
EHX HXs on-line	6	6	6	7	6	7	3	1	1
Emissions, lb/MM Btu									
SO_2	0.59	0.24	0.10	0.36	0.31	0.59	0.34	0.25	0.33
NO_x	0.26	0.16	0.21	0.12	0.15	0.08	0.21	0.15	0.07
N_2O	0.03	0.36	0.36	0.18	NA	0.29	0.18	0.23	0.54
CO	0.01	0.04	0.12	0.07	0.14	0.53	0.01	0.01	0.04
Heat-Transfer Coefficient, Btu/hr-ft^2-°F									
Combustor	16.5	13.1	10.3	18.3	16.3	14.8	22.3	20.6	14.7
External Heat Exchanger	75.0	70.7	58	84.2	57.7	75.4	98.7	91.6	83.8
Heat Flux, Btu/hr-ft^2									
Combustor	23,800	16,800	11,400	26,700	22,100	19,000	32,700	29,100	18,200
External Heat Exchanger	83,300	55,700	27,900	98,000	46,700	32,000	127,900	117,900	80,700
Combustion Efficiency, %	99.99	99.98	99.90	93.23	92.56	97.91	97.49	99.13	99.08
Boiler Efficiency, %	86.2	85.3	82.7	85.9	85.0	88.2	88.8	90.4	89.1
Boiler Efficiency Losses, %									
Dry Gas	5.7	6.8	9.4	5.9	6.4	7.4	5.9	6.2	7.6
Water in Fuel	6.3	6.3	6.2	0.3	0.3	0.3	0.9	0.9	0.9
Combustion of Fuel Hydrogen	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Unburned Carbon	0.1	0.1	0.3	6.0	6.6	2.5	2.0	0.7	0.7
Calcination/Sulfation	0.4	0.1	0.0	0.0	-0.1	0.1	0.1	0.0	0.1
Radiation and Convection	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Discharged Solids	0.4	0.6	0.6	1.0	0.9	0.7	1.4	0.9	0.8
Total Losses	13.8	14.7	17.3	14.1	15.0	11.8	11.2	9.6	10.9

TABLE 3-9

Impact of Load Reduction Using Constant Temperature Between Tests

	Test Number					
	CL1	CL5	CL4	BV2	BV9	BV10
Operational Conditions						
Load, %	100	75	54	100	70	56
Avg. Comb. Temp., °F	1554	1522	1537	1544	1539	1566
SGV, ft/sec	14.1	12.9	11.6	15.8	11.7	10.6
Excess Air, %	25.7	58.3	95.3	20.4	27	40.9
Sulfur Retention, %	67.5	74.4	51.1	90.1	85.8	86.4
Solids Recirc., lb/hr	3170	2430	NA*	7220	2030	730
Total Ca/S	4.0	1.9	2.2	2.4	1.8	2.3
Calcium Utilization, %	17.0	38.8	23.0	37.1	48.0	37.8
Comb. HXs on-line	7	3	1	12	10	5.5
EHX HXs on-line	6	4	0	7	4	3
Emissions, lb/MM Btu						
SO_2	0.59	0.58	0.81	0.36	0.51	0.49
NO_x	0.26	0.30	0.37	0.12	0.11	0.15
N_2O	0.03	0.06	0.07	0.18	0.19	0.14
CO	0.01	0.01	0.01	0.07	0.09	0.06
Heat-Transfer Coefficient, Btu/hr-ft^2-°F						
Combustor	16.5	17.0	19.0	18.3	18.6	17.8
External Heat Exchanger	75.0	81.6	NA	84.2	79.7	58.5
Heat Flux, Btu/hr-ft^2						
Combustor	23,800	23,800	27,900	26,700	26,200	25,600
External Heat Exchanger	83,300	85,300	NA	98,000	77,800	43,700
Combustion Efficiency, %	99.99	99.96	99.97	93.23	95.52	98.31
Boiler Efficiency, %	86.2	84.8	82.9	85.9	88.9	89.4
Boiler Efficiency Losses, %						
Dry Gas	5.7	7.0	8.8	5.9	6.0	7.3
Water in Fuel	6.3	6.4	6.4	0.3	0.3	0.3
Combustion of Fuel Hydrogen	0.5	0.5	0.5	0.5	0.5	0.5
Unburned Carbon	0.1	0.1	0.0	6.0	3.7	1.6
Calcination/Sulfation	0.4	0.0	0.1	0.0	-0.3	0.0
Radiation and Convection	0.4	0.4	0.4	0.4	0.4	0.4
Unburned Solids	0.4	0.7	0.8	1.0	0.5	0.5
Total Losses	13.8	15.2	17.1	14.1	11.1	10.6

* Not available.

Heat-transfer coefficients and heat fluxes in both the combustor and external heat exchanger were significantly reduced during operation with constant heat-transfer surface. This was due to a combination of decreased operational temperatures and recirculation rates as load was decreased. For constant temperature operation, overall heat-transfer coefficients and heat flux decreased in the external heat exchanger, and the overall heat-transfer coefficients and heat fluxes were relatively unaffected by load reduction in the combustor.

Combustion efficiencies were not affected for the reduced load testing with the more reactive Center lignite. Reducing load using either method resulted in improved combustion efficiency for Blacksville and Salt Creek testing, due to lower superficial gas velocities in the combustor. Lower operational velocities resulted in increased gas residence time and reduced the amount of carbon carried out of the system, which improved carbon burnout.

Figure 3-33 shows boiler efficiency losses at the 75% and 50% load conditions for the Center lignite and Blacksville bituminous using the two different methods of load reduction. Comparisons of the boiler efficiency losses shown in the figure must be made with caution, since a 300°F stack gas exit temperature was assumed for the boiler efficiency calculations for each test period (See Appendix G for the calculations used). In an operational CFB boiler, as load is reduced, there would likely be a corresponding change in the stack gas exit temperature, which would not decrease the boiler efficiency losses as significantly as reported here for the hot gases exiting the system. Another consideration when comparing the different test coals and load conditions is the level of excess air used at each test condition. An increase in excess air typically results in a decrease in boiler efficiency.

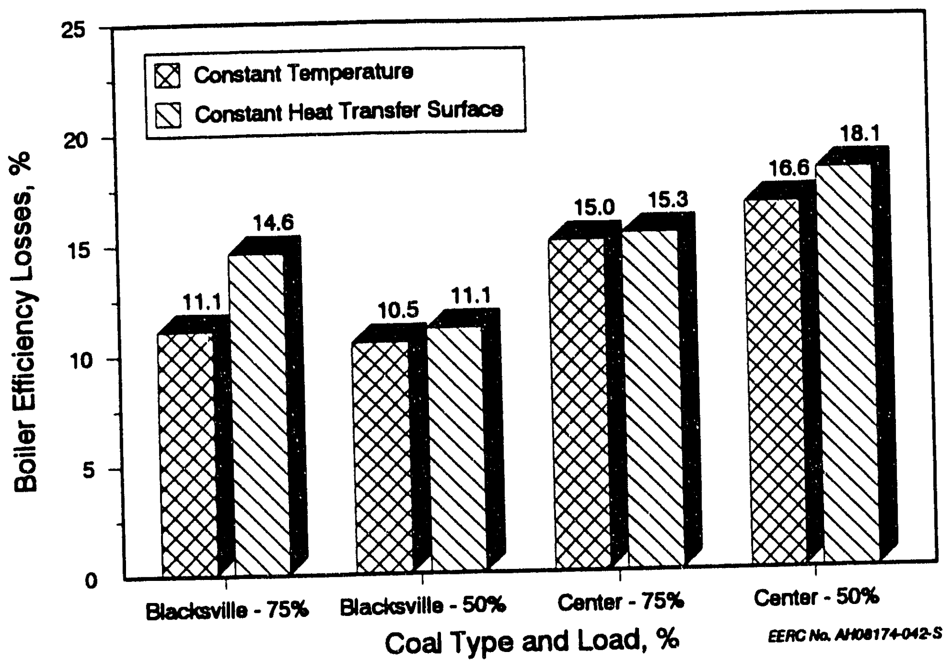

Figure 3-33. Boiler efficiency losses as a function of load, load reduction strategy, and coal type.

Reduced load operation at constant temperature resulted in higher boiler efficiencies (85.0% for Center and 88.9% for Blacksville at 75% load, 83.4% for Center and 89.5% for Blacksville at 50% load) than reduced load operation with constant heat-transfer surface (84.7% for Center and 85.4% for Blacksville at 75% load, 81.9% for Center and 88.9% for Blacksville at 50% load). This was mostly due to the greater quantities of fluidizing air required at lower operational temperatures to maintain similar velocities as a test at the same load but higher temperature. Again, no consideration was given here to the effect that this would actually have on the stack gas exit temperature in an operational CFB boiler. Boiler efficiencies were higher with the Blacksville bituminous coal than with the Center lignite because of the high moisture content in the lignite.

4.0 COMPARISON TO FULL SCALE

An excellent opportunity was available during this program to determine how well the EERC pilot-scale CFB simulates full scale. Tests were conducted on the EERC CFB pilot plant system at similar conditions to those already conducted at the 110 MW_e Colorado Ute Nucla CFBC power station. Similar tests were also conducted at a Pyropower, Inc., pilot plant system in San Diego, California. In all three cases, the coal and limestone utilized were from the same source. The comparison here is limited in scope to the available published test data for the full-scale Nucla system and the Pyropower pilot plant system.

4.1 Coal and Limestone Utilized

Table 4-1 compares the range of coal properties reported for the three different systems. Other than slightly lower coal moisture for testing at the EERC, the analyses reported for the three locations are very similar. An analysis of the limestone used at the EERC is shown in Table 1-1. The size distributions of the coal and limestone utilized at the EERC are shown in Figure 4-1.

4.2 Unit Operation

4.2.1 Bottom Ash/Fly Ash Split

The percentage of ash which remains in the combustor or downcomer as bed material compared to that which is carried out of the combustor is a function of the coal ash and sorbent size and of the cyclone cut point (50% of this particle size would be captured). Figure 4-2 shows size distributions of fly ash collected. It can be extrapolated

TABLE 4-1

Comparison of Coals Tested in the Nucla Power Station and Pyropower and EERC Pilot Plants

	Nucla	Pyropower	EERC
Proximate Analysis, wt%			
Moisture	7.8 - 10.2	7.2 - 10.0	6.8 - 7.9
Volatile	28.8 - 33.7	32.1 - 32.8	30.2 - 31.9
Fixed Carbon	40.4 - 45.1	41.3 - 42.7	41.6 - 44.7
Ash	12.1 - 23.0	14.6 - 18.7	16.9 - 20.2
Ultimate Analysis, wt%			
Carbon	55.6 - 63.2	57.6 - 60.0	57.6 - 60.4
Hydrogen	3.42 - 3.73	3.7 - 4.7	3.8 - 4.5
Nitrogen	0.52 - 1.61	1.1 - 1.3	1.1 - 1.3
Sulfur	0.43 - 0.58	0.4 - 0.6	0.4 - 0.5
Oxygen	8.22 - 10.4	8.7 - 10.0	8.5 - 9.9
Ash	12.1 - 23.0	14.6 - 18.7	16.9 - 20.2
Moisture	7.8 - 10.2	7.2 - 10.0	6.8 - 7.9
HHV, as-received, Btu/lb	9,674 - 11,090	10,500 - 11,300	9,976 - 10,563

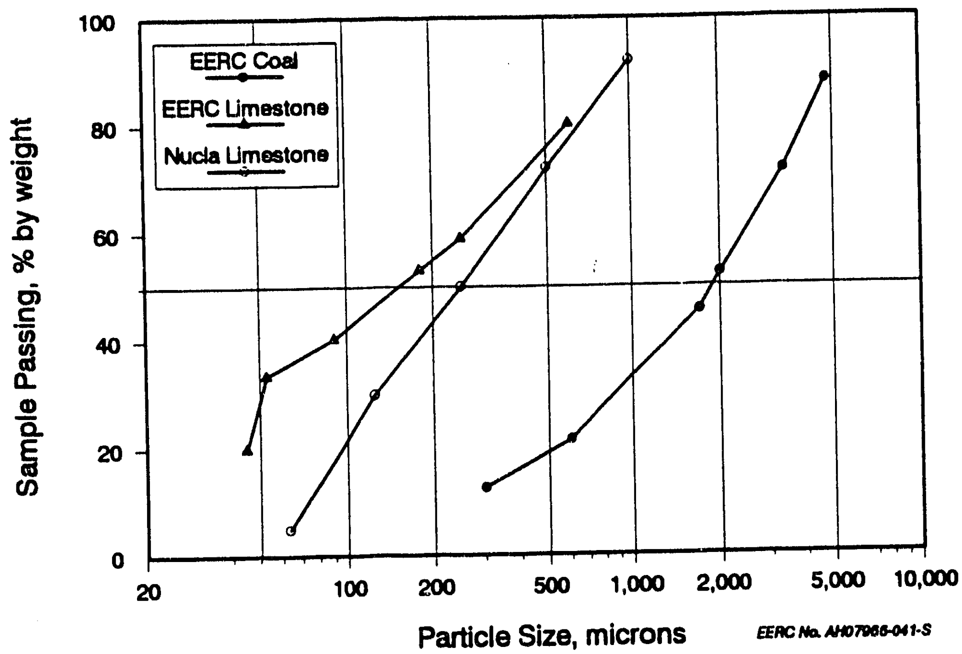

Figure 4-1. Size distributions of coal and limestone.

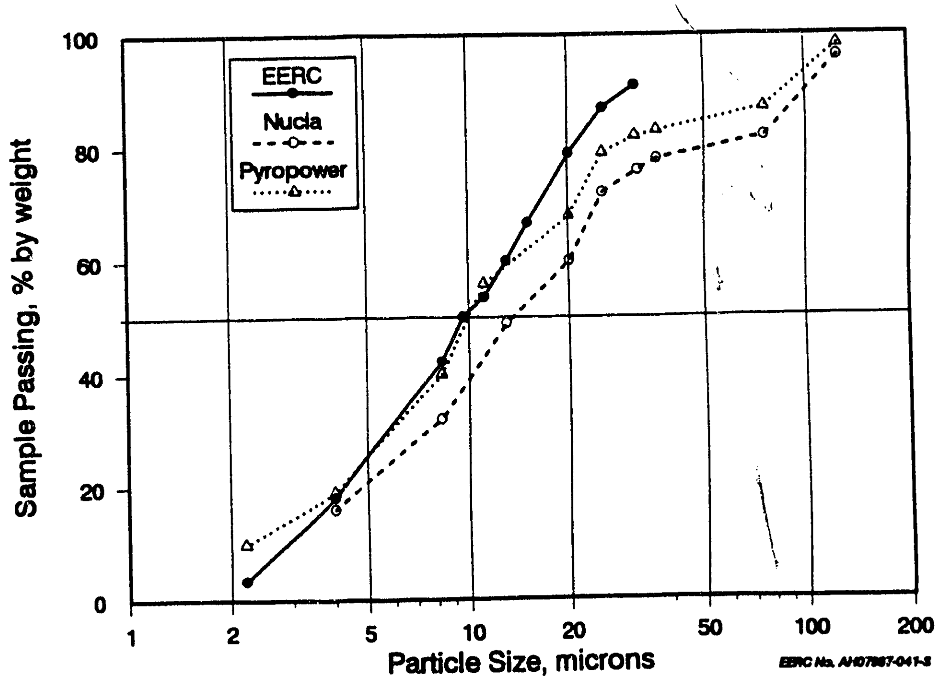

Figure 4-2. Size distributions of fly ash collected.

from this graph that the EERC was operating with a smaller cut point than Nucla and about the same cut point as Pyropower. Overall, the EERC fly ash top size was considerably smaller than either Nucla or Pyropower. Full-load operation at the EERC resulted in a bottom ash/total split of 26%. For the Pyropower pilot plant and the Nucla generating station, bottom ash splits ranged from approximately 10% to 19% and 11% to 17%, respectively. In addition to the difference in cut size, the high bottom ash split at the EERC may also have been due to various operational difficulties. A hole was found in one of the bags at the end of the run, and there was a tendency for the fly ash to hang up in the baghouse hopper. Either of these conditions may have caused the amount of ash retrieved from the baghouse to be artificially low, as evidenced by poor material balances.

4.2.2 Bed Temperature

Full-load testing was conducted on the EERC and Pyropower pilot plants at average bed temperatures similar to those obtained at the Nucla generating station. Figure 4-3 shows reasonably similar combustor temperature distributions for the two pilot units at full-load conditions. Cooled solids recirculating back into the bottom section of the EERC combustor from the external heat exchanger resulted in a slightly lower temperature distribution in the lower portion compared to the Pyropower combustor.

Partial-load tests were achieved by reducing the coal feed rate to a percentage of the full-load rate while maintaining the full-load heat-transfer surface configuration in the combustor. At partial-load conditions, the EERC combustor was at a lower average combustor temperature than was measured for either the Nucla or Pyropower systems, as shown in Figure 4-4. This could have been caused by operational differences in the recirculation rate since the EERC system had a smaller average recirculating material size. The presence of the external heat exchanger could also have caused the lower average temperature, even though it was extracting only minimal heat with a single cooling coil. Neither the Nucla or Pyropower systems utilizes an external heat exchanger.

4.3 Thermal Performance

4.3.1 Heat Flux and Heat Transfer

The heat flux and heat-transfer coefficients are influenced primarily by bed hydrodynamics. The solids recirculation rate, bed particle size and composition, superficial gas velocity, and bed temperature all influence heat transfer in the CFBC. These parameters were duplicated fairly well in the EERC pilot plant as compared to the commercial plant. Therefore, one may expect the bed hydrodynamics to be similar between the pilot- and full-scale units. However, combustor geometry also plays a key role in determining bed hydrodynamics. The increased wall effects for the smaller pilot-scale unit offset, to some degree, the increased height for larger units, resulting in similar bed densities for both systems. The relative degree of the differences in bed hydrodynamics and their importance in process comparison between pilot- and full-scale is difficult to assess, and further research is needed to quantify hydrodynamic differences between pilot- and full-scale systems.

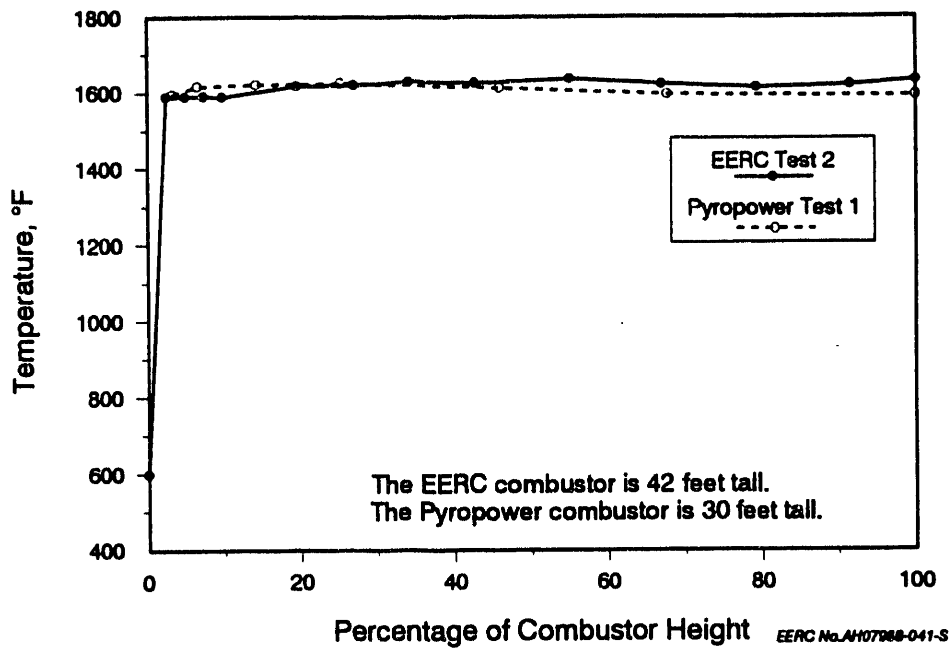

Figure 4-3. Combustor temperature distributions of the Pyropower and EERC pilot plants at full-load operation.

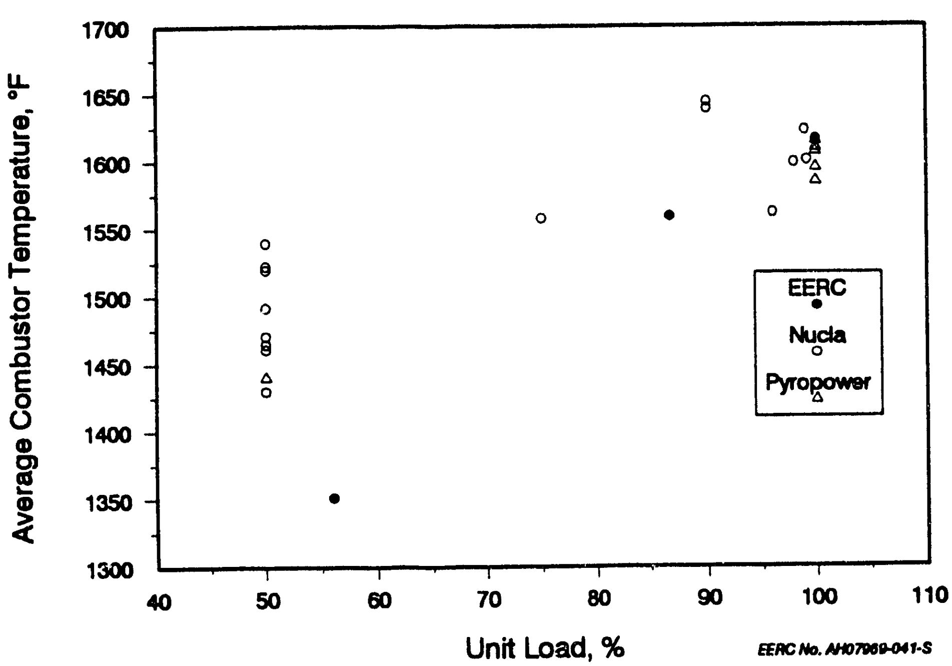

Figure 4-4. Comparison of combustor temperatures of the Nucla Power Station and the Pyropower and EERC pilot plants at partial-load operation.

A comparison of the heat flux data from the pilot- and full-scale plants indicates that a reasonable assessment of average heat flux can be measured in the pilot-scale unit. There appears to be a wider variation in localized heat flux measurements from the pilot-scale system. The measured overall heat flux from the pilot-scale testing ranged from 18,200 Btu/hr-ft^2 at 55% load to 26,000 Btu/hr-ft^2 at 88% load condition up to 32,600 Btu/hr-ft^2 at full-load condition. The measured heat flux from the Colorado Ute Nucla Station ranged from 21,200 to 23,400 Btu/hr-ft^2 at part load (55 MW_e) and from 31,700 to 33,900 Btu/hr-ft^2 at full-load conditions (105 MW_e). The differences in heat flux at the low-load condition were likely due to the lower combustor temperature in the pilot unit (1350°F), as compared to the Nucla system (1500°F). The calculations for heat flux and heat-transfer coefficient from the EERC CFB combustor heat exchange panels were based on the exposed area of the tubes plus the area included in the ⅛-inch weld gaps between the tubes.

At full-load conditions, localized heat fluxes measured in the pilot plant varied from a maximum of 53,650 Btu/hr-ft^2 7.5 feet above the distributor plate down to 27,700 Btu/hr-ft^2 32.5 feet above the distributor plate. At low-load conditions, localized heat fluxes measured in the pilot plant varied from a maximum of 25,000 Btu/hr-ft^2 7.5 feet above the distributor plate down to 17,100 Btu/hr-ft^2 32.5 feet above the distributor plate. At both load conditions with the EERC pilot plant, the localized heat flux increased slightly just before the combustor exit.

The heat-transfer coefficient in the EERC combustor dropped from 22.3 Btu/hr-ft^2-°F (Test Period 2 at full load) down to 14.4 Btu/hr-ft^2-°F (Test Period 4 at 55% of full load). The external heat exchanger, operated in a bubbling bed mode, had the heat-transfer coefficient decrease less significantly from 98.7 Btu/hr-ft^2-°F (three cooling coils in service) to 83.8 Btu/hr-ft^2-°F (one cooling coil in service) during reduced load testing.

4.3.2 Combustion Efficiency and CO Emissions

Combustion efficiency is a function of temperature, excess air, particle size, and residence time, the last two depending on the design of the combustor. Typically, full-scale units have greater residence time, leading to potentially better carbon burnout, but this can be offset at the pilot scale by increased wall effects and better cyclone efficiency.

The EERC combustion efficiencies shown in Figure 4-5 are for Tests 5 through 12, conducted at both high and low excess air conditions. While the low excess air tests are comparable to the Pyropower data, the EERC pilot plant may have slightly higher combustion efficiencies due to greater residence time, since the EERC combustor is 12 feet taller than the Pyropower unit. Combustion efficiencies from the EERC pilot unit are comparable to those from the Colorado Ute Nucla Station.

The level of carbon monoxide in the flue gas is an indication of combustion efficiency. The levels of CO emissions from the EERC pilot plant are comparable to the Pyropower unit and lower than those from Nucla, as shown in Figure 4-6. Better mixing at the pilot scale could account for the improvement over Nucla.

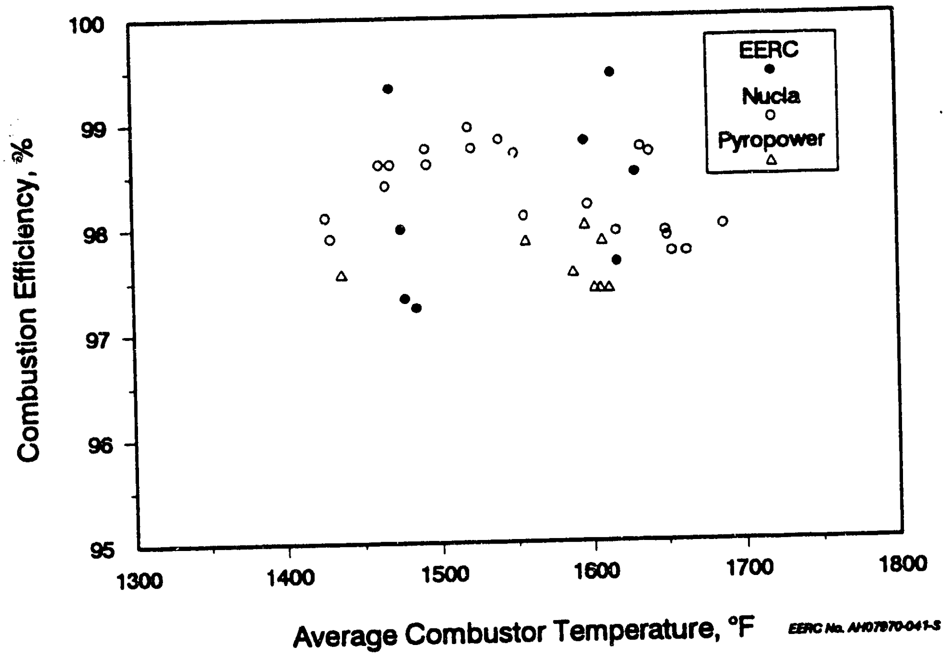

Figure 4-5. Comparison of combustion efficiency from the Nucla Power Station and the Pyropower and EERC pilot plant.

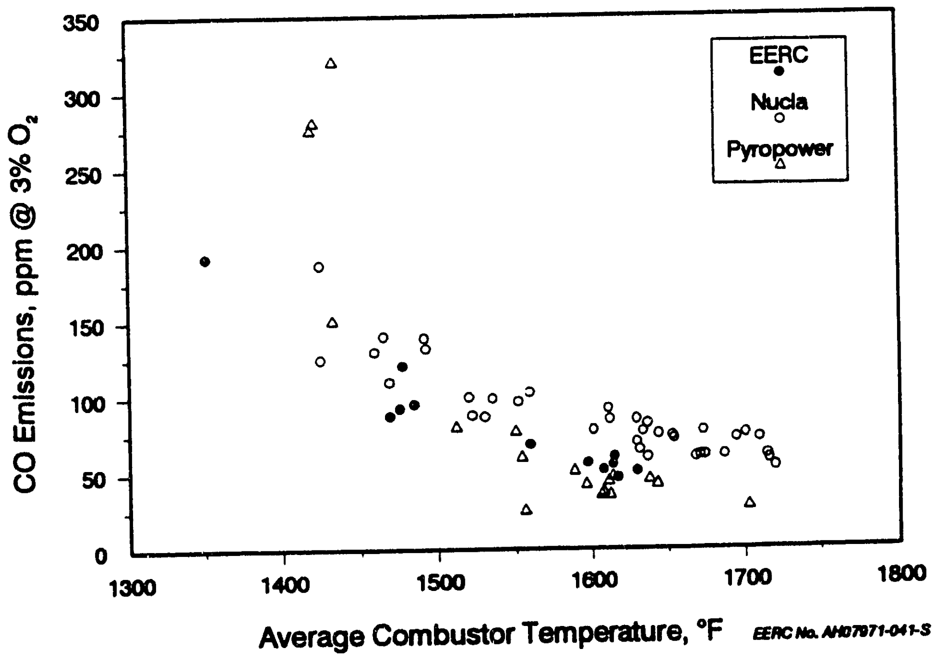

Figure 4-6. Comparison of CO emissions from the Nucla Power Station and the Pyropower and EERC pilot plants.

4.4 Emissions

4.4.1 Sorbent Performance

Some of the factors affecting sulfur capture in a fluidized-bed combustor are temperature, reactivity and particle size of the sorbent, adequate mixing of coal and sorbent, and residence time. In the comparison among the full-scale Nucla station, the Pyropower pilot plant, and the EERC pilot plant, the same coal and limestone were used, eliminating coal and sorbent properties as variables. The limestone was prepared at the Nucla Station for all pilot- and full-scale tests. Maximum sulfur capture for a number of coals has been noted to occur at a temperature of about 1550°F; the full-load tests performed at these facilities had average combustor temperatures above 1610°F. Since increasing residence time generally provides better sulfur capture, the full-scale plant, with its taller combustion chamber and operating at similar gas velocity, would be expected to achieve greater sulfur capture. However, pilot-scale units typically have better mixing than full-scale units due to increased wall effects, contributing to sulfur capture capabilities. The SO_2 retention as a function of the calcium-to-sulfur ratio is shown in Figure 4-7. Sulfur retention was generally lower in the EERC tests. Temperature variations both above and below the optimum temperature of 1550°F resulted in reduced sulfur capture.

Figure 4-8 shows the effect of the calcium-to-sulfur ratio on calcium utilization. The EERC data points are slightly lower than those reported by Pyropower and Nucla. This is consistent with the SO_2 retention findings.

4.4.2 NO_x and N_2O Emissions

A significant advantage of fluidized-bed combustion is the fact that lower operating temperatures result in lower NO_x emissions than those seen in a pulverized coal-fired process. Figure 4-9 shows good agreement among the three plants for NO_x emissions as a function of temperature. The NO_x emissions were higher for those EERC tests performed at a high level of excess air, as expected.

N_2O emissions are inversely proportional to temperature and directly proportional to oxygen content. Figure 4-10 shows a comparison between the EERC pilot plant data and those obtained at the Nucla station, both at high and low oxygen levels. The trends are similar in the two units; the higher N_2O emissions in the pilot plant versus the full-scale plant are consistent with reports from other researchers.

4.5 Summary

Tables 4-2, 4-3, and 4-4 summarize factors affecting the scalability of CFB data. Both physical parameters and operating conditions have an effect on unit performance. These tables indicate which parameters can be reliably scaled up, which need to be matched closely to full scale, and which require further research before scalability can be adequately assessed.

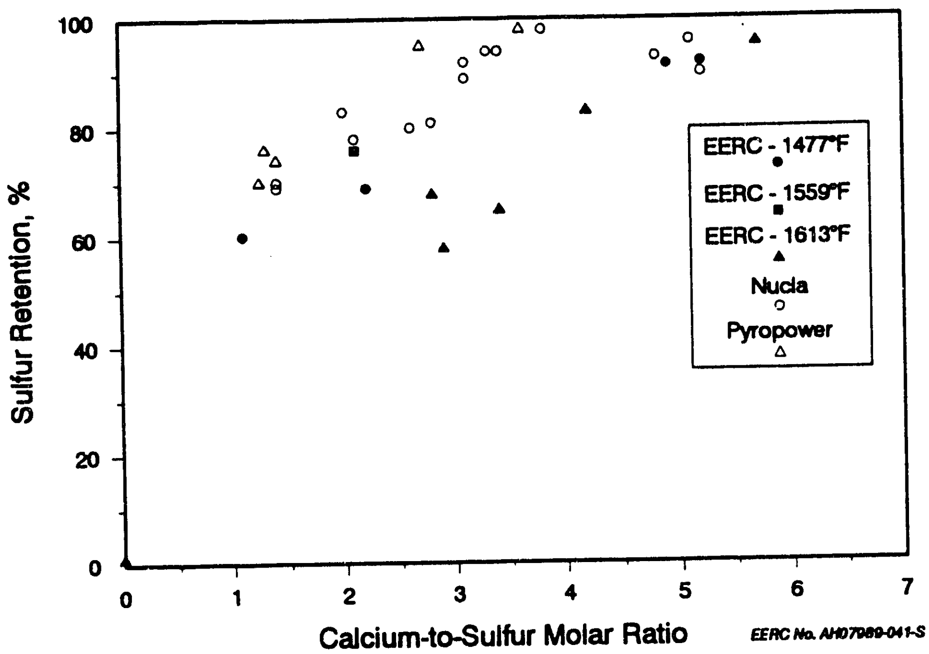

Figure 4-7. Sulfur retention as a function of the calcium-to-sulfur ratio.

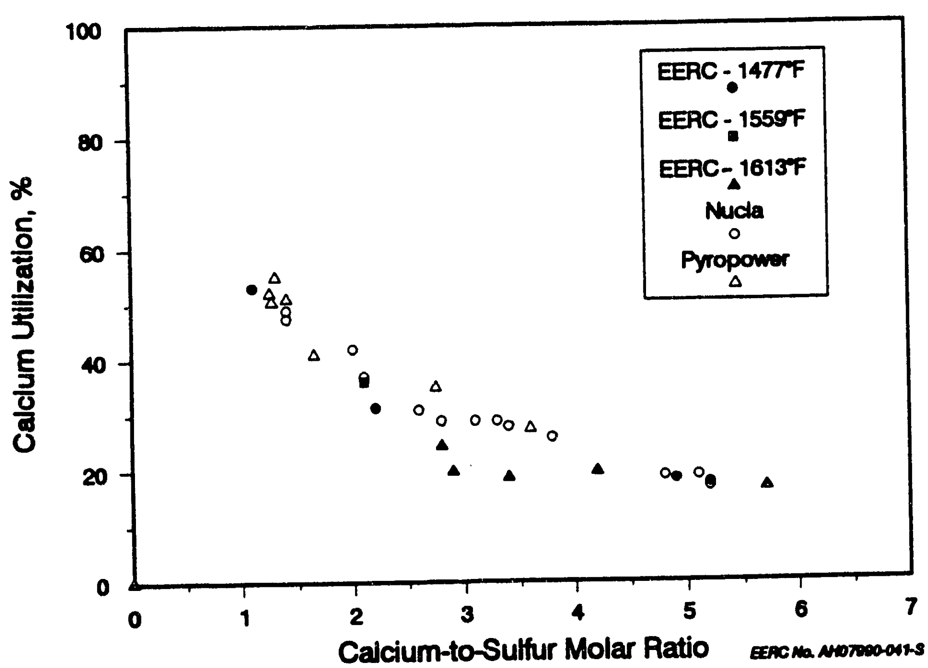

Figure 4-8. Effect of the calcium-to-sulfur ratio on calcium utilization.

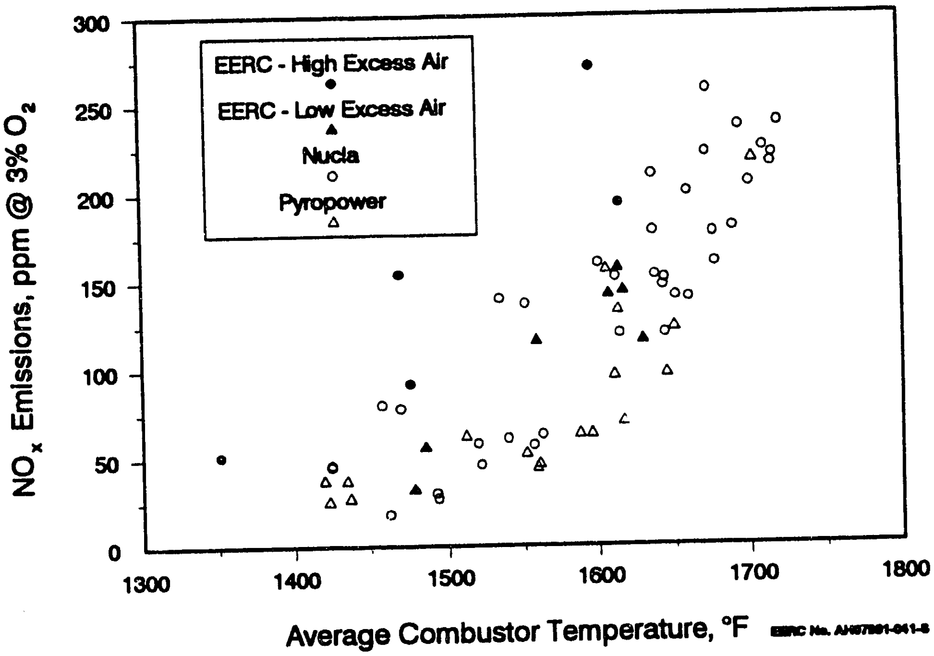

Figure 4-9. Comparison of NO_x emissions.

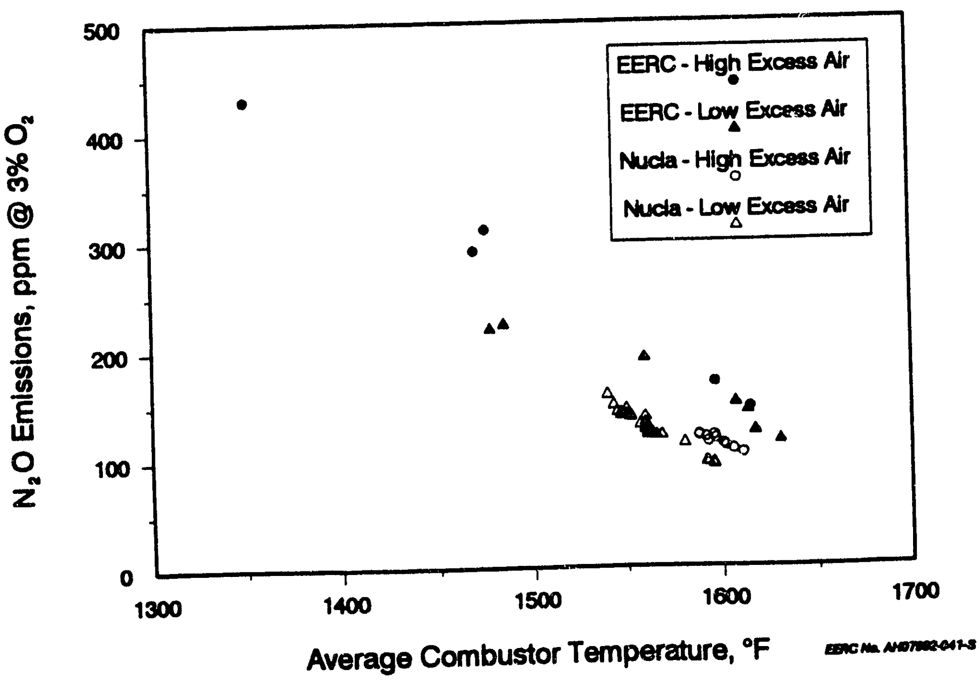

Figure 4-10. Comparison of N_2O emissions.

TABLE 4-2

Importance of Physical Configuration on Scalability of CFB Data

Physical Parameters	Effect on Performance	Scalability	Suggestions/Importance
Furnace cross section	Solids/gaseous mixing, emissions, temperature profile, heat absorption pattern.	The smaller cross section of the pilot plant allows better mixing of primary and secondary air with fuel, limestone, and recycle. High surface area-to-volume ratio can impact heat removal, if it was not accounted for in design. Shorter height (residence time) offsets mixing differences to give good combustion efficiency and sorbent performance data. Heat-transfer data can be obtained with properly designed heat-transfer surfaces. The good mixing, especially for secondary air, would tend to lower NO_x emissions; however, the wall effects increase NO_x emissions--the net result is usually higher NO_x emissions from pilot plants. N_2O emissions are also higher from pilot plants.	Refer to Table 4-3 to determine which parameters are scalable. In designing a new unit, surface-to-volume ratios need to be carefully evaluated. For the EERC unit, heat exchange panels have been designed to allow adequate heat removal while maintaining good temperature distribution.
Particle collection device (cyclone)	Carbon burnout, alkali (alkaline components in coal ash and limestone) utilization, ash splits, size of solids in combustion.	A particle collection device that produces the same cut point will give good bed versus fly ash split. A cut point that is too small will increase carbon burnout and improve alkali utilization. Some argue that the smaller cut point is needed to offset the short residence time, while others contend the cut size should be duplicated to ensure proper ash balances and not to skew performance data to unrealistic high carbon burnout and alkali utilization. Pilot-scale units with cyclones usually have a smaller cut point than full-scale units.	If possible, the cut point of the full-scale unit should be matched. This will ensure proper solids distribution in the combustor. Good mixing in the pilot plant should offset the lower residence time. Testing at more than one cut point can demonstrate the importance of meeting the design cut point in the commercial unit.
Furnace height/gas residence time	Sulfur capture, CO emissions, combustion efficiency, hydrocarbons.	Shorter residence time, i.e., shorter height, would cause poorer sulfur capture, higher CO and hydrocarbon emissions, and lower combustion efficiency. The superior mixing in the pilot scale versus full scale lessens or, in some cases, totally offsets the lower residence time. Better collection efficiency in cyclone would also improve sulfur capture and combustion efficiency in the pilot plant, offsetting residence time effects.	Gas residence time in pilot plant can be matched to full scale by varying velocity. Changes in velocity, however, will impact other conditions such as particle distribution, solids recirculation rate, and bottom-to-total ash split. It is, therefore, recommended to operate at same velocity as full scale.
Particle residence time	Sulfur capture, limestone utilization, carbon burnout.	Particle residence time is controlled by combustor height, velocity, wall effects, and cyclone collection efficiency. Longer residence times favor good limestone utilization, sulfur capture, and carbon burnout. The collection efficiency of the cyclone dominates the particle size. Therefore, pilot-scale units with high collection efficiencies may see better performance than full-scale ones. Other factors, such as gas residence time, favor the full-scale plant.	If possible, the cut point (cyclone collection efficiency) in the pilot plant should match the full-scale unit. This would not provide a perfect match between full and pilot scale because of height differences and stronger wall effects of pilot scale.
Hydrodynamics	Additional work needs to be performed to quantify.	Function of size of bed material, recirculation rate, velocity, unit cross section and height, presence of any heat-transfer surfaces in the combustor proper, and amount and location of secondary air.	A number of variables may impact the hydrodynamics of the combustor. More work is needed to assess the magnitude and direction these changes have on scalability.

TABLE 4-3

Scalability of Operational Parameters from Pilot-Scale CFBC

Operational Parameters	Effect on Performance	Scalability	Suggestions/Importance
Primary/secondary air split	NO_x emissions, temperature distribution, dense bed height.	Pilot plant is very sensitive to changes in PA/SA. In real life, changes are less pronounced due to poor mixing.	Determine the PA/SA ratio that gives the lowest NO_x without greatly impacting temperature profile. Run all tests at optimum PA/SA. Compare relative differences in NO_x between tests.
Bed temperature	Carbon burnout; optimum sorbent utilization; NO_x, N_2O, and CO emissions; heat absorption pattern.	Temperature effects appear to scale well between pilot and commercial units. These performances are also impacted by residence times.	Test at various temperatures within the range of characteristics of full-scale units.
Load	Heat absorption patterns; CO, N_2O, and NO_x emissions; carbon burnout; thermal efficiency; temperature distribution.	Data will be somewhat scalable if the correct temperature profiles are maintained. Mixing patterns may differ between units at low velocity, high excess air. Good mixing in the pilot plant should offset lower residence time.	It is important to match the temperature distribution of the commercial unit. Impacts of velocity and excess air changes should be evaluated. Load-following methods with and without external heat exchange should be compared.
Excess air	Thermal efficiency; CO, N_2O, and NO_x emissions; carbon burnout.	At very low excess air levels, pilot scale may give better performance due to good air/solids mixing and distribution. Trends should be similar at high excess air levels.	Test at low and high excess air levels. Keep in mind that at normal operation, excess air will not vary significantly. Only during load following and upset conditions will large variations be seen.
Calcium-to-sulfur ratio	Sulfur capture, limestone utilization, waste/disposal volumes, particulate generation, and NO_x and H_2O emissions.	Scalability is generally quite good. Most SO_2 released in bottom of plant combustor. Good mixing in the pilot plant also decreases the importance of height.	Determine the Ca/S ratio to meet NSPS. Tests at varying Ca/S ratios can be performed to determine the ratio to achieve other conditions. Bottom ash/fly ash split is important.
Solids recirculation rate	Control load, heat absorption pattern, heat-transfer coefficient.	Heat transfer shows reasonable scalability when care is taken to match bed densities of full-scale operation.	Operate at a representative recirculation rate approximately of 15-20 kg/m^2-sec.
Fuel size	Carbon burnout, bed versus fly ash split, solids density in combustor.	Bed versus fly ash split is scalable, providing the particle collection device operates at the same cut point. Carbon burnout similar. (Good mixing offsets short height in pilot plant.)	It is important to match the fuel specifications of the vendor or duplicate those in an existing operating unit.
Limestone size	Required Ca/S ratio, bed versus fly ash split.	Good scalability exists if particle collection operates at the same cut point.	Duplicate design size distribution for the unit (expected delivered size from quarry/supplier).

TABLE 4-4

Scalability of Measured Performance Parameters from Pilot-Scale CFBC

Performance Parameter	Scalability
Heat transfer	Heat transfer is primarily a function of the recirculation rate and the particle-size distribution in the combustor. Good correlation between the pilot- and full-scale units can be expected if these two parameters can be controlled, as seen by the EERC data.
Combustion efficiency	Carbon burnout will be controlled mainly by the cut point of the cyclone, with better carbon burnout being achieved for smaller cut points. CO will decrease as the gas residence, or combustor height, decreases, but should increase for well-mixed systems. Therefore, carbon burnout should be similar between full- and pilot-scale units if the cut point is similar. The impact of combustor height versus gas mixing offset each other from full- to pilot-scale systems, making overall combustion efficiency a scalable parameter.
Bottom ash/total ash split	The percentage of bottom ash will be primarily determined by size of the coal ash and limestone and by the cut size of the cyclone. Assuming the same coal and limestone sizing is used for the pilot- and full-scale testing, similar ash splits will be obtained only if the cyclone cut size is the same. If a smaller cut size is obtained in the pilot scale, as was done at the EERC versus the Colorado Ute Nucla Station, a higher fraction of the ash will be bottom ash.
Bed grain size	Assuming the same coal and limestone sizes are used for both systems, the bed grain size will be primarily a function of the cut size of the cyclone. However, unless there is a large difference in cut size between the full- and pilot-scale units, the bed grain size will be approximately the same.
Limestone utilization, sulfur capture, Ca/S ratio	Sulfur capture and limestone utilization between the full- and pilot-scale units are similar. Shorter combustor heights in pilot plants are offset by better particle and gas mixing. Smaller cyclone cut points in many pilot plants also favor better performance. Data from the EERC and the Pyropower pilot plant indicate similar performance to the Colorado Ute Nucla Station. The scalability of these data may change with differing full-scale designs.
CO emissions	CO emissions would be expected to increase in pilot plants because of the shorter residence times, but decrease because of the improved gas mixing. The net effect for the EERC pilot plant is a decrease in CO emissions as compared to full scale.
NO_x, N_2O emissions	NO_x emissions in the pilot plant are often higher than in full-scale units because of the high surface-to-volume ratio of the pilot plant. Better gas mixing in the pilot scale, especially of the secondary air, however, tends to reduce the NO_x in the pilot scale. NO_x emissions from the EERC pilot plant and Colorado Ute Nucla Station were similar. N_2O emissions have been observed by a number of researchers to be higher in pilot plants than in full-scale units, probably due to gas residence time effects, although wall effects may also be important. The temperature rise in the cyclone in full-scale units may also reduce N_2O. Data generated by the EERC showed similar trends of N_2O emissions with respect to operating conditions, but were consistently higher than those from the full-scale unit.

Table 3-6 compared the heat fluxes measured for the five different coals tested at the EERC. It has been attempted to limit comparison to similar conditions of average bed temperature, excess air level, superficial gas velocity, and the primary-to-secondary air split. The as-tested higher heating value is included in the table as an indicator of the coal rank. The average size of the recirculated bed material is indicated by the d_{50} (average size of the material). The most important factor affecting heat flux was the recirculation rate. The heat flux increased with increasing solids recirculation rates. This would be expected since solid densities are likely higher at correspondingly higher recirculation rates, and at higher solid densities there is more material to radiate and conduct heat to heat-transfer surfaces. This is consistent with the Nucla data from the tests with Salt Creek coal that clearly show that the heat flux increases as the normalized bed density increases.

As would be expected, the combustor heat-transfer coefficients followed the same trends as did the heat fluxes when comparing results obtained with the different coals tested (Table 3-6). The recirculation rate appears to have the most influence, because at higher recirculation rates the bed density is likely higher, as previously mentioned.

5.0 SUMMARY AND CONCLUSIONS

5.1 Summary

The following points summarize overall operability of the EERC CFB for the five different coals tested:

- The recirculation rate, overall solids system collection efficiency, amount of solid waste generated, and the bottom ash-to-total ash split were all affected by coal properties (ash and sulfur contents), limestone properties (size, reactivity, and hardness), geometry of the system (combustor cross section, location of secondary combustion air addition, and configuration of solids collection device used), and operating conditions (primary-to-secondary combustion air split and combustor velocity).

- Reinjection of ash from the secondary cyclone significantly increased the recirculation rate and decreased the average size of the material being recirculated.

- Operation on coals with ash containing high levels of sodium increased the potential for bed agglomeration, while some high-calcium-content coals promoted ash deposition downstream of the primary cyclone.

Results concerning sulfur capture and gaseous and solid emissions are summarized as follows:

- The amount of sulfur capture was primarily a function of the total alkali-to-sulfur ratio, with alkali being provided by the inherent alkali in the coal and added alkali supplied with limestone sorbent addition.

- The alkali-to-sulfur ratio required to capture 90% of the sulfur present in the coal usually decreased as the sulfur content increased, even though the total amount of sorbent required increased as the sulfur content increased.

- The optimum bed temperature resulting in maximum sulfur capture varied somewhat with coal type, with optimal sulfur capture at combustor temperatures of approximately 1550°F for the bituminous coals tested and approximately 100°F lower for most of the low-rank coals tested.

- There appeared to be an optimal sorbent size for maximum limestone utilization: small enough to be fluidized and circulated, while large enough not to pass through the primary solids capture device. For operation with the same type of limestone and the same coal type, use of a larger limestone size distribution resulted in improved sulfur capture.

- NO_x emissions were dependent upon the coal type and increased with increasing combustor operational temperatures, excess air levels, ratio of primary-to-secondary combustion air, and, with the exception of the Black Thunder subbituminous coal, increased with increasing sorbent feed rates.

- The low-rank lignites were higher emitters of NO_x than the higher-ranked bituminous coals at lower temperatures (1450°F), but emitted less NO_x at higher temperatures.

- N_2O emissions were even more dependent upon fuel properties than NO_x emissions, N_2O emissions being lowest with subbituminous, increasing with the lignite, and highest with bituminous. The distribution of the nitrogen between the volatiles and the fixed carbon was found to be the most important fuel property affecting N_2O emissions.

- N_2O emissions decreased with increasing temperature and sorbent add rate, increased as excess air levels increased, and did not show a clear trend as a function of the primary-to-secondary combustion air split.

- Total nitrogen oxides emissions, NO_x plus N_2O, tended to increase as the rank of the coal increased, but no apparent consistent trend emerged for total nitrogen oxide emissions as a function of average combustion temperature for the five coals tested.

- Carbon monoxide (CO) emissions tended to decrease with increasing temperature and decreasing levels of excess air for all ranks of coal.

- Dust loading into the baghouse for the high-ash, high-sulfur Asian lignite was the highest at 2.13 grains/scf, while dust loadings for the other coals ranged from 0.60 to 0.90 grains/scf; collection efficiency using woven fiberglass bags in the EERC pulse-jet baghouse was above 99.9% for each of the coals tested.

Results are summarized as follows for thermal performance with the five different coals tested using the EERC CFBC:

- Heat transfer (heat flux and heat-transfer coefficients) in the combustor and external heat exchanger was highly dependent upon the recirculation rate, improving as the recirculation rate increased, due largely to the increased concentration of hot solids particles in the system and partially to the increased amount of fines present that more effectively transfer heat to heat-transfer surfaces in the combustor and external heat exchanger.

- Combustor and external heat exchanger heat flux and heat-transfer coefficients usually increased with increasing combustor temperatures and velocities.

- Combustion efficiency generally increased with decreasing ranks of coal, due to the higher reactivity of the char for the lower-rank coals and their higher volatile content-to-fixed carbon ratio; over the range of test conditions, lignites generally approached 100% combustion efficiency independent of secondary ash addition, while combustion efficiencies as low as 90% were obtained for the Blacksville bituminous coal with no secondary ash addition.

- Combustion efficiency improved with increased amounts of excess air for all the high-rank coals tested.

- Operational parameters that affected boiler efficiencies included the coal properties (char reactivity, moisture, ash, and sulfur contents), amount of excess air, secondary ash recirculation, and the operational combustor temperature.

- Low-rank coals with higher levels of moisture than the other coals tested resulted in lower boiler efficiencies due to the increased amounts of energy required during combustion to vaporize the additional moisture.

- Heat losses due to ash and spent sorbent were dependent upon the total ash content of the coal relative to its heating value and to limestone feed rates; losses amounted to 6.8% for the high-sulfur, high-ash Asian lignite and ranged from 0.2% to 1.4% for the other coals tested.

The following points summarize the impacts of load reduction methods utilized for the EERC CFBC:

- For all coals, independent of the method of load reduction, boiler efficiencies decreased when load was reduced.

- Reduced load operation at constant temperature resulted in slightly higher boiler efficiencies than reduced load operation with constant heat-transfer surface; this was mostly due to the greater quantities of fluidizing air required at lower operational temperatures to maintain similar velocities as a test at the same load but higher temperature. However, comparisons of the boiler efficiency losses must be made with caution, since a 300°F stack gas exit temperature was assumed for the boiler efficiency calculations for each test period, and may not be representative of an operational boiler.

- The boiler efficiency did not decrease with load in every case, due to differences in the unburned carbon losses for a given coal at different load conditions.

- For each of the coals tested, dry gas losses (usually the most significant factor affecting boiler efficiencies) increased as load was reduced by either method, suggesting that boiler efficiency could be expected to decrease with decreasing load; because of the assumed exit gas temperature used in these calculations, dry gas losses in an operational boiler would not be as significant as reported here.

- SO_2 emissions were not significantly affected by turndown method. Operation with constant heat-transfer surface decreased NO_x emissions and increased N_2O and CO emissions as load (and temperature) decreased; at constant temperature, NO_x emissions increased slightly, while N_2O and CO emissions were unaffected by load reduction.

- Heat fluxes and heat-transfer coefficients in both the combustor and external heat exchanger showed definite decreases using the constant heat-transfer surface load reduction method, due to a combination of decreased operational temperatures and recirculation rates as load was decreased.

- As load was decreased using the constant-temperature load reduction method, overall heat fluxes and heat-transfer coefficients decreased in the external heat exchanger and remained relatively unaffected in the combustor.

- Combustion efficiencies for the reactive Center lignite were not affected by load reduction. Reducing load with either method improved combustion efficiency for both the Salt Creek and Blacksville bituminous coals, likely due to lower superficial gas velocities in the combustor. Lower operational velocity increases gas residence time and reduces the amount of carbon carried out of the system, resulting in improved carbon burnout.

The following is a summary provided on testing conducted with the EERC pilot-scale CFBC for comparison to similar testing conducted with the full-scale Colorado Ute Nucla CFB boiler and at another pilot plant system owned and operated by Pyropower, Inc.:

- Test conditions (solids recirculation rate, bed particle size and composition, superficial gas velocity, and average bed temperature) that have a significant influence on heat transfer in a CFBC were well duplicated in the EERC pilot plant compared to the full-scale operation at Nucla.

- The increased wall effects of the EERC pilot-scale unit offset to some degree the increased height for the larger full-scale system resulting in similar bed density distributions for both systems.

- A comparison of the heat-transfer data from the pilot- and full-scale plants indicates that a reasonable assessment of average heat flux over a wide range of conditions can be measured in the pilot-scale unit, even though there is a wider variation in localized heat flux measurements in a pilot-scale system.

- Combustion efficiencies obtained with the EERC pilot unit were comparable to those from the Colorado Ute Nucla Station, even though full-scale units with increased gas residence times have greater potential for better carbon burnout; this was offset on the pilot scale by increased wall effects, better gas/solids mixing, and better cyclone efficiency.

- The levels of CO emissions from the EERC pilot plant were slightly lower than Nucla, probably due to better mixing of solids on the pilot scale.

- Limestone utilization and sulfur capture as a function of either the average bed temperature or the alkali-to-sulfur ratio were also slightly lower with the EERC pilot plant as compared to Nucla.

- NO_x emissions as a function of temperature showed good agreement.

- The trends for N_2O emissions were similar in the two units; the higher N_2O emissions in the pilot-scale versus the full-scale plant are consistent with reports from other researchers.

5.2 Conclusions

In conclusion, all of the project goals originally established were met or surpassed for Project CFB. A pilot-scale CFBC system was successfully designed, constructed, and operated. It was demonstrated that several critical operational results can be obtained that are representative of full-scale operation. Due to the ability to easily alter the amount of heat-transfer surface utilized in either the combustor or the external heat exchanger, the EERC CFBC can be operated over a wide range of conditions with all ranks of coals.

While the original goal was to conduct testing with two different coals, additional testing was successfully conducted which resulted in the generation of a CFB database for five different coals. The EERC has established a pilot-scale CFBC system that can be operated free from vendor bias for the rapid transfer of technology in a free and open manner. The EERC CFB pilot plant system can be utilized for fundamental CFB research and is available for use by the public and private sectors to generate valuable data which will expand the current database.

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APPENDIX A

SALT CREEK BITUMINOUS COAL TEST RESULTS

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TEST MATRIX

The matrix of test parameters is shown in Table A-1. The calcium-to-sulfur ratio shown in the table includes calcium in the coal as well as in the limestone. Test 1 was performed at full load with no limestone addition to establish baseline sulfur emission data for the Salt Creek coal. Test 2 is a full-load test with the addition of limestone for sulfur capture. Tests 3 and 4 were partial-load tests, based on coal feed rate. In both partial-load tests, the temperature and superficial gas velocity were allowed to decrease, the excess air was not controlled, and the total heat-transfer surface in the combustor and external heat exchanger was held constant.

Tests 5 through 12 were all full-load tests. Temperature, Ca/S ratio, excess air level, and primary-to-secondary air split were varied to determine their effects on flue gas emissions and combustion efficiency. High and low values of each parameter were tested.

COAL AND LIMESTONE PROPERTIES

Salt Creek coal and limestone were provided by EPRI. The coal was crushed and sized to -¼". A sample of the coal was taken during crushing and grinding, and samples were obtained during each test period. These samples were submitted for proximate, ultimate, and sieve analysis. Additionally, the coal ash was analyzed by x-ray fluorescence for the determination of major mineral oxides and by computer-controlled scanning electron microscope (CCSEM) to define the size distribution of major mineral species. Table A-2 lists the results of the coal and mineral oxide analyses for each test period. The moisture ranged from 6.8% to 8.2%; the ash content ranged from 16.9% to 20.2%. The heating value, which ranged from 9,976 to 10,563 Btu/lb for the EERC tests, was a bit lower than the 11,100 Btu/lb observed at the Nucla station. The average particle-size distribution of the coal is shown in Figure A-1.

TABLE A-1

Test Matrix

Test #	Temperature (°F)	Load (%)	Ca/S	Excess Air (%)	PA/SA	Velocity (ft/sec)
1	1616	100	0.54	20	54:46	16
2	1616	100	2.04	20	54:46	16
3	**	75	2.04	20	56:44	**
4	**	50	2.04	30	**	**
5	1475	100	1.54	45	70:30	16
6	1475	100	1.54	15	50:50	16
7	1625	100	1.54	15	70:30	16
8	1625	100	1.54	45	50:50	16
9	1625	100	3.54	45	70:30	16
10	1625	100	3.54	15	50:50	16
11	1475	100	3.54	15	70:30	16
12	1475	100	3.54	45	50:50	16

** These conditions were varied as needed to obtain the desired load.

TABLE A-2

Coal Analyses

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12	Average
Proximate Analysis, as-received, wt%													
Moisture	6.8	7.9	7.8	7.5	6.8	7.8	7.8	7.5	8.2	7.9	7.9	7.9	7.65
Volatile Matter	31.9	31.1	30.9	30.8	31.6	30.6	31.5	30.2	30.2	30.8	31.3	31.7	31.04
Fixed Carbon	44.7	42.1	42.3	41.6	43.1	42.4	43.4	42.1	43.0	42.7	43.1	42.4	42.74
Ash	16.9	18.9	19.0	20.1	18.5	19.1	17.3	20.2	18.6	18.6	17.7	17.9	18.58
Ultimate Analysis, as-received, wt%													
Carbon	60.4	57.7	57.6	57.7	59.6	58.9	59.9	58.2	58.7	59.0	59.7	58.7	58.82
Hydrogen	5.3	4.9	5.0	5.2	5.3	5.0	5.0	4.9	4.7	5.0	4.7	4.9	4.98
Nitrogen	1.3	1.2	1.1	1.1	1.1	1.2	1.2	1.1	1.1	1.1	1.1	1.1	1.15
Oxygen	15.6	6.8	6.8	15.5	15.1	15.4	16.2	15.2	16.5	15.9	16.3	16.9	16.02
Ash	16.9	18.9	19.0	20.1	18.5	19.1	17.3	20.2	18.6	18.6	17.7	17.9	18.58
Ash Composition, as oxides, wt%													
Calcium, CaO	1.5	1.6	1.5	1.4	1.4	1.1	1.6	1.2	1.2	2.7	1.2	1.6	1.50
Magnesium, MgO	1.8	1.8	1.8	1.7	1.6	0.7	1.7	1.8	1.8	1.1	1.1	1.1	1.50
Sodium, Na_2O	0.5	0.2	0.4	0.0	0.0	0.6	0.3	0.6	0.2	0.0	0.0	0.0	0.23
Silica, SiO_2	59.3	58.9	57.8	57.7	59.1	67.9	59.0	58.7	57.6	60.5	62.8	59.8	59.93
Aluminum, Al_2O_3	31.4	30.9	31.1	31.1	31.5	33.3	31.4	31.3	31.3	28.6	29.6	29.1	30.88
Ferric, Fe_2O_3	2.7	2.8	3.1	2.8	2.6	2.2	2.0	2.3	2.1	2.7	2.4	8.5	3.02
Titanium, TiO_2	1.2	1.1	1.1	1.1	1.1	0.7	1.2	1.1	1.2	1.1	1.2	1.2	1.11
Phosphorous, P_2O_5	0.5	0.5	0.4	0.4	0.4	0.8	0.4	0.6	0.7	0.0	0.0	0.0	0.39
Potassium, K_2O	0.9	1.0	0.9	1.0	0.9	0.9	0.9	1.0	0.9	1.0	1.0	1.0	0.95
Sulfur, SO_3	0.9	1.1	1.0	0.9	0.9	0.5	1.0	1.2	1.2	0.8	0.7	1.3	0.96
High Heating Value, as-received, Btu/lb													
	10,563	10,013	10,084	9,976	10,421	10,258	10,445	10,228	10,307	10,175	10,544	10,279	10,274

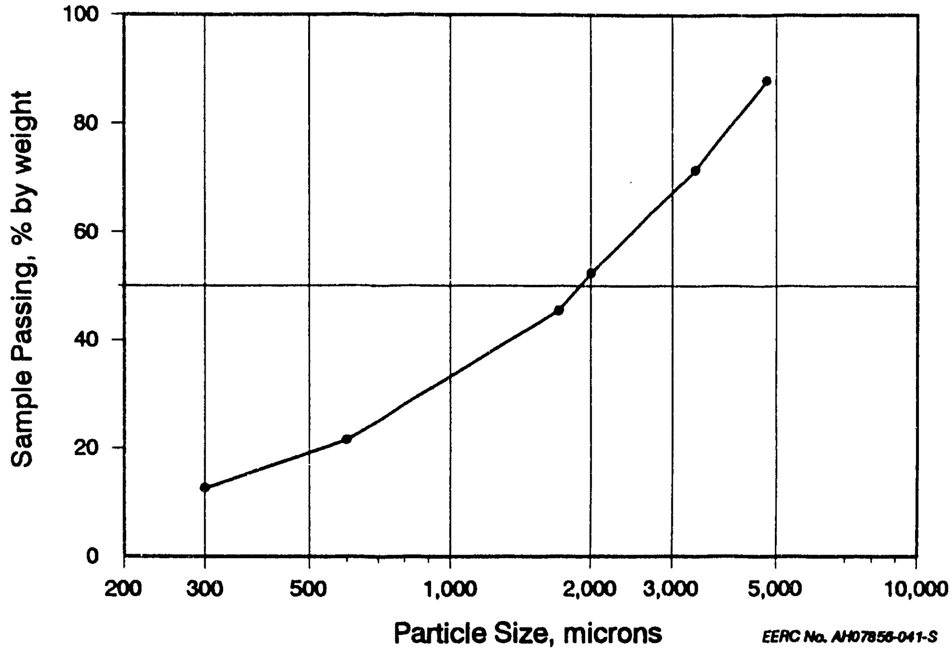

Figure A-1. Average particle-size distribution of Salt Creek coal.

The results of limestone analyses are shown in Table A-3. The limestone used for these tests had an elemental calcium content of 37% and no magnesium, compared to 36.3% calcium and 0.53% magnesium in the limestone used during the Nucla testing. The limestone was crushed and sized at the Nucla station prior to shipping to the EERC. The limestone particle-size distributions from test to test were consistent; however, there was a great deal of variability in particle size depending on the method of analysis, as shown in Figure A-2. The limestone was extremely cohesive and tended to agglomerate when subjected to vibration, such as that used in the sieve analyses. Subsequently, both Malvern and Coulter counter tests were performed, and results were obtained which were more consistent with the visual inspection of the limestone. The limestone used at Colorado Ute was sized by dry sieve analysis; Figure A-2 shows the size distribution similarity between the EERC and Colorado Ute limestones.

OPERATIONAL PERFORMANCE

Summary of Results

Upon completion of the run, data for each of the steady-state test periods were averaged. A summary of the process data for each test is presented in Table A-4. The twelve test periods correspond to those presented in the test matrix listed in Table A-1.

In general, the unit performed within the parameters specified in the original test plan. One notable exception was the actual calcium-to-sulfur ratio which was calculated at the conclusion of the run. The calcium-to-sulfur ratio was typically higher than specified in the test matrix. This can be attributed to limestone feed problems which will be discussed, along with specific results, in subsequent sections.

TABLE A-3

Average Limestone Analysis (% as oxide)

Component	Average
Silica	2.62
Aluminum	0.38
Iron	0.31
Titanium	0.02
Calcium	54.05
Magnesium	0.00
Sulfur	0.17
Sodium	0.00

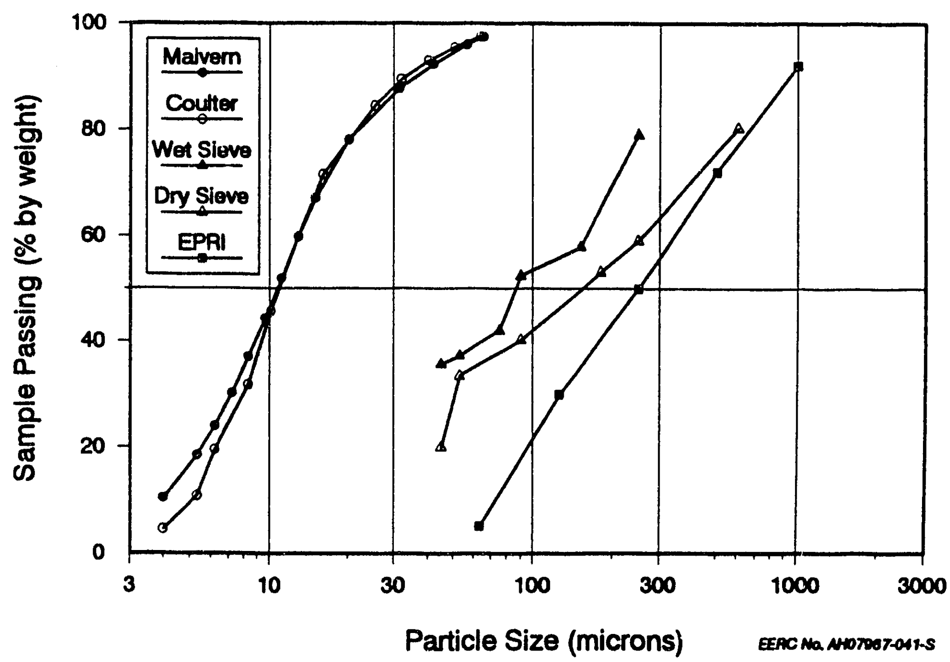

Figure A-2. Size distribution of Salt Creek limestone from Test 2 using several analyses.

General Operability

The unit performed well during testing of the Salt Creek coal. No major problems were encountered with the unit or auxiliary equipment. The coal was crushed and sized to -¼ inch and placed into storage hoppers. A rotary valve was used to transfer the coal from the storage hopper into the 1000-pound capacity main feed hopper as needed. The feed hopper was suspended from a load cell to determine the coal feed rate. A second rotary valve was used to feed and meter the coal to a horizontal screw feeder. In addition

TABLE A-4

Summary of Process Data

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Date:	01/22/91	01/23/91	01/23-24/91	01/24/91	01/25/91	01/29-30/91	01/30/91	01/30/91	01/30-31/91	01/31/91	1/31-2/1/91	02/01/91
Time: From	0830	0045	2022	1230	0300	2230	0535	1230	2128-2323	1015	2015	0400
To	1230	1237	0052	2030	0700	0230	0930	1630		1415	0015	0800
Coal Feed Rate, lb/hr	226	239	204	133	213	258	237	208	208	245	263	215
Limestone Feed Rate, lb/hr	0.0	9.1	6.2	4.5	6.3	3.4	8.6	9.0	15.1	12.8	16.4	15.8
Solids Recirculation Rate, lb/hr	7,658	12,046	8,923	2,777	14,210	9,577	10,601	7,357	8,922	9,597	12,012	13,124
Combustor dP, in. H_2O	49.7	43.7	55.9	44.8	29.0	43.3	42.4	38.4	37.9	40.1	40.4	46.2
Combustion Air												
EHX Flow, scfm	47	56	52	59	37	46	48	55	54	54	50	52
Primary Air, scfm	214	182	222	134	320	191	281	200	313	181	311	193
Secondary Air, scfm	225	243	146	143	161	254	143	235	141	254	154	261
Feed Assist Air, scfm	25	25	25	25	25	25	25	25	25	25	25	25
DC Aeration Air, scfm	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Purge Air, scfm	0	0	0	0	0	0	0	0	0	0	0	0
Total Air, scfm	524	519	457	373	555	528	509	528	546	527	553	544
PA/SA, %	50	46	60	52	64	45	65	48	67	45	65	45
Excess Air, %	20.8	21.5	23.4	54.2	43.7	17.0	18.7	40.7	46.0	20.4	17.0	45.5
FG SGV, ft/sec	16.7	16.6	14.2	10.3	16.5	15.7	16.3	16.6	17.0	16.7	16.5	16.0
EHX SGV, ft/sec	1.7	2.2	2.0	1.8	1.4	1.6	1.9	2.2	2.2	2.1	1.7	1.9
Flue Gas												
Flow Rate, scfm	484	497	436	412	600	490	474	520	503	520	620	601
Oxygen, %	3.65	3.76	4.00	7.40	6.44	3.11	3.35	6.12	6.65	3.60	3.10	6.63
SO_2, ppm	511	173	133	139	186	210	223	162	21	91	45	35
CO, %	0.0011	0.0010	0.0013	0.0042	0.0012	0.0026	0.0011	0.0007	0.0007	0.0008	0.0002	0.0015
NO_x, ppm	137	150	110	39	75	81	113	161	216	139	55	123
N_2O, ppm	145	136	180	325	251	217	112	120	135	120	222	232
CO_2, %	15.9	15.7	16.2	12.8	13.3	15.7	16.0	13.8	13.5	15.9	16.0	13.04
Ash												
Bed Material Add Rate, lb/hr	38	12	34	7	13	0	0	0	0	0	0	0
Cyclone Ash Add Rate, lb/hr	0	24	0	13	0	0	0	0	0	0	0	0
Bottom Ash Discharge Rate, lb/hr	0	21	31	21	13	13	0	10	0	10	0	11
Bottom Ash Unburned Carbon, %	0.33	0.21	0.31	0.95	0.39	1.24	0.38	0.20	0.12	0.48	0.29	0.19
Cyclone Ash Discharge Rate, lb/hr	0	24	0	0	34	20	5	10	36	8	40	19
Cyclone Ash Unburned Carbon, %	0.04	0.02	0.02	0.09	0.15	0.35	0.15	0.03	0.06	0.17	0.17	0.12
Baghouse Ash Discharge Rate, lb/hr	12	37	15	10	24	20	21	14	21	26	23	10
Baghouse Ash Unburned Carbon, %	10.30	8.85	5.84	4.46	9.87	17.94	9.45	4.69	6.76	12.17	17.60	7.68
Total Ash (meas.), lb/hr	12	82	46	31	70	53	26	34	57	44	63	40
Total Ash (calc.), lb/hr	38	50	43	29	42	48	44	41	45	49	55	45
Bottom Ash/Total Ash (meas.), %	0.0	26.1	67.4	67.2	18.5	24.8	0.0	29.9	0.0	22.6	0.0	26.4

continued...

TABLE A-4 (continued)

Air and Gas Temperatures, °F	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Combustor Temperatures												
Plenum	599	598	550	421	601	590	655	588	639	618	627	568
Section 1	1596	1590	1544	1304	1448	1432	1607	1593	1579	1577	1446	1437
Section 2	1620	1619	1565	1331	1471	1462	1620	1602	1592	1603	1467	1454
Section 3	1622	1623	1568	1370	1483	1484	1635	1622	1602	1631	1494	1480
Section 4	1617	1626	1569	1382	1491	1499	1641	1625	1607	1634	1504	1486
Section 5	1629	1636	1579	1402	1497	1513	1649	1638	1613	1649	1513	1495
Section 6	1608	1624	1562	1377	1492	1509	1643	1627	1608	1638	1509	1488
Section 7	1595	1614	1554	1367	1482	1497	1633	1611	1597	1624	1498	1476
Section 8	1591	1621	1560	1369	1495	1513	1646	1626	1609	1638	1512	1492
Section 9	1611	1631	1571	1382	1498	1522	1652	1635	1612	1650	1519	1500
PCD Exit	1608	1612	1559	1383	1490	1519	1645	1626	1600	1646	1513	1495
Average	1607	1613	1559	1351	1476	1478	1630	1615	1596	1617	1485	1470
EHX Temperatures												
Plenum	125	121	112	119	103	114	121	107	118	128	116	130
0.5' above Distributor Plate	1340	1438	1409	1048	1365	1206	1496	1505	1525	1420	1221	1324
1.5' above Distributor Plate	1339	1435	1412	1071	1358	1203	1489	1506	1526	1420	1210	1312
2.7' above Distributor Plate	1338	1430	1404	1064	1353	1191	1483	1495	1513	1409	1207	1319
3.8' above Distributor Plate	1218	1387	1343	1015	1247	1131	1428	1457	1482	1362	1156	1268
5.3' above Distributor Plate	1080	1270	1216	864	1100	995	1282	1322	1359	1268	1037	1138
Average	1263	1392	1357	1012	1285	1145	1435	1457	1481	1380	1166	1272
Downcomer Temperatures												
Section 3	1537	1532	1467	1199	1437	1443	1577	1544	1549	1561	1453	1427
Section 4	1527	1522	1459	1225	1425	1433	1577	1545	1548	1562	1447	1427
Section 6	1553	1562	1507	1319	1460	1470	1600	1577	1570	1588	1474	1459
Section 8	1571	1595	1536	1381	1476	1494	1621	1599	1588	1611	1492	1469
Cyclone Exit	731	772	697	550	731	729	756	728	737	750	698	688
Baghouse Inlet	467	382	444	334	350	358	408	410	417	317	320	385
Baghouse Outlet	392	321	365	272	289	311	344	346	356	269	273	326
ID Fan Inlet	316	253	275	196	210	261	296	294	303	234	225	261
Ambient	80	72	67	72	74	72	79	61	73	80	72	80
Air and Gas Pressures												
Primary Air, psia	16.3	16.6	16.6	16.2	16.6	16.1	16.2	16.1	16.3	16.1	16.5	16.4
Secondary Air, psia	14.5	15.0	14.6	14.6	14.8	14.8	14.4	14.8	14.6	15.0	14.8	15.1
Combustor Plenum, psia	78.3	70.7	69.0	58.1	66.0	58.5	57.3	62.3	59.0	57.4	63.8	61.8
Comb. dP, in. H_2O	49.7	43.7	55.9	44.8	29.0	43.3	42.4	38.4	37.9	40.1	40.4	46.2
Downcomer dP, in. H_2O	30.5	51.2	29.1	33.2	25.9	21.2	19.7	12.3	15.4	11.5	14.5	13.2
Cyclone Static, in. H_2O	2.7	2.1	2.0	1.3	2.4	2.0	2.4	2.3	3.5	1.7	2.2	6.0
Baghouse dP, in. H_2O	7.6	4.7	3.3	2.4	3.4	5.5	5.1	4.9	6.0	3.9	4.2	3.3
Baghouse Outlet, psia	12.8	13.5	13.7	14.1	13.5	13.0	12.8	13.5	13.0	13.2	13.5	13.2

to controlling the coal feed rate, the rotary valve serves to isolate the feed hopper from system pressure in the combustor. Isolation is necessary to prevent possible ignition of the coal before it reaches the combustor, as well as to maintain stable feed rates and weigh cell measurements. The horizontal screw feeder conveyed the feed material to a section of 3" pipe, vertical at the top and entering the combustor at an angle of approximately 30° from vertical. Coal and limestone were fed by gravity through this pipe. An air lance was used to assist the flow of material through the angled section of the gravity feed leg.

The limestone, crushed and sized prior to shipping and supplied along with the Salt Creek coal, was transferred to a 1000-pound capacity storage hopper. The configuration of the limestone feed system was identical to the fuel feed side, and metered limestone flowed by gravity to the horizontal screw feeder where it combined with the feed coal. Some minor problems were encountered with the screw feeder due to binding. Additional minor problems arose due to blockage of feed material in the gravity feed leg beneath the auger. A somewhat more persistent problem was encountered with the flow of limestone out of the feed hopper. The crushed limestone had a very high angle of repose which caused frequent "ratholing" and subsequent loss of sorbent feed. As a result, considerable attention had to be paid to the limestone feed hopper to maintain a continuous supply of sorbent to the combustor.

It is not anticipated that there would be any major coal feed problems unless there were significant differences in the surface moisture of the coal tested at the EERC and that used at a commercial plant. Limestone feed may present some problems at a commercial CFB using a feed system similar to that employed at the EERC. However, it is believed that minor design modifications would alleviate the limestone feed problems experienced during the EERC pilot plant test run.

One additional problem which surfaced during the course of testing was blinding of the baghouse bags over time. The combination of a relatively thick layer of ash on the baghouse bags with a high baghouse static pressure resulted in deformation of some of the bag cages and the development of a hole in at least one bag. The observed high pressure drop across the baghouse may be a function of the ash, considering the cohesive nature of the material. This could present problems in a commercial plant, but it is believed that a cage design which provided for more rigid constructions and on-line bag-cleaning procedures would alleviate any baghouse problems encountered during pilot-scale testing at the EERC. Another area of concern with regards to the fly ash is the design of commercial ash-handling systems. Particular attention must be paid to the design of fly ash hoppers to compensate for the cohesiveness of the ash and allow for adequate removal during operation.

The pilot-scale CFB has nineteen thermocouples located along the length of the combustor in nine sections. Also, there are five thermocouples in place along the length of the downcomer. During full-load testing, the temperature distribution throughout the combustor and downcomer was very uniform and, on the average, did not vary by more than 100°F, indicating good solids recirculation within the system. During partial-load tests, the combustor temperature distribution remained fairly uniform. However, temperatures in the downcomer were up to 200°F lower than the highest combustor temperatures, as would be expected due to proportional heat loss through refractory-lined walls.

Collector Performance

Chevron collectors with internal, sloped deflector plates were used in the particulate collection device during this test. The Chevron collectors were designed with an internal opening (drain) which ran vertically along the length of the rear of each collector. The geometry of the collectors was such that incoming solids entrained in the gas stream were forced to the back and downward out the angle of the deflector plates to the drain. Particulates entering the collector drains flowed by gravity into collection hoppers which fed into the downcomer. The particulate collection device housing the chevron collectors had three ducts into which the combustor exited. The main middle duct used during this test was referred to as Duct A, while the outside two ducts were referred to as Ducts B and C. Ducts B and C were designed to be brought on-line, if required, for higher velocity testing. Three stages of collectors were utilized in Duct A during this test. The first two stages are intended to capture the majority of the solids, while the third stage was designed with the intention of capturing smaller particles. The first stage used four chevron collectors, two in each of two rows. The second stage had a total of twelve chevron collectors, four in each of three rows. The third stage had a single row of four chevron collectors using a venturi-type configuration as an inlet to accelerate the flow into them. The Chevron collectors are described in more detail in Appendix F.

At the conclusion of the two weeks of testing, the three sets of collectors were removed for inspection. It appeared that all four collectors in stage one had been operating properly. In the second stage, the four collectors in the back row were plugged with fine bed material, while the first two rows appeared to have been operating with some slight blockages at their top and bottom. The third stage of collectors were entirely plugged with bed material fines. The outer two inlet venturies of Stage three had also warped, blocking much of the flow to the outside collectors. It appears that a combination of factors caused the blinding of the back row of stage two and all of the stage three collectors. All of the stage two and three collectors were one-half the size of the ones used in stage one, resulting in a smaller exit to the collection hoppers. All of the individual collectors that drained onto the back slope of the hopper plugged off. There did not appear to be sufficient spacing between the collector drains and the refractory to allow for a sufficient volume of solids to flow through. The stage three inlet venturies funneled all other remaining fines into four collectors, overloading this stage with more material than could be handled.

Operational temperatures in the downcomer remained high throughout testing, indicating good collector performance even though approximately half of the chevron collectors were plugged for, at least, the latter portion of testing. Use of chevron collectors appears to have resulted in a collector that more closely simulates the operation of a large cyclone collector used for a CFB utility or industrial boiler.

The design used for this test was not able to handle the large amount of recirculating fines. The recycle of the secondary cyclone catch back to the downcomer may have influenced the plugging problems noted above. Some of the plugging problems encountered during this test were specific to the limestone used; it was a smaller size than had been originally specified for operation with this pilot facility and was extremely cohesive.

No problems were encountered with the durability of the chevron collectors. They experienced more than 200 hours of high-temperature exposure at temperatures averaging approximately 1500°F and, on occasion, temperatures approaching 1700°F for short durations of a couple hours. The material of construction was 304 stainless steel. No apparent warpage was present, with many of the sharp edges only slightly dulled. The only damage that occurred was to the one-eighth-inch stainless steel sheet that was used to construct the inlet venturies for the third stage. This appears to be due to a combination of expansion and inadequate strength.

Recirculation Rates and Size Distributions

The solids recirculation rate was determined by calculating the heat balance around the external heat exchanger. The average solids recirculation rates for each test are shown in Table A-5. The recirculation ratio is the ratio of the solids recirculation rate to the input of coal ash and limestone into the combustor. Test 4 had low coal and sorbent feed rates to achieve the 55% load condition; however, the low superficial gas velocity in the combustor produced a very low recirculation rate, with a correspondingly low recirculation ratio.

The cyclone collection efficiency for this unit was very good. The higher the cyclone efficiency, the greater the proportion of material that stays within the system as opposed to escaping to the baghouse. In a commercial combustor, a cyclone collection efficiency of 99.0% to 99.5% or more is required to maintain sufficient solids in the system for stable operation. Consistency in the sulfur emissions, heat-transfer coefficient, and the temperature distribution in the combustor, downcomer, and external heat exchanger indicates uniform mixing and solids distribution throughout the system.

TABLE A-5

Solids Recirculation and Heat-Transfer Data

Test	Temperature (°F)	Ca/S	Excess Air (%)	Primary Air (%)	Solids Recirculation (lb/hr)	DC[1] d_{50} (μm)	H_o[2]	Heat Flux (Btu/hr-ft²)	Cyclone Efficiency (%)	Recirculation Ratio
1	1,607	0.3	20.8	50	7,660	300	19.1	32,600	99.84	202
2	1,613	3.2	21.5	46	12,050	210	22.3	32,700	99.49	227
3	1,559	2.5	23.4	60	8,920	240	20.6	29,100	99.83	202
4	1,351	2.9	54.2	52	2,780	110	14.7	18,200	99.63	91
5	1,476	2.5	43.7	64	14,210	220	20.8	27,600	99.60	326
6	1,478	1.4	17.0	45	9,580	240	20.4	27,500	99.59	196
7	1,630	3.3	18.7	65	10,600	240	23.4	34,800	99.76	225
8	1,615	3.8	40.7	48	7,360	220	20.6	30,500	99.68	149
9	1,596	6.0	46.0	67	8,920	270	22.7	32,900	99.36	170
10	1,617	4.9	20.4	45	9,600	220	19.8	29,300	99.64	172
11	1,485	5.2	17.0	65	12,010	250	20.6	27,400	99.47	198
12	1,470	5.6	45.5	45	13,120	220	19.6	26,000	99.78	254

[1] Downcomer.

[2] Heat-transfer coefficient (Btu/hr-ft²-°F).

The particle-size distributions throughout the run were fairly consistent. Figure A-3 shows the particle-size distributions in the downcomer for Test 1, Test 4, and the average of the remaining tests which were very similar. Test 1 had proportionally larger particles in the downcomer because it was performed early in the run and without limestone addition. Therefore, the bed was composed primarily of coal ash and relatively large-size start-up sand. Limestone was fed during Tests 2 through 12, which resulted in progressively smaller bed particle sizes as the bed turned over from predominantly silica sand and coal ash, to limestone and coal ash. The low velocity of Test 4 prevented larger particles from being carried out of the combustor, giving the smaller particle size shown in Figure A-3. Figure A-4 shows the particle sizes found in the combustor, downcomer, and baghouse during Tests 2 and 4.

Bottom Ash/Total Ash Split

An ash balance for each test period is given in Table A-6. Ash input to the system was composed of calculated quantities of coal ash, limestone ash, secondary cyclone ash, and bed material. The limestone-derived ash was further broken down into estimates of the sorbent which either was calcined or had undergone sulfation. The output of ash from the CFB system consisted of measured quantities of bottom ash (combustor and downcomer bed material), ash removed from the secondary cyclone, and baghouse ash (fly ash).

The ratios of bottom ash-to-total ash, as well as the percent closure, were calculated and are included in Table A-6. The average closure for the entire run was about 84%, but increased to near 90% with Test 1 taken out of the average. It is believed that significant quantities of fly ash were adhering to the bags and hopper in the baghouse during various tests and may not have been properly accounted for during the run, resulting in some relatively high bottom ash-to-total ash ratios.

Coal Ash/Limestone Split

Table A-7 shows the makeup of the bed material, secondary cyclone ash, and baghouse ash, as well as the solids input, based on an aluminum balance. Alumina was used as the tracer, since it makes up about 30% of the coal ash, and is virtually nonexistent in the limestone. This material balance was used to determine the contributions of coal ash and limestone at each solids removal point. Because secondary cyclone ash and bed material were added during some tests, the sum of the coal and limestone input do not always equal 100%. The closure is based on coal ash only. The contribution from the coal was determined by the aluminum material balance, shown in Table A-8, and the total contribution from the limestone and cyclone ash was obtained by difference. In those tests where bed material and/or secondary cyclone ash were added to the system, the calculated coal contribution may be artificially high; there was a high percentage of aluminum in the secondary cyclone ash, and a small amount in the bed material, that was not accounted for in the aluminum balance. The aluminum in the secondary cyclone ash was assumed to be the same as that in the baghouse ash.

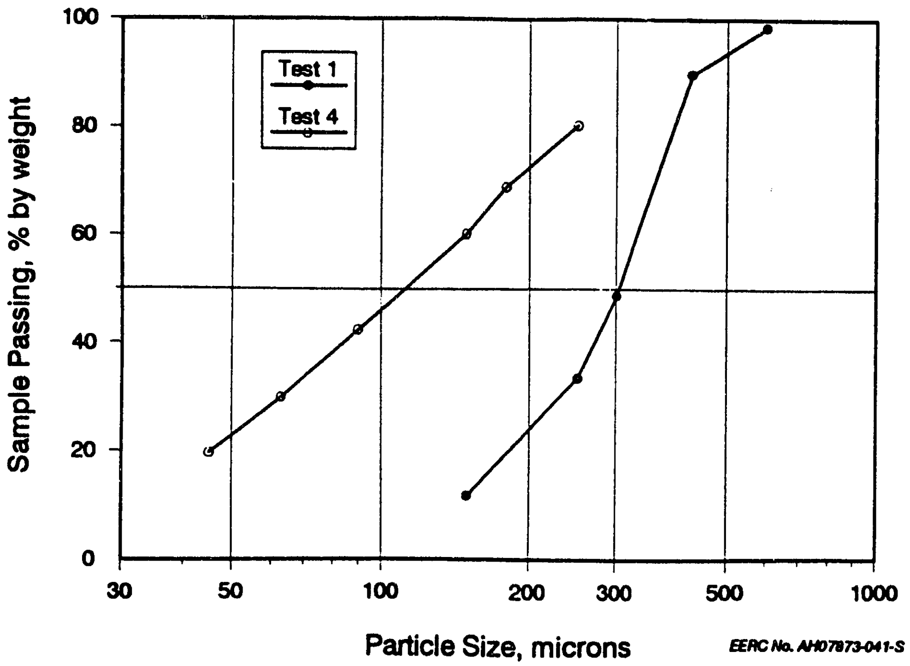

Figure A-3. Particle-size distributions of downcomer material for Tests 1 and 4.

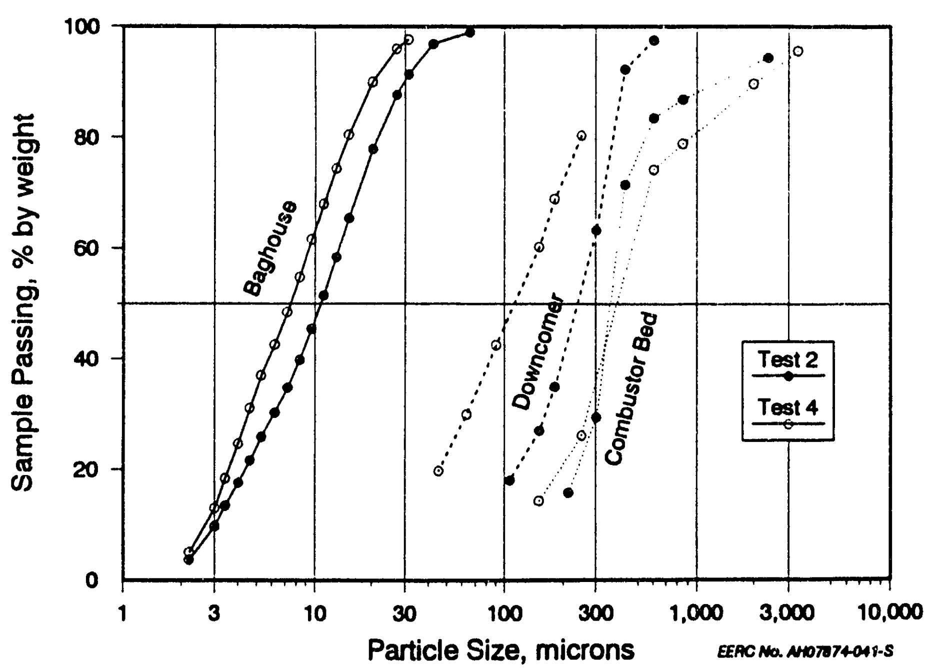

Figure A-4. Combustor, downcomer, and baghouse material particle-size distributions for Tests 2 and 4.

TABLE A-6

Ash Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Input, lb/hr												
Ash	38	44	38	26	37	45	39	40	37	43	44	36
Sorbent*												
CaO	0	4	2	2	3	1	4	4	7	6	7	7
$CaSO_4$	0	3	3	1	2	2	2	2	3	3	4	4
Bed Material	38	12	34	7	13	0	0	0	0	0	0	0
Cyclone Ash	0	24	0	13	0	0	0	0	0	0	0	0
Total Solids In	75	87	77	49	55	48	45	46	47	52	55	47
Output, lb/hr												
Bed Material	0	21	31	21	13	13	0	10	0	10	0	11
Cyclone Ash	0	24	0	0	34	20	5	10	36	8	40	19
Baghouse Ash	12	37	15	10	24	20	21	14	21	26	23	10
Total Solids Out	12	82	46	31	70	53	26	34	57	44	63	40
Closure, %	15.9	94.2	59.5	64.1	127.0	108.3	58.1	72.2	121.1	85.1	114.6	84.1
Bottom Ash/Total Ash, %	0.0	26.1	67.4	67.2	18.5	24.8	0.0	29.9	0.0	22.6	0.0	26.4

* The CaO and $CaSO_4$ mass inputs are included to express sorbent equivalent mass inputs.

TABLE A-7

Material Derived from Coal Ash and Limestone Based on Aluminum Material Balance (%)

	Coal	ls*	Coal	ls	Coal	ls	Coal	ls
	Test 1		Test 2		Test 3		Test 4	
Solids Input	50.28	0.00	50.18	8.01	49.27	6.47	53.30	6.15
Bed Drain	NA	NA	35.60	64.40	37.94	62.06	45.66	54.34
Cyclone Catch	NA	NA	87.38	12.62	NA	NA	NA	NA
Baghouse Catch	97.77	0.00	87.38	12.62	91.96	8.04	95.82	4.18
Closure	30.94		89.12		67.09		50.46	
	Test 5		Test 6		Test 7		Test 8	
Solids Input	67.46	9.04	93.81	6.19	86.54	13.46	87.07	12.93
Bed Drain	48.25	51.75	51.05	48.95	NA	NA	35.78	64.21
Cyclone Catch	80.32	19.68	81.68	18.32	85.99	14.01	92.97	7.02
Baghouse Catch	80.32	19.68	81.68	18.32	85.99	14.01	92.97	7.02
Closure	140.06		85.54		57.76		62.94	
	Test 9		Test 10		Test 11		Test 12	
Solids Input	78.86	21.14	82.67	17.33	80.06	19.94	76.74	23.25
Bed Drain	NA	NA	55.24	44.76	NA	NA	53.61	46.39
Cyclone Catch	74.76	25.24	84.97	15.03	81.76	18.24	87.63	12.37
Baghouse Catch	74.76	25.24	84.97	15.03	81.76	18.24	87.63	12.37
Closure	114.79		80.49		117.05		86.13	

* Limestone.

THERMAL PERFORMANCE

Energy and Material Balances

Fuel and flue gas balances were calculated, and the results are presented in Tables A-9 and A-10, respectively. The theoretical fuel feed rates were calculated using actual fuel characteristics and measured O_2 and CO_2 flue gas concentrations. The theoretical flue gas rates were calculated using the theoretical coal feed rates, coal analyses, and excess air levels. The measured fuel feed rates were all slightly higher than the theoretical values, while the measured flue gas flow rates varied from 6.9% greater to 13.8% less than theoretical.

The energy balances for the twelve tests are presented in Table A-11, both in Btu/hr and as percentages. The energy input was made up of the energy potential of the fuel, the primary and secondary combustion air, the external heat exchanger fluidizing air, the energy released from the sulfation of the sorbent, and the energy available from the unburned carbon present in the ash added back to the system. Measurable heat loss sources were the combustor heat exchange doors, the external heat exchanger cooling coils, the flue gas, the unburned carbon in the ash removed, the heat present in the drained ash, and the energy absorbed during calcination of the sorbent. The unmeasurable heat loss due to convection and radiation was estimated using a correlation

TABLE A-8

Aluminum Material Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Coal Ash Feed Rate, lb/hr	37.92	43.87	38.10	25.97	37.31	45.48	38.58	40.40	37.31	42.95	44.18	36.29
Al_2O_3 in Coal Ash, %	31.40	30.90	31.10	31.10	31.50	33.30	31.40	31.30	31.30	28.60	29.60	29.10
Baghouse Ash Out, lb/hr	12.00	36.98	15.00	10.25	23.50	19.50	20.92	13.50	20.83	26.02	23.00	10.00
Al_2O_3 in Baghouse Ash, %	30.70	27.00	28.60	29.80	25.30	27.20	27.00	29.10	23.40	24.30	24.20	25.50
Ash from Coal, %	97.77	87.38	91.96	95.82	80.32	81.68	85.99	92.97	74.76	84.97	81.76	87.63
Ash from Coal, lb/hr	11.73	32.32	13.79	9.82	18.87	15.93	17.99	12.55	15.58	22.11	18.80	8.76
Cyclone Ash Out, lb/hr	0.00	23.93	0.00	0.00	33.75	20.00	5.00	10.00	36.46	8.16	40.25	19.25
Al_2O_3 in Cyclone Ash, %	0.00	27.00	0.00	0.00	25.30	27.20	27.00	29.10	23.40	24.30	24.20	25.50
Ash from Coal, %	0.00	87.38	0.00	0.00	80.32	81.68	85.99	92.97	74.76	84.97	81.76	87.63
Ash from Coal, lb/hr	0.00	20.91	0.00	0.00	27.11	16.34	4.30	9.30	27.26	6.94	32.91	16.87
Bed Material Out, lb/hr	0.00	21.48	31.00	21.00	13.00	13.00	0.00	10.00	0.00	10.00	0.00	10.50
Al_2O_3 in Bed Material, %	0.00	11.00	11.80	14.20	15.20	17.00	0.00	11.20	0.00	15.80	0.00	15.60
Ash from Coal, %	0.00	35.60	37.94	45.66	48.25	51.05	0.00	35.78	0.00	55.24	0.00	53.61
Ash from Coal, lb/hr	0.00	7.65	11.76	9.59	6.27	6.64	0.00	3.58	0.00	5.52	0.00	5.63
Total Ash from Coal, lb/hr	11.73	60.87	25.56	19.41	52.25	38.90	22.29	25.43	42.83	34.57	51.71	31.26
Closure, %	30.94	138.75	67.09	74.75	140.06	85.54	57.76	62.94	114.79	80.49	117.05	86.13

TABLE A-9

Fuel Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Fuel Feed Rate, meas., lb/hr	226	239	204	133	213	258	237	208	208	245	263	215
Fuel Feed Rate, theor., lb/hr	224	232	201	129	202	238	223	200	200	230	250	202
Difference, %	0.9	2.9	1.7	3.0	5.2	7.7	6.1	3.7	3.7	6.0	5.1	5.9

meas. = Feed rate calculated by linear regression performed on coal feed hopper weight loss over time.
theor. = Theoretical feed rate calculated on the basis of the coal analysis, the combustion air, and the excess air for each test period.

TABLE A-10

Flue Gas Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Flue Gas Flow, meas., scfm	484	497	436	412	600	490	474	520	503	520	620	601
Flue Gas Flow, theor., scfm	551	545	480	387	581	552	532	548	566	550	577	564
Difference, %	-13.8	-9.6	-10.1	5.9	3.2	-12.7	-12.2	-5.4	-12.4	-5.8	6.9	6.2

meas. = The flue gas flow measured during the run through an orifice located just upstream of the ID fan.
theor. = Theoretical flue gas flow calculated on the basis of the coal analysis and the theoretical coal feed rate for each test period.

TABLE A-11

Energy Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Input, Btu/hr												
Coal	2,339,731	2,294,154	1,996,875	1,271,024	2,081,315	2,407,862	2,296,306	2,024,574	2,040,599	2,315,633	2,601,353	2,054,400
Primary Air	123,260	106,355	118,703	51,743	187,102	109,755	179,788	117,030	196,614	108,082	191,643	104,516
Secondary Air	129,595	142,002	78,100	55,503	94,135	145,958	91,494	137,510	88,571	151,672	94,897	141,341
EHX Air	2,348	3,046	2,592	3,068	1,185	2,135	2,224	2,808	2,697	2,877	2,442	2,886
Ash (chem.) *	1,739	364	1,495	968	718	0	0	0	0	0	0	0
Sorbent Sulfation	0	4,153	3,930	2,274	3,697	2,759	3,173	3,155	5,127	4,670	6,151	5,445
Total	2,596,672	2,550,073	2,201,696	1,384,579	2,368,151	2,668,470	2,572,985	2,285,076	2,333,608	2,582,933	2,896,487	2,308,589
Input, percent												
Coal	90.1	90.0	90.7	91.8	87.9	90.2	89.2	88.6	87.4	89.7	89.8	89.0
Primary Air	4.7	4.2	5.4	3.7	7.9	4.1	7.0	5.1	8.4	4.2	6.6	4.5
Secondary Air	5.0	5.6	3.5	4.0	4.0	5.5	3.6	6.0	3.8	5.9	3.3	6.1
EHX Air	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ash (chem.)*	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sorbent Sulfation	0.0	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.2	0.2	0.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Output, Btu/hr												
Flue Gas (sens.)	1,050,433	1,046,155	894,096	624,257	1,013,950	995,720	1,038,901	1,068,724	1,077,220	1,073,862	1,037,880	6995,851
Ash (sens.)	4,929	34,154	18,462	10,752	26,494	19,856	10,814	14,004	23,472	18,268	24,041	14,863
Ash (chem.) *	17,415	46,846	13,700	9,241	34,124	52,568	27,951	9,260	20,156	45,494	58,027	11,411
Combustor	678,548	679,588	604,595	378,895	575,066	571,907	722,880	633,823	684,027	608,517	569,426	540,704
EHX	364,474	287,674	88,448	60,560	305,532	599,535	281,443	88,927	91,504	421,689	748,209	300,730
Sorbent Calcination	0	6,986	4,711	3,409	4,833	2,604	6,565	6,856	11,528	9,805	12,562	11,720
Conduction and Radiation Losses	470,794	473,689	447,626	347,235	407,566	408,532	481,895	474,655	465,484	475,620	411,910	404,671
Total	2,586,593	2,575,092	2,071,638	1,434,349	2,367,566	2,650,722	2,570,447	2,296,249	2,373,392	2,653,255	2,862,056	2,279,949
Output, percent												
Flue Gas (sens.)	40.6	40.6	43.2	43.5	42.8	37.6	40.4	46.5	45.4	40.5	36.3	43.7
Ash (sens.)	0.2	1.3	0.9	0.7	1.1	0.7	0.4	0.6	1.0	0.7	0.8	0.7
Ash (chem.) *	0.7	1.8	0.7	0.6	1.4	2.0	1.1	0.4	0.8	1.7	2.0	0.5
Combustor	26.2	26.4	29.2	26.4	24.3	21.6	28.1	27.6	28.8	22.9	19.9	23.7
EHX	14.1	11.2	4.3	4.2	12.9	22.6	10.9	3.9	3.9	15.9	26.1	13.2
Sorbent Calcination	0.0	0.3	0.2	0.2	0.2	0.1	0.3	0.3	0.5	0.4	0.4	0.5
Conduction and Radiation Losses	18.2	18.4	21.6	24.2	17.2	15.4	18.7	20.7	19.6	17.9	14.4	17.7
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Closure	99.6	101.0	94.1	103.6	100.0	99.3	99.9	100.5	101.7	102.7	98.8	98.8

* The heat of combustion coefficient for pure carbon which was used is an average of values found in the *Standard Handbook for Mechanical Engineers*, Baumeister and Marks (1967) and *Perry's Chemical Engineering Handbook*, Perry et al. (1984).

developed from a number of tests on this unit, relating average combustor temperature to heat loss. Approximately 40% of the heat was removed by the flue gas, while 31% to 46% of the heat was removed through the combustor heat exchange doors and external heat exchanger cooling coils. Average wall losses accounted for about 19% of the total heat loss.

The material balances for the twelve test periods are shown in Table A-12. The material balance closures were generally good, with the greatest deviation from complete closure occurring in Test 1 at 97.6%.

Combustion Efficiency

Combustion efficiencies for all twelve tests are shown in Table A-13. The combustion efficiency calculation is based on the amount of unburned carbon removed in the bottom ash and fly ash as a function of the carbon input as coal feed and bed material addition. The percentage of unburned carbon in each ash stream was calculated as the difference between the loss-on-ignition (LOI) and the carbonate as (CO_2) present in the sample. Results of the unburned carbon calculations are shown in Table A-14.

The combustion efficiencies for Tests 1 through 4 are shown as a function of bed temperature in Figure A-5. Tests 1, 2, and 3 were performed at relatively low levels of excess air (21% - 24%), while the excess air in Test 4 was 54%. Tests 3 and 4 were low load tests, 85% and 55%, respectively. The high calculated combustion efficiency for Test 1 can be attributed in part to the fact that no bottom ash was removed during the test, and the baghouse discharge rate was relatively low. During this test, the unit was operated with a sand bed; limestone feed was not initiated until Test 2.

The expected trend of higher combustion efficiency with higher temperature is not seen for the first 4 tests (see Figure A-5). The average superficial gas velocity for each test is given in Table A-4. In Tests 3 and 4, the gas velocity was decreased from a nominal 16 ft/sec to 13.9 and 10.0 ft/sec, respectively. This impacts the system in two ways. The gas and solids residence times increase with the decrease in velocity. A second effect was a shift in particle-size distribution. As shown in Figure A-4, the size distribution in the downcomer and baghouse shifted to a smaller size for Test 4. The increased gas residence time and the decreased cut point caused an increase in carbon burnout for Tests 3 and 4 that offset the expected temperature effects.

Figures A-6 and A-7 show the impacts of changing bed temperature and velocity on carbon burnout. In Figure A-6 the percentage of unburned carbon in the bed material is plotted as a function of temperature. As expected, the amount of unburned carbon increases as temperature decreases. This would tend to indicate a poorer combustion efficiency at lower temperatures. The opposite trend is noted with the baghouse catch; that is, the low-temperature tests have less unburned carbon in the baghouse catch than the high-temperature tests. However, if one plots the unburned carbon in the baghouse catch versus velocity as in Figure A-7, it can be seen that as the velocity decreases (increased residence time and decreased cut point), the amount of unburned carbon decreases. This would indicate a higher combustion efficiency as velocity decreases. The improved burnout at the lower velocities apparently offset the poorer burnout caused by the lower temperature, with the net effect being no significant difference in carbon burnout for the three load tests.

TABLE A-12

Material Balance

Total Mass Balance	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Input, lb/hr												
Combustion Air	2,225	2,202	1,920	1,536	2,371	2,247	2,160	2,244	2,326	2,239	2,358	2,317
Additional Air	171	171	171	171	171	171	171	171	171	171	171	171
Bed Material	38	12	34	7	13	0	0	0	0	0	0	0
Cyclone Ash	0	24	0	13	0	0	0	0	0	0	0	0
Coal Feed	224	232	201	129	202	238	223	200	200	230	250	202
Sorbent Feed	0	9	6	4	6	3	9	9	15	13	16	15
Total Mass In	2,658	2,651	2,332	1,861	2,764	2,660	2,562	2,624	2,713	2,654	2,795	2,706
Input, %												
Combustion Air	83.7	83.1	82.3	82.6	85.8	84.5	84.3	85.5	85.7	84.4	84.4	85.6
Feed Assist Air	6.4	6.5	7.3	9.2	6.2	6.4	6.7	6.5	6.3	6.5	6.1	6.3
Bed Material	1.4	0.5	1.5	0.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cyclone Ash	0.0	0.9	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coal Feed	8.4	8.8	8.6	6.9	7.3	8.9	8.7	7.6	7.4	8.7	8.9	7.5
Sorbent Feed	0.0	0.3	0.3	0.2	0.2	0.1	0.3	0.3	0.6	0.5	0.6	0.6
Total Mass In	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Output, lb/hr												
Measured Flue Gas	2,269	2,331	2,047	1,919	2,795	2,294	2,224	2,428	2,353	2,439	2,911	2,833
Flue Gas Leaks	313	224	208	-114	-89	291	270	131	292	140	-201	-175
Ash Out:												
Bed Material	0	21	31	21	13	13	0	10	0	10	0	11
Baghouse	12	37	15	10	24	20	21	14	21	26	23	10
Cyclone Ash	0	24	0	0	34	20	5	10	36	8	40	19
Total Mass Out	2,594	2,638	2,300	1,836	2,776	2,638	2,520	2,592	2,703	2,624	2,773	2,698
Output, %												
Measured Flue Gas	87.5	88.4	89.0	104.5	100.7	87.0	88.2	93.7	87.1	93.0	105.0	105.0
Flue Gas Leaks	12.0	8.5	9.0	-6.2	-3.2	11.0	10.7	5.0	10.8	5.3	-7.2	-6.5
Ash Out												
Bed Material	0.0	0.8	1.3	1.1	0.5	0.5	0.0	0.4	0.0	0.4	0.0	0.4
Baghouse	0.5	1.4	0.7	0.6	0.8	0.7	0.8	0.5	0.8	1.0	0.8	0.4
Cyclone Ash	0.0	0.9	0.0	0.0	1.2	0.8	0.2	0.4	1.3	0.3	1.5	0.7
Total Mass Out	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Closure	97.6	99.5	98.6	98.7	100.5	99.2	98.3	98.8	99.6	98.9	99.2	99.7

TABLE A-13

Combustion Efficiency

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Input												
Coal Feed Rate, lb/hr	224.0	232.0	200.5	129.0	202.0	237.6	222.5	200.3	200.4	230.4	249.6	202.3
Coal Carbon, %	60.4	57.7	57.6	57.7	59.6	58.9	59.9	59.9	59.9	59.9	59.9	59.9
Carbon Feed Rate, lb/hr	135.3	133.7	115.4	74.4	120.4	13[illegible]8	133.2	119.9	120.0	137.9	149.4	121.1
Bed Material Add Rate, lb/hr	37.5	12.1	34.2	7.3	13.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Unburned Carbon, %	0.3	0.2	0.3	0.9	0.4	1.2	0.4	0.2	0.1	0.5	0.3	0.2
Bed Carbon Feed Rate, lb/hr	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cyclone Ash Add Rate, lb/hr	0.0	24.4	0.0	12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Unburned Carbon, %	0.04	0.02	0.02	0.09	0.15	0.35	0.15	0.03	0.06	0.17	0.17	0.12
Cyclone Ash Carbon Feed Rate, lb/hr	0.0	0.0	0.0	0.0	0.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Input, lb/hr	135.4	133.8	115.5	74.5	120.4	139.8	133.2	119.9	120.0	137.9	149.4	121.1
Output												
Bottom Ash Discharge Rate, lb/hr	0.0	21.5	31.0	21.0	13.0	13.0	0.0	10.0	0.0	10.0	0.0	10.5
Unburned Carbon, %	0.3	0.2	0.3	0.9	0.4	1.2	0.4	0.2	0.1	0.5	0.3	0.2
Bottom Ash Carbon Discharge Rate, lb/hr	0.0	0.0	0.1	0.2	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Cyclone Ash Discharge Rate, lb/hr	0.0	23.9	0.0	0.0	33.8	20.0	5.0	10.0	36.5	8.2	40.3	19.3
Unburned Carbon, %	0.0	0.0	0.0	0.1	0.2	0.4	0.1	0.0	0.1	0.2	0.2	0.1
Cyclone Carbon Discharge Rate, lb/hr	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.0
Baghouse Discharge Rate, lb/hr	12.0	37.0	15.0	10.3	23.5	19.5	20.9	13.5	20.8	26.0	23.0	10.0
Unburned Carbon, %	10.3	8.9	5.8	4.5	9.9	17.9	9.4	4.7	6.8	12.2	17.6	7.7
Baghouse Carbon Discharge Rate, lb/hr	1.2	3.3	0.9	0.5	2.3	3.5	2.0	0.6	1.4	3.2	4.0	0.8
Total Output, lb/hr	1.2	3.3	1.0	0.7	2.4	3.7	2.0	0.7	1.4	3.2	4.1	0.8
Combustion Efficiency, %	99.09	97.51	99.16	99.12	97.99	97.33	98.51	99.45	98.81	97.66	97.24	99.33

TABLE A-14

Unburned Carbon, %

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Combustor Bed Material												
Unburned Carbon	0.34	0.33	0.40	1.34	0.7	1.49	0.52	0.37	0.25	0.7	0.84	0.78
Carbonate (as CO_2)	0.04	0.43	0.33	1.44	1.13	0.91	0.50	0.61	0.46	0.81	2.01	2.18
Unburned Coal Carbon	0.33	0.21	0.31	0.95	0.39	1.24	0.38	0.20	0.12	0.48	0.29	0.19
Secondary Cyclone Ash												
Unburned Carbon	0.06	0.08	0.05	0.42	0.24	0.44	0.21	0.07	0.1	0.22	0.36	0.42
Carbonate (as CO_2)	0.06	0.21	0.10	1.20	0.32	0.33	0.23	0.14	0.15	0.20	0.68	1.11
Unburned Coal Carbon	0.04	0.02	0.02	0.09	0.15	0.35	0.15	0.03	0.06	0.17	0.17	0.12
Baghouse Ash												
Unburned Carbon	10.34	8.90	5.86	4.82	9.94	17.98	9.48	4.71	6.82	12.24	17.82	7.83
Carbonate (as CO_2)	0.15	0.18	0.07	1.33	0.26	0.13	0.12	0.06	0.21	0.25	0.81	0.56
Unburned Coal Carbon	10.30	8.85	5.84	4.46	9.87	17.94	9.45	4.69	6.76	12.17	17.60	7.68

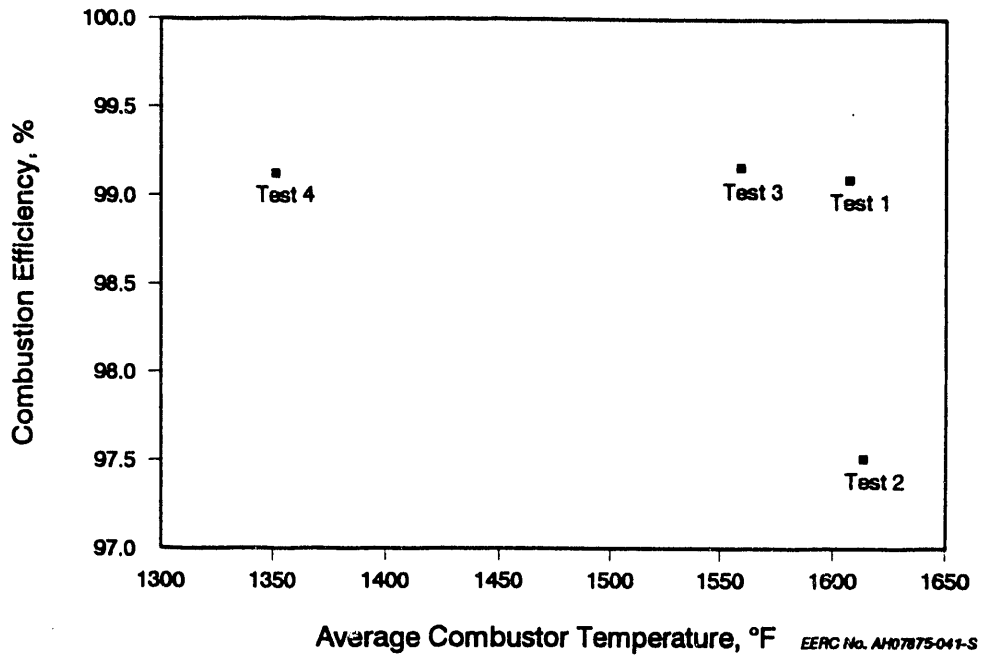

Figure A-5. Combustion efficiencies as a function of average combustor temperature for Tests 1 through 4.

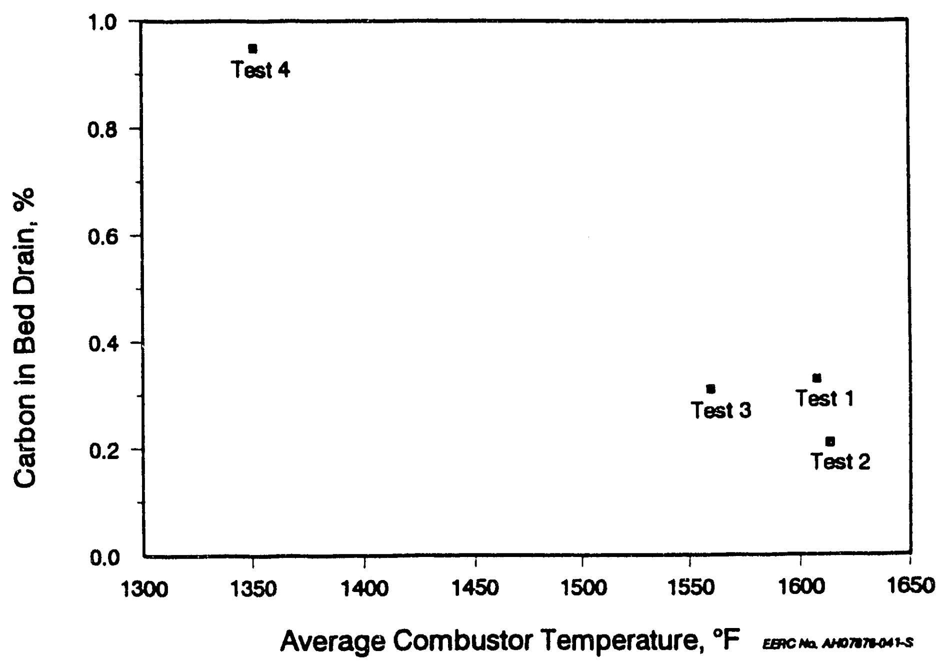

Figure A-6. Percentage of unburned carbon in the combustor bed material as a function of temperature for Tests 1 through 4.

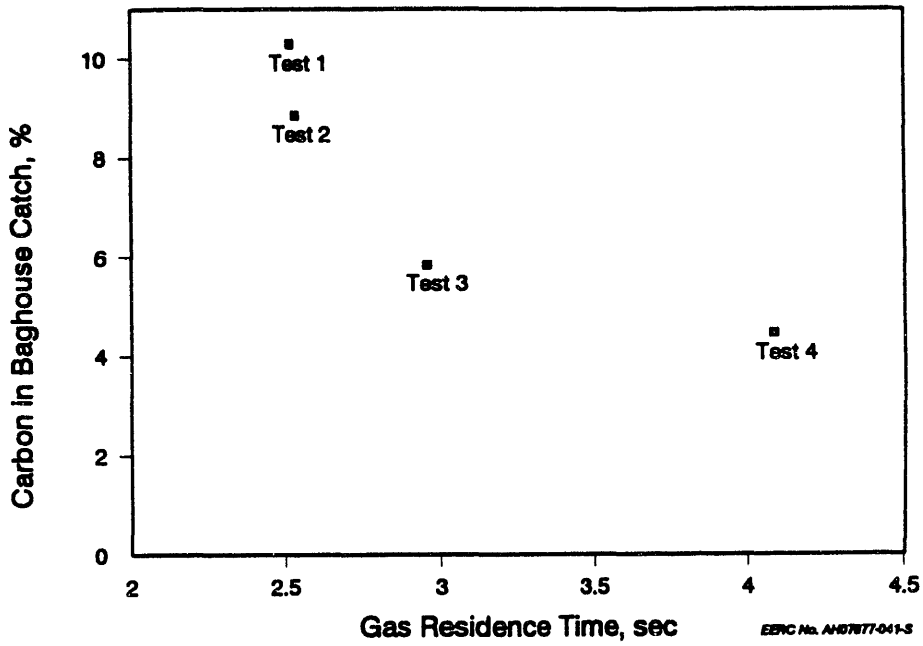

Figure A-7. Percentage of unburned carbon in the fly ash as a function of gas residence time for Tests 1 through 4.

Figure A-8 shows the combustion efficiencies for Tests 5 through 12 as a function of temperature. Combustion efficiency increased with increasing bed temperature and excess air level. The relatively high combustion efficiency in Test 12 may be the result of insufficient bag cleaning at the end of the test, suggested by the low baghouse discharge rate for this test. Figures A-9 and A-10 show the amount of unburned carbon in the bed drain and baghouse catch as a function of temperature for Tests 5 through 12. The percentage carbon in both the bed drain and baghouse catch is higher at the lower temperatures and excess air levels. This is different than that noted for Tests 2 through 4, and reinforces the previous observations of the effect of velocity on carbon burnout and overall combustion efficiency.

Boiler Efficiency

Boiler efficiencies were calculated for each test period using a modified version of ASME PTC 4.1. The modifications to PTC 4.1 are those recommended in EPRI's "Atmospheric Fluidized-Bed Combustion Performance Guidelines." Basically, the modification is a method to account for heat losses and gains associated with calcination and sulfation of the sorbent.

Table A-15 summarizes the results of the boiler efficiency calculations. For each test, boiler radiation and convective losses were assumed to be 0.4% of the heat input from the coal. While these losses were actually much greater for the EERC pilot plant, 0.4% was chosen to be representative of a full-scale system. An exit gas temperature of 300°F was used in the calculations.

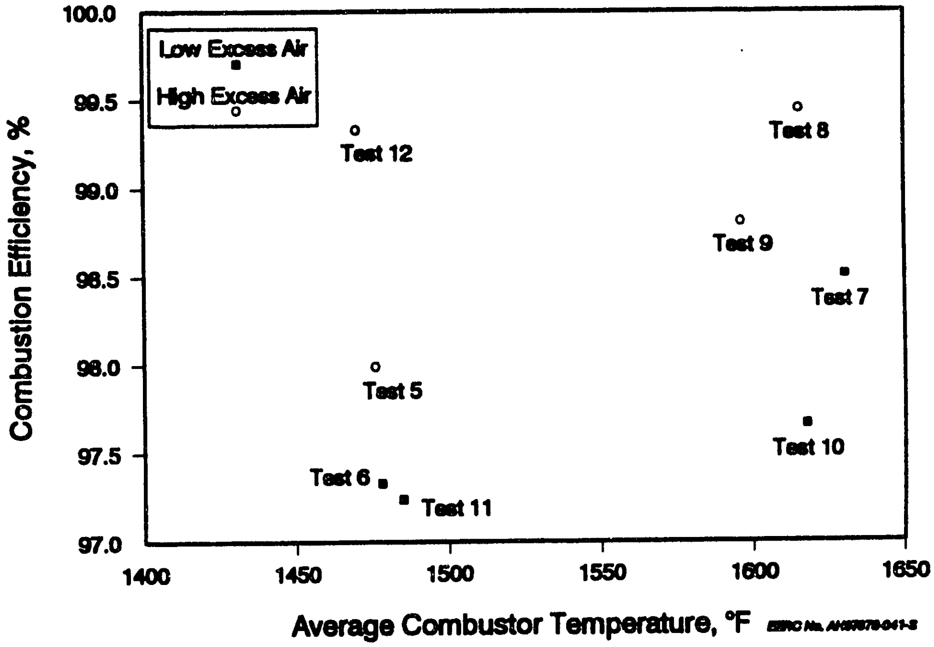

Figure A-8. Combustion efficiencies as a function of temperature for Tests 5 through 12.

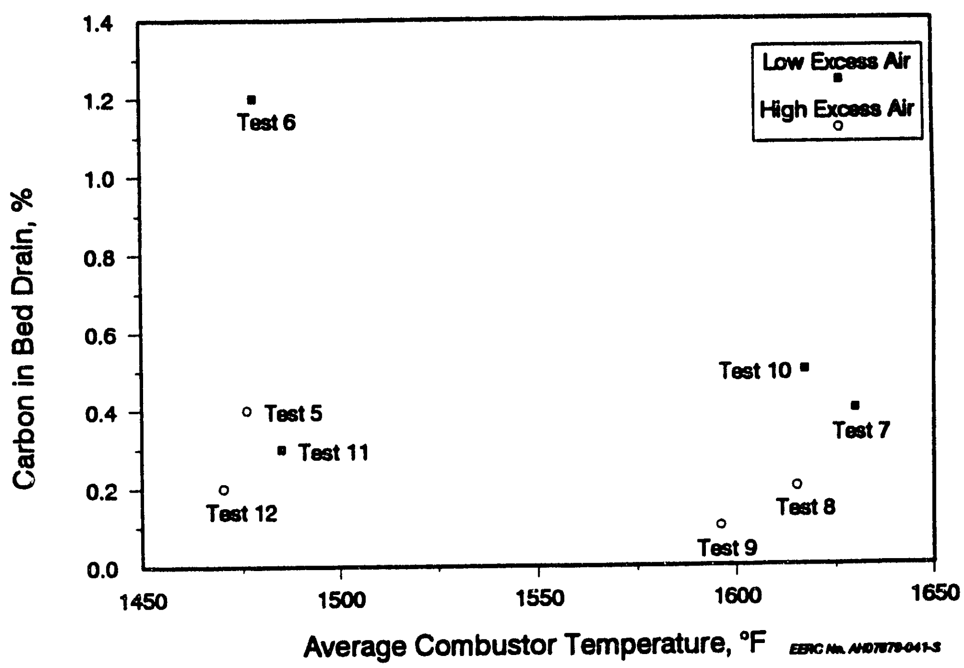

Figure A-9. Percentage of unburned carbon in the bed material drain as a function of temperature for Tests 5 through 12.

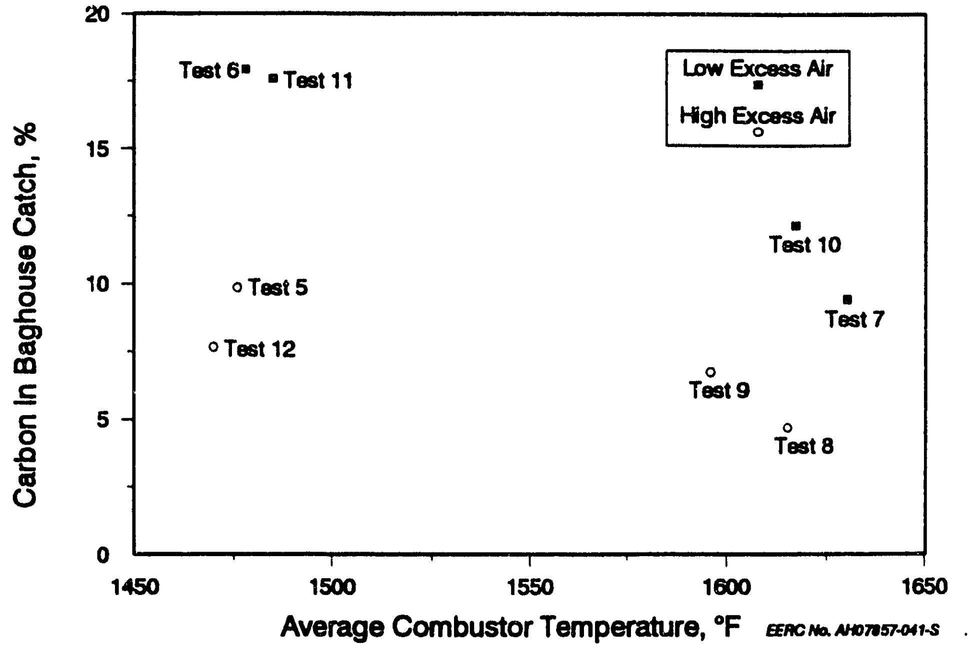

Figure A-10. Percentage of unburned carbon in the fly ash as a function of temperature for Tests 5 through 12.

The boiler efficiencies for all twelve tests were close to 90%, even under low-load conditions in Test 4. The greatest loss were in the dry flue gas (5.4% to 7.6%). Depending on the test, the water in the fuel, unburned carbon in the ash, or hot solids removal was the next largest contributor to boiler efficiency loss. The combustion of fuel hydrogen, sorbent calcination and sulfation, and, of course, radiation and convection losses were fairly consistent for all twelve tests.

Heat-Transfer Coefficient and Heat Flux

During testing, the combustor heat exchange surface used for heat removal included the doors in Sections 2, 3, 4, 6, 7, and 8. Flow rates and the temperatures of the cooling water used in these heat exchange surfaces was monitored to allow the calculation of heat-transfer coefficients and heat flux as a function of position in the combustor. In the external heat exchanger, the number of cooling coils used to control the temperature ranged from 1 to 11. Heat-transfer coefficient and heat flux are calculated for the EHX as a whole. The average values of heat-transfer coefficient and heat flux for each combustor section which contains one or more heat exchange doors, and for the external heat exchanger, have been calculated for each of the twelve tests and are presented in Tables A-16 and A-17. Table A-18 presents the average heat-transfer coefficient and heat flux for all twelve tests, along with the average pressure drop across combustor Sections 2, 4, 6, and 8. These data are also summarized in Table A-5 to help facilitate comparison to test conditions. The average heat flux for the Colorado Ute Nucla Station is in the range of 31,700 to 33,900 Btu/hr-ft^2 at full load and 21,200 to 23,400 Btu/hr-ft^2 at low load. For the twelve tests reported here, the heat flux in the combustor ranged from about 26,000 to 34,750 Btu/hr-ft^2 for full-load tests and about 18,200 Btu/hr-ft^2 at 55% load; in the external heat exchanger, full-load heat flux ranged from about 88,800 to 127,900 Btu/hr-ft^2, and the 55% load test has an EHX heat flux of 80,750 Btu/hr-ft^2.

TABLE A-15

Boiler Efficiency

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Assumed Flue Gas Exit Temperature, °F	300	300	300	300	300	300	300	300	300	300	300	300
Losses, Btu/hr												
Dry Gas	137,704	141,533	127,546	100,302	148,802	143,094	133,854	149,061	146,778	137,936	150,416	143,123
Water in Fuel	18,150	21,839	18,635	11,529	16,368	22,083	20,680	17,901	19,581	21,689	23,496	19,043
Comb. of Fuel Hydrogen	12,076	11,230	9,971	6,666	10,818	11,646	11,065	9,706	8,976	11,180	11,368	9,648
Unburned Carbon	17,415	46,846	13,700	9,241	34,124	52,568	27,951	9,260	20,156	45,494	58,027	11,411
Sorbent Calcination	0	6,986	4,711	3,409	4,833	2,604	6,565	6,856	11,528	9,805	12,562	11,720
Radiation and Convection*	9,464	9,292	8,087	5,148	8,420	9,749	9,296	8,195	8,262	9,377	10,527	8,318
Discharged Solids	4,929	34,154	18,462	10,752	26,494	19,856	10,814	14,004	23,472	18,268	24,041	14,863
Sorbent Sulfation	0	-4,153	-3,930	-2,274	-3,697	-2,759	-3,173	-3,155	-5,127	-4,670	-6,151	-5,445
Total Loss, Btu/hr	199,739	267,728	197,181	144,772	246,163	258,841	217,051	211,827	233,626	249,079	284,287	212,680
Losses, %												
Dry Gas	5.8	5.9	6.2	7.6	6.7	5.4	5.4	6.9	6.8	5.4	5.5	6.4
Water in Fuel	0.8	0.9	0.9	0.9	0.7	0.8	0.8	0.8	0.9	0.8	0.9	0.8
Comb. of Fuel Hydrogen	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Unburned Carbon	0.7	2.0	0.7	0.7	1.5	2.0	1.1	0.4	0.9	1.8	2.1	0.5
Sorbent Calcination	0.0	0.3	0.2	0.3	0.2	0.1	0.3	0.3	0.5	0.4	0.5	0.5
Radiation and Convection*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Discharged Solids	0.2	1.4	0.9	0.8	1.2	0.8	0.4	0.6	1.1	0.7	0.9	0.7
Sorbent Sulfation	0.0	-0.2	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2
Total Loss, %	8.4	11.2	9.6	10.9	11.1	9.8	8.8	9.8	10.8	9.7	10.3	9.5
Boiler Efficiency	91.6	88.8	90.4	89.1	88.9	90.2	91.2	90.2	89.2	90.3	89.7	90.5

* Assumes 0.4% radiative and convective losses.

TABLE A-16

Individual Heat-Transfer Coefficients, Btu/hr-ft^2-°F

Combustor Section	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12	Average	Combustor Height
2	36.9	34.6	35.6	20.4	28.9	31.9	34.0	28.6	32.0	25.8	28.9	29.5	30.6	7.5
3	27.0	27.8	22.7	16.1	23.7	21.9	25.9	22.1	26.1	23.1	24.1	22.8	23.6	12.5
4	19.2	19.0	18.7	14.2	19.8	18.6	22.6	18.5	20.9	19.2	18.7	17.4	18.9	17.5
6	19.6	20.7	18.7	14.7	19.0	19.1	20.9	18.9	21.2	19.7	19.8	16.5	19.1	27.5
7	17.9	19.3	17.3	13.7	19.8	19.6	22.8	20.0	22.1	20.0	19.7	17.9	19.2	32.5
8	19.1	20.3	17.7	14.7	20.9	17.9	21.3	19.2	21.9	19.4	22.2	18.0	19.4	37.5
Overall	22.3	22.3	20.6	14.7	20.8	20.4	23.4	20.6	22.7	19.8	20.6	19.6	20.7	
EHX	101.4	98.7	91.6	83.8	82.5	81.0	93.9	87.9	89.4	90.3	83.4	86.9	89.2	

TABLE A-17

Individual Heat Flux, Btu/hr-ft^2

Combustor Section	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12	Average	Combustor Height
2	53,646	50,739	49,879	25,029	38,457	41,966	49,946	42,125	46,299	38,305	38,488	38,817	42,808	7.5
3	39,687	40,489	32,966	20,772	32,261	30,180	38,849	33,182	38,243	34,692	32,547	30,531	33,700	12.5
4	28,489	28,317	26,795	17,981	26,484	25,405	33,556	27,542	30,335	28,518	25,528	23,482	26,869	17.5
6	28,890	30,449	26,475	18,535	25,405	26,236	31,366	28,091	30,784	29,001	26,540	22,008	26,982	27.5
7	26,198	28,386	24,419	17,059	26,270	26,308	33,821	29,329	31,567	29,255	26,272	23,636	26,877	32.5
8	27,761	29,975	25,040	18,118	27,198	25,093	32,216	28,805	31,869	29,001	29,721	24,298	27,425	37.5
Overall	32,623	32,672	29,067	18,216	27,647	27,496	34,754	30,472	32,886	29,256	27,376	25,995	29,038	
EXH	121,491	127,855	117,931	80,747	101,844	88,820	125,086	118,569	122,005	112,450	90,692	100,243	108,978	

TABLE A-18

Average Heat-Transfer Coefficient, Heat Flux, and Bed Density

Section	dP (in. H_2O col.)	H_o (Btu/hr-ft^2-°F)	Flux (Btu/hr-ft^2)	Bed Density (lb/ft^3)
2	38.6	30.6	38,900	40.32
4	3.2	18.9	24,300	1.67
6	1.5	19.0	24,400	0.78
8	0.2	18.4	22,400	0.10
1-8	44.2	20.7	26,400	

One of the expected trends is the decrease in heat-transfer coefficient and heat flux as a function of height (see Figures A-11 and A-12). The overall mass density of bed material in the combustor decreases with combustor height. The decrease in pressure drop with combustor height provides a measure of this decrease in mass density. At the bottom of the combustor, below the secondary air port, there is a relatively dense bed, and high heat fluxes and heat-transfer coefficients similar to those of bubbling beds are present. In the higher velocity region above the secondary air ports, the bed is less dense. This transition from a dense to a dilute bed is common for all CFBCs, irrespective of the type and location of secondary air ports, or if secondary air is used at all. The transition point from dense to dilute bed will change somewhat, however, depending upon the design of the unit. The heat flux and heat-transfer coefficients are expected to follow a similar trend for all units.

The impact of operating conditions on heat transfer can be seen by comparing values from test to test. As load is decreased, the velocity also decreases, causing a decrease in solids recirculation rate and a decrease in the density within the upper regions of the bed. As expected, both the combustor heat flux and heat-transfer coefficients decrease, as shown graphically in Figures A-11 and A-12, respectively, for full and 55% load situations. Another expected trend is the impact of operating temperature on heat flux. As shown in Figure A-13, the heat flux increases as the average-bed temperature (driving force for heat transfer) increases. The heat-transfer coefficient did not vary with temperature over this range of test conditions.

Other conditions appear to have smaller impacts on the heat flux and heat-transfer coefficients. It should be noted that the differences measured were within the standard deviation of the averages and, therefore, may not be statistically significant. As the Ca/S was increased from an average of 2.1 to 4.0, the heat flux and heat-transfer coefficient decreased. It would be expected that as the limestone feed rate increased, the amount of fine solids would increase, thereby increasing the solids recirculation rate, and increase the heat flux and heat-transfer coefficient. Therefore, this effect may be due to random error in measurement. The other effect noted was a slight increase in the heat flux and heat-transfer coefficient as the primary-to-total air split was increased from an average of 48% to 67%. This could be a real effect, resulting from more solids in the primary zone being carried into the upper reaches of the combustor as the amount of primary air increased. Higher velocities exist in the primary zone at higher primary air ratios.

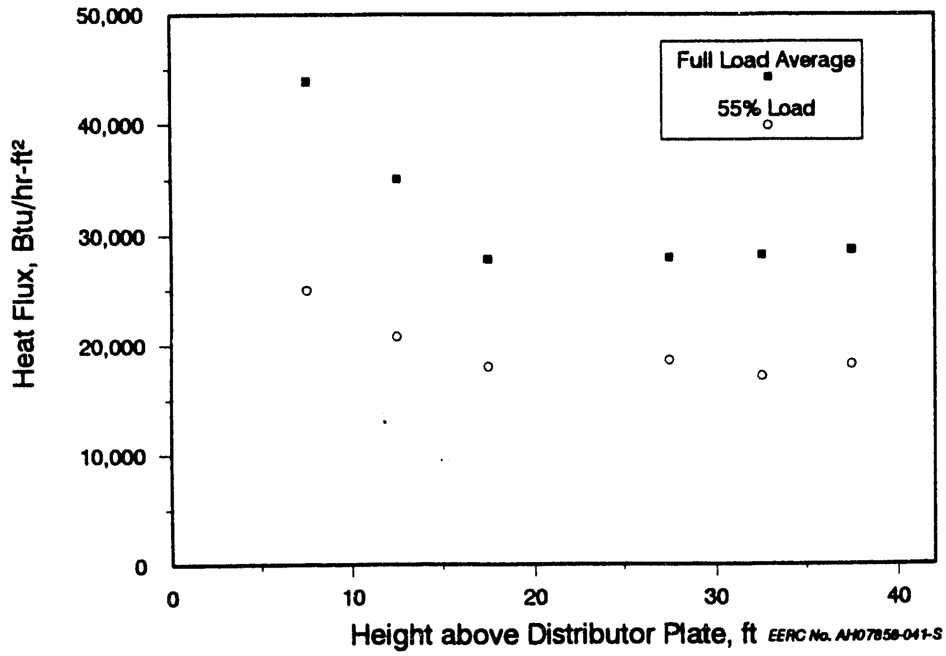

Figure A-11. Heat flux as a function of combustor height.

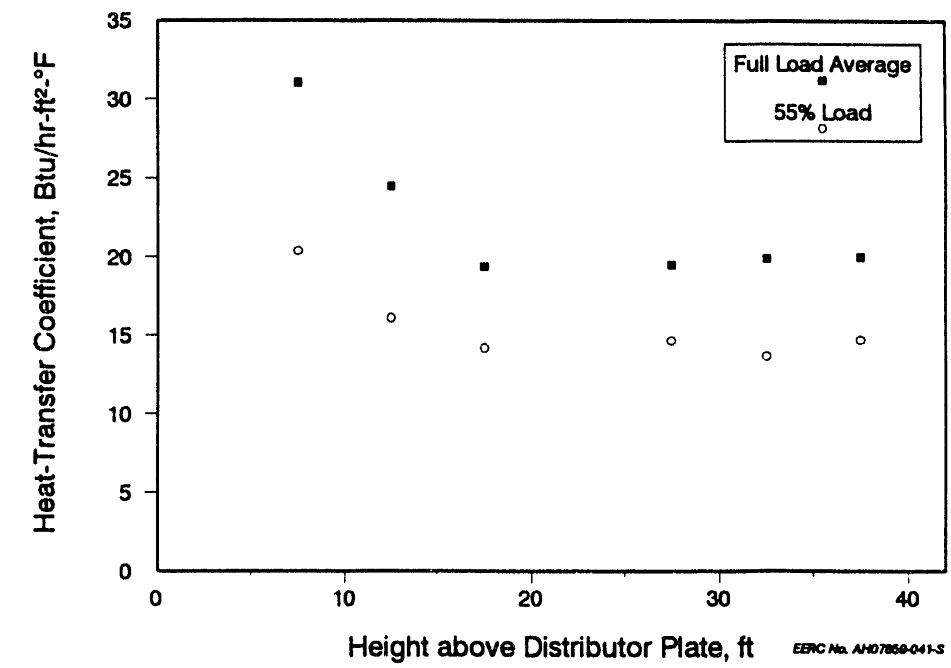

Figure A-12. Heat-transfer coefficient as a function of combustor height.

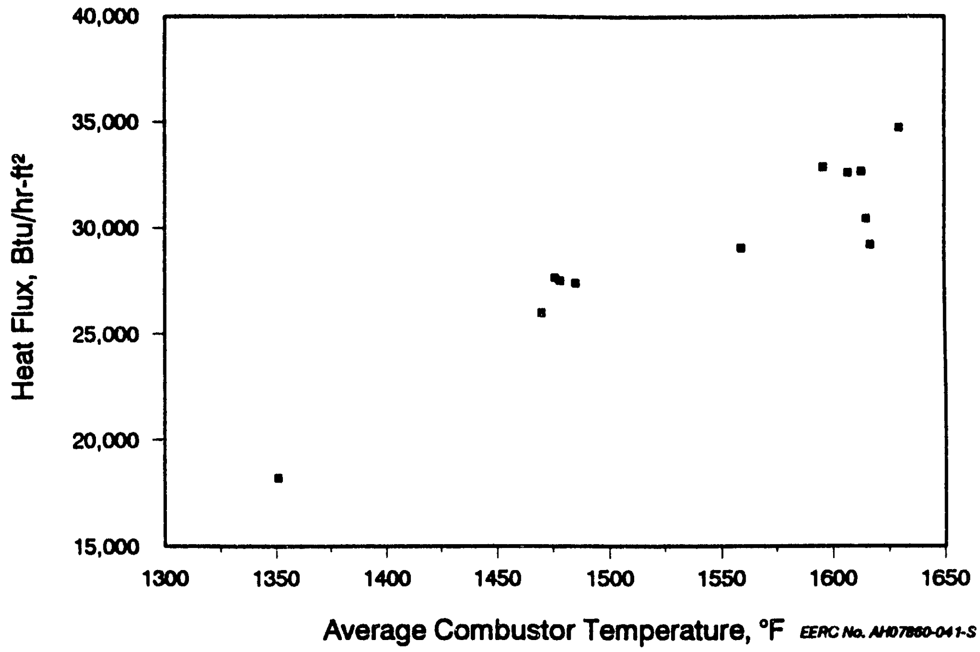

Figure A-13. Heat flux as a function of average bed temperature.

Pressure and Temperature Profiles

The pressure profiles for the run are shown in Figures A-14 and A-15 and are typical of a circulating fluidized-bed combustor. The figures show a dense phase in the lower portion of the combustor, similar to a bubbling bed, and a dilute phase in the remainder of the combustor. Variations in the pressure profiles from test to test are due to differences in bed inventory and combustor velocity.

Figure A-16 illustrates the temperature profile for the Salt Creek run. The temperature profiles are relatively uniform; areas of lower temperature are caused by heat-transfer doors in those sections of the combustor.

ENVIRONMENTAL PERFORMANCE

The flue gas emissions for each test period are shown in Table A-19. Figure A-17 shows the average emission levels at different load conditions. Reduced load was obtained by decreasing the coal feed rate to 85% or 55% of the full-load feed rate. Heat exchange surfaces in the combustor and external heat exchanger remained constant, so that the temperature in the partial-load conditions dropped accordingly. Excess air (54%) was allowed to increase during the 55% load test. Furthermore, superficial gas velocity in the combustor decreased, as a result of lower air flow rates and lower combustor temperatures. The N_2O emissions were highest at the 55% load condition, as expected; the formation of N_2O is inversely proportional to temperature and directly proportional to excess air. NO_x showed the opposite trend, but to a lesser degree. In terms of the three load tests, the SO_2 emissions were lowest during the 85% load test, when the average temperature was 1559°F. Calcium utilization was greatest at this temperature, as shown in Table A-19.

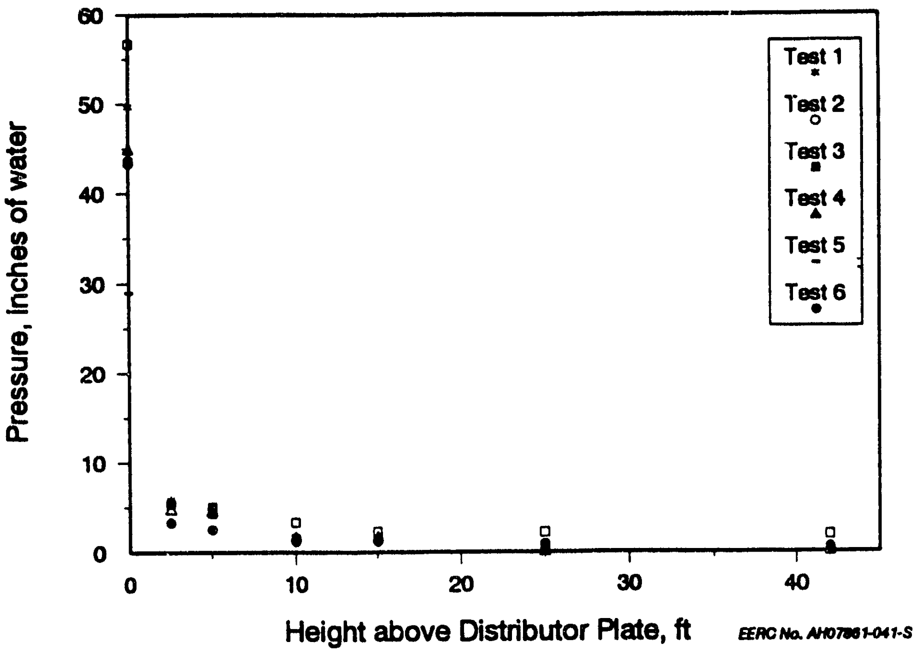

Figure A-14. Pressure profiles of Tests 1 through 6.

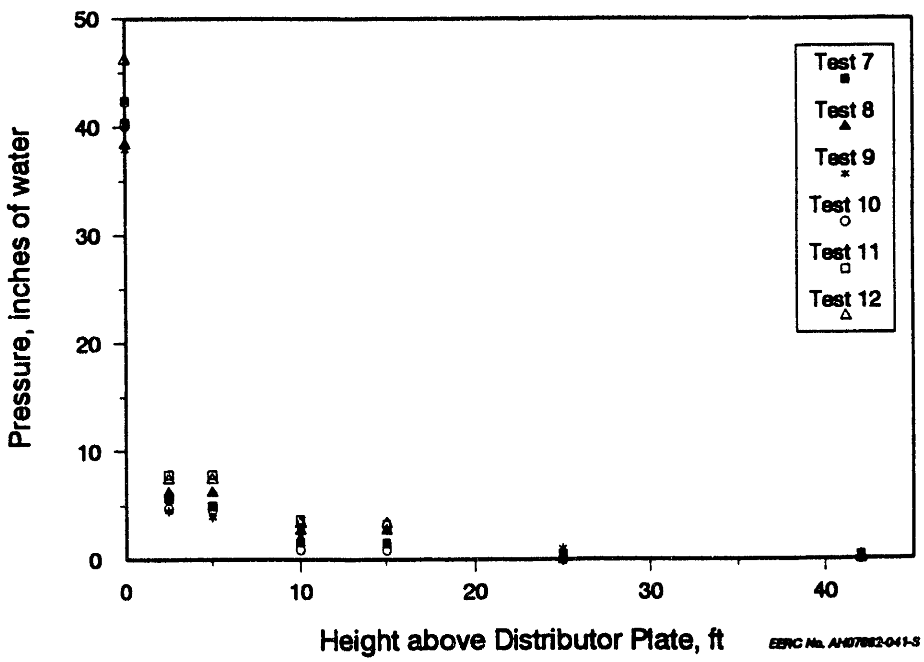

Figure A-15. Pressure profiles of Tests 7 through 12.

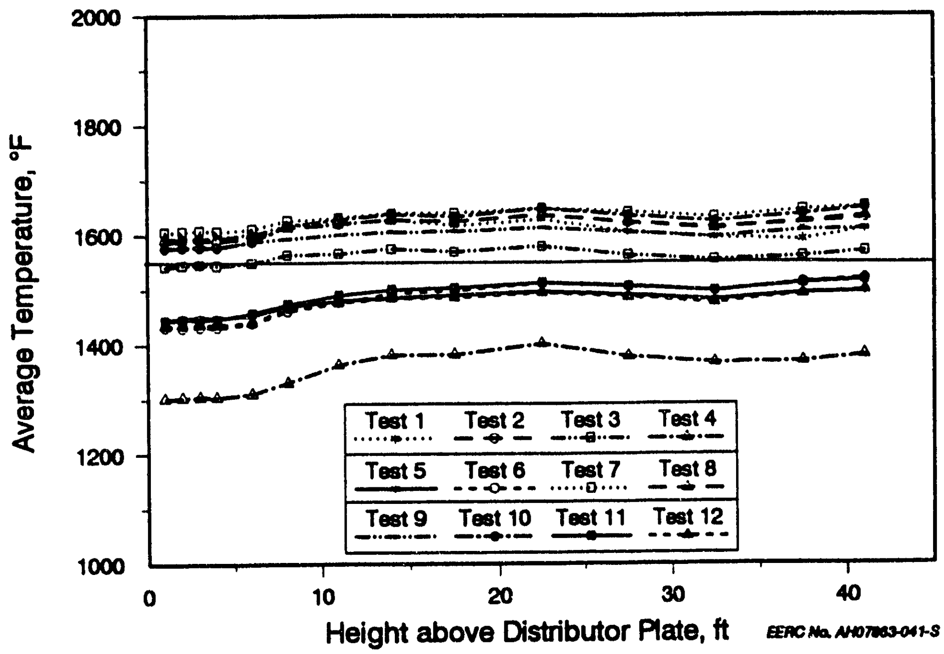

Figure A-16. Temperature profiles of all tests (1 through 12).

SO_2 Emissions

Figure A-18 shows SO_2 retention as a function of alkali-to-sulfur (A/S) ratio for full-load Tests 1, 2, and 10, presented as both alkali in the limestone alone as well as total alkali content. These three tests were performed at the same bed temperature, excess air level, and primary air split. SO_2 retention increased with greater alkali addition. In order to achieve 70% retention, an added A/S ratio of about 2.5 would be required at these operating conditions. The average bed temperature of 1625°F used for these tests is above the optimal temperature window for sulfur capture (1500° to 1550°F). Therefore, lower add rates of sorbent would be needed to meet 70% retention within the optimal sulfur capture window. About 7% to 10% of the sulfur retention was due to the alkali inherent to the coal.

Figure A-19 presents the sulfur retention as a function of total alkali-to-sulfur ratio for all of the tests, with the exception of the 55% load test. The increase in sulfur retention with increasing A/S ratio is evident. Also important is the effect of temperature on sulfur retention. At a given A/S ratio, the lowest retention was obtained at 1613°, higher at 1417°, and the highest at 1559°F. This trend is as expected, as the optimal sulfur capture is usually achieved in the range of 1500° to 1550°F. The impact of alkali-to-sulfur ratio and temperature on SO_2 emissions is shown in Figure A-20.

Figure A-21 shows that the calcium utilization was greatest at a low calcium-to-sulfur ratio, decreased as Ca/S ratio was increased to about 3.0, then leveled off at a calcium utilization of about 20% with increasing Ca/S. This is the normal trend for any calcium-based sulfur control system. At low Ca/S ratios, only a portion of the sulfur is captured, so there is a relatively high driving force. As the Ca/S ratio increases, more sulfur is captured and less is available in the gas stream for capture, thereby reducing the sulfur concentration driving force.

TABLE A-19

Emissions Data

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
O_2, %	3.65	3.76	4.00	7.40	6.44	3.11	3.35	6.12	6.65	3.60	3.10	6.63
CO Content, ppm	11	10	13	42	12	26	11	7	7	8	2	15
CO Content,[1] ppm	12	10	14	55	15	26	11	9	9	8	2	18
CO Emission, lb/MM Btu	0.009	0.008	0.011	0.044	0.012	0.022	0.009	0.007	0.007	0.007	0.902	0.015
CO_2 Content, %	15.9	15.7	16.2	12.8	13.3	15.7	16.0	13.8	13.5	15.9	16.0	13.0
CO_2 Content,[1] %	16.5	16.4	17.1	17.0	16.4	15.8	16.3	16.7	16.9	16.5	16.1	16.3
NO_x Content, ppm	137	150	110	39	75	31	113	161	216	139	55	123
NO_x Content,[1] ppm	142	157	116	51	92	32	116	194	271	144	56	154
NO_x Emission, lb/MM Btu	0.188	0.211	0.148	0.067	0.123	0.044	0.155	0.253	0.350	0.194	0.075	0.206
N_2O Content, ppm	145	136	180	325	251	217	112	120	135	120	222	232
N_2O Content,[1] ppm	150	142	191	430	310	218	115	146	169	124	223	290
N_2O Emission, lb/MM Btu	0.190	0.183	0.233	0.536	0.395	0.289	0.147	0.182	0.208	0.159	0.287	0.371
SO_2 Content, ppm	511	173	133	139	136	210	223	162	21	91	45	35
SO_2 Content[1], ppm	530	181	141	184	168	211	227	196	26	94	45	44
SO_2 Emission, lb/MM Btu	0.978	0.338	0.251	0.334	0.311	0.408	0.424	0.356	0.047	0.176	0.084	0.082
SO_2 Retention,[2] %	0.9	67.7	75.9	67.8	68.9	60.2	57.8	64.8	95.3	82.9	91.5	92.0
Ca/S ratio (ls[3] only)	0.0	2.7	2.1	2.4	2.2	1.1	2.9	3.4	5.6	4.1	4.9	5.1
Ca/S ratio (total)	0.3	3.1	2.4	2.8	2.5	1.4	3.2	3.7	5.9	4.8	5.2	5.5
Ca Utiliz. (ls[3] only)	0.0	24.9	36.7	27.8	31.9	54.0	20.2	19.1	17.1	20.1	18.8	18.0
Ca Utiliz. (total)	2.7	21.8	31.2	24.1	27.6	42.3	17.8	17.3	16.2	17.2	17.7	16.8
Alkali-to-Sulfur (total)	0.41	3.15	2.52	2.81	2.49	1.58	3.31	3.90	5.92	4.82	5.17	5.47
Alkali Utilization (total)	2.1	21.5	30.1	24.1	27.6	38.2	17.5	16.6	16.1	17.2	17.7	16.8
Avg. Comb. Temp., °F	1607	1613	1559	1351	1476	1478	1630	1615	1596	1617	1485	1470
Moisture in FG, vol%	8.2	7.9	7.9	6.9	7.3	8.0	7.9	7.0	6.5	7.8	7.6	6.8
Moist-Free Coal Carbon, %	64.8	62.6	62.4	62.4	63.9	63.8	64.9	62.9	63.9	64.0	64.9	63.8
Moist-Free Coal Sulfur, %	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6

[1] Corrected to 3% O_2.
[2] Moisture-free coal carbon and sulfur values used in the sulfur retention calculation.
[3] Limestone.

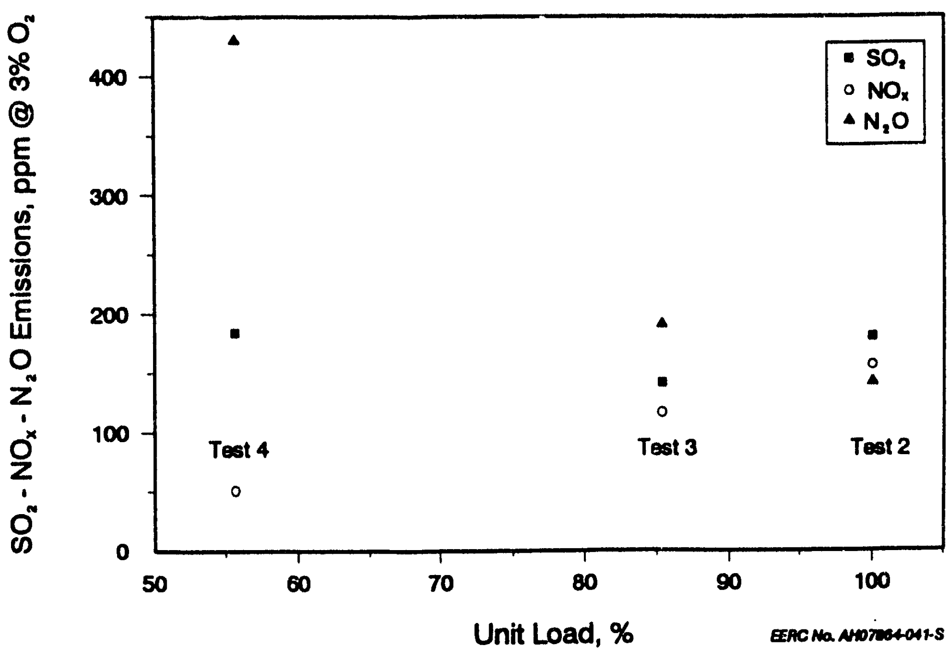

Figure A-17. Flue gas emissions as functions of load.

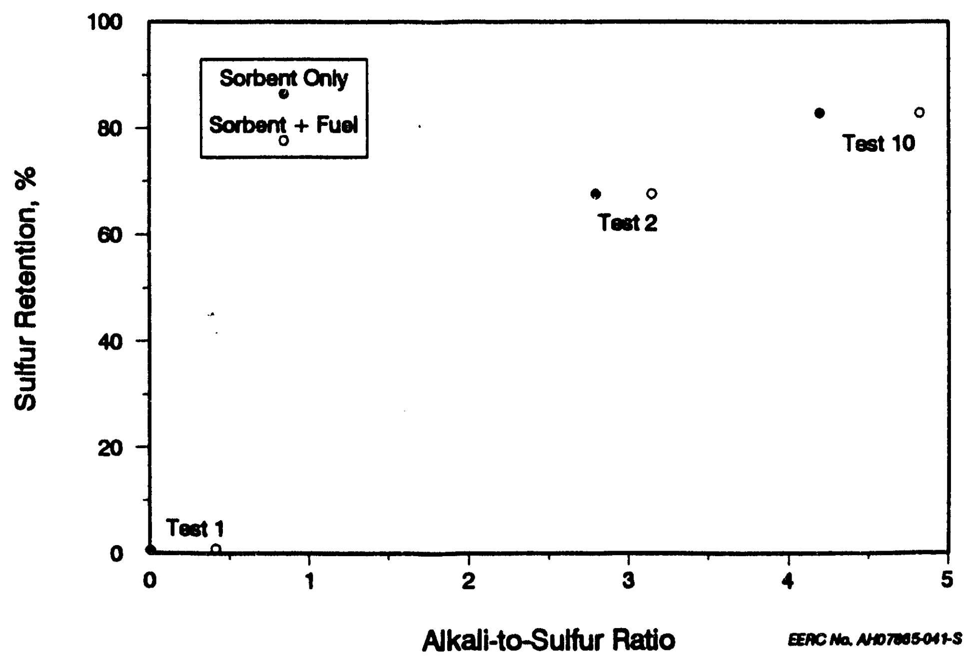

Figure A-18. SO_2 retention as a function of alkali-to-sulfur ratio for Tests 1, 2, and 10.

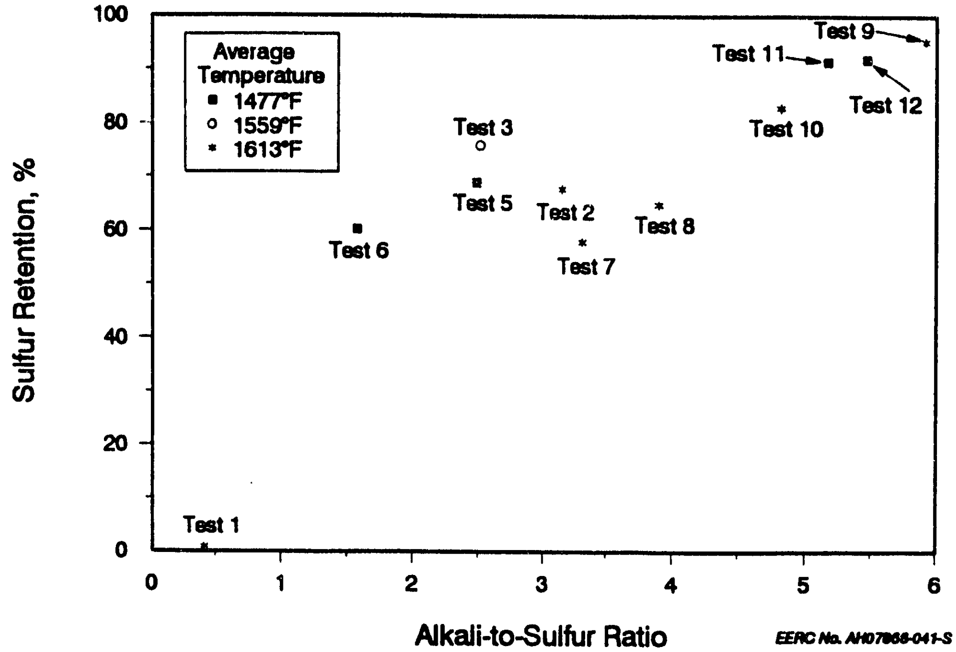

Figure A-19. Sulfur retention as a function of total alkali-to-sulfur ratio for all tests except the 55% load test.

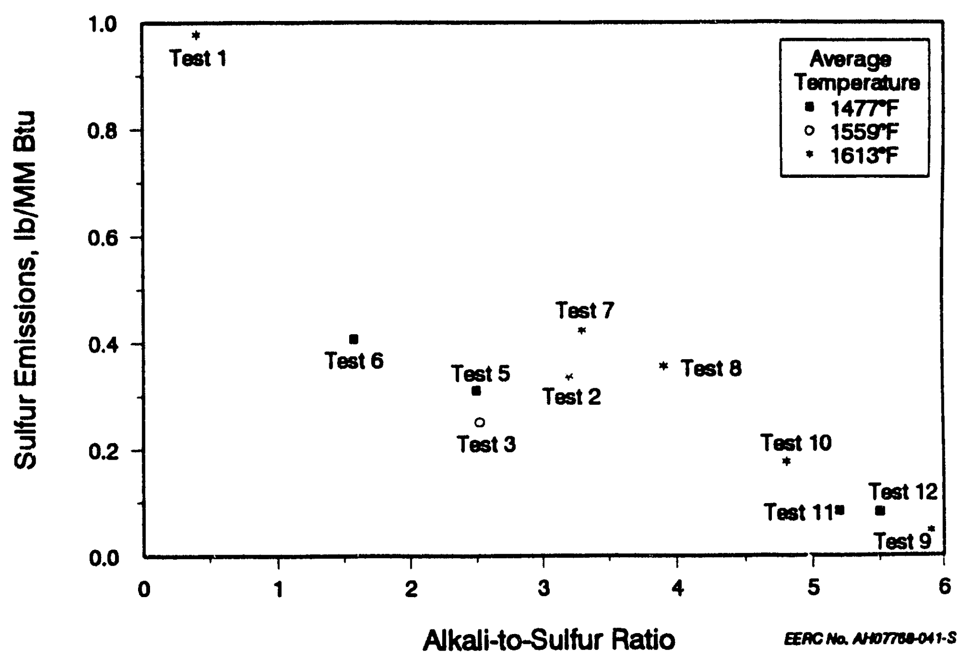

Figure A-20. Impact of alkali-to-sulfur ratio and temperature on sulfur emissions.

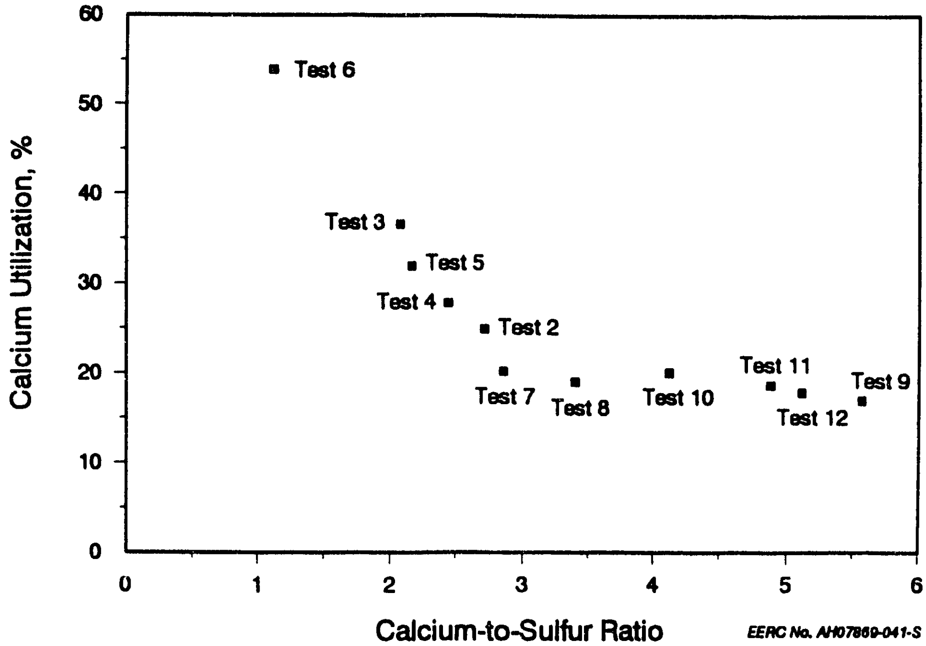

Figure A-21. Calcium utilization as a function of added calcium-to-sulfur ratio.

NO_x Emissions

NO_x emissions ranged from 32 to 271 ppm (0.04 to 0.35 lb/MM Btu), corrected to 3% O_2. NO_x emissions are dependent upon several factors, including temperature, oxygen content, and alkali-to-sulfur ratio. Figure A-22 shows some of these effects. At low temperature and low excess air (oxygen content), the NO_x levels were predictably low. NO_x increased with an increase in temperature and/or an increase in excess air. High temperature and high excess air produced the greatest NO_x emissions. In each temperature-excess air system, more NO_x was released at the higher calcium-to-sulfur ratio. These trends are similar to those produced in other FBC systems, both bubbling and circulating designs.

N_2O Emissions

N_2O emissions were greatest at low temperature, as shown in Figure A-23. The effect of excess air on N_2O emissions is negligible at high temperature (greater than 1500°F); however, at lower temperature, the N_2O emissions are significantly greater at the higher level of excess air. This trend is evident at a temperature of approximately 1475°F in Figure A-23, although the test matrix did not include a low temperature (1350°F)-low excess air (20%) operating condition to verify the trend. Values of N_2O, corrected to 3% O_2, ranged from 115 to 430 ppm (0.15 to 0.54 lb/MM Btu). Currently, there are no federal standards controlling N_2O emissions.

CO Emissions

Table A-19 indicated that the CO emissions from all tests were very low (2 to 55 ppm corrected to 3% O_2). Figure A-24 is a graph of the CO concentration corrected to 3% O_2 as a function of temperature which shows that the CO emissions were greatest at low temperatures, as expected.

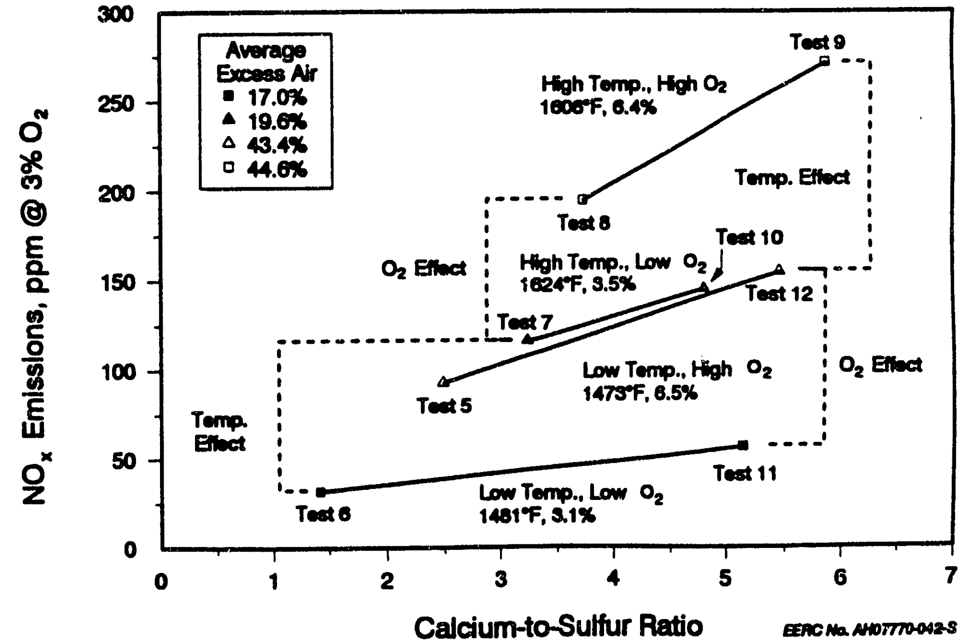

Figure A-22. The effects of calcium-to-sulfur ratio, excess air, and temperature on NO_x emissions.

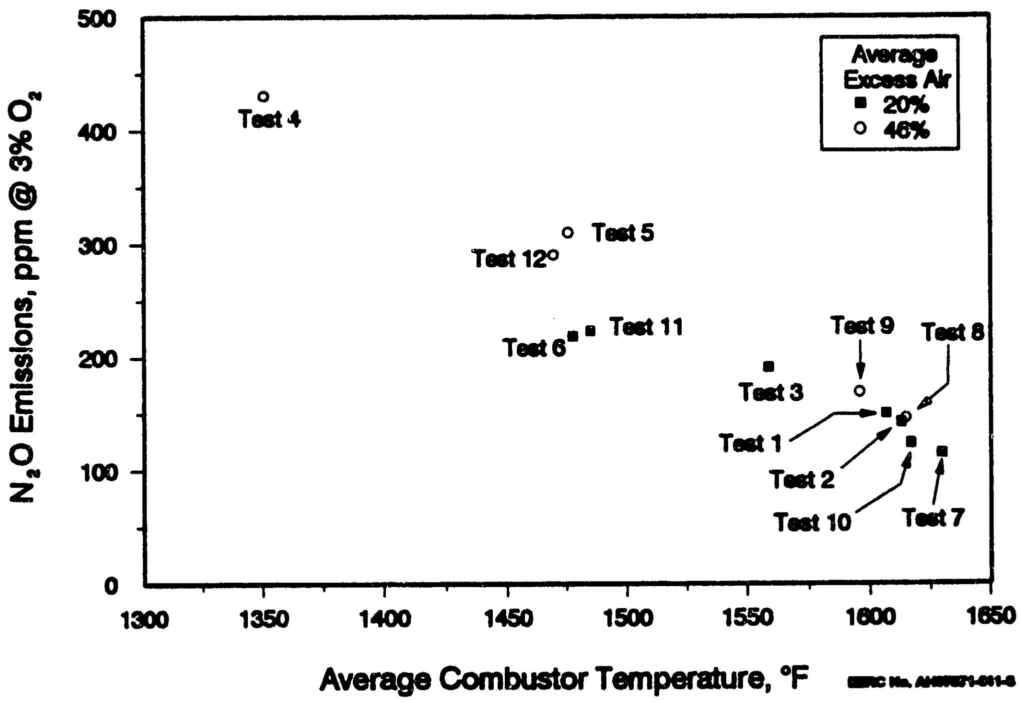

Figure A-23. The effects of temperature and excess air on N_2O emissions.

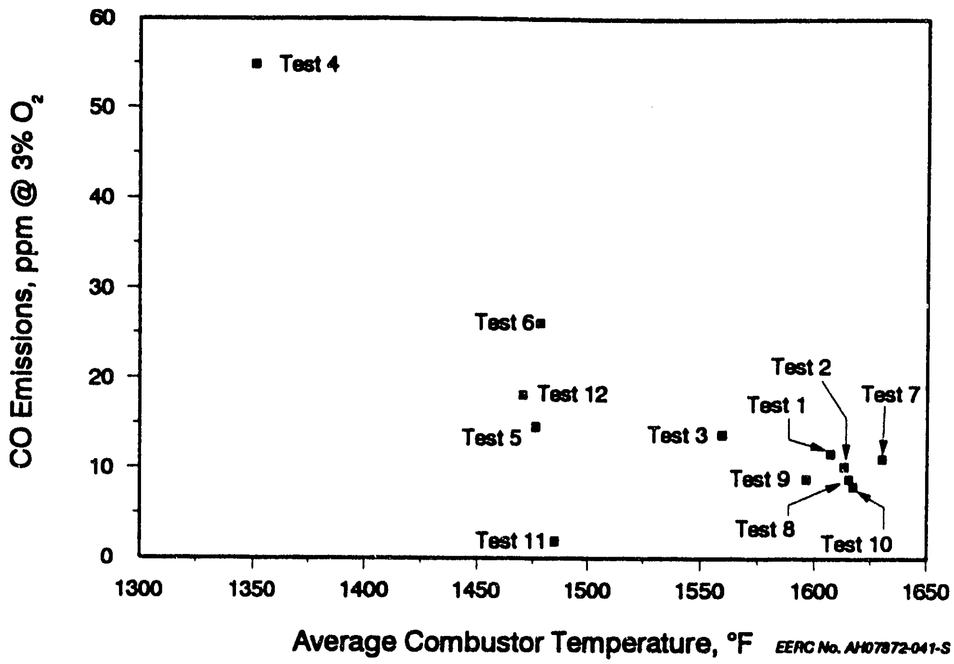

Figure A-24. CO emissions as a function of temperature.

SUMMARIES OF TEST DATA

This section contains the summaries of test data for each test period, including averages and standard deviations of many of the data points recorded by the computerized data acquisition system.

22-Jan-91

CFB-SC1-0191 — TEST 1

(0830-1230)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1596	12.3
TC11021	AFS Ex	°F	1508	11.9
TC15001	C Plenum	°F	599	5.7
TC15004	C 1-1'	°F	1595	24.4
TC15005	C 1-2'	°F	1595	24.0
TC15006	C 1-3'	°F	1596	23.3
TC15007	C 1-4'	°F	1595	23.4
TC15008	C 1-4'	°F	1598	23.7
TC15009	C 1-4'	°F	1598	24.0
TC15012	C 2-6'	°F	N/A	N/A
TC15013	C 2-8'	°F	1620	23.4
TC15022	C 3-11'	°F	1620	22.5
TC15023	C 3-14'	°F	1624	21.3
TC15024	C 3-14'	°F	1630	21.3
TC15025	C 3-14'	°F	1632	22.5
TC15032	C 4-17.5'	°F	1617	17.9
TC15042	C 5-22.5'	°F	1629	17.9
TC15052	C 6-27.5'	°F	1608	15.9
TC15053	C 6-27.5'	°F	1617	16.6
TC15054	C 6-27.5'	°F	1593	15.9
TC15062	C 7-32.5'	°F	1595	15.4
TC15071	C 8-37.5'	°F	1591	14.1
TC15073	C 9-41'	°F	1611	15.1
TC15999	Ambient	°F	80	0.8
TC16001	EHX Plenm	°F	125	7.2
TC16012	EHX 0.5'	°F	1339	44.3
TC16013	EHX 1.5'	°F	1339	43.2
TC16014	EHX 2.7'	°F	1338	45.8
TC16015	EHX 3.8'	°F	1218	45.3
TC16017	EHX 5.3'	°F	1080	41.3
TC16018	EHX Exit	°F	19	50.9
TC16021	Crc A in	°F	1608	15.5
TC16031	DC 8-36'	°F	1571	16.4
TC16032	DC 6-28'	°F	1553	31.2
TC16033	DC 4-18'	°F	1527	34.6
TC16034	DC3-11.5'	°F	1538	30.9
TC16035	DC3-10.5'	°F	1535	33.0
T(A,C)	Comb Temp	°F	1607	19.5
T(A,EHX)	EHX Temp	°F	1339	44.5
EA	Excs Air	%	20.9	3.6
SR	S Reten	%	5.7	7.0
R(PCA)	%Flow PCA	%	54.3	3.5
R(SCA)	%Flow SCA	%	46.0	3.1
R(Q,IN)	%Enrg in	%	24.5	2.5
R(CHX)	CHX Ratio	%	64.7	3.2
R(EHX)	EHX Ratio	%	35.3	3.2
F(PCA)	PCA Flow	SCFM	214.0	23.5
F(EHX)	E FG Flow	SCFM	46.7	8.9
F(SCA)	SCA Flow	SCFM	225.0	5.7
F(TCA)	TCA Flow	SCFM	491.6	19.9
F(FG,BH)	BH Flow	SCFM	480.7	35.9
F(TFG)	TFG Flow	SCFM	484.3	39.0
W(SR)	Recirc Rt	lbs/hr	7657	1649

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 8

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
2E,W	8	39	165	1620	4.45	278958	36.9	53646
3NE	14	40	159	1629	1.73	103186	27.0	39687
4SE	17.5	40	131	1617	1.63	74071	19.2	28489
6NE	27.5	41	136	1606	1.58	75114	19.6	28890
7SE	32.5	41	127	1595	1.58	68115	17.9	26198
8E,W	37.5	42	139	1591	2.95	144359	19.1	27761
	Overall	39	147	1607	12.61	678548	22.3	32623
			From Data Sheets=>		13.92			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
1-4	4	39	140	1339	7.20	364474	101.4	121491
			From Data Sheets=>		6.18			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	511	78.9	SO2-A	ppm	530	79.7
E-Sulfur	lb/MM Btu	0.96	0.1				
CO	ppm	11	4.6	CO	ppm	12	4.5
CO2	%	15.92	0.5	CO2	%	16.52	0.2
N2O	ppm	144	14.3	N2O	ppm	150	14.7
E-N2O	lb/MM Btu	0.19	0.0				
NOx	ppm	137	30.9	NOx	ppm	143	35.1
E-NOx	lb/MM Btu	0.19	0.0				
O2-A	%	3.65	0.5				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	226.8	11.3
W(S)	LS Fd Rt	lbs/hr	0.0	0.0
V(FG)	FG SGV	ft/sec	16.5	0.9
V(S,C)	Comb SGV	ft/sec	14.9	0.7
V(S,EHX)	EHX SGV	ft/sec	1.7	0.4
FT18003	CHX Flow	gpm	12.6	0.2
FT19003	EHX Flow	gpm	7.2	1.4
PT15998	Barom.	psia	14.0	0.0
PT15081	Comb dP	in H2O	49.7	4.5
Q(CA)	CA Heat in	Btu/hr	2350	67.4
Q(CHX)	CHX HtRmv	Btu/hr	653307	23987.1
Q(EHX)	EHX HtRmv	Btu/hr	357437	44963.3
Q(EHX,IN)	FG Ht in	Btu/hr	N/A	N/A
Q(F)	Fuel Enrg in	Btu/hr	N/A	N/A
Q(FG)	FG Ht out	Btu/hr	242017	18528.3
Q(IN)	Tot Enrg in	Btu/hr	N/A	N/A
Q(OUT)	Tot Enrg out	Btu/hr	N/A	N/A
BH A/C			1.84	0.1
A/SRATIO			0.61	0.0

23-Jan-91

CFB-SC1-0191 — TEST 2

(0045-1237)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1617	11.4
TC11021	AFS Ex	°F	1527	12.6
TC15001	C Plenum	°F	598	18.6
TC15004	C 1-1'	°F	1588	13.0
TC15005	C 1-2'	°F	1589	13.5
TC15006	C 1-3'	°F	1591	13.4
TC15007	C 1-4'	°F	1588	13.5
TC15008	C 1-4'	°F	1590	13.5
TC15009	C 1-4'	°F	1589	13.7
TC15012	C 2-6'	°F	N/A	N/A
TC15013	C 2-8'	°F	1618	15.6
TC15022	C 3-11'	°F	1620	14.6
TC15023	C 3-14'	°F	1625	14.3
TC15024	C 3-14'	°F	1630	14.7
TC15025	C 3-14'	°F	1632	15.6
TC15032	C 4-17.5'	°F	1625	13.7
TC15042	C 5-22.5'	°F	1636	14.0
TC15052	C 6-27.5'	°F	1624	13.0
TC15053	C 6-27.5'	°F	1630	13.9
TC15054	C 6-27.5'	°F	1614	12.7
TC15062	C 7-32.5'	°F	1614	12.8
TC15071	C 8-37.5'	°F	1621	14.2
TC15073	C 9-41'	°F	1631	13.7
TC15999	Ambient	°F	72	1.3
TC16001	EHX Plenm	°F	121	4.0
TC16012	EHX 0.5'	°F	1438	21.5
TC16013	EHX 1.5'	°F	1435	21.0
TC16014	EHX 2.7'	°F	1430	20.7
TC16015	EHX 3.8'	°F	1388	19.6
TC16017	EHX 5.3'	°F	1270	17.2
TC16018	EHX Exit	°F	1434	21.0
TC16021	Crc A in	°F	1612	12.6
TC16031	DC 8-36'	°F	1595	16.5
TC16032	DC 6-28'	°F	1562	28.3
TC16033	DC 4-18'	°F	1522	35.6
TC16034	DC3-11.5'	°F	1531	26.8
TC16035	DC3-10.5'	°F	1534	29.7
T(A,C)	Comb Temp	°F	1613	13.0
T(A,EHX)	EHX Temp	°F	1435	21.0
EA	Excs Air	%	21.8	5.2
SR	S Reten	%	66.3	12.5
R(PCA)	%Flow PCA	%	49.2	4.8
R(SCA)	%Flow SCA	%	50.7	4.8
R(Q,IN)	%Enrg in	%	30.6	3.7
R(CHX)	CHX Ratio	%	69.0	1.2
R(EHX)	EHX Ratio	%	31.0	1.2
F(PCA)	PCA Flow	SCFM	181.7	36.5
F(EHX)	E FG Flow	SCFM	56.4	2.4
F(SCA)	SCA Flow	SCFM	243.2	10.9
F(TCA)	TCA Flow	SCFM	481.3	30.6
F(FG,BH)	BH Flow	SCFM	497.3	24.4
F(TFG)	TFG Flow	SCFM	497.3	24.4
W(SR)	Recirc Rt	lbs/hr	12046	3546

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 8

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
2E,W	8	39	149	1618	4.78	263844	34.6	50739
3NE	14	40	171	1629	1.60	105273	27.8	40489
4SE	17.5	39	132	1625	1.58	73625	19.0	28317
6NE	27.5	40	152	1623	1.41	79168	20.7	30449
7SE	32.5	41	146	1614	1.40	73803	19.3	28386
8E,W	37.5	41	148	1621	2.91	155872	20.3	29975
	Overall	39	150	1613	12.32	679588	22.3	32672
			From Data Sheets=>		13.68			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
1-2,9	3	38	139	1435	5.74	287674	98.7	127855
			From Data Sheets=>		6.19			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	173	70.9	SO2-A	ppm	179	67.7
SO2E	lb/MM Btu	0.33	0.1				
CO	ppm	10	4.4	CO	ppm	10	4.6
CO2	%	15.71	0.7	CO2	%	16.41	0.2
N2O	ppm	136	12.2	N2O	ppm	143	16.9
N2OE	lb/MM Btu	0.18	0.0				
NOx	ppm	150	29.5	NOx	ppm	158	35.4
NOxE	lb/MM Btu	0.21	0.0				
O2-A	%	3.76	0.8				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	238.2	12.4
W(S)	LS Fd Rt	lbs/hr	9.5	*
V(FG)	FG SGV	ft/sec	16.2	1.1
V(S,C)	Comb SGV	ft/sec	14.7	1.0
V(S,EHX)	EHX SGV	ft/sec	2.2	0.1
FT18003	CHX Flow	gpm	12.3	0.2
FT19003	EHX Flow	gpm	5.7	0.0
PT15998	Barom.	psia	14.4	0.0
PT15081	Comb dP	in H2O	43.7	15.1
Q(CA)	CA Heat in	Btu/hr	2359	142.3
Q(CHX)	CHX HtRmv	Btu/hr	640019	32222.6
Q(EHX)	EHX HtRmv	Btu/hr	286611	8593.2
Q(EHX,IN)	FG Ht in	Btu/hr	N/A	N/A
Q(F)	Fuel Enrg in	Btu/hr	N/A	N/A
Q(FG)	FG Ht out	Btu/hr	250470	12471.6
Q(IN)	Tot Enrg in	Btu/hr	N/A	N/A
Q(OUT)	Tot Enrg out	Btu/hr	N/A	N/A
BH A/C			1.90	0.1
A/SRATIO			2.59	1.6

* Calculated Value

23,24-Jan-91

CFB-SC1-0191 — TEST 3

(2157-0052)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1550	9.0
TC11021	AFS Ex	°F	1455	7.7
TC15001	C Plenum	°F	550	5.7
TC15004	C 1-1'	°F	1543	7.8
TC15005	C 1-2'	°F	1545	8.7
TC15006	C 1-3'	°F	1546	7.9
TC15007	C 1-4'	°F	1544	8.2
TC15008	C 1-4'	°F	1546	8.1
TC15009	C 1-4'	°F	1544	8.6
TC15012	C 2-6'	°F	N/A	N/A
TC15013	C 2-8'	°F	1565	9.2
TC15022	C 3-11'	°F	1567	9.9
TC15023	C 3-14'	°F	1570	9.2
TC15024	C 3-14'	°F	1577	8.9
TC15025	C 3-14'	°F	1578	8.9
TC15032	C 4-17.5'	°F	1569	8.4
TC15042	C 5-22.5'	°F	1579	8.9
TC15052	C 6-27.5'	°F	1562	8.4
TC15053	C 6-27.5'	°F	1572	9.1
TC15054	C 6-27.5'	°F	1556	7.4
TC15062	C 7-32.5'	°F	1554	8.0
TC15071	C 8-37.5'	°F	1560	8.1
TC15073	C 9-41'	°F	1571	9.0
TC15999	Ambient	°F	67	0.7
TC16001	EHX Plenm	°F	112	1.3
TC16012	EHX 0.5'	°F	1410	7.1
TC16013	EHX 1.5'	°F	1412	8.0
TC16014	EHX 2.7'	°F	1404	6.8
TC16015	EHX 3.8'	°F	1342	8.6
TC16017	EHX 5.3'	°F	1215	11.8
TC16018	EHX Exit	°F	1409	7.2
TC16021	Crc A in	°F	1559	6.9
TC16031	DC 8-36'	°F	1536	7.9
TC16032	DC 6-28'	°F	1506	19.2
TC16033	DC 4-18'	°F	1457	31.5
TC16034	DC3-11.5'	°F	1465	17.7
TC16035	DC3-10.5'	°F	1468	22.9
T(A,C)	Comb Temp	°F	1560	8.4
T(A,EHX)	EHX Temp	°F	1407	7.1
EA	Excs Air	%	23.1	4.4
SR	S Reten	%	73.6	2.2
R(PCA)	%Flow PCA	%	64.7	2.4
R(SCA)	%Flow SCA	%	35.3	2.4
R(Q,IN)	%Enrg in	%	32.3	2.4
R(CHX)	CHX Ratio	%	86.8	0.5
R(EHX)	EHX Ratio	%	13.2	0.5
F(PCA)	PCA Flow	scfm	221.4	29.4
F(EHX)	E FG Flow	scfm	51.3	1.0
F(SCA)	SCA Flow	scfm	145.8	4.8
F(TCA)	TCA Flow	scfm	418.9	30.4
F(FG,BH)	BH Flow	scfm	435.5	5.2
F(TFG)	TFG Flow	scfm	434.8	4.9
W(SR)	Recirc Rt	lbs/hr	8923	4794

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 8

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
2E,W	8	39	163	1565	4.20	259369	35.6	49879
3NE	14	40	126	1575	2.00	85712	22.7	32966
4SE	17.5	40	140	1569	1.40	69666	18.7	26795
6NE	27.5	41	147	1563	1.30	68835	18.7	26475
7SE	32.5	41	147	1554	1.20	63489	17.3	24419
8E,W	37.5	41	150	1560	2.40	130210	17.7	25040
	Overall	39	149	1560	11.08	604595	20.6	29067
				From Data Sheets=>	12.50			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
9	1	39	119	1407	2.21	88448	91.6	117931
				From Data Sheets=>	2.40			

EMISSIONS DATA

As Measured: Tag	Units	Average	Std Dev	Corrected to 3% O2: Tag	Units	Average	Std Dev
SO2-A	ppm	138	13.8	SO2-A	ppm	127	17.3
E-Sulfur	lb/MM Btu	0.25	0.0				
CO	ppm	13	4.2	CO	ppm	14	4.3
CO2	%	16.30	0.6	CO2	%	17.21	0.2
N2O	ppm	179	4.4	N2O	ppm	190	5.9
E-N2O	lb/MM Btu	0.23	0.0				
NOx	ppm	109	15.5	NOx	ppm	116	20.2
E-NOx	lb/MM Btu	0.15	0.0				
O2-A	%	3.95	0.6				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	203.2	5.1
W(S)	LS Fd Rt	lbs/hr	6.7	*
V(FG)	FG SGV	ft/sec	13.8	0.8
V(S,C)	Comb SGV	ft/sec	12.4	0.7
V(S,EHX)	EHX SGV	ft/sec	2.0	0.1
FT18003	CHX Flow	gpm	11.1	0.1
FT19003	EHX Flow	gpm	2.2	0.0
PT15998	Barom.	psia	14.5	0.0
PT15081	Comb dP	in H2O	56.7	2.7
Q(CA)	CA Heat in	Btu/hr	2014	76.6
Q(CHX)	CHX HtRmv	Btu/hr	590164	22038.8
Q(EHX)	EHX HtRmv	Btu/hr	89689	1593.9
Q(EHX,IN)	FG Ht in	Btu/hr	N/A	N/A
Q(F)	Fuel Enrg in	Btu/hr	N/A	N/A
Q(FG)	FG Ht out	Btu/hr	216439	3162.9
Q(IN)	Tot Enrg in	Btu/hr	N/A	N/A
Q(OUT)	Tot Enrg out	Btu/hr	N/A	N/A
BH A/C			1.68	0.0
A/SRATIO			1.82	0.9

* Calculated Value

24-Jan-91

CFB-SC1-0191 — TEST 4

(1230-2030)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1392	11.4
TC11021	AFS Ex	°F	1310	9.2
TC15001	C Plenum	°F	421	5.7
TC15004	C 1-1'	°F	1302	17.8
TC15005	C 1-2'	°F	1304	17.5
TC15006	C 1-3'	°F	1305	18.1
TC15007	C 1-4'	°F	1304	18.5
TC15008	C 1-4'	°F	1304	19.0
TC15009	C 1-4'	°F	1304	18.5
TC15012	C 2-6'	°F	N/A	N/A
TC15013	C 2-8'	°F	1331	20.0
TC15022	C 3-11'	°F	1363	18.7
TC15023	C 3-14'	°F	1377	17.1
TC15024	C 3-14'	°F	1392	16.1
TC15025	C 3-14'	°F	1375	19.5
TC15032	C 4-17.5'	°F	1382	15.5
TC15042	C 5-22.5'	°F	1402	14.4
TC15052	C 6-27.5'	°F	1377	13.4
TC15053	C 6-27.5'	°F	1387	14.1
TC15054	C 6-27.5'	°F	1371	12.6
TC15062	C 7-32.5'	°F	1367	12.6
TC15071	C 8-37.5'	°F	1369	12.0
TC15073	C 9-41'	°F	1382	13.0
TC15999	Ambient	°F	72	1.2
TC16001	EHX Plenm	°F	119	4.4
TC16012	EHX 0.5'	°F	1048	144.6
TC16013	EHX 1.5'	°F	1071	14.7
TC16014	EHX 2.7'	°F	1064	14.0
TC16015	EHX 3.8'	°F	1015	18.2
TC16017	EHX 5.3'	°F	864	24.0
TC16018	EHX Exit	°F	1055	14.9
TC16021	Crc A in	°F	1383	12.4
TC16031	DC 8-36'	°F	1381	11.0
TC16032	DC 6-28'	°F	1319	21.9
TC16033	DC 4-18'	°F	1225	40.1
TC16034	DC3-11.5'	°F	1202	25.9
TC16035	DC3-10.5'	°F	1196	31.3
T(A,C)	Comb Temp	°F	1351	15.2
T(A,EHX)	EHX Temp	°F	1061	48.8
EA	Excs Air	%	54.4	5.2
SR	S Reten	%	66.2	5.3
R(PCA)	%Flow PCA	%	57.7	4.6
R(SCA)	%Flow SCA	%	42.8	4.1
R(Q,IN)	%Enrg in	%	18.2	3.4
R(CHX)	CHX Ratio	%	84.5	1.2
R(EHX)	EHX Ratio	%	15.5	1.2
F(PCA)	PCA Flow	scfm	133.5	30.2
F(EHX)	E FG Flow	scfm	58.8	1.0
F(SCA)	SCA Flow	scfm	143.2	' 6
F(TCA)	TCA Flow	scfm	336.1	23.3
F(FG,BH)	BH Flow	scfm	344.2	5.1
F(TFG)	TFG Flow	scfm	411.7	38.8
W(SR)	Recirc Rt	lbs/hr	2777	678

HEAT-TRANSFER COEFFICIENTS

—Combustor—　　Number of Doors in Service===> 8

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
2E,W	8	40	103	1331	4.10	130153	20.4	25029
3NE	14	39	90	1381	2.11	54007	16.1	20772
4SE	17.5	40	117	1382	1.20	46751	14.2	17981
6NE	27.5	41	121	1378	1.20	48190	14.7	18535
7SE	32.5	41	121	1367	1.11	44353	13.7	17059
8E,W	37.5	42	134	1369	2.04	94212	14.7	18118
	Overall	39	111	1351	10.49	378895	14.7	18216
			From Data Sheets=>		11.76			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
9	1	39	98	1061	2.08	60560	83.8	80747
			From Data Sheets=>		2.39			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	139	22.4	SO2-A	ppm	184	28.1
E-Sulfur	lb/MM Btu	0.32	0.1				
CO	ppm	42	13.5	CO	ppm	55	17.8
CO2	%	12.83	0.5	CO2	%	16.98	0.4
N2O	ppm	325	11.0	N2O	ppm	431	13.1
E-N2O	lb/MM Btu	0.52	0.0				
NOx	ppm	39	4.7	NOx	ppm	51	7.2
E-NOx	lb/MM Btu	0.07	0.0				
O2-A	%	7.40	0.5				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	130.7	7.9
W(S)	LS Fd Rt	lbs/hr	5.9	*
V(FG)	FG SGV	ft/sec	10.0	0.7
V(S,C)	Comb SGV	ft/sec	9.0	0.6
V(S,EHX)	EHX SGV	ft/sec	1.8	0.1
FT18003	CHX Flow	gpm	10.5	0.1
FT19003	EHX Flow	gpm	2.1	0.1
PT15998	Barom.	psia	14.6	0.0
PT15081	Comb dP	in H2O	44.8	2.9
Q(CA)	CA Heat in	Btu/hr	1295	66.7
Q(CHX)	CHX HtRmv	Btu/hr	333285	17567.2
Q(EHX)	EHX HtRmv	Btu/hr	60848	4516.6
Q(EHX,IN)	FG Ht in	Btu/hr	N/A	N/A
Q(F)	Fuel Enrg in	Btu/hr	N/A	N/A
Q(FG)	FG Ht out	Btu/hr	192159	15866.9
Q(IN)	Tot Enrg in	Btu/hr	N/A	N/A
Q(OUT)	Tot Enrg out	Btu/hr	N/A	N/A
BH A/C			1.31	0.0
A/SRATIO			3.19	1.8

* Calculated Value

25-Jan-91

CFB-SC1-0191 — TEST 5

(0300-0700)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1482	14.3
TC11021	AFS Ex	°F	1405	12.6
TC15001	C Plenum	°F	601	6.2
TC15004	C 1-1'	°F	1446	12.2
TC15005	C 1-2'	°F	1449	12.4
TC15006	C 1-3'	°F	1450	12.7
TC15007	C 1-4'	°F	1448	12.7
TC15008	C 1-4'	°F	1451	12.5
TC15009	C 1-4'	°F	1448	11.8
TC15012	C 2-6'	°F	N/A	N/A
TC15013	C 2-8'	°F	1471	16.7
TC15022	C 3-11'	°F	1480	15.3
TC15023	C 3-14'	°F	1485	15.6
TC15024	C 3-14'	°F	1487	14.6
TC15025	C 3-14'	°F	1488	16.7
TC15032	C 4-17.5'	°F	1491	16.2
TC15042	C 5-22.5'	°F	1497	15.8
TC15052	C 6-27.5'	°F	1492	16.1
TC15053	C 6-27.5'	°F	1494	16.1
TC15054	C 6-27.5'	°F	1483	14.3
TC15062	C 7-32.5'	°F	1482	14.4
TC15071	C 8-37.5'	°F	1494	16.2
TC15073	C 9-41'	°F	1498	16.1
TC15999	Ambient	°F	74	1.3
TC16001	EHX Plenm	°F	103	4.4
TC16012	EHX 0.5'	°F	1365	13.4
TC16013	EHX 1.5'	°F	1358	12.2
TC16014	EHX 2.7'	°F	1353	14.3
TC16015	EHX 3.8'	°F	1247	23.0
TC16017	EHX 5.3'	°F	1100	22.0
TC16018	EHX Exit	°F	1331	10.4
TC16021	Crc A in	°F	1490	15.9
TC16031	DC 8-36'	°F	1476	15.0
TC16032	DC 6-28'	°F	1460	19.3
TC16033	DC 4-18'	°F	1425	29.2
TC16034	DC3-11.5'	°F	1437	24.3
TC16035	DC3-10.5'	°F	1437	26.0
T(A,C)	Comb Temp	°F	1476	14.4
T(A,EHX)	EHX Temp	°F	1358	13.0
EA	Excs Air	%	43.9	5.7
SR	S Reten	%	68.1	2.2
R(PCA)	%Flow PCA	%	68.7	3.6
R(SCA)	%Flow SCA	%	31.2	3.5
R(Q,IN)	%Enrg in	%	24.4	3.6
R(CHX)	CHX Ratio	%	63.1	1.6
R(EHX)	EHX Ratio	%	36.9	1.6
F(PCA)	PCA Flow	scfm	320.3	23.2
F(EHX)	E FG Flow	scfm	36.9	2.9
F(SCA)	SCA Flow	scfm	160.8	19.2
F(TCA)	TCA Flow	scfm	514.2	14.8
F(FG,BH)	BH Flow	scfm	421.2	7.3
F(TFG)	TFG Flow	scfm	599.9	36.1
W(SR)	Recirc Rt	lbs/hr	14210	2883

HEAT-TRANSFER COEFFICIENTS

—Combustor—　Number of Doors in Service===> 8

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
2E,W	8	39	140	1471	3.96	199974	28.9	38457
3NE	14	39	123	1487	2.00	83879	23.7	32261
4SE	17.5	40	155	1491	1.20	68857	19.8	26484
6NE	27.5	40	150	1490	1.20	66053	19.0	25405
7SE	32.5	41	155	1482	1.20	68302	19.8	26270
8E,W	37.5	42	191	1494	1.90	141432	20.9	27198
	Overall	40	150	1476	10.48	575066	20.8	27647
			From Data Sheets=>		11.46			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
1-2,8,9	4	39	123	1358	7.24	305532	82.5	101844
			From Data Sheets=>		7.74			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	136	10.3	SO2-A	ppm	168	11.8
E-Sulfur	lb/MM Btu	0.31	0.0				
CO	ppm	12	4.1	CO	ppm	15	5.3
CO2	%	13.31	0.6	CO2	%	16.45	0.2
N2O	ppm	251	5.1	N2O	ppm	310	12.3
E-N2O	lb/MM Btu	0.39	0.0				
NOx	ppm	75	9.0	NOx	ppm	93	13.8
E-NOx	lb/MM Btu	0.12	0.0				
O2-A	%	6.44	0.6				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	211.9	10.9
W(S)	LS Fd Rt	lbs/hr	7.0	*
V(FG)	FG SGV	ft/sec	16.0	0.5
V(S,C)	Comb SGV	ft/sec	14.7	0.5
V(S,EHX)	EHX SGV	ft/sec	1.4	0.1
FT18003	CHX Flow	gpm	10.5	0.1
FT19003	EHX Flow	gpm	7.2	0.1
PT15998	Barom.	psia	14.5	0.0
PT15081	Comb dP	in H2O	29.0	6.1
Q(CA)	CA Heat in	Btu/hr	2431	42.4
Q(CHX)	CHX HtRmv	Btu/hr	523339	22039.0
Q(EHX)	EHX HtRmv	Btu/hr	306413	11745.2
Q(EHX,IN	FG Ht in	Btu/hr	N/A	N/A
Q(F)	Fuel Enrg in	Btu/hr	N/A	N/A
Q(FG)	FG Ht out	Btu/hr	293439	18856.3
Q(IN)	Tot Enrg in	Btu/hr	N/A	N/A
Q(OUT)	Tot Enrg out	Btu/hr	N/A	N/A
BH A/C			1.61	0.0
A/SRATIO			2.03	0.6

* Calculated Value

29,30-Jan-91

CFB-SC1-0191 — TEST 6

(2230-0230)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1540	15.7
TC11021	AFS Ex	°F	1474	11.6
TC15001	C Plenum	°F	590	5.0
TC15004	C 1-1'	°F	1433	10.4
TC15005	C 1-2'	°F	1431	10.5
TC15006	C 1-3'	°F	1433	10.3
TC15007	C 1-4'	°F	1431	9.8
TC15008	C 1-4'	°F	1434	10.6
TC15009	C 1-4'	°F	1433	10.2
TC15012	C 2-6'	°F	N/A	N/A
TC15013	C 2-8'	°F	1462	10.6
TC15022	C 3-11'	°F	1477	11.2
TC15023	C 3-14'	°F	1491	10.3
TC15024	C 3-14'	°F	1497	11.1
TC15025	C 3-14'	°F	1494	11.5
TC15032	C 4-17.5'	°F	1499	12.2
TC15042	C 5-22.5'	°F	1513	11.6
TC15052	C 6-27.5'	°F	1509	12.2
TC15053	C 6-27.5'	°F	1514	13.1
TC15054	C 6-27.5'	°F	1498	11.5
TC15062	C 7-32.5'	°F	1497	12.2
TC15071	C 8-37.5'	°F	1513	13.0
TC15073	C 9-41'	°F	1522	13.6
TC15999	Ambient	°F	72	1.5
TC16001	EHX Plenm	°F	114	3.7
TC16012	EHX 0.5'	°F	1206	19.1
TC16013	EHX 1.5'	°F	1203	19.0
TC16014	EHX 2.7'	°F	1191	18.0
TC16015	EHX 3.8'	°F	1131	19.8
TC16017	EHX 5.3'	°F	995	17.2
TC16018	EHX Exit	°F	1160	19.9
TC16021	Crc A in	°F	1519	13.3
TC16031	DC 8-36'	°F	1494	13.8
TC16032	DC 6-28'	°F	1470	25.0
TC16033	DC 4-18'	°F	1433	41.7
TC16034	DC3-11.5'	°F	1443	30.2
TC16035	DC3-10.5'	°F	1444	33.3
T(A,C)	Comb Temp	°F	1478	11.1
T(A,EHX)	EHX Temp	°F	1200	18.6
EA	Excs Air	%	17.1	4.0
SR	S Reten	%	58.5	4.6
R(PCA)	%Flow PCA	%	48.9	2.1
R(SCA)	%Flow SCA	%	51.5	1.8
R(Q,IN)	%Enrg in	%	27.5	2.7
R(CHX)	CHX Ratio	%	48.5	1.4
R(EHX)	EHX Ratio	%	51.5	1.4
F(PCA)	PCA Flow	scfm	191.1	17.5
F(EHX)	E FG Flow	scfm	45.8	2.3
F(SCA)	SCA Flow	scfm	254.4	4.2
F(TCA)	TCA Flow	scfm	492.2	15.1
F(FG,BH)	BH Flow	scfm	490.1	2.9
F(TFG)	TFG Flow	scfm	490.1	2.9
W(SR)	Recirc Rt	lbs/hr	9577	1109

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 8

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
2E,W	8	39	147	1462	4.03	218225	31.9	41966
3NE	14	38	117	1494	2.00	78467	21.9	30180
4SE	17.5	38	132	1499	1.40	66053	18.6	25405
6NE	27.5	39	131	1507	1.48	68212	19.1	26236
7SE	32.5	40	154	1497	1.20	68400	19.6	26308
8E,W	37.5	40	109	1513	3.80	130483	17.9	25093
	Overall	39	130	1478	12.60	571907	20.4	27496
				From Data Sheets=>	13.91			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
1-4,8-12	9	38	103	1200	18.52	599535	81.0	88820
				From Data Sheets=>	19.88			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	210	27.2	SO2-A	ppm	211	22.3
E-Sulfur	lb/MM Btu	0.40	0.0				
CO	ppm	26	3.4	CO	ppm	26	3.7
CO2	%	15.74	0.5	CO2	%	15.83	0.2
N2O	ppm	217	15.8	N2O	ppm	219	22.9
E-N2O	lb/MM Btu	0.28	0.0				
NOx	ppm	31	1.9	NOx	ppm	32	2.4
E-NOx	lb/MM Btu	0.04	0.0				
O2-A	%	3.11	0.6				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	257.5	11.0
W(S)	LS Fd Rt	lbs/hr	6.4	*
V(FG)	FG SGV	ft/sec	15.6	0.6
V(S,C)	Comb SGV	ft/sec	14.1	0.4
V(S,EHX)	EHX SGV	ft/sec	1.6	0.1
FT18003	CHX Flow	gpm	12.6	0.0
FT19003	EHX Flow	gpm	18.5	0.0
PT15998	Barom.	psia	14.3	0.0
PT15081	Comb dP	in H2O	43.3	0.6
Q(CA)	CA Heat in	Btu/hr	2352	36.8
Q(CHX)	CHX HtRmv	Btu/hr	562086	26040.0
Q(EHX)	EHX HtRmv	Btu/hr	597310	29669.5
Q(EHX,IN	FG Ht in	Btu/hr	N/A	N/A
Q(F)	Fuel Enrg in	Btu/hr	N/A	N/A
Q(FG)	FG Ht out	Btu/hr	241541	1905.8
Q(IN)	Tot Enrg in	Btu/hr	N/A	N/A
Q(OUT)	Tot Enrg out	Btu/hr	N/A	N/A
BH A/C			1.87	0.0
A/SRATIO			1.33	0.7

* Calculated Value

30-Jan-91

CFB-SC1-0191 — TEST 7

(0535-0930)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1634	7.8
TC11021	AFS Ex	°F	1540	7.3
TC15001	C Plenum	°F	655	4.3
TC15004	C 1-1'	°F	1607	8.4
TC15005	C 1-2'	°F	1608	9.5
TC15006	C 1-3'	°F	1609	8.9
TC15007	C 1-4'	°F	1607	9.3
TC15008	C 1-4'	°F	1610	8.7
TC15009	C 1-4'	°F	1607	9.5
TC15012	C 2-6'	°F	1612	13.02
TC15013	C 2-8'	°F	1628	8.8
TC15022	C 3-11'	°F	1632	8.8
TC15023	C 3-14'	°F	1637	9.9
TC15024	C 3-14'	°F	1643	9.0
TC15025	C 3-14'	°F	1642	9.1
TC15032	C 4-17.5'	°F	1641	8.8
TC15042	C 5-22.5'	°F	1649	8.2
TC15052	C 6-27.5'	°F	1643	8.2
TC15053	C 6-27.5'	°F	1649	8.7
TC15054	C 6-27.5'	°F	1633	8.2
TC15062	C 7-32.5'	°F	1633	8.0
TC15071	C 8-37.5'	°F	1646	8.2
TC15073	C 9-41'	°F	1652	8.5
TC15999	Ambient	°F	79	2.9
TC16001	EHX Plenm	°F	121	4.2
TC16012	EHX 0.5'	°F	1496	5.7
TC16013	EHX 1.5'	°F	1489	5.8
TC16014	EHX 2.7'	°F	1483	6.1
TC16015	EHX 3.8'	°F	1428	8.0
TC16017	EHX 5.3'	°F	1282	6.5
TC16018	EHX Exit	°F	1474	6.4
TC16021	Crc A in	°F	1645	9.8
TC16031	DC 8-36'	°F	1621	7.8
TC16032	DC 6-28'	°F	1600	17.7
TC16033	DC 4-18'	°F	1577	34.5
TC16034	DC3-11.5'	°F	1579	28.7
TC16035	DC3-10.5'	°F	1576	31.8
T(A,C)	Comb Temp	°F	1630	8.3
T(A,EHX)	EHX Temp	°F	1489	5.4
EA	Excs Air	%	18.8	2.5
SR	S Reten	%	56.6	6.1
R(PCA)	%Flow PCA	%	69.9	1.5
R(SCA)	%Flow SCA	%	30.1	1.4
R(Q,IN)	%Enrg in	%	28.6	4.3
R(CHX)	CHX Ratio	%	70.5	0.8
R(EHX)	EHX Ratio	%	29.5	0.8
F(PCA)	PCA Flow	scfm	281.4	17.4
F(EHX)	E FG Flow	scfm	47.4	1.2
F(SCA)	SCA Flow	scfm	142.6	3.4
F(TCA)	TCA Flow	scfm	473.0	15.3
F(FG,BH)	BH Flow	scfm	456.7	17.4
F(TFG)	TFG Flow	scfm	474.0	9.9
W(SR)	Recirc Rt	lbs/hr	10601	2069

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 8

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
2E,W	8	40	158	1628	4.38	259720	34.0	49946
3NE	14	40	141	1641	2.00	101006	25.9	38849
4SE	17.5	39	153	1641	1.53	87246	22.6	33556
6NE	27.5	40	143	1642	1.58	81552	20.9	31366
7SE	32.5	41	152	1633	1.58	87934	22.8	33821
8E,W	37.5	41	135	1646	3.55	167522	21.3	32216
	Overall	39	147	1630	13.32	722880	23.4	34754
			From Data Sheets=>		14.62			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
1-2,9	3	39	158	1489	4.74	281443	93.9	125086
			From Data Sheets=>		5.18			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	223	33.7	SO2-A	ppm	227	30.6
E-Sulfur	lb/MM Btu	0.42	0.1				
CO	ppm	11	3.0	CO	ppm	11	3.0
CO2	%	16.02	0.3	CO2	%	16.34	0.2
N2O	ppm	112	8.0	N2O	ppm	115	9.7
E-N2O	lb/MM Btu	0.14	0.0				
NOx	ppm	113	6.5	NOx	ppm	115	7.8
E-NOx	lb/MM Btu	0.15	0.0				
O2-A	%	3.35	0.4				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	233.8	14.1
W(S)	LS Fd Rt	lbs/hr	9.2	*
V(FG)	FG SGV	ft/sec	16.1	0.6
V(S,C)	Comb SGV	ft/sec	14.5	0.4
V(S,EHX)	EHX SGV	ft/sec	1.9	0.0
FT18003	CHX Flow	gpm	13.3	0.2
FT19003	EHX Flow	gpm	4.7	0.0
PT15998	Barom.	psia	14.2	0.0
PT15081	Comb dP	in H2O	42.4	1.4
Q(CA)	CA Heat in	Btu/hr	2568	50.0
Q(CHX)	CHX HtRmv	Btu/hr	672816	23383.2
Q(EHX)	EHX HtRmv	Btu/hr	281315	4916.3
Q(EHX,IN	FG Ht in	Btu/hr	N/A	N/A
Q(F)	Fuel Enrg in	Btu/hr	N/A	N/A
Q(FG)	FG Ht out	Btu/hr	238394	4749.3
Q(IN)	Tot Enrg in	Btu/hr	N/A	N/A
Q(OUT)	Tot Enrg out	Btu/hr	N/A	N/A
BH A/C			1.74	0.1
A/SRATIO			2.18	1.6

* Calculated Value

30-Jan-91

CFB-SC1-0191 — TEST 8

(1230-1630)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1610	8.1
TC11021	AFS Ex	°F	1512	7.7
TC15001	C Plenum	°F	588	7.5
TC15004	C 1-1'	°F	1593	5.4
TC15005	C 1-2'	°F	1594	5.3
TC15006	C 1-3'	°F	1594	5.2
TC15007	C 1-4'	°F	1591	5.2
TC15008	C 1-4'	°F	1596	5.7
TC15009	C 1-4'	°F	1592	6.1
TC15012	C 2-6'	°F	1602	5.18
TC15013	C 2-8'	°F	1614	6.5
TC15022	C 3-11'	°F	1621	6.1
TC15023	C 3-14'	°F	1623	7.8
TC15024	C 3-14'	°F	1632	6.0
TC15025	C 3-14'	°F	1629	7.6
TC15032	C 4-17.5'	°F	1625	7.9
TC15042	C 5-22.5'	°F	1638	7.9
TC15052	C 6-27.5'	°F	1627	8.2
TC15053	C 6-27.5'	°F	1632	8.5
TC15054	C 6-27.5'	°F	1612	7.0
TC15062	C 7-32.5'	°F	1611	7.0
TC15071	C 8-37.5'	°F	1626	8.8
TC15073	C 9-41'	°F	1635	9.0
TC15999	Ambient	°F	61	9.7
TC16001	EHX Plenm	°F	107	8.5
TC16012	EHX 0.5'	°F	1505	6.8
TC16013	EHX 1.5'	°F	1506	7.3
TC16014	EHX 2.7'	°F	1495	8.0
TC16015	EHX 3.8'	°F	1457	9.4
TC16017	EHX 5.3'	°F	1322	7.5
TC16018	EHX Exit	°F	1479	7.6
TC16021	Crc A in	°F	1626	10.2
TC16031	DC 8-36'	°F	1599	24.8
TC16032	DC 6-28'	°F	1577	18.4
TC16033	DC 4-18'	°F	1545	36.0
TC16034	DC3-11.5'	°F	1545	29.1
TC16035	DC3-10.5'	°F	1543	32.4
T(A,C)	Comb Temp	°F	1615	6.3
T(A,EHX)	EHX Temp	°F	1502	7.3
EA	Excs Air	%	40.8	2.9
SR	S Reten	%	63.3	5.7
R(PCA)	%Flow PCA	%	52.2	1.6
R(SCA)	%Flow SCA	%	47.7	1.8
R(Q,IN)	%Enrg in	%	30.9	4.2
R(CHX)	CHX Ratio	%	87.1	0.5
R(EHX)	EHX Ratio	%	12.9	0.5
F(PCA)	PCA Flow	scfm	199.9	11.0
F(EHX)	E FG Flow	scfm	54.6	0.8
F(SCA)	SCA Flow	scfm	235.4	3.8
F(TCA)	TCA Flow	scfm	495.6	12.5
F(FG,BH)	BH Flow	scfm	487.3	5.7
F(TFG)	TFG Flow	scfm	519.5	30.4
W(SR)	Recirc Rt	lbs/hr	7357	2161

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 8

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
2E,W	8	39	140	1614	4.33	219048	28.6	42125
3NE	14	39	125	1628	2.00	86274	22.1	33182
4SE	17.5	39	134	1625	1.50	71609	18.5	27542
6NE	27.5	40	137	1623	1.50	73036	18.9	28091
7SE	32.5	40	142	1611	1.50	76256	20.0	29329
8E,W	37.5	41	126	1626	3.50	149784	19.2	28805
	Overall	39	134	1615	13.36	633823	20.6	30472
		From Data Sheets=>			14.33			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
9	1	39	153	1502	1.56	88927	87.9	118569
		From Data Sheets=>			1.80			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	162	25.4	SO2-A	ppm	196	28.9
E-Sulfur	lb/MM Btu	0.35	0.1				
CO	ppm	7	1.2	CO	ppm	9	1.4
CO2	%	13.81	0.4	CO2	%	16.71	0.3
N2O	ppm	120	2.6	N2O	ppm	146	5.4
E-N2O	lb/MM Btu	0.18	0.0				
NOx	ppm	161	6.3	NOx	ppm	194	10.4
E-NOx	lb/MM Btu	0.25	0.0				
O2-A	%	6.12	0.3				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	208.7	14.3
W(S)	LS Fd Rt	lbs/hr	9.2	*
V(FG)	FG SGV	ft/sec	16.4	0.5
V(S,C)	Comb SGV	ft/sec	15.0	0.5
V(S,EHX)	EHX SGV	ft/sec	2.2	0.0
FT18003	CHX Flow	gpm	13.4	0.1
FT19003	EHX Flow	gpm	1.6	0.0
PT15998	Barom.	psia	14.4	0.0
PT15081	Comb dP	in H2O	38.4	1.6
Q(CA)	CA Heat in	Btu/hr	2393	41.5
Q(CHX)	CHX HtRmv	Btu/hr	598450	21905.8
Q(EHX)	EHX HtRmv	Btu/hr	88806	2637.0
Q(EHX,IN	FG Ht in	Btu/hr	N/A	N/A
Q(F)	Fuel Enrg in	Btu/hr	N/A	N/A
Q(FG)	FG Ht out	Btu/hr	265203	15839.5
Q(IN)	Tot Enrg in	Btu/hr	N/A	N/A
Q(OUT)	Tot Enrg out	Btu/hr	N/A	N/A
BH A/C			1.86	0.0
A/SRATIO			1.88	1.2

* Calculated Value

30-Jan-91

CFB-SC1-0191 — TEST 9

(2128-2323)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1585	5.8
TC11021	AFS Ex	°F	1495	7.2
TC15001	C Plenum	°F	639	2.4
TC15004	C 1-1'	°F	1578	5.6
TC15005	C 1-2'	°F	1578	5.8
TC15006	C 1-3'	°F	1581	5.0
TC15007	C 1-4'	°F	1578	5.2
TC15008	C 1-4'	°F	1581	5.5
TC15009	C 1-4'	°F	1577	6.0
TC15012	C 2-6'	°F	1589	5.26
TC15013	C 2-8'	°F	1595	6.1
TC15022	C 3-11'	°F	1601	5.7
TC15023	C 3-14'	°F	1604	6.2
TC15024	C 3-14'	°F	1608	6.0
TC15025	C 3-14'	°F	1607	6.8
TC15032	C 4-17.5'	°F	1607	6.9
TC15042	C 5-22.5'	°F	1613	6.5
TC15052	C 6-27.5'	°F	1608	6.3
TC15053	C 6-27.5'	°F	1610	6.0
TC15054	C 6-27.5'	°F	1598	5.7
TC15062	C 7-32.5'	°F	1597	5.3
TC15071	C 8-37.5'	°F	1609	6.5
TC15073	C 9-41'	°F	1612	6.7
TC15999	Ambient	°F	73	0.8
TC16001	EHX Plenm	°F	118	2.3
TC16012	EHX 0.5'	°F	1525	5.5
TC16013	EHX 1.5'	°F	1526	5.9
TC16014	EHX 2.7'	°F	1513	5.2
TC16015	EHX 3.8'	°F	1482	4.9
TC16017	EHX 5.3'	°F	1359	6.9
TC16018	EHX Exit	°F	1503	4.9
TC16021	Crc A in	°F	1600	7.7
TC16031	DC 8-36'	°F	1588	8.5
TC16032	DC 6-28'	°F	1570	16.0
TC16033	DC 4-18'	°F	1548	26.3
TC16034	DC3-11.5'	°F	1550	22.6
TC16035	DC3-10.5'	°F	1549	25.5
T(A,C)	Comb Temp	°F	1597	5.5
T(A,EHX)	EHX Temp	°F	1522	4.8
EA	Excs Air	%	46.1	2.2
SR	S Reten	%	95.1	1.3
R(PCA)	%Flow PCA	%	71.7	1.0
R(SCA)	%Flow SCA	%	28.4	1.2
R(Q,IN)	%Enrg in	%	30.2	4.3
R(CHX)	CHX Ratio	%	87.3	0.5
R(EHX)	EHX Ratio	%	12.7	0.5
F(PCA)	PCA Flow	scfm	312.8	15.1
F(EHX)	E FG Flow	scfm	54.1	0.8
F(SCA)	SCA Flow	scfm	141.6	2.6
F(TCA)	TCA Flow	scfm	508.6	13.7
F(FG,BH)	BH Flow	scfm	503.1	3.5
F(TFG)	TFG Flow	scfm	503.1	3.5
W(SR)	Recirc Rt	lbs/hr	8922	1213

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 8

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
2E,W	8	40	149	1595	4.40	240755	32.0	46299
3NE	14	40	140	1606	2.00	99432	26.1	38243
4SE	17.5	40	153	1607	1.40	78871	20.9	30335
6NE	27.5	41	155	1605	1.40	80039	21.2	30784
7SE	32.5	41	168	1597	1.30	82075	22.1	31567
8E,W	37.5	41	151	1609	3.00	165719	21.9	31869
	Overall	39	151	1597	12.23	684027	22.7	32886
			From Data Sheets=>		13.50			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
9	1	40	158	1522	1.55	91504	89.4	122005
			From Data Sheets=>		1.80			

EMISSIONS DATA

As Measured: Tag	Units	Average	Std Dev	Corrected to 3% O2: Tag	Units	Average	Std Dev
SO2-A	ppm	21	6.0	SO2-A	ppm	26	7.3
E-Sulfur	lb/MM Btu	0.05	0.0				
CO	ppm	7	0.4	CO	ppm	9	0.5
CO2	%	13.46	0.3	CO2	%	16.89	0.2
N2O	ppm	135	2.6	N2O	ppm	169	4.3
E-N2O	lb/MM Btu	0.21	0.0				
NOx	ppm	216	11.4	NOx	ppm	272	17.2
E-NOx	lb/MM Btu	0.35	0.0				
O2-A	%	6.65	0.2				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	208.8	13.4
W(S)	LS Fd Rt	lbs/hr	16.6	*
V(FG)	FG SGV	ft/sec	16.7	0.4
V(S,C)	Comb SGV	ft/sec	15.2	0.4
V(S,EHX)	EHX SGV	ft/sec	2.2	0.0
FT18003	CHX Flow	gpm	12.2	0.2
FT19003	EHX Flow	gpm	1.6	0.0
PT15998	Barom.	psia	14.5	0.0
PT15081	Comb dP	in H2O	37.9	1.4
Q(CA)	CA Heat in	Btu/hr	2596	26.5
Q(CHX)	CHX HtRmv	Btu/hr	631326	21662.4
Q(EHX)	EHX HtRmv	Btu/hr	91498	3067.2
Q(EHX,IN	FG Ht in	Btu/hr	N/A	N/A
Q(F)	Fuel Enrg in	Btu/hr	N/A	N/A
Q(FG)	FG Ht out	Btu/hr	251732	1568.4
Q(IN)	Tot Enrg in	Btu/hr	N/A	N/A
Q(OUT)	Tot Enrg out	Btu/hr	N/A	N/A
BH A/C			1.92	0.0
A/SRATIO			5.21	2.7

* Calculated Value

31-Jan-91

CFB-SC1-0191 — TEST 10

(1032-1417)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1646	10.2
TC11021	AFS Ex	°F	1551	7.9
TC15001	C Plenum	°F	618	5.3
TC15004	C 1-1'	°F	1576	8.0
TC15005	C 1-2'	°F	1578	8.3
TC15006	C 1-3'	°F	1578	7.8
TC15007	C 1-4'	°F	1576	8.0
TC15008	C 1-4'	°F	1579	8.5
TC15009	C 1-4'	°F	1577	7.5
TC15012	C 2-6'	°F	1589	8.13
TC15013	C 2-8'	°F	1618	9.4
TC15022	C 3-11'	°F	1628	9.7
TC15023	C 3-14'	°F	1634	9.0
TC15024	C 3-14'	°F	1640	8.9
TC15025	C 3-14'	°F	1642	10.9
TC15032	C 4-17.5'	°F	1634	9.0
TC15042	C 5-22.5'	°F	1649	9.9
TC15052	C 6-27.5'	°F	1638	9.3
TC15053	C 6-27.5'	°F	1645	9.3
TC15054	C 6-27.5'	°F	1623	7.9
TC15062	C 7-32.5'	°F	1624	8.1
TC15071	C 8-37.5'	°F	1638	8.9
TC15073	C 9-41'	°F	1650	10.6
TC15999	Ambient	°F	80	1.1
TC16001	EHX Plenm	°F	128	4.6
TC16012	EHX 0.5'	°F	1420	12.8
TC16013	EHX 1.5'	°F	1420	13.2
TC16014	EHX 2.7'	°F	1409	12.8
TC16015	EHX 3.8'	°F	1382	19.7
TC16017	EHX 5.3'	°F	1268	15.7
TC16018	EHX Exit	°F	1388	13.5
TC16021	Crc A in	°F	1646	10.7
TC16031	DC 8-36'	°F	1611	11.8
TC16032	DC 6-28'	°F	1588	16.8
TC16033	DC 4-18'	°F	1562	34.9
TC16034	DC3-11.5'	°F	1561	34.6
TC16035	DC3-10.5'	°F	1560	36.7
T(A,C)	Comb Temp	°F	1617	7.9
T(A,EHX)	EHX Temp	°F	1416	12.7
EA	Excs Air	%	20.5	3.5
SR	S Reten	%	82.3	4.9
R(PCA)	%Flow PCA	%	48.2	2.2
R(SCA)	%Flow SCA	%	51.6	2.5
R(Q,IN)	%Enrg in	%	29.8	5.6
R(CHX)	CHX Ratio	%	56.8	1.3
R(EHX)	EHX Ratio	%	43.2	1.3
F(PCA)	PCA Flow	scfm	180.5	17.4
F(EHX)	E FG Flow	scfm	54.1	6.4
F(SCA)	SCA Flow	scfm	254.9	12.0
F(TCA)	TCA Flow	scfm	494.4	15.3
F(FG,BH)	BH Flow	scfm	386.9	9.9
F(TFG)	TFG Flow	scfm	519.8	33.4
W(SR)	Recirc Rt	lbs/hr	9597	1102

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 8

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
2E,W	8	39	134	1618	4.20	199185	25.8	38305
3NE	14	39	140	1639	1.80	90200	23.1	34692
4SE	17.5	40	145	1634	1.40	74148	19.2	28518
6NE	27.5	41	166	1636	1.20	75403	19.7	29001
7SE	32.5	41	158	1624	1.30	76064	20.0	29255
8E,W	37.5	42	141	1638	3.03	150807	19.4	29001
	Overall	40	143	1617	11.74	608517	19.8	29256
			From Data Sheets=>		12.93			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
8-12	5	39	171	1416	6.35	421689	90.3	112450
			From Data Sheets=>		6.80			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	91	27.4	SO2-A	ppm	94	26.8
E-Sulfur	lb/MM Btu	0.17	0.0				
CO	ppm	8	0.8	CO	ppm	8	0.7
CO2	%	15.91	0.6	CO2	%	16.47	0.4
N2O	ppm	120	6.8	N2O	ppm	124	9.0
E-N2O	lb/MM Btu	0.16	0.0				
NOx	ppm	139	13.3	NOx	ppm	145	17.2
E-NOx	lb/MM Btu	0.19	0.0				
O2-A	%	3.60	0.5				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	244.1	18.9
W(S)	LS Fd Rt	lbs/hr	12.1	*
V(FG)	FG SGV	ft/sec	16.5	0.5
V(S,C)	Comb SGV	ft/sec	15.1	0.5
V(S,EHX)	EHX SGV	ft/sec	2.1	0.3
FT18003	CHX Flow	gpm	11.7	0.3
FT19003	EHX Flow	gpm	6.3	0.0
PT15998	Barom.	psia	14.4	0.0
PT15081	Comb dP	in H2O	40.1	2.1
Q(CA)	CA Heat in	Btu/hr	2436	35.8
Q(CHX)	CHX HtRmv	Btu/hr	553558	19144.6
Q(EHX)	EHX HtRmv	Btu/hr	420874	16120.2
Q(EHX,IN	FG Ht in	Btu/hr	N/A	N/A
Q(F)	Fuel Enrg in	Btu/hr	N/A	N/A
Q(FG)	FG Ht out	Btu/hr	262890	17131.6
Q(IN)	Tot Enrg in	Btu/hr	N/A	N/A
Q(OUT)	Tot Enrg out	Btu/hr	N/A	N/A
BH A/C			1.48	0.0
A/SRATIO			3.33	1.3

* Calculated Value

31-Jan-91,01-Feb-91

CFB-SC1-0191 — TEST 11

(2015-0015)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1535	10.0
TC11021	AFS Ex	°F	1463	8.0
TC15001	C Plenum	°F	627	3.9
TC15004	C 1-1'	°F	1444	7.8
TC15005	C 1-2'	°F	1447	7.0
TC15006	C 1-3'	°F	1447	7.6
TC15007	C 1-4'	°F	1446	6.6
TC15008	C 1-4'	°F	1449	7.7
TC15009	C 1-4'	°F	1447	7.5
TC15012	C 2-6'	°F	1458	8.03
TC15013	C 2-8'	°F	1475	10.0
TC15022	C 3-11'	°F	1491	9.2
TC15023	C 3-14'	°F	1498	9.3
TC15024	C 3-14'	°F	1501	9.6
TC15025	C 3-14'	°F	1503	10.5
TC15032	C 4-17.5'	°F	1504	9.6
TC15042	C 5-22.5'	°F	1513	9.2
TC15052	C 6-27.5'	°F	1509	9.5
TC15053	C 6-27.5'	°F	1512	9.7
TC15054	C 6-27.5'	°F	1498	8.3
TC15062	C 7-32.5'	°F	1498	8.6
TC15071	C 8-37.5'	°F	1512	9.3
TC15073	C 9-41'	°F	1519	9.9
TC15999	Ambient	°F	72	1.2
TC16001	EHX Plenm	°F	116	3.3
TC16012	EHX 0.5'	°F	1221	14.5
TC16013	EHX 1.5'	°F	1210	14.1
TC16014	EHX 2.7'	°F	1207	13.0
TC16015	EHX 3.8'	°F	1156	11.3
TC16017	EHX 5.3'	°F	1037	7.6
TC16018	EHX Exit	°F	1193	10.4
TC16021	Crc A in	°F	1513	10.7
TC16031	DC 8-36'	°F	1492	8.0
TC16032	DC 6-28'	°F	1474	16.5
TC16033	DC 4-18'	°F	1447	36.4
TC16034	DC3-11.5'	°F	1453	25.0
TC16035	DC3-10.5'	°F	1453	28.8
T(A,C)	Comb Temp	°F	1485	8.4
T(A,EHX)	EHX Temp	°F	1214	12.3
EA	Excs Air	%	17.2	2.7
SR	S Reten	%	91.3	1.8
R(PCA)	%Flow PCA	%	69.8	1.9
R(SCA)	%Flow SCA	%	30.1	1.8
R(Q,IN)	%Enrg in	%	24.0	3.1
R(CHX)	CHX Ratio	%	39.0	1.2
R(EHX)	EHX Ratio	%	61.0	1.2
F(PCA)	PCA Flow	scfm	310.5	19.7
F(EHX)	E FG Flow	scfm	50.2	1.0
F(SCA)	SCA Flow	scfm	154.1	9.1
F(TCA)	TCA Flow	scfm	517.5	16.3
F(FG,BH)	BH Flow	scfm	419.8	5.5
F(TFG)	TFG Flow	scfm	620.0	41.8
W(SR)	Recirc Rt	lbs/hr	12012	1623

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 8

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
2E,W	8	39	141	1475	3.90	200135	28.9	38488
3NE	14	39	148	1501	1.55	84622	24.1	32547
4SE	17.5	40	142	1504	1.30	66372	18.7	25528
6NE	27.5	40	166	1506	1.10	69003	19.8	26540
7SE	32.5	41	165	1498	1.10	68306	19.7	26272
8E,W	37.5	41	170	1512	2.40	154548	22.2	29721
	Overall	39	153	1485	9.95	569426	20.6	27376
				From Data Sheets=>	11.35			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
1-7,9-12	11	38	127	1214	16.82	748209	83.4	90692
				From Data Sheets=>	17.88			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	45	9.7	SO2-A	ppm	41	9.0
E-Sulfur	lb/MM Btu	0.08	0.0				
CO	ppm	19	2.1	CO	ppm	19	2.1
CO2	%	15.99	0.4	CO2	%	16.09	0.4
N2O	ppm	222	8.5	N2O	ppm	223	12.8
E-N2O	lb/MM Btu	0.29	0.0				
NOx	ppm	55	4.5	NOx	ppm	56	5.7
E-NOx	lb/MM Btu	0.08	0.0				
O2-A	%	3.10	0.4				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	264.3	11.0
W(S)	LS Fd Rt	lbs/hr	15.0	*
V(FG)	FG SGV	ft/sec	16.1	0.5
V(S,C)	Comb SGV	ft/sec	14.7	0.4
V(S,EHX)	EHX SGV	ft/sec	1.7	0.0
FT18003	CHX Flow	gpm	9.9	0.3
FT19003	EHX Flow	gpm	16.8	0.0
PT15998	Barom.	psia	14.5	0.0
PT15081	Comb dP	in H2O	40.4	1.4
Q(CA)	CA Heat in	Btu/hr	2557	37.4
Q(CHX)	CHX HtRmv	Btu/hr	485153	21336.7
Q(EHX)	EHX HtRmv	Btu/hr	758573	24871.4
Q(EHX,IN	FG Ht in	Btu/hr	N/A	N/A
Q(F)	Fuel Enrg in	Btu/hr	N/A	N/A
Q(FG)	FG Ht out	Btu/hr	303232	17754.9
Q(IN)	Tot Enrg in	Btu/hr	N/A	N/A
Q(OUT)	Tot Enrg out	Btu/hr	N/A	N/A
BH A/C			1.60	0.0
A/SRATIO			4.08	1.7

* Calculated Value

01-Feb-91

CFB-SC1-0191 — TEST 12

(0400-0800)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1491	9.7
TC11021	AFS Ex	°F	1412	8.0
TC15001	C Plenum	°F	568	2.6
TC15004	C 1-1'	°F	1436	12.9
TC15005	C 1-2'	°F	1438	12.2
TC15006	C 1-3'	°F	1438	12.3
TC15007	C 1-4'	°F	1437	12.5
TC15008	C 1-4'	°F	1438	12.4
TC15009	C 1-4'	°F	1435	12.3
TC15012	C 2-6'	°F	1442	13.32
TC15013	C 2-8'	°F	1466	15.3
TC15022	C 3-11'	°F	1477	13.0
TC15023	C 3-14'	°F	1482	13.7
TC15024	C 3-14'	°F	1485	13.4
TC15025	C 3-14'	°F	1487	14.6
TC15032	C 4-17.5'	°F	1486	12.1
TC15042	C 5-22.5'	°F	1495	12.7
TC15052	C 6-27.5'	°F	1488	11.5
TC15053	C 6-27.5'	°F	1495	12.5
TC15054	C 6-27.5'	°F	1477	9.9
TC15062	C 7-32.5'	°F	1476	11.0
TC15071	C 8-37.5'	°F	1492	10.2
TC15073	C 9-41'	°F	1500	11.9
TC15999	Ambient	°F	80	1.2
TC16001	EHX Plenm	°F	130	2.1
TC16012	EHX 0.5'	°F	1324	14.6
TC16013	EHX 1.5'	°F	1311	12.8
TC16014	EHX 2.7'	°F	1319	14.0
TC16015	EHX 3.8'	°F	1268	13.2
TC16017	EHX 5.3'	°F	1138	10.9
TC16018	EHX Exit	°F	1292	13.7
TC16021	Crc A in	°F	1495	11.5
TC16031	DC 8-36'	°F	1469	38.1
TC16032	DC 6-28'	°F	1459	12.4
TC16033	DC 4-18'	°F	1427	28.6
TC16034	DC3-11.5'	°F	1428	18.4
TC16035	DC3-10.5'	°F	1426	23.6
T(A,C)	Comb Temp	°F	1470	12.2
T(A,EHX)	EHX Temp	°F	1317	11.7
EA	Excs Air	%	46.2	5.5
SR	S Reten	%	91.5	1.1
R(PCA)	%Flow PCA	%	48.2	1.9
R(SCA)	%Flow SCA	%	51.7	1.8
R(Q,IN)	%Enrg in	%	28.6	3.0
R(CHX)	CHX Ratio	%	60.8	1.0
R(EHX)	EHX Ratio	%	39.2	1.0
F(PCA)	PCA Flow	scfm	193.4	13.1
F(EHX)	E FG Flow	scfm	52.4	0.8
F(SCA)	SCA Flow	scfm	261.3	4.2
F(TCA)	TCA Flow	scfm	502.6	15.7
F(FG,BH)	BH Flow	scfm	407.7	5.9
F(TFG)	TFG Flow	scfm	601.4	15.5
W(SR)	Recirc Rt	lbs/hr	13124	3671

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 8

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
2E,W	8	40	149	1466	3.70	201849	29.5	38817
3NE	14	40	145	1485	1.50	79380	22.8	30531
4SE	17.5	40	133	1486	1.30	61053	17.4	23482
6NE	27.5	41	153	1487	1.02	57220	16.5	22008
7SE	32.5	42	154	1476	1.10	61452	17.9	23636
8E,W	37.5	43	144	1492	2.50	126349	18.0	24298
	Overall	40	146	1470	10.16	540704	19.6	25995
			From Data Sheets=>		11.12			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°	Heat Flux Btu/ft²hr
1-4	4	40	163	1317	4.86	300730	86.9	100243
			From Data Sheets=>		5.20			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	35	5.7	SO2-A	ppm	34	7.9
E-Sulfur	lb/MM Btu	0.08	0.0				
CO	ppm	15	1.9	CO	ppm	18	2.4
CO2	%	13.04	0.6	CO2	%	16.33	0.3
N2O	ppm	232	7.6	N2O	ppm	291	18.2
E-N2O	lb/MM Btu	0.37	0.0				
NOx	ppm	123	6.1	NOx	ppm	154	5.7
E-NOx	lb/MM Btu	0.21	0.0				
O2-A	%	6.63	0.6				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	214.9	10.6
W(S)	LS Fd Rt	lbs/hr	11.9	*
V(FG)	FG SGV	ft/sec	15.7	0.5
V(S,C)	Comb SGV	ft/sec	14.4	0.4
V(S,EHX)	EHX SGV	ft/sec	1.9	0.0
FT18003	CHX Flow	gpm	10.2	0.2
FT19003	EHX Flow	gpm	4.9	0.0
PT15998	Barom.	psia	14.4	0.0
PT15081	Comb dP	in H2O	46.2	1.4
Q(CA)	CA Heat in	Btu/hr	2240	32.4
Q(CHX)	CHX HtRmv	Btu/hr	468966	21672.4
Q(EHX)	EHX HtRmv	Btu/hr	302080	7402.1
Q(EHX,IN	FG Ht in	Btu/hr	N/A	N/A
Q(F)	Fuel Enrg in	Btu/hr	N/A	N/A
Q(FG)	FG Ht out	Btu/hr	287058	13565.9
Q(IN)	Tot Enrg in	Btu/hr	N/A	N/A
Q(OUT)	Tot Enrg out	Btu/hr	N/A	N/A
BH A/C			1.56	0.0
A/SRATIO			4.71	1.8

* Calculated Value

APPENDIX B

CENTER LIGNITE TEST RESULTS

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TEST MATRIX

The matrix of test parameters is shown in Table B-1. Test 0 was a baseline test to establish emission levels without limestone addition. The unit was started up using silica sand, and steady-state data were taken. Test 1 established the baseline conditions for 70% sulfur capture. Tests 2 and 3 simulated load variances for those combustors that do not operate with an external heat exchanger. Tests 4 and 5 repeated the load conditions of Tests 2 and 3, but were done in a manner to simulate those combustors that are designed with an external heat exchanger. The limestone feed rate was lowered for Test 6 to help generate a Ca/S ratio versus sulfur retention curve. Tests 7 through 10 were designed to look at temperature effects on emissions; solid samples were not taken for these test periods.

COAL AND LIMESTONE PROPERTIES

The coal used for this test was supplied by BNI Coal. It was taken from their Center mine and shipped by truck to Grand Forks, North Dakota. The sample received was stoker grade, crushed to minus 2 inches. The sorbent for the test was New Enterprise limestone. Crushing was performed with a Williams hammer-mill crusher. The material exited the crusher and was conveyed to a vibrating screen. The coal was screened to -¼ inch. The size distribution of the as-crushed sample is shown in Figure B-1.

TABLE B-1

Test Matrix

Test #	Temperature (°F)	Load (%)	Excess Air (%)	Sulfur Retention (%)
0	1550	100	25	No ls[1] Feed
1	1550	100	25	70
2	**[2]	75	**	70
3	**	50	**	70
4	1550	50	25	70
5	1550	75	25	70
6	1550	100	25	50
7	1550	100	25	70
8	1475	100	25	70
9	1400	100	25	70
10	1475	100	25	70

Note: Baseline conditions are as follows:

Average Combustor Temperature	1550°F
Velocity	16 fps
Excess Air	25%
Primary Air:Secondary Air	60:40
Coal Size	-¼ inch
Limestone Size	-20 mesh

[1] Limestone.
[2] These conditions were varied as needed to obtain the desired load.

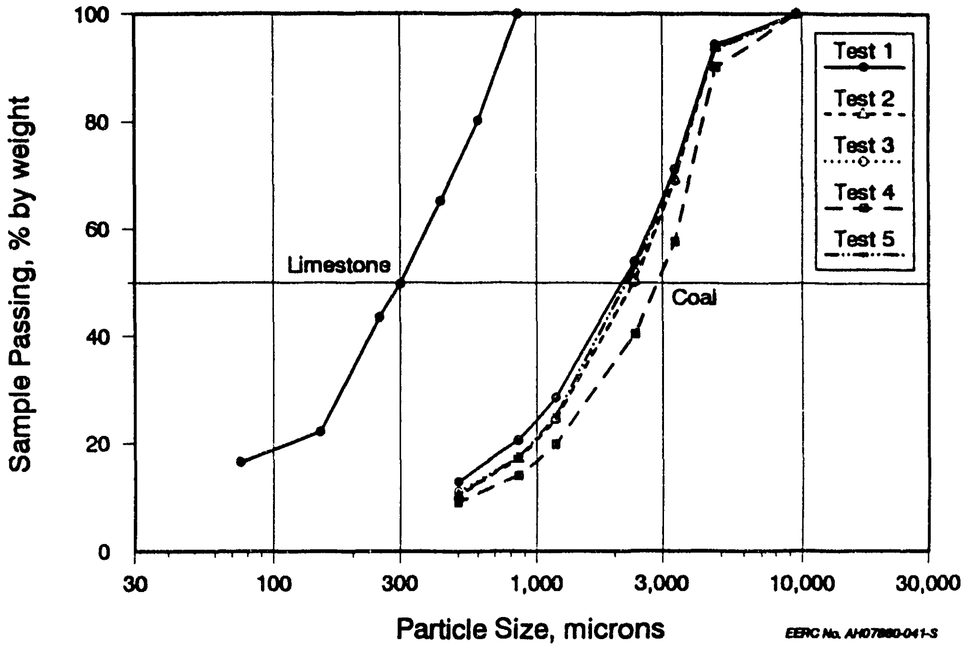

Figure B-1. Size distributions of Center lignite and New Enterprise limestone.

Limestone was crushed separately using the Williams hammer-mill crusher and screened to -20 mesh (841 microns) The limestone crushed well once-through, with only a small amount greater than 20 mesh (separated into barrels for additional crushing) and not many fines. The size distribution for an as-crushed limestone sample is shown in Figure B-1. About 18% was less than 200 mesh (75 microns); 100% was less than 20 mesh (841 microns), with what appears to be a good distribution. The D_{50} was approximately 300 microns.

The sized coal and limestone from final screening were routed into 2-ton capacity storage totes which were on standby waiting to be transferred by forklift and crane to storage hoppers having net capacities of approximately 3000 pounds and 1000 pounds for the coal and limestone, respectively.

Proximate and ultimate analyses of the coal and XRFA of the coal ash and limestone were performed. Results of the coal analyses for each test period are shown in Table B-2, and the limestone analysis is shown in Table B-3. The coal is typified by its high moisture (37%), low ash (5%), and low sulfur (0.6%). The sodium content of the ash at 3.7% is midrange for a North Dakota lignite.

OPERATIONAL PERFORMANCE

General Operability

During the first week of testing with Center lignite, a couple of operational problems were encountered that increased the length of start-up. First, a leak in one of the flexible joints of the secondary air manifold had to be patched. Next, after the system

TABLE B-2

Coal Analyses

	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Tests 7-10	Averages	Tests 0-6 Average
Proximate Analysis, as-received, wt%										
Moisture	39.2	37.0	36.9	36.6	37.1	37.1	35.9	22.5	35.29	37.11
Volatile Matter	27.9	28.9	29.3	29.1	29.3	28.5	29.7	36.6	29.91	28.96
Fixed Carbon	29.3	29.0	28.6	29.4	28.4	28.7	28.7	34.7	29.60	28.87
Ash	3.7	5.1	5.2	4.9	5.3	5.6	5.7	6.1	5.19	5.07
Ultimate Analysis, as-received, wt%										
Carbon	40.95	40.92	40.94	41.29	40.99	40.49	40.71	43.81	41.26	40.90
Hydrogen	7.02	7.24	6.80	6.76	7.26	7.19	6.95	6.77	7.00	7.03
Nitrogen	0.49	0.55	0.57	0.57	0.54	0.54	0.54	0.73	0.57	0.54
Sulfur	0.52	0.64	0.55	0.55	0.57	0.79	0.95	0.72	0.66	0.65
Oxygen	47.33	45.56	45.95	45.93	45.37	45.34	45.14	41.81	45.30	45.80
Ash	3.66	5.08	5.17	4.87	5.25	5.63	5.69	6.14	5.19	5.05
Ash Composition, as oxides, %										
Calcium, CaO	19.6	23.2	23.0	24.4	24.2	20.9	NA	21.1	22.80	22.55
Magnesium, MgO	8.2	10.4	10.5	10.8	11.7	9.6	NA	7.0	10.01	10.20
Sodium, Na_2O	3.5	3.9	3.6	4.2	3.1	3.9	NA	9.7	4.73	3.70
Silica, SiO_2	12.7	14.8	15.2	14.6	14.4	15.3	NA	15.1	14.90	14.50
Aluminum, Al_2O_3	11.6	9.1	9.5	9.6	9.6	9.0	NA	8.4	9.19	9.73
Ferric, Fe_2O_3	21.0	14.9	16.6	13.4	13.1	17.5	NA	12.3	14.63	16.08
Titanium, TiO_2	0.2	0.4	0.3	0.4	0.3	0.3	NA	0.6	0.38	0.32
Phosphorous, P_2O_5	0.6	0.7	0.6	0.7	0.7	0.6	NA	1.1	0.74	0.65
Potassium, K_2O	0.3	0.4	0.5	0.4	0.3	0.5	NA	0.6	0.46	0.40
Sulfur, SO_3	22.3	22.2	20.1	21.6	22.6	22.4	NA	24.0	22.15	21.87
High Heating Value, moisture-free, Btu/lb	11,415	11,043	10,993	11,039	10,969	10,968	NA	9,633	10,866	11,071
High Heating Value, as-received, Btu/lb	6,939	6,955	6,941	7,002	6,897	6,901	NA	7,461	7,014	6,939

TABLE B-3

Limestone Analysis (%)

Component	Average
Silica	3.44
Aluminum	0.69
Iron	0.42
Calcium	51.32
Magnesium	3.02
Sulfur	0.31
Sodium	0.08
Potassium	0.42

had heated up and coal feed was initiated, it was discovered that the coal feed system would not feed at a rate sufficient to obtain the required operational temperatures. This was unexpected, because relatively low-speed control settings had been used during the previous test with bituminous coal, and the expected coal feed rates for the lignite testing were only slightly greater. New sprockets were installed to increase the rotational speed of the coal feed rotary valve approximately threefold, resulting in satisfactory operation. The addition of a rotary seal valve below the coal and limestone feed valves, to eliminate the backflow of flue gas into the feed system, significantly reduced coal plugs in the gravity feed line into the combustor. The only serious coal feed plug was the result of a foreign object introduced with the coal that had temporarily jammed the coal feed rotary valve.

Overall operation of the system was good, one exception being that the sulfur capture was difficult to control and was not very responsive to changes in the addition rate of limestone. Based upon temperature distribution in the combustor and downcomer, it appeared that the particle collection device was functioning well, even though postrun inspection showed that most of the chevron collectors were plugged with ash. Some small agglomerates of about one-eighth-inch diameter were noted in the combustor bed material, but did not pose any operational problem.

Because of the problem of ash buildup and chevron collector plugging, a decision was made to remove the particle collection device and install a cyclone. After the first seven tests on the Center lignite were completed, the modifications associated with the fabrication and installation of a refractory-lined cyclone were completed. Curing of the refractory was completed in two stages. Initially, a low-temperature cure up to 600°F was performed using the natural gas preheater. Final high-temperature curing up to 1650°F was completed using a Beulah North Dakota lignite.

Upon completion of curing, testing of the Center lignite was resumed. Testing proceeded smoothly and on schedule through Test 10, when operational problems were suddenly encountered. Plugging occurred either at the cyclone exit into the downcomer or elsewhere inside the downcomer. The only indication of any problem was an increase in the pressure drops measured across the upper sections of the downcomer. As a result of the plug, all but a small portion of the bed material moved out of the combustor and collected in the cone of the cyclone. A temperature excursion up to 2000°F, indicated only by the bottom thermocouple in the combustor, occurred. A normal temperature profile existed in the remainder of the combustor even with the lack of bed material. Testing was discontinued at this time, and a final test at an average temperature of 1625°F was not performed.

Summary of Results

Upon completion of the run, data for each of the steady-state test periods were averaged. A summary of the process data for each test is presented in Table B-4. The ten test periods correspond to those presented in the test matrix listed in Table B-1. Summaries of the run data are presented at the end of Appendix B.

Recirculation Rates and Size Distributions

The solids recirculation rate was determined by calculating the heat balance around the external heat exchanger. The average solids recirculation rates for each test are

TABLE B-4

Summary of Process Data

	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
Time: From	1100	0800	1015	0115	1026	1630	1640	1415	0110	0545	1030
To	1300	2015	1417	0515	1430	2030	0040	2041	0310	0745	1230
Date	3/19/91	3/21/91	3/22/91	3/23/91	3/23/91	3/23/91	4/15-16/91	7/24/91	7/25/91	7/25/91	7/25/91
Coal Feed Rate, lb/hr	333	301	221	149	173	235	284	258	254	260	300
Limestone Feed Rate, lb/hr	0	20	6	0	3	7	5	14	12	10	9
Solids Recirculation Rate, lb/hr	4158	3171	2448	1221	385	2428	3750	6964	9457	11641	13953
Combustion Air											
EHX Flow, scfm	36	63	80	44	51	57	55	50	63	51	52
Primary Air, scfm	221	180	152	155	196	190	201	175	179	182	203
Secondary Air, scfm	201	189	154	172	120	155	169	178	161	178	180
Feed Assist Air, scfm	19	19	19	19	19	19	19	19	19	19	19
DC Aeration Air, scfm	0	0	0	0	0	0	0	0	0	0	0
Purge Air, scfm	0	0	0	0	0	0	0	13.3	13.3	13.3	13.3
Total Air, scfm	477	451	404	390	386	422	445	422	422	430	455
PA/SA, %	56	56	60	53	67	62	60	56	61	56	59
Excess Air, %	22.0	25.7	56.7	100.0	95.3	58.3	22.1	23.8	23.4	27.1	27.1
FG Superficial Gas Velocity, ft/sec	14.6	14.1	11.3	9.5	11.6	12.9	16.5	15.4	15.0	14.5	16.1
EHX Superficial Gas Velocity, ft/sec	1.2	2.2	2.2	0.9	1.8	1.9	1.7	1.8	2.2	1.7	1.9
Comb. dP, in. H_2O	47.6	50.5	53.4	50.6	42.8	39.1	49.0	58.6	62.4	72.8	65.7
Flue Gas											
Flow Rate, scfm	564	562	477	463	445	505	493	484	495	520	541
Oxygen, %	3.8	4.3	7.6	11.5	10.3	7.7	3.8	4.0	4.0	4.5	4.5
SO_2, ppm	727	311	99	27	261	238	439	373	20	3	10
CO, %	0.0015	0.0010	0.0042	0.0075	0.0009	0.0013	0.0011	0.0044	0.0025	0.0128	0.0069
NO_x, ppm	135	187	91	82	165	172	174	125	92	63	98
N_2O, ppm	46	21	95	145	32	36	20	ND*	ND	ND	ND
CO_2, %	16.3	16.5	13.0	8.8	10.2	12.8	16.4	16.3	15.8	15.7	15.3
Ash											
Bed Material Add Rate, lb/hr	3.1	11.4	25.4	5.2	28.6	17.1	8.9	0	0	0	0
Bottom Ash Discharge Rate, lb/hr	25	14	24	17	22	22	17	19	19.1	19.1	19.1
Bottom Ash Unburned Carbon, %	0.00	0.00	0.00	0.04	0.00	0.06	0.00	0.00	0.00	0.00	0.00
Cyclone Ash Discharge Rate, lb/hr	0	0	0	0	0	0	0	0	0	0	0
Cyclone Ash Unburned Carbon, %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Baghouse Ash Discharge Rate, lb/hr	1	9	3	3	1	6	1	8	8	8	8
Baghouse Ash Unburned Carbon, %	0.00	0.22	0.78	1.80	1.67	0.37	0.00	0.00	0.00	0.00	0.00
Total Ash (meas.), lb/hr	26	22	27	20	23	28	18	27	27	27	27
Total Ash (calc.), lb/hr	13	29	17	8	11	19	22	27	27	26	25
Bottom Ash/Total Ash (meas.), %	94.6	61.1	89.2	84.2	94.3	78.6	97.1	70.5	70.5	70.5	70.5

* Not determined.

continued...

TABLE B-4 (continued)

	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
Time: From	1100	0800	1015	0115	1026	1630	1640	1415	0110	0545	1030
To	1300	2015	1417	0515	1430	2030	0040	2041	0310	0745	1230
Date	3/19/91	3/21/91	3/22/91	3/23/91	3/23/91	3/23/91	4/15-16/91	7/24/91	7/25/91	7/25/91	7/25/91
Air and Gas Temperature											
Combustor											
Plenum	569	545	435	385	461	508	526	495	481	470	518
Section 1	1492	1525	1336	1079	1515	1477	1542	1511	1433	1340	1437
Section 2	1516	1552	1368	1082	1527	1492	1575	1536	1455	1356	1456
Section 3	1560	1582	1414	1186	1556	1542	1615	1557	1475	1385	1470
Section 4	1551	1571	1405	1215	1562	1523	1589	1557	1480	1397	1477
Section 5	1567	1587	1428	1337	1555	1558	1619	1578	1496	1410	1485
Section 6	1542	1565	1391	1330	1551	1561	1576	1572	1492	1413	1487
Section 7	1531	1556	1376	1310	1549	1564	1554	1572	1481	1406	1482
Section 8	1524	1550	1355	1245	1542	1564	1523	1572	1493	1416	1487
Section 9	1548	1575	1388	1304	1545	1567	1570	1564	1482	1413	1484
PCD Exit	1523	1541	1359	1267	1469	1512	1536	1526	1461	1392	1451
Average	1526	1554	1375	1185	1537	1522	1570	1545	1465	1378	1464
EHX											
Plenum	108	123	128	106	113	118	118	125	126	117	128
0.5' above Distributor Plate	1161	1247	888	550	1270	1176	1080	1351	1246	1200	1368
1.5' above Distributor Plate	1149	1228	884	545	1271	1160	1070	1321	1220	1175	1338
2.7' above Distributor Plate	1159	1246	888	550	1266	1175	1081	1346	1232	1184	1350
3.8' above Distributor Plate	945	1161	832	447	1139	1109	962	1322	1220	1172	1327
5.3' above Distributor Plate	825	1058	746	398	980	996	831	1235	1166	1102	1253
Average	1157	1240	887	549	1269	1170	1077	1339	1233	1186	1351
Downcomer											
Section 3	1488	1531	1269	1038	1379	1441	1469	1546	1444	1381	1479
Section 4	1470	1499	1287	1083	1397	1447	1452	1518	1422	1360	1451
Section 6	1491	1523	1329	1154	1438	1492	1502	1525	1444	1371	1450
Section 8	1525	1550	1354	1209	1466	1515	1522	1558	1484	1413	1485
Ambient	80	75	76	76	79	78	73	83	79	75	83

shown in Table B-5. The recirculation rates for the first seven tests (0-6) are low compared to those from the last four tests (7-10). This reflects differences in operation with the particle collection device for the first set of tests versus the cyclone for the second set of tests. It should be noted that ash from the secondary 18-inch cyclone was recycled to the downcomer for both weeks of testing. The relative recirculation rates for the tests are consistent with the operating conditions for each test. The recirculation rate decreased as the combustor velocity was decreased for the load tests. As the velocity is lowered, a smaller maximum particle size is carried out of the combustor, resulting in a lower recirculation rate. Similarly, increasing the velocity carries larger particles out of the combustor, resulting in a higher recirculation rate. The reason for the lower recirculation rate of Test 7 compared to 8 through 10 is unknown.

Primary cyclone collection efficiency is defined as one minus the ratio of fly ash collected to recirculation rate. During both weeks of testing, ash collected in the secondary 18-inch cyclone was recirculated. This resulted in an overall collection efficiency approaching 100% for all tests.

The particle-size distributions throughout the run were fairly consistent. Figure B-2 shows the particle-size distributions for the combustor bed material, downcomer material, ash-fouling section ash, and baghouse ash, respectively, for several of the tests.

Bottom Ash/Total Ash Split

The ash balance for the first eight test periods are presented in Table B-6. No balances were performed for the short duration emission tests (8, through 10). Ash input to the system was composed of calculated quantities of coal and limestone ash, based on their respective analyses and feed rates. The limestone-derived ash was further broken

TABLE B-5

Solids Recirculation and Heat-Transfer Data

Test	Temperature (°F)	Ca/S	Excess Air (%)	Primary Air (%)	Solids Recirculation (lb/hr)	DC[1] d_{50} (μm)	H_o[2]	Heat Flux (Btu/hr-ft^2)	Cyclone Efficiency (%)	Recirculation Ratio
0	1,526	0.9	22.0	56	4,158	330	18.1	25,547	99.97	341
1	1,554	4.0	25.7	56	3,171	330	16.5	23,818	99.73	90
2	1,375	2.6	56.7	60	2,448	250	13.1	16,782	99.88	142
3	1,185	1.2	100.0	53	1,221	300	10.3	11,398	99.74	169
4	1,537	2.2	95.3	67	ND[3]	280	19.0	26,946	99.66	32
5	1,522	1.9	58.3	62	2,428	ND	17.0	23,768	99.75	122
6	1,570	1.3	22.1	60	3,750	ND	16.5	23,860	99.99	179
7	1,545	3.1	23.8	56	6,964	ND	19.5	27,352	99.89	231
8	1,465	2.8	23.4	61	9,457	ND	19.0	25,290	ND	ND
9	1,378	2.5	27.1	56	11,641	ND	20.5	25,521	ND	ND
10	1,464	2.3	27.1	59	13,953	ND	21.8	28,812	ND	ND

[1] Downcomer.
[2] Heat-transfer coefficient (Btu/hr-ft^2-°F).
[3] Not determined.

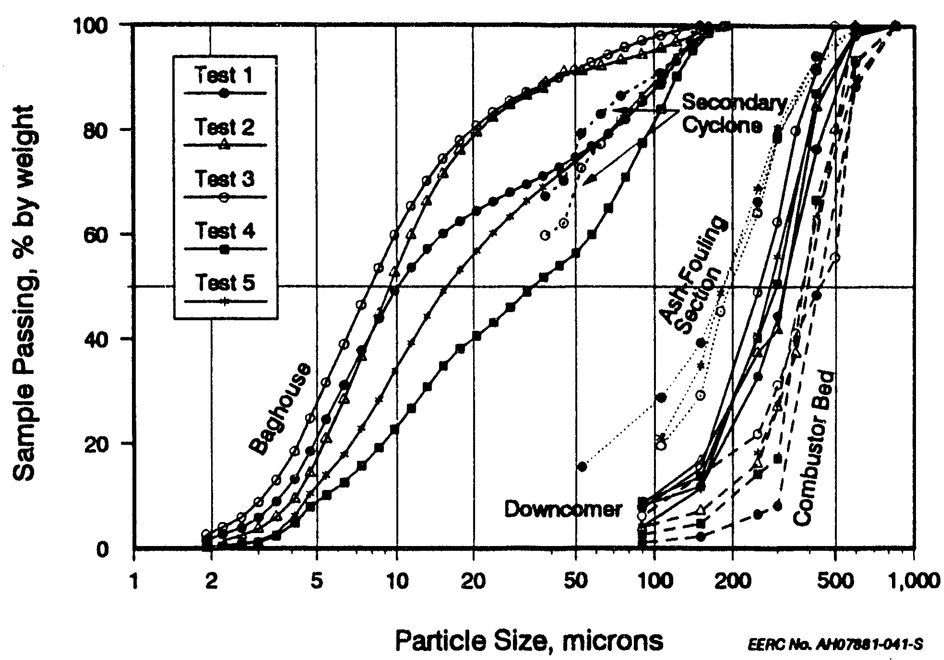

Figure B-2. Size distribution of combustor bed material, downcomer, ash-fouling section ash, secondary cyclone ash, and baghouse ash.

TABLE B-6

Ash Balance

	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Input, lb/hr								
Ash	13	16	12	8	9	13	17	18
Sorbent*								
CaO	0	9	2	0	1	2	2	7
$CaSO_4$	0	4	2	0	1	3	3	4
Total Solids In	13	29	17	8	11	19	21	28
Output, lb/hr								
Bed Material	25	14	24	17	22	22	17	19
Cyclone Ash	0	0	0	0	0	0	0	0
Baghouse Ash	1	9	3	3	1	6	1	8
Total Solids Out	26	22	27	20	23	28	18	27
Closure, %	202.9	75.0	161.9	265.7	206.4	148.7	82.2	98.0
Bottom Ash/Total Ash, %	94.6	61.1	89.2	84.2	94.3	78.6	97.1	70.5

* The CaO and $CaSO_4$ mass inputs are included to express sorbent equivalent mass inputs.

down into estimates of the sorbent which was either calcined or had undergone sulfation. The output was composed of measured quantities of bottom ash (drained from the combustor bed), fly ash removed from the secondary cyclone, and fly ash removed from the baghouse.

The ratios of bottom ash-to-total ash, as well as the percent closures, are included in Table B-6. The poor closure for some of the tests are likely due to errors in measuring small amounts of material and, possibly, from the carryover of some of the initial bed material that is not accounted for in the input stream. The bottom-to-total ash split for the tests ranged from about 61% to about 97%. These high bottom-to-total ash splits are likely due to the high collection efficiency of the secondary cyclone. If a full-scale system did not reinject ash from a secondary collection device, a greater proportion of fly ash would be generated.

An alumina material balance, which had been used for determining the contributions of coal ash and limestone at each solids removal point, was not performed for the Center lignite run. Insufficient analyses were performed on the solids streams to calculate an alumina balance.

THERMAL PERFORMANCE

Energy and Material Balances

The measured and theoretical fuel and flue gas flow rates are presented in Tables B-7 and B-8, respectively. The theoretical fuel feed rate was calculated using actual fuel characteristics, measured combustion air, and measured O_2 and CO_2 concentrations in the flue gas. The theoretical flue gas rates were calculated using the actual coal feed rate and excess air level for each test. In most cases, the measured and theoretical rates were similar.

The energy balances for each test are presented in Table B-9 both as Btu/hr and percentages. The energy input was made up of the energy potential of the fuel, the primary and secondary combustion air, the external heat exchanger fluidizing air, and the energy released from the sulfation of the sorbent. Measurable heat loss sources were the combustor heat exchange doors, the external heat exchanger cooling coils, the flue gas, the unburned carbon in the ash removed, the heat present in the ash removed, and the energy absorbed during calcination of the sorbent. Flue gas losses include a correction for leakage. The unmeasurable heat loss due to convection and radiation is based upon a correlation developed from testing with several coals that takes into account the average operational combustor temperature.

The material balances for the eleven test periods are shown in Table B-10. Material balance inputs are the combustion air, additional air (including the external heat exchanger fluidizing air, pressure tap purges, downcomer assist air, and coal feed assist air), coal and sorbent feed rates, and bed material addition. Outputs are the measured flue gas, flue gas leaks (based on the difference between the measured and the theoretical flue gas flow rates shown in Table B-8), and measured quantities of bed material, secondary cyclone ash, and baghouse ash removed from the system. Good material balance closures were obtained for all tests and ranged from 100.1% to 101.2%.

TABLE B-7

Fuel Balance

	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
Fuel Feed Rate, meas., lb/hr	333	301	221	149	173	235	284	258	254	260	300
Fuel Feed Rate, theor., lb/hr	339	311	231	157	169	233	297	286	287	283	299
Difference, %	-1.7	-3.2	-4.4	-5.7	2.4	0.6	-4.4	-11.1	-12.9	-9.0	0.2

meas. = Feed rate calculated on coal feed hopper weight loss over time.
theor. = Theoretical feed rate calculated on the basis of the coal analysis, the combustion air, and the excess air for each test period.

TABLE B-8

Flue Gas Balance

	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
Stack Gas Flow, meas., scfm	564	561	477	436	445	509	497	484	495	520	541
Stack Gas Flow, theor., scfm	557	525	459	429	429	478	510	499	499	507	534
Difference, %	1.2	6.6	3.9	1.5	3.7	6.1	-2.8	-3.1	-0.8	2.5	1.2

meas. = The flue gas flow measured during the run through an orifice located just upstream of the ID fan.
theor. = Theoretical flue gas flow calculated on the basis of the coal analysis and the theoretical coal feed rate for each test period.

TABLE B-9

Energy Balance[1]

	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
Input, Btu/hr											
Coal	2,204,724	2,031,905	1,506,930	1,034,497	1,094,871	1,513,192	1,961,141	2,055,658	2,061,404	2,032,674	2,147,595
Primary Air	120,011	93,645	60,491	53,061	82,896	90,878	101,220	80,031	79,695	79,754	98,019
Secondary Air	108,829	98,758	61,208	58,994	51,052	73,982	85,029	81,403	71,886	78,044	87,058
EHX Air	1,125	3,362	4,595	1,449	1,917	2,522	2,737	2,312	3,261	2,373	2,612
Sorbent Sulfation	0	6,440	3,804	0	1,330	4,342	3,556	4,645	8,052	7,403	6,953
Total	2,434,689	2,234,110	1,637,028	1,148,000	1,232,066	1,684,915	2,153,683	2,224,049	2,224,297	2,200,248	2,342,236
Input, %											
Coal	90.6	90.9	92.1	90.1	88.9	89.8	91.1	92.4	92.7	92.4	91.7
Primary Air	4.9	4.2	3.7	4.6	6.7	5.4	4.7	3.6	3.6	3.6	4.2
Secondary Air	4.5	4.4	3.7	5.1	4.1	4.4	3.9	3.7	3.2	3.5	3.7
EHX Air	0.0	0.2	0.3	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Sorbent Sulfation	0.0	0.3	0.2	0.0	0.1	0.3	0.2	0.2	0.4	0.3	0.3
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Output, Btu/hr											
Flue Gas (sens.)	1,011,877	968,771	729,347	620,306	728,562	848,878	939,254	905,411	867,136	839,600	918,557
Ash (sens.)	10,074	8,793	9,400	6,056	9,021	10,872	7,047	10,658	10,104	9,499	10,067
Ash (chem.)[2]	ND[3]	1,086	1,739	2,906	353	1,321	ND	ND	ND	ND	ND
Combustor	531,377	433,486	305,424	207,451	70,060	185,391	434,247	426,694	460,285	464,483	524,375
EHX	514,786	374,779	250,752	125,386	0	255,779	443,469	408,775	563,214	604,912	461,067
Sorbent Calcination	0	15,167	4,443	0	2,375	5,132	3,677	10,954	9,422	7,660	6,588
Conduction and Radiation Losses	431,699	445,213	358,819	267,115	437,008	429,527	452,936	440,869	402,257	360,267	401,775
Total	2,499,814	2,247,294	1,659,923	1,229,220	1,247,377	1,736,901	2,280,630	2,203,361	2,312,418	2,286,421	2,322,429
Output, %											
Flue Gas (sens.)	40.5	43.1	43.9	50.5	58.4	48.9	41.2	41.1	37.5	36.7	39.6
Ash (sens.)	0.4	0.4	0.6	0.5	0.7	0.6	0.3	0.5	0.4	0.4	0.4
Ash (chem.)	0.0	0.0	0.1	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Combustor	21.3	19.3	18.4	16.9	5.6	10.7	19.0	19.4	19.9	20.3	22.6
EHX	20.6	16.7	15.1	10.2	0.0	14.7	19.4	18.6	24.4	26.5	19.9
Sorbent Calcination	0.0	0.7	0.3	0.0	0.2	0.3	0.2	0.5	0.4	0.3	0.3
Conduction and Radiation Losses	17.3	19.8	21.6	21.7	35.0	24.7	19.9	20.0	17.4	15.8	17.3
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Closure	102.7	100.6	101.4	107.1	101.2	103.1	105.9	99.1	104.2	103.9	99.2

[1] Theoretical coal feed rate used in all calculations.
[2] The heat of combustion coefficient for pure carbon is an average of values found in the *Standard Handbook for Mechanical Engineers*, Baumeister and Marks (1967), and *Perry's Chemical Engineering Handbook*, Perry et al. (1984).
[3] Not determined.

TABLE B-10

Material Balance

	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
Input, lb/hr											
Combustion Air	2096	1978	1763	1695	1679	1842	1947	1843	1842	1881	1994
Additional Air	88	88	88	88	88	88	88	149	149	149	149
Bed Material	3	11	25	5	29	17	9	0	0	0	0
Coal Feed	339	311	231	157	169	233	297	286	287	283	299
Sorbent Feed	0	20	6	0	3	7	5	14	12	10	9
Total Mass in	2526	2408	2113	1945	1968	2187	2345	2293	2290	2323	2451
Input, %											
Combustion Air	83.0	82.1	83.4	87.1	85.3	84.2	83.0	80.4	80.4	80.9	81.8
Additional Air	3.5	3.7	4.2	4.5	4.5	4.0	3.8	6.5	6.5	6.4	6.1
Bed Material	0.1	0.5	1.2	0.3	1.5	0.8	0.4	0.0	0.0	0.0	0.0
Coal Feed	13.4	12.9	10.9	8.1	8.6	10.7	12.6	12.5	12.5	12.3	11.7
Sorbent Feed	0.0	0.8	0.3	0.0	0.2	0.3	0.2	0.6	0.5	0.4	0.4
Total Mass in	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Output, lb/hr											
Measured Flue Gas	2561	2558	2173	1978	2022	2312	2272	2215	2260	2374	2465
Flue Gas Leaks	-30	-168	-184	-30	-76	-141	63	70	19	-58	-30
Ash Out											
Bed Material	25	14	24	17	22	22	17	19	19	19	19
Baghouse	1	9	3	3	1	6	1	8	8	8	8
Cyclone Ash	0	0	0	0	0	0	0	0	0	0	0
Total Mass Out	2557	2412	2115	1968	1969	2200	2353	2312	2306	2343	2462
Output, %											
Measured Flue Gas	100.1	106.0	102.7	100.5	102.7	105.1	96.6	95.8	98.0	101.3	100.1
Flue Gas Leaks	-1.2	-7.0	-4.0	-1.5	-3.8	-6.4	2.7	3.0	0.8	-2.5	-1.2
Ash Out											
Bed Material	1.0	0.6	1.1	0.9	1.1	1.0	0.7	0.8	0.8	0.8	0.8
Baghouse	0.1	0.4	0.1	0.2	0.1	0.3	0.0	0.3	0.3	0.3	0.3
Cyclone Ash	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Mass Out	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Closure	101.2	100.2	100.1	101.2	100.1	100.6	100.3	100.8	100.7	100.8	100.4

Combustion Efficiency

The combustion efficiencies for Tests 1 through 5 are presented in Table B-11 and Figure B-3. The combustion efficiencies for the five tests were very high, with very little unburned carbon in the drained bed material or baghouse ash (Table B-12). Insufficient samples were taken during Tests 0, 6, and 7 for combustion efficiency to be calculated. Solid samples were not taken for the emission tests (8 through 10).

Boiler Efficiency

Boiler efficiencies were calculated for each test period using a modified version of ASME PTC 4.1. The modifications to the PTC 4.1 are those recommended in EPRI's "Atmospheric Fluidized-Bed Combustion Performance Guidelines." The basic modification made to PTC 4.1 is a method to account for the heat losses and gains associated with calcination and sulfation of the limestone.

Table B-13 summarizes the results of boiler efficiency calculations for the Center lignite tests. In performing these calculations, boiler radiation and convective losses were assumed to be 0.4%. Although these losses were much higher for our pilot plant, 0.4% was chosen as a number that is representative of a full-scale system. Vendors may quote slightly different radiation and convective losses. The boiler efficiency numbers presented here also do not include unaccounted losses and manufacturing margins that are typically specified by the vendor. An exit gas temperature of 300°F was used in the efficiency calculations.

For full-load operation, the boiler efficiency was approximately 86.5%. As the load was reduced, the boiler efficiency decreased at a rate of ½ percentage point for each 10% increase in excess air. The moisture and hydrogen accounted for about 6.8% of the losses and is constant for all tests. The loss due to solids removal increased as the limestone feed rate was increased due to the generation of more solids. Contributions due to sorbent calcination and sulfation are also a function of sorbent feed rate. The major change between tests is the dry flue gas losses, which are directly related to excess air level.

Heat-Transfer Coefficient and Heat Flux

During testing, the combustor heat exchange surfaces used for heat removal were in Sections 2, 3, 4, 6, 7, and 8. Flow rates and temperatures of the cooling water in the combustor heat exchangers were monitored to allow calculation of heat-transfer coefficients and heat fluxes as a function of position in the combustor. Heat transfer and heat flux within the EHX were also calculated based upon the total flow and overall temperature difference of the cooling water from the EHX heat exchange coils. The average values of heat-transfer coefficient and heat flux for each combustor section which contains one or more heat exchangers, as well as from the EHX, are presented in Tables B-14 and B-15. The combustor heat-transfer data are also summarized in Table B-5 to facilitate comparison to test conditions.

The combustor heat flux calculated for this run ranged from 11,398 Btu/hr-ft^2 for Test 3 to 28,812 Btu/hr-ft^2 for Test 10. Similarly, the EHX heat flux ranged from 27,864 Btu/hr-ft^2 to 122,951 Btu/hr-ft^2 for Tests 3 and 10, respectively. The low heat fluxes observed during Tests 2 and 3 were the result of reduced load while operating with

TABLE B-11

Combustion Efficiency

	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
Input											
Coal Feed Rate, lb/hr	339.0	310.8	230.8	156.9	169.0	233.4	296.7	286.2	287.0	283.0	299.0
Coal Carbon, %	41.0	40.9	40.9	41.3	41.0	40.5	40.7	43.8	43.8	43.8	43.8
Carbon Feed Rate, lb/hr	138.8	127.2	94.5	64.8	69.3	94.5	120.8	125.4	125.7	124.0	131.0
Total, lb/hr	138.8	127.2	94.5	64.8	69.3	94.5	120.8	125.4	125.7	124.0	131.0
Output											
Bottom Ash Discharge Rate, lb/hr	25	14	24	17	22	22	17	19	19	19	19
Unburned Carbon, %	ND[1]	0	0.34	0.83	0.00	0.26	ND	ND	ND	ND	ND
Bottom Ash Carbon Discharge Rate, lb/hr	0.00	0.00	0.08	0.14	0.00	0.06	0.00	0.00	0.00	0.00	0.00
Baghouse Discharge Rate, lb/hr	1	9	3	3	1	6	1	8	8	8	8
Unburned Carbon, %	ND	0.90	1.45	2.03	1.92	0.60	ND	ND	ND	ND	ND
Baghouse Carbon Discharge Rate, lb/hr	0.00	0.08	0.04	0.07	0.03	0.04	0.00	0.00	0.00	0.00	0.00
Total, lb/hr	0.00	0.08	0.12	0.21	0.03	0.09	0.00	0.00	0.00	0.00	0.00
Combustion Efficiency, %	ND	99.94	99.87	99.68	99.96	99.90	ND	ND	ND	ND	ND

[1] Not determined.

TABLE B-12

Unburned Carbon (%)

	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
Combustor Bed Material											
Loss on Ignition	ND	0.00	0.59	1.12	0.00	0.34	ND	ND	ND	ND	ND
Carbonate (as CO_2)	ND	0.31	0.92	1.08	0.01	0.28	ND	0.44	ND	ND	ND
Unburned Carbon	ND	0.00	0.34	0.83	0.00	0.26	ND	ND	ND	ND	ND
Baghouse Ash											
Loss on Ignition	ND	1.15	1.70	2.12	2.02	0.68	ND	ND	ND	ND	ND
Carbonate (as CO_2)	ND	0.93	0.92	0.32	0.35	0.31	ND	ND	ND	ND	ND
Unburned Carbon	ND	0.90	1.45	2.03	1.92	0.60	ND	ND	ND	ND	ND

TABLE B-13

Boiler Efficiency

	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
Assumed flue gas exit temp. °F	300	300	300	300	300	300	300	300	300	300	300
Losses, Btu/hr											
Dry Gas	129,923	122,887	109,129	103,481	102,659	113,212	121,088	118,579	118,579	120,480	126,896
Water in Fuel	158,347	137,027	101,481	68,427	74,711	103,181	126,922	76,732	76,946	75,874	80,164
Comb. of Fuel Hydrogen	10,763	11,588	7,425	5,035	6,319	8,532	10,469	14,562	14,603	14,399	15,213
Unburned Carbon	ND	1,086	1,739	2,906	353	1,321	ND	ND	ND	ND	ND
Sorbent Calcination	0	15,167	4,443	0	2,375	5,132	3,677	10,954	9,422	7,660	6,588
Radiation and Convection[1]	9,409	8,646	6,408	4,394	4,662	6,443	8,324	8,541	8,565	8,446	8,923
Discharged Solids	10,074	8,793	9,400	6,056	9,021	10,872	7,047	10,658	10,104	9,499	10,067
Sorbent Sulfation	0	-6,440	-3,804	0	-1,330	-4,342	-3,556	-4,645	-8,052	-7,403	-6,953
Total	318,516	298,753	236,220	190,299	198,769	244,350	273,970	235,381	230,167	228,954	240,898
Losses, %											
Dry Gas	5.5	5.7	6.8	9.4	8.8	7.0	5.8	5.6	5.5	5.7	5.7
Water in Fuel	6.7	6.3	6.3	6.2	6.4	6.4	6.1	3.6	3.6	3.6	3.6
Comb. of Fuel Hydrogen	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.7	0.7	0.7	0.7
Unburned Carbon	0.0	0.1	0.1	0.3	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Sorbent Calcination	0.0	0.7	0.3	0.0	0.2	0.3	0.2	0.5	0.4	0.4	0.3
Radiation and Convection[1]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Discharged Solids	0.4	0.4	0.6	0.6	0.8	0.7	0.3	0.5	0.5	0.4	0.5
Sorbent Sulfation	0.0	-0.3	-0.2	0.0	-0.1	-0.3	-0.2	-0.2	-0.4	-0.4	-0.3
Total	13.5	13.8	14.7	17.3	17.1	15.2	13.2	11.0	10.7	10.8	10.8
Boiler Efficiency, %	86.5	86.2	85.3	82.7	82.9	84.8	86.8	89.0	89.3	89.2	89.2

[1] Assumes 0.4% radiative and convective losses.

TABLE B-14

Individual Heat-Transfer Coefficients (Btu/hr-ft^2-°F)

Combustor Section	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Average	Combustor Height
2	27.8	26.5	22.0	14.1	21.1	22.4	24.9	26.0	27.2	31.0	31.4	24.9	7.5
3	21.2	21.3	15.8	10.6	off	19.8	off	18.7	18.9	21.4	22.7	18.9	12.5
4	17.2	16.2	12.5	9.5	off	17.1	15.9	15.1	14.5	15.0	16.6	15.0	17.5
6	17.6	17.4	13.7	11.6	off	off	17.2	16.6	15.6	14.9	16.8	15.7	27.5
7	16.9	16.1	12.6	11.2	off	off	15.0	14.0	13.3	13.5	15.8	14.3	32.5
8	16.1	16.1	8.7	10.1	off	off	16.7	off	14.1	13.2	15.5	13.8	37.5
Overall	18.1	16.5	13.1	10.3	19.0	17.0	16.5	19.5	19.0	20.5	21.8	17.4	
EHX	72.7	75.0	70.7	58.0	off	81.6	68.8	91.8	98.5	97.5	103.6	81.8	

TABLE B-15

Individual Heat Flux (Btu/hr-ft^2)

Combustor Section	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Average	Combustor Height
2	38,760	38,182	28,282	14,392	29,859	30,878	36,119	36,270	35,766	37,577	41,025	33,374	7.5
3	30,518	31,090	20,976	11,957	off	28,100	off	26,574	25,457	26,835	30,061	25,730	12.5
4	24,834	23,788	16,580	10,922	off	24,020	23,440	21,624	19,683	19,166	22,403	20,646	17.5
6	25,236	25,264	17,857	14,492	off	off	24,965	23,877	21,304	19,288	22,784	21,674	27.5
7	23,985	23,339	16,197	13,828	off	off	21,621	19,894	17,931	17,281	21,226	19,478	32.5
8	22,886	23,289	11,065	11,887	off	off	23,462	off	19,280	16,988	20,959	18,727	37.5
Overall	25,547	23,818	16,782	11,398	26,946	23,768	23,860	27,352	25,290	25,521	28,812	23,554	
EHX	76,265	83,284	55,723	27,864	off	85,260	65,699	109,007	107,279	100,819	122,951	83,415	

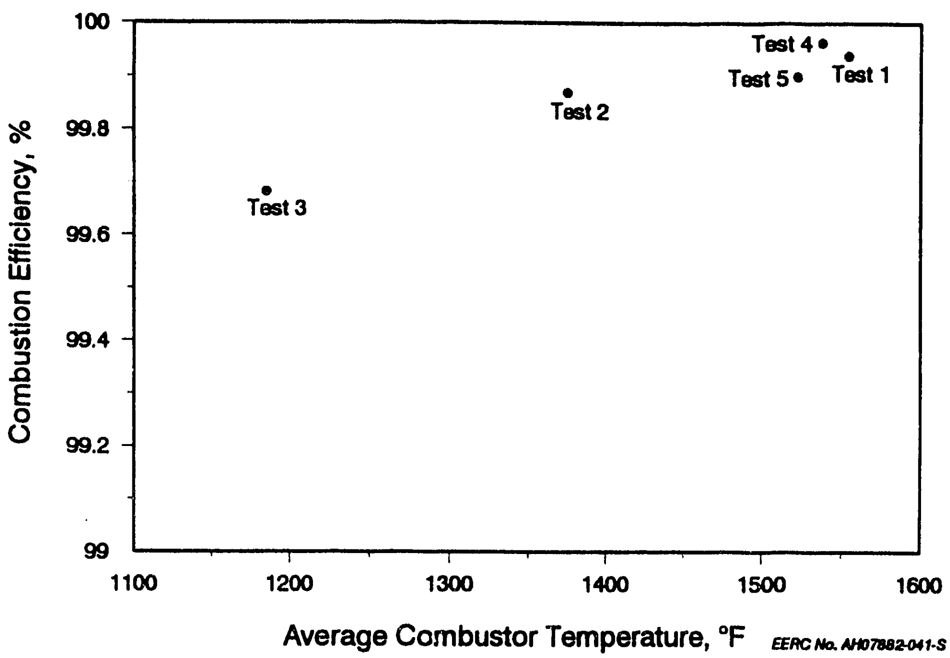

Figure B-3. Combustion efficiency as a function of temperature.

constant heat-transfer surface. During constant heat-transfer load reduction, the total amount of heat-transfer surface kept in service is equivalent to that used during the full-load baseline test with sorbent addition. By reducing load under constant heat-transfer conditions, operational temperatures and velocity are reduced, lowering the solids recirculation rate, thereby decreasing heat transfer. For Tests 4 and 5, which utilized a constant temperature load reduction technique, heat-transfer surface was taken out of service, and combustor temperatures and velocity were maintained near full-load levels. Therefore, heat-transfer performance was affected to a lesser degree.

The heat flux measured for the full-load tests is similar to the 24,500 to 35,800 Btu/hr-ft^2 observed in previous runs on this unit and on full-scale units. There was limited variability in heat flux between the full-load tests. Similar trends were seen with the heat-transfer coefficients.

Pressure and Temperature Profiles

The pressure profiles for Tests 7 through 10 are presented in Figure B-4, and the temperature profiles for Tests 0 through 10 are presented in Figure B-5. The pressure profiles for Tests 0 through 6 were not plotted because the pressure taps quickly plugged with ash during those tests. Following Test 6, a continuous air purge system was added to keep the pressure taps clear. The temperature profile for the full-load tests are quite uniform; areas of lower temperature are caused by heat-transfer doors in those sections of the combustor. The low-load tests (2 and 3) which correspond to those systems without an external heat exchanger have a much lower temperature in the bottom of the combustor than the top.

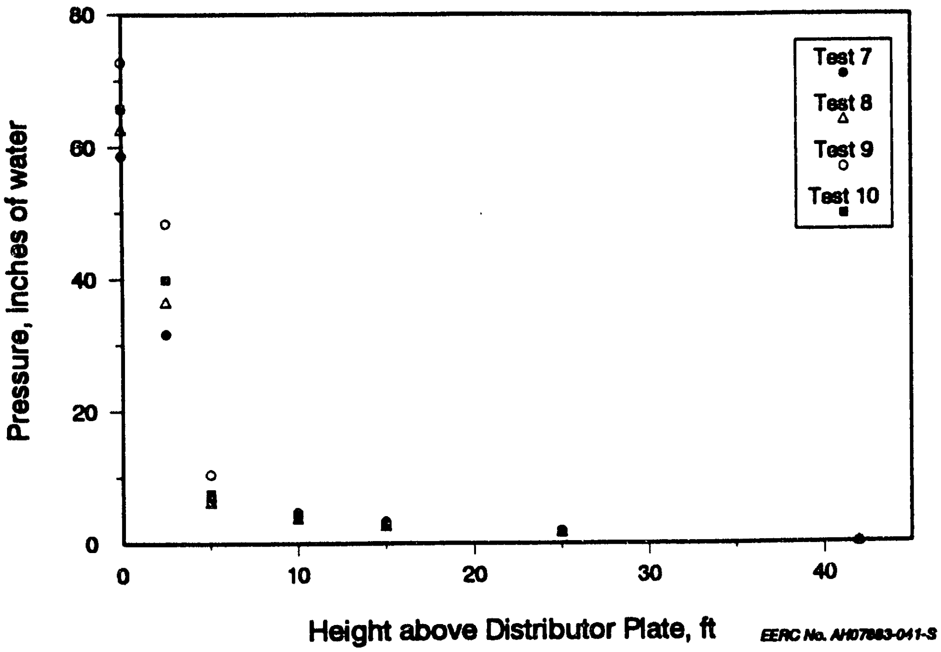

Figure B-4. Combustor pressure profiles.

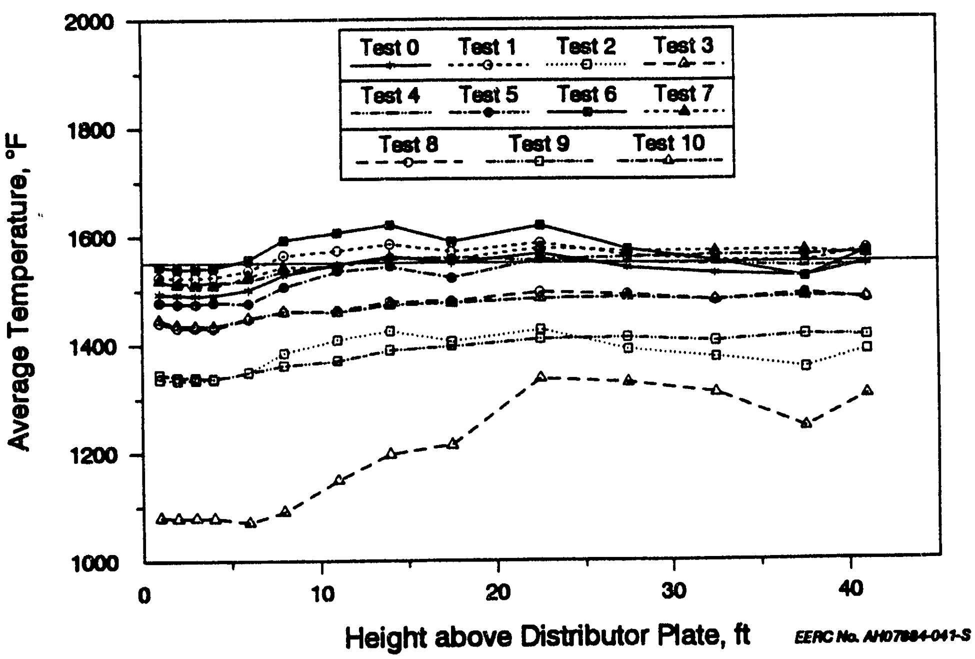

Figure B-5. Combustor temperature profiles.

ENVIRONMENTAL PERFORMANCE

Average flue gas emissions for each of the steady-state test periods are presented in Table B-16 and discussed in the following sections. All of the emissions are represented graphically in relation to average combustor temperature. The trends noted in all cases were the same as expected based on previous experience.

SO_2 Emissions

Uncontrolled sulfur emissions for the Center lignite, corrected to 3% oxygen, were 760 ppm (1.406 lb/MM Btu). For those tests with limestone addition, the average concentration of SO_2 in the flue gas varied from 3 to 459 ppm (0.006 to 0.839 lb/MM Btu), depending upon the operating temperature and ratio of calcium to sulfur in the system. Figure B-6 shows that the lowest SO_2 emissions occurred under Test 8, 9, and 10 conditions, during which the average combustor temperature ranged from 1375° to 1475°F. These data indicate that the optimum temperature for sulfur capture using the Center lignite is approximately 1400° to 1450°F. This is lower than is reported for other coals; however, it is consistent with tests using North Dakota lignites in bubbling beds where the optimum sulfur capture was obtained at approximately 1425°F.[1]

Figure B-7 is a plot of the measured sulfur retention versus total alkali-to-sulfur (Ca/S) ratio expressed on a molar basis. The data can be separated into two sets: those at 1545°F and those at lower temperatures. At equivalent Ca/S ratios, the sulfur retention was approximately 30% more for the low-temperature tests as compared to those at 1545°F, indicating that low-temperature operation is preferred for this coal in terms of sulfur capture. Overall, a Ca/S ratio of approximately 2 (1.0 from limestone plus 1.0 inherent with coal) is needed to achieve an SO_2 retention of 90% for combustor temperatures between 1400° and 1450°F. As shown in Figure B-7, the alkali inherent in the coal ash was sufficient to achieve 23% SO_2 retention at 1550°F.

NO_x Emissions

Flue gas emissions of NO_x (corrected to 3% O_2) ranged from 69 to 278 ppm (0.090 to 0.368 lb/MM Btu). The effect of temperature on NO_x emissions is shown in Figure B-8, with NO_x increasing with increasing temperature. NO_x emissions were high during Tests 2 through 5 due to the excess air levels required for these load tests. The low NO_x values for Tests 2 and 3 (122 and 156 ppm) relative to Tests 4 and 5 (278 and 232 ppm) indicate that NO_x emissions will be lower at low load for those combustion systems operating without an external heat exchanger. This is due to the corresponding lower combustor temperatures.

N_2O Emissions

Although emissions of nitrous oxide (N_2O) are currently unregulated, relatively high values have been measured from FBC systems. Because N_2O is both a greenhouse gas and an ozone destroyer, it may become regulated sometime in the future. The N_2O

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[1] Mann, M.D.; Zobeck, B.J.; Hajicek, D.R. "Comparison of FBC Performance as a Function of Coal Rank," 88-JPGC/FACT-3.

TABLE B-16

Emission Data

	Test 0	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
O_2, %	3.78	4.25	7.57	11.51	10.31	7.67	3.77	4.02	3.99	4.50	4.50
CO Content, ppm	15	10	42	75	9	13	11	44	25	128	69
CO Content,[1] ppm	16	11	56	143	16	18	12	47	27	140	75
CO Emission, lb/MM Btu	0.013	0.008	0.044	0.118	0.013	0.014	0.009	0.037	0.022	0.112	0.062
CO_2 Content, %	16.3	16.5	13.0	8.8	10.2	12.8	16.4	16.3	15.8	15.7	15.3
CO_2 Content,[1] %	17.0	17.7	17.4	16.7	17.2	17.3	17.1	17.3	16.7	17.1	16.7
NO_x Content, ppm	135	187	91	82	165	172	174	125	92	63	98
NO_x Content,[1] ppm	141	201	122	156	278	232	182	133	97	69	107
NO_x Emission, lb/MM Btu	0.188	0.256	0.159	0.211	0.368	0.302	0.236	0.172	0.131	0.090	0.144
N_2O Content, ppm	46	21	95	145	32	36	20	NA[4]	NA	NA	NA
N_2O Content,[1] ppm	48	22	127	275	54	49	21	NA	NA	NA	NA
N_2O Emission, lb/MM Btu	0.061	0.027	0.158	0.356	0.068	0.060	0.026	NA	NA	NA	NA
SO_2 Content, ppm	727	311	99	27	261	238	439	373	20	3	10
SO_2 Content,[1] ppm	760	334	133	51	439	321	459	395	21	3	11
SO_2 Emission, lb/MM Btu	1.406	0.593	0.240	0.097	0.810	0.581	0.829	0.716	0.040	0.006	0.020
SO_2 Retention,[2] %	23.2	67.5	84.8	93.9	51.1	74.4	56.5	62.9	97.9	99.7	98.9
Ca/S Ratio (ls[3] only)	0.0	2.9	1.3	0.0	0.9	1.1	0.5	2.0	1.7	1.4	1.2
Ca/S Ratio (total)	0.92	3.97	2.58	1.23	2.22	1.92	1.28	3.06	2.77	2.47	2.20
Ca Utiliz. (ls[3] only)	0.0	23.1	63.3	0.0	54.2	69.9	113.1	30.9	56.1	69.3	84.5
Ca Utiliz. (total)	25.3	17.0	32.9	76.0	23.0	38.8	44.1	20.5	35.3	40.4	45.0
Alkali-to-Sulfur (total)	0.92	4.13	2.75	1.43	2.36	2.06	1.28	3.49	3.20	2.89	2.62
Alkali Utilization (total)	25.3	16.3	30.8	65.8	21.6	36.1	44.1	18.0	30.6	34.5	37.7
Avg. Comb. Temp., °F	1526	1554	1375	1185	1537	1522	1570	1545	1465	1378	1464
Moisture in FG, vol%	15.6	15.3	12.6	9.7	10.9	12.9	14.2	14.1	14.1	14.1	14.1
Theor. FG Flow Rate, scfm	557	525	459	429	429	478	510	499	499	507	534
Meas. FG Flow Rate, scfm	564	561	477	436	445	509	497	484	495	520	541
Moisture-Free Coal Carbon, %	65.0	65.0	64.8	65.1	65.2	64.3	56.6	56.6	56.6	56.6	56.6
Moisture-Free Coal Sulfur, %	1.01	1.01	0.87	0.87	0.91	1.25	0.93	0.93	0.93	0.93	0.93

[1] Corrected to 3% O_2.
[2] Moisture-free coal carbon and sulfur values used in the sulfur retention calculation.
[3] Limestone.
[4] Not available.

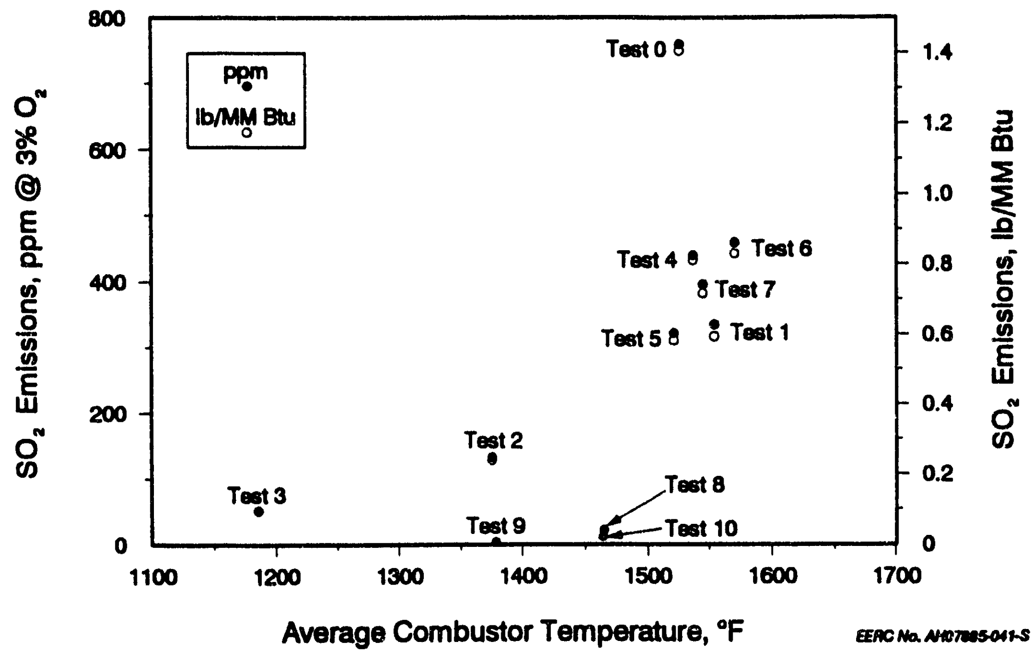

Figure B-6. SO_2 emissions as a function of average combustor temperature.

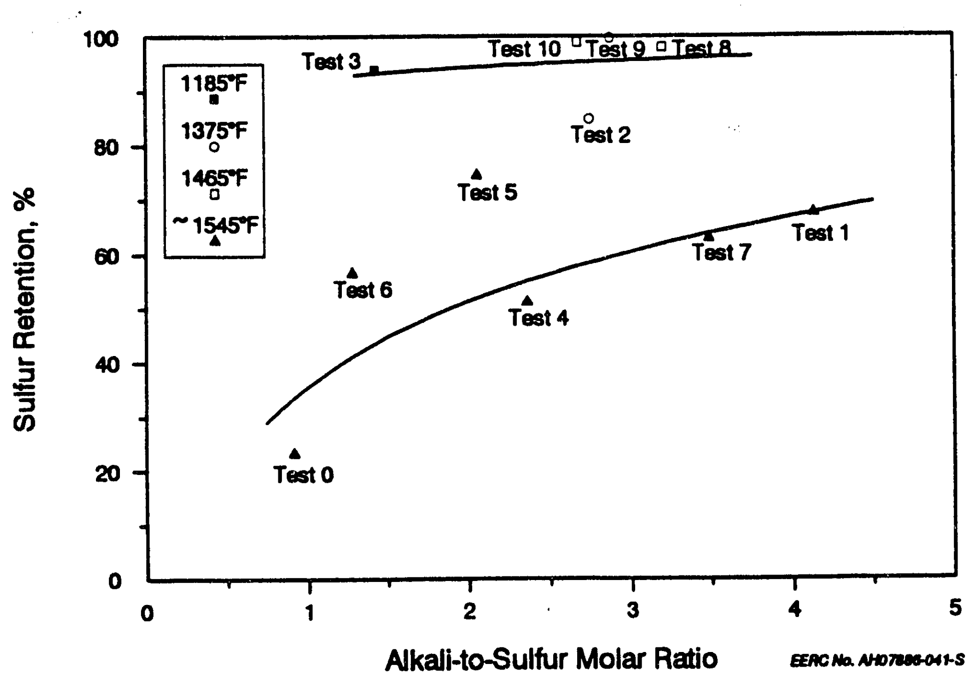

Figure B-7. SO_2 retention as a function of alkali-to-sulfur molar ratio.

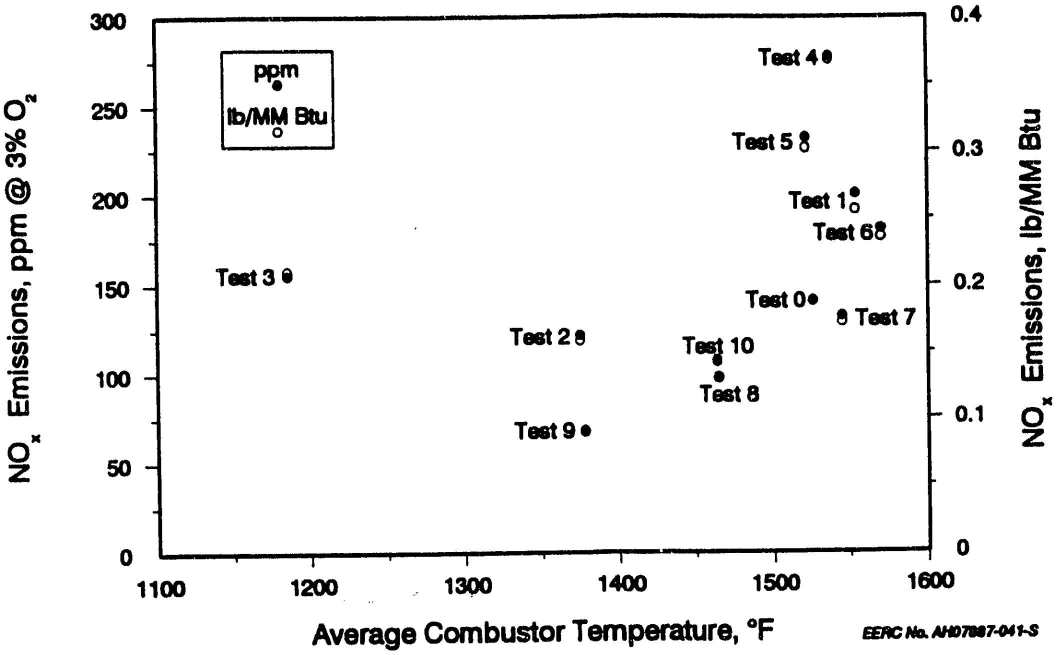

Figure B-8. NO_x emissions as a function of average combustor temperature.

emissions from the Center lignite test burn ranged from 21 to 275 ppm (corrected to 3% O_2), as shown in Figure B-9. N_2O is linearly dependent upon temperature and increases as temperature is decreased. This is the opposite trend of NO_x. For low-load conditions obtained without using the external heat exchanger, high N_2O emissions were measured, due to the low temperatures. When varying load by taking heat-transfer surface out of service (simulating use of an external heat exchanger), N_2O emissions were approximately 50 ppm. No significant differences in N_2O emissions were seen for testing with and without limestone. For comparison purposes, the N_2O emissions from the test burn with Salt Creek bituminous coal ranged from 115 to 430 ppm over a temperature range of 1350° to 1625°F.

CO Emissions

The measured emissions of CO varied from 11 to 143 ppm (corrected to 3% O_2), as shown in Figure B-10. The CO concentrations decreased as the average operating temperature increased.

SINTERING, AGGLOMERATION, AND DEPOSIT EVALUATION

Although FBCs typically operate at relatively low temperatures, evidence from pilot, industrial, and utility boilers indicates that certain ash components can cause ash-related problems. These ash-related problems can manifest themselves as agglomeration and sintering of bed material, or as deposition on the heat exchange tube surfaces and refractory walls. These ash-related phenomena have been shown to cause a loss in steam

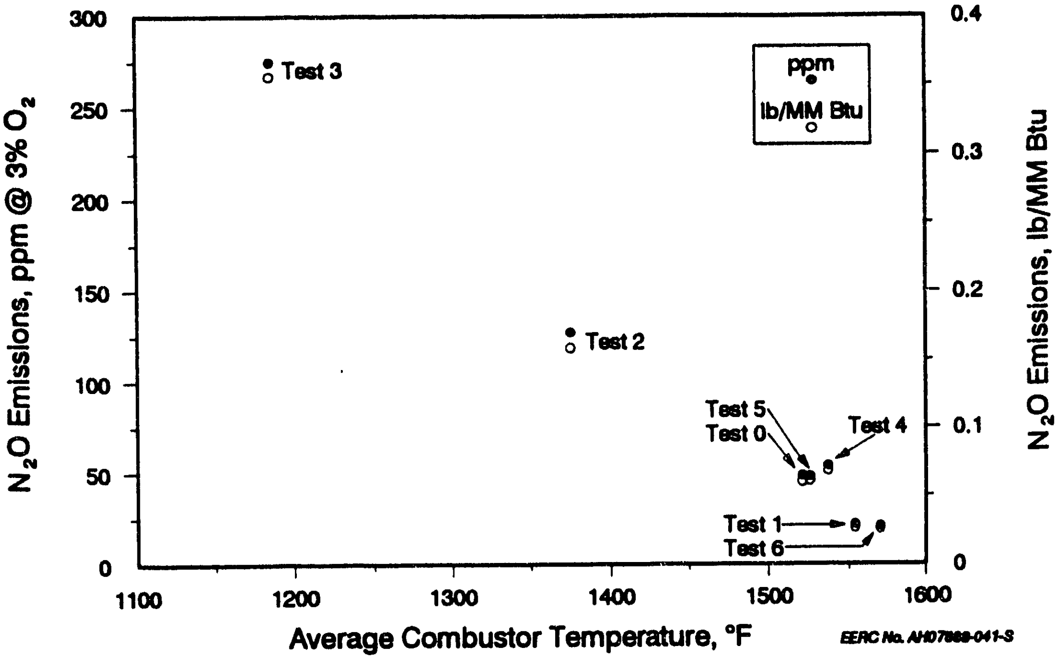

Figure B-9. N_2O emissions as a function of average combustor temperature.

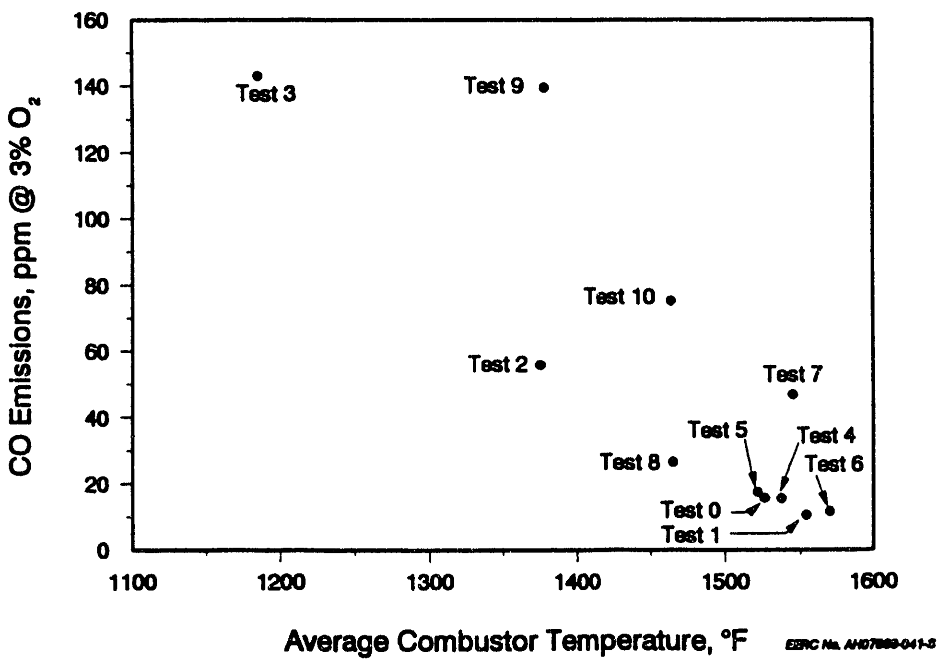

Figure B-10. CO emissions as a function of average combustor temperature.

temperature; operating difficulties; and, in some cases, unplanned shutdowns. Experience at the EERC has shown fuels with high sodium and potassium levels to be the most troublesome, particularly with bed agglomeration. Large agglomerates have been reported at the MDU Heskett bubbling FBC using a high-sodium (up to 12% NaO in the ash) Beulah North Dakota lignite, although the agglomeration is typically controlled on this unit by using a high bed turnover rate. High calcium and sulfur in the fuel have also been demonstrated to produce ash-related problems. Because of the nature of the ash from North Dakota lignites and experience burning this fuel in pc-fired systems, an important goal of this study was to determine the nature of any ash-related problems.

After the first week of testing, some small agglomerates of about one-eighth-inch diameter were noted in the combustor bed material, but did not pose any operational problems. Postrun visual inspection of the system after the last week of testing showed the formation of high-temperature agglomerates in the bottom of the combustor. This was likely an artifact of the plugging in the downcomer and a consequence of the temperature excursion. Bed material agglomerates slightly larger than one-inch diameter and one-half inch thick were found in the drained bed material. These were quite friable. The material that collected and plugged the cyclone and downcomer appeared to be extremely cohesive, but was relatively easy to clean out of the cyclone cone and downcomer. The material forming the plug could be broken with finger pressure. Some slightly larger and harder agglomerates, along with some ash deposits, were found in the material removed from the downcomer and external heat exchanger.

Two air-cooled probes located at the exit of the cyclone are used to investigate the degree of ash deposition or slagging that could be expected at the leading edge of the convective pass region of a circulating fluidized-bed boiler. Air flow to the probes was controlled to maintain a probe surface temperature of approximately 1000°F. Only a thin layer of deposit less than one millimeter thick was present on the probes after the last week of testing. This contrasts to a much thicker deposit that formed during the first week of testing using Center lignite when the probes installed in the ash-fouling section were uncooled. Ash deposition would not likely be a problem in the convective pass region of a CFB boiler firing this coal. Some soot-blowing potential would be recommended, however.

Postrun inspection of system components revealed several hard deposits had formed on the walls of the refractory and on some of the uncooled surfaces. The deposits were not very thick and were composed of a very fine-grained matrix, with most of the particles less than one micron. A few larger particles (1-10 microns) were found intermixed in the fine-grained matrix. The elemental analyses show that the deposit was primarily composed of calcium and sulfur. XRD identified the major phases as $CaSO_4$ and $Ca_5(PO_4)_3OH$ with minor amounts of MgO. This composition differs from both the coal and the limestone analyses, showing an enrichment in the calcium and sulfur. The most likely mechanism for the formation of this deposit is deposition of fine-grained calcium oxide. Sulfation of the calcium oxide and subsequent sintering of the particles produce a very hard, tenacious deposit. Some of the ash particles appear to have stuck to the deposit; however, it is unlikely that any of the constituents in these ash particles caused the deposit to form or gave it strength.

A similar phenomenon has been noted in pc-fired boilers firing high-calcium western United States subbituminous coals. In these systems, calcium sulfate-based deposits are found primarily in the reheat section of the boiler where flue gas temperatures range from 1650° to 1200°F. These deposits are very tenacious and difficult to remove using conventional soot blowers if they are allowed to build up and develop strength over time. It is recommended for any FBC built to burn North Dakota lignite that a conservative design be used in the back pass ensuring adequate soot-blowing coverage to prevent buildup of calcium sulfate-based deposits.

SUMMARIES OF TEST DATA

This section contains the summaries of test data for each test period, including averages and standard deviations of many of the data points recorded by the computerized data acquisition system.

19-Mar-91

CFB-CL1-0291 — TEST 0

(1100-1300)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1523	4.1
TC11021	AFS Ex	°F	1420	4.8
TC15001	C Plenum	°F	569	5.5
TC15004	C 1-1'	°F	1494	7.1
TC15005	C 1-2'	°F	1493	6.2
TC15006	C 1-3'	°F	1491	6.9
TC15007	C 1-4'	°F	1488	6.8
TC15008	C 1-4'	°F	1494	6.4
TC15009	C 1-4'	°F	1492	7.6
TC15012	C 2-6'	°F	1502	6.3
TC15013	C 2-8'	°F	1529	5.6
TC15022	C 3-11'	°F	1549	6.8
TC15023	C 3-14'	°F	1559	6.4
TC15024	C 3-14'	°F	1565	5.5
TC15025	C 3-14'	°F	1565	6.0
TC15032	C 4-17.5'	°F	1551	6.9
TC15042	C 5-22.5'	°F	1567	5.1
TC15052	C 6-27.5'	°F	1544	4.3
TC15053	C 6-27.5'	°F	1554	5.2
TC15054	C 6-27.5'	°F	1527	4.5
TC15062	C 7-32.5'	°F	1531	4.6
TC15071	C 8-37.5'	°F	1524	4.8
TC15073	C 9-41'	°F	1548	5.2
TC15999	Ambient	°F	80	1.1
TC16001	EHX Plenm	°F	108	3.7
TC16012	EHX 0.5'	°F	1161	20.7
TC16013	EHX 1.5'	°F	1149	18.7
TC16014	EHX 2.7'	°F	1159	18.4
TC16015	EHX 3.8'	°F	945	19.4
TC16017	EHX 5.3'	°F	825	24.3
TC16018	EHX Exit	°F	1038	20.4
TC16021	Crc A in	°F	1539	3.9
TC16031	DC 8-36'	°F	1525	5.9
TC16032	DC 6-28'	°F	1491	20.2
TC16033	DC 4-18'	°F	1470	23.8
TC16034	DC3-11.5'	°F	1482	21.4
TC16035	DC3-10.5'	°F	1493	24.4
T(A,C)	Comb Temp	°F	1526	4.9
T(A,EHX)	EHX Temp	°F	1157	19.0
EA	Excess Air	%	22.0	3.6
SR	S Reten	%	6.2	4.3
R(PCA)	%Flow PCA	%	55.8	2.1
R(SCA)	%Flow SCA	%	43.9	1.7
R(Q,IN)	%Enrg in	%	116.7	5.0
R(CHX)	CHX Ratio	%	49.1	1.4
R(EHX)	EHX Ratio	%	50.9	1.4
F(PCA)	PCA Flow	SCFM	221.1	16.1
F(SCA)	SCA Flow	SCFM	200.5	4.3
F(FG,BH)	BH Flow	SCFM	555.5	8.0
F(TFG)	TFG Flow	SCFM	563.5	18.9
W(SR)	Recirc Rt	lbs/hr	4158	427.3

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service==> 8

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	38	136	1529	4.10	201551	27.8	38760
3NE	14	38	126	1563	1.80	79346	21.2	30518
4SE	17.5	38	109	1551	1.80	64569	17.2	24834
6NE	27.5	39	112	1542	1.80	65614	17.6	25236
7SE	32.5	39	112	1531	1.70	62360	16.9	23985
8E,W	37.5	40	106	1524	3.60	119006	16.1	22886
	Overall	37	119	1526	12.98	531377	18.1	25547
			From Data Sheets=>		14.80			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-9	9	37	107	1157	14.76	514786	72.7	76265
			From Data Sheets=>		15.80			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Averages	Std Dev	Tag	Units	Averages	Std Dev
SO2-A	ppm	727	37.46	SO2-A	ppm	760	36.79
SO2-AE	lb/MM Btu	1.46	0.07				
CO	ppm	15	2.57	CO	ppm	16	2.55
CO2	%	16.26	0.45	CO2	%	17.00	0.23
N2O	ppm	46	3.15	N2O	ppm	48	3.85
N2OE	lb/MM Btu	0.06	0.01				
NOx	ppm	135	8.50	NOx	ppm	141	10.58
NOxE	lb/MM Btu	0.19	0.02				
O2-A	%	3.78	0.48				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	333.4	13.1
W(S)	LS Fd Rt	lbs/hr	0.1	0.2
V(FG)	FG SGV	ft/sec	14.6	0.6
V(S,C)	Comb SGV	ft/sec	13.4	0.5
V(S,EHX)	EHX SGV	ft/sec	1.2	0.1
FT18003	CHX Flow in	gpm	13.0	0.0
FT19003	EHX Flow in	gpm	14.8	0.1
PT15998	Barometric	psia	14.4	0.0
PT15081	Comb dP	in. H2O	47.6	3.5
Q(CA)	CA Heat in	KBtu/hr	104.8	4.3
Q(CHX)	CHX HtRmv	KBtu/hr	500.3	16.6
Q(EHX)	EHX HtRmv	KBtu/hr	519.2	19.3
Q(F)	Fuel Enrg in	KBtu/hr	1275.0	50.9
Q(FG)	FG Enrg out	KBtu/hr	277.1	9.4
Q(IN)	Tot Enrg in	KBtu/hr	1380.6	51.4
Q(OUT)	Tot Enrg out	KBtu/hr	1596.6	21.5
BH A/C			2.1	0.0
A/SRATIO			1.63	0.6

21-Mar-91

CFB-CL1-0291 — TEST 1

(0800-2015)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1541	14.2
TC11021	AFS Ex	°F	1434	12.1
TC15001	C Plenum	°F	545	13.4
TC15004	C 1-1'	°F	1525	16.6
TC15005	C 1-2'	°F	1524	16.6
TC15006	C 1-3'	°F	1524	15.9
TC15007	C 1-4'	°F	1522	15.9
TC15008	C 1-4'	°F	1526	16.5
TC15009	C 1-4'	°F	1527	16.2
TC15012	C 2-6'	°F	1538	15.9
TC15013	C 2-8'	°F	1565	14.6
TC15022	C 3-11'	°F	1574	14.8
TC15023	C 3-14'	°F	1579	14.8
TC15024	C 3-14'	°F	1588	14.4
TC15025	C 3-14'	°F	1588	15.0
TC15032	C 4-17.5'	°F	1571	14.3
TC15042	C 5-22.5'	°F	1587	13.8
TC15052	C 6-27.5'	°F	1568	14.8
TC15053	C 6-27.5'	°F	1576	14.5
TC15054	C 6-27.5'	°F	1551	14.7
TC15062	C 7-32.5'	°F	1556	14.6
TC15071	C 8-37.5'	°F	1550	16.2
TC15073	C 9-41'	°F	1575	14.8
TC15999	Ambient	°F	75	2.0
TC16001	EHX Plenm	°F	123	11.0
TC16012	EHX 0.5'	°F	1246	35.6
TC16013	EHX 1.5'	°F	1228	38.6
TC16014	EHX 2.7'	°F	1246	34.4
TC16015	EHX 3.8'	°F	1161	54.6
TC16017	EHX 5.3'	°F	1058	58.6
TC16018	EHX Exit	°F	1058	15.7
TC16021	Crc A in	°F	1556	8.8
TC16031	DC 8-36'	°F	1550	13.9
TC16032	DC 6-28'	°F	1523	29.0
TC16033	DC 4-18'	°F	1498	42.5
TC16034	DC3-11.5'	°F	1511	45.9
TC16035	DC3-10.5'	°F	1511	52.5
T(A,C)	Comb Temp	°F	1554	14.5
T(A,EHX)	EHX Temp	°F	1240	36.0
EA	Excess Air	%	25.7	5.4
SR	S Reten	%	62.5	26.8
R(PCA)	%Flow PCA	%	56.1	4.4
R(SCA)	%Flow SCA	%	44.0	4.4
R(Q,IN)	%Enrg in	%	111.0	6.2
R(CHX)	CHX Ratio	%	53.1	2.0
R(EHX)	EHX Ratio	%	46.9	2.0
F(PCA)	PCA Flow	SCFM	179.5	23.6
F(SCA)	SCA Flow	SCFM	189.3	15.1
F(FG BH)	BH Flow	SCFM	536.0	20.8
F(TFG)	TFG Flow	SCFM	561.3	48.7
W(SR)	Recirc Rt	lbs/hr	3171	486.5

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 7

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q BTU/hr	U BTU/ft2Fhr	Heat Flux BTU/ft2hr
2E	8	38	123	1565	2.32	99272	26.5	38182
3NE	14	38	124	1585	1.88	80835	21.3	31090
4SE	17.5	38	103	1571	1.90	61849	16.2	23788
6NE	27.5	39	112	1565	1.80	65686	17.4	25264
7SE	32.5	39	106	1556	1.82	60682	16.1	23339
8E,W	37.5	41	106	1550	3.69	121102	16.1	23289
	Overall	37	112	1554	11.63	433486	16.5	23818
			From Data Sheets=>		13.41			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-2,5-8	6	38	130	1240	8.09	374779	75.0	83284
			From Data Sheets=>		8.55			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	311	263.34	SO2-A	ppm	327	260.11
SO2-AE	lb/MM Btu	0.60	0.48				
CO	ppm	10	1.98	CO	ppm	11	2.21
CO2	%	16.45	0.77	CO2	%	17.68	0.40
N2O	ppm	20	2.82	N2O	ppm	22	3.44
N2OE	lb/MM Btu	0.03	0.00				
NOx	ppm	187	22.57	NOx	ppm	202	30.36
NOxE	lb/MM Btu	0.27	0.04				
O2-A	%	4.25	0.72				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal FdRt	lbs/hr	301.1	21.4
W(S)	LS FdRt	lbs/hr	17.8	5.8
V(FG)	FG SGV	ft/sec	14.1	0.8
V(S,C)	Comb SGV	ft/sec	12.8	0.7
V(S,EHX)	EHX SGV	ft/sec	2.2	0.7
FT18003	CHX Flowi	gpm	11.6	0.1
FT19003	EHX Flowi	gpm	8.1	0.1
PT15998	Barometric	psia	14.3	0.0
PT15081	Comb dP	in. H2O	50.5	2.7
Q(CA)	CA Heat in	KBtu/hr	90.6	5.9
Q(CHX)	CHX HtRmv	KBtu/hr	425.7	21.3
Q(EHX)	EHX HtRmv	KBtu/hr	376.0	25.3
Q(F)	Fuel Enrg in	KBtu/hr	1151.5	82.0
Q(FG)	FG Enrg out	KBtu/hr	278.6	24.6
Q(IN)	Tot Enrg in	KBtu/hr	1245.2	83.3
Q(OUT)	Tot Enrg out	KBtu/hr	1380.4	52.4
BH A/C			2.0	0.1
A/SRATIO			5.13	1.1

22-Mar-91

CFB-CL1-0291 — TEST 2

(1015-1417)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1359	7.1
TC11021	AFS Ex	°F	1248	5.4
TC15001	C Plenum	°F	435	2.9
TC15004	C 1-1'	°F	1337	18.8
TC15005	C 1-2'	°F	1335	17.9
TC15006	C 1-3'	°F	1336	18.3
TC15007	C 1-4'	°F	1335	18.5
TC15008	C 1-4'	°F	1337	18.3
TC15009	C 1-4'	°F	1338	18.5
TC15012	C 2-6'	°F	1350	18.4
TC15013	C 2-8'	°F	1385	17.6
TC15022	C 3-11'	°F	1409	12.7
TC15023	C 3-14'	°F	1419	11.9
TC15024	C 3-14'	°F	1430	11.6
TC15025	C 3-14'	°F	1427	12.3
TC15032	C 4-17.5'	°F	1405	10.8
TC15042	C 5-22.5'	°F	1428	10.8
TC15052	C 6-27.5'	°F	1394	9.7
TC15053	C 6-27.5'	°F	1406	9.9
TC15054	C 6-27.5'	°F	1372	10.8
TC15062	C 7-32.5'	°F	1376	9.6
TC15071	C 8-37.5'	°F	1355	10.1
TC15073	C 9-41'	°F	1388	9.2
TC15999	Ambient	°F	76	1.0
TC16001	EHX Plenm	°F	128	2.3
TC16012	EHX 0.5'	°F	888	14.9
TC16013	EHX 1.5'	°F	884	14.5
TC16014	EHX 2.7'	°F	888	14.4
TC16015	EHX 3.8'	°F	832	10.9
TC16017	EHX 5.3'	°F	746	9.0
TC16018	EHX Exit	°F	838	13.0
TC16021	Crc A in	°F	1394	9.4
TC16031	DC 8-36'	°F	1354	10.1
TC16032	DC 6-28'	°F	1329	19.3
TC16033	DC 4-18'	°F	1287	47.2
TC16034	DC3-11.5'	°F	1273	41.7
TC16035	DC3-10.5'	°F	1264	47.0
T(A,C)	Comb Temp	°F	1375	13.5
T(A,EHX)	EHX Temp	°F	887	14.5
EA	Excess Air	%	56.7	6.4
SR	S Reten	%	83.9	5.2
R(PCA)	%Flow PCA	%	59.9	3.4
R(SCA)	%Flow SCA	%	40.0	4.4
R(Q,IN)	%Enrg in	%	119.0	9.2
R(CHX)	CHX Ratio	%	54.7	1.7
R(EHX)	EHX Ratio	%	45.3	1.7
F(PCA)	PCA Flow	SCFM	151.8	37.7
F(SCA)	SCA Flow	SCFM	153.6	3.6
F(FG,BH)	BH Flow	SCFM	477.3	4.2
F(TFG)	TFG Flow	SCFM	477.3	4.2
W(SR)	Recirc Rt	lbs/hr	2448	324.4

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 7

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q BTU/hr	U BTU/ft2Fhr	Heat Flux BTU/ft2hr
2E	8	37	99	1385	2.40	73534	22.0	28282
3NE	14	38	99	1425	1.80	54538	15.8	20976
4SE	17.5	38	83	1405	1.90	43108	12.5	16580
6NE	27.5	39	90	1390	1.80	46427	13.7	17857
7SE	32.5	39	86	1376	1.80	42113	12.6	16197
8E,W	37.5	40	83	1355	2.70	57539	8.7	11065
	Overall	37	90	1375	11.62	305424	13.1	16782
			From Data Sheets=>		12.40			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-2,5-8	6	37	98	887	8.22	250752	70.7	55723
			From Data Sheets=>		8.60			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	99	34.30	SO2-A	ppm	132	41.56
SO2-AE	lb/MM Btu	0.25	0.08				
CO	ppm	42	6.11	CO	ppm	56	8.70
CO2	%	12.95	0.40	CO2	%	17.37	0.32
N2O	ppm	95	7.38	N2O	ppm	126	12.71
N2OE	lb/MM Btu	0.16	0.02				
NOx	ppm	91	4.82	NOx	ppm	122	9.69
NOxE	lb/MM Btu	0.16	0.01				
O2-A	%	7.57	0.52				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fdrt	lbs/hr	221.0	18.1
W(S)	LS Fdrt	lbs/hr	3.0	3.0
V(FG)	FG SGV	ft/sec	11.3	0.7
V(S,C)	Comb SGV	ft/sec	10.4	0.8
V(S,EHX)	EHX SGV	ft/sec	2.2	0.0
FT18003	CHX Flowi	gpm	11.6	0.0
FT19003	EHX Flowi	gpm	8.2	0.0
PT15998	Barometric	psia	14.3	0.0
PT15081	Comb dP	in. H2O	53.4	2.1
Q(CA)	CA Heat in	KBtu/hr	65.8	5.6
Q(CHX)	CHX HtRmv	KBtu/hr	307.6	17.0
Q(EHX)	EHX HtRmv	KBtu/hr	254.3	10.0
Q(F)	Fuel Enrg in	KBtu/hr	845.1	68.5
Q(FG)	FG Enrg out	KBtu/hr	228.4	9.5
Q(IN)	Tot Enrg in	KBtu/hr	914.3	68.1
Q(OUT)	Tot Enrg out	KBtu/hr	1090.4	22.8
BH A/C			1.8	0.0
A/SRATIO			2.35	0.9

23-Mar-91

CFB-CL1-0291 — TEST 3

(0115-0515)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1267	12.8
TC11021	AFS Ex	°F	1151	7.4
TC15001	C Plenum	°F	385	3.7
TC15004	C 1-1'	°F	1080	38.1
TC15005	C 1-2'	°F	1079	37.5
TC15006	C 1-3'	°F	1080	38.2
TC15007	C 1-4'	°F	1078	38.7
TC15008	C 1-4'	°F	1079	38.0
TC15009	C 1-4'	°F	1080	38.5
TC15012	C 2-6'	°F	1072	41.8
TC15013	C 2-8'	°F	1092	49.5
TC15022	C 3-11'	°F	1150	69.1
TC15023	C 3-14'	°F	1202	81.6
TC15024	C 3-14'	°F	1208	80.2
TC15025	C 3-14'	°F	1183	81.6
TC15032	C 4-17.5'	°F	1215	84.3
TC15042	C 5-22.5'	°F	1337	50.4
TC15052	C 6-27.5'	°F	1341	16.4
TC15053	C 6-27.5'	°F	1349	18.6
TC15054	C 6-27.5'	°F	1301	12.6
TC15062	C 7-32.5'	°F	1310	17.9
TC15071	C 8-37.5'	°F	1245	10.6
TC15073	C 9-41'	°F	1304	15.4
TC15999	Ambient	°F	76	1.0
TC16001	EHX Plenm	°F	106	2.6
TC16012	EHX 0.5'	°F	550	63.3
TC16013	EHX 1.5'	°F	545	62.3
TC16014	EHX 2.7'	°F	550	63.1
TC16015	EHX 3.8'	°F	447	38.7
TC16017	EHX 5.3'	°F	398	26.3
TC16018	EHX Exit	°F	489	45.2
TC16021	Crc A in	°F	1316	18.4
TC16031	DC 8-36'	°F	1209	11.7
TC16032	DC 6-28'	°F	1154	20.5
TC16033	DC 4-18'	°F	1083	40.2
TC16034	DC3-11.5'	°F	1042	40.4
TC16035	DC3-10.5'	°F	1033	40.6
T(A,C)	Comb Temp	°F	1185	33.0
T(A,EHX)	EHX Temp	°F	549	62.9
EA	Excess Air	%	100.0	0.0
SR	S Reten	%	93.5	3.3
R(PCA)	%Flow PCA	%	52.6	4.3
R(SCA)	%Flow SCA	%	47.2	4.3
R(Q,IN)	%Enrg in	%	130.0	4.5
R(CHX)	CHX Ratio	%	61.3	3.3
R(EHX)	EHX Ratio	%	38.7	3.3
F(PCA)	PCA Flow	SCFM	154.7	20.7
F(SCA)	SCA Flow	SCFM	172.4	4.9
F(FG,BH)	BH Flow	SCFM	435.9	3.6
F(TFG)	TFG Flow	SCFM	435.9	3.6
W(SR)	Recirc Rt	lbs/hr	1221	182.4

HEAT-TRANSFER COEFFICIENTS

—Combustor—　　Number of Doors in Service===> 7

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q BTU/hr	U BTU/ft2Fhr	Heat Flux BTU/ft2hr
2E	8	39	71	1092	2.30	37419	14.1	14392
3NE	14	39	73	1198	1.80	31088	10.6	11957
4SE	17.5	38	68	1215	1.90	28397	9.5	10922
6NE	27.5	39	81	1330	1.80	37679	11.6	14492
7SE	32.5	39	79	1310	1.80	35953	11.2	13828
8E,W	37.5	40	73	1245	3.70	61812	10.1	11887
	Overall	38	74	1185	11.58	207451	10.3	11398
			From Data Sheets=>		13.30			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-2,5-8	6	38	68	549	8.24	125386	58.0	27864
			From Data Sheets=>		8.60			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	27	12.78	SO2-A	ppm	51	25.65
SO2-AE	lb/MM Btu	0.10	0.05				
CO	ppm	75	16.33	CO	ppm	143	29.14
CO2	%	8.78	0.47	CO2	%	16.66	0.43
N2O	ppm	145	7.83	N2O	ppm	276	15.85
N2OE	lb/MM Btu	0.37	0.02				
NOx	ppm	82	9.00	NOx	ppm	156	18.98
NOxE	lb/MM Btu	0.22	0.03				
O2-A	%	11.51	0.39				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal FdRt	lbs/hr	148.5	7.3
W(S)	LS FdRt	lbs/hr	0.0	*
V(FG)	FG SGV	ft/sec	9.5	0.7
V(S,C)	Comb SGV	ft/sec	8.9	0.7
V(S,EHX)	EHX SGV	ft/sec	0.9	0.1
FT18003	CHX Flowi	gpm	11.6	0.0
FT19003	EHX Flowi	gpm	8.2	0.0
PT15998	Barometric	psia	14.2	0.0
PT15081	Comb dP	in. H2O	50.6	2.5
Q(CA)	CA Heat in	KBtu/hr	62.8	5.6
Q(CHX)	CHX HtRmv	KBtu/hr	195.9	21.0
Q(EHX)	EHX HtRmv	KBtu/hr	124.4	20.5
Q(F)	Fuel Enrg in	KBtu/hr	567.6	28.6
Q(FG)	FG Enrg out	KBtu/hr	200.1	1.4
Q(IN)	Tot Enrg in	KBtu/hr	631.3	30.5
Q(OUT)	Tot Enrg out	KBtu/hr	820.5	36.6
BH A/C			1.7	0.0
A/SRATIO			1.43	*

* Calculated values

23-Mar-91

CFB-CL1-0291—TEST 4

(1026-1430)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1469	8.2
TC11021	AFS Ex	°F	1328	13.6
TC15001	C Plenum	°F	461	12.4
TC15004	C 1-1'	°F	1516	13.5
TC15005	C 1-2'	°F	1514	13.3
TC15006	C 1-3'	°F	1514	13.1
TC15007	C 1-4'	°F	1512	13.1
TC15008	C 1-4'	°F	1518	13.1
TC15009	C 1-4'	°F	1516	13.3
TC15012	C 2-6'	°F	1518	13.7
TC15013	C 2-8'	°F	1535	12.9
TC15022	C 3-11'	°F	1550	11.3
TC15023	C 3-14'	°F	1557	10.2
TC15024	C 3-14'	°F	1555	10.5
TC15025	C 3-14'	°F	1560	10.7
TC15032	C 4-17.5'	°F	1562	10.4
TC15042	C 5-22.5'	°F	1555	8.1
TC15052	C 6-27.5'	°F	1551	6.5
TC15053	C 6-27.5'	°F	1555	7.1
TC15054	C 6-27.5'	°F	1548	7.0
TC15062	C 7-32.5'	°F	1549	6.2
TC15071	C 8-37.5'	°F	1542	5.7
TC15073	C 9-41'	°F	1545	6.4
TC15999	Ambient	°F	79	0.8
TC16001	EHX Plenm	°F	113	5.2
TC16012	EHX 0.5'	°F	1270	25.4
TC16013	EHX 1.5'	°F	1271	25.7
TC16014	EHX 2.7'	°F	1266	26.4
TC16015	EHX 3.8'	°F	1139	59.6
TC16017	EHX 5.3'	°F	980	72.1
TC16018	EHX Exit	°F	1059	21.7
TC16021	Crc A in	°F	1537	5.1
TC16031	DC 8-36'	°F	1466	12.1
TC16032	DC 6-28'	°F	1438	22.6
TC16033	DC 4-18'	°F	1397	38.7
TC16034	DC3-11.5'	°F	1383	40.7
TC16035	DC3-10.5'	°F	1374	41.7
T(A,C)	Comb Temp	°F	1537	9.6
T(A,EHX)	EHX Temp	°F	1269	25.7
EA	Excess Air	%	95.3	4.3
SR	S Reten	%	47.2	17.8
R(PCA)	%Flow PCA	%	66.7	4.7
R(SCA)	%Flow SCA	%	33.0	5.1
R(Q,IN)	%Enrg in	%	79.6	4.9
R(CHX)	CHX Ratio	%	100.0	0.0
R(EHX)	EHX Ratio	%	0.0	0.0
F(PCA)	PCA Flow	SCFM	195.5	20.9
F(SCA)	SCA Flow	SCFM	120.4	21.6
F(FG,BH)	BH Flow	SCFM	441.6	16.8
F(TFG)	TFG Flow	SCFM	445.4	26.7
W(SR)	Recirc Rt	lbs/hr	385	69.6

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service==> 1

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q BTU/hr	U BTU/ft2Fhr	Heat Flux BTU/ft2hr
2E	8	44	122	1535	2.00	77634	21.1	29859
3	14	125	178	1557	0.00	0	0.0	0
4	17.5	121	167	1562	0.00	0	0.0	0
6	27.5	127	199	1551	0.00	0	0.0	0
7	32.5	128	190	1549	0.00	0	0.0	0
8	37.5	128	171	1542	0.00	0	0.0	0
	Overall	44	122	1537	1.79	70060	19.0	26946
			From Data Sheets=>		2.00			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
None	0	72	72	1269	0.04	13	0.0	0
			From Data Sheets=>		0.00			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	261	103.78	SO2-A	ppm	438	168.76
SO2-AE	lb/MM Btu	0.83	0.33				
CO	ppm	9	3.52	CO	ppm	16	5.91
CO2	%	10.21	0.46	CO2	%	17.19	0.46
N2O	ppm	32	2.33	N2O	ppm	54	5.07
N2OE	lb/MM Btu	0.07	0.01				
NOx	ppm	165	7.87	NOx	ppm	278	13.21
NOxE	lb/MM Btu	0.38	0.02				
O2-A	%	10.31	0.36				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal FdRt	lbs/hr	173.1	11.5
W(S)	LS FdRt	lbs/hr	3.1	*
V(FG)	FG SGV	ft/sec	11.6	0.6
V(S,C)	Comb SGV	ft/sec	10.7	0.6
V(S,EHX)	EHX SGV	ft/sec	1.8	0.3
FT18003	CHX Flowi	gpm	1.8	0.0
FT19003	EHX Flowi	gpm	0.0	0.0
PT15998	Barometric	psia	14.2	0.0
PT15081	Comb dP	in. H2O	42.8	1.8
Q(CA)	CA Heat in	KBtu/hr	69.7	4.4
Q(CHX)	CHX HtRmv	KBtu/hr	63.8	2.8
Q(EHX)	EHX HtRmv	KBtu/hr	0.0	0.0
Q(F)	Fuel Enrg in	KBtu/hr	661.9	44.7
Q(FG)	FG Enrg out	KBtu/hr	217.7	8.5
Q(IN)	Tot Enrg in	KBtu/hr	733.1	47.0
Q(OUT)	Tot Enrg out	KBtu/hr	581.5	8.2
BH A/C			1.7	0.1
A/SRATIO			2.32	*

* Calculated values

23-Mar-91

CFB-CL1-0291—TEST 5

(1630-2030)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1512	10.5
TC11021	AFS Ex	°F	1383	10.1
TC15001	C Plenum	°F	508	8.6
TC15004	C 1-1'	°F	1478	26.6
TC15005	C 1-2'	°F	1476	26.8
TC15006	C 1-3'	°F	1475	27.1
TC15007	C 1-4'	°F	1474	26.6
TC15008	C 1-4'	°F	1481	25.6
TC15009	C 1-4'	°F	1480	25.8
TC15012	C 2-6'	°F	1477	29.4
TC15013	C 2-8'	°F	1507	25.2
TC15022	C 3-11'	°F	1536	20.7
TC15023	C 3-14'	°F	1539	19.1
TC15024	C 3-14'	°F	1549	19.6
TC15025	C 3-14'	°F	1544	20.3
TC15032	C 4-17.5'	°F	1523	20.7
TC15042	C 5-22.5'	°F	1558	18.0
TC15052	C 6-27.5'	°F	1562	16.9
TC15053	C 6-27.5'	°F	1563	18.4
TC15054	C 6-27.5'	°F	1558	16.8
TC15062	C 7-32.5'	°F	1564	16.4
TC15071	C 8-37.5'	°F	1563	16.2
TC15073	C 9-41'	°F	1567	16.0
TC15999	Ambient	°F	78	1.7
TC16001	EHX Plenm	°F	118	3.9
TC16012	EHX 0.5'	°F	1176	21.3
TC16013	EHX 1.5'	°F	1160	22.9
TC16014	EHX 2.7'	°F	1175	21.9
TC16015	EHX 3.8'	°F	1109	22.0
TC16017	EHX 5.3'	°F	996	19.6
TC16018	EHX Exit	°F	1035	17.7
TC16021	Crc A in	°F	1551	10.8
TC16031	DC 8-36'	°F	1515	13.4
TC16032	DC 6-28'	°F	1492	22.3
TC16033	DC 4-18'	°F	1447	52.5
TC16034	DC3-11.5'	°F	1444	48.2
TC16035	DC3-10.5'	°F	1438	53.6
T(A,C)	Comb Temp	°F	1521	20.9
T(A,EHX)	EHX Temp	°F	1170	21.7
EA	Excess Air	%	58.3	11.3
SR	S Reten	%	62.1	20.9
R(PCA)	%Flow PCA	%	62.1	9.8
R(SCA)	%Flow SCA	%	38.4	10.0
R(Q,IN)	%Enrg in	%	97.7	5.6
R(CHX)	CHX Ratio	%	38.8	3.8
R(EHX)	EHX Ratio	%	61.2	3.8
F(PCA)	PCA Flow	SCFM	190.4	29.0
F(SCA)	SCA Flow	SCFM	154.8	46.3
F(FG,BH)	BH Flow	SCFM	501.0	30.8
F(TFG)	TFG Flow	SCFM	508.9	25.2
W(SR)	Recirc Rt	lbs/hr	2428	486.2

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 3

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q BTU/hr	U BTU/ft2Fhr	Heat Flux BTU/ft2hr
2E	8	41	128	1507	1.84	80283	22.4	30878
3NE	14	40	128	1544	1.66	73059	19.8	28100
4SE	17.5	40	115	1523	1.66	62451	17.1	24020
6	27.5	131	209	1561	0.00	0	0.0	0
7	32.5	135	201	1564	0.00	0	0.0	0
8	37.5	136	187	1563	0.00	0	0.0	0
	Overall	38	124	1521	4.33	185391	17.0	23768
			From Data Sheets=>		5.16			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-4	4	38	125	1170	5.87	255779	81.6	85260
			From Data Sheets=>		6.28			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	238	149.62	SO2-A	ppm	315	181.63
SO2-AE	lb/MM Btu	0.59	0.34				
CO	ppm	13	2.62	CO	ppm	18	3.28
CO2	%	12.80	1.08	CO2	%	17.27	0.39
N2O	ppm	36	4.37	N2O	ppm	49	8.66
N2OE	lb/MM Btu	0.06	0.01				
NOx	ppm	172	12.16	NOx	ppm	233	24.05
NOxE	lb/MM Btu	0.32	0.03				
O2-A	%	7.67	0.98				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal FdRt	lbs/hr	234.8	12.4
W(S)	LS FdRt	lbs/hr	6.7	*
V(FG)	FG SGV	ft/sec	12.9	0.8
V(S,C)	Comb SGV	ft/sec	11.6	0.8
V(S,EHX)	EHX SGV	ft/sec	1.9	0.3
FT18003	CHX Flowi	gpm	4.3	1.2
FT19003	EHX Flowi	gpm	5.9	1.0
PT15998	Barometric	psia	14.3	0.0
PT15081	Comb dP	in. H2O	39.1	2.2
Q(CA)	CA Heat in	KBtu/hr	81.2	7.2
Q(CHX)	CHX HtRmv	KBtu/hr	157.8	22.5
Q(EHX)	EHX HtRmv	KBtu/hr	247.1	14.8
Q(F)	Fuel Enrg in	KBtu/hr	892.4	49.3
Q(FG)	FG Enrg out	KBtu/hr	250.6	11.8
Q(IN)	Tot Enrg in	KBtu/hr	975.6	52.6
Q(OUT)	Tot Enrg out	KBtu/hr	953.6	21.4
BH A/C			1.9	0.1
A/SRATIO			2.03	*

* Calculated values

15,16-Apr-91

CFB-CL2-0391—TEST 6

(1640-0040)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1536	8.6
TC11021	AFS Ex	°F	1404	8.0
TC15001	C Plenum	°F	526	7.9
TC15004	C 1-1'	°F	1545	19.3
TC15005	C 1-2'	°F	1540	19.2
TC15006	C 1-3'	°F	1540	19.3
TC15007	C 1-4'	°F	1538	19.0
TC15008	C 1-4'	°F	1547	19.4
TC15009	C 1-4'	°F	1542	19.4
TC15012	C 2-6'	°F	1557	18.2
TC15013	C 2-8'	°F	1593	16.9
TC15022	C 3-11'	°F	1607	14.7
TC15023	C 3-14'	°F	1616	14.0
TC15024	C 3-14'	°F	1623	13.8
TC15025	C 3-14'	°F	1623	14.8
TC15032	C 4-17.5'	°F	1589	13.3
TC15042	C 5-22.5'	°F	1619	12.2
TC15052	C 6-27.5'	°F	1585	11.6
TC15053	C 6-27.5'	°F	1593	12.5
TC15054	C 6-27.5'	°F	1550	11.5
TC15062	C 7-32.5'	°F	1554	10.9
TC15071	C 8-37.5'	°F	1523	12.2
TC15073	C 9-41'	°F	1570	10.9
TC15999	Ambient	°F	73	3.5
TC16001	EHX Plenm	°F	118	4.7
TC16012	EHX 0.5'	°F	1080	23.7
TC16013	EHX 1.5'	°F	1070	20.9
TC16014	EHX 2.7'	°F	1081	22.7
TC16015	EHX 3.8'	°F	962	20.0
TC16017	EHX 5.3'	°F	831	14.2
TC16018	EHX Exit	°F	1022	17.6
TC16021	Crc A in	°F	1530	11.1
TC16031	DC 8-36'	°F	1522	7.3
TC16032	DC 6-28'	°F	1502	9.9
TC16033	DC 4-18'	°F	1452	23.9
TC16034	DC3-9.5'	°F	1489	46.5
TC16035	DC3-8.5'	°F	1448	34.3
T(A,C)	Comb Temp	°F	1570	13.7
T(A,EHX)	EHX Temp	°F	1077	22.3
EA	Excess Air	%	22.1	6.4
SR	S Reten	%	44.1	14.9
R(PCA)	%Flw PCA	%	60.2	1.9
R(SCA)	%Flw SCA	%	39.8	1.9
R(Q,IN)	%Enrg in	%	113.4	7.1
R(CHX)	CHX Ratio	%	49.4	1.7
R(EHX)	EHX Ratio	%	50.6	1.7
F(PCA)	PCA Flw	SCFM	201.3	18.2
F(EHX)	E-FIG Flw	SCFM	54.8	1.5
F(SCA)	SCA Flw	SCFM	169.1	3.7
F(TCA,F)	TCA Flw	SCFM	426.0	19.3
F(FG,BH)	BH Flw	SCFM	496	8.6
F(TFG)	TFG Flw	SCFM	496.7	13.3
W(SR)	Recirc Rt	lbs/hr	3750	308.3

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service==> 7

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q BTU/hr	U BTU/ft2Fhr	Heat Flux BTU/ft2hr
2E,W	8	44	141	1593	3.86	187817	24.0	36119
3	14	123	189	1621	0.00	0	0.0	0
4SE	17.5	44	112	1589	1.80	60943	15.9	23440
6NE	27.5	45	126	1576	1.60	64908	17.2	24965
7SE	32.5	45	115	1554	1.60	56214	15.0	21621
8E,W	37.5	46	118	1523	3.40	122002	16.7	23462
	Overall	44	125	1570	10.72	434247	16.5	23860
			From Data Sheets=>		12.26			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-9	9	43	121	1077	11.33	443469	68.8	65699
			From Data Sheets=>		12.00			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	439	130.41	SO2-A	ppm	456	125.87
SO2-AE	lb/MM Btu	0.87	0.23				
CO	ppm	11	2.01	CO	ppm	12	2.05
CO2	%	16.38	0.82	CO2	%	17.12	0.33
N2O	ppm	20	2.36	N2O	ppm	21	3.06
N2OE	lb/MM Btu	0.03	0.00				
NOx	ppm	174	22.98	NOx	ppm	183	32.69
NOxE	lb/MM Btu	0.25	0.04				
O2-A	%	3.77	0.83				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal FdRt	lbs/hr	284.2	19.8
W(S)	LS FdRt	lbs/hr	4.8	*
V(FG)	FG SGV	ft/sec	16.5	0.8
V(S,C)	Comb SGV	ft/sec	12.7	0.5
V(S,EHX)	EHX SGV	ft/sec	1.7	0.1
FT18003	CHX Flwi	gpm	10.7	0.2
FT19003	EHX Flwi	gpm	11.3	0.1
PT15998	Barometric	in. H2O	14.4	0.0
PT15081	Comb dP	in. H2O	49.0	1.8
Q(CA)	CA Heat in	KBtu/hr	89.8	4.8
Q(CHX)	CHX HtRmv	KBtu/hr	428.1	17.4
Q(EHX)	EHX HtRmv	KBtu/hr	439.2	23.7
Q(F)	Fuel Enrg in	KBtu/hr	1154.4	81.6
Q(FG)	FG Enrg out	KBtu/hr	244.7	6.0
Q(IN)	Tot Enrg in	KBtu/hr	1246.6	82.0
Q(OUT)	Tot Enrg out	KBtu/hr	1410.1	32.0
BH A/C			1.9	0.0
A/SRATIO			1.97	*
DOORS	CHX On		7	0
COILS	EHX On		9.0	0.0

* Calculated values

24-Jul-91

CFB-CL3-0491—TEST 7

(1415-2041)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1526	11.1
TC11021	AFS Ex	°F	1310	7.2
TC15001	C Plenum	°F	495	5.3
TC15004	C 1-1'	°F	1518	12.2
TC15005	C 1-2'	°F	1511	12.1
TC15006	C 1-3'	°F	1509	11.3
TC15007	C 1-4'	°F	1505	11.4
TC15008	C 1-4'	°F	1513	11.8
TC15009	C 1-4'	°F	1508	11.6
TC15012	C 2-6'	°F	1527	11.6
TC15013	C 2-8'	°F	1544	12.4
TC15022	C 3-11'	°F	1543	11.5
TC15023	C 3-14'	°F	1554	11.0
TC15024	C 3-14'	°F	1570	12.8
TC15025	C 3-14'	°F	1561	12.0
TC15032	C 4-17.5'	°F	1557	11.9
TC15042	C 5-22.5'	°F	1578	12.3
TC15052	C 6-27.5'	°F	1577	11.7
TC15053	C 6-27.5'	°F	1579	12.2
TC15054	C 6-27.5'	°F	1560	12.6
TC15062	C 7-32.5'	°F	1572	12.3
TC15071	C 8-37.5'	°F	1572	11.7
TC15073	C 9-41'	°F	1564	12.6
TC15999	Ambient	°F	83	1.6
TC16001	EHX Plenm	°F	125	3.7
TC16012	EHX 0.5'	°F	1351	16.6
TC16013	EHX 1.5'	°F	1321	15.8
TC16014	EHX 2.7'	°F	1346	15.6
TC16015	EHX 3.8'	°F	1322	14.8
TC16017	EHX 5.3'	°F	1235	11.4
TC16018	EHX Exit	°F	1319	15.2
TC16021	Crc A in	°F	1575	12.3
TC16031	DC 8-36'	°F	1558	16.9
TC16032	DC 6-28'	°F	1525	20.7
TC16033	DC 4-18'	°F	1518	40.0
TC16034	DC3-9.5'	°F	1549	30.9
TC16035	DC3-8.5'	°F	1543	34.8
T(A,C)	Comb Temp	°F	1545	11.7
T(A,EHX)	EHX Temp	°F	1339	15.9
EA	Excess Air	%	23.8	5.3
SR	S Reten	%	52.7	24.3
R(PCA)	%Flw PCA	%	55.6	2.7
R(SCA)	%Flw SCA	%	44.4	2.7
R(Q,IN)	%Enrg in	%	128.3	8.1
R(CHX)	CHX Ratio	%	50.8	1.0
R(EHX)	EHX Ratio	%	49.2	1.0
F(PCA)	PCA Flw	SCFM	175.0	21.1
F(EHX)	E-FIG Flw	SCFM	49.6	1.8
F(SCA)	SCA Flw	SCFM	178.1	5.0
F(TCA,F)	TCA Flw	SCFM	401.8	21.2
F(FG,BH)	BH Flw	SCFM	484	8.7
F(TFG)	TFG Flw	SCFM	483.8	8.7
W(SR)	Recirc Rt	lbs/hr	6964	498.5

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 6

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q BTU/hr	U BTU/ft2Fhr	Heat Flux BTU/ft2hr
2E,W	8	69	149	1544	4.69	188606	26.0	36270
3NE	14	69	144	1562	1.85	69092	18.7	26574
4SE	17.5	69	129	1557	1.85	56223	15.1	21624
6NE	27.5	69	136	1572	1.85	62080	16.6	23877
7SE	32.5	69	149	1572	1.29	51724	14.0	19894
8	37.5	138	186	1572	0.00	0	0.0	0
	Overall	68	143	1545	11.45	426694	19.5	27352
			From Data Sheets=>		11.53			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-4,8	5	67	151	1339	9.72	408775	91.8	109007
			From Data Sheets=>		9.59			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	373	207.89	SO2-A	ppm	390	203.28
SO2-AE	lb/MM Btu	0.74	0.39				
CO	ppm	44	7.30	CO	ppm	47	7.21
CO2	%	16.31	0.64	CO2	%	17.29	0.25
N2O	ppm	N/A	N/A	N2O	ppm	N/A	N/A
N2OE	lb/MM Btu	N/A	N/A				
NOx	ppm	125	14.60	NOx	ppm	134	20.10
NOxE	lb/MM Btu	0.18	0.03				
O2-A	%	4.02	0.71				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal FdRt	lbs/hr	257.6	15.6	TC13131AFPE-F2"		874	29.2
W(S)	LS FdRt	lbs/hr	14.3	*	TC13132AFPE-F6"		1062	18.8
V(FG)	FG SGV	ft/sec	15.4	0.8	TC13133AFPE-B6"		585	18.1
V(S,C)	Comb SGV	ft/sec	11.8	0.6	TC13134AFPE-F10"		947	23.2
V(S,EHX)	EHX SGV	ft/sec	1.8	0.1	TC13231AFPW-F2"		935	23.2
FT18003	CHX Flwi	gpm	11.4	0.2	TC13232AFPW-F6"		1053	17.2
FT19003	EHX Flwi	gpm	9.7	0.2	TC13233AFPW-B6"		555	17.8
PT15081	Comb dP	in. H2O	58.6	2.3	TC13234AFPW-F10'		994	18.2
Q(CA)	CA Heat in	KBtu/hr	80.9	4.4				
Q(CHX)	CHX HtRmv	KBtu/hr	419.9	16.3				
Q(EHX)	EHX HtRmv	KBtu/hr	406.3	13.9				
Q(EHX,IN	FG Ht in	KBtu/hr	2.1	0.2				
Q(F)	Fuel Enrg in	KBtu/hr	983.2	61.4				
Q(FG)	FG Enrg out	KBtu/hr	238.7	4.2				
Q(IN)	Tot Enrg in	KBtu/hr	1066.2	62.3				
Q(OUT)	Tot Enrg out	KBtu/hr	1362.2	31.1				
BH A/C			1.8	0.0				
A/SRATIO			3.49	*				
DOORS	CHXs On		6	0				
COILS	EHXs On		5.0	0.0				

* Calculated values

25-Jul-91

CFB-CL3-0491—TEST 8

(0110-0310)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1461	6.2
TC11021	AFS Ex	°F	1267	6.1
TC15001	C Plenum	°F	481	4.6
TC15004	C 1-1'	°F	1441	9.1
TC15005	C 1-2'	°F	1432	9.4
TC15006	C 1-3'	°F	1432	8.2
TC15007	C 1-4'	°F	1428	8.0
TC15008	C 1-4'	°F	1434	8.8
TC15009	C 1-4'	°F	1431	9.1
TC15012	C 2-6'	°F	1448	9.3
TC15013	C 2-8'	°F	1461	6.9
TC15022	C 3-11'	°F	1463	7.8
TC15023	C 3-14'	°F	1475	6.1
TC15024	C 3-14'	°F	1484	6.2
TC15025	C 3-14'	°F	1479	6.9
TC15032	C 4-17.5'	°F	1480	6.4
TC15042	C 5-22.5'	°F	1496	6.6
TC15052	C 6-27.5'	°F	1498	5.7
TC15053	C 6-27.5'	°F	1498	7.0
TC15054	C 6-27.5'	°F	1481	5.8
TC15062	C 7-32.5'	°F	1481	6.3
TC15071	C 8-37.5'	°F	1493	6.3
TC15073	C 9-41'	°F	1482	6.7
TC15999	Ambient	°F	78	1.2
TC16001	EHX Plenm	°F	126	1.9
TC16012	EHX 0.5'	°F	1246	18.0
TC16013	EHX 1.5'	°F	1220	16.7
TC16014	EHX 2.7'	°F	1232	17.6
TC16015	EHX 3.8'	°F	1220	12.2
TC16017	EHX 5.3'	°F	1166	7.4
TC16018	EHX Exit	°F	1236	16.7
TC16021	Crc A in	°F	1495	6.0
TC16031	DC 8-36'	°F	1484	5.2
TC16032	DC 6-28'	°F	1444	9.4
TC16033	DC 4-18'	°F	1422	29.9
TC16034	DC3-9.5'	°F	1452	27.7
TC16035	DC3-8.5'	°F	1436	43.4
T(A,C)	Comb Temp	°F	1465	7.0
T(A,EHX)	EHX Temp	°F	1233	17.2
EA	Excess Air	%	23.4	4.5
SR	S Reten	%	97.4	2.3
R(PCA)	%Flw PCA	%	60.5	3.7
R(SCA)	%Flw SCA	%	39.5	3.7
R(Q,IN)	%Enrg in	%	149.1	3.4
R(CHX)	CHX Ratio	%	45.5	1.1
R(EHX)	EHX Ratio	%	54.5	1.1
F(PCA)	PCA Flw	SCFM	178.6	18.6
F(EHX)	E-FIG Flw	SCFM	62.5	1.5
F(SCA)	SCA Flw	SCFM	161.1	13.9
F(TCA,F)	TCA Flw	SCFM	409.0	22.9
F(FG,BH)	BH Flw	SCFM	495	2.2
F(TFG)	TFG Flw	SCFM	494.9	2.2
W(SR)	Recirc Rt	lbs/hr	9457	651.3

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 7

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q BTU/hr	U BTU/ft2Fhr	Heat Flux BTU/ft2hr
2E,W	8	69	147	1461	4.80	185984	27.2	35766
3NE	14	70	136	1479	2.00	66189	18.9	25457
4SE	17.5	69	120	1480	2.00	51177	14.5	19683
6NE	27.5	70	125	1492	2.00	55390	15.6	21304
7SE	32.5	70	132	1481	1.50	46619	13.3	17931
8E	37.5	70	129	1493	1.70	50129	14.1	19280
	Overall	70	135	1465	14.18	460285	19.0	25290
			From Data Sheets=>		14.00			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-7	7	68	144	1233	14.84	563214	98.5	107279
			From Data Sheets=>		14.43			

EMISSIONS DATA

As Measured: Tag	Units	Average	Std Dev	Corrected to 3% O2: Tag	Units	Average	Std Dev
SO2-A	ppm	20	18.46	SO2-A	ppm	20	18.07
SO2-AE	lb/MM Btu	0.04	0.04				
CO	ppm	25	5.66	CO	ppm	27	6.03
CO2	%	15.76	0.55	CO2	%	16.68	0.17
N2O	ppm	N/A	N/A	N2O	ppm	N/A	N/A
N2OE	lb/MM Btu	N/A	N/A				
NOx	ppm	92	16.03	NOx	ppm	99	19.97
NOxE	lb/MM Btu	0.14	0.03				
O2-A	%	3.99	0.63				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal FdRt	lbs/hr	254.2	6.1
W(S)	LS FdRt	lbs/hr	12.3	*
V(FG)	FG SGV	ft/sec	15.0	0.8
V(S,C)	Comb SGV	ft/sec	11.4	0.5
V(S,EHX)	EHX SGV	ft/sec	2.2	0.1
FT18003	CHX Flwi	gpm	14.2	0.1
FT19003	EHX Flwi	gpm	14.8	0.1
PT15081	Comb dP	in. H2O	62.4	3.3
Q(CA)	CA Heat in	KBtu/hr	77.0	6.1
Q(CHX)	CHX HtRmv	KBtu/hr	468.9	18.0
Q(EHX)	EHX HtRmv	KBtu/hr	561.4	16.4
Q(EHX,IN	FG Ht in	KBtu/hr	3.0	0.2
Q(F)	Fuel Enrg in	KBtu/hr	972.3	24.1
Q(FG)	FG Enrg out	KBtu/hr	241.0	1.4
Q(IN)	Tot Enrg in	KBtu/hr	1052.3	27.2
Q(OUT)	Tot Enrg out	KBtu/hr	1571.3	27.0
BH A/C			1.9	0.0
A/SRATIO			3.21	*
DOORS	CHXs On		7	0
COILS	EHXs On		7.0	0.0

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	736	24.3
TC13132	AFPE-F6"	906	15.7
TC13133	AFPE-B6"	453	15.0
TC13134	AFPE-F10"	648	46.4
TC13231	AFPW-F2"	760	21.7
TC13232	AFPW-F6"	915	17.3
TC13233	AFPW-B6"	466	11.9
TC13234	AFPW-F10'	820	20.2

* Calculated values

25-Jul-91

CFB-CL3-0491 — TEST 9

(0545-0745)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1392	5.4
TC11021	AFS Ex	°F	1193	5.4
TC15001	C Plenum	°F	470	8.6
TC15004	C 1-1'	°F	1345	10.3
TC15005	C 1-2'	°F	1340	9.5
TC15006	C 1-3'	°F	1340	10.2
TC15007	C 1-4'	°F	1336	10.0
TC15008	C 1-4'	°F	1341	10.3
TC15009	C 1-4'	°F	1337	10.8
TC15012	C 2-6'	°F	1350	10.1
TC15013	C 2-8'	°F	1362	10.9
TC15022	C 3-11'	°F	1371	8.9
TC15023	C 3-14'	°F	1387	7.6
TC15024	C 3-14'	°F	1392	6.7
TC15025	C 3-14'	°F	1390	6.8
TC15032	C 4-17.5'	°F	1397	7.3
TC15042	C 5-22.5'	°F	1410	5.4
TC15052	C 6-27.5'	°F	1416	5.2
TC15053	C 6-27.5'	°F	1415	6.3
TC15054	C 6-27.5'	°F	1408	6.4
TC15062	C 7-32.5'	°F	1406	6.0
TC15071	C 8-37.5'	°F	1416	5.8
TC15073	C 9-41'	°F	1413	6.2
TC15999	Ambient	°F	75	1.2
TC16001	EHX Plenm	°F	117	3.2
TC16012	EHX 0.5'	°F	1200	23.5
TC16013	EHX 1.5'	°F	1175	21.8
TC16014	EHX 2.7'	°F	1184	21.9
TC16015	EHX 3.8'	°F	1172	15.0
TC16017	EHX 5.3'	°F	1102	13.4
TC16018	EHX Exit	°F	1180	20.6
TC16021	Crc A in	°F	1421	5.5
TC16031	DC 8-36'	°F	1413	6.8
TC16032	DC 6-28'	°F	1371	17.9
TC16033	DC 4-18'	°F	1360	26.0
TC16034	DC3-9.5'	°F	1386	26.2
TC16035	DC3-8.5'	°F	1376	32.1
T(A,C)	Comb Temp	°F	1378	7.6
T(A,EHX)	EHX Temp	°F	1186	22.5
EA	Excess Air	%	27.1	2.5
SR	S Reten	%	99.6	0.3
R(PCA)	%Flw PCA	%	55.7	9.4
R(SCA)	%Flw SCA	%	44.3	9.4
R(Q,IN)	%Enrg in	%	151.9	5.4
R(CHX)	CHX Ratio	%	44.2	1.5
R(EHX)	EHX Ratio	%	55.8	1.5
F(PCA)	PCA Flw	SCFM	181.9	57.5
F(EHX)	E-FIG Flw	SCFM	50.9	4.0
F(SCA)	SCA Flw	SCFM	178.0	20.6
F(TCA,F)	TCA Flw	SCFM	412.6	62.8
F(FG,BH)	BH Flw	SCFM	520	10.6
F(TFG)	TFG Flw	SCFM	519.8	10.6
W(SR)	Recirc Rt	lbs/hr	11641	1008.0

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 7

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q BTU/hr	U BTU/ft2Fhr	Heat Flux BTU/ft2hr
2E,W	8	69	150	1362	4.80	195398	31.0	37577
3NE	14	69	139	1390	2.00	69771	21.4	26835
4SE	17.5	69	118	1397	2.00	49831	15.0	19166
6NE	27.5	69	120	1413	2.00	50150	14.9	19288
7SE	32.5	69	129	1406	1.50	44931	13.5	17281
8E	37.5	70	125	1416	1.60	44169	13.2	16988
	Overall	68	134	1378	14.11	464483	20.5	25521
			From Data Sheets=>		13.90			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-4,8,	8	68	153	1186	14.30	604912	97.5	100819
10-12			From Data Sheets=>		13.97			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	3	2.31	SO2-A	ppm	4	2.58
SO2-AE	lb/MM Btu	0.01	0.01				
CO	ppm	128	16.27	CO	ppm	139	17.63
CO2	%	15.67	0.33	CO2	%	17.09	0.19
N2O	ppm	N/A	N/A	N2O	ppm	N/A	N/A
N2OE	lb/MM Btu	N/A	N/A				
NOx	ppm	63	7.76	NOx	ppm	69	8.77
NOxE	lb/MM Btu	0.09	0.01				
O2-A	%	4.50	0.32				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal FdRt	lbs/hr	259.7	7.2
W(S)	LS FdRt	lbs/hr	10.0	*
V(FG)	FG SGV	ft/sec	14.5	2.2
V(S,C)	Comb SGV	ft/sec	11.1	1.6
V(S,EHX)	EHX SGV	ft/sec	1.7	0.1
FT18003	CHX Flwi	gpm	14.1	0.1
FT19003	EHX Flwi	gpm	14.3	0.1
PT15081	Comb dP	in. H2O	72.8	6.0
Q(CA)	CA Heat in	KBtu/hr	81.4	15.0
Q(CHX)	CHX HtRmv	KBtu/hr	486.8	29.2
Q(EHX)	EHX HtRmv	KBtu/hr	614.2	17.9
Q(EHX,IN	FG Ht in	KBtu/hr	2.1	0.2
Q(F)	Fuel Enrg in	KBtu/hr	993.2	27.3
Q(FG)	FG Enrg out	KBtu/hr	247.7	4.5
Q(IN)	Tot Enrg in	KBtu/hr	1076.3	29.8
Q(OUT)	Tot Enrg out	KBtu/hr	1648.7	39.1
BH A/C			2.0	0.0
A/SRATIO			2.82	*
DOORS	CHXs On		7	0
COILS	EHXs On		8.5	0.5

Tag	Desc	Average	Std Dev
TC13131AFPE-F2"		670	14.4
TC13132AFPE-F6"		843	10.1
TC13133AFPE-B6"		396	11.3
TC13134AFPE-F10"		551	28.8
TC13231AFPW-F2"		686	14.1
TC13232AFPW-F6"		853	9.6
TC13233AFPW-B6"		416	7.8
TC13234AFPW-F10'		757	13.6

* Calculated values

25-Jul-91

CFB-CL3-0491 — TEST 10

(1030-1230)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1451	5.0
TC11021	AFS Ex	°F	1248	4.3
TC15001	C Plenum	°F	518	5.2
TC15004	C 1-1'	°F	1446	12.8
TC15005	C 1-2'	°F	1436	12.2
TC15006	C 1-3'	°F	1435	12.3
TC15007	C 1-4'	°F	1431	11.4
TC15008	C 1-4'	°F	1438	12.5
TC15009	C 1-4'	°F	1433	11.5
TC15012	C 2-6'	°F	1450	12.5
TC15013	C 2-8'	°F	1461	11.6
TC15022	C 3-11'	°F	1460	9.4
TC15023	C 3-14'	°F	1470	9.5
TC15024	C 3-14'	°F	1476	10.3
TC15025	C 3-14'	°F	1474	9.7
TC15032	C 4-17.5'	°F	1477	8.0
TC15042	C 5-22.5'	°F	1485	8.7
TC15052	C 6-27.5'	°F	1489	8.9
TC15053	C 6-27.5'	°F	1490	9.4
TC15054	C 6-27.5'	°F	1482	7.9
TC15062	C 7-32.5'	°F	1482	8.1
TC15071	C 8-37.5'	°F	1487	8.5
TC15073	C 9-41'	°F	1484	9.4
TC15999	Ambient	°F	83	1.1
TC16001	EHX Plenm	°F	128	3.0
TC16012	EHX 0.5'	°F	1368	13.8
TC16013	EHX 1.5'	°F	1338	13.2
TC16014	EHX 2.7'	°F	1350	11.8
TC16015	EHX 3.8'	°F	1327	7.0
TC16017	EHX 5.3'	°F	1253	6.0
TC16018	EHX Exit	°F	1345	10.3
TC16021	Crc A in	°F	1493	7.4
TC16031	DC 8-36'	°F	1485	6.7
TC16032	DC 6-28'	°F	1450	5.9
TC16033	DC 4-18'	°F	1451	7.1
TC16034	DC3-9.5'	°F	1484	10.7
TC16035	DC3-8.5'	°F	1474	11.2
T(A,C)	Comb Temp	°F	1464	9.9
T(A,EHX)	EHX Temp	°F	1351	12.9
EA	Excess Air	%	27.1	3.9
SR	S Reten	%	98.7	1.8
R(PCA)	%Flw PCA	%	58.8	3.8
R(SCA)	%Flw SCA	%	41.2	3.8
R(Q,IN)	%Enrg in	%	124.8	5.9
R(CHX)	CHX Ratio	%	53.2	1.0
R(EHX)	EHX Ratio	%	46.8	1.0
F(PCA)	PCA Flw	SCFM	203.0	27.9
F(EHX)	E-FIG Flw	SCFM	52.3	1.4
F(SCA)	SCA Flw	SCFM	180.3	12.4
F(TCA,F)	TCA Flw	SCFM	439.0	21.2
F(FG,BH)	BH Flw	SCFM	541	2.5
F(TFG)	TFG Flw	SCFM	540.6	2.5
W(SR)	Recirc Rt	lbs/hr	13953	505.8

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 7

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q BTU/hr	U BTU/ft2Fhr	Heat Flux BTU/ft2hr
2E,W	8	69	156	1461	4.93	213332	31.4	41025
3NE	14	69	147	1473	2.00	78159	22.7	30061
4SE	17.5	69	127	1477	2.00	58248	16.6	22403
6NE	27.5	69	128	1487	2.00	59238	16.8	22784
7SE	32.5	69	142	1482	1.50	55187	15.8	21226
8E	37.5	69	138	1487	1.60	54493	15.5	20959
	Overall	69	143	1464	14.14	524375	21.8	28812
			From Data Sheets=>		14.03			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft^{2}hr°F	Heat Flux Btu/ft^{2}hr
1-2,10-12	5	68	164	1351	9.62	461067	103.6	122951
			From Data Sheets=>		9.50			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	10	13.35	SO2-A	ppm	10	14.02
SO2-AE	lb/MM Btu	0.02	0.03				
CO	ppm	69	12.35	CO	ppm	76	13.86
CO2	%	15.31	0.54	CO2	%	16.70	0.35
N2O	ppm	N/A	N/A	N2O	ppm	N/A	N/A
N2OE	lb/MM Btu	N/A	N/A				
NOx	ppm	98	13.63	NOx	ppm	108	17.82
NOxE	lb/MM Btu	0.15	0.03				
O2-A	%	4.50	0.50				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal FdRt	lbs/hr	299.6	13.0
W(S)	LS FdRt	lbs/hr	8.6	*
V(FG)	FG SGV	ft/sec	16.1	0.8
V(S,C)	Comb SGV	ft/sec	12.3	0.6
V(S,EHX)	EHX SGV	ft/sec	1.9	0.1
FT18003	CHX Flwi	gpm	14.1	0.0
FT19003	EHX Flwi	gpm	9.6	0.1
PT15081	Comb dP	in. H2O	65.7	2.8
Q(CA)	CA Heat in	KBtu/hr	91.8	4.5
Q(CHX)	CHX HtRmv	KBtu/hr	525.3	21.4
Q(EHX)	EHX HtRmv	KBtu/hr	461.4	9.5
Q(EHX,IN	FG Ht in	KBtu/hr	2.4	0.2
Q(F)	Fuel Enrg in	KBtu/hr	1151.4	45.1
Q(FG)	FG Enrg out	KBtu/hr	262.1	1.5
Q(IN)	Tot Enrg in	KBtu/hr	1246.3	46.4
Q(OUT)	Tot Enrg out	KBtu/hr	1548.8	26.1
BH A/C			2.1	0.0
A/SRATIO			2.43	*
DOORS	CHXs On		7	0
COILS	EHXs On		5.0	0.0

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	789	21.0
TC13132	AFPE-F6"	939	15.4
TC13133	AFPE-B6"	491	16.9
TC13134	AFPE-F10"	725	40.3
TC13231	AFPW-F2"	803	18.3
TC13232	AFPW-F6"	947	13.2
TC13233	AFPW-B6"	502	13.6
TC13234	AFPW-F10'	862	17.8

* Calculated values

APPENDIX C

BLACKSVILLE BITUMINOUS COAL TEST RESULTS

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LIST OF FIGURES

LIST OF TABLES

TEST MATRIX

Table C-1 shows the test matrix that was used for the Blacksville bituminous coal. Test duration was 231 hours of continuous testing, resulting in the successful completion of 18 scheduled test periods plus one additional test within the scheduled time. Each of the scheduled tests were conducted over a 6-hour test period.

Test 1 was a baseline test without limestone feed to determine the maximum sulfur emissions generated by this coal. Test 2 served as a baseline with limestone feed to establish the nominal calcium-to-sulfur ratio for 90% sulfur capture to be used in the latter test periods. Tests 6 and 3 were high- and low-temperature tests, respectively. Test 14 was operated at the same conditions as Test 13, except that secondary air addition was through Section 3 (10.5 feet above distributor plate level) of the combustor instead of Section 2 (5.75 feet above distributor plate level). Tests 9 through 12 were load tests performed at approximately 50% and 75% of full load established in Test 2. Turndown

TABLE C-1

Test Matrix

Test #	Temp. (°F)	Load (%)	Sulfur Ret. (%) or Ca/S ratio	PA/SA Split	SGV (ft/sec)	Excess Air (%)	Sec. Air Port
1	1550	100	No ls[1]	60:40	16	25	2
2	1550	100	90%	60:40	16	25	2
3	1425	100	same Ca/S as 2	60:40	15[2]	25	2
4	1550	100	same Ca/S as 2	70:30	19	15	2
5	1550	100	same Ca/S as 2	50:50	19	45	2
6	1675	100	same Ca/S as 2	60:40	17[2]	25	2
7	1550	100	same Ca/S as 2	50:50	13	15	2
8	1550	100	same Ca/S as 2	70:30	13	45	2
9	1550	75	same Ca/S as 2	80:20	12[2]	25	2
10	1550	50	same Ca/S as 2	90:10	8[2]	25	2
11	1000	50	same Ca/S as 2	90:10	10[2]	100[2]	2
12	1400	75	same Ca/S as 2	90:10	12[2]	50[2]	2
12a	1400	75	same Ca/S as 2	60:40	12[2]	50[2]	2
13	1550	100	95%	60:40	16	25	2
14	1550	100	95%	60:40	16	25	3
15	1550	100	70%	60:40	16	25	2
16	1550	100	same Ca/S as 2	60:40	16	25	2
17	1550	100	same Ca/S as 2	60:40	16	25	2
18	1550	100	No ls	60:40	16	25	2

[1] Limestone.

[2] Estimated values.

philosophies that would be used for CFB boilers with and without external heat exchangers were investigated. The addition of Test 12a provided more emission data for different primary/secondary combustion air splits. During Tests 13 and 15, the Ca/S ratio was adjusted to obtain 95% and 70% sulfur capture, respectively. Tests 4, 5, 7, and 8 were N_2O tests. Operational conditions that were varied included the primary/secondary air split, velocity, and excess air to determine the effects of these variables specifically on N_2O as well as other emissions. Tests 16 and 17 were at baseline operating conditions, using fine New Enterprise limestone for Test 16 and fine Colorado Ute limestone for Test 17. Test 18 was without limestone feed, operating with a bed of limestone and coal ash.

COAL AND LIMESTONE PROPERTIES

The coal and limestone used for this test were supplied by the Empire State Electric Energy Research Corporation (ESEERCO). Two railcars of the Blacksville coal, a bituminous coal from the Pittsburgh #8 seam, along with one railcar of the New Enterprise limestone were received at the EERC. Proximate and ultimate analyses of the coal and x-ray fluorescence analysis of the coal ash and limestone were performed. Coal samples from Tests 1, 5, 9, 13, 17, and 18 were analyzed, and the averages of these analyses are shown in Table C-2. Limestone samples from Tests 2 through 15 were composited; the results of the analysis on the composite, as well as the analysis of the Colorado Ute limestone, are shown in Table C-3. Size distributions of the coal and limestones are shown in Figures C-1 and C-2, respectively.

OPERATIONAL PERFORMANCE

General Operability

Overall operation for this test was very good. There were occasional hang-ups of coal in either the coal weigh hopper or in the rotary feed valve used for controlling the coal feed rate. This was the result of an accumulation of surface moisture on coal that had been processed and stored in movable sealed storage hoppers. The coal feed rate when using freshly processed coal from the storage silos did fluctuate slightly, but did not present any significant feed problems. The smaller-sized New Enterprise limestone used in Test 16 and the Colorado Ute limestone used in Test 17, which also had a fine consistency, were both difficult to feed steadily into the combustion system. It tended to "rathole" and "bridge" in the weigh hopper and was even difficult to feed out of the movable storage hoppers. The use of a vibrator had little effect on producing uniform feed rates, and, as a result, frequent pounding on hoppers and rotary valves was necessary to maintain limestone feed.

For this test, it was decided to use recirculation from the 25-inch refractory-lined primary cyclone only. Ash from the secondary stainless steel cyclone was routed to a collection barrel. Recirculation rates tended to be relatively low compared to tests conducted with other fuels when secondary cyclone ash was recirculated. Even with low recirculation rates, reasonable heat transfer to heat exchange surfaces in the combustor and external heat exchanger were obtained.

TABLE C-2

Coal Analyses
Average of Tests 1, 5, 9, 13, 17, and 18

Proximate Analysis, as-received, wt%	
Moisture	2.9
Volatile Matter	35.1
Fixed Carbon	53.8
Ash	8.2
Ultimate Analysis, % as-received, wt%	
Carbon	74.4
Hydrogen	5.3
Nitrogen	1.3
Sulfur	2.4
Oxygen	8.4
Ash	8.2
Ash Composition, as oxides, wt%	
Calcium, CaO	5.6
Magnesium, MgO	1.2
Sodium, Na_2O	0.7
Silica, SiO_2	43.6
Aluminum, Al_2O_3	22.7
Ferric, Fe_2O_3	16.6
Titanium, TiO_2	0.7
Phosphorous, P_2O_5	0.4
Potassium, K_2O	1.7
Sulfur, SO_3	6.8
High Heating Value (as-received), Btu/lb	13,274

TABLE C-3

Average Limestone Analysis (% as oxide)

Component	New Enterprise (Coarse)	New Enterprise (Fine)	Colorado Ute (Fine)
Silica	2.96	2.66	2.81
Aluminum	0.78	0.59	0.48
Iron	0.42	0.44	0.26
Titanium	0.03	0.01	0.00
Calcium	51.77	51.77	54.19
Magnesium	2.77	3.23	0.95
Sulfur	0.21	0.22	0.30
Sodium	0.06	0.36	0.04
Potassium	0.32	0.06	0.29

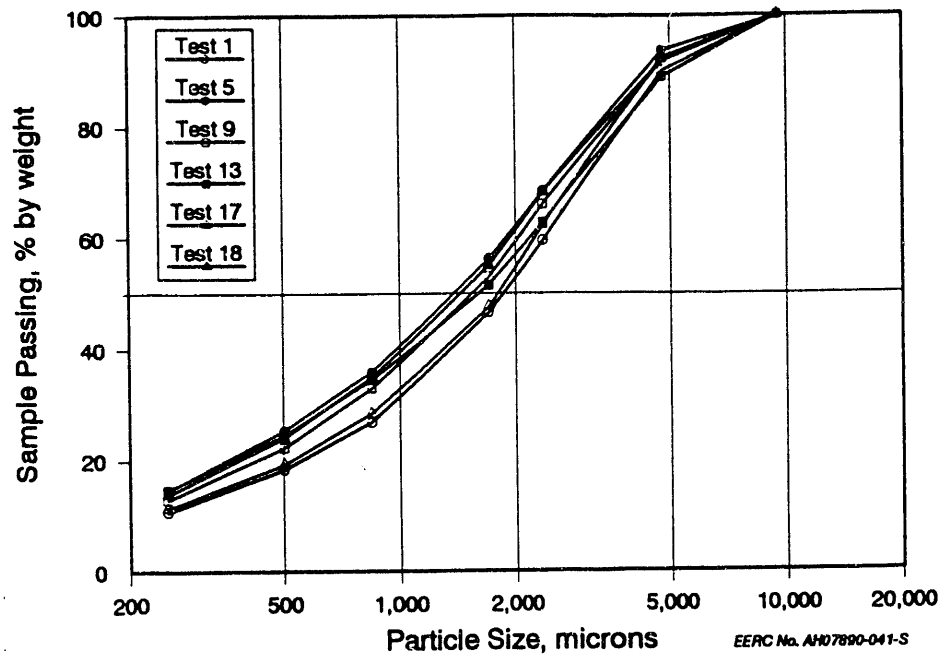

Figure C-1. Particle-size distribution of coal.

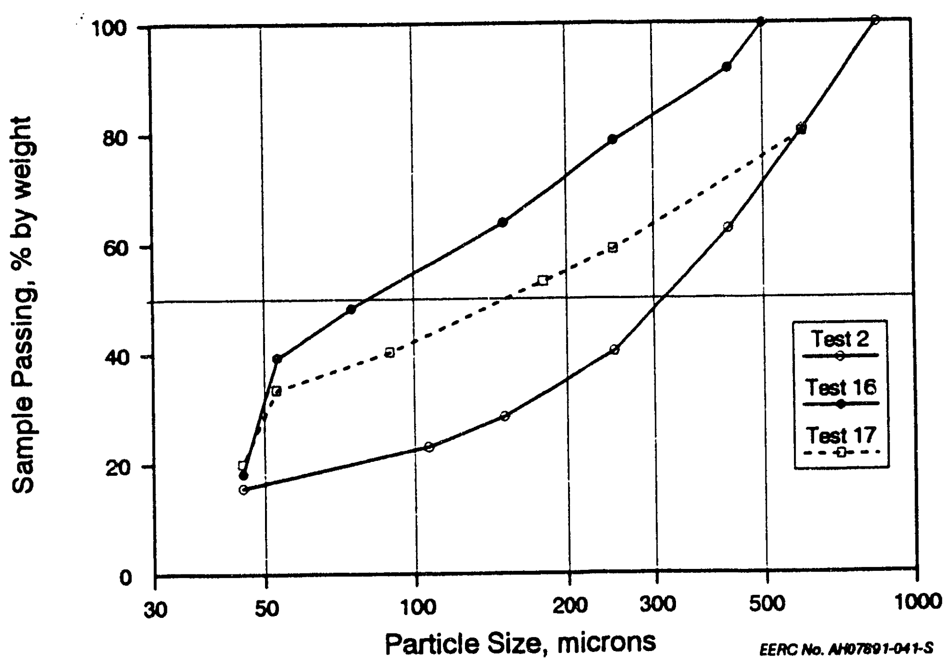

Figure C-2. Particle-size distribution of limestone.

This was the first test in which proportional, integral, and differential (PID) control loops were incorporated for controlling the combustor velocity, the velocity through the external heat exchanger, and the primary/secondary combustion air (PA/SA) split. These control loops were very successful, reducing the amount of interaction required to maintain steady state conditions. The most obvious difference in data obtained using automatic control compared to the previous manual control method is in how much more concisely we can control the EHX velocity and the PA/SA split. Obtaining precise velocity through the combustor can still be challenging at some of the extreme conditions even with automatic control.

Summary of Results

Upon completion of the run, the data from the data acquisition system and operator's log sheets were averaged over each of the nineteen test periods. Certain data points were deleted before the averages were calculated, such as emissions data from time periods when the gas analyzers were calibrated or the sample conditioner was purged, and baghouse pressure drop when the baghouse was bypassed. A summary of the process data for the 19 tests conducted is presented in Table C-4. The 19 test periods correspond to those presented in the test matrix listed in Table C-1. Summaries of the run data, showing averages and standard deviations for most of the data collected by the data acquisition system, are included at the end of this appendix.

Recirculation Rates and Size Distributions

The average solids recirculation rates, determined by a heat balance around the external heat exchanger, are shown in Table C-5. Recirculation rates were, on the average, lower during this test compared to previously conducted tests with other coals. This was primarily due to not recirculating the fly ash collected from the secondary cyclone back into the downcomer. The Blacksville coal has a high sulfur content that requires a significant limestone feed rate. Thus a large amount of solids are being steadily fed into the system, making it less critical to have an overall high collection efficiency to retain sufficient solids for recirculation. Additionally, when solids recirculation is too high, it can cause operational problems in the shell-and-tube combustion air heater and result in high temperatures downstream in the baghouse. As the recirculation rate increases, it appears that particulate loading increases as well, and the water-jacketed flue gas heat exchangers cannot keep up, resulting in high inlet temperatures into the baghouse. In a full-scale system, this could correspond to higher heat-transfer rates in the convective pass region along with greater erosion potential. The advantages of recirculating additional fines include potentially higher limestone utilization and combustion efficiency.

All of the low velocity tests (7 through 12) had low recirculation rates. The lowest recirculation rates encountered were for the 50% load tests (10 and 11) conducted at the lowest velocities (10.6 and 9.1 ft/sec, respectively). Switching over to secondary air addition through Section 3 at a level of 10.5 feet above the distributor plate also resulted in a low recirculation rate. Normally, secondary air addition is through Section 2 at 5.75 feet above the distributor plate. Section 1 of the combustor, as described earlier, is tapered, starting at a 14-inch inside diameter, increasing to the 20-inch inside diameter over its 5-foot length. This allows sufficient velocity in this section to keep the solids fluidized. Then secondary air is introduced at the Section 2 level, resulting in full

TABLE C-4

Summary of Process Data

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Time:	1745-2345	1530-2140	0135-0735	1315-1805	0215-0815	1230-1830	1015-1615	0215-0815	1815-0015
Date:	10/7/91	10/8/91	10/9/91	10/9/91	10/10/91	10/10/91	10/11/91	10/11/91	10/11-10/12
Coal Feed Rate, lb/hr	174	174	176	214	171	165	147	133	127
Limestone Feed Rate, lb/hr	0	36	33	41	46	40	21	10	18
Solids Recirculation Rate, lb/hr	4168	7217	5262	9494	4316	2517	2097	1481	2026
Combustion Air									
EHX Flow, scfm	44	50	56	49	52	48	77	66	70
Primary Air, scfm	262	253	249	358	239	245	136	223	230
Secondary Air, scfm	166	172	170	139	257	162	181	113	41
Feed Assist Air, scfm	18	18	19	19	16	16	16	18	17
DC Aeration Air, scfm	0	0	0	0	22	22	0	0	0
Purge Air, scfm	16	16	16	16	16	16	16	16	16
Total Air, scfm	505	507	510	581	601	509	425	435	374
PA/SA, %	60	59	60	70	50	60	50	67	81
Excess Air, %	28.3	20.4	30.8	19.9	54.8	31.0	21.3	53.0	27.0
FG SGV, ft/sec	16.1	15.8	15.2	18.4	18.4	16.4	13.6	13.6	11.7
EHX SGV, ft/sec	1.5	1.8	1.8	1.9	1.8	1.8	2.2	2.0	2.2
Comb. dP, in. H_2O	37.8	44.9	46.4	38.1	38.5	36.6	44.7	43.8	44.4
Flue Gas									
Flow Rate, scfm	508	508	517	605	607	504	433	424	375
Oxygen, %	4.7	3.6	5.0	3.5	7.4	4.9	3.6	7.2	4.5
SO_2, ppm	1540	194	592	233	398	1497	676	336	267
CO, %	0.0124	0.0089	0.0207	0.0121	0.0037	0.0075	0.0033	0.0081	0.0107
NO_x, ppm	109	91	31	118	172	233	75	132	79
N_2O, ppm	152	140	236	119	115	46	110	127	142
CO_2, %	13.7	16.2	15.2	16.1	12.8	15.3	17.0	13.2	15.5
Ash									
Bed Material Add Rate, lb/hr	5	0	0	0	27	17	0	0	0
Bottom Ash Discharge Rate, lb/hr	0.69	21	21	5	5	3	4	5.2	4.2
Bottom Ash Unburned Carbon, %	6	1.50	5.26	2.36	0.63	0.81	0.80	0.46	0.59
Cyclone Ash Discharge Rate, lb/hr	50.14	33	38	60	61	58	17	12	17
Cyclone Ash Unburned Carbon, %	8	27.79	32.71	7.84	22.33	6.41	24.86	30.48	25.41
Baghouse Ash Discharge Rate, lb/hr	43.39	2.6	6.3	1	4.3	3	3	3	1
Baghouse Ash Unburned Carbon, %	19	10.46	21.43	12.37	11.13	6.47	8.60	9.07	11.16
Total Ash (meas.), lb/hr	15	57	66	66	70	64	24	20	22
Total Ash (calc.), lb/hr	26.8	46	40	52	48	38	31	22	28
Bottom Ash/Total Ash (meas.), %		36.6	32.3	7.7	6.4	5.1	16.7	25.9	19.0

continued...

TABLE C-4 (continued)

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Time:	1745-2345	1530-2140	0135-0735	1315-1805	0215-0815	1230-1830	1015-1615	0215-0815	1815-0015
Date:	10/7/91	10/8/91	10/9/91	10/9/91	10/10/91	10/10/91	10/11/91	10/11/91	10/11-10/12
Air and Gas Temperatures, °F									
Combustor Temperatures									
Plenum	548	528	513	624	575	563	407	412	411
Section 1	1548	1528	1401	1527	1554	1746	1555	1578	1554
Section 2	1625	1564	1438	1570	1607	1791	1617	1613	1587
Section 3	1595	1551	1441	1563	1585	1737	1608	1565	1549
Section 4	1556	1545	1442	1570	1541	1666	1559	1494	1513
Section 5	1566	1557	1456	1577	1556	1675	1589	1506	1526
Section 6	1553	1555	1454	1585	1547	1652	1530	1485	1516
Section 7	1484	1515	1421	1556	1478	1554	1546	1431	1484
Section 8	1477	1486	1434	1576	1485	1548	1544	1426	1485
Section 9	1547	1568	1472	1606	1556	1640	1600	1481	1532
PCD Exit	1541	1546	1481	1599	1531	1606	1567	1438	1510
Average	1558	1544	1432	1560	1555	1698	1578	1535	1539
EHX Temperatures									
Plenum	129	119	127	116	122	118	131	117	128
0.5' above Distributor Plate	1218	1337	1120	1396	1265	1367	928	1050	1093
1.5' above Distributor Plate	1209	1322	1107	1370	1231	1374	907	1030	1093
2.7' above Distributor Plate	1214	1328	1102	1379	1249	1370	913	1033	1088
3.8' above Distributor Plate	1190	1317	1081	1346	1210	1280	912	1000	1073
5.3' above Distributor Plate	1065	1232	1043	1281	1125	1176	848	892	1000
Average	1214	1329	1110	1382	1248	1370	916	1038	1091
Downcomer Temperatures									
Section 3	1551	1562	1478	1592	1555	1607	1570	1458	1512
Section 4	1533	1534	1452	1571	1544	1621	1550	1436	1489
Section 6	1539	1535	1457	1571	1566	1641	1548	1456	1488
Section 8	1565	1562	1486	1597	1590	1668	1596	1496	1538
Ambient	87	73	76	76	77	80	78	70	78

continued...

TABLE C-4 (continued)

	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18
Time:	0750-1215	1500-2100	1320-1920	0325-0815	1100-1700	0120-0720	1750-2045	0525-1125	1630-1730
Date:	10/12/91	10/12/91	10/13/91	10/14/91	10/14/91	10/15/91	10/15/91	10/16/91	10/16/91
Coal Feed Rate, lb/hr	93	88	133	156	169	176	193	173	188
Limestone Feed Rate, lb/hr	19	19	25	40	44	23	36	40	0
Solids Recirculation Rate, lb/hr	730	1056	1783	4811	2240	3603	4204	3966	2839
Combustion Air									
EHX Flow, scfm	48	65	50	44	58	53	61	51	54
Primary Air, scfm	249	218	328	263	243	252	238	255	249
Secondary Air, scfm	0	0	0	173	165	170	168	166	168
Feed Assist Air, scfm	17	17	16	18	18	17	19	20	19
DC Aeration Air, scfm	0	0	8	7	8	7	9	10	9
Purge Air, scfm	16	16	16	16	16	16	16	16	16
Total Air, scfm	330	315	417	519	507	515	510	517	515
PA/SA, %	89	88	92	60	60	60	60	60	60
Excess Air, %	40.9	51.1	33.5	36.8	42.1	28.9	21.7	30.3	32
FG SGV, ft/sec	10.6	9.1	12.4	16.1	16	16	15.9	16.1	16
EHX SGV, ft/sec	1.3	1.3	1.4	1.6	1.7	1.7	2	1.6	1.7
Comb. Dp, in. H_2O	43.6	46.6	41.7	45.9	45.9	39.3	36.9	43.7	39
Flue Gas									
Flow Rate, scfm	321	312	424	519	525	520	514	524	507
Oxygen, %	6.1	7.2	5.3	5.6	6.2	4.8	3.8	4.9	5.2
SO_2, ppm	232	251	152	154	753	572	555	296	1491
CO, %	0.0069	0.0514	0.0157	0.0051	0.0062	0.0057	0.0040	0.0011	0.0016
NO_x, ppm	95	49	100	126	119	122	124	136	137
N_2O, ppm	98	180	ND[1]	ND	78	131	103	118	124
CO_2, %	14.1	12.6	14.6	14.7	14.0	14.7	16.0	14.8	13.7
Ash									
Bed Material Add Rate, lb/hr	8	0	0	0	0	0	8	8	8
Bottom Ash Discharge Rate, lb/hr	3.7	17.2	4.2	4	4	4.3	4.6	3.8	1.6
Bottom Ash Unburned Carbon, %	0.37	2.70	3.49	0.80	0.49	0.01	0.11	0.00	0.05
Cyclone Ash Discharge Rate, lb/hr	8	3	36	46	55	38	52	46	31
Cyclone Ash Unburned Carbon, %	14.15	33.93	21.32	16.03	11.64	29.27	18.29	23.90	39.28
Baghouse Ash Discharge Rate, lb/hr	3	3	4	6	3	3	5	2	4
Baghouse Ash Unburned Carbon, %	8.19	14.87	11.09	9.42	6.80	7.56	7.63	9.13	11.68
Total Ash (meas.), lb/hr	15	24	44	56	62	45	62	52	37
Total Ash (calc.), lb/hr	25	23	33	46	43	35	44	46	14
Bottom Ash/Total Ash (meas.), %	25.2	73.2	9.5	7.2	6.5	9.6	7.5	7.3	4.4

[1] Not determined.

continued...

TABLE C-4 (continued)

	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 13
Time:	0750-1215	1500-2100	1320-1920	0325-0815	1100-1700	0120-0720	1750-2045	0525-1125	1630-1730
Date:	10/12/91	10/12/91	10/13/91	10/14/91	10/14/91	10/15/91	10/15/91	10/16/91	10/16/91
Air and Gas Temperatures, °F									
Combustor Temperatures									
Plenum	368	320	425	524	506	527	546	543	538
Section 1	1561	1440	1500	1536	1642	1541	1558	1549	1561
Section 2	1600	1473	1542	1580	1683	1611	1627	1604	1637
Section 3	1554	1433	1507	1559	1633	1589	1605	1583	1613
Section 4	1519	1387	1466	1537	1549	1550	1566	1545	1558
Section 5	1567	1385	1466	1548	1564	1570	1582	1559	1577
Section 6	1560	1350	1446	1544	1545	1562	1575	1549	1565
Section 7	1574	1272	1357	1476	1438	1487	1500	1476	1474
Section 8	1568	1222	1354	1490	1429	1495	1506	1478	1474
Section 9	1582	1271	1433	1550	1534	1565	1577	1553	1564
PCD Exit	1533	1273	1414	1531	1498	1562	1586	1545	1561
Average	1566	1390	1473	1540	1590	1557	1572	1552	1569
EHX Temperatures									
Plenum	112	134	113	118	122	123	132	122	120
0.5' above Distributor Plate	846	526	926	1287	997	1127	1156	1128	1057
1.5' above Distributor Plate	848	525	915	1267	978	1101	1126	1099	1034
2.7' above Distributor Plate	844	520	908	1267	971	1106	1131	1103	1040
3.8' above Distributor Plate	800	525	873	1212	962	1093	1130	1080	1022
5.3' above Distributor Plate	719	504	798	1084	895	1006	1051	985	935
Average	846	524	917	1274	982	1111	1137	1110	1044
Downcomer Temperatures									
Section 3	1498	1308	1437	1547	1532	1573	1583	1558	1583
Section 4	1493	1281	1408	1520	1508	1539	1550	1524	1546
Section 6	1509	1283	1415	1526	1517	1549	1556	1535	1552
Section 8	1593	1336	1449	1556	1552	1577	1587	1563	1580
Ambient	73	84	72	78	73	79	82	77	80

TABLE C-5

Solids Recirculation and Heat-Transfer Data

Test	Temp. (°F)	Ca/S	Excess Air (%)	Primary Air (%)	Solids Recirculation (lb/hr)	DC[1] d_{50} (μm)	H_o[2]	Heat Flux (Btu/hr-ft²)	Cyclone Efficiency (%)	Recirculation Ratio
1	1,558	0.1	28.3	60	4,168	349	14.4	26,534	99.66	291
2	1,544	2.4	20.4	59	7,217	305	19.1	26,665	99.50	144
3	1,432	2.4	30.8	60	5,262	272	19.2	24,589	99.15	111
4	1,560	2.4	19.9	70	9,494	316	22.2	31,285	99.36	163
5	1,555	3.3	54.8	50	4,316	373	18.6	26,336	98.48	72
6	1,698	2.9	31.0	60	2,517	392	20.2	31,298	97.58	47
7	1,573	1.7	21.3	50	2,097	301	18.8	27,100	99.05	63
8	1,535	1.0	53.0	67	1,481	324	17.9	25,207	98.99	72
9	1,539	1.8	27.0	81	2,026	263	18.6	26,203	99.12	71
10	1,566	2.3	40.9	89	730	211	17.8	25,643	98.49	28
11	1,390	2.6	51.1	88	1,056	180	14.8	18,938	99.40	40
12	1,473	2.3	33.5	92	1,783	309	16.3	22,096	97.75	50
13	1,540	3.0	36.8	60	4,811	329	18.2	25,691	98.93	91
14	1,590	3.5	42.1	60	2,240	314	17.8	26,009	97.41	39
15	1,557	1.7	28.9	60	3,603	344	17.4	24,976	98.87	96
16	1,572	2.5	21.7	60	4,204	343	17.9	25,927	98.64	80
17	1,552	2.9	30.3	60	3,966	340	17.9	25,627	98.78	73
18	1,569	0.1	32.0	60	2,839	509	17.8	25,730	98.77	183

[1] Downcomer.
[2] Heat-transfer coefficient (Btu/hr-ft²-°F).

operational velocity up the remaining combustor sections, which have a uniform 20-inch inside diameter. Section 3 secondary air addition creates a low-velocity region in Section 2, causing less solids to be blown upward to the full velocity region where they can be conveyed up and out of the combustor into the primary cyclone.

Recirculation rates for Tests 16 and 17, conducted with two difference types of fine-sized limestone, were each lower than for Test 2. Test 2 was run at the same type of conditions and with the same limestone as Test 16, but with a larger particle size. The finer-sized limestone does not seem to stay in the system long enough to sulfate and is carried more readily to the baghouse.

Cyclone efficiency is defined as one minus the ratio of total fly ash collected (including both baghouse and secondary cyclone ash) to the recirculation rate. The lowest cyclone efficiency, 97.4%, was calculated for Test 14, while Test 1 had the highest, 99.7%.

The particle-size distributions of the combustor bed material, downcomer, secondary cyclone ash, and baghouse ash are shown in Figures C-3 through C-5.

Fly Ash/Bottom Ash Splits

The ash balance for all of the test periods is shown in Table C-6 and includes ratios of bottom ash-to-total ash and percent closure. The bottom ash-to-total ash ratio was generally in the range of 5% to 35%. In most instances, more material was being removed than was being added during the test periods. Tests 3, 10, and 18 had the poorest closures. Test 3 had high material removal rates from the combustor bed,

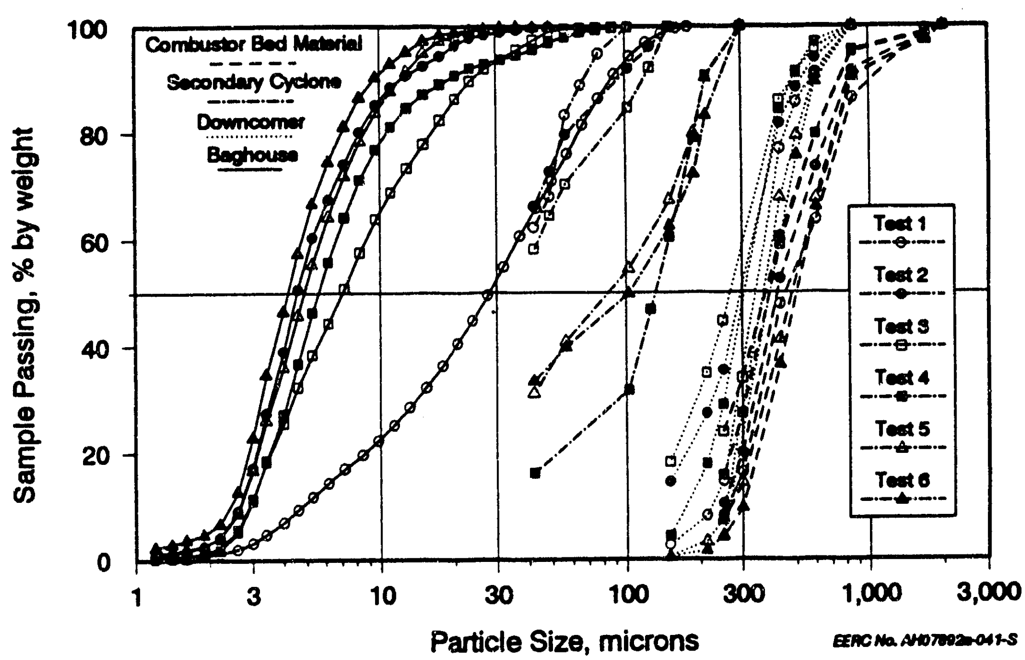

Figure C-3. Particle-size distributions of the combustor bed material, downcomer, secondary cyclone ash, and baghouse ash.

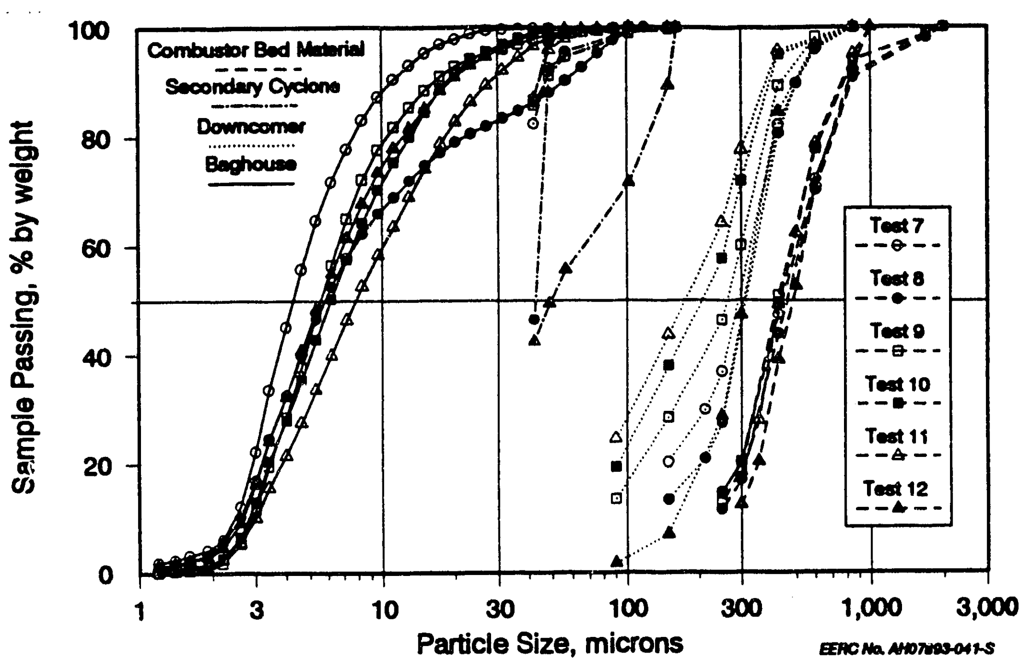

Figure C-4. Particle-size distributions of the combustor bed material, downcomer, secondary cyclone ash, and baghouse ash.

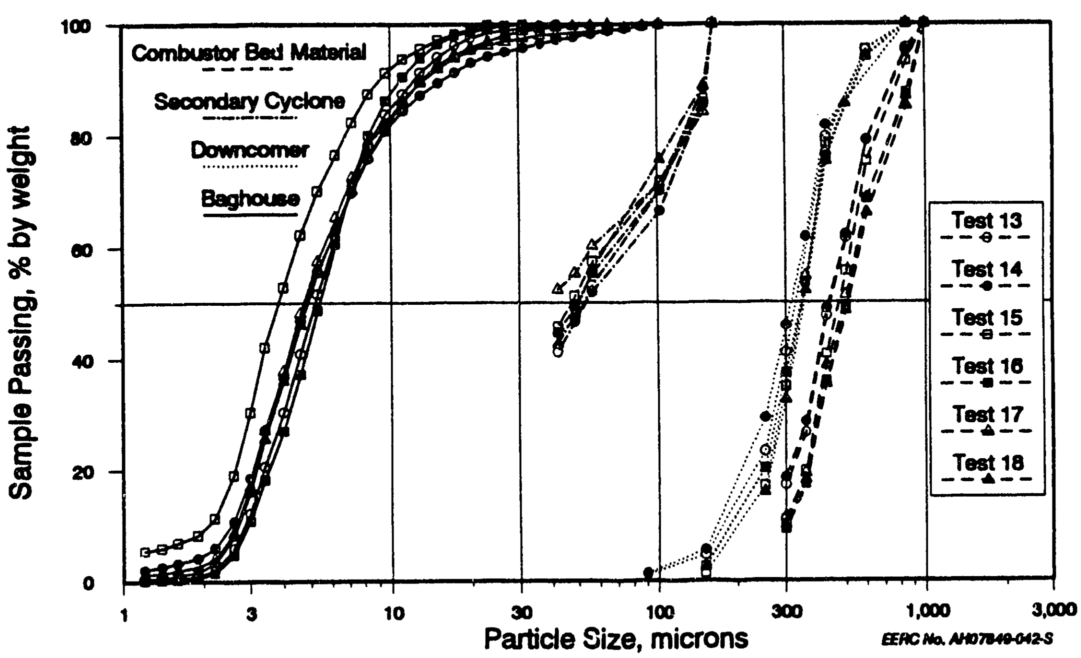

Figure C-5. Particle-size distributions of the combustor bed material, downcomer, secondary cyclone ash, and baghouse ash.

TABLE C-6

Ash Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Input (lb/hr)									
Ash	15	16	14	18	15	14	13	11	11
Sorbent*									
CaO	0	13	13	15	20	21	7	1	5
$CaSO_4$	0	18	12	20	14	3	11	10	12
Bed Material	0	0	0	0	27	17	0	0	0
Total Solids In	15	46	40	53	75	56	31	22	28
Output (lb/hr)									
Bed Material	5	21	21	5	5	3	4	5	4
Cyclone Ash	6	33	38	60	61	58	17	12	17
Baghouse Ash	8	3	6	1	4	3	3	3	1
Total Solids Out	19	57	66	66	70	64	24	20	22
Closure (%)	132.0	122.9	163.8	125.3	93.2	115.5	76.6	91.9	79.0
Bottom Ash/Total Ash (%)	26.8	36.6	32.3	7.7	6.4	5.1	16.7	25.9	19.0

	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18
Input (lb/hr)									
Ash	9	8	12	14	13	15	16	15	14
Sorbent*									
CaO	7	7	8	14	17	11	12	16	0
$CaSO_4$	10	8	13	20	18	5	20	16	0
Bed Material	8	0	0	0	0	0	8	8	8
Total Solids In	33	23	33	48	49	31	56	55	23
Output (lb/hr)									
Bed Material	4	17	4	4	4	4	5	4	2
Cyclone Ash	8	3	36	46	55	38	52	46	31
Baghouse Ash	3	3	4	6	3	3	5	2	4
Total Solids Out	15	24	44	56	62	45	62	52	37
Closure (%)	44.4	101.4	133.1	115.2	127.6	146.5	110.5	95.2	160.4
Bottom Ash/Total Ash (%)	25.2	73.2	9.5	7.2	6.5	9.6	7.5	7.3	4.4

* The CaO and $CaSO_4$ mass inputs are included to express sorbent equivalent mass inputs.

secondary cyclone, and baghouse. Test 10 was a low-load, low-velocity test with very little material removed from the secondary cyclone. Test 18 had no limestone addition and a much higher secondary cyclone ash removal rate than Test 1, which also had no limestone addition. The combined output of secondary cyclone and baghouse ash in most instances very closely matches the total input of the limestone and coal ash. It appears that operation would be possible without much bottom ash removal.

Coal Ash/Limestone Split

An aluminum balance was performed to determine the composition of each ash stream. Al_2O_3 was used as a tracer, since it is prevalent in the coal ash and almost non-existent in the limestone. The percentage of each ash stream that came from the coal, as well as the proportions of coal and limestone as inputs for each test, are shown in

Table C-7. The percentage of limestone in the ash is determined by difference. For several tests, such as Test 5, bed material was added during the test; for these tests, the sum of the coal and limestone input does not total 100%, and the percentages of ash from both the coal and limestone are artificially high, since the aluminum in the added bed material is not accounted for. Test 18 shows a greater than 100% contribution of coal ash to the baghouse ash because the percentage of aluminum in the baghouse ash was greater than that in the coal; this is probably due to the aluminum in the bed material added during that test. Table C-8 shows the aluminum balance for each test. The closure in this table and in Table C-7 is based on the coal ash only.

The baghouse material typically was made up of over 80% fly ash. This indicates the limestone is not degrading to any great extent and producing fines. Recycle from the baghouse would do little to improve sulfur capture for this coal. The material collected in the secondary cyclone, however, contained 40-78% limestone. Recycle of this stream could potentially increase sulfur capture and improve the utilization of the limestone. The bed drain contained 82%-86% limestone, indicating that most of the ash in the coal is being removed as fly ash.

THERMAL PERFORMANCE

Energy and Material Balances

The measured and theoretical fuel and flue gas flow rates are shown in Tables C-9 and C-10, respectively. The theoretical coal feed rate is calculated using the coal analysis and the actual air flow rates and flue gas emissions for each test period. The measured coal feed rate is determined by calculating the weight loss over time of the coal weigh hopper. The fuel balance for most of the tests was fairly good; the largest difference between measured and theoretical was for Test 10, which was a 50% load test and, consequently, had a very low coal feed rate. Fourteen of the eighteen tests had a negative difference; that is, the theoretical feed rate was greater than the measured. Other tests have shown the same trend.

The theoretical flue gas rates were calculated using the coal analysis and theoretical coal feed rates for each test. The actual air and flue gas flow rates were measured with orifice plates. In all cases, the measured flue gas flow rate was less than the theoretical, with the greatest difference observed for Test 10.

The energy balances for the eighteen tests are shown in Table C-11, both as Btu/hr and as percentages. The energy input is made up of the energy potential of the fuel, the primary and secondary combustion air, the external heat exchanger fluidizing air, the carbon present in the added bed material, and the energy released from the sulfation of the sorbent. Measurable heat loss sources consist of the combustor heat exchange doors, the external heat exchanger cooling coils, the heat of the flue gas (including a correction for leakage), the heat of the solids removed from the system, the unburned carbon in the ash removed, and the energy absorbed during calcination of the sorbent. The unmeasurable heat loss due to convection and radiation is estimated using a correlation, which relates heat loss to average combustor temperature, that was developed from the data generated from testing with all five coals. The energy balances for all eighteen tests were generally quite good, ranging from 90.6% closure for Test 10 to 108.2% closure for Test 11.

TABLE C-7

Material Derived from Coal Ash and Limestone Based on Aluminum Material Balance (%)

	Coal	ls[1]	Coal	ls	Coal	ls
	Test 1		Test 2		Test 3	
Solids Input	100.00	0.00	34.30	65.70	35.75	64.25
Bed Drain	19.78	0.00	17.67	82.33	16.65	83.35
Cyclone Catch	74.89	0.00	50.22	49.78	39.52	60.48
Baghouse Catch	95.59	0.00	86.78	13.22	84.58	15.42
Aluminum Balance Closure	90.32		144.94		165.94	
	Test 4		Test 5		Test 6	
Solids Input	34.02	65.98	19.22	45.03	25.30	45.49
Bed Drain	15.64	84.36	14.18	85.82	17.16	82.84
Cyclone Catch	21.81	78.19	32.54	67.46	23.53	76.47
Baghouse Catch	81.50	18.50	81.03	18.97	83.62	16.38
Aluminum Balance Closure	81.44		165.89		114.41	
	Test 7		Test 8		Test 9	
Solids Input	43.54	56.46	49.16	50.84	40.61	59.39
Bed Drain	15.39	84.61	15.22	84.78	17.15	82.85
Cyclone Catch	55.60	44.40	67.24	32.76	56.14	43.86
Baghouse Catch	92.67	7.33	93.97	6.03	87.72	12.28
Aluminum Balance Closure	98.85		109.66		100.44	
	Test 10		Test 11		Test 12	
Solids Input	28.11	45.14	34.01	65.99	34.54	65.46
Bed Drain	16.27	83.73	15.31	84.69	13.51	86.49
Cyclone Catch	55.26	44.74	61.84	38.16	36.62	63.38
Baghouse Catch	82.02	17.98	86.40	13.60	85.96	14.04
Aluminum Balance Closure	84.92		94.00		149.54	
	Test 13		Test 14		Test 15	
Solids Input	31.39	68.61	30.74	69.26	41.39	58.61
Bed Drain	13.20	86.80	13.88	86.12	12.47	87.53
Cyclone Catch	28.95	71.05	27.27	72.73	47.58	52.42
Baghouse Catch	78.95	21.05	75.77	24.23	98.68	1.32
Aluminum Balance Closure	129.35		133.87		143.50	
	Test 16		Test 17		Test 18	
Solids Input	29.39	54.90	27.87	56.50	63.52	0.00
Bed Drain	15.24	84.76	16.83	83.17	12.87	87.13
Cyclone Catch	27.00	73.00	38.72	61.28	54.71	45.29
Baghouse Catch	68.28	31.72	75.33	24.67	105.38	-5.38
Aluminum Balance Closure	116.96		136.91		146.85	

[1] Limestone.

TABLE C-8

Aluminum Material Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Coal Ash Feed Rate, lb/hr	14.70	15.66	14.47	18.05	14.51	14.46	13.11	10.64	10.94
Al_2O_3 in Coal Ash, %	22.70	22.70	22.70	22.70	23.20	23.20	23.20	23.20	22.80
Secondary Cyclone Ash Out, lb/hr	6.40	33.40	38.30	60.00	61.30	58.30	16.70	11.70	17.20
Al_2O_3 in Secondary Cyclone Ash, %	17.00	11.40	8.97	4.95	7.55	5.46	12.90	15.60	12.80
Ash from Coal, %	74.89	50.22	39.52	21.81	32.54	23.53	55.60	67.24	56.14
Ash from Coal, lb/hr	4.79	16.77	15.13	13.08	19.95	13.72	9.29	7.87	9.66
Baghouse Ash Out, lb/hr	7.80	2.60	6.30	1.00	4.30	2.70	3.30	3.20	0.70
Al_2O_3 in Baghouse Ash, %	21.70	19.70	19.20	18.50	18.80	19.40	21.50	21.80	20.00
Ash from Coal, %	95.59	86.78	84.58	81.50	81.03	83.62	92.67	93.97	87.72
Ash from Coal, lb/hr	7.46	2.26	5.33	0.81	3.48	2.26	3.06	3.01	0.61
Bed Material Out, lb/hr	5.20	20.80	21.30	5.10	4.50	3.30	4.00	5.20	4.20
Al_2O_3 in Bed Material, %	4.49	4.01	3.78	3.55	3.29	3.98	3.57	3.53	3.91
Ash from Coal, %	19.78	17.67	16.65	15.64	14.18	17.16	15.39	15.22	17.15
Ash from Coal, lb/hr	1.03	3.67	3.55	0.80	0.64	0.57	0.62	0.79	0.72
Total Ash from Coal, lb/hr	13.28	22.70	24.01	14.70	24.07	16.54	12.96	11.67	10.99
Closure, %	90.32	144.94	165.94	81.44	165.89	114.41	98.85	109.66	100.44

	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18
Coal Ash Feed Rate, lb/hr	8.72	7.73	11.61	14.18	13.32	14.83	15.52	14.80	14.45
Al_2O_3 in Coal Ash, %	22.80	22.80	22.80	22.80	22.70	22.70	22.70	22.70	22.30
Secondary Cyclone Ash Out, lb/hr	8.30	3.30	36.00	46.00	55.00	37.80	52.00	46.20	31.10
Al_2O_3 in Secondary Cyclone Ash, %	12.60	14.10	8.35	6.60	6.19	10.80	6.13	8.79	12.20
Ash from Coal, %	55.26	61.84	36.62	28.95	27.27	47.58	27.00	38.72	54.71
Ash from Coal, lb/hr	4.59	2.04	13.18	13.32	15.00	17.98	14.04	17.89	17.02
Baghouse Ash Out, lb/hr	2.70	3.00	4.20	5.70	3.00	2.80	5.00	2.30	3.80
Al_2O_3 in Baghouse Ash, %	18.70	19.70	19.60	18.00	17.20	22.40	15.50	17.10	23.50
Ash from Coal, %	82.02	86.40	85.96	78.95	75.77	98.68	68.28	75.33	105.38
Ash from Coal, lb/hr	2.21	2.59	3.61	4.50	2.27	2.76	3.41	1.73	4.00
Bed Material Out, lb/hr	3.70	17.20	4.20	4.00	4.00	4.30	4.60	3.80	1.60
Al_2O_3 in Bed Material, %	3.71	3.49	3.08	3.01	3.15	2.83	3.46	3.82	2.87
Ash from Coal, %	16.27	15.31	13.51	13.20	13.88	12.47	15.24	16.83	12.87
Ash from Coal, lb/hr	0.60	2.63	0.57	0.53	0.56	0.54	0.70	0.64	0.21
Total Ash from Coal, lb/hr	7.40	7.27	17.36	18.34	17.83	21.28	18.16	20.26	21.22
Closure, %	84.92	94.00	149.54	129.35	133.87	143.50	116.96	136.91	146.85

TABLE C-9

Fuel Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Fuel Feed Rate, meas., lb/hr	174	174	176	214	171	165	147	133	127
Fuel Feed Rate, theor., lb/hr	178	190	176	219	176	176	159	129	133
Difference, %	-2.6	-9.6	0.1	-2.6	-2.9	-6.2	-8.5	3.2	-4.6

	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18
Fuel Feed Rate, meas., lb/hr	93	88	133	156	159	176	193	173	188
Fuel Feed Rate, theor., lb/hr	106	94	141	172	162	180	188	180	175
Difference, %	-14.4	-7.1	-5.6	-10.1	-1.8	-2.3	2.6	-3.8	6.8

meas. = Feed rate calculated by linear regression performed on coal feed hopper weight loss over time.
theor.. = Theoretical feed rate calculated on the basis of the coal analysis, the combustion air, and the excess air for each test period.

TABLE C-10

Flue Gas Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Stack Gas Flow, meas., scfm	508	508	517	605	607	504	433	424	375
Stack Gas Flow, theor., scfm	534	538	539	616	632	536	451	457	395
Difference, %	-5.3	-5.9	-4.2	-1.7	-4.0	-6.2	-4.0	-7.8	-5.4

	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18
Stack Gas Flow, meas., scfm	321	312	424	519	525	520	514	524	507
Stack Gas Flow, theor., scfm	348	331	440	548	534	544	540	547	544
Difference, %	-8.2	-6.2	-3.7	-5.5	-1.7	-4.7	-5.1	-4.3	-7.2

meas. = The flue gas flow measured during the run through an orifice located just upstream of the ID fan.
theor. = Theoretical flue gas flow calculated on the basis of the coal analysis and theoretical coal feed rate for each test period.

TABLE C-11

Energy Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Input, Btu/hr									
Coal	2,353,424	2,507,769	2,316,487	2,889,013	2,323,083	2,315,168	2,098,822	1,703,067	1,751,876
Primary Air	134,170	127,441	120,840	217,930	132,141	131,443	49,623	84,641	85,057
Secondary Air	84,893	86,609	82,647	84,507	141,817	87,057	65,993	42,833	15,216
EHX Air	2,018	2,531	3,207	2,200	2,591	2,055	4,541	3,406	3,894
Ash (chem.)*	0	0	0	0	2,411	1,904	0	0	0
Sorbent Sulfation	0	28,353	19,694	31,920	22,005	5,527	17,368	15,762	18,566
Total	2,574,505	2,752,703	2,542,876	3,225,569	2,624,047	2,543,153	2,236,347	1,849,708	1,874,610
Input, %									
Coal	91.4	91.1	91.1	89.6	88.5	91.0	93.9	92.1	93.5
Primary Air	5.2	4.6	4.8	6.8	5.0	5.2	2.2	4.6	4.5
Secondary Air	3.3	3.1	3.3	2.6	5.4	3.4	3.0	2.3	0.8
EHX Air	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
Ash (chem.)*	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0
Sorbent Sulfation	0.0	1.0	0.8	1.0	0.8	0.2	0.8	0.9	1.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Output, Btu/hr									
Flue Gas (sens.)	958,929	989,064	940,386	1,170,013	1,129,546	1,016,626	840,913	784,131	709,681
Ash (sens.)	7,679	22,476	24,029	26,387	27,861	27,986	9,684	7,921	8,685
Ash (chem.)*	93,412	139,032	211,324	69,707	200,018	55,518	62,939	54,681	63,041
Combustor	827,847	831,959	767,165	976,101	821,692	976,497	704,592	655,383	681,281
EHX	431,017	514,324	598,884	678,562	393,309	190,021	367,035	161,726	233,484
Sorbent Calcination	0	27,346	25,201	31,253	34,930	30,717	16,086	7,354	13,865
Conduction and Radiation Losses	211,716	204,215	145,608	212,550	209,685	284,441	221,927	199,526	201,610
Total	2,530,601	2,728,416	2,712,597	3,164,572	2,817,041	2,581,806	2,223,176	1,870,722	1,911,648
Output, %									
Flue Gas (sens.)	37.9	36.3	34.7	37.0	40.1	39.4	37.8	41.9	37.1
Ash (sens.)	0.6	0.8	0.9	0.8	1.0	1.1	0.4	0.4	0.5
Ash (chem.)*	3.7	5.1	7.8	2.2	7.1	2.2	2.8	2.9	3.3
Combustor	2.7	30.5	28.3	30.8	29.2	37.8	31.7	35.0	35.6
EHX	17.0	18.9	22.1	21.4	14.0	7.4	16.5	8.6	12.2
Sorbent Calcination	0.0	1.0	0.9	1.0	1.2	1.2	0.7	0.4	0.7
Conduction and Radiation Losses	8.4	7.5	5.4	6.7	7.4	11.0	10.0	10.7	10.5
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Closure	98.3	99.1	106.7	98.1	107.4	101.5	99.4	101.1	102.0

* The heat of combustion coefficient for pure carbon is an average of values found in *Perry's Chemical Engineering Handbook* (1984), and the *Standard Handbook for Mechanical Engineers*, Baumeister and Marks (1967).

continued...

TABLE C-11 (continued)

	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18
Input, Btu/hr									
Coal	1,395,697	1,237,395	1,858,730	2,270,316	2,131,801	2,374,531	2,485,343	2,369,254	2,313,849
Primary Air	81,564	57,010	128,554	130,201	116,812	125,211	122,553	131,975	126,770
Secondary Air	0	0	0	85,398	79,542	84,319	86,487	85,934	85,581
EHX Air	2,093	3,566	2,261	1,927	3,141	2,578	3,391	2,547	2,411
Ash (chem.)*	432	0	0	0	0	128	0	57	0
Sorbent Sulfation	15,136	13,062	21,299	26,338	15,053	19,725	22,229	23,941	0
Total	1,494,920	1,311,033	2,010,844	2,514,180	2,346,349	2,606,492	2,720,002	2,613,709	2,528,611
Input, %									
Coal	93.4	94.4	92.4	90.3	90.9	91.1	91.4	90.6	91.5
Primary Air	5.5	4.3	6.4	5.2	5.0	4.8	4.5	5.0	5.0
Secondary Air	0.0	0.0	0.0	3.4	3.4	3.2	3.2	3.3	3.4
EHX Air	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ash (chem.)*	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sorbent Sulfation	1.0	1.0	1.1	1.0	0.6	0.8	0.8	0.9	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Output, Btu/hr									
Flue Gas (sens.)	635,932	492,983	739,229	997,980	954,450	1,010,865	1,017,698	1,005,564	1,008,965
Ash (sens.)	5,904	8,256	16,733	21,906	25,301	17,851	24,690	20,751	14,620
Ash (chem.)*	19,853	28,597	116,786	111,887	93,374	158,906	139,438	158,539	178,423
Combustor	364,803	590,857	689,387	801,555	811,466	779,236	808,926	799,562	802,783
EHX	98,249	168,219	210,075	371,861	314,341	474,921	493,452	475,371	439,104
Sorbent Calcination	14,324	14,477	18,920	30,793	33,627	17,618	27,806	30,946	0
Conduction and Radiation Losses	215,676	123,989	167,227	202,131	228,179	210,987	218,801	208,382	217,239
Total	1,354,740	1,427,378	1,958,358	2,538,113	2,460,738	2,670,385	2,730,812	2,699,116	2,661,133
Output, %									
Flue Gas (sens.)	46.9	34.5	37.7	39.3	38.8	37.9	37.3	37.3	37.9
Ash (sens.)	0.4	0.6	0.9	0.9	1.0	0.7	0.9	0.8	0.5
Ash (chem.)*	1.5	2.0	6.0	4.4	3.8	6.0	5.1	5.9	6.7
Combustor	26.9	41.4	35.2	31.6	33.0	29.2	29.6	29.6	30.2
EHX	7.3	11.8	10.7	14.7	12.8	17.8	18.1	17.6	16.5
Sorbent Calcination	1.1	1.0	1.0	1.2	1.4	0.7	1.0	1.1	0.0
Conduction and Radiation Losses	15.9	8.7	8.5	8.0	9.3	7.9	8.0	7.7	8.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Closure	90.6	108.9	97.4	101.0	104.9	102.5	100.4	103.3	105.2

* The heat of combustion coefficient for pure carbon is an average of values found in *Perry's Chemical Engineering Handbook* (1984), and the *Standard Handbook for Mechanical Engineers*, Baumeister and Marks (1967).

The material balances, which ranged from 99.9% closure for Test 10 to 102.0% for Test 3, are presented in Table C-12. The inputs are the combustion air, additional air (composed of external heat exchanger fluidizing air, pressure tap purges, downcomer assist air, and coal feed assist air), coal and limestone feeds, and bed material addition. Outputs consist of measured flue gas, flue gas leaks (based on the theoretical flue gas flow rate shown in Table C-10), and measured quantities of bed material, secondary cyclone ash, and baghouse ash removed from the system.

Combustion Efficiency

The combustion efficiencies, shown in Table C-13, ranged from a low of 89.4% for Test 5, a high-velocity, high excess air test, to 98.3% for Test 10, a low-load, low-velocity test. In both cases, superficial gas velocity plays a key role: as velocity increases, particle residence time and, hence, carbon burnout decrease. The combustion efficiencies for several tests, conducted at the same temperature, are plotted as a function of superficial gas velocity in Figure C-6. The effect of combustor temperature is shown in Figure C-7. The tests shown in this figure were all conducted at similar velocities. The percentage of unburned carbon in each ash stream was calculated as the difference between the loss on ignition (LOI) and the carbonate content (as CO_2). These values are shown in Table C-14.

Boiler Efficiency

Boiler efficiencies were calculated for each test period using ASME PTC 4.1, modified according to the recommendations in EPRI's "Atmospheric Fluidized-Bed Combustion Performance Guidelines" to account for the heat losses and gains associated with calcination and sulfation of the limestone.

Table C-15 summarizes the results of the boiler efficiency calculations for this run. Boiler radiation and convective losses were assumed to be 0.4%; although the actual losses at the pilot scale are much greater, 0.4% was chosen to be representative of a full-scale system. The exit gas temperature was assumed to be 300°F. The boiler efficiency ranged from 81.4% to 90.2%. An increase in unburned carbon losses at low temperatures, low velocity, and low loads had the greatest impacts on boiler efficiency.

Heat-Transfer Coefficient and Heat Flux

The heat-transfer coefficient and the heat flux for each of the combustor sections containing heat exchange panels, as well as for the EHX, are shown in Tables C-16 and C-17, respectively. The overall values for each test are also presented in Table C-5, to facilitate comparison with operating conditions. The values for each combustor section are based on the average temperature in the section; the overall values for each test are based on the average combustor temperature. The combustor heat fluxes ranged from 18,938 Btu/hr-ft^2 for Test 11, a low-temperature, low-load test, to about 31,300 Btu/hr-ft^2 for the Tests 4 and 6. Test 4 was a high-velocity (18.4 ft/sec) test with a resulting high recirculation rate; Test 6 was high-temperature (1698°F) test. The heat flux within the EHX ranged from 32,040 Btu/hr-ft^2 to 97,966 Btu/hr-ft^2 for Tests 11 and 2, respectively.

TABLE C-12

Material Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Input, lb/hr									
Combustion Air	2160	2169	2178	2500	2507	2087	1803	1839	1564
Additional Air	153	154	156	159	245	243	144	152	147
Bed Material	0	0	0	0	27	17	0	0	0
Coal Feed	178	190	176	219	176	176	159	129	133
Sorbent Feed	0	36	33	41	46	40	21	10	18
Total Mass In	2492	2548	2542	2919	3001	2561	2128	2129	1862
Input, %									
Combustion Air	86.7	85.1	85.7	85.7	83.6	81.5	84.7	86.4	84.0
Feed Assist Air	6.1	6.0	6.1	5.4	8.2	9.5	6.8	7.1	7.9
Bed Material	0.0	0.0	0.0	0.0	0.9	0.7	0.0	0.0	0.0
Coal Feed	7.2	7.5	6.9	7.5	5.9	6.9	7.5	6.1	7.1
Sorbent Feed	0.0	1.4	1.3	1.4	1.5	1.6	1.0	0.5	1.0
Total Mass In	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Output, lb/hr									
Measured Flue Gas	2362	2386	2424	2841	2833	2366	2043	1982	1759
Flue Gas Leaks	124	140	102	49	114	148	82	155	96
Ash Out	5	21	21	5	5	3	4	5	4
Bed Material	8	3	6	1	4	3	3	3	1
Baghouse	6	33	38	60	61	58	17	12	17
Cyclone Ash									
Total Mass Out	2505	2582	2592	2956	3017	2578	2149	2157	1877
Output, %									
Measured Flue Gas	94.3	92.4	93.5	96.1	93.9	91.8	95.1	91.9	93.7
Flue Gas Leaks	5.0	5.4	3.9	1.7	3.8	5.7	3.8	7.2	5.1
Ash Out	0.2	0.8	0.8	0.2	0.1	0.1	0.2	0.2	0.2
Bed Material	0.3	0.1	0.2	0.0	0.1	0.1	0.2	0.1	0.0
Baghouse	0.3	1.3	1.5	2.0	2.0	2.3	0.8	0.5	0.9
Cyclone Ash									
Total Mass Out	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Closure	100.5	101.3	102.0	101.2	100.6	100.7	101.0	101.3	100.8

continued...

TABLE C-12 (continued)

	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18
Input, lb/hr									
Combustion Air	1364	1291	1729	2194	2136	2173	2137	2163	2158
Additional Air	146	149	178	184	186	184	195	206	199
Bed Material	8	0	0	0	0	0	8	8	8
Coal Feed	106	94	141	172	162	180	188	180	175
Sorbent Feed	19	19	25	40	44	23	36	40	0
Total Mass In	1643	1553	2072	2590	2527	2560	2565	2596	2541
Input, %									
Combustion Air	83.0	83.1	83.4	84.7	84.5	84.9	83.3	83.3	84.9
Feed Assist Air	8.9	9.6	8.6	7.1	7.4	7.2	7.6	7.9	7.8
Bed Material	0.5	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.3
Coal Feed	6.4	6.0	6.8	6.6	6.4	7.0	7.3	6.9	6.9
Sorbent Feed	1.1	1.2	1.2	1.6	1.7	0.9	1.4	1.6	0.0
Total Mass In	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Output, lb/hr									
Measured Flue Gas	1503	1452	1985	2435	2457	2431	2411	2453	2361
Flue Gas Leaks	124	89	73	133	43	113	123	106	171
Ash Out	4	17	4	4	4	4	5	4	2
Bed Material	3	3	4	6	3	3	5	2	4
Baghouse	8	3	36	46	55	38	52	46	31
Cyclone Ash									
Total Mass Out	1642	1564	2102	2624	2562	2589	2595	2611	2569
Output, %									
Measured Flue Gas	91.6	92.8	94.4	92.8	95.9	93.9	92.9	93.9	91.9
Flue Gas Leaks	7.5	5.7	3.5	5.1	1.7	4.4	4.7	4.1	6.7
Ash Out	0.2	1.1	0.2	0.2	0.2	0.2	0.2	0.1	0.1
Bed Material	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.1
Baghouse	0.5	0.2	1.7	1.8	2.1	1.5	2.0	1.8	1.2
Cyclone Ash									
Total Mass Out	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Closure	99.9	100.7	101.4	101.3	101.4	101.2	101.2	100.6	101.1

TABLE C-13

Combustion Efficiency

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Input									
Coal Feed Rate, lb/hr	178.4	190.1	175.6	219.0	176.1	175.5	159.1	129.1	132.8
Coal Carbon, %	74.4	74.4	74.4	74.4	74.4	74.4	74.4	74.4	74.4
Carbon Feed Rate, lb/hr	132.7	141.4	130.6	162.8	130.9	130.5	118.3	96.0	98.8
Bed Material Add Rate, lb/hr	0	0	0	0	27	16.7	0	0	0
Bed Material Carbon, %	0.69	1.50	5.26	2.36	0.63	0.84	0.80	0.46	0.59
Carbon Feed Rate, lb/hr	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0
Total, lb/hr	132.7	141.4	130.6	162.8	131.1	130.6	118.3	96.0	98.8
Output									
Bottom Ash Discharge Rate, lb/hr	5	21	21	5	5	3	4	5	4
Unburned Carbon, %	0.69	1.50	5.26	2.36	0.63	0.81	0.80	0.46	0.59
Bottom Ash Carbon Discharge Rate, lb/hr	0.04	0.31	1.12	0.12	0.63	0.03	0.03	0.02	0.02
Cyclone Ash Discharge Rate, lb/hr	6	33	38	60	61	58	17	12	17
Unburned Carbon, %	50.14	27.79	32.71	7.84	22.33	6.41	24.86	30.48	25.41
Cyclone Ash Carbon Discharge Rate, lb/hr	3.21	9.28	12.53	4.70	13.69	3.74	4.15	3.57	4.37
Baghouse Discharge Rate, lb/hr	8	3	6	1	4	3	3	3	1
Unburned Carbon, %	43.39	10.46	21.43	12.37	11.13	6.47	8.60	9.07	11.16
Baghouse Carbon Discharge Rate, lb/hr	3.38	0.27	1.35	0.12	0.48	0.17	0.28	0.29	0.08
Total, lb/hr	6.63	9.87	15.00	4.95	14.19	3.94	4.47	3.88	4.47
Combustion Efficiency, %	95.00	93.02	88.51	96.96	89.17	96.98	96.22	95.96	95.47

continued...

TABLE C-13 (continued)

	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18
Input									
Coal Feed Rate, lb/hr	105.8	93.8	140.9	172.1	161.6	180.0	188.4	179.6	175.4
Coal Carbon, %	74.4	74.4	74.4	74.4	74.4	74.4	74.4	74.4	74.4
Carbon Feed Rate, lb/hr	78.7	69.7	104.8	128.0	120.2	133.8	140.1	133.6	130.4
Bed Material Add Rate, lb/hr	8.3	0	0	0	0	0	8.3	8.3	8.3
Bed Material Carbon, %	0.37	2.70	3.49	0.80	0.49	0.01	0.11	0.00	0.05
Carbon Feed Rate, lb/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total, lb/hr	78.7	69.7	104.8	128.0	120.2	133.8	140.1	133.6	130.4
Output									
Bottom Ash Discharge Rate, lb/hr	4	17	4	4	4	4	5	4	2
Unburned Carbon, %	0.37	2.70	3.49	0.80	0.49	0.01	0.11	0.00	0.05
Bottom Ash Carbon Discharge Rate, lb/hr	0.01	0.46	0.15	0.03	0.02	0.00	0.01	0.00	0.00
Cyclone Ash Discharge Rate, lb/hr	8	3	36	46	55	38	52	46	31
Unburned Carbon, %	14.15	33.93	21.32	16.03	11.64	29.27	18.29	23.90	39.28
Cyclone Ash Carbon Discharge Rate, lb/hr	1.17	1.12	7.68	7.37	6.40	11.07	9.51	11.04	12.22
Baghouse Discharge Rate, lb/hr	3	3	4	6	3	3	5	2	4
Unburned Carbon, %	8.19	14.87	11.09	9.42	6.80	7.56	7.63	9.13	11.68
Baghouse Carbon Discharge Rate, lb/hr	0.22	0.45	0.47	0.54	0.20	0.21	0.38	0.21	0.44
Total, lb/hr	1.41	2.03	8.29	7.94	6.63	11.28	9.90	11.25	12.66
Combustion Efficiency, %	98.21	97.09	92.09	93.80	94.49	91.57	92.94	91.58	90.29

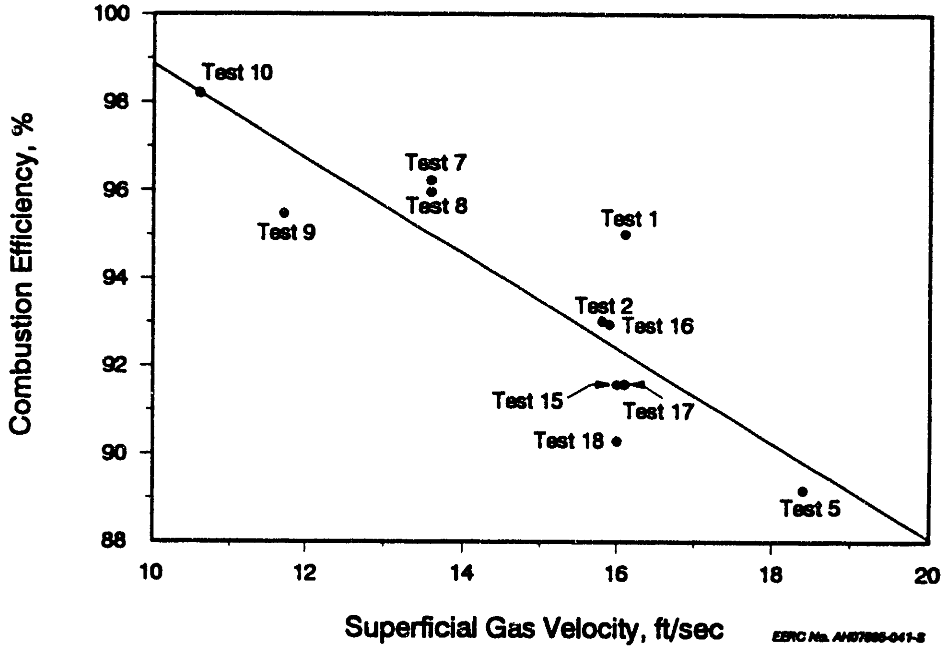

Figure C-6. Combustion efficiency as a function of superficial gas velocity.

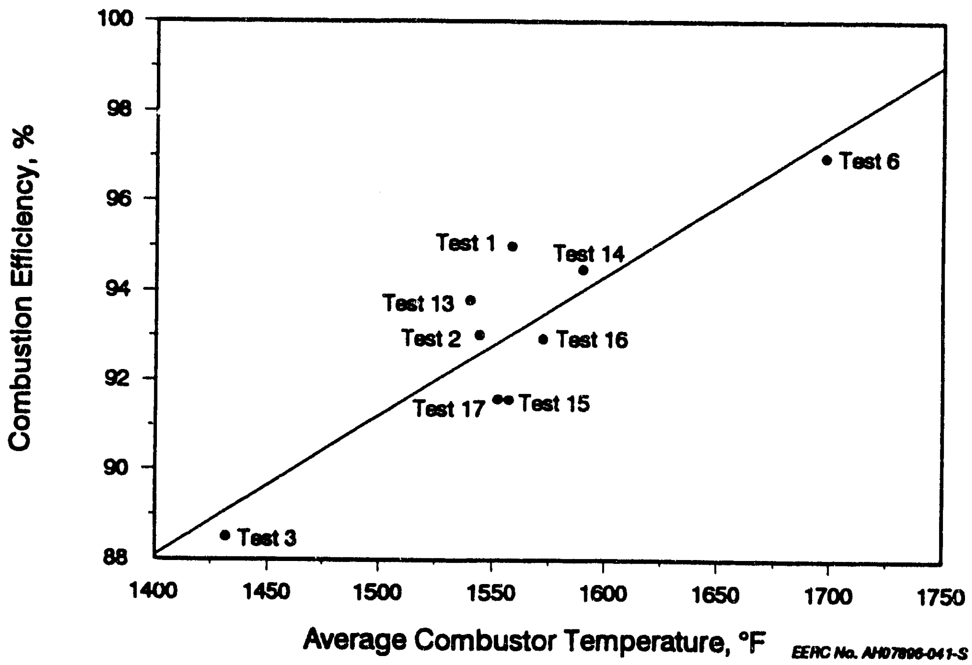

Figure C-7. Effect of average combustor temperature.

TABLE C-14

Unburned Carbon (%)

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Combustor Bed Material									
Loss on Ignition	0.72	1.67	6.87	2.98	0.83	1.03	1.03	0.63	0.70
Carbonate (as CO_2)	0.11	0.63	5.90	2.28	0.72	0.81	0.84	0.61	0.42
Unburned Coal Carbon*	0.69	1.50	5.26	2.36	0.63	0.81	0.80	0.46	0.59
Secondary Cyclone Ash									
Loss on Ignition	50.24	28.02	34.32	8.04	22.49	6.53	24.94	30.62	25.49
Carbonate (as CO_2)	0.35	0.83	5.92	0.74	0.59	0.43	0.31	0.51	0.28
Unburned Coal Carbon*	50.14	27.79	32.71	7.84	22.33	6.41	24.86	30.48	25.41
Baghouse Ash									
Loss on Ignition	43.47	10.56	21.78	12.60	11.21	6.52	8.64	9.10	11.24
Carbonate (as CO_2)	0.31	0.36	1.27	0.83	0.30	0.19	0.16	0.12	0.29
Unburned Coal Carbon*	43.39	10.46	21.43	12.37	11.13	6.47	8.60	9.07	11.16
	Test 10	**Test 11**	**Test 12**	**Test 13**	**Test 14**	**Test 15**	**Test 16**	**Test 17**	**Test 18**
Combustor Bed Material									
Loss on Ignition	0.53	3.74	4.90	1.12	0.85	0.14	0.21	0.00	0.09
Carbonate (as CO_2)	0.59	3.83	5.18	1.18	1.33	0.48	0.37	0.59	0.15
Unburned Coal Carbon*	0.37	2.70	3.49	0.80	0.49	0.01	0.11	0.00	0.05
Secondary Cyclone Ash									
Loss on Ignition	14.42	34.86	21.66	16.38	11.83	29.36	18.84	24.13	39.32
Carbonate (as CO_2)	1.00	3.42	1.24	1.30	0.69	0.32	2.03	0.85	0.13
Unburned Coal Carbon*	14.15	33.93	21.32	16.03	11.64	29.27	18.29	23.90	39.28
Baghouse Ash									
Loss on Ignition	8.26	15.22	11.30	9.56	6.97	7.59	7.90	9.32	11.71
Carbonate (as CO_2)	0.27	1.27	0.78	0.53	0.62	0.11	0.98	0.68	0.10
Unburned Coal Carbon*	8.19	14.87	11.09	9.42	6.80	7.56	7.63	9.13	11.68

* Unburned Coal Carbon = Loss on ignition (LOI) - carbonate (as CO_2)

The low combustor heat fluxes observed during Tests 11 and 12 were the result of reduced load while operating with constant heat-transfer surface. During constant heat-transfer load reduction, the total amount of heat-transfer surface kept in service is equivalent to that used during the full-load baseline test with sorbent addition. By reducing load under constant heat-transfer conditions, operational temperatures and velocity are reduced, lowering the solids recirculation rate, thereby decreasing heat transfer. Tests 9 and 10 were run under constant temperature load reduction conditions. During constant temperature load reduction, heat-transfer surface was taken off-line, and combustor temperatures and velocity were maintained near full-load levels. Therefore, heat-transfer performance was affected to a lesser degree.

Pressure and Temperature Profiles

The pressure profiles for the run are shown in Figures C-8 through C-10 and are typical of a circulating fluidized-bed combustor. The figures show a dense phase in the lower portion of the combustor, similar to a bubbling bed, and a dilute phase in the rest of the combustor. Variations in pressure profiles are due to differences in bed inventory and combustor velocity.

TABLE C-15

Boiler Efficiency

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Assumed Flue Gas Exit Temp. (°F)	300	300	300	300	300	300	300	300	300
Losses, Btu/hr									
Dry Gas	134,791	136,824	137,138	156,503	160,456	136,420	115,173	118,395	101,345
Water in Fuel	6,122	6,524	6,026	7,516	6,043	6,023	5,460	4,430	4,557
Comb. of Fuel Hydrogen	10,671	11,371	10,504	13,100	10,534	10,498	9,517	7,722	7,944
Unburned Carbon	93,412	139,032	211,324	69,707	200,018	55,518	62,939	54,681	63,041
Sorbent Calcination	0	27,346	25,201	31,253	34,930	30,717	16,086	7,354	13,865
Radiation and Convection*	9,472	10,094	9,324	11,628	9,350	9,318	8,448	6,855	7,051
Discharged Solids	7,679	22,476	24,029	26,387	27,861	27,986	9,684	7,921	8,685
Sorbent Sulfation	0	-28,353	-19,694	-31,920	-22,005	-5,527	-17,368	-15,762	-18,566
Total	262,147	325,313	403,852	284,173	427,187	270,953	209,938	191,596	187,923
Losses, %									
Dry Gas	5.8	5.9	5.9	5.5	7.1	6.2	5.9	6.7	6.0
Water in Fuel	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Comb. of Fuel Hydrogen	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.5
Unburned Carbon	4.0	6.0	9.1	2.5	8.8	2.5	3.2	3.1	3.7
Sorbent Calcination	0.0	1.2	1.1	1.1	1.5	1.4	0.8	0.4	0.8
Radiation and Convection*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Discharged Solids	0.3	1.0	1.0	0.9	1.2	1.3	0.5	0.4	0.5
Sorbent Sulfation	0.0	-1.2	-0.8	-1.1	-1.0	-0.3	-0.9	-0.9	-1.1
Total	11.4	14.1	17.3	10.0	18.8	12.4	10.8	10.8	11.1
Boiler Efficiency	88.6	85.9	82.7	90.0	81.2	87.6	89.2	89.2	88.9

	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18
Assumed Flue Gas Exit Temp. (°F)	300	300	300	300	300	300	300	300	300
Losses, Btu/hr									
Dry Gas	89,618	85,607	113,020	140,990	137,822	139,578	138,036	140,317	139,667
Water in Fuel	3,631	3,219	4,835	5,906	5,546	6,177	6,465	6,163	6,019
Comb. of Fuel Hydrogen	6,329	5,611	8,428	10,295	9,666	10,767	11,270	10,743	10,492
Unburned Carbon	19,853	28,597	116,786	111,887	93,374	158,906	139,438	158,539	178,423
Sorbent Calcination	14,324	14,477	18,920	30,793	33,627	17,618	27,806	30,946	0
Radiation and Convection*	5,618	4,980	7,481	9,138	8,580	9,557	10,003	9,536	9,313
Discharged Solids	5,904	8,256	16,733	21,906	25,301	17,851	24,690	20,751	14,620
Sorbent Sulfation	-15,136	-13,062	-21,299	-26,338	-15,053	-19,725	-22,229	-23,941	0
Total	130,140	137,686	264,905	304,575	298,864	340,731	335,480	353,055	358,535
Losses, %									
Dry Gas	7.3	7.4	6.4	6.8	6.5	6.0	5.4	6.1	5.6
Water in Fuel	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2
Comb. of Fuel Hydrogen	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.4
Unburned Carbon	1.6	2.5	6.6	5.4	4.4	6.8	5.4	6.9	7.1
Sorbent Calcination	1.2	1.2	1.1	1.5	1.6	0.8	1.1	1.3	0.0
Radiation and Convection*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Discharged Solids	0.5	0.7	0.9	1.1	1.2	0.8	1.0	0.9	0.6
Sorbent Sulfation	-1.2	-1.1	-1.2	-1.3	-0.7	-0.8	-0.9	-1.0	0.0
Total	10.6	11.8	15.0	14.7	14.2	14.6	13.1	15.4	14.4
Boiler Efficiency	89.4	88.2	85.0	85.3	85.8	85.4	86.9	84.6	85.6

* Assumes 0.4% radiative and convective losses.

TABLE C-16

Individual Heat-Transfer Coefficients (Btu/hr-ft^2-°F)

Combustor Section	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
2	17.5	22.2	21.0	21.3	18.0	21.0	18.0	18.4	19.4	19.3
3	21.1	21.1	24.3	25.3	20.9	23.7	20.4	19.8	20.5	19.1
4	23.2	21.7	22.9	28.5	23.6	27.0	23.0	22.5	22.5	17.5
5	23.2	24.7	22.5	28.4	22.7	25.5	21.3	19.4	19.9	off
6	16.5	18.0	26.4	18.1	15.7	16.8	15.2	13.4	14.4	6.8
7	14.4	12.9	14.6	21.1	16.6	17.6	18.7	16.9	17.7	off
8	14.4	17.6	15.0	19.0	15.1	15.8	16.6	15.8	16.5	off
Overall	18.6	19.1	19.2	22.2	18.6	20.2	18.8	17.9	18.6	17.8
EHX	77.4	84.2	67.9	65.1	78.2	67.8	66.6	77.8	79.8	58.5

Combustor Section	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18	Average	Combustor Height
2	18.4	20.9	21.2	23.1	17.6	17.4	18.8	16.7	19.5	7.5
3	17.9	19.6	20.8	22.6	19.9	20.3	20.1	19.6	20.9	12.5
4	19.1	20.2	22.2	21.7	22.4	23.5	23.0	22.9	22.6	17.5
5	19.0	21.0	23.8	23.9	23.5	24.2	23.1	24.6	23.0	22.5
6	11.8	13.4	15.6	15.0	15.8	16.0	15.8	15.9	15.6	27.5
7	11.4	13.2	15.5	14.2	15.5	15.8	15.0	15.2	15.7	32.5
8	10.5	12.0	13.7	12.4	13.9	13.8	13.7	13.7	14.7	37.5
Overall	14.8	16.3	18.2	17.8	17.4	17.9	17.9	17.8	18.3	
EHX	75.4	57.7	73.4	80.4	70.4	71.4	70.6	69.4	71.8	

TABLE C-17

Individual Heat Flux (Btu/hr-ft^2)

Combustor Section	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
2	26,666	31,574	27,263	30,679	27,029	34,687	27,311	27,538	28,273	28,352
3	30,775	29,570	31,051	35,727	20,169	37,297	30,100	28,270	28,997	27,212
4	32,908	30,341	29,250	39,972	32,865	40,574	32,654	30,691	31,015	24,489
5	33,068	34,368	29,155	39,914	31,839	38,513	30,997	26,840	27,756	off
6	23,244	25,151	33,763	26,236	22,099	25,289	21,992	18,256	20,021	9,753
7	19,672	17,955	18,936	29,664	22,384	24,916	26,480	22,234	24,098	off
8	19,644	24,176	19,526	26,947	20,433	22,297	23,126	20,380	22,140	off
Overall	26,534	26,665	24,589	31,285	26,336	31,298	27,100	25,207	26,203	25,643
EHX	82,098	97,966	66,543	82,250	87,402	84,454	54,376	71,878	77,828	43,666

Combustor Section	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18	Average	Combustor Height
2	24,812	29,559	30,886	35,670	26,676	26,644	28,117	25,891	28,757	7.5
3	23,305	27,041	29,692	33,444	28,348	29,849	29,212	29,146	29,434	12.5
4	24,022	27,009	31,021	30,711	31,609	33,412	32,306	32,488	31,519	17.5
5	23,952	28,062	33,452	33,946	33,558	34,763	32,676	35,277	32,243	22.5
6	14,553	17,692	22,007	21,252	22,573	23,026	22,320	22,685	21,773	27.5
7	13,417	16,567	21,082	18,886	21,350	21,878	20,476	20,818	21,224	32.5
8	11,851	15,064	18,873	16,464	19,341	19,343	18,854	18,701	19,833	37.5
Overall	18,938	22,096	25,691	26,009	24,976	25,927	25,627	25,730	25,881	
EHX	32,042	46,683	82,636	69,854	70,359	73,104	70,425	65,053	69,923	

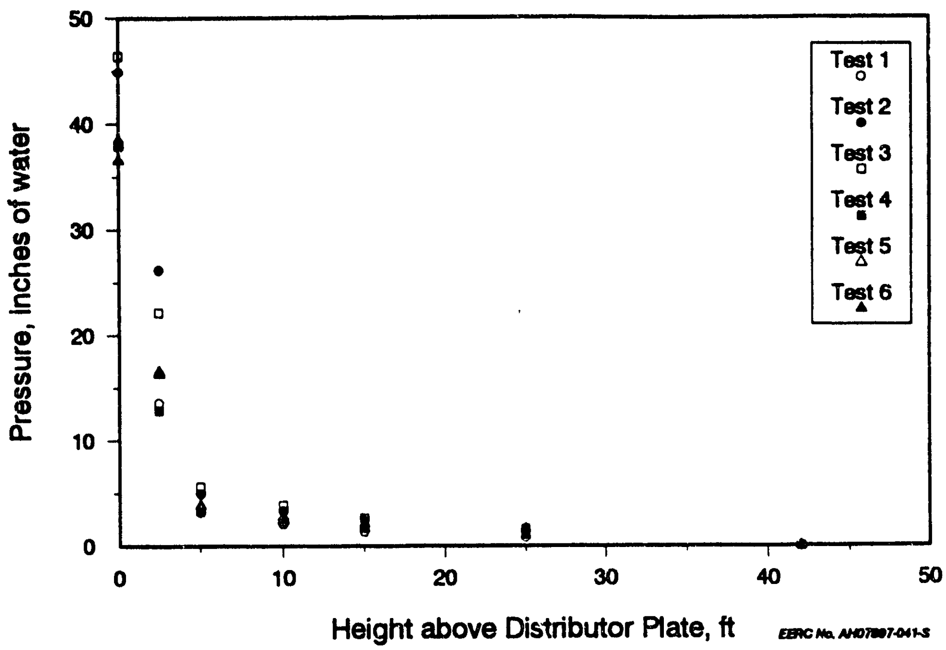

Figure C-8. Pressure profiles of Tests 1 through 6.

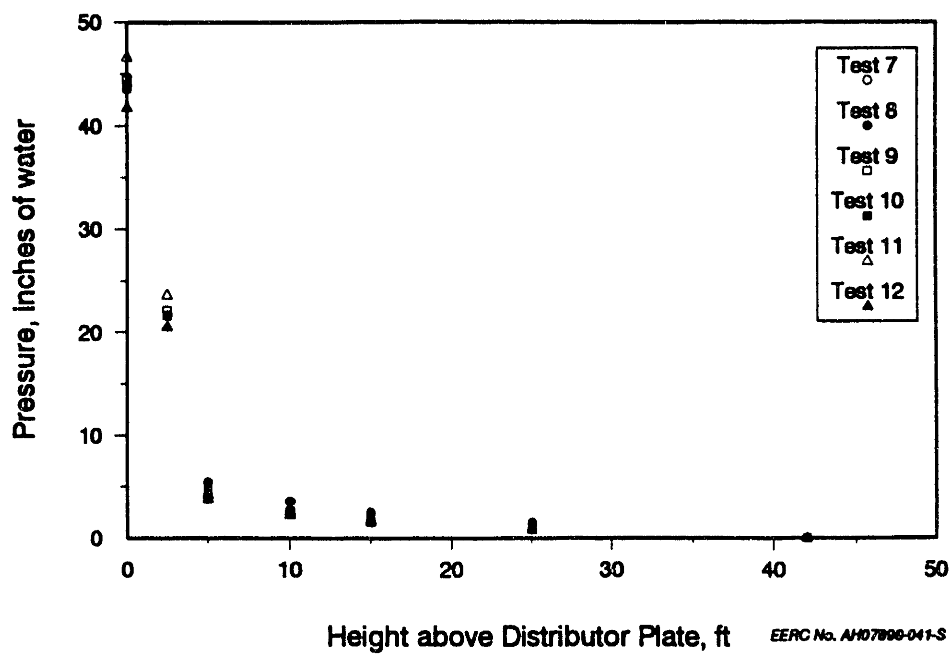

Figure C-9. Pressure profiles of Tests 7 through 12.

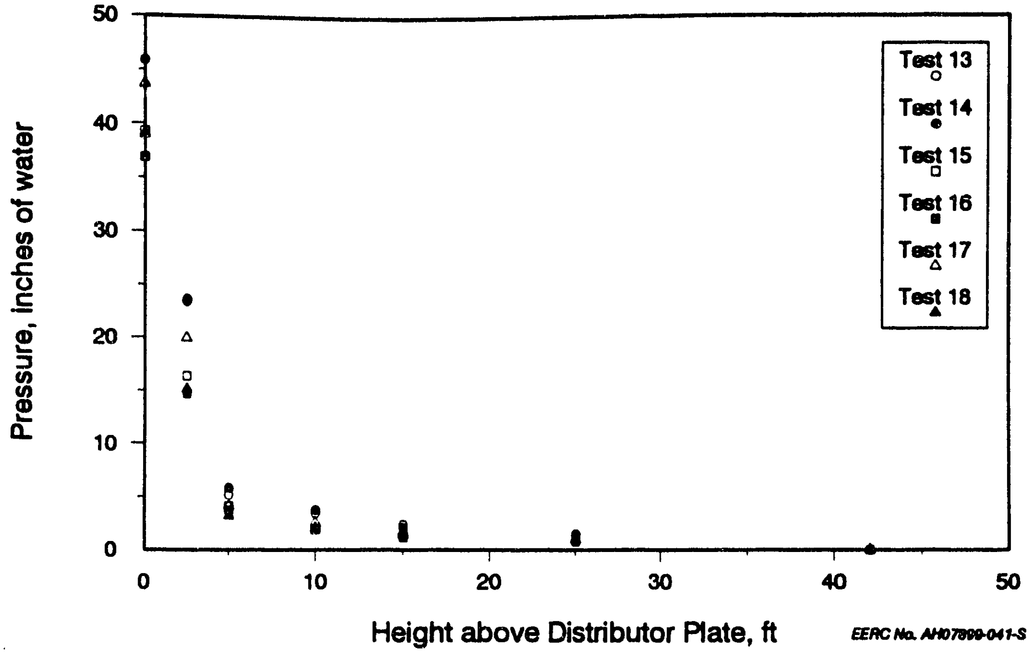

Figure C-10. Pressure profiles of Tests 13 through 18.

The temperature profiles for the run are shown in Figures C-11 through C-13. In general, the temperature distributions were fairly uniform throughout the combustor. The high-temperature test (Test 6) and a low-temperature, low-load test (Tests 11) had the greatest variations. Because of the relatively low solids recirculation rates throughout most of the tests, the external heat exchanger did not remove much heat from the system. Most of the heat removal occurred in the combustor. These two factors accounted for the nonuniform temperature distribution in the combustor, with a higher temperature at the bottom than the top. Starting with Test 10, the temperature reading located 3 feet above the distributor plate was about 30° lower than those located at 2 and 4 feet. An attempt was made to replace the thermocouple, but it could not be removed from the combustor. Postrun inspection revealed that the thermocouple had melted, and it had to be cut away before it could be replaced.

ENVIRONMENTAL PERFORMANCE

Average flue gas emissions for each of the steady-state test periods are shown in Table C-18. Emissions of individual flue gas constituents are discussed in detail in the following sections.

SO_2 Emissions

The relationship between temperature and flue gas SO_2 emissions is shown in Figure C-14. Sulfur retention is greatest at temperatures between 1475° and 1550°F and decreases at higher and lower temperatures. Test 6 (1698°F) had virtually the same alkali-to-sulfur ratio as Test 13 (1540°F), but their respective sulfur retentions were 19% and 91%. Tests 5, 6, 13, and 14 had alkali-to-sulfur ratios near 3, while the alkali-to-sulfur ratios for the remaining tests shown in Figure C-14 were about 2.3. Obviously, temperature control is a very critical operating parameter with this coal.

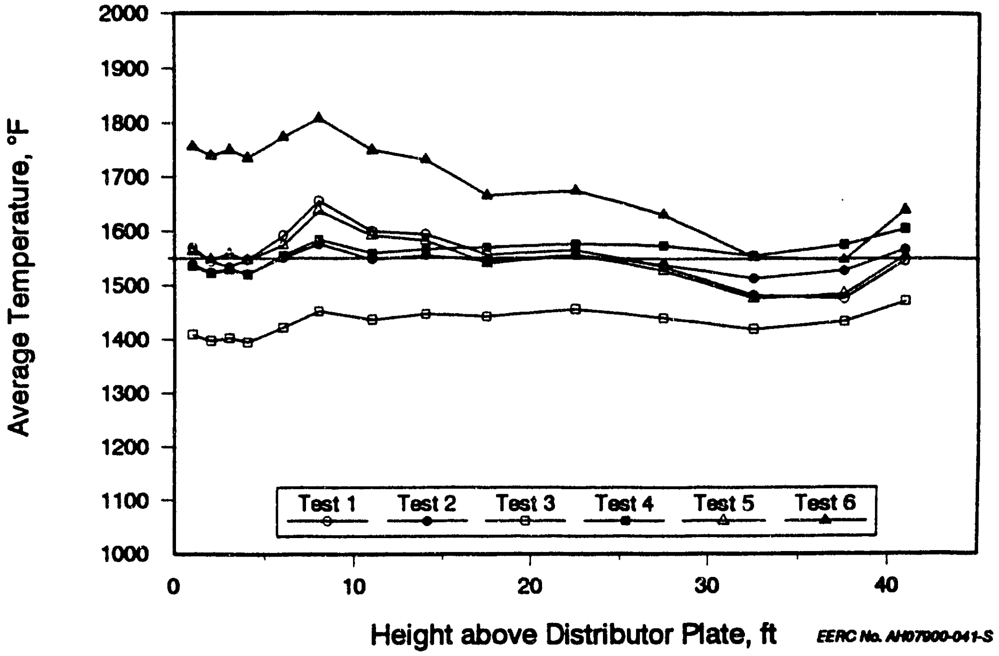

Figure C-11. Temperature profiles of Tests 1 through 6.

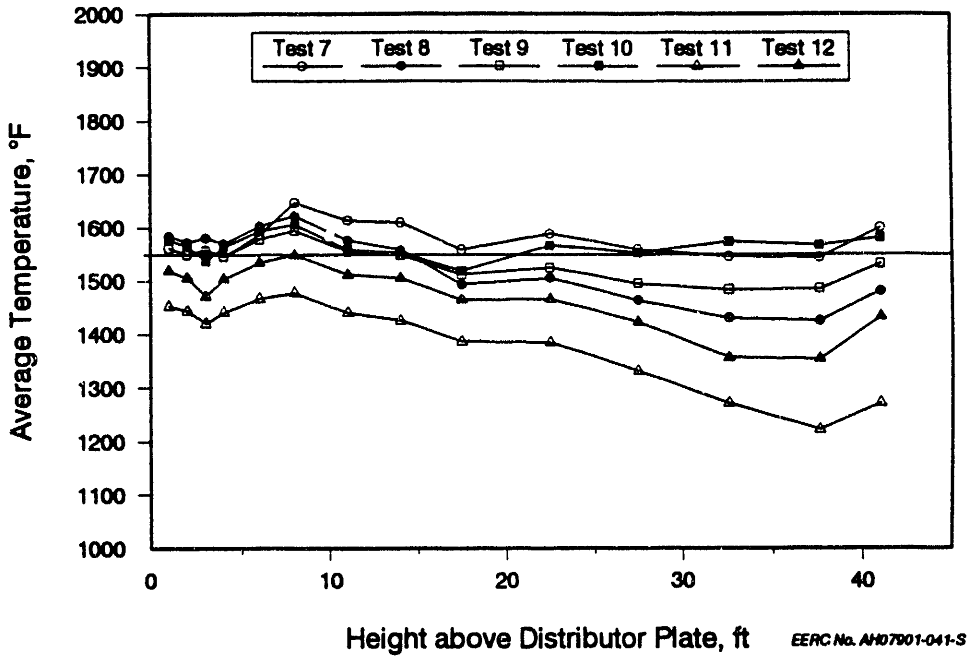

Figure C-12. Temperature profiles of Tests 7 through 12.

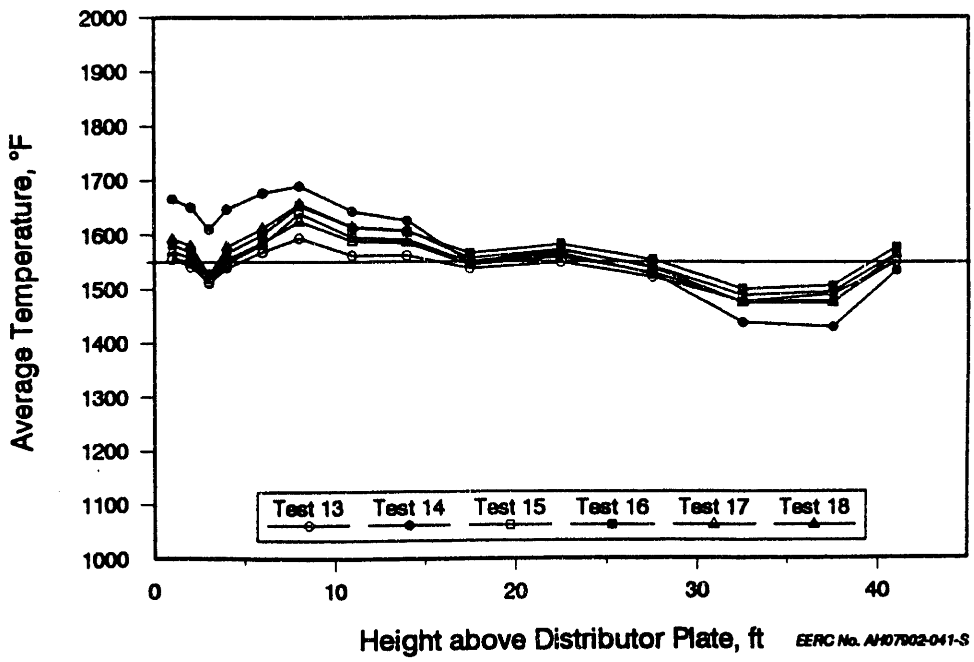

Figure C-13. Temperature profiles of Tests 13 through 18.

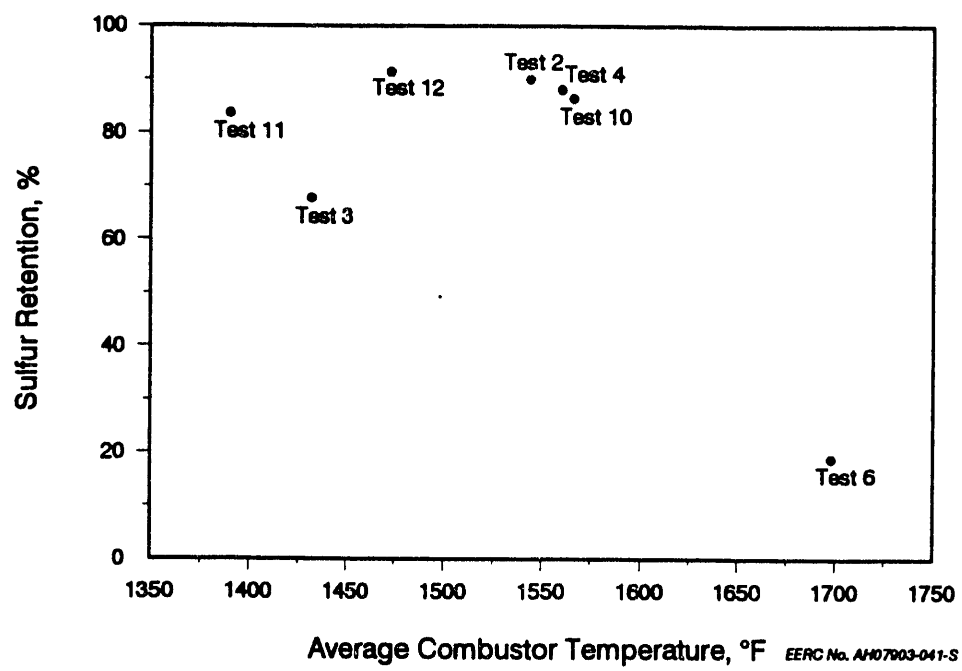

Figure C-14. Relationship between temperature and flue gas SO_2 emissions.

TABLE C-18

Emissions Data

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10
O_2, %	4.73	3.57	4.95	3.50	7.40	4.92	3.64	7.19	4.49	6.10
CO Content, ppm	124	89	207	121	37	70	33	81	107	69
CO Content,[1] ppm	137	88	232	124	48	78	34	105	117	84
CO Emission, lb/MM Btu	0.118	0.071	0.178	0.098	0.037	0.064	0.025	0.080	0.091	0.064
CO_2 Content, %	13.7	16.2	15.2	16.1	12.8	15.3	17.0	13.2	15.5	14.1
CO_2 Content,[1] %	15.2	16.7	17.0	16.6	16.9	17.1	17.6	17.2	16.9	17.1
NO_x Content, ppm	109	91	31	118	172	234	75	132	79	95
NO_x Content,[1] ppm	120	94	35	122	228	264	78	174	86	115
NO_x Emission, lb/MM Btu	0.170	0.120	0.044	0.157	0.288	0.328	0.095	0.215	0.110	0.145
N_2O Content, ppm	152	140	236	119	115	46	110	127	142	98
N_2O Content,[1] ppm	168	145	264	122	152	52	114	167	154	119
N_2O Emission, lb/MM Btu	0.227	0.177	0.318	0.151	0.183	0.062	0.133	0.197	0.187	0.142
SO_2 Content, ppm	1540	194	592	233	398	1464	676	336	267	232
SO_2 Content,[1] ppm	1703	201	664	239	527	1637	701	438	291	280
SO_2 Emission, lb/MM Btu	3.350	0.358	1.163	0.431	0.928	2.929	1.187	0.760	0.513	0.489
SO_2 Retention,[2] %	7.1	90.1	67.7	88.1	74.3	18.8	67.1	78.9	85.8	86.4
Ca/S ratio (ls[3] only)	0.0	2.3	2.3	2.3	3.2	2.8	1.6	0.9	1.7	2.2
Ca/S ratio (total)	0.11	2.43	2.42	2.41	3.29	2.92	1.73	1.02	1.79	2.29
Ca Utiliz. (ls[3] only)	0.0	38.9	29.3	38.3	23.3	6.7	41.2	86.1	51.1	39.7
Ca Utiliz. (total)	64.3	37.1	28.0	36.6	22.5	6.4	38.8	77.4	48.0	37.8
Alkali-to-Sulfur	0.12	2.44	2.43	2.42	3.31	2.93	1.74	1.03	1.80	2.30
Alkali Utilization	57.5	36.9	27.8	36.4	22.4	6.4	38.5	76.4	47.7	37.6
Avg. Comb. Temp., °F	1558	1544	1432	1560	1555	1698	1578	1535	1539	1566
Moisture in FG, vol%	7.6	7.9	7.4	7.9	6.6	7.5	7.9	6.7	7.6	7.1
Moist-Free Coal Carbon, %	76.6	76.6	76.6	76.6	76.6	76.6	76.6	76.6	76.6	76.6
Moist-Free Coal Sulfur, %	2.47	2.47	2.47	2.47	2.47	2.47	2.47	2.47	2.47	2.47

[1] Corrected to 3% O_2.
[2] Moisture-free coal carbon and sulfur values used in the sulfur retention calculation.
[3] Limestone.

continued...

TABLE C-18 (continued)

	Test 11	Test 12	Test 12A	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18
O_2, %	7.15	5.26	6.34	5.63	6.22	4.75	3.77	4.88	5.19
CO Content, ppm	456	157	139	51	62	57	40	11	16
CO Content,[1] ppm	601	179	171	60	72	64	42	12	18
CO Emission, lb/MM Btu	0.529	0.140	0.133	0.046	0.058	0.051	0.033	0.009	0.015
CO_2 Content, %	12.6	14.6	13.7	14.7	14.0	14.7	16.0	14.8	13.7
CO_2 Content,[1], %	16.4	16.7	16.8	17.2	16.3	16.3	16.7	16.6	15.6
NO_x Content, ppm	49	100	115	126	119	122	124	136	137
NO_x Content,[1] ppm	63	114	141	148	144	135	129	152	156
NO_x Emission, lb/MM Btu	0.082	0.147	0.180	0.184	0.182	0.177	0.166	0.197	0.215
N_2O Content, ppm	180	NA[4]	NA	NA	74	131	103	118	124
N_2O Content,[1] ppm	234	NA	NA	NA	90	145	108	132	141
N_2O Emission, lb/MM Btu	0.290	NA	NA	NA	0.114	0.182	0.132	0.163	0.186
SO_2 Content, ppm	251	152	219	154	753	572	555	296	1491
SO_2 Content,[1] ppm	326	172	268	181	914	634	580	331	1697
SO_2 Emission, lb/MM Btu	0.591	0.311	0.476	0.313	1.608	1.159	1.037	0.596	3.249
SO_2 Retention,[2] %	83.6	91.4	86.8	91.3	55.4	67.9	71.2	83.5	9.9
Ca/S ratio (ls[3] only)	2.5	2.2	2.3	2.9	3.3	1.6	2.4	2.9	0.0
Ca/S ratio (total)	2.59	2.27	2.38	2.99	3.46	1.69	2.49	3.02	0.14
Ca Utiliz. (ls[3] only)	33.7	42.3	38.2	31.7	16.5	43.1	30.0	28.8	0.0
Ca Utiliz. (total)	32.3	40.3	36.5	30.6	16.0	40.2	28.6	27.7	72.5
Alkali-to-Sulfur	2.60	2.28	2.39	3.00	3.47	1.70	2.50	3.03	0.15
Alkali Utilization	32.1	40.1	36.3	30.5	15.9	39.9	28.5	27.6	66.3
Avg. Comb. Temp., °F	1390	1473	1491	1540	1590	1557	1572	1552	1569
Moisture in FG, vol%	6.7	7.3	7.32	7.2	7.0	7.5	7.8	7.5	7.4
Moist-Free Coal Carbon, %	76.6	76.6	76.6	76.6	76.6	76.6	76.6	76.6	76.6
Moist-Free Coal Sulfur, %	2.47	2.47	2.47	2.47	2.47	2.47	2.47	2.47	2.47

[1] Corrected to 3% O_2.
[2] Moisture-free coal carbon and sulfur values used in the sulfur retention calculation.
[3] Limestone.
[4] Not available.

Figure C-15 shows the effect of alkali-to-sulfur ratio on SO_2 emissions. The total alkali content includes the calcium in the limestone and both the calcium and sodium in the coal ash. The tests shown were operated at temperatures ranging from 1539° to 1578°F, with an average temperature of 1555°F. The sulfur emission levels for Tests 1 and 18, with no limestone feed, were 1703 and 1697 ppm (corrected to 3%O_2), respectively; this corresponds to 3.35 and 3.25 lb/MM Btu for Tests 1 and 18, respectively, and sulfur retentions of 7% and 10%.

Sulfur emissions are also affected by the solids recirculation rate. Figure C-16 shows that, as recirculation rate increases, sulfur emissions decrease. With a higher recirculation rate, limestone stays in the system longer and has more time to react with the sulfur.

NO_x Emissions

The NO_x emissions for this run ranged from 35 ppm (corrected to 3% O_2) for Test 3 to 261 ppm (corrected to 3% O_2) for Test 6. Figure C-17 shows that NO_x emissions increase with increasing temperature. These tests were operated at similar conditions of velocity, excess air, and alkali-to-sulfur ratio.

The NO_x emissions for several 1550°F tests are shown as a function of excess air in Figure C-18. As expected, the NO_x emissions increased with increasing excess air. A decrease in NO_x with increasing Ca/S ratio was also observed.

N_2O Emissions

The relationship between N_2O emissions and combustor temperature is shown in Figure C-19. N_2O emissions data from all of the tests, except Tests 12 and 13, during which the N_2O analyzer was not functioning, are shown in this figure. As expected, N_2O emissions decrease with increasing temperature. N_2O emissions also increased with increasing excess air, and decreased with increasing Ca/S ratio.

CO Emissions

The CO emissions as a function of average combustor temperature are shown in Figure C-20. While there is a tendency for CO emissions to decrease with increasing temperature, this trend is not consistent for all tests. Other factors such as excess air and primary air split, also have a small effect on CO emissions. Test 11, the 50% load, low-temperature test had the highest CO emissions at 668 ppm (corrected to 3% O_2). The next highest, 232 ppm, was measured for Test 3, also a low-temperature test.

LIMESTONE PERFORMANCE

Tests 15, 16, and 17 were limestone tests. Test 15 used the same sized New Enterprise limestone used in Tests 2 through 14; Test 16 used a finer size of the same limestone, and Test 17 used a fine-sized Colorado Ute limestone. All three tests were run at the same velocity (16 ft/sec). Tests 15 and 17 had the same temperature (1555°F), while Test 16 was slightly higher (1572°F). Test 16 was also operated at a lower excess air (22%) compared to Tests 15 and 17 (29% and 30%, respectively). The test matrix called

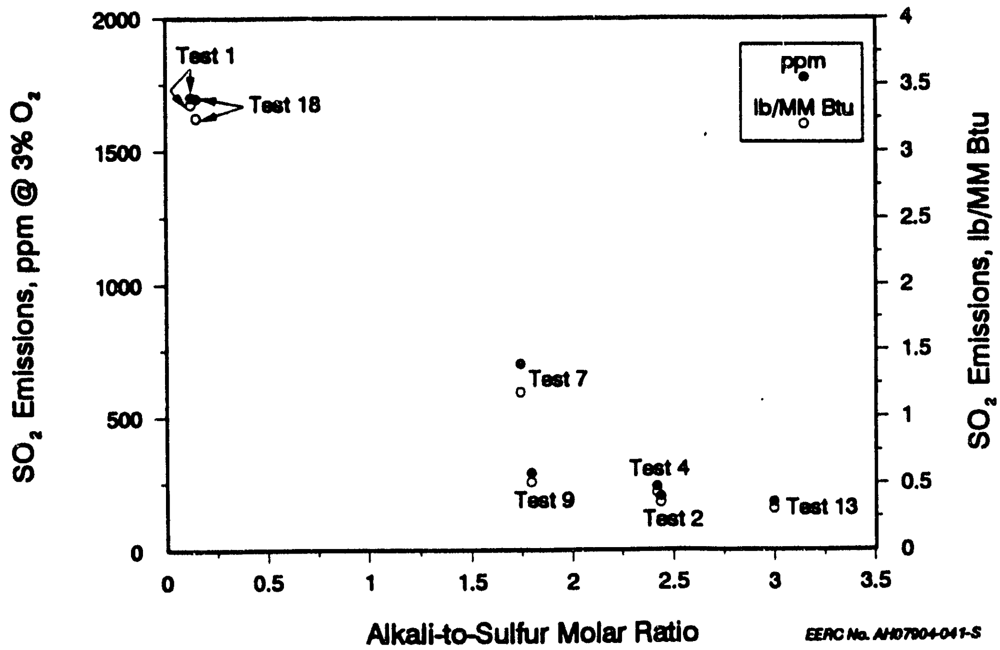

Figure C-15. Effect of alkali-to-sulfur ratio on SO_2 emissions.

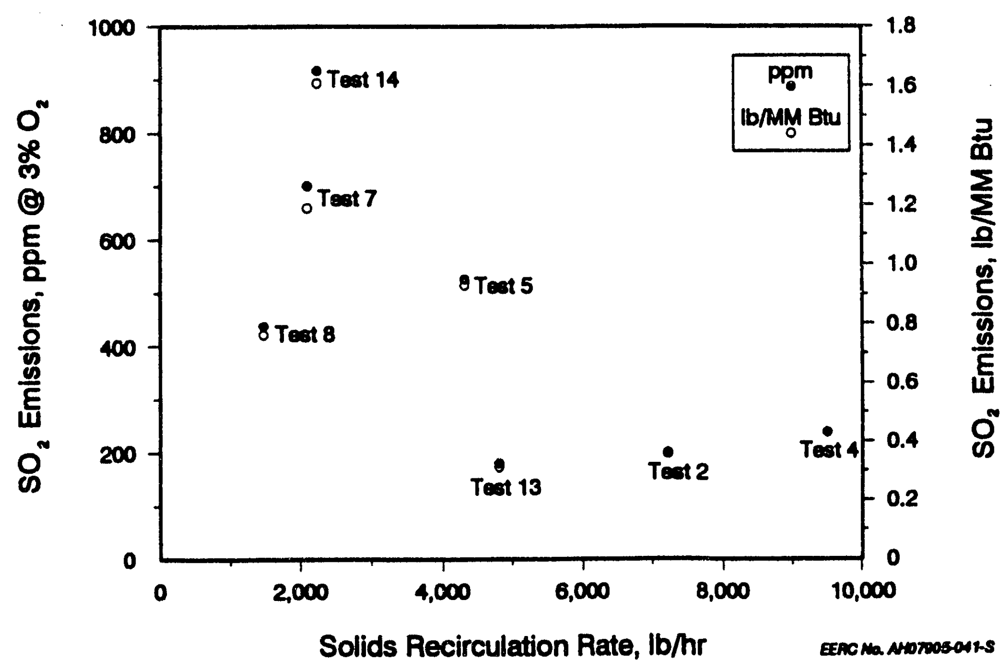

Figure C-16. Effect of solids recirculation rate on SO_2 emissions.

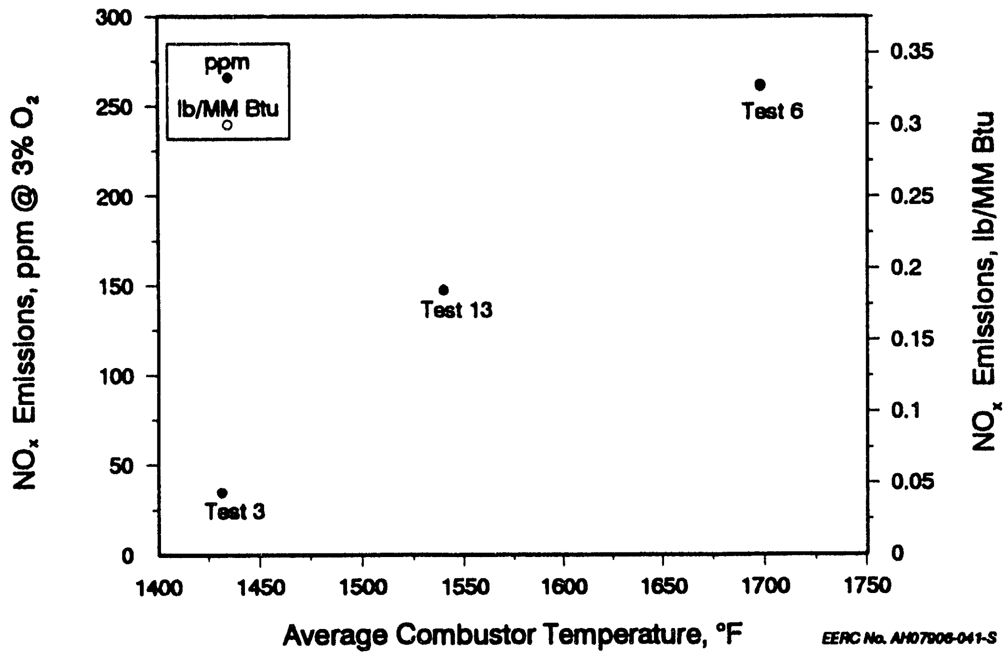

Figure C-17. NO_x emissions as a function of average combustor temperature.

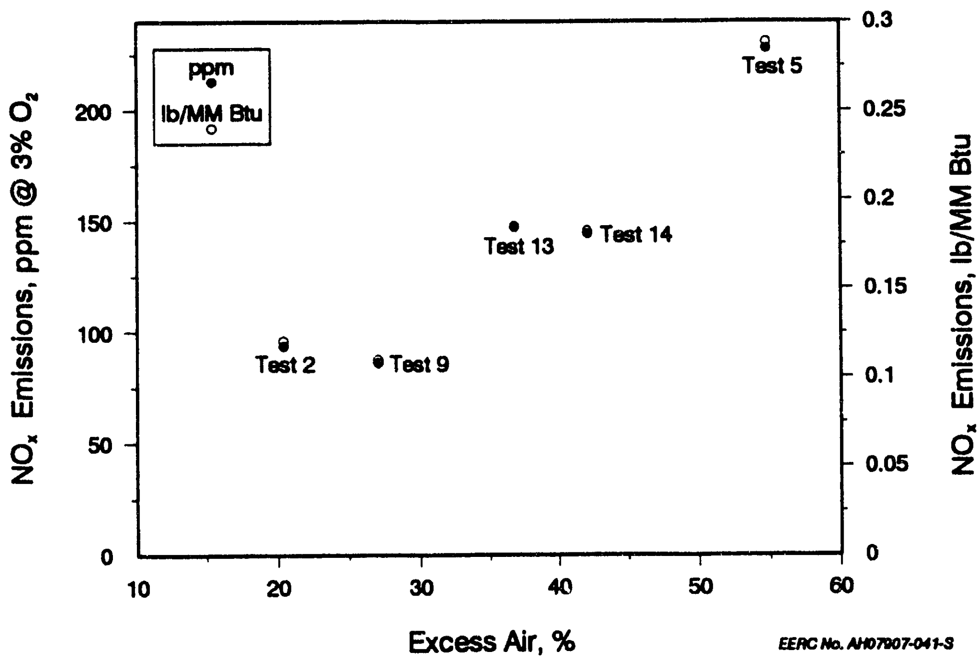

Figure C-18. NO_x emissions as a function of excess air.

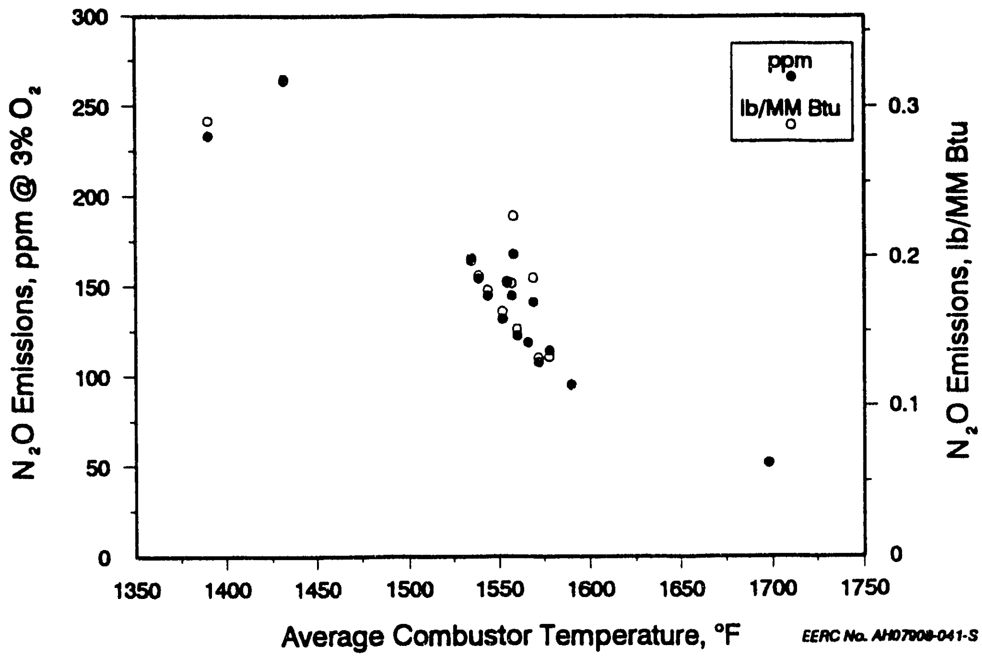

Figure C-19. N_2O emissions as a function of average combustor temperature.

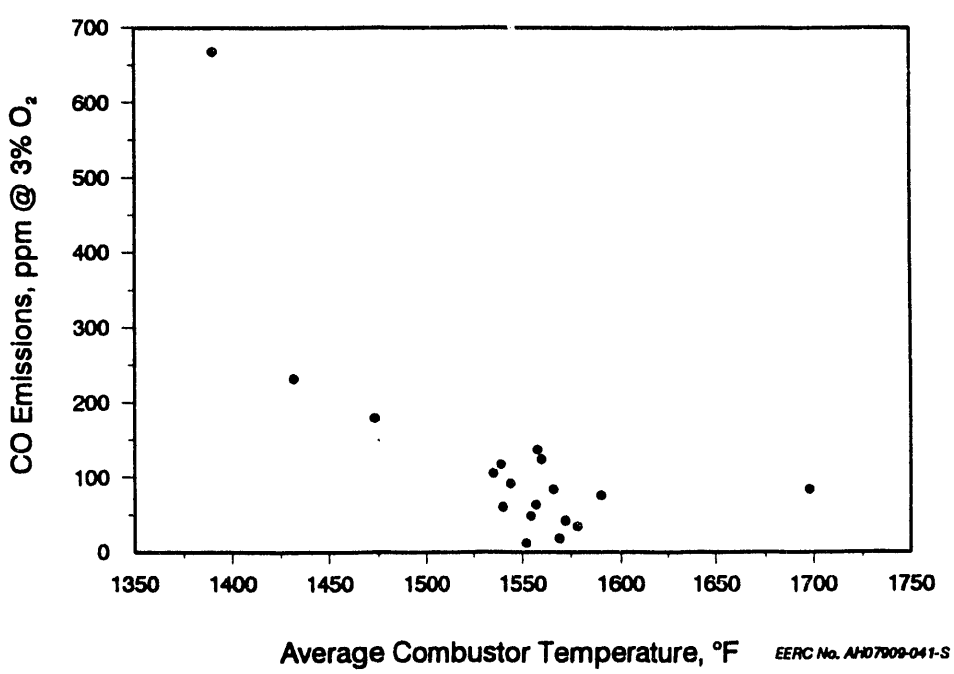

Figure C-20. CO emissions as a function of average combustor temperature.

for all three tests to be run at an alkali-to-sulfur ratio to achieve 70% sulfur retention; the actual retentions for Tests 15, 16, and 17 were 70%, 71%, and 84%, respectively. The alkali-to-sulfur ratios required to achieve these levels of sulfur retention were 1.6, 2.4, and 2.8.

Figure C-21 shows the effect of limestone type and size on several parameters. Alkali utilization and heat-transfer coefficient are both more sensitive to limestone particle size than type. This indicates the reactivities of these two limestones are similar. The poorer utilization and higher alkali-to-sulfur ratio required for 70% sulfur retention for the finer limestones is due to a shorter residence time in the combustor, either because the larger particles stayed in the bed until attrition made them small enough to be carried out of the combustor, or because the smaller particles were not captured by the primary cyclone and recirculated back to the combustor.

The NO_x, N_2O, and CO emissions shown in Figure C-21 reveal the interactions of several operating parameters. The relative NO_x emissions for the three tests may result from an excess air effect (see Figure C-18), since the excess air for Test 16 was lower than the other two, as well as a limestone source effect. The lower N_2O emissions for Test 16 may have been influenced by the higher temperature for that test (see Figure C-19), as well as limestone differences. While both limestone size and source appear to have an effect on CO emissions, Figure C-20 suggests that these differences may be random.

SUMMARIES OF TEST DATA

This section contains the summaries of test data for each test period, including averages and standard deviations of many of the data points recorded by the computerized data acquisition system.

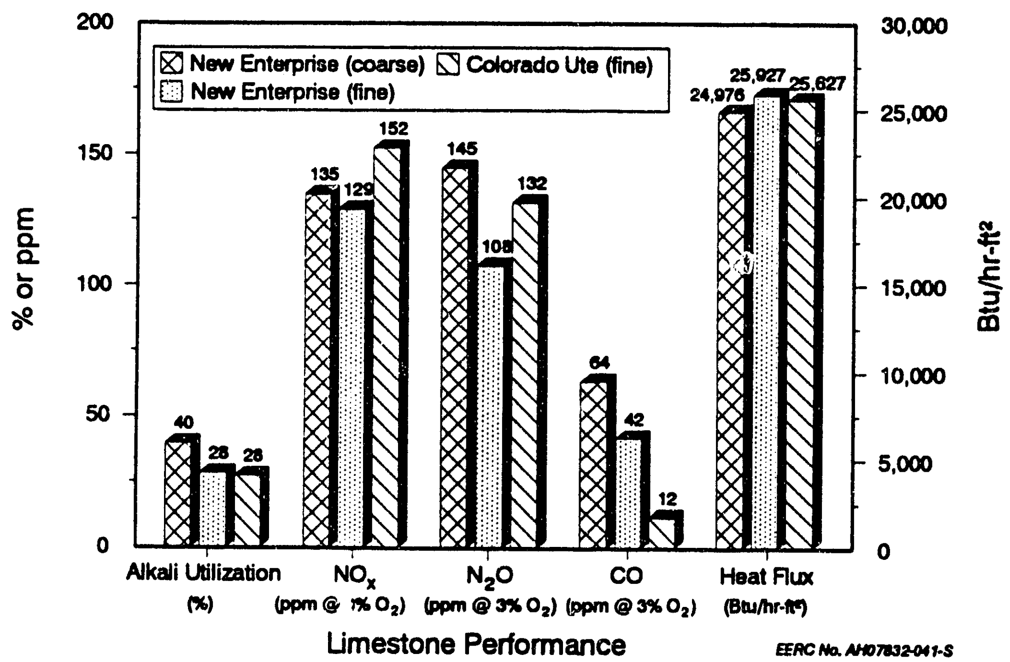

Figure C-21. Effect of limestone type, size, and source.

07-Oct-91

CFB-BV1-0791 — TEST 1

(1745-2345)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1541	6.4
TC11021	AFS Ex	°F	1301	4.8
TC15001	C Plenum	°F	548	4.5
TC15004	C 1-1'	°F	1570	10.1
TC15005	C 1-2'	°F	1545	10.7
TC15006	C 1-3'	°F	1534	9.6
TC15007	C 1-4'	°F	1543	9.4
TC15008	C 1-4'	°F	1557	9.8
TC15009	C 1-4'	°F	1543	10.4
TC15012	C 2-6'	°F	1593	10.9
TC15013	C 2-8'	°F	1657	14.0
TC15022	C 3-11'	°F	1600	10.7
TC15023	C 3-14'	°F	1591	9.2
TC15024	C 3-14'	°F	1582	8.4
TC15025	C 3-14'	°F	1610	10.1
TC15032	C 4-17.5'	°F	1556	8.4
TC15042	C 5-22.5'	°F	1566	6.2
TC15052	C 6-27.5'	°F	1553	6.6
TC15053	C 6-27.5'	°F	1562	8.0
TC15054	C 6-27.5'	°F	1492	5.4
TC15062	C 7-32.5'	°F	1484	5.9
TC15071	C 8-37.5'	°F	1477	6.3
TC15073	C 9-41'	°F	1547	5.5
TC15999	Ambient	°F	87	1.8
TC16001	EHX Plenm	°F	129	3.9
TC16012	EHX 0.5'	°F	1218	13.9
TC16013	EHX 1.5'	°F	1209	13.5
TC16014	EHX 2.7'	°F	1214	13.3
TC16015	EHX 3.8'	°F	1190	12.1
TC16017	EHX 5.3'	°F	1065	6.7
TC16018	EHX Exit	°F	1126	13.6
TC16021	Crc A in	°F	1531	4.8
TC16031	DC 8-36'	°F	1565	4.6
TC16032	DC 6-28'	°F	1539	4.1
TC16033	DC 4-18'	°F	1533	5.6
TC16034	DC3-9.5'	°F	1553	3.6
TC16035	DC3-8.5'	°F	1550	4.7
T(A,C)	Comb Temp	°F	1558	6.8
T(A,EHX)	EHX Temp	°F	1214	13.4
EA	Excess Air	%	28.3	4.0
SR	S Reten	%	13.7	2.4
R(PCA)	%Flw PCA	%	60.3	4.2
R(SCA)	%Flw SCA	%	39.7	4.2
R(Q,IN)	% Enrg in	%	78.0	5.0
R(CHX)	CHX Ratio	%	62.4	1.6
R(EHX)	EHX Ratio	%	37.6	1.6
F(PCA)	PCA Flw	SCFM	262.2	40.6
F(EHX)	EHX Flw	SCFM	43.7	1.8
F(TPA)	TPCA Flw	SCFM	307.9	37.8
F(SCA)	SCA Flw	SCFM	165.9	18.2
F(TCA,F)	TCA Flw	SCFM	508.9	36.4
F(FG,BH)	BH Flw	SCFM	503.0	9.5
F(TFG)	TFG Flw	SCFM	503.0	9.5

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	57	130	1657	3.78	138664	17.5	26666
3NE,SW	14	56	137	1594	3.97	160029	21.1	30775
4SE,NW	17.5	57	136	1556	4.33	171120	23.2	32908
5E	22.5	57	141	1566	2.05	85976	23.2	33068
6NE	27.5	57	124	1536	1.80	60434	16.5	23244
7SE,NW	32.5	58	121	1484	3.23	102294	14.4	19672
8E,W	37.5	58	113	1477	3.70	102149	14.4	19644
	Overall	57	129	1558	22.89	827847	18.6	26534
			From Data Sheets=>		22.86			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-4,10-12	7	55	153	1214	8.79	431017	77.4	82098
			From Data Sheets=>		9.18			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	1540	87.8	SO2-A	ppm	1703	76.2
SO2-AE	lb/MM Btu	3.02	0.1				
SO2-B	ppm	1554	61.6	SO2-B	ppm	1696	33.4
SO2-BE	lb/MM Btu	3.05	0.1				
CO	ppm	124	16.4	CO	ppm	137	19.6
CO2	%	13.71	0.6	CO2	%	15.17	0.5
N2O	ppm	152	5.8	N2O	ppm	168	9.2
N2OE	lb/MM Btu	0.21	0.0				
NOx	ppm	109	10.6	NOx	ppm	121	14.2
NOxE	lb/MM Btu	0.15	0.0				
O2-A	%	4.73	0.5				
O2-B	%	4.52	0.4				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	173.8	11.9	TC13131	AFPE-F2"	1113	22.2
W(S)	LS Fd Rt	lbs/hr	0.0	0.1	TC13132	AFPE-F6"	1198	15.6
V(FG)	FG SGV	ft/sec	16.1	1.1	TC13133	AFPE-B6"	886	31.0
V(S,C)	Comb SGV	ft/sec	15.0	1.1	TC13134	AFPE-F10"	1168	20.8
V(S,EHX)	EHX SGV	ft/sec	1.5	0.1	TC13231	AFPW-F2"	1064	30.8
FT18003	CHX Flow	gpm	22.9	0.3	TC13232	AFPW-F6"	1160	30.1
FT19003	EHX Flow	gpm	8.8	0.1	TC13233	AFPW-B6"	837	49.6
PT15081	Comb dP	in. H2O	37.8	4.0	TC13234	AFPW-F10"	1130	32.9
Q(CA)	CA Heat in	KBtu/hr	102.5	9.0	DOORS	CHXs On	12	0
Q(CHX)	CHX HtRmv	KBtu/hr	715.7	42.7	COILS	EHXs On	7	0
Q(EHX)	EHX HtRmv	KBtu/hr	431.0	13.4	BH A/C		1.9	0.0
Q(EHX,IN	FG Enrg in	KBtu/hr	1.8	0.2	A/SRATIO		0.1	0.1
Q(F)	Fuel Enrg in	KBtu/hr	2319.1	158.9	Feed Air	scfm	18.0	
Q(FG)	FG Enrg out	KBtu/hr	245.6	4.7	DC Air	scfm	0.0	
Q(IN)	Tot Enrg in	KBtu/hr	2423.4	160.4	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1887.5	47.6				
W(SR)	Recirc Rt	lbs/hr	4168	217.9				

08-Oct-91

CFB-BV1-0791 — TEST 2

(1530-2140)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1546	7.2
TC11021	AFS Ex	°F	1304	6.9
TC15001	C Plenum	°F	528	4.8
TC15004	C 1-1'	°F	1538	12.4
TC15005	C 1-2'	°F	1524	11.1
TC15006	C 1-3'	°F	1531	11.8
TC15007	C 1-4'	°F	1520	12.0
TC15008	C 1-4'	°F	N/A	N/A
TC15009	C 1-4'	°F	1523	12.7
TC15012	C 2-6'	°F	1551	12.4
TC15013	C 2-8'	°F	1577	14.6
TC15022	C 3-11'	°F	1549	11.0
TC15023	C 3-14'	°F	1553	10.2
TC15024	C 3-14'	°F	1549	10.6
TC15025	C 3-14'	°F	1565	11.1
TC15032	C 4-17.5'	°F	1545	7.1
TC15042	C 5-22.5'	°F	1557	8.8
TC15052	C 6-27.5'	°F	1555	9.0
TC15053	C 6-27.5'	°F	1559	9.8
TC15054	C 6-27.5'	°F	1504	7.8
TC15062	C 7-32.5'	°F	1515	7.5
TC15071	C 8-37.5'	°F	1528	8.8
TC15073	C 9-41'	°F	1568	10.3
TC15999	Ambient	°F	73	2.8
TC16001	EHX Plenm	°F	119	5.8
TC16012	EHX 0.5'	°F	1337	11.8
TC16013	EHX 1.5'	°F	1322	12.0
TC16014	EHX 2.7'	°F	1328	12.7
TC16015	EHX 3.8'	°F	1317	9.4
TC16017	EHX 5.3'	°F	1232	7.4
TC16018	EHX Exit	°F	1276	9.3
TC16021	Crc A in	°F	1551	7.9
TC16031	DC 8-36'	°F	1562	5.4
TC16032	DC 6-28'	°F	1535	5.8
TC16033	DC 4-18'	°F	1534	7.4
TC16034	DC3-9.5'	°F	1566	6.7
TC16035	DC3-8.5'	°F	1559	7.8
T(A,C)	Comb Temp	°F	1544	9.3
T(A,EHX)	EHX Temp	°F	1329	10.9
EA	Excess Air	%	20.4	3.9
SR	S Reten	%	90.8	1.9
R(PCA)	%Flw PCA	%	59.3	3.8
R(SCA)	%Flw SCA	%	40.7	3.8
R(Q,IN)	% Enrg in	%	82.6	4.8
R(CHX)	CHX Ratio	%	59.8	1.1
R(EHX)	EHX Ratio	%	40.2	1.1
F(PCA)	PCA Flw	SCFM	252.5	25.5
F(EHX)	EHX Flw	SCFM	49.6	4.1
F(TPA)	TPCA Flw	SCFM	300.9	26.1
F(SCA)	SCA Flw	SCFM	171.6	18.6
F(TCA,F)	TCA Flw	SCFM	506.8	21.8
F(FG,BH)	BH Flw	SCFM	506.2	6.2
F(TFG)	TFG Flw	SCFM	506.2	6.2

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	57	153	1577	3.40	164184	22.2	31574
3NE,SW	14	56	152	1555	3.22	153764	21.1	29570
4SE,NW	17.5	56	146	1545	3.50	157771	21.7	30341
5E	22.5	57	163	1557	1.68	89356	24.7	34368
6NE	27.5	57	139	1539	1.58	65394	18.0	25151
7SE,NW	32.5	57	122	1515	2.88	93368	12.9	17955
8E,W	37.5	58	154	1528	2.63	125717	17.6	24176
	Overall	56	147	1544	18.34	831959	19.1	26665
		From Data Sheets=>			18.90			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-4,10-12	7	56	165	1329	9.41	514324	84.2	97966
		From Data Sheets=>			9.87			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	194	41.9	SO2-A	ppm	201	42.5
SO2-AE	lb/MM Btu	0.32	0.1				
SO2-B	ppm	190	37.2	SO2-B	ppm	204	38.9
SO2-BE	lb/MM Btu	0.32	0.1				
CO	ppm	89	19.7	CO	ppm	88	26.6
CO2	%	16.20	0.5	CO2	%	16.73	0.2
N2O	ppm	140	7.2	N2O	ppm	145	10.2
N2OE	lb/MM Btu	0.16	0.0				
NOx	ppm	91	7.7	NOx	ppm	94	8.8
NOxE	lb/MM Btu	0.11	0.0				
O2-A	%	3.57	0.5				
O2-B	%	4.22	0.4				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	173.5	12.8	TC13131	AFPE-F2"	1012	28.9
W(S)	LS Fd Rt	lbs/hr	35.7	2.7	TC13132	AFPE-F6"	1133	20.6
V(FG)	FG SGV	ft/sec	15.8	0.7	TC13133	AFPE-B6"	742	25.3
V(S,C)	Comb SGV	ft/sec	14.8	0.6	TC13134	AFPE-F10"	1038	52.2
V(S,EHX)	EHX SGV	ft/sec	1.8	0.1	TC13231	AFPW-F2"	1010	26.4
FT18003	CHX Flow	gpm	16.3	0.1	TC13232	AFPW-F6"	1107	19.1
FT19003	EHX Flow	gpm	9.4	0.3	TC13233	AFPW-B6"	727	19.3
PT15081	Comb dP	in. H2O	44.9	2.4	TC13234	AFPW-F10'	1069	25.2
Q(CA)	CA Heat in	KBtu/hr	102.1	5.0	DOORS	CHXs On	12	0
Q(CHX)	CHX HtRmv	KBtu/hr	763.7	30.3	COILS	EHXs On	7	0
Q(EHX)	EHX HtRmv	KBtu/hr	513.7	12.8	BH A/C		1.9	0.0
Q(EHX,IN	FG Enrg in	KBtu/hr	2.2	0.3	A/SRATIO		2.8	0.2
Q(F)	Fuel Enrg in	KBtu/hr	2345.0	114.4	Feed Air	scfm	18.1	
Q(FG)	FG Enrg out	KBtu/hr	250.5	3.2	DC Air	scfm	0.0	
Q(IN)	Tot Enrg in	KBtu/hr	2449.0	112.4	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	2011.9	35.6				
W(SR)	Recirc Rt	lbs/hr	7217	357.4				

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CFB-BV1-0791 — TEST 3

(0135-0735)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1481	8.8
TC11021	AFS Ex	°F	1253	8.4
TC15001	C Plenum	°F	513	7.8
TC15004	C 1-1'	°F	1410	20.2
TC15005	C 1-2'	°F	1398	20.3
TC15006	C 1-3'	°F	1403	19.0
TC15007	C 1-4'	°F	1395	17.5
TC15008	C 1-4'	°F	N/A	N/A
TC15009	C 1-4'	°F	1397	19.7
TC15012	C 2-6'	°F	1423	21.3
TC15013	C 2-8'	°F	1452	19.8
TC15022	C 3-11'	°F	1437	16.3
TC15023	C 3-14'	°F	1444	17.1
TC15024	C 3-14'	°F	1441	16.2
TC15025	C 3-14'	°F	1454	16.7
TC15032	C 4-17.5'	°F	1442	17.4
TC15042	C 5-22.5'	°F	1456	15.2
TC15052	C 6-27.5'	°F	1454	14.6
TC15053	C 6-27.5'	°F	1457	15.4
TC15054	C 6-27.5'	°F	1411	15.1
TC15062	C 7-32.5'	°F	1421	15.4
TC15071	C 8-37.5'	°F	1434	14.1
TC15073	C 9-41'	°F	1472	14.6
TC15999	Ambient	°F	76	3.6
TC16001	EHX Plenm	°F	127	4.6
TC16012	EHX 0.5'	°F	1120	29.0
TC16013	EHX 1.5'	°F	1107	29.3
TC16014	EHX 2.7'	°F	1102	29.8
TC16015	EHX 3.8'	°F	1081	28.1
TC16017	EHX 5.3'	°F	1043	23.6
TC16018	EHX Exit	°F	1051	24.7
TC16021	Crc A in	°F	1458	14.0
TC16031	DC 8-36'	°F	1486	8.0
TC16032	DC 6-28'	°F	1457	7.6
TC16033	DC 4-18'	°F	1452	10.5
TC16034	DC3-9.5'	°F	1479	11.0
TC16035	DC3-8.5'	°F	1477	10.1
T(A,C)	Comb Temp	°F	1431	17.2
T(A,EHX)	EHX Temp	°F	1110	28.3
EA	Excess Air	%	30.8	5.9
SR	S Reten	%	69.9	4.3
R(PCA)	%Flw PCA	%	59.9	5.2
R(SCA)	%Flw SCA	%	40.1	5.2
R(Q,IN)	% Enrg in	%	78.3	7.5
R(CHX)	CHX Ratio	%	51.9	1.6
R(EHX)	EHX Ratio	%	48.1	1.6
F(PCA)	PCA Flw	SCFM	249.0	31.9
F(EHX)	EHX Flw	SCFM	56.4	3.6
F(TPA)	TPCA Flw	SCFM	304.7	30.8
F(SCA)	SCA Flw	SCFM	170.3	26.7
F(TCA,F)	TCA Flw	SCFM	508.9	21.7
F(FG,BH)	BH Flw	SCFM	511.8	17.2
F(TFG)	TFG Flw	SCFM	511.8	17.2

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	57	158	1452	2.82	141765	21.1	27263
3NE,SW	14	56	169	1447	2.85	161466	24.3	31051
4SE,NW	17.5	59	164	1442	2.90	152099	22.9	29250
5E	22.5	56	159	1456	1.47	75803	22.5	29155
6NE	27.5	60	163	1441	1.70	87784	26.4	33763
7SE,NW	32.5	60	120	1421	3.27	98468	14.6	18936
8E,W	37.5	59	132	1434	2.77	101534	15.0	19526
	Overall	55	150	1431	16.16	767165	19.2	24589
			From Data Sheets=>		17.78			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-7,9,	12	55	129	1110	16.09	598884	67.9	66543
13-16			From Data Sheets=>		16.82			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	592	75.3	SO2-A	ppm	666	98.4
SO2-AE	lb/MM Btu	1.05	0.1				
SO2-B	ppm	579	74.6	SO2-B	ppm	662	93.4
SO2-BE	lb/MM Btu	1.03	0.1				
CO	ppm	207	50.4	CO	ppm	233	62.2
CO2	%	15.17	0.6	CO2	%	17.02	0.6
N2O	ppm	236	11.7	N2O	ppm	265	22.9
N2OE	lb/MM Btu	0.29	0.0				
NOx	ppm	31	4.1	NOx	ppm	35	4.7
NOxE	lb/MM Btu	0.04	0.0				
O2-A	%	4.95	0.7				
O2-B	%	5.21	0.6				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	175.7	16.1	TC13131	AFPE-F2"	888	25.5
W(S)	LS Fd Rt	lbs/hr	32.9	5.1	TC13132	AFPE-F6"	1032	18.5
V(FG)	FG SGV	ft/sec	15.2	0.8	TC13133	AFPE-B6"	653	18.8
V(S,C)	Comb SGV	ft/sec	14.3	0.6	TC13134	AFPE-F10"	867	41.1
V(S,EHX)	EHX SGV	ft/sec	1.8	0.1	TC13231	AFPW-F2"	899	22.1
FT18003	CHX Flow	gpm	16.2	0.2	TC13232	AFPW-F6"	1014	18.2
FT19003	EHX Flow	gpm	16.1	0.2	TC13233	AFPW-B6"	654	17.3
PT15081	Comb dP	in. H2O	46.4	3.1	TC13234	AFPW-F10"	961	22.0
Q(CA)	CA Heat in	KBtu/hr	98.9	6.0	DOORS	CHXs On	12	0
Q(CHX)	CHX HtRmv	KBtu/hr	642.0	37.2	COILS	EHXs On	12	0
Q(EHX)	EHX HtRmv	KBtu/hr	595.4	31.3	BH A/C		1.9	0.1
Q(EHX,IN	FG Enrg in	KBtu/hr	2.8	0.3	A/SRATIO		2.7	0.6
Q(F)	Fuel Enrg in	KBtu/hr	2338.4	214.8	Feed Air	scfm	18.6	
Q(FG)	FG Enrg out	KBtu/hr	246.8	9.0	DC Air	scfm	0.0	
Q(IN)	Tot Enrg in	KBtu/hr	2440.0	217.4	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1889.3	68.6				
W(SR)	Recirc Rt	lbs/hr	5262	676.0				

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CFB-BV1-0791 — TEST 4

(1315-1805)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1599	7.6
TC11021	AFS Ex	°F	1356	7.9
TC15001	C Plenum	°F	624	3.5
TC15004	C 1-1'	°F	1537	6.7
TC15005	C 1-2'	°F	1522	6.6
TC15006	C 1-3'	°F	1530	6.7
TC15007	C 1-4'	°F	1520	5.6
TC15008	C 1-4'	°F	N/A	N/A
TC15009	C 1-4'	°F	1520	6.9
TC15012	C 2-6'	°F	1556	8.6
TC15013	C 2-8'	°F	1585	9.9
TC15022	C 3-11'	°F	1560	7.2
TC15023	C 3-14'	°F	1567	7.6
TC15024	C 3-14'	°F	1559	6.2
TC15025	C 3-14'	°F	1576	8.1
TC15032	C 4-17.5'	°F	1570	8.3
TC15042	C 5-22.5'	°F	1577	6.4
TC15052	C 6-27.5'	°F	1585	6.6
TC15053	C 6-27.5'	°F	1587	7.7
TC15054	C 6-27.5'	°F	1552	6.6
TC15062	C 7-32.5'	°F	1556	6.4
TC15071	C 8-37.5'	°F	1576	6.8
TC15073	C 9-41'	°F	1606	8.7
TC15999	Ambient	°F	76	3.1
TC16001	EHX Plenm	°F	116	6.3
TC16012	EHX 0.5'	°F	1396	9.3
TC16013	EHX 1.5'	°F	1370	10.4
TC16014	EHX 2.7'	°F	1379	10.3
TC16015	EHX 3.8'	°F	1346	8.3
TC16017	EHX 5.3'	°F	1281	8.9
TC16018	EHX Exit	°F	1308	9.4
TC16021	Crc A in	°F	1587	7.1
TC16031	DC 8-36'	°F	1597	5.7
TC16032	DC 6-28'	°F	1571	6.1
TC16033	DC 4-18'	°F	1571	7.9
TC16034	DC3-9.5'	°F	1600	7.2
TC16035	DC3-8.5'	°F	1585	7.9
T(A,C)	Comb Temp	°F	1560	6.5
T(A,EHX)	EHX Temp	°F	1382	8.9
EA	Excess Air	%	19.9	3.7
SR	S Reten	%	89.0	3.2
R(PCA)	%Flw PCA	%	70.2	4.8
R(SCA)	%Flw SCA	%	29.8	4.8
R(Q,IN)	% Enrg in	%	77.2	2.6
R(CHX)	CHX Ratio	%	54.7	1.5
R(EHX)	EHX Ratio	%	45.3	1.5
F(PCA)	PCA Flw	SCFM	358.2	33.6
F(EHX)	EHX Flw	SCFM	49.0	6.9
F(TPA)	TPCA Flw	SCFM	408.0	31.6
F(SCA)	SCA Flw	SCFM	138.9	28.7
F(TCA,F)	TCA Flw	SCFM	581.0	22.8
F(FG,BH)	BH Flw	SCFM	605.1	8.7
F(TFG)	TFG Flw	SCFM	605.1	8.6

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service====> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	56	148	1585	3.50	159533	21.3	30679
3NE,SW	14	55	153	1567	3.80	185779	25.3	35727
4SE,NW	17.5	56	165	1570	3.80	207857	28.5	39972
5E	22.5	56	172	1577	1.80	103776	28.4	39914
6NE	27.5	57	127	1574	1.94	68214	18.1	26236
7SE,NW	32.5	57	150	1556	3.30	154252	21.1	29664
8E,W	37.5	57	156	1576	2.82	140125	19.0	26947
	Overall	55	154	1560	19.81	976101	22.2	31285
			From Data Sheets=>		20.96			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-4,5-7,	11	54	118	1382	21.31	678562	65.1	82250
13-16			From Data Sheets=>		21.34			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	232	72.7	SO2-A	ppm	239	72.8
SO2-AE	lb/MM Btu	0.39	0.1				
SO2-B	ppm	178	50.0	SO2-B	ppm	189	50.1
SO2-BE	lb/MM Btu	0.30	0.1				
CO	ppm	121	49.7	CO	ppm	124	50.2
CO2	%	16.11	0.6	CO2	%	16.58	0.6
N2O	ppm	119	8.9	N2O	ppm	123	11.3
N2OE	lb/MM Btu	0.14	0.0				
NOx	ppm	118	9.6	NOx	ppm	122	10.9
NOxE	lb/MM Btu	0.14	0.0				
O2-A	%	3.50	0.5				
O2-B	%	4.06	0.4				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	213.5	6.3	TC13131	AFPE-F2"	1009	24.1
W(S)	LS Fd Rt	lbs/hr	40.8	2.5	TC13132	AFPE-F6"	1136	17.9
V(FG)	FG SGV	ft/sec	18.4	0.8	TC13133	AFPE-B6"	747	20.2
V(S,C)	Comb SGV	ft/sec	17.3	0.7	TC13134	AFPE-F10"	957	41.0
V(S,EHX)	EHX SGV	ft/sec	1.9	0.2	TC13231	AFPW-F2"	1000	20.9
FT18003	CHX Flow	gpm	19.8	0.2	TC13232	AFPW-F6"	1118	17.6
FT19003	EHX Flow	gpm	21.3	0.3	TC13233	AFPW-B6"	749	15.5
PT15081	Comb dP	in. H2O	38.1	3.3	TC13234	AFPW-F10"	1064	20.5
Q(CA)	CA Heat in	KBtu/hr	128.1	7.1	DOORS	CHXs On	12	0
Q(CHX)	CHX HtRmv	KBtu/hr	815.7	39.2	COILS	EHXs On	11	0
Q(EHX)	EHX HtRmv	KBtu/hr	675.1	35.6	BH A/C		2.3	0.0
Q(EHX,IN	FG Enrg in	KBtu/hr	2.0	0.4	A/SRATIO		2.6	0.2
Q(F)	Fuel Enrg in	KBtu/hr	2849.5	86.9	Feed Air	scfm	19.3	
Q(FG)	FG Enrg out	KBtu/hr	301.2	4.7	DC Air	scfm	0.0	
Q(IN)	Tot Enrg in	KBtu/hr	2979.7	86.7	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	2286.7	58.9				
W(SR)	Recirc Rt	lbs/hr	9494	776.9				

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CFB-BV1-0791 — TEST 5

(0215-0815)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1531	17.7
TC11021	AFS Ex	°F	1311	16.3
TC15001	C Plenum	°F	575	4.9
TC15004	C 1-1'	°F	1564	36.7
TC15005	C 1-2'	°F	1548	34.6
TC15006	C 1-3'	°F	1558	35.9
TC15007	C 1-4'	°F	1547	33.4
TC15008	C 1-4'	°F	N/A	N/A
TC15009	C 1-4'	°F	1548	34.7
TC15012	C 2-6'	°F	1575	34.1
TC15013	C 2-8'	°F	1639	41.9
TC15022	C 3-11'	°F	1593	35.9
TC15023	C 3-14'	°F	1577	30.5
TC15024	C 3-14'	°F	1577	29.0
TC15025	C 3-14'	°F	1594	32.7
TC15032	C 4-17.5'	°F	1541	24.5
TC15042	C 5-22.5'	°F	1556	24.2
TC15052	C 6-27.5'	°F	1547	23.1
TC15053	C 6-27.5'	°F	1551	24.5
TC15054	C 6-27.5'	°F	1487	20.4
TC15062	C 7-32.5'	°F	1478	18.9
TC15071	C 8-37.5'	°F	1485	18.8
TC15073	C 9-41'	°F	1556	23.2
TC15999	Ambient	°F	77	2.0
TC16001	EHX Plenm	°F	122	5.6
TC16012	EHX 0.5'	°F	1265	28.4
TC16013	EHX 1.5'	°F	1231	27.0
TC16014	EHX 2.7'	°F	1249	26.8
TC16015	EHX 3.8'	°F	1210	15.8
TC16017	EHX 5.3'	°F	1125	12.2
TC16018	EHX Exit	°F	1173	18.0
TC16021	Crc A in	°F	1536	20.5
TC16031	DC 8-36'	°F	1590	17.1
TC16032	DC 6-28'	°F	1566	16.1
TC16033	DC 4-18'	°F	1544	19.2
TC16034	DC3-9.5'	°F	1562	23.6
TC16035	DC3-8.5'	°F	1547	25.7
T(A,C)	Comb Temp	°F	1555	28.5
T(A,EHX)	EHX Temp	°F	1248	27.3
EA	Excess Air	%	54.8	10.3
SR	S Reten	%	76.3	10.0
R(PCA)	%Flw PCA	%	50.0	2.7
R(SCA)	%Flw SCA	%	50.0	2.7
R(Q,IN)	% Enrg in	%	78.7	8.5
R(CHX)	CHX Ratio	%	63.7	3.2
R(EHX)	EHX Ratio	%	36.3	3.2
F(PCA)	PCA Flw	SCFM	239.0	26.7
F(EHX)	EHX Flw	SCFM	52.1	7.9
F(TPA)	TPCA Flw	SCFM	292.1	23.9
F(SCA)	SCA Flw	SCFM	256.5	15.7
F(TCA,F)	TCA Flw	SCFM	583.9	25.3
F(FG,BH)	BH Flw	SCFM	599.4	13.4
F(TFG)	TFG Flw	SCFM	599.4	13.4

HEAT-TRANSFER COEFFICIENTS

—Combustor—　　Number of Doors in Service===> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	56	138	1639	3.43	140551	18.0	27029
3NE,SW	14	56	139	1583	3.80	156881	20.9	30169
4SE,NW	17.5	57	147	1541	3.80	170899	23.6	32865
5E	22.5	57	154	1556	1.70	82782	22.7	31839
6NE	27.5	57	117	1528	1.90	57457	15.7	22099
7SE,NW	32.5	58	128	1478	3.33	116399	16.6	22384
8E,W	37.5	58	134	1485	2.80	106253	15.1	20433
	Overall	55	137	1555	20.14	821692	18.6	26336
				From Data Sheets=>	20.76			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-4,8,9	6	56	130	1248	10.59	393309	78.2	87402
				From Data Sheets=>	11.13			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	398	183.9	SO2-A	ppm	526	230.1
SO2-AE	lb/MM Btu	0.83	0.3				
SO2-B	ppm	354	137.8	SO2-B	ppm	495	182.4
SO2-BE	lb/MM Btu	0.75	0.3				
CO	ppm	37	26.6	CO	ppm	49	36.1
CO2	%	12.80	1.0	CO2	%	16.95	0.8
N2O	ppm	114	15.6	N2O	ppm	153	27.2
N2OE	lb/MM Btu	0.17	0.0				
NOx	ppm	172	15.6	NOx	ppm	228	20.9
NOxE	lb/MM Btu	0.26	0.0				
O2-A	%	7.40	0.9				
O2-B	%	8.17	0.9				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	171.1	20.1	TC13131	AFPE-F2"	979	30.3
W(S)	LS Fd Rt	lbs/hr	45.6	7.3	TC13132	AFPE-F6"	1092	23.4
V(FG)	FG SGV	ft/sec	18.4	0.7	TC13133	AFPE-B6"	801	23.0
V(S,C)	Comb SGV	ft/sec	17.3	0.7	TC13134	AFPE-F10"	946	44.9
V(S,EHX)	EHX SGV	ft/sec	1.8	0.3	TC13231	AFPW-F2"	962	25.5
FT18003	CHX Flow	gpm	20.1	0.1	TC13232	AFPW-F6"	1078	23.2
FT19003	EHX Flow	gpm	10.6	0.1	TC13233	AFPW-B6"	776	21.3
PT15081	Comb dP	in. H2O	38.5	4.4	TC13234	AFPW-F10'	1030	26.7
Q(CA)	CA Heat in	KBtu/hr	123.9	5.6	DOORS	CHXs On	12	0
Q(CHX)	CHX HtRmv	KBtu/hr	690.6	41.2	COILS	EHXs On	6	0
Q(EHX)	EHX HtRmv	KBtu/hr	394.8	38.8	BH A/C		2.2	0.2
Q(EHX,IN	FG Enrg in	KBtu/hr	2.3	0.5	A/SRATIO		3.7	0.7
Q(F)	Fuel Enrg in	KBtu/hr	2282.4	267.4	Feed Air	scfm	16.1	
Q(FG)	FG Enrg out	KBtu/hr	294.7	6.7	DC Air	scfm	22.0	
Q(IN)	Tot Enrg in	KBtu/hr	2408.6	267.4	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1873.7	62.4				
W(SR)	Recirc Rt	lbs/hr	4359	354.7				

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CFB-BV1-0791 — TEST 6

(1235-1830)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1606	11.1
TC11021	AFS Ex	°F	1355	8.0
TC15001	C Plenum	°F	563	4.7
TC15004	C 1-1'	°F	1757	12.3
TC15005	C 1-2'	°F	1740	12.3
TC15006	C 1-3'	°F	1750	12.2
TC15007	C 1-4'	°F	1735	12.1
TC15008	C 1-4'	°F	N/A	N/A
TC15009	C 1-4'	°F	1737	12.0
TC15012	C 2-6'	°F	1774	12.2
TC15013	C 2-8'	°F	1808	17.6
TC15022	C 3-11'	°F	1749	12.9
TC15023	C 3-14'	°F	1724	9.5
TC15024	C 3-14'	°F	1727	9.0
TC15025	C 3-14'	°F	1744	11.7
TC15032	C 4-17.5'	°F	1665	9.4
TC15042	C 5-22.5'	°F	1675	8.1
TC15052	C 6-27.5'	°F	1652	8.4
TC15053	C 6-27.5'	°F	1658	8.2
TC15054	C 6-27.5'	°F	1583	8.2
TC15062	C 7-32.5'	°F	1554	7.8
TC15071	C 8-37.5'	°F	1548	9.3
TC15073	C 9-41'	°F	1640	9.1
TC15999	Ambient	°F	80	1.9
TC16001	EHX Plenm	°F	118	4.0
TC16012	EHX 0.5'	°F	1366	31.4
TC16013	EHX 1.5'	°F	1373	31.5
TC16014	EHX 2.7'	°F	1369	31.8
TC16015	EHX 3.8'	°F	1280	19.3
TC16017	EHX 5.3'	°F	1176	12.4
TC16018	EHX Exit	°F	1250	21.1
TC16021	Crc A in	°F	1621	8.3
TC16031	DC 8-36'	°F	1668	10.9
TC16032	DC 6-28'	°F	1641	11.1
TC16033	DC 4-18'	°F	1621	13.3
TC16034	DC3-9.5'	°F	1623	26.9
TC16035	DC3-8.5'	°F	1589	45.7
T(A,C)	Comb Temp	°F	1698	9.4
T(A,EHX)	EHX Temp	°F	1370	31.6
EA	Excess Air	%	31.1	9.2
SR	S Reten	%	26.3	12.2
R(PCA)	%Flw PCA	%	60.0	2.7
R(SCA)	%Flw SCA	%	40.0	2.7
R(Q,IN)	% Enrg in	%	82.4	8.4
R(CHX)	CHX Ratio	%	81.3	1.1
R(EHX)	EHX Ratio	%	18.7	1.1
F(PCA)	PCA Flw	SCFM	245.6	26.2
F(EHX)	EHX Flw	SCFM	48.1	3.2
F(TPA)	TPCA Flw	SCFM	291.6	22.7
F(SCA)	SCA Flw	SCFM	162.4	11.1
F(TCA,F)	TCA Flw	SCFM	485.8	22.1
F(FG,BH)	BH Flw	SCFM	504.3	9.8
F(TFG)	TFG Flw	SCFM	504.1	16.8

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	55	157	1808	3.55	180374	21.0	34687
3NE,SW	14	56	158	1731	3.80	193945	23.7	37297
4SE,NW	17.5	56	163	1665	3.95	210987	27.0	40574
5E	22.5	55	164	1675	1.85	100133	25.5	38513
6NE	27.5	56	124	1631	1.95	65750	16.8	25289
7SE,NW	32.5	57	135	1554	3.32	129565	17.6	24916
8E,W	37.5	57	138	1548	2.87	115944	15.8	22297
	Overall	55	150	1698	20.63	976497	20.2	31298
			From Data Sheets=>		21.29			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
3-4,8	3	55	124	1370	5.53	190021	67.8	84454
			From Data Sheets=>		5.60			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	1464	275.9	SO2-A	ppm	1637	270.2
SO2-AE	lb/MM Btu	2.58	0.4				
SO2-B	ppm	1481	305.2	SO2-B	ppm	1743	315.1
SO2-BE	lb/MM Btu	2.61	0.5				
CO	ppm	70	11.9	CO	ppm	78	12.8
CO2	%	15.21	0.6	CO2	%	17.09	0.9
N2O	ppm	46	2.3	N2O	ppm	52	4.0
N2OE	lb/MM Btu	0.06	0.0				
NOx	ppm	234	24.0	NOx	ppm	264	30.9
NOxE	lb/MM Btu	0.30	0.0				
O2-A	%	4.94	0.8				
O2-B	%	5.78	0.7				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	165.2	16.7	TC13131	AFPE-F2"	1076	18.6
W(S)	LS Fd Rt	lbs/hr	40.1	5.1	TC13132	AFPE-F6"	1178	14.0
V(FG)	FG SGV	ft/sec	16.4	0.7	TC13133	AFPE-B6"	865	15.8
V(S,C)	Comb SGV	ft/sec	15.5	0.7	TC13134	AFPE-F10"	1105	24.2
V(S,EHX)	EHX SGV	ft/sec	1.8	0.1	TC13231	AFPW-F2"	1062	15.1
FT18003	CHX Flow	gpm	20.6	0.4	TC13232	AFPW-F6"	1164	14.4
FT19003	EHX Flow	gpm	5.5	0.3	TC13233	AFPW-B6"	830	14.6
PT15081	Comb dP	in. H2O	36.6	3.9	TC13234	AFPW-F10'	1126	14.7
Q(CA)	CA Heat in	KBtu/hr	99.6	5.7	DOORS	CHXs On	12	0
Q(CHX)	CHX HtRmv	KBtu/hr	825.7	42.1	COILS	EHXs On	3	0
Q(EHX)	EHX HtRmv	KBtu/hr	189.1	11.6	BH A/C	OUT	1.9	0.2
Q(EHX,IN	FG Enrg in	KBtu/hr	1.9	0.2	A/SRATIO	OUT	3.4	0.5
Q(F)	Fuel Enrg in	KBtu/hr	2204.6	222.3	Feed Air	scfm	16.0	
Q(FG)	FG Enrg out	KBtu/hr	252.5	6.8	DC Air	scfm	21.6	
Q(IN)	Tot Enrg in	KBtu/hr	2305.9	222.3	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1860.5	47.9				
W(SR)	Recirc Rt	lbs/hr	2515	485.6				

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CFB-BV1-0791 — TEST 7

(1015-1615)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1567	24.4
TC11021	AFS Ex	°F	1312	18.4
TC15001	C Plenum	°F	407	5.1
TC15004	C 1-1'	°F	1563	17.8
TC15005	C 1-2'	°F	1550	16.9
TC15006	C 1-3'	°F	1559	17.6
TC15007	C 1-4'	°F	1547	17.5
TC15008	C 1-4'	°F	N/A	N/A
TC15009	C 1-4'	°F	1547	17.9
TC15012	C 2-6'	°F	1587	18.7
TC15013	C 2-8'	°F	1648	21.0
TC15022	C 3-11'	°F	1614	17.3
TC15023	C 3-14'	°F	1602	15.7
TC15024	C 3-14'	°F	1606	16.2
TC15025	C 3-14'	°F	1622	18.2
TC15032	C 4-17.5'	°F	1559	17.6
TC15042	C 5-22.5'	°F	1589	16.5
TC15052	C 6-27.5'	°F	1580	16.8
TC15053	C 6-27.5'	°F	1583	17.5
TC15054	C 6-27.5'	°F	1517	17.3
TC15062	C 7-32.5'	°F	1546	18.5
TC15071	C 8-37.5'	°F	1544	19.3
TC15073	C 9-41'	°F	1600	16.8
TC15999	Ambient	°F	78	1.8
TC16001	EHX Plenm	°F	131	3.2
TC16012	EHX 0.5'	°F	928	36.4
TC16013	EHX 1.5'	°F	907	35.0
TC16014	EHX 2.7'	°F	913	35.6
TC16015	EHX 3.8'	°F	912	30.0
TC16017	EHX 5.3'	°F	848	20.7
TC16018	EHX Exit	°F	893	31.9
TC16021	Crc A in	°F	1583	18.5
TC16031	DC 8-36'	°F	1596	15.2
TC16032	DC 6-28'	°F	1548	14.5
TC16033	DC 4-18'	°F	1550	19.1
TC16034	DC3-9.5'	°F	1577	17.7
TC16035	DC3-8.5'	°F	1564	20.0
T(A,C)	Comb Temp	°F	1578	14.1
T(A,EHX)	EHX Temp	°F	916	35.6
EA	Excess Air	%	21.3	6.5
SR	S Reten	%	69.5	7.1
R(PCA)	%Flw PCA	%	50.0	3.0
R(SCA)	%Flw SCA	%	50.0	3.0
R(Q,IN)	% Enrg in	%	83.2	12.6
R(CHX)	CHX Ratio	%	60.5	2.6
R(EHX)	EHX Ratio	%	39.5	2.6
F(PCA)	PCA Flw	SCFM	135.8	20.3
F(EHX)	EHX Flw	SCFM	77.4	9.9
F(TPA)	TPCA Flw	SCFM	213.4	20.4
F(SCA)	SCA Flw	SCFM	180.6	9.1
F(TCA,F)	TCA Flw	SCFM	426.0	19.4
F(FG,BH)	BH Flw	SCFM	433.4	6.7
F(TFG)	TFG Flw	SCFM	433.4	6.7

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 10

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	55	131	1648	3.78	142015	18.0	27311
3NE,SW	14	56	138	1610	3.80	156521	20.4	30100
4SE,NW	17.5	56	138	1559	4.10	169803	23.0	32654
5E	22.5	56	137	1589	2.00	80592	21.3	30997
6NE	27.5	56	113	1560	2.00	57179	15.2	21992
7NW	32.5	57	130	1546	1.90	68849	18.7	26480
8W	37.5	57	149	1544	1.30	60128	16.6	23126
	Overall	55	134	1578	17.90	704592	18.8	27100
		From Data Sheets=>			18.88			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-9	9	55	99	916	16.43	367035	66.6	54376
		From Data Sheets=>			16.73			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	676	169.1	SO2-A	ppm	698	163.7
SO2-AE	lb/MM Btu	1.07	0.2				
SO2-B	ppm	637	139.8	SO2-B	ppm	691	136.8
SO2-BE	lb/MM Btu	1.00	0.2				
CO	ppm	33	14.9	CO	ppm	34	15.9
CO2	%	17.00	0.7	CO2	%	17.63	0.5
N2O	ppm	110	11.1	N2O	ppm	115	17.0
N2OE	lb/MM Btu	0.12	0.0				
NOx	ppm	75	8.5	NOx	ppm	78	11.2
NOxE	lb/MM Btu	0.09	0.0				
O2-A	%	3.64	0.8				
O2-B	%	4.47	0.8				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	146.7	21.0	TC13131	AFPE-F2"	879	39.7
W(S)	LS Fd Rt	lbs/hr	21.0	1.6	TC13132	AFPE-F6"	1044	32.9
V(FG)	FG SGV	ft/sec	13.6	0.6	TC13133	AFPE-B6"	577	24.2
V(S,C)	Comb SGV	ft/sec	12.8	0.5	TC13134	AFPE-F10"	837	56.8
V(S,EHX)	EHX SGV	ft/sec	2.2	0.3	TC13231	AFPW-F2"	1040	62.8
FT18003	CHX Flow	gpm	17.9	0.1	TC13232	AFPW-F6"	1152	54.7
FT19003	EHX Flow	gpm	16.4	0.1	TC13233	AFPW-B6"	779	67.4
PT15081	Comb dP	in. H2O	44.7	2.0	TC13234	AFPW-F10'	1091	58.6
Q(CA)	CA Heat in	KBtu/hr	63.4	4.1	DOORS	CHXs On	10	0
Q(CHX)	CHX HtRmv	KBtu/hr	565.3	38.1	COILS	EHXs On	9	0
Q(EHX)	EHX HtRmv	KBtu/hr	369.4	28.2	BH A/C	OUT	1.6	0.1
Q(EHX,IN	FG Enrg in	KBtu/hr	4.1	0.7	A/SRATIO	OUT	2.1	0.3
Q(F)	Fuel Enrg in	KBtu/hr	1957.6	276.9	Feed Air	scfm	16.1	
Q(FG)	FG Enrg out	KBtu/hr	215.2	3.3	DC Air	scfm	0.0	
Q(IN)	Tot Enrg in	KBtu/hr	2025.2	276.5	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1656.5	49.5				
W(SR)	Recirc Rt	lbs/hr	2097	179.2				

11-Oct-91

CFB-BV1-0791 — TEST 8

(0215-0815)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1438	15.2
TC11021	AFS Ex	°F	1201	12.3
TC15001	C Plenum	°F	412	6.6
TC15004	C 1-1'	°F	1584	35.8
TC15005	C 1-2'	°F	1573	33.9
TC15006	C 1-3'	°F	1581	34.6
TC15007	C 1-4'	°F	1572	33.6
TC15008	C 1-4'	°F	N/A	N/A
TC15009	C 1-4'	°F	1570	34.0
TC15012	C 2-6'	°F	1603	36.9
TC15013	C 2-8'	°F	1623	37.8
TC15022	C 3-11'	°F	1577	32.6
TC15023	C 3-14'	°F	1553	30.4
TC15024	C 3-14'	°F	1555	31.7
TC15025	C 3-14'	°F	1569	32.0
TC15032	C 4-17.5'	°F	1494	28.8
TC15042	C 5-22.5'	°F	1506	24.9
TC15052	C 6-27.5'	°F	1485	22.5
TC15053	C 6-27.5'	°F	1490	24.0
TC15054	C 6-27.5'	°F	1419	21.0
TC15062	C 7-32.5'	°F	1431	20.8
TC15071	C 8-37.5'	°F	1426	21.8
TC15073	C 9-41'	°F	1481	20.5
TC15999	Ambient	°F	70	2.7
TC16001	EHX Plenm	°F	117	4.8
TC16012	EHX 0.5'	°F	1050	35.6
TC16013	EHX 1.5'	°F	1030	35.2
TC16014	EHX 2.7'	°F	1033	38.4
TC16015	EHX 3.8'	°F	1000	39.7
TC16017	EHX 5.3'	°F	892	38.6
TC16018	EHX Exit	°F	995	40.5
TC16021	Crc A in	°F	1465	18.5
TC16031	DC 8-36'	°F	1496	11.9
TC16032	DC 6-28'	°F	1456	10.9
TC16033	DC 4-18'	°F	1436	12.9
TC16034	DC3-9.5'	°F	1464	12.3
TC16035	DC3-8.5'	°F	1452	12.9
T(A,C)	Comb Temp	°F	1535	28.5
T(A,EHX)	EHX Temp	°F	1037	36.2
EA	Excess Air	%	53.0	12.4
SR	S Reten	%	80.5	4.5
R(PCA)	%Flw PCA	%	66.8	7.6
R(SCA)	%Flw SCA	%	33.2	7.6
R(Q,IN)	% Enrg in	%	76.6	7.8
R(CHX)	CHX Ratio	%	77.1	1.8
R(EHX)	EHX Ratio	%	22.9	1.8
F(PCA)	PCA Flw	SCFM	223.1	40.1
F(EHX)	EHX Flw	SCFM	65.6	4.6
F(TPA)	TPCA Flw	SCFM	290.5	34.4
F(SCA)	SCA Flw	SCFM	112.9	33.2
F(TCA,F)	TCA Flw	SCFM	435.0	21.8
F(FG,BH)	BH Flw	SCFM	421.5	7.1
F(TFG)	TFG Flw	SCFM	423.5	11.2

HEAT-TRANSFER COEFFICIENTS

—Combustor—　Number of Doors in Service===> 10

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	55	130	1623	3.80	143197	18.4	27538
3NE,SW	14	56	133	1559	3.80	147001	19.8	28270
4SE,NW	17.5	55	130	1494	4.30	159593	22.5	30691
5E	22.5	56	126	1506	2.00	69784	19.4	26840
6NE	27.5	55	103	1465	2.00	47466	13.4	18256
7NW	32.5	57	115	1431	2.00	57809	16.9	22234
8W	37.5	57	133	1426	1.40	52987	15.8	20380
	Overall	55	126	1535	18.54	655383	17.9	25207
			From Data Sheets=>		19.30			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-2,9	3	55	114	1037	5.51	161726	77.8	71878
			From Data Sheets=>		5.72			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	336	91.1	SO2-A	ppm	436	102.7
SO2-AE	lb/MM Btu	0.68	0.2				
SO2-B	ppm	331	94.8	SO2-B	ppm	437	109.2
SO2-BE	lb/MM Btu	0.67	0.2				
CO	ppm	81	22.9	CO	ppm	106	31.6
CO2	%	13.21	1.2	CO2	%	17.23	1.1
N2O	ppm	127	15.8	N2O	ppm	167	26.4
N2OE	lb/MM Btu	0.18	0.0				
NOx	ppm	132	20.9	NOx	ppm	174	32.6
NOxE	lb/MM Btu	0.20	0.0				
O2-A	%	7.19	1.1				
O2-B	%	7.46	0.8				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	133.4	16.7	TC13131	AFPE-F2"	712	35.1
W(S)	LS Fd Rt	lbs/hr	9.6	0.9	TC13132	AFPE-F6"	896	25.2
V(FG)	FG SGV	ft/sec	13.6	0.7	TC13133	AFPE-B6"	500	40.1
V(S,C)	Comb SGV	ft/sec	12.7	0.7	TC13134	AFPE-F10"	648	65.4
V(S,EHX)	EHX SGV	ft/sec	2.0	0.2	TC13231	AFPW-F2"	736	32.5
FT18003	CHX Flow	gpm	18.5	0.2	TC13232	AFPW-F6"	895	22.8
FT19003	EHX Flow	gpm	5.5	0.1	TC13233	AFPW-B6"	515	32.5
PT15081	Comb dP	in. H2O	43.8	1.6	TC13234	AFPW-F10"	817	31.0
Q(CA)	CA Heat in	KBtu/hr	69.8	5.0	DOORS	CHXs On	10	0
Q(CHX)	CHX HtRmv	KBtu/hr	549.8	43.2	COILS	EHXs On	3	0
Q(EHX)	EHX HtRmv	KBtu/hr	162.5	11.5	BH A/C		1.6	0.0
Q(EHX,IN	FG Enrg in	KBtu/hr	3.1	0.4	A/SRATIO		1.0	0.4
Q(F)	Fuel Enrg in	KBtu/hr	1765.5	237.6	Feed Air	scfm	17.7	
Q(FG)	FG Enrg out	KBtu/hr	205.9	8.2	DC Air	scfm	0.0	
Q(IN)	Tot Enrg in	KBtu/hr	1850.3	221.3	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1394.6	64.7				
W(SR)	Recirc Rt	lbs/hr	1481	180.0				

11,12-Oct-91

CFB-BV1-0791 — TEST 9

(1815-0015)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1510	11.5
TC11021	AFS Ex	°F	1249	11.1
TC15001	C Plenum	°F	411	3.9
TC15004	C 1-1'	°F	1561	11.9
TC15005	C 1-2'	°F	1550	12.5
TC15006	C 1-3'	°F	1557	12.2
TC15007	C 1-4'	°F	1548	11.7
TC15008	C 1-4'	°F	N/A	N/A
TC15009	C 1-4'	°F	1544	11.0
TC15012	C 2-6'	°F	1579	12.6
TC15013	C 2-8'	°F	1595	13.9
TC15022	C 3-11'	°F	1555	11.8
TC15023	C 3-14'	°F	1543	11.2
TC15024	C 3-14'	°F	1546	11.1
TC15025	C 3-14'	°F	1559	11.9
TC15032	C 4-17.5'	°F	1513	11.4
TC15042	C 5-22.5'	°F	1526	11.0
TC15052	C 6-27.5'	°F	1516	12.1
TC15053	C 6-27.5'	°F	1521	12.1
TC15054	C 6-27.5'	°F	1451	12.0
TC15062	C 7-32.5'	°F	1484	12.2
TC15071	C 8-37.5'	°F	1485	13.7
TC15073	C 9-41'	°F	1532	13.2
TC15999	Ambient	°F	78	1.5
TC16001	EHX Plenm	°F	128	5.2
TC16012	EHX 0.5'	°F	1093	30.6
TC16013	EHX 1.5'	°F	1093	30.0
TC16014	EHX 2.7'	°F	1088	31.2
TC16015	EHX 3.8'	°F	1073	24.8
TC16017	EHX 5.3'	°F	1000	16.9
TC16018	EHX Exit	°F	1052	23.3
TC16021	Crc A in	°F	1516	12.9
TC16031	DC 8-36'	°F	1538	8.1
TC16032	DC 6-28'	°F	1488	9.7
TC16033	DC 4-18'	°F	1489	10.9
TC16034	DC3-9.5'	°F	1517	9.9
TC16035	DC3-8.5'	°F	1506	10.2
T(A,C)	Comb Temp	°F	1539	10.3
T(A,EHX)	EHX Temp	°F	1091	30.7
EA	Excess Air	%	27.0	3.2
SR	S Reten	%	86.8	2.3
R(PCA)	%Flw PCA	%	80.8	7.3
R(SCA)	%Flw SCA	%	19.2	7.3
R(Q,IN)	% Enrg in	%	84.8	14.6
R(CHX)	CHX Ratio	%	70.3	1.6
R(EHX)	EHX Ratio	%	29.7	1.6
F(PCA)	PCA Flw	SCFM	230.3	24.5
F(EHX)	EHX Flw	SCFM	70.1	7.5
F(TPA)	TPCA Flw	SCFM	302.2	27.4
F(SCA)	SCA Flw	SCFM	41.2	29.2
F(TCA,F)	TCA Flw	SCFM	375.0	29.0
F(FG,BH)	BH Flw	SCFM	374.9	8.8
F(TFG)	TFG Flw	SCFM	374.9	8.8

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 10

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	55	135	1595	3.70	147021	19.4	28273
3NE,SW	14	56	135	1549	3.80	150787	20.5	28997
4SE,NW	17.5	56	134	1513	4.10	161278	22.5	31015
5E	22.5	57	129	1526	2.00	72167	19.9	27756
6NE	27.5	56	108	1496	2.00	52055	14.4	20021
7NW	32.5	58	124	1484	1.90	62654	17.7	24098
8W	37.5	57	142	1485	1.35	57564	16.5	22140
	Overall	55	131	1539	17.94	681281	18.6	26203
			From Data Sheets=>		18.85			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
5-7,8	4	55	114	1091	7.87	233484	79.7	77828
			From Data Sheets=>		7.90			

EMISSIONS DATA

As Measured: Tag	Units	Average	Std Dev	Corrected to 3% O2: Tag	Units	Average	Std Dev
SO2-A	ppm	267	48.2	SO2-A	ppm	290	50.7
SO2-AE	lb/MM Btu	0.46	0.1				
SO2-B	ppm	274	54.5	SO2-B	ppm	321	60.4
SO2-BE	lb/MM Btu	0.47	0.1				
CO	ppm	107	24.3	CO	ppm	117	27.5
CO2	%	15.49	0.4	CO2	%	16.89	0.4
N2O	ppm	142	6.7	N2O	ppm	154	9.7
N2OE	lb/MM Btu	0.17	0.0				
NOx	ppm	79	7.0	NOx	ppm	86	8.5
NOxE	lb/MM Btu	0.10	0.0				
O2-A	%	4.49	0.4				
O2-B	%	5.70	0.4				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	127.0	20.8	TC13131	AFPE-F2"	724	33.4
W(S)	LS Fd Rt	lbs/hr	18.1	3.5	TC13132	AFPE-F6"	920	24.7
V(FG)	FG SGV	ft/sec	11.7	0.9	TC13133	AFPE-B6"	444	25.9
V(S,C)	Comb SGV	ft/sec	11.0	0.8	TC13134	AFPE-F10"	624	55.5
V(S,EHX)	EHX SGV	ft/sec	2.2	0.2	TC13231	AFPW-F2"	913	34.9
FT18003	CHX Flow	gpm	17.9	0.0	TC13232	AFPW-F6"	1052	26.7
FT19003	EHX Flow	gpm	7.9	0.1	TC13233	AFPW-B6"	698	26.3
PT15081	Comb dP	in. H2O	44.4	2.1	TC13234	AFPW-F10"	971	32.6
Q(CA)	CA Heat in	KBtu/hr	55.0	6.4	DOORS	CHXs On	10	0
Q(CHX)	CHX HtRmv	KBtu/hr	553.5	32.7	COILS	EHXs On	4	0
Q(EHX)	EHX HtRmv	KBtu/hr	233.2	12.2	BH A/C		1.4	0.0
Q(EHX,IN	FG Enrg in	KBtu/hr	3.5	0.5	A/SRATIO		2.1	0.6
Q(F)	Fuel Enrg in	KBtu/hr	1694.8	275.7	Feed Air	scfm	16.7	
Q(FG)	FG Enrg out	KBtu/hr	183.4	4.7	DC Air	scfm	0.0	
Q(IN)	Tot Enrg in	KBtu/hr	1753.1	276.8	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1449.2	38.4				
W(SR)	Recirc Rt	lbs/hr	2026	194.3				

12-Oct-91

CFB-BV1-0791 — TEST 10

(0750-1215)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1533	11.4
TC11021	AFS Ex	°F	1253	10.2
TC15001	C Plenum	°F	368	3.8
TC15004	C 1-1'	°F	1578	21.2
TC15005	C 1-2'	°F	1565	20.4
TC15006	C 1-3'	°F	1538	17.8
TC15007	C 1-4'	°F	1563	20.0
TC15008	C 1-4'	°F	1574	20.1
TC15009	C 1-4'	°F	1559	19.4
TC15012	C 2-6'	°F	1594	18.9
TC15013	C 2-8'	°F	1606	17.1
TC15022	C 3-11'	°F	1560	15.1
TC15023	C 3-14'	°F	1547	13.3
TC15024	C 3-14'	°F	1557	11.1
TC15025	C 3-14'	°F	1557	12.6
TC15032	C 4-17.5'	°F	1519	10.3
TC15042	C 5-22.5'	°F	1567	7.6
TC15052	C 6-27.5'	°F	1560	26.1
TC15053	C 6-27.5'	°F	1562	24.7
TC15054	C 6-27.5'	°F	1537	42.0
TC15062	C 7-32.5'	°F	1574	15.2
TC15071	C 8-37.5'	°F	1568	15.9
TC15073	C 9-41'	°F	1582	11.4
TC15999	Ambient	°F	73	3.3
TC16001	EHX Plenm	°F	112	7.0
TC16012	EHX 0.5'	°F	846	62.5
TC16013	EHX 1.5'	°F	848	63.2
TC16014	EHX 2.7'	°F	844	63.3
TC16015	EHX 3.8'	°F	800	43.5
TC16017	EHX 5.3'	°F	719	25.6
TC16018	EHX Exit	°F	826	38.3
TC16021	Crc A in	°F	1579	13.1
TC16031	DC 8-36'	°F	1593	9.2
TC16032	DC 6-28'	°F	1509	9.0
TC16033	DC 4-18'	°F	1493	10.5
TC16034	DC3-9.5'	°F	1506	21.9
TC16035	DC3-8.5'	°F	1489	33.7
T(A,C)	Comb Temp	°F	1566	8.2
T(A,EHX)	EHX Temp	°F	846	63.1
EA	Excess Air	%	40.9	3.9
SR	S Reten	%	87.4	1.7
R(PCA)	%Flw PCA	%	88.9	3.4
R(SCA)	%Flw SCA	%	11.1	3.4
R(Q,IN)	% Enrg in	%	88.7	21.3
R(CHX)	CHX Ratio	%	76.9	4.1
R(EHX)	EHX Ratio	%	23.1	4.1
F(PCA)	PCA Flw	SCFM	249.4	23.4
F(EHX)	EHX Flw	SCFM	48.4	2.8
F(TPA)	TPCA Flw	SCFM	295.6	20.4
F(SCA)	SCA Flw	SCFM	5.1	16.0
F(TCA,F)	TCA Flw	SCFM	333.0	25.8
F(FG,BH)	BH Flw	SCFM	321.2	6.2
F(TFG)	TFG Flw	SCFM	321.2	6.2

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 5

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	57	136	1606	3.70	147432	19.3	28352
3NE,SW	14	57	128	1554	4.00	141503	19.1	27212
4SE	17.5	57	124	1519	1.90	63671	17.5	24489
5	22.5	100	206	1567	0.00	0	0.0	0
6NE	27.5	58	114	1553	0.90	25358	6.8	9753
7	32.5	121	215	1574	0.00	0	0.0	0
8	37.5	134	203	1568	0.00	0	0.0	0
	Overall	56	129	1566	10.05	364803	17.8	25643
			From Data Sheets=>		10.50			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
3-4,8	3	56	100	846	4.49	98249	58.5	43666
			From Data Sheets=>		4.72			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	232	34.5	SO2-A	ppm	280	39.0
SO2-AE	lb/MM Btu	0.44	0.1				
SO2-B	ppm	213	28.0	SO2-B	ppm	282	32.9
SO2-BE	lb/MM Btu	0.40	0.1				
CO	ppm	69	9.0	CO	ppm	84	10.6
CO2	%	14.14	0.6	CO2	%	17.09	0.7
N2O	ppm	98	6.6	N2O	ppm	119	10.3
N2OE	lb/MM Btu	0.13	0.0				
NOx	ppm	95	8.0	NOx	ppm	115	10.6
NOxE	lb/MM Btu	0.13	0.0				
O2-A	%	6.10	0.4				
O2-B	%	7.44	0.4				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	92.5	15.9	TC13131	AFPE-F2"	676	37.8
W(S)	LS Fd Rt	lbs/hr	18.7	0.6	TC13132	AFPE-F6"	848	24.3
V(FG)	FG SGV	ft/sec	10.6	0.8	TC13133	AFPE-B6"	389	25.9
V(S,C)	Comb SGV	ft/sec	10.0	0.8	TC13134	AFPE-F10"	511	55.5
V(S,EHX)	EHX SGV	ft/sec	1.3	0.0	TC13231	AFPW-F2"	866	37.2
FT18003	CHX Flow	gpm	10.0	0.9	TC13232	AFPW-F6"	978	25.7
FT19003	EHX Flow	gpm	4.5	0.0	TC13233	AFPW-B6"	664	31.4
PT15081	Comb dP	in. H2O	43.6	3.5	TC13234	AFPW-F10"	882	33.3
Q(CA)	CA Heat in	KBtu/hr	46.8	5.2	DOORS	CHXs On	5	0
Q(CHX)	CHX HtRmv	KBtu/hr	331.9	44.7	COILS	EHXs On	3	0
Q(EHX)	EHX HtRmv	KBtu/hr	98.0	11.4	BH A/C		1.2	0.0
Q(EHX,IN	FG Enrg in	KBtu/hr	1.9	0.3	A/SRATIO		3.0	0.8
Q(F)	Fuel Enrg in	KBtu/hr	1234.5	212.3	Feed Air	scfm	16.5	
Q(FG)	FG Enrg out	KBtu/hr	159.6	3.6	DC Air	scfm	0.0	
Q(IN)	Tot Enrg in	KBtu/hr	1283.2	212.2	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1087.9	38.0				
W(SR)	Recirc Rt	lbs/hr	730	132.7				

12-Oct-91

CFB-BV1-0791 — TEST 11

(1500-2100)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1273	45.7
TC11021	AFS Ex	°F	1060	38.5
TC15001	C Plenum	°F	320	14.1
TC15004	C 1-1'	°F	1453	20.9
TC15005	C 1-2'	°F	1444	20.6
TC15006	C 1-3'	°F	1421	18.9
TC15007	C 1-4'	°F	1442	19.3
TC15008	C 1-4'	°F	1448	19.9
TC15009	C 1-4'	°F	1438	20.8
TC15012	C 2-6'	°F	1467	19.8
TC15013	C 2-8'	°F	1479	19.3
TC15022	C 3-11'	°F	1441	17.5
TC15023	C 3-14'	°F	1425	16.5
TC15024	C 3-14'	°F	1414	17.8
TC15025	C 3-14'	°F	1440	16.5
TC15032	C 4-17.5'	°F	1387	14.8
TC15042	C 5-22.5'	°F	1385	19.0
TC15052	C 6-27.5'	°F	1350	22.2
TC15053	C 6-27.5'	°F	1363	20.5
TC15054	C 6-27.5'	°F	1284	22.8
TC15062	C 7-32.5'	°F	1272	24.6
TC15071	C 8-37.5'	°F	1222	31.8
TC15073	C 9-41'	°F	1271	40.3
TC15999	Ambient	°F	84	1.2
TC16001	EHX Plenm	°F	134	3.8
TC16012	EHX 0.5'	°F	526	53.9
TC16013	EHX 1.5'	°F	525	53.1
TC16014	EHX 2.7'	°F	520	54.0
TC16015	EHX 3.8'	°F	525	50.4
TC16017	EHX 5.3'	°F	504	44.4
TC16018	EHX Exit	°F	545	49.8
TC16021	Crc A in	°F	1274	37.7
TC16031	DC 8-36'	°F	1336	53.4
TC16032	DC 6-28'	°F	1283	51.6
TC16033	DC 4-18'	°F	1281	52.5
TC16034	DC3-9.5'	°F	1309	55.9
TC16035	DC3-8.5'	°F	1306	56.9
T(A,C)	Comb Temp	°F	1390	18.7
T(A,EHX)	EHX Temp	°F	524	53.8
EA	Excess Air	%	51.1	6.3
SR	S Reten	%	84.7	5.2
R(PCA)	%Flw PCA	%	87.6	4.3
R(SCA)	%Flw SCA	%	12.4	4.3
R(Q,IN)	% Enrg in	%	100.7	10.9
R(CHX)	CHX Ratio	%	75.6	2.4
R(EHX)	EHX Ratio	%	24.4	2.4
F(PCA)	PCA Flw	SCFM	217.5	24.6
F(EHX)	EHX Flw	SCFM	64.5	3.9
F(TPA)	TPCA Flw	SCFM	276.5	23.5
F(SCA)	SCA Flw	SCFM	6.3	17.2
F(TCA,F)	TCA Flw	SCFM	316.1	29.3
F(FG,BH)	BH Flw	SCFM	311.6	9.1
F(TFG)	TFG Flw	SCFM	311.6	9.1

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	56	128	1479	3.60	129024	18.4	24812
3NE,SW	14	57	124	1426	3.63	121187	17.9	23305
4SE,NW	17.5	57	126	1387	3.60	124916	19.1	24022
5E	22.5	57	126	1385	1.80	62276	19.0	23952
6NE	27.5	57	99	1332	1.80	37837	11.8	14553
7SE,NW	32.5	58	97	1272	3.54	69766	11.4	13417
8E,W	37.5	57	91	1222	3.64	61626	10.5	11851
	Overall	56	113	1390	20.52	590857	14.8	18938
		From Data Sheets=>			21.61			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
3-9	7	56	99	524	7.84	168219	75.4	32042
		From Data Sheets=>			8.27			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	251	84.3	SO2-A	ppm	326	107.4
SO2-AE	lb/MM Btu	0.53	0.2				
SO2-B	ppm	212	67.0	SO2-B	ppm	278	84.4
SO2-BE	lb/MM Btu	0.45	0.1				
CO	ppm	456	238.4	CO	ppm	601	328.1
CO2	%	12.64	0.7	CO2	%	16.44	0.8
N2O	ppm	180	9.7	N2O	ppm	234	17.1
N2OE	lb/MM Btu	0.26	0.0				
NOx	ppm	49	6.4	NOx	ppm	63	8.5
NOxE	lb/MM Btu	0.07	0.0				
O2-A	%	7.15	0.6				
O2-B	%	7.26	0.9				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	87.6	10.5	TC13131	AFPE-F2"	454	45.3
W(S)	LS Fd Rt	lbs/hr	18.9	3.2	TC13132	AFPE-F6"	661	37.6
V(FG)	FG SGV	ft/sec	9.1	0.9	TC13133	AFPE-B6"	243	33.6
V(S,C)	Comb SGV	ft/sec	8.7	0.8	TC13134	AFPE-F10"	289	52.3
V(S,EHX)	EHX SGV	ft/sec	1.3	0.0	TC13231	AFPW-F2"	638	49.1
FT18003	CHX Flow	gpm	20.5	0.1	TC13232	AFPW-F6"	789	38.5
FT19003	EHX Flow	gpm	7.8	0.0	TC13233	AFPW-B6"	489	40.0
PT15081	Comb dP	in. H2O	46.6	2.7	TC13234	AFPW-F10"	671	46.0
Q(CA)	CA Heat in	KBtu/hr	34.4	5.6	DOORS	CHXs On	12	0
Q(CHX)	CHX HtRmv	KBtu/hr	520.6	45.2	COILS	EHXs On	7	0
Q(EHX)	EHX HtRmv	KBtu/hr	167.5	17.4	BH A/C		1.2	0.0
Q(EHX,IN	FG Enrg in	KBtu/hr	3.2	0.4	A/SRATIO		3.0	0.7
Q(F)	Fuel Enrg in	KBtu/hr	1168.5	139.0	Feed Air	scfm	17.2	
Q(FG)	FG Enrg out	KBtu/hr	139.1	6.1	DC Air	scfm	0.0	
Q(IN)	Tot Enrg in	KBtu/hr	1206.1	141.3	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1199.9	62.8				
W(SR)	Recirc Rt	lbs/hr	1056	91.0				

13-Oct-91

CFB-BV1-0791 — TEST 12

(1320-1920)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1414	30.0
TC11021	AFS Ex	°F	1081	30.9
TC15001	C Plenum	°F	425	22.8
TC15004	C 1-1'	°F	1520	22.6
TC15005	C 1-2'	°F	1506	23.3
TC15006	C 1-3'	°F	1472	22.1
TC15007	C 1-4'	°F	1503	22.7
TC15008	C 1-4'	°F	1512	22.6
TC15009	C 1-4'	°F	1499	22.4
TC15012	C 2-6'	°F	1535	23.9
TC15013	C 2-8'	°F	1549	24.8
TC15022	C 3-11'	°F	1512	23.7
TC15023	C 3-14'	°F	1502	24.0
TC15024	C 3-14'	°F	1501	23.7
TC15025	C 3-14'	°F	1516	25.3
TC15032	C 4-17.5'	°F	1466	24.9
TC15042	C 5-22.5'	°F	1466	25.1
TC15052	C 6-27.5'	°F	1446	25.0
TC15053	C 6-27.5'	°F	1454	25.2
TC15054	C 6-27.5'	°F	1371	23.9
TC15062	C 7-32.5'	°F	1357	25.4
TC15071	C 8-37.5'	°F	1354	26.0
TC15073	C 9-41'	°F	1433	28.0
TC15999	Ambient	°F	72	6.0
TC16001	EHX Plenm	°F	113	8.0
TC16012	EHX 0.5'	°F	926	51.6
TC16013	EHX 1.5'	°F	915	46.8
TC16014	EHX 2.7'	°F	908	51.0
TC16015	EHX 3.8'	°F	873	34.7
TC16017	EHX 5.3'	°F	798	16.4
TC16018	EHX Exit	°F	949	45.9
TC16021	Crc A in	°F	1411	26.8
TC16031	DC 8-36'	°F	1449	24.1
TC16032	DC 6-28'	°F	1415	23.8
TC16033	DC 4-18'	°F	1408	23.8
TC16034	DC3-9.5'	°F	1443	22.4
TC16035	DC3-8.5'	°F	1430	25.3
T(A,C)	Comb Temp	°F	1473	24.0
T(A,EHX)	EHX Temp	°F	917	49.8
EA	Excess Air	%	33.5	7.0
SR	S Reten	%	90.9	11.0
R(PCA)	%Flw PCA	%	91.9	0.5
R(SCA)	%Flw SCA	%	8.1	0.5
R(Q,IN)	% Enrg in	%	80.8	6.8
R(CHX)	CHX Ratio	%	76.0	2.6
R(EHX)	EHX Ratio	%	24.0	2.6
F(PCA)	PCA Flw	SCFM	327.9	23.0
F(EHX)	EHX Flw	SCFM	49.7	2.5
F(TPA)	TPCA Flw	SCFM	378.4	23.6
F(SCA)	SCA Flw	SCFM	0.0	0.0
F(TCA,F)	TCA Flw	SCFM	411.7	23.6
F(FG,BH)	BH Flw	SCFM	423.6	11.8
F(TFG)	TFG Flw	SCFM	424.1	12.2

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	56	135	1549	3.90	153706	20.9	29559
3NE,SW	14	56	128	1507	3.90	140611	19.6	27041
4SE,NW	17.5	57	127	1466	4.00	140449	20.2	27009
5E	22.5	57	131	1466	1.97	72961	21.0	28062
6NE	27.5	56	102	1424	2.02	46000	13.4	17692
7SE,NW	32.5	57	100	1357	3.97	86149	13.2	16567
8E,W	37.5	57	97	1354	3.90	78333	12.0	15064
	Overall	57	117	1473	22.73	689387	16.3	22096
			From Data Sheets=>		23.66			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-4,8,9	6	56	108	917	8.07	210075	57.7	46683
			From Data Sheets=>		8.70			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	152	57.2	SO2-A	ppm	172	58.9
SO2-AE	lb/MM Btu	0.41	1.1				
SO2-B	ppm	113	45.8	SO2-B	ppm	133	48.3
SO2-BE	lb/MM Btu	0.27	0.6				
CO	ppm	157	36.5	CO	ppm	180	45.6
CO2	%	14.58	1.8	CO2	%	16.70	2.0
N2O	ppm	N/A	N/A	N2O	ppm	N/A	N/A
N2OE	lb/MM Btu	0.00	0.0				
NOx	ppm	100	15.8	NOx	ppm	115	19.2
NOxE	lb/MM Btu	0.27	1.1				
O2-A	%	5.26	0.8				
O2-B	%	5.90	0.9				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	133.4	12.3	TC13131	AFPE-F2"	612	72.2
W(S)	LS Fd Rt	lbs/hr	24.7	2.8	TC13132	AFPE-F6"	824	53.9
V(FG)	FG SGV	ft/sec	12.4	0.7	TC13133	AFPE-B6"	441	57.9
V(S,C)	Comb SGV	ft/sec	11.8	0.7	TC13134	AFPE-F10"	464	88.8
V(S,EHX)	EHX SGV	ft/sec	1.4	0.0	TC13231	AFPW-F2"	804	76.6
FT18003	CHX Flow	gpm	22.7	0.1	TC13232	AFPW-F6"	964	62.1
FT19003	EHX Flow	gpm	8.1	0.0	TC13233	AFPW-B6"	685	71.5
PT15081	Comb dP	in. H2O	41.7	2.9	TC13234	AFPW-F10"	868	77.0
Q(CA)	CA Heat in	KBtu/hr	69.1	5.8	DOORS	CHXs On	12	0
Q(CHX)	CHX HtRmv	KBtu/hr	650.8	50.7	COILS	EHXs On	6	0
Q(EHX)	EHX HtRmv	KBtu/hr	206.5	32.1	BH A/C		1.6	0.0
Q(EHX,IN	FG Enrg in	KBtu/hr	2.1	0.2	A/SRATIO		2.6	0.4
Q(F)	Fuel Enrg in	KBtu/hr	1780.9	165.1	Feed Air	scfm	15.8	
Q(FG)	FG Enrg out	KBtu/hr	201.9	7.0	DC Air	scfm	7.6	
Q(IN)	Tot Enrg in	KBtu/hr	1851.8	165.7	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1491.2	89.1				
W(SR)	Recirc Rt	lbs/hr	1783	292.8				

13-Oct-91

CFB-BV1-0791 — TEST 12A

(2000-2200)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1413	5.2
TC11021	AFS Ex	°F	1099	9.1
TC15001	C Plenum	°F	430	8.5
TC15004	C 1-1'	°F	1545	10.3
TC15005	C 1-2'	°F	1530	9.4
TC15006	C 1-3'	°F	1497	8.0
TC15007	C 1-4'	°F	1527	9.7
TC15008	C 1-4'	°F	1537	9.8
TC15009	C 1-4'	°F	1525	11.1
TC15012	C 2-6'	°F	1558	9.4
TC15013	C 2-8'	°F	1590	9.7
TC15022	C 3-11'	°F	1540	8.7
TC15023	C 3-14'	°F	1520	6.6
TC15024	C 3-14'	°F	1522	6.5
TC15025	C 3-14'	°F	1538	7.6
TC15032	C 4-17.5'	°F	1471	8.7
TC15042	C 5-22.5'	°F	1481	7.4
TC15052	C 6-27.5'	°F	1458	8.6
TC15053	C 6-27.5'	°F	1466	8.2
TC15054	C 6-27.5'	°F	1380	7.5
TC15062	C 7-32.5'	°F	1354	9.2
TC15071	C 8-37.5'	°F	1355	12.2
TC15073	C 9-41'	°F	1442	12.8
TC15999	Ambient	°F	82	1.5
TC16001	EHX Plenm	°F	128	3.6
TC16012	EHX 0.5'	°F	910	43.5
TC16013	EHX 1.5'	°F	898	41.3
TC16014	EHX 2.7'	°F	894	44.2
TC16015	EHX 3.8'	°F	853	24.6
TC16017	EHX 5.3'	°F	774	11.1
TC16018	EHX Exit	°F	857	22.1
TC16021	Crc A in	°F	1419	10.0
TC16031	DC 8-36'	°F	1459	7.5
TC16032	DC 6-28'	°F	1425	5.8
TC16033	DC 4-18'	°F	1420	6.4
TC16034	DC3-9.5'	°F	1463	1.8
TC16035	DC3-8.5'	°F	1434	9.1
T(A,C)	Comb Temp	°F	1491	6.7
T(A,EHX)	EHX Temp	°F	901	42.7
EA	Excess Air	%	42.9	3.0
SR	S Reten	%	87.8	1.5
R(PCA)	%Flw PCA	%	60.3	1.6
R(SCA)	%Flw SCA	%	39.7	1.6
R(Q,IN)	% Enrg in	%	86.9	7.8
R(CHX)	CHX Ratio	%	76.0	2.5
R(EHX)	EHX Ratio	%	24.0	2.5
F(PCA)	PCA Flw	SCFM	205.3	21.9
F(EHX)	EHX Flw	SCFM	50.2	2.1
F(TPA)	TPCA Flw	SCFM	260.5	16.6
F(SCA)	SCA Flw	SCFM	137.9	6.0
F(TCA,F)	TCA Flw	SCFM	431.6	18.6
F(FG,BH)	BH Flw	SCFM	447.1	16.3
F(TFG)	TFG Flw	SCFM	447.1	16.3

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	56	132	1590	3.90	149239	19.7	28700
3NE,SW	14	56	126	1527	3.90	135108	18.5	25982
4SE,NW	17.5	57	126	1471	4.00	139048	19.9	26740
5E	22.5	58	133	1481	2.00	75501	21.6	29039
6NE	27.5	56	103	1435	2.00	46760	13.5	17985
7SE,NW	32.5	58	99	1354	4.00	83495	12.8	16057
8E,W	37.5	57	96	1355	3.90	75651	11.6	14548
	Overall	56	116	1491	22.73	687681	16.0	22041
			From Data Sheets=>		23.70			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-4,8,9	6	55	106	901	8.05	202483	56.6	44996
			From Data Sheets=>		8.70			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	219	29.9	SO2-A	ppm	268	32.7
SO2-AE	lb/MM Btu	0.43	0.1				
SO2-B	ppm	172	24.0	SO2-B	ppm	218	27.5
SO2-BE	lb/MM Btu	0.34	0.0				
CO	ppm	139	8.1	CO	ppm	171	11.6
CO2	%	13.68	0.4	CO2	%	16.80	0.5
N2O	ppm	N/A	N/A	N2O	ppm	N/A	N/A
N2OE	lb/MM Btu	N/A	N/A				
NOx	ppm	115	7.2	NOx	ppm	141	8.5
NOxE	lb/MM Btu	0.16	0.0				
O2-A	%	6.34	0.3				
O2-B	%	6.79	0.3				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	121.9	9.8	TC13131	AFPE-F2"	640	19.7
W(S)	LS Fd Rt	lbs/hr	26.0	1.4	TC13132	AFPE-F6"	843	13.8
V(FG)	FG SGV	ft/sec	13.0	0.7	TC13133	AFPE-B6"	467	13.4
V(S,C)	Comb SGV	ft/sec	12.5	0.6	TC13134	AFPE-F10"	495	43.2
V(S,EHX)	EHX SGV	ft/sec	1.4	0.0	TC13231	AFPW-F2"	839	21.7
FT18003	CHX Flow	gpm	22.7	0.1	TC13232	AFPW-F6"	990	15.2
FT19003	EHX Flow	gpm	8.1	0.0	TC13233	AFPW-B6"	721	17.3
PT15081	Comb dP	in. H2O	44.9	2.9	TC13234	AFPW-F10"	902	20.3
Q(CA)	CA Heat in	KBtu/hr	72.0	4.9	DOORS	CHXs On	12	0
Q(CHX)	CHX HtRmv	KBtu/hr	631.5	38.7	COILS	EHXs On	6	0
Q(EHX)	EHX HtRmv	KBtu/hr	199.1	23.2	BH A/C		1.7	0.1
Q(EHX,IN	FG Enrg in	KBtu/hr	2.3	0.2	A/SRATIO		2.9	0.3
Q(F)	Fuel Enrg in	KBtu/hr	1628.0	131.2	Feed Air	scfm	17.6	
Q(FG)	FG Enrg out	KBtu/hr	212.1	8.3	DC Air	scfm	7.6	
Q(IN)	Tot Enrg in	KBtu/hr	1701.4	129.5	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1487.4	48.4				
W(SR)	Recirc Rt	lbs/hr	1425	184.1				

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CFB-BV1-0791 — TEST 13

(0325-0815)

Tag	Desc	Units	Average	Std Dev
TC11011	FCD Ex	°F	1531	9.0
TC11021	AFS Ex	°F	1216	9.9
TC15001	C Plenum	°F	524	3.3
TC15004	C 1-1'	°F	1554	14.3
TC15005	C 1-2'	°F	1541	13.9
TC15006	C 1-3'	°F	1510	12.0
TC15007	C 1-4'	°F	1537	13.7
TC15008	C 1-4'	°F	1547	13.9
TC15009	C 1-4'	°F	1533	13.8
TC15012	C 2-6'	°F	1568	14.4
TC150[illegible]	C 2-8'	°F	1593	15.8
TC15022	C 3-11'	°F	1561	13.9
TC15023	C 3-14'	°F	1557	14.4
TC15024	C 3-14'	°F	1557	14.0
TC15025	C 3-14'	°F	1570	13.8
TC15032	C 4-17.5'	°F	1537	15.0
TC15042	C 5-22.5'	°F	1548	12.2
TC15052	C 6-27.5'	°F	1544	12.6
TC15053	C 6-27.5'	°F	1546	13.1
TC15054	C 6-27.5'	°F	1473	12.3
TC15062	C 7-32.5'	°F	1476	12.6
TC15071	C 8-37.5'	°F	1490	12.6
TC15073	C 9-41'	°F	1550	11.7
TC15999	Ambient	°F	78	1.2
TC16001	EHX Plenm	°F	118	4.2
TC16012	EHX 0.5'	°F	1287	14.0
TC16013	EHX 1.5'	°F	1267	12.6
TC16014	EHX 2.7'	°F	1267	13.9
TC16015	EHX 3.8'	°F	1212	18.8
TC16017	EHX 5.3'	°F	1084	25.2
TC16018	EHX Exit	°F	1214	13.3
TC16021	Crc A in	°F	1530	10.9
TC16031	DC 8-36'	°F	1556	7.6
TC16032	DC 6-28'	°F	1526	6.9
TC16033	DC 4-18'	°F	1520	8.5
TC16034	DC3-9.5'	°F	1558	10.0
TC16035	DC3-8.5'	°F	1536	9.7
T(A,C)	Comb Temp	°F	1540	12.3
T(A,EHX)	EHX Temp	°F	1274	12.9
EA	Excess Air	%	36.8	5.9
SR	S Reten	%	91.9	4.0
R(PCA)	%Flw PCA	%	59.9	1.9
R(SCA)	%Flw SCA	%	40.1	1.9
R(Q,IN)	% Enrg in	%	85.3	10.6
R(CHX)	CHX Ratio	%	66.3	1.8
R(EHX)	EHX Ratio	%	33.7	1.8
F(PCA)	PCA Flw	SCFM	263.0	19.3
F(EHX)	EHX Flw	SCFM	43.6	5.6
F(TPA)	TPCA Flw	SCFM	307.6	20.1
F(SCA)	SCA Flw	SCFM	172.5	6.5
F(TCA,F)	TCA Flw	SCFM	513.3	19.7
F(FG,BH)	BH Flw	SCFM	512.4	11.6
F(TFG)	TFG Flw	SCFM	514.3	16.5

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft^{2}hr°F	Heat Flux Btu/ft^{2}hr
2E,W	8	56	137	1593	4.00	160605	21.2	30886
3NE,SW	14	56	134	1562	4.00	154400	20.8	29692
4SE,NW	17.5	56	137	1537	4.00	161311	22.2	31021
5E	22.5	57	144	1548	2.00	86974	23.8	33452
6NE	27.5	56	114	1521	2.00	57219	15.6	22007
7SE,NW	32.5	57	112	1476	4.00	109627	15.5	21082
8E,W	37.5	57	107	1490	3.90	98140	13.7	18873
	Overall	56	126	1540	22.92	801555	18.2	25691
			From Data Sheets=>		23.90			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft^{2}hr°F	Heat Flux Btu/ft^{2}hr
1-4,8,9	6	56	148	1274	8.04	371861	73.4	82636
			From Data Sheets=>		8.65			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	154	74.6	SO2-A	ppm	181	87.8
SO2-AE	lb/MM Btu	0.29	0.1				
SO2-B	ppm	123	55.9	SO2-B	ppm	140	63.7
SO2-BE	lb/MM Btu	0.23	0.1				
CO	ppm	51	25.1	CO	ppm	61	31.0
CO2	%	14.70	1.0	CO2	%	17.21	0.8
N2O	ppm	N/A	N/A	N2O	ppm	N/A	N/A
N2OE	lb/MM Btu	0.00	ERR				
NOx	ppm	126	10.9	NOx	ppm	148	12.4
NOxE	lb/MM Btu	0.17	0.0				
O2-A	%	5.63	0.7				
O2-B	%	5.21	0.8				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	156.3	19.1	TC13131	AFPE-F2"	765	37.1
W(S)	LS Fd Rt	lbs/hr	40.2	16.0	TC13132	AFPE-F6"	951	26.4
V(FG)	FG SGV	ft/sec	16.1	0.6	TC13133	AFPE-B6"	555	29.7
V(S,C)	Comb SGV	ft/sec	15.1	0.5	TC13134	AFPE-F10"	625	56.5
V(S,EHX)	EHX SGV	ft/sec	1.6	0.2	TC13231	AFPW-F2"	1010	40.8
FT18003	CHX Flow	gpm	22.9	0.1	TC13232	AFPW-F6"	1150	33.2
FT19003	EHX Flow	gpm	8.0	0.1	TC13233	AFPW-B6"	930	38.8
PT15081	Comb dP	in. H2O	45.9	2.2	TC13234	AFPW-F10'	1079	42.2
Q(CA)	CA Heat in	KBtu/hr	103.7	4.4	DOORS	CHXs On	12	0
Q(CHX)	CHX HtRmv	KBtu/hr	730.7	42.4	COILS	EHXs On	6	0
Q(EHX)	EHX HtRmv	KBtu/hr	370.9	23.8	BH A/C		2.0	0.0
Q(EHX,IN	FG Enrg in	KBtu/hr	1.7	0.3	A/SRATIO		3.7	1.4
Q(F)	Fuel Enrg in	KBtu/hr	2084.0	252.7	Feed Air	scfm	17.5	
Q(FG)	FG Enrg out	KBtu/hr	252.7	7.8	DC Air	scfm	7.2	
Q(IN)	Tot Enrg in	KBtu/hr	2187.1	250.1	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1835.0	58.8				
W(SR)	Recirc Rt	lbs/hr	4811	282.2				

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CFB-BV1-0791 — TEST 14

(1100-1700)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1498	9.2
TC11021	AFS Ex	°F	1190	10.0
TC15001	C Plenum	°F	506	6.5
TC15004	C 1-1'	°F	1666	15.2
TC15005	C 1-2'	°F	1651	14.8
TC15006	C 1-3'	°F	1610	12.8
TC15007	C 1-4'	°F	1643	14.0
TC15008	C 1-4'	°F	1656	13.8
TC15009	C 1-4'	°F	1643	14.7
TC15012	C 2-6'	°F	1677	14.5
TC15013	C 2-8'	°F	1690	14.5
TC15022	C 3-11'	°F	1642	12.9
TC15023	C 3-14'	°F	1623	12.1
TC15024	C 3-14'	°F	1617	11.3
TC15025	C 3-14'	°F	1635	12.0
TC15032	C 4-17.5'	°F	1549	10.4
TC15042	C 5-22.5'	°F	1564	9.3
TC15052	C 6-27.5'	°F	1545	10.6
TC15053	C 6-27.5'	°F	1554	10.6
TC15054	C 6-27.5'	°F	1480	9.3
TC15062	C 7-32.5'	°F	1438	8.8
TC15071	C 8-37.5'	°F	1429	9.9
TC15073	C 9-41'	°F	1534	10.3
TC15999	Ambient	°F	73	5.6
TC16001	EHX Plenm	°F	122	6.8
TC16012	EHX 0.5'	°F	997	18.8
TC16013	EHX 1.5'	°F	978	18.2
TC16014	EHX 2.7'	°F	971	18.5
TC16015	EHX 3.8'	°F	962	19.0
TC16017	EHX 5.3'	°F	895	21.8
TC16018	EHX Exit	°F	992	19.2
TC16021	Crc A in	°F	1518	9.0
TC16031	DC 8-36'	°F	1552	6.6
TC16032	DC 6-28'	°F	1517	6.9
TC16033	DC 4-18'	°F	1508	9.1
TC16034	DC3-9.5'	°F	1541	19.6
TC16035	DC3-8.5'	°F	1522	21.7
T(A,C)	Comb Temp	°F	1590	10.3
T(A,EHX)	EHX Temp	°F	982	18.2
EA	Excess Air	%	42.1	4.3
SR	S Reten	%	59.0	11.1
R(PCA)	%Flw PCA	%	60.1	1.6
R(SCA)	%Flw SCA	%	39.9	1.6
R(Q,IN)	% Enrg in	%	85.6	17.1
R(CHX)	CHX Ratio	%	71.2	1.3
R(EHX)	EHX Ratio	%	28.8	1.3
F(PCA)	PCA Flw	SCFM	242.9	18.2
F(EHX)	EHX Flw	SCFM	58.1	3.6
F(TPA)	TPCA Flw	SCFM	300.2	18.4
F(SCA)	SCA Flw	SCFM	165.4	2.1
F(TCA,F)	TCA Flw	SCFM	498.9	18.1
F(FG,BH)	BH Flw	SCFM	521.5	8.1
F(TFG)	TFG Flw	SCFM	521.5	8.1

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	55	148	1690	4.00	185482	23.1	35670
3NE,SW	14	56	143	1625	4.00	173908	22.6	33444
4SE,NW	17.5	56	135	1549	4.01	159697	21.7	30711
5E	22.5	56	145	1564	2.00	88260	23.9	33946
6NE	27.5	55	111	1526	2.00	55255	15.0	21252
7SE,NW	32.5	56	105	1438	4.00	98209	14.2	18886
8E,W	37.5	56	100	1429	3.90	85611	12.4	16464
	Overall	55	127	1590	22.80	811466	17.8	26009
			From Data Sheets=>		23.91			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-4,8,9	6	54	114	982	10.47	314341	80.5	69854
			From Data Sheets=>		11.00			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	753	208.6	SO2-A	ppm	914	241.2
SO2-AE	lb/MM Btu	1.43	0.4				
SO2-B	ppm	758	208.0	SO2-B	ppm	964	256.3
SO2-BE	lb/MM Btu	1.44	0.4				
CO	ppm	62	17.9	CO	ppm	72	25.1
CO2	%	13.97	0.5	CO2	%	16.29	3.4
N2O	ppm	74	3.6	N2O	ppm	90	5.3
N2OE	lb/MM Btu	0.10	0.0				
NOx	ppm	119	9.5	NOx	ppm	144	14.8
NOxE	lb/MM Btu	0.16	0.0				
O2-A	%	6.22	0.4				
O2-B	%	6.89	0.4				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	158.8	24.4
W(S)	LS Fd Rt	lbs/hr	43.9	3.8
V(FG)	FG SGV	ft/sec	16.0	0.6
V(S,C)	Comb SGV	ft/sec	15.1	0.5
V(S,EHX)	EHX SGV	ft/sec	1.7	0.1
FT18003	CHX Flow	gpm	22.8	0.1
FT19003	EHX Flow	gpm	10.5	0.0
PT15081	Comb dP	in. H2O	45.9	2.2
Q(CA)	CA Heat in	KBtu/hr	96.0	4.4
Q(CHX)	CHX HtRmv	KBtu/hr	773.5	42.9
Q(EHX)	EHX HtRmv	KBtu/hr	312.7	13.6
Q(EHX,IN	FG Enrg in	KBtu/hr	2.8	0.3
Q(F)	Fuel Enrg in	KBtu/hr	2119.4	325.5
Q(FG)	FG Enrg out	KBtu/hr	255.9	4.4
Q(IN)	Tot Enrg in	KBtu/hr	2217.9	326.9
Q(OUT)	Tot Enrg out	KBtu/hr	1860.8	50.6
W(SR)	Recirc Rt	lbs/hr	2240	140.5

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	950	27.5
TC13132	AFPE-F6"	1067	19.5
TC13133	AFPE-B6"	730	25.0
TC13134	AFPE-F10"	903	40.9
TC13231	AFPW-F2"	953	44.2
TC13232	AFPW-F6"	1068	39.7
TC13233	AFPW-B6"	749	61.5
TC13234	AFPW-F10"	1011	44.1
DOORS	CHXs On	12	0
COILS	EHXs On	6	0
BH A/C		2.0	0.0
A/SRATIO		3.9	0.9
Feed Air	scfm	17.5	
DC Air	scfm	7.7	
Purge Air	scfm	15.5	

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CFB-BV1-0791 — TEST 15

(0120-0720)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1562	10.8
TC11021	AFS Ex	°F	1233	8.1
TC15001	C Plenum	°F	527	2.9
TC15004	C 1-1'	°F	1558	14.2
TC15005	C 1-2'	°F	1547	13.0
TC15006	C 1-3'	°F	1513	11.0
TC15007	C 1-4'	°F	1546	12.7
TC15008	C 1-4'	°F	1555	13.6
TC15009	C 1-4'	°F	1541	13.4
TC15012	C 2-6'	°F	1582	13.9
TC15013	C 2-8'	°F	1640	16.0
TC15022	C 3-11'	°F	1594	12.6
TC15023	C 3-14'	°F	1584	11.7
TC15024	C 3-14'	°F	1583	12.3
TC15025	C 3-14'	°F	1602	13.0
TC15032	C 4-17.5'	°F	1550	11.7
TC15042	C 5-22.5'	°F	1570	10.4
TC15052	C 6-27.5'	°F	1562	10.0
TC15053	C 6-27.5'	°F	1566	10.9
TC15054	C 6-27.5'	°F	1494	9.4
TC15062	C 7-32.5'	°F	1487	9.0
TC15071	C 8-37.5'	°F	1495	9.3
TC15073	C 9-41'	°F	1564	10.0
TC15999	Ambient	°F	79	1.6
TC16001	EHX Plenm	°F	123	3.6
TC16012	EHX 0.5'	°F	1127	9.6
TC16013	EHX 1.5'	°F	1101	9.6
TC16014	EHX 2.7'	°F	1106	9.6
TC16015	EHX 3.8'	°F	1093	8.0
TC16017	EHX 5.3'	°F	1006	6.3
TC16018	EHX Exit	°F	1063	7.4
TC16021	Crc A in	°F	1553	10.3
TC16031	DC 8-36'	°F	1577	7.2
TC16032	DC 6-28'	°F	1549	7.2
TC16033	DC 4-18'	°F	1539	9.1
TC16034	DC3-9.5'	°F	1585	11.0
TC16035	DC3-8.5'	°F	1560	11.0
T(A,C)	Comb Temp	°F	1557	11.2
T(A,EHX)	EHX Temp	°F	1111	9.0
EA	Excess Air	%	28.9	4.3
SR	S Reten	%	70.2	3.6
R(PCA)	%Flw PCA	%	60.0	1.7
R(SCA)	%Flw SCA	%	40.0	1.7
R(Q,IN)	% Enrg in	%	78.8	8.4
R(CHX)	CHX Ratio	%	58.8	2.0
R(EHX)	EHX Ratio	%	41.2	2.0
F(PCA)	PCA Flw	SCFM	252.0	19.5
F(EHX)	EHX Flw	SCFM	52.8	1.4
F(TPA)	TPCA Flw	SCFM	305.4	20.1
F(SCA)	SCA Flw	SCFM	169.7	2.7
F(TCA,F)	TCA Flw	SCFM	508.3	19.9
F(FG,BH)	BH Flw	SCFM	512.9	3.9
F(TFG)	TFG Flw	SCFM	512.9	3.9

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	56	125	1640	4.00	138714	17.6	26676
3NE,SW	14	56	131	1590	4.00	150532	19.9	28948
4SE,NW	17.5	56	138	1550	4.00	164368	22.4	31609
5E	22.5	56	143	1570	2.00	87250	23.5	33558
6NE	27.5	56	114	1541	2.00	58690	15.8	22573
7SE,NW	32.5	57	112	1487	4.00	111021	15.5	21350
8E,W	37.5	57	108	1495	3.90	100572	13.9	19341
	Overall	56	124	1557	22.84	779236	17.4	24976
			From Data Sheets=>		23.90			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-9	9	55	113	1111	16.56	474921	70.4	70359
			From Data Sheets=>		17.27			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	572	80.3	SO2-A	ppm	632	73.6
SO2-AE	lb/MM Btu	1.04	0.1				
SO2-B	ppm	621	93.5	SO2-B	ppm	726	87.7
SO2-BE	lb/MM Btu	1.13	0.1				
CO	ppm	57	18.8	CO	ppm	63	20.2
CO2	%	14.73	0.4	CO2	%	16.33	0.4
N2O	ppm	131	9.0	N2O	ppm	145	14.0
N2OE	lb/MM Btu	0.16	0.0				
NOx	ppm	122	9.4	NOx	ppm	135	11.4
NOxE	lb/MM Btu	0.16	0.0				
O2-A	%	4.75	0.5				
O2-B	%	5.67	0.5				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	175.9	16.6	TC13131	AFPE-F2"	879	30.9
W(S)	LS Fd Rt	lbs/hr	23.0	5.3	TC13132	AFPE-F6"	1029	22.0
V(FG)	FG SGV	ft/sec	16.0	0.6	TC13133	AFPE-B6"	656	28.4
V(S,C)	Comb SGV	ft/sec	15.1	0.6	TC13134	AFPE-F10"	719	58.1
V(S,EHX)	EHX SGV	ft/sec	1.7	0.0	TC13231	AFPW-F2"	882	26.5
FT18003	CHX Flow	gpm	22.8	0.2	TC13232	AFPW-F6"	1030	20.3
FT19003	EHX Flow	gpm	16.6	0.1	TC13233	AFPW-B6"	687	20.5
PT15081	Comb dP	in. H2O	39.3	1.9	TC13234	AFPW-F10"	939	26.4
Q(CA)	CA Heat in	KBtu/hr	100.4	4.8	DOORS	CHXs On	12	0
Q(CHX)	CHX HtRmv	KBtu/hr	680.3	48.8	COILS	EHXs On	9	0
Q(EHX)	EHX HtRmv	KBtu/hr	475.1	19.6	BH A/C		2.0	0.0
Q(EHX,IN	FG Enrg in	KBtu/hr	2.3	0.2	A/SRATIO		1.8	0.3
Q(F)	Fuel Enrg in	KBtu/hr	2348.1	221.1	Feed Air	scfm	17.4	
Q(FG)	FG Enrg out	KBtu/hr	253.1	1.7	DC Air	scfm	7.4	
Q(IN)	Tot Enrg in	KBtu/hr	2450.9	221.7	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1901.3	55.8				
W(SR)	Recirc Rt	lbs/hr	3602	296.6				

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CFB-BV1-0791 — TEST 16

(1750-2045)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1586	9.3
TC11021	AFS Ex	°F	1251	8.0
TC15001	C Plenum	°F	546	6.0
TC15004	C 1-1'	°F	1582	23.1
TC15005	C 1-2'	°F	1567	22.3
TC15006	C 1-3'	°F	1521	19.0
TC15007	C 1-4'	°F	1562	21.7
TC15008	C 1-4'	°F	1576	20.7
TC15009	C 1-4'	°F	1560	21.3
TC15012	C 2-6'	°F	1600	21.6
TC15013	C 2-8'	°F	1653	22.2
TC15022	C 3-11'	°F	1612	16.1
TC15023	C 3-14'	°F	1599	13.1
TC15024	C 3-14'	°F	1598	12.3
TC15025	C 3-14'	°F	1619	15.1
TC15032	C 4-17.5'	°F	1566	10.3
TC15042	C 5-22.5'	°F	1582	8.6
TC15052	C 6-27.5'	°F	1575	7.6
TC15053	C 6-27.5'	°F	1582	9.0
TC15054	C 6-27.5'	°F	1504	7.6
TC15062	C 7-32.5'	°F	1500	6.3
TC15071	C 8-37.5'	°F	1506	5.5
TC15073	C 9-41'	°F	1577	8.3
TC15999	Ambient	°F	82	1.9
TC16001	EHX Plenm	°F	132	4.1
TC16012	EHX 0.5'	°F	1156	20.2
TC16013	EHX 1.5'	°F	1126	20.6
TC16014	EHX 2.7'	°F	1131	23.6
TC16015	EHX 3.8'	°F	1130	15.7
TC16017	EHX 5.3'	°F	1051	8.2
TC16018	EHX Exit	°F	1090	17.6
TC16021	Crc A in	°F	1565	6.4
TC16031	DC 8-36'	°F	1587	6.3
TC16032	DC 6-28'	°F	1556	6.6
TC16033	DC 4-18'	°F	1550	6.1
TC16034	DC3-9.5'	°F	1601	7.7
TC16035	DC3-8.5'	°F	1565	11.3
T(A,C)	Comb Temp	°F	1572	12.9
T(A,EHX)	EHX Temp	°F	1137	20.8
EA	Excess Air	%	21.7	4.5
SR	S Reten	%	73.5	13.0
R(PCA)	%Flw PCA	%	59.7	5.9
R(SCA)	%Flw SCA	%	40.3	5.9
R(Q,IN)	% Enrg in	%	72.9	7.5
R(CHX)	CHX Ratio	%	58.4	1.7
R(EHX)	EHX Ratio	%	41.6	1.7
F(PCA)	PCA Flw	SCFM	238.2	38.4
F(EHX)	EHX Flw	SCFM	60.5	13.3
F(TPA)	TPCA Flw	SCFM	301.4	33.2
F(SCA)	SCA Flw	SCFM	168.1	30.8
F(TCA,F)	TCA Flw	SCFM	504.6	22.5
F(FG,BH)	BH Flw	SCFM	513.5	86.9
F(TFG)	TFG Flw	SCFM	513.5	86.9

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	55	124	1653	4.00	138550	17.4	26644
3NE,SW	14	55	132	1605	4.00	155216	20.3	29849
4SE,NW	17.5	55	142	1566	4.00	173740	23.5	33412
5E	22.5	57	147	1582	2.00	90384	24.2	34763
6NE	27.5	56	115	1554	2.00	59867	16.0	23026
7SE,NW	32.5	56	112	1500	4.07	113768	15.8	21878
8E,W	37.5	56	109	1506	3.80	100586	13.8	19343
	Overall	54	125	1572	22.86	808926	17.9	25927
			From Data Sheets=>		23.87			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-9	9	54	114	1137	16.33	493452	71.4	73104
			From Data Sheets=>		17.10			

EMISSIONS DATA

As Measured: Tag	Units	Average	Std Dev	Corrected to 3% O2: Tag	Units	Average	Std Dev
SO2-A	ppm	555	277.9	SO2-A	ppm	574	277.1
SO2-AE	lb/MM Btu	0.93	0.5				
SO2-B	ppm	524	219.2	SO2-B	ppm	580	224.3
SO2-BE	lb/MM Btu	0.87	0.3				
CO	ppm	40	17.5	CO	ppm	42	18.3
CO2	%	15.97	0.7	CO2	%	16.68	0.3
N2O	ppm	103	7.0	N2O	ppm	108	9.7
N2OE	lb/MM Btu	0.12	0.0				
NOx	ppm	124	15.7	NOx	ppm	130	19.7
NOxE	lb/MM Btu	0.15	0.0				
O2-A	%	3.77	0.6				
O2-B	%	4.92	0.7				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	193.4	19.5	TC13131	AFPE-F2"	1076	29.2
W(S)	LS Fd Rt	lbs/hr	36.3	10.2	TC13132	AFPE-F6"	1201	20.7
V(FG)	FG SGV	ft/sec	15.9	0.7	TC13133	AFPE-B6"	936	25.9
V(S,C)	Comb SGV	ft/sec	14.9	0.6	TC13134	AFPE-F10"	919	51.9
V(S,EHX)	EHX SGV	ft/sec	2.0	0.4	TC13231	AFPW-F2"	1058	31.5
FT18003	CHX Flow	gpm	22.9	0.2	TC13232	AFPW-F6"	1189	23.8
FT19003	EHX Flow	gpm	16.3	0.0	TC13233	AFPW-B6"	925	24.1
PT15081	Comb dP	in. H2O	36.9	2.9	TC13234	AFPW-F10'	1115	26.0
Q(CA)	CA Heat in	KBtu/hr	98.5	6.4	DOORS	CHXs On	12	0
Q(CHX)	CHX HtRmv	KBtu/hr	687.3	37.5	COILS	EHXs On	9	0
Q(EHX)	EHX HtRmv	KBtu/hr	488.3	23.2	BH A/C		2.0	0.4
Q(EHX,IN	FG Enrg in	KBtu/hr	3.0	0.8	A/SRATIO		2.7	0.8
Q(F)	Fuel Enrg in	KBtu/hr	2579.9	259.6	Feed Air	scfm	18.5	
Q(FG)	FG Enrg out	KBtu/hr	254.3	40.9	DC Air	scfm	8.7	
Q(IN)	Tot Enrg in	KBtu/hr	2681.3	258.7	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1932.7	62.9				
W(SR)	Recirc Rt	lbs/hr	4204	416.9				

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(0525-1125)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1545	12.6
TC11021	AFS Ex	°F	1265	9.4
TC15001	C Plenum	°F	543	5.5
TC15004	C 1-1'	°F	1569	25.8
TC15005	C 1-2'	°F	1557	24.6
TC15006	C 1-3'	°F	1517	20.0
TC15007	C 1-4'	°F	1552	23.9
TC15008	C 1-4'	°F	1564	24.7
TC15009	C 1-4'	°F	1549	24.4
TC15012	C 2-6'	°F	1585	26.8
TC15013	C 2-8'	°F	1624	27.8
TC15022	C 3-11'	°F	1587	23.7
TC15023	C 3-14'	°F	1579	22.1
TC15024	C 3-14'	°F	1579	23.2
TC15025	C 3-14'	°F	1595	23.9
TC15032	C 4-17.5'	°F	1545	19.6
TC15042	C 5-22.5'	°F	1559	19.0
TC15052	C 6-27.5'	°F	1549	19.0
TC15053	C 6-27.5'	°F	1555	19.2
TC15054	C 6-27.5'	°F	1483	16.6
TC15062	C 7-32.5'	°F	1476	16.0
TC15071	C 8-37.5'	°F	1478	16.4
TC15073	C 9-41'	°F	1553	17.4
TC15999	Ambient	°F	77	1.7
TC16001	EHX Plenm	°F	122	3.7
TC16012	EHX 0.5'	°F	1128	18.7
TC16013	EHX 1.5'	°F	1099	18.2
TC16014	EHX 2.7'	°F	1103	18.4
TC16015	EHX 3.8'	°F	1080	12.7
TC16017	EHX 5.3'	°F	985	6.9
TC16018	EHX Exit	°F	1074	19.0
TC16021	Crc A in	°F	1539	16.3
TC16031	DC 8-36'	°F	1563	10.7
TC16032	DC 6-28'	°F	1535	10.3
TC16033	DC 4-18'	°F	1524	11.8
TC16034	DC3-9.5'	°F	1570	12.9
TC16035	DC3-8.5'	°F	1547	14.0
T(A,C)	Comb Temp	°F	1552	21.3
T(A,EHX)	EHX Temp	°F	1110	18.1
EA	Excess Air	%	30.3	6.7
SR	S Reten	%	84.8	4.7
R(PCA)	%Flw PCA	%	60.3	6.0
R(SCA)	%Flw SCA	%	39.7	6.0
R(Q,IN)	% Enrg in	%	80.6	11.9
R(CHX)	CHX Ratio	%	59.2	1.8
R(EHX)	EHX Ratio	%	40.8	1.8
F(PCA)	PCA Flw	SCFM	255.4	33.4
F(EHX)	EHX Flw	SCFM	50.6	1.5
F(TPA)	TPCA Flw	SCFM	307.8	33.3
F(SCA)	SCA Flw	SCFM	166.3	31.2
F(TCA,F)	TCA Flw	SCFM	510.0	19.4
F(FG,BH)	BH Flw	SCFM	524.8	10.4
F(TFG)	TFG Flw	SCFM	524.8	10.4

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service==> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	55	128	1624	4.00	146208	18.8	28117
3NE,SW	14	55	131	1584	4.00	151902	20.1	29212
4SE,NW	17.5	55	139	1545	3.98	167991	23.0	32306
5E	22.5	57	142	1559	2.00	84957	23.1	32676
6NE	27.5	55	113	1529	2.00	58032	15.8	22320
7SE,NW	32.5	57	109	1476	4.02	106475	15.0	20476
8E,W	37.5	56	107	1478	3.85	98039	13.7	18854
	Overall	54	124	1552	23.04	799562	17.9	25627
			From Data Sheets=>		23.85			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-9	9	54	113	1110	16.30	475371	70.6	70425
			From Data Sheets=>		17.18			

EMISSIONS DATA

As Measured: Tag	Units	Average	Std Dev	Corrected to 3% O2: Tag	Units	Average	Std Dev
SO2-A	ppm	296	95.3	SO2-A	ppm	329	100.6
SO2-AE	lb/MM Btu	0.53	0.2				
SO2-B	ppm	355	38.1	SO2-B	ppm	384	39.7
SO2-BE	lb/MM Btu	0.63	0.1				
CO	ppm	11	3.4	CO	ppm	12	4.2
CO2	%	14.83	1.1	CO2	%	16.57	1.1
N2O	ppm	118	6.0	N2O	ppm	132	10.0
N2OE	lb/MM Btu	0.15	0.0				
NOx	ppm	136	44.3	NOx	ppm	153	53.1
NOxE	lb/MM Btu	0.18	0.1				
O2-A	%	4.88	0.8				
O2-B	%	4.38	0.5				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	173.0	19.1
W(S)	LS Fd Rt	lbs/hr	40.4	N/A
V(FG)	FG SGV	ft/sec	16.1	0.6
V(S,C)	Comb SGV	ft/sec	15.0	0.5
V(S,EHX)	EHX SGV	ft/sec	1.6	0.1
FT18003	CHX Flow	gpm	23.0	0.2
FT19003	EHX Flow	gpm	16.3	0.1
PT15081	Comb dP	in. H2O	43.7	2.3
Q(CA)	CA Heat in	KBtu/hr	102.6	4.7
Q(CHX)	CHX HtRmv	KBtu/hr	689.5	44.6
Q(EHX)	EHX HtRmv	KBtu/hr	473.5	17.9
Q(EHX,IN	FG Enrg in	KBtu/hr	2.3	0.2
Q(F)	Fuel Enrg in	KBtu/hr	2308.2	254.7
Q(FG)	FG Enrg out	KBtu/hr	258.0	4.8
Q(IN)	Tot Enrg in	KBtu/hr	2413.3	254.1
Q(OUT)	Tot Enrg out	KBtu/hr	1909.3	56.0
W(SR)	Recirc Rt	lbs/hr	3966	467.9

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	1023	56.3
TC13132	AFPE-F6"	1153	42.8
TC13133	AFPE-B6"	885	54.3
TC13134	AFPE-F10"	853	86.3
TC13231	AFPW-F2"	1005	51.0
TC13232	AFPW-F6"	1142	40.6
TC13233	AFPW-B6"	875	44.1
TC13234	AFPW-F10'	1063	50.1
DOORS	CHXs On	12	0
COILS	EHXs On	9	0
BH A/C		2.0	0.0
A/SRATIO		2.9	N/A
Feed Air	scfm	20.0	
DC Air	scfm	9.5	
Purge Air	scfm	15.5	

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(1630-1730)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1561	4.6
TC11021	AFS Ex	°F	1269	4.8
TC15001	C Plenum	°F	538	2.6
TC15004	C 1-1'	°F	1581	5.4
TC15005	C 1-2'	°F	1569	4.2
TC15006	C 1-3'	°F	1529	4.5
TC15007	C 1-4'	°F	1566	5.0
TC15008	C 1-4'	°F	1578	4.5
TC15009	C 1-4'	°F	1560	5.5
TC15012	C 2-6'	°F	1605	5.2
TC15013	C 2-8'	°F	1670	12.9
TC15022	C 3-11'	°F	1620	9.4
TC15023	C 3-14'	°F	1607	9.3
TC15024	C 3-14'	°F	1607	5.2
TC15025	C 3-14'	°F	1625	6.9
TC15032	C 4-17.5'	°F	1558	5.2
TC15042	C 5-22.5'	°F	1577	4.0
TC15052	C 6-27.5'	°F	1565	3.8
TC15053	C 6-27.5'	°F	1570	3.3
TC15054	C 6-27.5'	°F	1494	5.0
TC15062	C 7-32.5'	°F	1474	5.8
TC15071	C 8-37.5'	°F	1474	3.5
TC15073	C 9-41'	°F	1564	5.5
TC15999	Ambient	°F	80	1.2
TC16001	EHX Plenm	°F	120	2.4
TC16012	EHX 0.5'	°F	1057	13.5
TC16013	EHX 1.5'	°F	1034	15.5
TC16014	EHX 2.7'	°F	1040	15.6
TC16015	EHX 3.8'	°F	1022	8.5
TC16017	EHX 5.3'	°F	935	4.9
TC16018	EHX Exit	°F	999	13.1
TC16021	Crc A in	°F	1551	3.0
TC16031	DC 8-36'	°F	1580	3.6
TC16032	DC 6-28'	°F	1552	2.3
TC16033	DC 4-18'	°F	1546	4.3
TC16034	DC3-9.5'	°F	1597	2.7
TC16035	DC3-8.5'	°F	1569	4.5
T(A,C)	Comb Temp	°F	1569	3.1
T(A,EHX)	EHX Temp	°F	1044	14.9
EA	Excess Air	%	32.0	2.6
SR	S Reten	%	16.3	3.4
R(PCA)	%Flw PCA	%	59.5	4.8
R(SCA)	%Flw SCA	%	40.5	4.8
R(Q,IN)	% Enrg in	%	72.6	1.8
R(CHX)	CHX Ratio	%	62.2	1.7
R(EHX)	EHX Ratio	%	37.8	1.7
F(PCA)	PCA Flw	SCFM	249.3	27.3
F(EHX)	EHX Flw	SCFM	53.8	0.9
F(TPA)	TPCA Flw	SCFM	299.1	24.5
F(SCA)	SCA Flw	SCFM	168.3	24.7
F(TCA,F)	TCA Flw	SCFM	503.2	16.0
F(FG,BH)	BH Flw	SCFM	506.9	2.9
F(TFG)	TFG Flw	SCFM	506.9	2.9

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 12

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	54	121	1670	4.00	134635	16.7	25891
3NE,SW	14	53	129	1613	4.00	151557	19.6	29146
4SE,NW	17.5	54	139	1558	4.00	168939	22.9	32488
5E	22.5	53	145	1577	2.00	91721	24.6	35277
6NE	27.5	54	113	1543	2.00	58980	15.9	22685
7SE,NW	32.5	55	108	1474	4.10	108253	15.2	20818
8E,W	37.5	55	105	1474	3.90	97247	13.7	18701
	Overall	54	122	1569	23.52	802783	17.8	25730
			From Data Sheets=>		24.00			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-9	9	53	106	1044	16.54	439104	69.4	65053
			From Data Sheets=>		17.30			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	1491	45.7	SO2-A	ppm	1698	67.4
SO2-AE	lb/MM Btu	2.93	0.1				
SO2-B	ppm	1531	33.7	SO2-B	ppm	1736	38.3
SO2-BE	lb/MM Btu	3.01	0.1				
CO	ppm	16	3.7	CO	ppm	18	4.3
CO2	%	13.70	0.3	CO2	%	15.59	0.2
N2O	ppm	124	2.3	N2O	ppm	141	3.2
N2OE	lb/MM Btu	0.17	0.0				
NOx	ppm	137	14.7	NOx	ppm	156	18.7
NOxE	lb/MM Btu	0.19	0.0				
O2-A	%	5.19	0.3				
O2-B	%	5.12	0.3				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	188.2	4.3	TC13131	AFPE-F2"	1124	16.9
W(S)	LS Fd Rt	lbs/hr	0.0	0.0	TC13132	AFPE-F6"	1231	12.8
V(FG)	FG SGV	ft/sec	16.0	0.5	TC13133	AFPE-B6"	988	15.1
V(S,C)	Comb SGV	ft/sec	15.1	0.6	TC13134	AFPE-F10"	1006	30.5
V(S,EHX)	EHX SGV	ft/sec	1.7	0.0	TC13231	AFPW-F2"	1094	14.3
FT18003	CHX Flow	gpm	23.5	0.0	TC13232	AFPW-F6"	1215	11.7
FT19003	EHX Flow	gpm	16.5	0.0	TC13233	AFPW-B6"	954	11.6
PT15081	Comb dP	in. H2O	39.0	0.9	TC13234	AFPW-F10'	1151	15.4
Q(CA)	CA Heat in	KBtu/hr	99.2	3.8	DOORS	CHXs On	12	0
Q(CHX)	CHX HtRmv	KBtu/hr	698.2	22.7	COILS	EHXs On	9	0
Q(EHX)	EHX HtRmv	KBtu/hr	424.2	22.6	BH A/C		1.9	0.0
Q(EHX,IN	FG Enrg in	KBtu/hr	2.3	0.2	A/SRATIO		0.1	0.0
Q(F)	Fuel Enrg in	KBtu/hr	2513.0	55.7	Feed Air	scfm	19.3	
Q(FG)	FG Enrg out	KBtu/hr	249.9	1.3	DC Air	scfm	8.7	
Q(IN)	Tot Enrg in	KBtu/hr	2615.1	58.5	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1872.8	24.8				
W(SR)	Recirc Rt	lbs/hr	2838	133.2				

APPENDIX D

BLACK THUNDER SUBBITUMINOUS COAL TEST RESULTS

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TEST MATRIX

The matrix of test parameters is shown in Table D-1. Test 1 was a baseline test at nominal conditions of 1550°F, primary-to-secondary air split of 60:40, flue gas superficial gas velocity of 16.0 ft/sec, and 25% excess air. No limestone was fed during this test. Test 2 maintained the same operating conditions as Test 1, with the addition of limestone. In order to turn the bed over from the start-up sand to a limestone/coal ash bed more quickly, bed material was drained from the combustor and replaced with end-of-run bed material from the Blacksville run. This operation was performed in four 200-pound increments. Tests 3 and 9 were low- and high-temperature tests, respectively; Tests 4 and 8 were run at low and high excess air, respectively. Test 5 was a low-sulfur-capture test. Tests 6 and 7 were low-load tests; in Test 6, the heat-transfer configuration was to be the same as in Test 5, allowing temperature to drift. In Test 7, heat-transfer surface was to be removed to increase the average combustor temperature to 1550°F. However, Test 7 was run first, and the heat-transfer configuration was almost identical to that of Test 5; since Test 6 would then have been essentially a repeat of Test 7, with the addition of a single heat-transfer coil, it was deleted from the matrix.

COAL AND LIMESTONE PROPERTIES

The coal used for this test was supplied by ARCO Coal Company. The limestone used was New Enterprise. Coal and limestone preparation was as described earlier. The coal was screened to -¼". The size distributions of the coal and limestone are shown in Figure D-1.

The sized coal was stored in 2-ton capacity coal totes until it was needed, at which time it was transferred by forklift and crane to storage hoppers having net capacities of 3500 pounds. The prepared limestone was placed directly into 1000-pound capacity storage hoppers.

TABLE D-1

Test Matrix

Test No.	Average Temperature, °F	Sulfur Retention or Ca/S	PA/SA	Superficial Gas Velocity, ft/sec	Excess Air, %
1	1550	No ls[1]	60:40	16.0	25
2	1550	90%	60:40	16.0	25
3	1450	Same Ca/S as 2	60:40	15.2	25
4	1550	Same Ca/S as 2	60:40	16.0	5
5	1550	70%	60:40	16.0	25
6	*[2]	Same Ca/S as 2	80:20	12.0	25
7	1550	Same Ca/S as 2	80:20	12.0	25
8	1550	Same Ca/S as 2	60:40	16.0	45
9	1650	Same Ca/S as 2	60:40	16.8	25

[1] Limestone.
[2] Not specified–dependent on operating conditions.

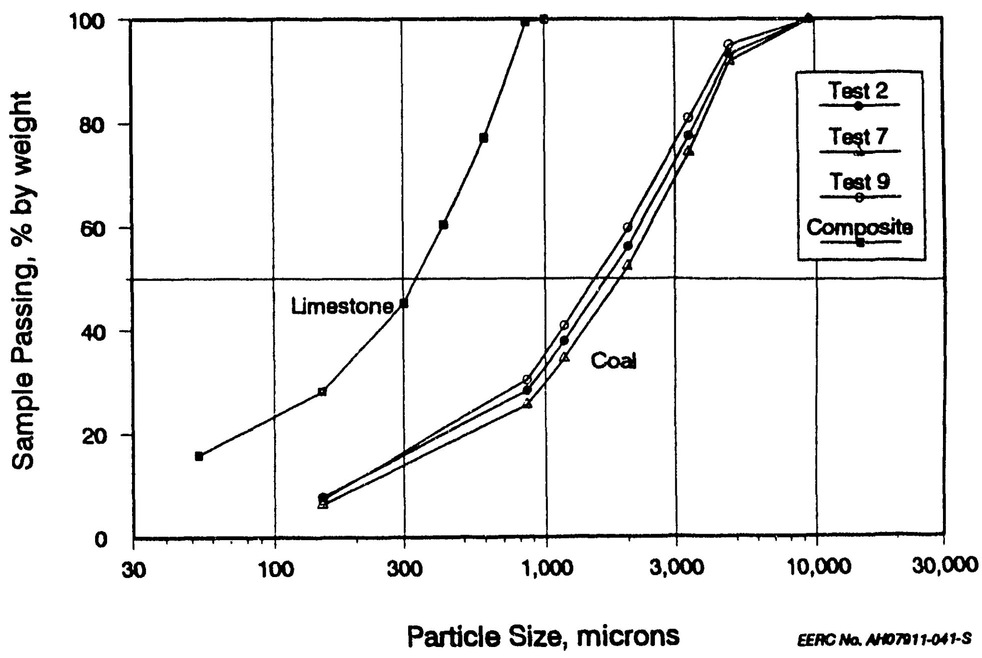

Figure D-1. Coal and limestone particle-size distribution.

Proximate and ultimate analyses of the coal and XRFA of the coal ash from Tests 2, 7, and 9 were performed. The coal samples from the three tests showed little variability, so the average of the three was used for all tests. If there had been much variability, particularly in the sulfur analysis, samples from all the tests would have been analyzed. The results of the coal analyses are shown in Table D-2. XRFA was performed on a sample of limestone that was composited from all the tests. The limestone analysis is shown in Table D-3.

OPERATIONAL PERFORMANCE

General Operability

While overall operability of the system was good, several problems were encountered during testing with the Black Thunder coal. The coal was difficult to feed, hanging up in the transition section between the coal hopper and the rotary feed valve. For the first day after coal feed was initiated, the speed of the rotary feed valve had to be increased to maintain a constant coal feed rate, until the speed controller setting was at a maximum. The pockets in the rotary feeder apparently filled up with coal, requiring increasingly faster rotation. A hole was drilled just below the rotary feeder, and a compressed air line was attached, connected to manual control valve located in the control room. The rotary valve could then be periodically blown clean to help maintain a consistent coal feed rate.

Limestone feed also proved problematic. Because of the relatively low limestone feed rates required for this run, an Accurate limestone feeder was again utilized as during a portion of the Blacksville coal testing. Some of the limestone was wet and sticky; this tended to pack into the feed screw, halting its operation. A larger sleeve was installed around the screw, and the wettest limestone was mixed with drier material to help alleviate the feed problems.

TABLE D-2

Coal Analyses (Average of Tests 2, 7, and 9)

Proximate Analysis, as-received, wt%	
Moisture	27.6
Volatile Matter	33.2
Fixed Carbon	34.6
Ash	4.6
Ultimate Analysis, as-received, wt%	
Carbon	49.9
Hydrogen	6.6
Nitrogen	0.6
Sulfur	0.3
Oxygen	38.0
Ash	4.6
Ash Composition, as oxides, wt%	
Calcium, CaO	24.4
Magnesium, MgO	7.9
Sodium, Na_2O	0.5
Silica, SiO_2	28.5
Aluminum, Al_2O_3	16.4
Ferric, Fe_2O_3	6.4
Titanium, TiO_2	1.4
Phosphorous, P_2O_5	1.3
Potassium, K_2O	0.9
Sulfur, SO_3	12.4
High Heating Value, moisture-free, Btu/lb	11,941

TABLE D-3

Average Limestone Analysis

Component, as oxide, %	Average
Silica	2.96
Aluminum	0.62
Titanium	0.38
Iron	0.02
Calcium	51.76
Magnesium	2.93
Sulfur	0.26
Sodium	0.06
Potassium	0.33

Because of the low limestone feed rate and the low ash content of the coal, it would have taken a number of days to displace the sand bed used at start-up with a limestone/coal ash bed. To facilitate bed turnover at the end of Test 1, when limestone feed was initiated, bed material was drained and replaced with bed material remaining from the Blacksville run. The low-sulfur content of the coal resulted in a very slow response time in terms of sulfur capture when operating conditions were changed.

In addition to the feed problems, material tended to hang up in the downcomer. This was evidenced by large fluctuations in the downcomer pressure drops. The ability to inject compressed air into several sections of the downcomer was incorporated into the pilot system as a result of problems encountered during CFB testing with the Center lignite; this air was used to keep the downcomer clear.

The secondary cyclone catch was recycled back into the system after Test 1 to maintain solids inventory and increase the solids recirculation rate. The cyclone catch was collected in a barrel for short periods (usually one-half hour) when bed inventory was high, indicated by an increase in the solids recirculation rate (near 20,000 lb/hr), or when there was too much sorbent built up in the bed, indicated by very low SO_2 emissions (less than 10 ppm).

Summary of Results

Upon completion of the run, data for each of the steady-state test periods were averaged. A summary of the process data for each test period is presented in Table D-4. The eight test periods correspond to the tests outlined in the test matrix in Table D-1. They are presented in the order used in Table D-1, even though they were actually run in the order 1, 5, 2, 3, 4, 9, 8, 7, to accommodate the slow system response times. Summaries of the run data are included at the end of this appendix.

Recirculation Rates and Size Distributions

The solids recirculation rate for each test was determined by calculating a heat balance around the external heat exchanger. The average solids recirculation rates for each test are shown in Table D-5. The recirculation rate for Test 1 was very low, 2245 lb/hr, because the ash captured by the secondary cyclone was collected in a barrel. For the remainder of the run, the secondary cyclone catch was recycled back into the unit, except for brief periods when the ash was diverted to a barrel to control bed inventory or sulfur emissions. Tests 2 through 4 had recirculation rates typical for full load tests on this unit. The solids recirculation for Test 9 may have been higher due to the higher velocity in the combustor during this test. The lowest recirculation rate observed after the reinjection of secondary cyclone ash was initiated occurred in Test 7, the low-load test. This is due in part to the low superficial gas velocity in the combustor, the decreased solids input, and the use of secondary cyclone ash drain for sulfur control prior to the test. Secondary cyclone ash drain before Test 8 also contributed to the low recirculation rate in that test.

The particle-size distributions are shown in Figure D-2. The combustor bed material in Test 1 was relatively large, since the system was operating with a predominantly sand bed at that time. Test 1 was also the only test during which secondary cyclone ash was collected rather than recycled back into the system.

Fly Ash/Total Ash Split

The ash balance for each test period is presented in Table D-6. Ash input to the system was composed of calculated quantities of coal and limestone ash, based on their respective analyses and feed rates. The limestone-derived ash was further broken down into estimates of the sorbent which was either calcined or had undergone sulfation. The output consisted of the measured quantities of bottom ash (drained from the combustor bed), fly ash collected from the secondary cyclone, and fly ash removed from the baghouse.

TABLE D-4

Summary of Process Data

Test #:	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9
Time:	1325-1425	0930-1220	1625-2100	1130-1235	0745-0925	2100-0130	0945-1415	2125-2315
Date:	11/18/91	11/20/91	11/20/91	11/21/91	11/20/91	11/22,23/91	11/22/91	11/21/91
Coal Feed Rate, lb/hr	250.4	273	301	315	278	229	246	272
Limestone Feed Rate, lb/hr	0	7	0	15	6	4	7	5
Solids Recirculation Rate, lb/hr	2,245	12,020	11,205	13,478	9,320	4,093	7,806	16,588
Combustion Air								
EHX Flow, scfm	62.2	49	52	60	48	57	58	54
Primary Air, scfm	225.4	246	254	236	237	262	242	242
Secondary Air, scfm	160.4	160	169	156	160	52	162	161
Feed Assist Air, scfm	17.9	19	19	19	19	19	19	17
DC Aeration Air, scfm	0	4	5	5	0	5	5	5
Purge Air, scfm	15.5	16	16	16	16	16	16	16
Total Air, scfm	481	493	514	492	480	411	502	494
PA/SA, %	60	60	60	60	60	79	60	60
Excess Air, %	33.8	26.7	23.8	8.8	22.5	23.5	43.5	30.1
FG SGV, ft/sec	16.1	16.1	16.0	15.8	15.9	13.0	16.1	16.9
EHX SGV, ft/sec	1.8	1.8	1.8	2.2	1.8	1.9	2.2	2.2
Flue Gas								
Flow Rate, scfm	519	597	611	599	587	477	595	601
Oxygen, %	5.2	4.4	4.1	1.7	3.9	4.0	6.4	4.9
SO_2, ppm	341	80	4	128	135	98	11	38
CO, %	0.0002	0.0010	0.0017	0.0011	0.0007	0.0007	0.0004	0.0006
NO_x, ppm	218	174	156	136	156	177	205	227
N_2O, ppm	22	40	58	32	N/A	35	31	22
CO_2, %	15.0	15.4	15.6	17.8	16.2	16.0	13.9	15.0
Ash								
Bed Material Add Rate, lb/hr	0	0	0	0	0	0	0	0
Bottom Ash Discharge Rate, lb/hr	0	0	2	0	0	0	0	0
Bottom Ash Unburned Carbon, %	0.21	0.44	2.89	2.53	2.53	0.22	0.74	0.45
Cyclone Ash Discharge Rate, lb/hr	10	0	0	0	0	0	0	0
Cyclone Ash Unburned Carbon, %	1.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Baghouse Ash Discharge Rate, lb/hr	4.1	10.1	6.3	10.1	7.6	2	6	7
Baghouse Ash Unburned Carbon, %	8.80	1.34	1.34	0.81	0.81	0.18	0.27	0.14
Total Ash (meas.), lb/hr	14	10	8	10	8	2	6	7
Total Ash (calc.), lb/hr	12	18	14	24	17	13	16	16
Bottom Ash/Total Ash (meas.), %	0.0	0.0	23.2	0.0	0.0	0.0	0.0	0.0

continued...

TABLE D-4 (continued)

Test #:	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9
Time:	1325-1425	0930-1220	1625-2100	1130-1235	0745-0925	2100-0130	0945-1415	2125-2315
Date:	11/18/91	11/20/91	11/20/91	11/21/91	11/20/91	11/22,23/91	11/22/91	11/21/91
Air and Gas Temperatures (°F)								
Combustor Temperatures								
Plenum	525	578	587	617	571	505	559	626
Section 1	1,591	1,516	1,409	1,494	1,513	1,528	1,521	1,621
Section 2	1,643	1,556	1,449	1,533	1,551	1,566	1,553	1,642
Section 3	1,602	1,546	1,454	1,529	1,542	1,535	1,539	1,628
Section 4	1,522	1,542	1,457	1,533	1,539	1,511	1,527	1,627
Section 5	1,548	1,556	1,469	1,548	1,555	1,534	1,546	1,643
Section 6	1,540	1,569	1,477	1,558	1,567	1,535	1,553	1,652
Section 7	1,502	1,555	1,444	1,545	1,553	1,493	1,524	1,634
Section 8	1,491	1,560	1,463	1,557	1,558	1,531	1,549	1,649
Section 9	1,594	1,611	1,514	1,602	1,611	1,579	1,592	1,691
PCD Exit	1,554	1,548	1,474	1,589	1,554	1,518	1,526	1,637
Average	1,575	1,547	1,448	1,532	1,545	1,536	1,540	1,637
EHX Temperatures								
Plenum	122	122	126	129	119	113	120	125
0.5' above Distributor Plate	959	1,345	1,230	1,339	1,356	1,172	1,382	1,557
1.5' above Distributor Plate	942	1,313	1,212	1,314	1,322	1,159	1,371	1,528
2.7' above Distributor Plate	950	1,329	1,207	1,320	1,339	1,156	1,382	1,544
3.8' above Distributor Plate	926	1,309	1,218	1,331	1,312	1,136	1,366	1,533
5.3' above Distributor Plate	843	1,239	1,165	1,280	1,232	1,089	1,312	1,482
Average	950	1,328	1,216	1,314	1,339	1,162	1,378	1,543
Downcomer Temperatures								
Section 3	1,545	1,520	1,464	1,526	1,554	1,487	1,531	1,629
Section 4	1,520	1,519	1,437	1,512	1,543	1,454	1,500	1,622
Section 6	1,553	1,541	1,463	1,553	1,551	1,508	1,530	1,633
Section 8	1,576	1,556	1,473	1,570	1,567	1,529	1,545	1,640
Ambient	74	77	79	78	76	68	72	76
Air and Gas Pressure (in. H_2O)								
Comb. dP	41.8	46.1	42.6	41.2	47.0	36.3	36.4	35.9

TABLE D-5

Solids Recirculation and Heat-Transfer Data

Test	Temperature (°F)	Total Ca/S	Excess Air (%)	Primary Air (%)	Solids Recirculation (lb/hr)	DC[1] d_{50} (µm)	H_o[2]	Heat Flux (Btu/hr-ft²)	Cyclone Efficiency (%)	Recirculation Ratio
1	1,575	2.1	33.8	60	2,245	376	16.8	28,628	99.38	195
2	1,547	4.6	26.7	60	12,020	376	23.4	32,929	99.92	603
3	1,448	2.1	23.8	60	11,205	309	20.0	26,339	99.94	806
4	1,532	6.4	8.8	60	13,478	317	20.5	28,795	99.93	465
5	1,545	4.1	22.5	60	9,320	ND[3]	23.6	33,076	99.92	495
7	1,536	3.5	23.5	79	4,093	314	19.0	26,919	99.95	292
8	1,540	4.7	43.5	60	7,806	331	20.2	28,570	99.93	432
9	1,637	4.0	30.1	60	16,588	326	22.8	34,009	99.96	927

[1] Downcomer.
[2] Heat-transfer coefficient (Btu/hr-ft²-°F).
[3] Not determined.

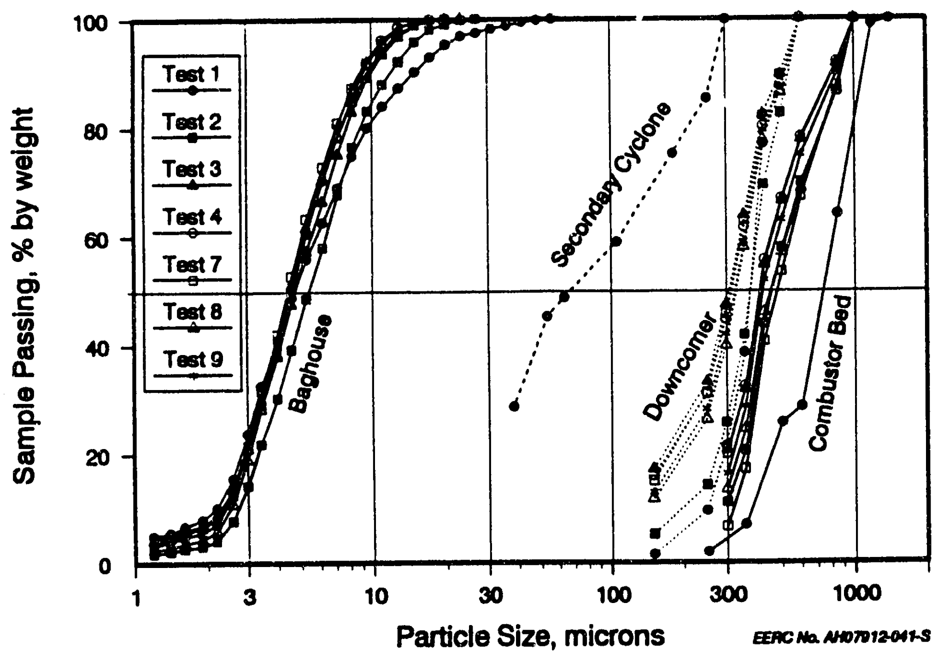

Figure D-2. Baghouse, secondary cyclone, downcomer, and bed material particle-size distributions.

The ratios of bottom ash to total ash, as well as the ash closure for each test, are also shown in Table D-6. Since bed inventory, measured by pressure drop across the combustor, was uniform for most of the run, bed material drain was minimal; hence the bottom ash-to-total ash split for all tests except Test 3 was zero. The average closure for the eight tests was poor, about 41%. The reason for the poor closure was the intermittent use of secondary cyclone ash collection to control both bed inventory and sulfur retention; cyclone ash was collected between tests, rather than during them. Tests 7 and 8 were both preceded by periods of cyclone ash drain. Even the best closure, 60.5% for Test 3, was poor. The small quantities of ash input provide for a very large margin of error; a one-pound difference in the amount of ash collected could be a 5% to 10% difference in the closure.

TABLE D-6

Ash Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9
Input, lb/hr								
Ash	12	13	14	15	13	11	11	12
Sorbent *								
CaO	0	3	0	7	3	2	3	2
$CaSO_4$	0	2	0	2	1	1	2	2
Total Solids In	12	18	14	24	18	13	16	16
Output, lb/hr								
Bed Material	0	0	2	0	0	0	0	0
Cyclone Ash	10	0	0	0	0	0	0	0
Baghouse Ash	4	10	6	10	8	2	6	7
Total Solids Out	14	10	8	10	8	2	6	7
Closure, %	116.8	56.4	60.1	41.8	44.7	16.4	33.6	44.5
Bottom Ash/Total Ash, %	0.0	0.0	23.2	0.0	0.0	0.0	0.0	0.0

* The CaO and $CaSO_4$ mass inputs are included to express sorbent equivalent mass inputs.

Coal Ash/Limestone Split

An aluminum balance was performed to determine the composition of each ash stream. Al_2O_3 was used as a tracer. While there was a small percentage of Al_2O_3 in the limestone (0.62%), it was generally less than 2% of the total Al_2O_3 fed; therefore, only the aluminum in the coal ash was considered in the aluminum balance. The proportions of coal and limestone as solid inputs for each test, as well as the percentage of each ash stream that came from the coal, are shown in Table D-7. The percentage of limestone in each ash stream is determined by difference. No aluminum balance was performed for Test 5 because solids samples were not taken during that test. Every test except 4 and 9 shows a greater than 100% contribution of coal ash to the baghouse ash because the percentage of aluminum in the baghouse ash was greater than that in the coal. Table D-8 shows the aluminum balance for each test. The closure in this table and in Table D-7 is based on the coal ash only.

THERMAL PERFORMANCE

Energy and Material Balances

The measured and theoretical fuel and flue gas flow rates are shown in Tables D-9 and D-10, respectively. Theoretical coal feed rate is calculated using the coal analysis and the actual air flow rates and flue gas emissions. The measured coal feed rate is determined by calculating the weight loss over time of the coal weigh hopper. The fuel balances for this run were fairly close for all eight tests, with the greatest difference between measured and theoretical, -3.8%, occurring during Test 7.

The theoretical flue gas rates were calculated using the coal analyses and theoretical fuel feed rates for each test. The actual air and flue gas flow rates were measured with orifice plates. With the exception of Test 1, the measured flue gas volume was greater than the theoretical.

TABLE D-7

Material Derived from Coal Ash and Limestone Based on Aluminum Material Balance (%)

	Coal	ls[1]	Coal	ls	Coal	ls	Coal	ls
	Test 1		Test 2		Test 3		Test 4	
Solids Input	100.00	0.00	71.87	28.13	100.00	0.00	62.18	37.82
Bed Drain	10.98	0.00	29.45	70.55	24.09	75.91	24.51	75.49
Cyclone Catch	78.05	0.00	NA[2]	NA	NA	NA	NA	NA
Baghouse Catch	107.93	0.00	101.22	0.00	114.02	0.00	79.27	0.00
Aluminum Bal. Closure	101.48		80.03		56.36		54.10	
	Test 7		Test 8		Test 9			
Solids Input	84.49	15.51	69.57	30.43	75.63	24.37		
Bed Drain	25.37	74.63	27.87	72.13	27.87	72.13		
Cyclone Catch	NA	NA	NA	NA	NA	NA		
Baghouse Catch	109.15	0.00	101.83	0.00	75.61	0.00		

[1] Limestone.
[2] Not applicable.

TABLE D-8

Aluminum Material Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9
Coal Ash, lb/hr	11.90	12.77	13.56	14.80	12.82	10.89	11.43	12.42
Al_2O_3 in coal ash, %	16.40	16.40	16.40	16.40	16.40	16.40	16.40	16.40
Bed Material Drain, lb/hr	0.00	0.00	1.90	0.00	0.00	0.00	0.00	0.00
Al_2O_3 in Bed Material, %	1.80	4.83	3.95	4.02	ND[1]	4.16	4.57	4.57
Ash from Coal, %	10.98	29.45	24.09	24.51	0.00	25.37	27.87	27.87
Ash from Coal, lb/hr	0.00	0.00	0.46	0.00	0.00	0.00	0.00	0.00
Baghouse Drain, lb/hr	4.10	10.10	6.30	10.10	7.60	2.20	5.50	7.30
Al_2O_3 in Baghouse Ash, %	17.70	16.60	18.70	13.00	ND	17.90	16.70	12.40
Ash from Coal, %	107.93	101.22	114.02	79.27	0.00	109.15	101.83	75.61
Ash from Coal, lb/hr	4.43	10.22	7.18	8.01	0.00	2.40	5.60	5.52
Secondary Cyclone Drain, lb/hr	9.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3 in Cyclone Ash, %	12.8	NA[2]	NA	NA	NA	NA	NA	NA
Ash from Coal, %	78.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ash from Coal, lb/hr	7.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Ash from Coal, lb/hr	12.07	10.22	7.64	8.01	0.00	2.40	5.60	5.52
Closure	101.48	80.03	56.36	54.10	0.00	22.05	49.00	44.46

[1] Not determined.
[2] Not applicable.

TABLE D-9

Fuel Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9
Fuel Feed Rate, meas., lb/hr	250	273	301	315	278	229	246	272
Fuel Feed Rate, theor., lb/hr	259	278	295	322	279	237	249	271
Difference, %	-3.5	-2.1	1.8	-2.3	-0.7	-3.8	-1.3	0.6

meas. = Feed rate determined by weight loss of the coal feed hopper over time.
theor. = Theoretical feed rate calculated on the basis of the coal analysis, the combustion air, and the excess air for each test period.

TABLE D-10

Flue Gas Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9
Fuel Feed Rate, meas., scfm	519	597	611	599	587	477	595	601
Fuel Feed Rate, theor., scfm	538	554	578	560	540	462	558	553
Difference, %	-3.7	7.2	5.3	6.4	8.0	3.0	6.2	7.9

meas. = The flue gas flow measured during the run through an orifice located just upstream of the ID fan.
theor. = Theoretical flue gas flow calculated on the basis of the coal analysis and the theoretical coal feed rate for each test period..

The energy balances for the eight tests are shown in Table D-11, both as Btu/hr and as percentages. The energy input is made up of the energy potential of the fuel, the primary and secondary combustion air, the external heat exchanger fluidizing air, and the energy released from the sulfation of the sorbent. Measurable heat loss sources are the combustor heat exchange doors, the external heat exchange cooling coils, the heat of the flue gas (including a correction for leakage), the heat of the ash removed, the unburned carbon in the ash removed, and the energy absorbed during calcination of the sorbent. The unmeasurable heat loss due to convection and radiation is estimated using a correlation developed from the data generated during testing with all five coals. The correlation relates heat loss to average combustor temperature. The energy balances for all eight tests were very good. The material balances are presented in Table D-12. Closure was near 100% for all eight tests.

Combustion Efficiency

The combustion efficiencies, shown in Table D-13 and Figure D-3, were greater than 99% for all eight tests, and greater than 99.9% for all but Test 1. The percentage of unburned carbon in each ash stream was calculated as the difference between the loss on ignition (LOI) and the carbonate content (as CO_2). These values are shown in Table D-14. The highest percentage of unburned carbon in the baghouse was seen in Test 1; however, because of the low baghouse ash drain rate during this test, the combustion efficiency was still high.

TABLE D-11

Energy Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9
Input, Btu/hr								
Coal	2,158,285	2,317,325	2,459,712	2,684,533	2,326,485	1,975,930	2,073,352	2,252,377
Primary Air	112,830	136,619	142,961	141,033	130,238	126,950	130,936	147,795
Secondary Air	80,293	88,616	95,213	93,463	87,942	24,963	87,742	98,551
EHX Air	3,262	2,435	2,639	3,468	2,267	2,900	3,144	2,898
Sorbent Sulfation	0	2,662	100	3,375	2,014	1,582	3,003	2,578
Total	2,354,670	2,547,658	2,700,624	2,925,873	2,548,946	2,132,325	2,298,177	2,504,199
Input, %								
Coal	91.7	91.0	91.1	91.8	91.3	92.7	90.2	89.9
Primary Air	4.8	5.4	5.3	4.8	5.1	6.0	5.7	5.9
Secondary Air	3.4	3.5	3.5	3.2	3.5	1.2	3.8	3.9
EHX Air	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sorbent Sulfation	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Output, Btu/hr								
Flue Gas (sens.)	993,676	1,017,893	1,008,625	1,070,294	1,001,269	840,465	1,016,557	1,082,546
Ash (sens.)	5,611	3,994	3,018	3,951	3,002	869	2,172	3,066
Ash (chem.) *	6,577	1,914	1,969	1,155	869	55	213	145
Combustor	744,325	856,153	821,767	748,664	859,971	699,893	742,817	884,241
EHX	371,307	580,504	759,244	790,674	580,405	357,685	362,426	333,508
Sorbent Calcination	0	5,668	77	11,107	4,673	2,681	5,209	4,136
Conduction and Radiation Losses	220,260	205,882	153,943	197,807	204,475	199,839	202,079	252,715
Total	2,341,756	2,672,008	2,748,642	2,823,652	2,654,664	2,101,486	2,331,472	2,560,357
Output, %								
Flue Gas (sens.)	42.4	38.1	36.7	37.9	37.7	40.0	43.6	42.3
Ash (sens.)	0.2	0.1	0.1	0.1	0.1	0.0	0.1	0.1
Ash (chem.) *	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Combustor	31.8	32.0	29.9	26.5	32.4	33.3	31.9	34.5
EHX	15.9	21.7	27.6	28.0	21.9	17.0	15.5	13.0
Sorbent Calcination	0.0	0.2	0.0	0.4	0.2	0.1	0.2	0.2
Conduction and Radiation Losses	9.4	7.7	5.6	7.0	7.7	9.5	8.7	9.9
Total	99.5	100.0	101.8	100.0	100.0	100.0	100.0	100.0
Closure	99.4	104.9	101.7	96.5	104.1	98.6	101.4	102.2

* The heat of combustion coefficient for pure carbon is an average of values found in *Perry's Chemical Engineering Handbook* Perry et al. (1984) and the *Standard Handbook for Mechanical Engineers*, Baumeister and Marks (1967).

Boiler Efficiency

Boiler efficiencies were calculated for each test period using ASME PTC 4.1, modified according to the recommendations in EPRI's "Atmospheric Fluidized-Bed Combustion Performance Guidelines" to account for the heat losses and gains associated with calcination and sulfation of the limestone.

TABLE D-12

Material Balance

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9
Total Mass Balance								
Input, lb/hr								
Combustion Air	2051	2082	2173	2070	2040	1697	2117	2092
Additional Air	153	175	180	181	156	183	183	170
Bed Material	0	0	0	0	0	0	0	0
Coal Feed	259	278	295	322	279	237	249	271
Sorbent Feed	0	7	0	15	6	4	7	5
Total Mass In	2463	2543	2649	2589	2481	2121	2555	2538
Input, %								
Combustion Air	83.3	81.9	82.0	80.0	82.2	80.0	82.8	82.4
Feed Assist Air	6.2	6.9	6.8	7.0	6.3	8.6	7.2	6.7
Bed Material	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coal Feed	10.5	10.9	11.2	12.5	11.3	11.2	9.7	10.7
Sorbent Feed	0.0	0.3	0.0	0.6	0.2	0.2	0.3	0.2
Total Mass In	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Output, lb/hr								
Measured Flue Gas	2390	2747	2809	2761	2706	2196	2736	2765
Flue Gas Leaks	89	-198	-149	-177	-216	-65	-169	-219
Ash Out								
Bed Material	0	0	2	0	0	0	0	0
Baghouse	4	10	6	10	8	2	6	7
Cyclone Ash	10	0	0	0	0	0	0	0
Total Mass Out	2493	2558	2668	2594	2498	2133	2573	2553
Output, %								
Measured Flue Gas	95.9	107.4	105.3	106.4	108.3	102.9	106.4	108.3
Flue Gas Leaks	3.6	-7.8	-5.6	-6.8	-8.6	-3.0	-6.6	-8.6
Ash out	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Bed Material	0.2	0.4	0.2	0.4	0.3	0.1	0.2	0.3
Baghouse	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cyclone Ash								
Total Mass Out	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Closure	101.2	100.6	100.7	100.2	100.7	100.5	100.7	100.6

TABLE D-13

Combustion Efficiency

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9
Input								
Coal Feed Rate, lb/hr	259.20	278.30	295.40	322.40	279.40	237.30	249.00	270.50
Coal Carbon, %	49.90	49.90	49.90	49.90	49.90	49.90	49.90	49.90
Total, lb/hr	129.20	138.70	147.30	160.70	139.30	118.30	124.10	134.80
Output								
Bottom Ash Discharge Rate, lb/hr	0.00	0.00	2.00	0.00	0.00	0.00	0.00	0.00
Unburned Carbon, %	0.21	0.44	2.89	2.53	2.53	0.22	0.74	0.45
Bottom Ash Carbon Discharge Rate, lb/hr	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00
Cyclone Discharge Rate, lb/hr	9.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Unburned Carbon, %	1.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cyclone Carbon Discharge Rate, lb/hr	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Baghouse Discharge Rate, lb/hr	4.00	10.00	6.00	10.00	8.00	2.00	6.00	7.00
Unburned Carbon, %	8.80	1.34	1.34	0.81	0.81	0.18	0.27	0.14
Baghouse Carbon Discharge Rate, lb/hr	0.36	0.14	0.08	0.08	0.06	0.00	0.02	0.01
Total, lb/hr	0.47	0.14	0.14	0.08	0.06	0.00	0.02	0.01
Combustion Efficiency, %	99.64	99.90	99.91	99.95	99.96	100.00	99.99	99.99

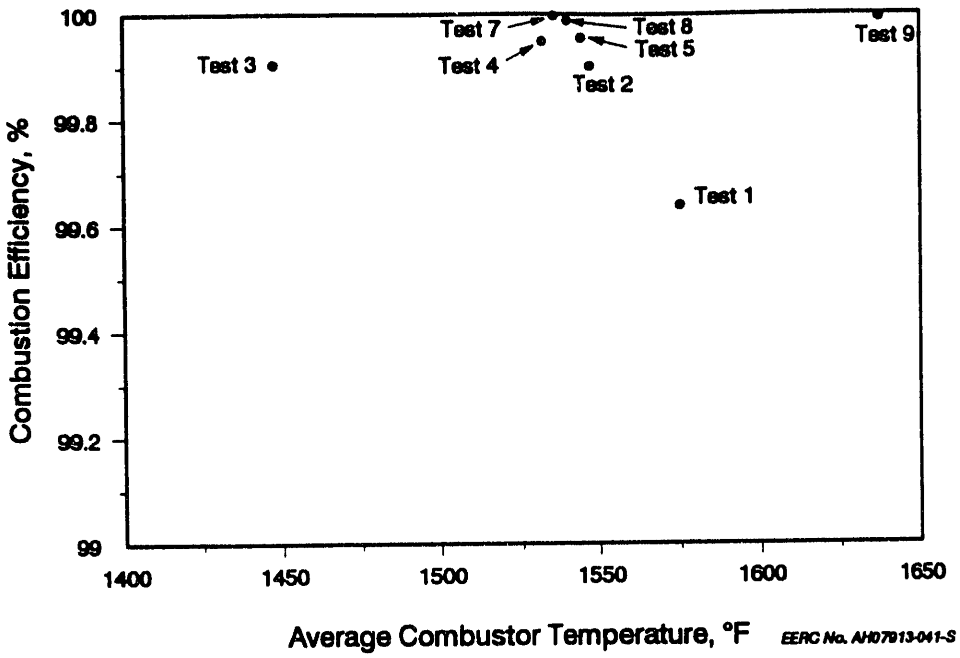

Figure D-3. Combustion efficiencies.

TABLE D-14

Unburned Carbon (%)

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9
Combustor Bed Material								
Loss on Ignition	0.24	0.56	4.01	3.41	3.41	0.37	0.94	0.62
Carbonate (as CO_2)	0.11	0.44	4.09	3.22	3.22	0.56	0.75	0.64
Unburned Carbon	0.21	0.44	2.89	2.53	2.53	0.22	0.74	0.45
Secondary Cyclone Ash								
Loss on Ignition	1.19	NA[1]	NA	NA	NA	NA	NA	NA
Carbonate (as CO_2)	0.4	NA	NA	NA	NA	NA	NA	NA
Unburned Carbon	1.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Baghouse Ash								
Loss on Ignition	8.94	1.47	1.56	0.97	0.97	0.27	0.4	0.28
Carbonate (as CO_2)	0.51	0.46	0.79	0.58	0.58	0.34	0.46	0.51
Unburned Carbon	8.80	1.34	1.34	0.81	0.81	0.18	0.27	0.14

[1] Not applicable.

Table D-15 summarizes the results of the boiler efficiency calculations for this run. Boiler radiation and convective losses were assumed to be 0.4%; although the actual losses at the pilot scale are much greater, 0.4% was chosen to be representative of a full-scale system. The exit gas temperature was assumed to be 300°F.

TABLE D-15

Boiler Efficiency

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9
Assumed Flue Gas Exit Temp., °F	300	300	300	300	300	300	300	300
Losses, Btu/hr								
Dry Gas	130,817	134,137	139,894	134,977	130,910	112,041	137,204	134,839
Water in Fuel	85,152	91,427	97,044	105,914	91,788	77,957	81,801	88,864
Comb. of Fuel Hydrogen	10,954	11,761	12,484	13,625	11,808	10,029	10,523	11,432
Unburned Carbon	6,577	1,914	1,969	1,155	869	55	213	145
Sorbent Calcination	0	5,668	77	11,107	4,673	2,681	5,209	4,136
Radiation and Convection *	8,969	9,630	10,221	11,155	9,668	8,211	8,616	9,360
Discharged Solids	5,611	3,994	3,018	3,951	3,002	869	2,172	3,066
Sorbent Sulfation	0	-2,662	-100	-3,375	-2,014	-1,582	-3,003	-2,578
Total	248,079	255,867	264,607	278,059	250,703	210,260	242,735	249,263
Losses, %								
Dry Gas	6.0	5.7	5.4	5.0	5.5	5.7	6.5	5.7
Water in Fuel	3.9	3.9	3.7	3.9	3.8	3.9	3.8	3.8
Comb. of Fuel Hydrogen	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Unburned Carbon	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Sorbent Calcination	0.0	0.2	0.0	0.4	0.2	0.1	0.2	0.2
Radiation and Convection *	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Discharged Solids	0.3	0.2	0.1	0.1	0.1	0.0	0.1	0.1
Sorbent Sulfation	0.0	-0.1	0.0	-0.1	-0.1	-0.1	-0.1	-0.1
Total	11.5	10.8	10.2	10.2	10.4	10.6	11.4	10.6
Boiler Efficiency	88.5	89.2	89.8	89.8	89.6	89.4	88.6	89.4

* Assumes 0.4% radiative and convective losses.

Boiler efficiencies for this run ranged from 88.6% to 89.9%. The moisture and hydrogen in the fuel accounted for about 4.3% of the losses in all tests. The difference in boiler efficiencies between the eight tests is due to differences in the loss from the dry flue gas; this was greatest (6.5%) for Test 8, the high excess air test, and lowest (5.0%) for Test 4, the low excess air test.

Heat-Transfer Coefficient and Heat Flux

The heat-transfer coefficients and heat flux for each of the combustor sections containing heat exchange surface, as well as the EHX, are shown in Tables D-16 and D-17, respectively. The overall values for each test are also presented in Table D-5 to facilitate comparison with test conditions. The combustor heat fluxes for this run ranged from 26,339 Btu/hr-ft^2 for Test 3, the low-temperature test, to 34,009 Btu/hr-ft^2 for Test 9, the high-temperature, high-velocity test. Test 7, the low-load test which was conducted at low velocity and an intermediate operating temperature, also had a low average heat flux of 26,919 Btu/hr-ft^2. Inspection of the data in Table D-5 shows that for those tests in which secondary cyclone ash was recycled back into the system the solids recirculation rate was highest for Test 9 and lowest for Test 7. Therefore, both the average combustor temperature and the solids recirculation rate had a significant effect on heat flux for the Black Thunder subbituminous coal.

Table D-16

Individual Heat-Transfer Coefficients, Btu/hr-ft^2-°F

Combustor Section	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9	Average	Combustor Height
2	20.2	21.9	20.8	20.9	21.9	19.0	19.1	21.5	20.7	7.5
3	24.6	23.6	22.8	23.0	22.8	21.2	21.7	24.4	23.0	12.5
4	25.3	39.4	30.7	26.9	39.5	27.3	28.5	32.6	31.3	17.5
5	26.5	28.3	27.2	27.7	26.7	23.9	25.3	29.1	26.8	22.5
6	19.9	18.1	16.7	18.0	18.1	15.7	17.7	20.4	18.1	27.5
7	14.5	21.0	17.4	18.3	10.5	16.2	17.8	21.2	17.1	32.5
8	16.8	16.8	17.1	off	8.8	off	off	off	14.9	37.5
Overall	20.0	23.4	20.0	20.5	23.6	19.0	20.2	22.8	21.2	
EHX	66.3	82.6	78.9	82.0	81.9	56.1	78.0	79.6	75.7	

TABLE D-17

Individual Heat Flux, Btu/hr-ft^2

Combustor Section	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9	Average	Combustor Height
2	30,796	31,699	28,048	29,811	31,553	27,739	27,793	32,679	30,015	7.5
3	35,394	33,301	30,196	32,300	32,178	29,895	30,588	36,182	32,504	12.5
4	34,599	54,093	40,357	37,430	54,121	37,610	39,474	47,775	43,182	17.5
5	36,524	39,658	35,700	38,541	37,456	33,567	35,703	43,284	37,554	22.5
6	27,581	26,052	22,565	25,856	25,997	22,185	25,120	30,749	25,763	27.5
7	20,153	29,946	22,994	26,164	14,903	22,471	25,154	31,912	24,212	32.5
8	23,095	24,278	22,913	off	12,712	off	off	off	20,750	37.5
Overall	28,628	32,929	26,339	28,795	33,076	26,919	28,570	34,009	29,908	
EHX	55,008	96,751	84,360	95,839	96,734	59,614	96,647	111,169	87,015	

Heat flux in the EHX ranged from 55,008 Btu/hr-ft^2 to 111,169 Btu/hr-ft^2 for Tests 1 and 9, respectively. The EHX heat flux for Test 7 was only slightly higher than during Test 1 at 59,614 Btu/hr-ft^2 and reflects the change in the size distribution of the bed material in the EHX, as well as the increase in solids recirculation rate with secondary cyclone recycle after Test 1.

Pressure and Temperature Profiles

The pressure profiles for this run are shown in Figure D-4 and are typical of a CFB, with a dense phase in the lower portion of the combustor, similar to a bubbling bed, and a dilute phase in the rest of the combustor. The pressure profiles for all eight tests are quite uniform, with some variation due to differences in bed inventory and superficial gas velocity in the combustor.

Figure D-5 shows the temperature profiles for each test. The lower temperature at the bottom of the combustor is the result of cooler solids flowing into combustor Section 1 from the external heat exchanger. The temperature distribution in Test 1, with a much higher temperature in the bottom than at the top, is a function of the low solids recirculation rate (2245 lb/hr) resulting from the removal of secondary cyclone ash from the system.

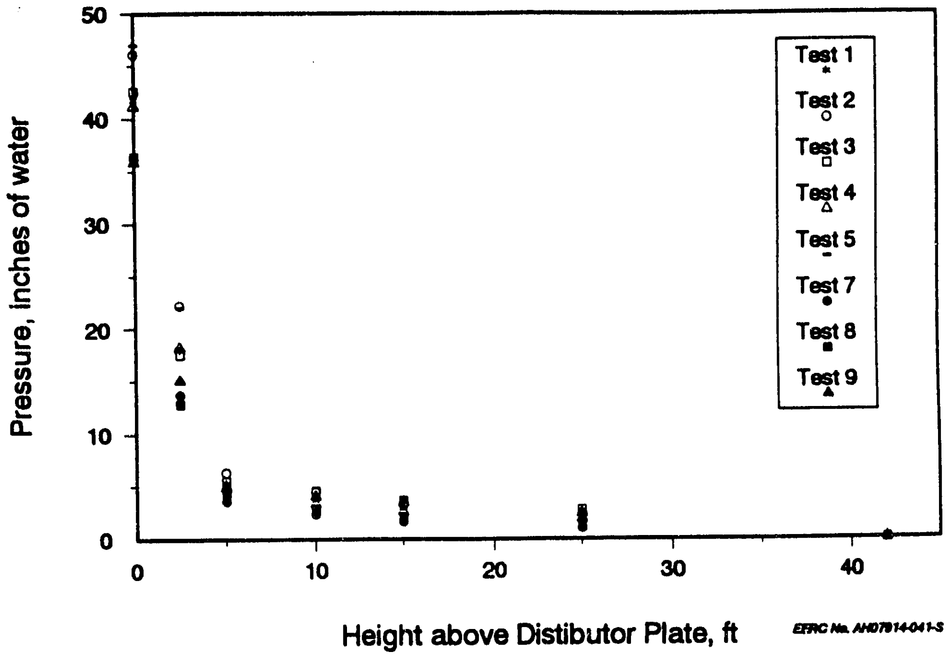

Figure D-4. Combustor pressure profiles.

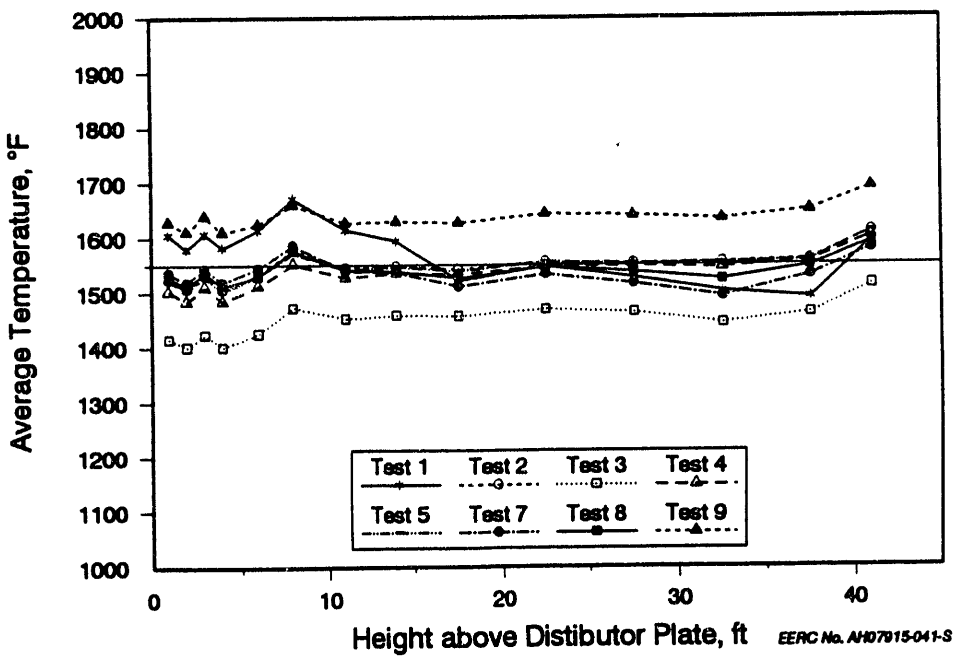

Figure D-5. Combustor temperature profiles.

ENVIRONMENTAL PERFORMANCE

Average flue gas emissions for each of the steady-state test periods are presented in Table D-18 and discussed in the following sections.

SO_2 Emissions

The sulfur retention for the low-, medium-, and high-temperature tests (Tests 3, 2, and 9, respectively) are shown as a function of temperature in Figure D-6. The expected trend is optimum sulfur capture at a particular temperature or temperature range, with less sulfur capture at lower and higher temperatures. For the Black Thunder subbituminous coal, optimum sulfur capture appears to occur at or near 1450°F. Test 9 had much higher sulfur retention than expected; this is due to the relatively large amount of limestone added to the system prior to this test. The high recirculation rate (>16,000 lb/hr) indicated that most of the limestone stayed in the system, rather than being removed in the secondary cyclone drain.

TABLE D-18

Emission Data

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 7	Test 8	Test 9
O_2, %	5.15	4.44	4.06	1.72	3.85	4.00	6.38	4.88
CO Content, ppm	2	10	17	11	7	7	4	6
CO Content,[1] ppm	3	11	18	10	8	7	5	6
CO Emission, lb/MM Btu	0.002	0.009	0.015	0.008	0.006	0.006	0.004	0.005
CO_2 Content, %	15.0	15.4	15.6	17.8	16.2	16.0	13.9	15.0
CO_2 Content,[1] %	17.1	16.8	16.6	16.6	17.0	16.9	17.2	16.7
NO_x Content, ppm	218	174	156	136	156	177	205	227
NO_x Content,[1] ppm	248	189	166	127	164	188	252	253
NO_x Emission, lb/MM Btu	0.321	0.249	0.221	0.169	0.213	0.245	0.324	0.334
N_2O Content, ppm	22	40	58	32	N/A[2]	35	31	22
N_2O Content,[1] ppm	25	44	62	30	0	37	38	24
N_2O Emission, lb/MM Btu	0.031	0.055	0.079	0.038	0.000	0.046	0.046	0.031
SO_2 Content,[3] ppm	341	80	4	128	135	98	11	38
SO_2 Content,[1] ppm	388	87	4	120	142	103	13	43
SO_2 Emission, lb/MM Btu	0.698	0.160	0.007	0.221	0.256	0.188	0.023	0.079
SO_2 Retention,[3] %	2.9	77.7	99.0	69.3	64.3	73.9	96.8	89.1
Ca/S ratio (ls[4] only)	0.0	2.5	0.0	4.3	2.1	1.4	2.6	1.9
Ca/S ratio (total)	2.06	4.60	2.10	6.36	4.15	3.47	4.67	3.97
Ca Utiliz. (ls[4] only)	0.0	30.6	0.0	16.1	30.9	52.5	37.1	46.8
Ca Utiliz. (total)	1.4	16.9	47.2	10.9	15.5	21.3	20.7	22.4
Alkali-to-Sulfur (total)	2.11	4.64	2.14	6.40	4.19	3.51	4.71	4.01
Alkali Utilization	1.4	16.7	46.3	10.8	15.4	21.0	20.5	22.2
Avg. Comb. Temp., °F	1575	1547	1448	1532	1545	1536	1540	1637
Moisture in FG, %	11.6	12.0	12.2	13.4	12.3	12.2	10.9	11.7
Moist-Free Coal Carbon, %	68.8	68.8	68.8	68.8	68.8	68.8	68.8	68.8
Moist-Free Coal Sulfur, %	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4

[1] Corrected to 3% O_2.
[2] Not available.
[3] Moisture-free coal carbon and sulfur values used in the sulfur retention calculation.
[4] Limestone.

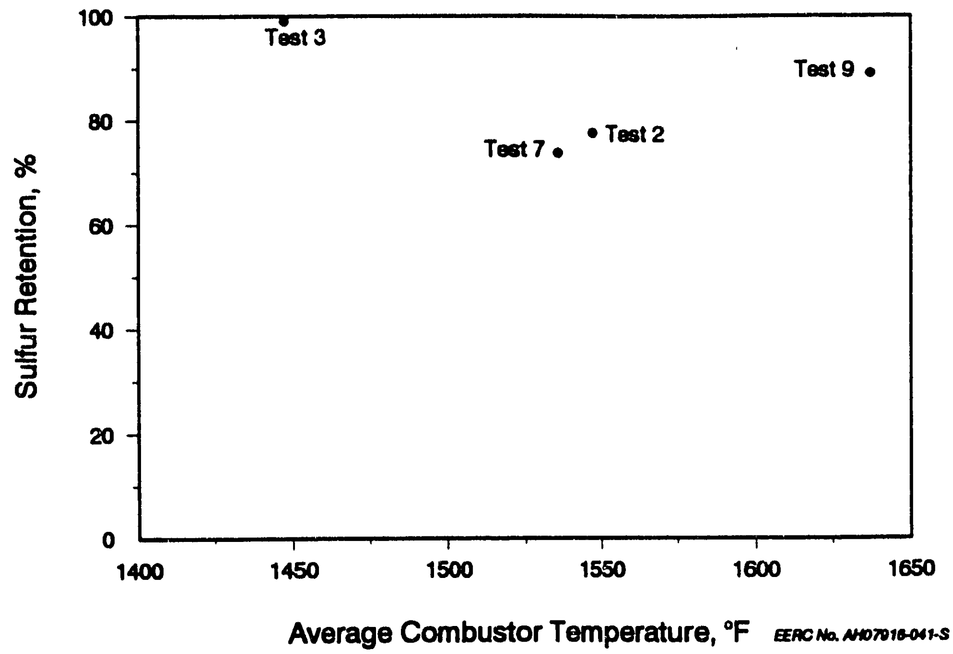

Figure D-6. Sulfur retention as a function of average combustor temperature.

Figure D-7 shows the effect of excess air on sulfur emissions for three tests with similar temperatures: Tests 2, 4, and 8. As expected, the high excess air test had the lowest sulfur emissions.

Finally, the effect of alkali-to-sulfur ratio on sulfur retention is shown in Figure D-8. Tests 1, 2, and 5 were operated at similar temperature and excess air. Test 1, with no limestone feed, served as the baseline for sulfur emissions. Sulfur retention increases with increasing alkali-to-sulfur ratio.

NO_x Emissions

NO_x emissions for this coal ranged from 127 ppm (corrected to 3% O_2) for Test 4, to 253 ppm (corrected to 3% O_2) for Test 9. Figure D-9 shows the NO_x emissions as a function of temperature for Tests 2, 3, 7, and 9. There appears to be a slight relationship between temperature and NO_x emissions for Tests 3, 7, and 2; the higher NO_x for Test 9 shows the additional effects of higher excess air and calcium in the bed.

Typically, there is a positive relationship between NO_x emissions and limestone addition; however, this coal produced the opposite effect, as shown in Figure D-10. Tests 2, 5, and 7 had similar temperatures (1545°, 1541°, and 1532°F, respectively) and excess air levels (26.7%, 22.5%, and 23.5%, respectively); Test 1 had both higher temperature (1573°F) and higher excess air (33.8%), which may account for some of the difference.

Figure D-11 shows the NO_x emissions as a function of excess air for Tests 2, 4, and 8. These tests had similar temperatures (1529° to 1545°F); Tests 2 and 8 had added calcium-to-sulfur ratios of about 2.5; Test 4 had an added calcium-to-sulfur ratio of 4.3. There is a strong positive correlation between excess air and NO_x emissions for these three tests.

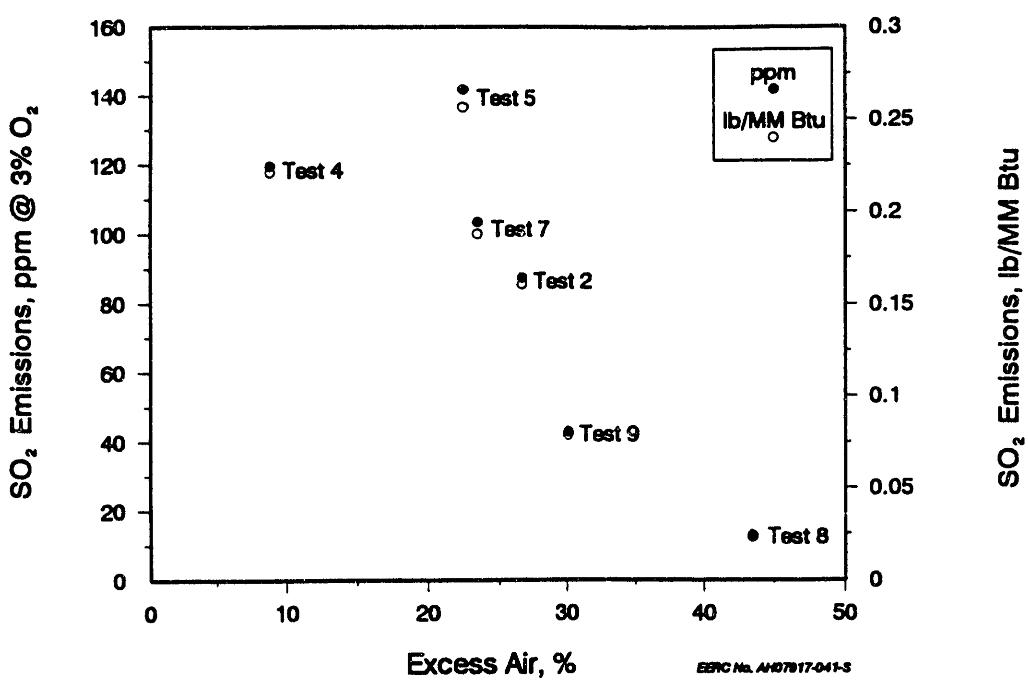

Figure D-7. SO_2 emissions as a function of excess air.

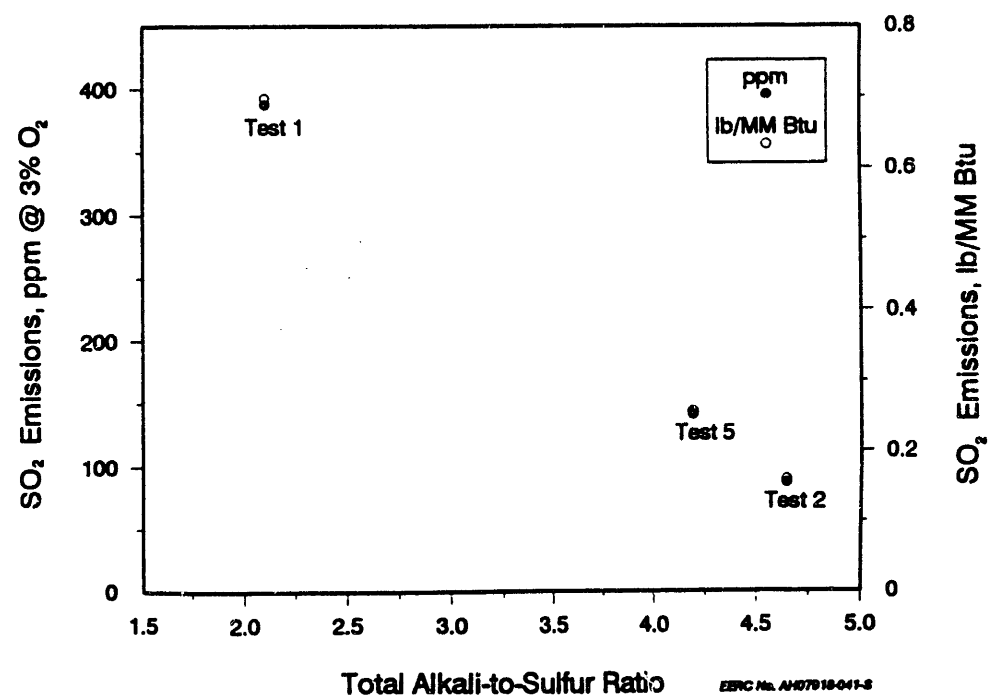

Figure D-8. SO_2 emissions as a function of alkali-to-sulfur ratio.

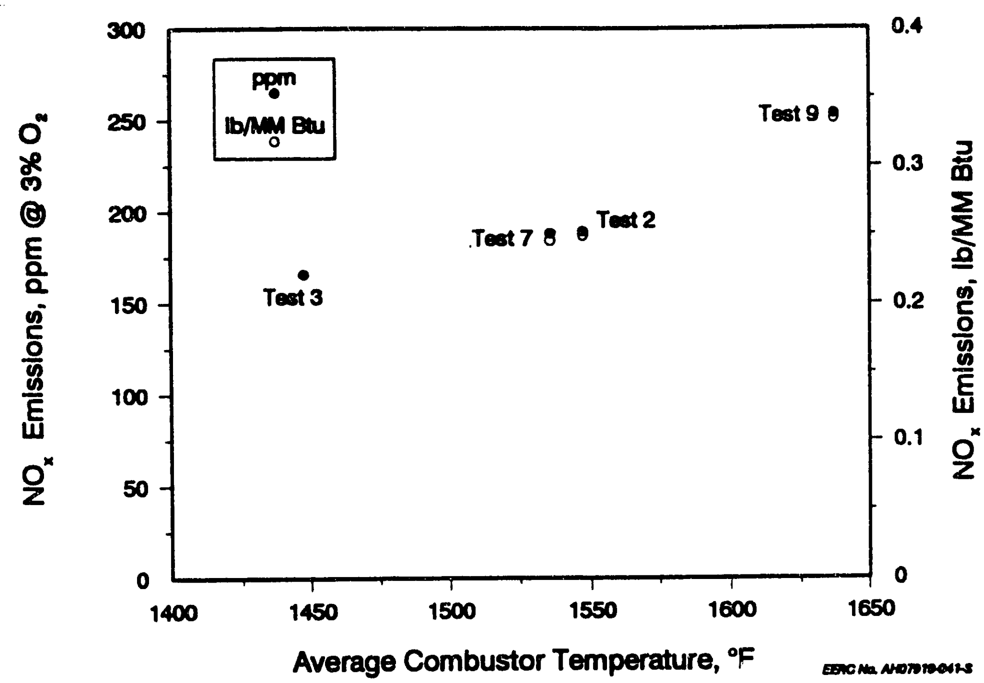

Figure D-9. NO_x emissions as a function of average combustor temperature.

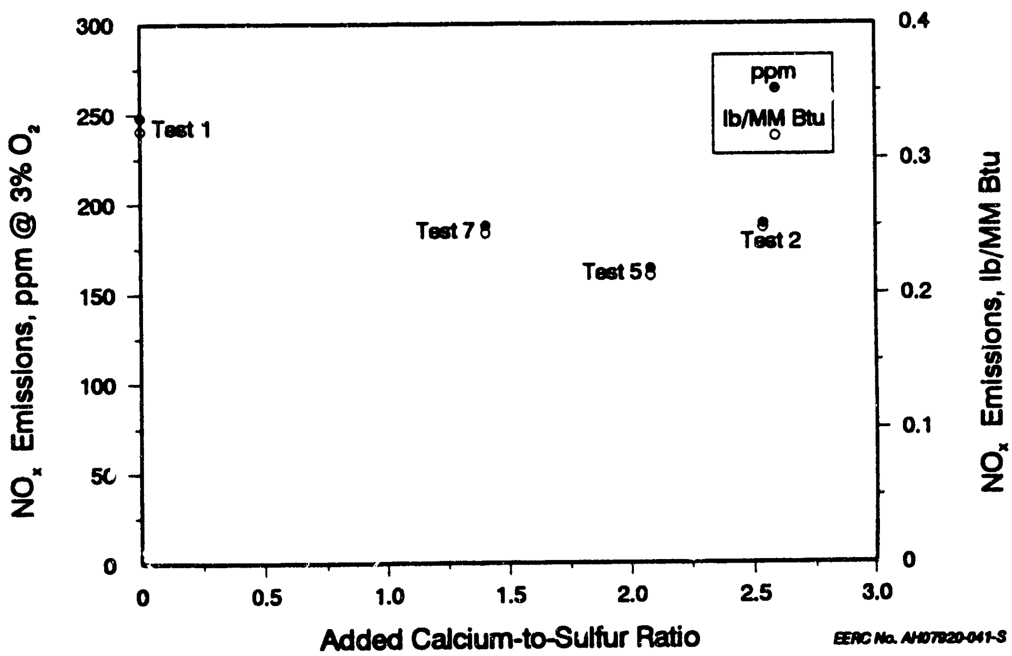

Figure D-10. Relationship between NO_x emissions and added calcium-to-sulfur ratio.

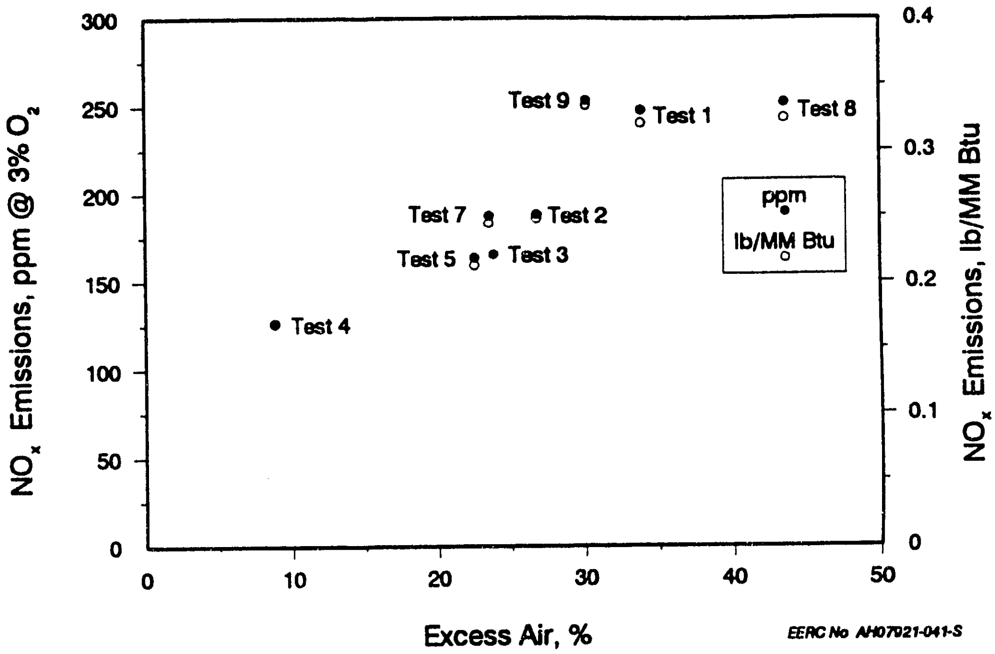

Figure D-11. NO_x emissions as a function of excess air.

N_2O Emissions

The N_2O emissions for all 7 tests (no N_2O measurements were made during Test 5) were quite low; Test 3 had the highest N_2O emissions at 62 ppm (corrected to 3% O_2). The N_2O emissions as a function of average combustor temperature are shown in Figure D-12. As expected, levels of N_2O decreased as combustor temperature increased. However, N_2O emissions, like NO_x, showed an unexpected relationship with alkali-to-sulfur ratio.

All three tests were operated at approximately the same temperature (from 1529°F for Test 4 to 1545°F for Test 2), and Tests 2 and 8 had the same calcium-to-sulfur ratio (2.5), while Test 4 had a higher calcium-to-sulfur ratio (4.3). At this temperature, there is no specific effect of excess air on N_2O.

CO Emissions

CO emissions for the entire run were very low, with a high of 18 ppm (corrected to 3% O_2) for Test 3. Figure D-13 shows a decrease in CO emissions as average combustor temperature increases.

SUMMARIES OF TEST DATA

This section contains the summaries of test data for each test period, including averages and standard deviations of many of the data points recorded by the computerized data acquisition system.

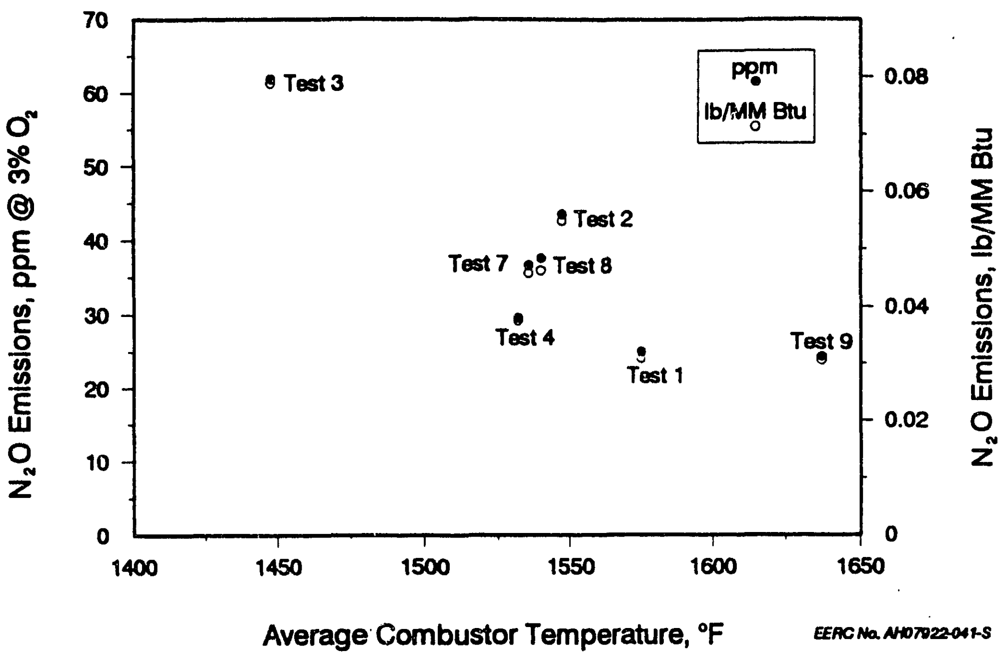

Figure D-12. N_2O emissions as a function of average combustor temperature.

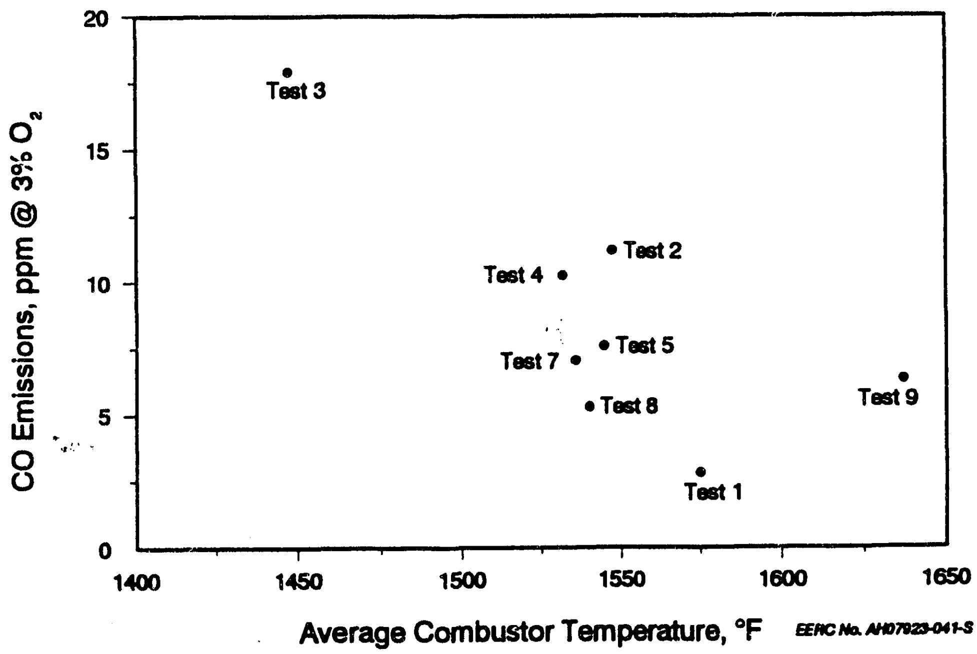

Figure D-13. CO emissions as a function of average combustor temperature.

18-Nov-91

CFB-BT1-0891 — TEST 1

(1325-1425)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1554	22.4
TC11021	AFS Ex	°F	432	5.3
TC15001	C Plenum	°F	525	5.3
TC15004	C 1-1'	°F	1605	14.0
TC15005	C 1-2'	°F	1580	14.5
TC15006	C 1-3'	°F	1608	14.6
TC15007	C 1-4'	°F	1571	14.1
TC15008	C 1-4'	°F	1598	14.7
TC15009	C 1-4'	°F	1578	16.4
TC15012	C 2-6'	°F	1614	14.2
TC15013	C 2-8'	°F	1672	12.6
TC15022	C 3-11'	°F	1614	13.9
TC15023	C 3-14'	°F	1590	10.8
TC15024	C 3-14'	°F	1583	11.8
TC15025	C 3-14'	°F	1608	13.2
TC15032	C 4-17.5'	°F	1522	10.5
TC15042	C 5-22.5'	°F	1548	10.7
TC15052	C 6-27.5'	°F	1540	11.9
TC15053	C 6-27.5'	°F	1553	12.7
TC15054	C 6-27.5'	°F	1490	14.2
TC15062	C 7-32.5'	°F	1502	21.8
TC15071	C 8-37.5'	°F	1491	14.5
TC15073	C 9-41'	°F	1594	19.6
TC15999	Ambient	°F	74	0.8
TC16001	EHX Plenm	°F	122	1.6
TC16012	EHX 0.5'	°F	959	36.3
TC16013	EHX 1.5'	°F	942	32.3
TC16014	EHX 2.7'	°F	950	35.0
TC16015	EHX 3.8'	°F	926	25.2
TC16017	EHX 5.3'	°F	843	15.2
TC16018	EHX Exit	°F	900	28.4
TC16021	Crc A in	°F	1582	17.6
TC16031	DC 8-36'	°F	1576	17.6
TC16032	DC 6-28'	°F	1553	18.6
TC16033	DC 4-18'	°F	1520	12.6
TC16034	DC3-9.5'	°F	1552	13.7
TC16035	DC3-8.5'	°F	1539	11.9

T(A,C)	Comb Temp	°F	1575	11.5
T(A,EHX)	EHX Temp	°F	950	34.9
EA	Excess Air	%	33.8	13.0
SR	S Reten	%	15.2	12.1
R(PCA)	% Flw PCA	%	59.6	2.0
R(SCA)	% Flw SCA	%	40.4	2.0
R(Q,IN)	% Enrg in	%	76.0	5.1
R(CHX)	CHX Ratio	%	62.4	2.2
R(EHX)	EHX Ratio	%	37.6	2.2
F(PCA)	PCA Flw	scfm	225.4	20.5
F(EHX)	EHX Flw	scfm	62.2	2.5
F(TPA)	TPCA Flw	scfm	290.0	19.9
F(SCA)	SCA Flw	scfm	160.4	4.5
F(TAIR)	TCA Flw	scfm	485.7	18.8
F(FG,BH)	BH Flw	scfm	518.9	5.2
F(TFG)	TFG Flw	scfm	518.9	5.2
W(SR)	Recirc Rt	lbs/hr	2245	150.4

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 10

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	45	148	1672	3.10	160140	20.2	30796
3NE,SW	14	44	155	1594	3.30	184046	24.6	35394
4SE,NW	17.5	44	153	1522	3.30	179916	25.3	34599
5E	22.5	44	171	1548	1.50	94963	26.5	36524
6NE	27.5	46	141	1528	1.50	71710	19.9	27581
7SE	32.5	44	109	1502	1.60	52397	14.5	20153
8W	37.5	47	117	1491	1.70	60048	16.8	23095
	Overall	44	145	1575	14.68	744325	20.0	28628
			From Data Sheets=>		16.00			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-9	9	43	120	950	9.62	371307	66.3	55008
			From Data Sheets=>		10.60			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	341	105.0	SO2-A	ppm	372	79.2
SO2-AE	lb/MM Btu	0.68	0.2				
SO2-B	ppm	351	103.0	SO2-B	ppm	301	88.3
SO2-BE	lb/MM Btu	0.70	0.2				
CO	ppm	2	0.5	CO	ppm	3	0.7
CO2	%	15.02	1.3	CO2	%	16.70	0.7
N2O	ppm	22	2.0	N2O	ppm	25	4.1
N2OE	lb/Mm Btu	0.03	0.0				
NOx	ppm	218	18.5	NOx	ppm	246	42.2
NOxE	lb/Mm Btu	0.32	0.1				
O2-A	%	5.15	1.5				
O2-B	%	4.78	1.6				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	250	23.2	TC13131	AFPE-F2"	888	40.0
W(S)	LS Fd Rt	lbs/hr	0	0.0	TC13132	AFPE-F6"	1046	30.5
V(FG)	FG SGV	ft/sec	16.1	0.4	TC13133	AFPE-B6"	926	46.4
V(S,C)	Comb SGV	ft/sec	14.5	0.6	TC13134	AFPE-F10"	577	59.7
V(S,EHX)	EHX SGV	ft/sec	1.8	0.1	TC13231	AFPW-F2"	911	35.9
FT18003	CHX Flow	gpm	14.7	0.4	TC13232	AFPW-F6"	1035	27.5
FT19003	EHX Flow	gpm	9.6	0.2	TC13233	AFPW-B6"	812	27.6
PT15081	Comb dP	in. H2O	41.8	1.5	TC13234	AFPW-F10'	953	33.3
Q(CA)	CA Heat in	KBtu/hr	92.9	4.5	DOORS	CHXs On	10	0
Q(CHX)	CHX HtRmv	KBtu/hr	619.2	36.8	COILS	EHXs On	9	0
Q(EHX)	EHX HtRmv	KBtu/hr	372.6	19.4	BH A/C		2.0	0.0
Q(EHX,IN	E FG Ht in	KBtu/hr	2.8	0.4	A/SRATIO		1.8	0.0
Q(F)	Fuel Enrg in	KBtu/hr	2227.3	206.1	Feed Air	scfm	17.9	
Q(FG)	FG Enrg out	KBtu/hr	258.2	2.0	DC Air	scfm	0.0	
Q(IN)	Tot Enrg in	KBtu/hr	2322.9	204.8	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1755.1	34.1				

20-Nov-91

CFB-BT1-0891 — TEST 2

(0930-1220)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1548	5.8
TC11021	AFS Ex	°F	1417	8.7
TC15001	C Plenum	°F	578	7.0
TC15004	C 1-1'	°F	1524	7.9
TC15005	C 1-2'	°F	1507	7.3
TC15006	C 1-3'	°F	1532	7.6
TC15007	C 1-4'	°F	1501	7.2
TC15008	C 1-4'	°F	1513	7.5
TC15009	C 1-4'	°F	1500	7.2
TC15012	C 2-6'	°F	1534	7.0
TC15013	C 2-8'	°F	1578	7.3
TC15022	C 3-11'	°F	1546	5.5
TC15023	C 3-14'	°F	1547	5.7
TC15024	C 3-14'	°F	1539	4.7
TC15025	C 3-14'	°F	1561	6.6
TC15032	C 4-17.5'	°F	1542	4.8
TC15042	C 5-22.5'	°F	1556	4.3
TC15052	C 6-27.5'	°F	1569	4.5
TC15053	C 6-27.5'	°F	1569	5.6
TC15054	C 6-27.5'	°F	1523	6.1
TC15062	C 7-32.5'	°F	1555	4.1
TC15071	C 8-37.5'	°F	1560	4.6
TC15073	C 9-41'	°F	1611	6.1
TC15999	Ambient	°F	77	1.4
TC16001	EHX Plenm	°F	122	3.0
TC16012	EHX 0.5'	°F	1345	11.0
TC16013	EHX 1.5'	°F	1313	10.6
TC16014	EHX 2.7'	°F	1329	10.6
TC16015	EHX 3.8'	°F	1309	8.3
TC16017	EHX 5.3'	°F	1239	6.5
TC16018	EHX Exit	°F	1301	12.1
TC16021	Crc A in	°F	1570	5.4
TC16031	DC 8-36'	°F	1556	11.0
TC16032	DC 6-28'	°F	1541	10.0
TC16033	DC 4-18'	°F	1519	29.2
TC16034	DC3-9.5'	°F	1544	32.9
TC16035	DC3-8.5'	°F	1496	41.5

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 10

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	44	133	1578	3.70	164833	21.9	31699
3NE,SW	14	44	137	1549	3.73	173165	23.6	33301
4SE,NW	17.5	43	170	1542	4.43	281281	39.4	54093
5E	22.5	44	154	1556	1.87	103110	28.3	39658
6NE	27.5	44	118	1554	1.83	67736	18.1	26052
7NW	32.5	46	131	1555	1.83	77859	21.0	29946
8W	37.5	45	114	1560	1.83	63122	16.8	24278
	Overall	44	141	1547	17.60	856153	23.4	32929
			From Data Sheets=>		19.22			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-2,5-7,	8	42	158	1328	10.07	580504	82.6	96751
10-12			From Data Sheets=>		10.87			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	80	34.1	SO2-A	ppm	84	33.6
SO2-AE	lb/MM Btu	0.16	0.1				
SO2-B	ppm	91	44.4	SO2-B	ppm	78	38.0
SO2-BE	lb/MM Btu	0.18	0.1				
CO	ppm	10	14.0	CO	ppm	11	13.2
CO2	%	15.41	0.5	CO2	%	16.20	0.4
N2O	ppm	40	1.3	N2O	ppm	43	2.3
N2OE	lb/Mm Btu	0.06	0.0				
NOx	ppm	174	14.0	NOx	ppm	183	21.9
NOxE	lb/Mm Btu	0.25	0.0				
O2-A	%	4.44	0.5				
O2-B	%	3.87	0.7				

T(A,C)	Comb Temp	°F	1547	4.5
T(A,EHX)	EHX Temp	°F	1328	10.7
EA	Excess Air	%	26.7	4.1
SR	S Reten	%	80.9	7.7
R(PCA)	% Flw PCA	%	60.0	4.7
R(SCA)	% Flw SCA	%	40.0	4.7
R(Q,IN)	% Enrg in	%	78.8	4.3
R(CHX)	CHX Ratio	%	52.1	1.4
R(EHX)	EHX Ratio	%	47.9	1.4
F(PCA)	PCA Flw	scfm	245.9	26.5
F(EHX)	EHX Flw	scfm	49.4	1.2
F(TPA)	TPCA Flw	scfm	291.1	24.3
F(SCA)	SCA Flw	scfm	159.5	25.3
F(TAIR)	TCA Flw	scfm	485.2	19.8
F(FG,BH)	BH Flw	scfm	596.8	12.6
F(TFG)	TFG Flw	scfm	596.8	12.6
W(SR)	Recirc Rt	lbs/hr	10274	1222.9

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	273	13.2
W(S)	LS Fd Rt	lbs/hr	7	1.2
V(FG)	FG SGV	ft/sec	16.1	0.7
V(S,C)	Comb SGV	ft/sec	14.2	0.6
V(S,EHX)	EHX SGV	ft/sec	1.8	0.1
FT18003	CHX Flow	gpm	17.6	0.3
FT19003	EHX Flow	gpm	10.1	0.1
PT15081	Comb dP	in. H2O	46.1	2.3
Q(CA)	CA Heat in	KBtu/hr	100.1	5.2
Q(CHX)	CHX HtRmv	KBtu/hr	632.5	31.2
Q(EHX)	EHX HtRmv	KBtu/hr	581.3	18.9
Q(EHX,IN	E FG Ht in	KBtu/hr	2.2	0.2
Q(F)	Fuel Enrg in	KBtu/hr	2418.9	130.4
Q(FG)	FG Enrg out	KBtu/hr	296.0	6.2
Q(IN)	Tot Enrg in	KBtu/hr	2518.6	128.6
Q(OUT)	Tot Enrg out	KBtu/hr	1992.6	39.6

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	758	40.3
TC13132	AFPE-F6"	962	31.4
TC13133	AFPE-B6"	765	47.2
TC13134	AFPE-F10"	374	58.0
TC13231	AFPW-F2"	788	32.0
TC13232	AFPW-F6"	954	24.6
TC13233	AFPW-B6"	660	30.2
TC13234	AFPW-F10'	832	36.3
DOORS	CHXs On	10	0
COILS	EHXs On	8	0
BH A/C		2.3	0.0
A/SRATIO		3.9	0.5
Feed Air	scfm	18.5	
DC Air	scfm	4.2	
Purge Air	scfm	15.5	

20-Nov-91

CFB-BT1-0891 — TEST 3

(1625-2100)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1474	8.7
TC11021	AFS Ex	°F	1366	8.9
TC15001	C Plenum	°F	587	5.6
TC15004	C 1-1'	°F	1416	17.5
TC15005	C 1-2'	°F	1402	16.8
TC15006	C 1-3'	°F	1423	16.9
TC15007	C 1-4'	°F	1397	15.9
TC15008	C 1-4'	°F	1410	16.7
TC15009	C 1-4'	°F	1397	16.4
TC15012	C 2-6'	°F	1425	17.2
TC15013	C 2-8'	°F	1473	17.6
TC15022	C 3-11'	°F	1453	13.5
TC15023	C 3-14'	°F	1456	11.4
TC15024	C 3-14'	°F	1448	12.7
TC15025	C 3-14'	°F	1472	13.4
TC15032	C 4-17.5'	°F	1457	10.7
TC15042	C 5-22.5'	°F	1469	10.4
TC15052	C 6-27.5'	°F	1477	10.4
TC15053	C 6-27.5'	°F	1479	11.1
TC15054	C 6-27.5'	°F	1437	8.1
TC15062	C 7-32.5'	°F	1444	8.3
TC15071	C 8-37.5'	°F	1463	7.8
TC15073	C 9-41'	°F	1514	10.9
TC15999	Ambient	°F	79	1.4
TC16001	EHX Plenm	°F	125	4.7
TC16012	EHX 0.5'	°F	1230	25.4
TC16013	EHX 1.5'	°F	1212	25.5
TC16014	EHX 2.7'	°F	1207	24.4
TC16015	EHX 3.8'	°F	1218	17.5
TC16017	EHX 5.3'	°F	1165	12.3
TC16018	EHX Exit	°F	1200	21.4
TC16021	Crc A in	°F	1487	10.9
TC16031	DC 8-36'	°F	1473	8.1
TC16032	DC 6-28'	°F	1463	8.6
TC16033	DC 4-18'	°F	1437	34.8
TC16034	DC3-9.5'	°F	1464	37.7
TC16035	DC3-8.5'	°F	1463	20.6

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 12

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	43	126	1473	3.48	145847	20.8	28048
3NE,SW	14	43	135	1459	3.38	157019	22.8	30196
4SE,NW	17.5	44	144	1457	4.18	209856	30.7	40357
5E	22.5	43	158	1469	1.62	92820	27.2	35700
6NE	27.5	44	116	1464	1.62	58668	16.7	22565
7SE,NW	32.5	45	120	1444	3.20	119568	17.4	22994
8E,W	37.5	44	121	1463	3.10	119148	17.1	22913
	Overall	43	131	1448	18.52	821767	20.0	26339
			From Data Sheets=>		20.58			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-12	12	41	147	1216	14.39	759244	78.9	84360
			From Data Sheets=>		16.00			

EMISSIONS DATA

As Measured: Tag	Units	Average	Std Dev	Corrected to 3% O2: Tag	Units	Average	Std Dev
SO2-A	ppm	4	2.8	SO2-A	ppm	4	3.0
SO2-AE	lb/MM Btu	0.01	0.0				
SO2-B	ppm	1	0.6	SO2-B	ppm	1	0.7
SO2-BE	lb/MM Btu	0.00	0.0				
CO	ppm	17	4.0	CO	ppm	18	4.4
CO2	%	15.58	0.6	CO2	%	16.55	0.3
N2O	ppm	58	2.5	N2O	ppm	62	3.7
N2OE	lb/Mm Btu	0.08	0.0				
NOx	ppm	156	10.9	NOx	ppm	166	15.9
NOxE	lb/Mm Btu	0.22	0.0				
O2-A	%	4.06	0.5				
O2-B	%	3.71	0.5				

T(A,C)	Comb Temp	°F	1448	12.5
T(A,EHX)	EHX Temp	°F	1216	24.1
EA	Excess Air	%	23.8	3.4
SR	S Reten	%	99.2	0.7
R(PCA)	% Flw PCA	%	60.1	4.1
R(SCA)	% Flw SCA	%	39.9	4.1
R(Q,IN)	% Enrg in	%	75.2	4.3
R(CHX)	CHX Ratio	%	46.1	3.8
R(EHX)	EHX Ratio	%	53.9	3.8
F(PCA)	PCA Flw	scfm	253.9	31.3
F(EHX)	EHX Flw	scfm	51.5	10.7
F(TPA)	TPCA Flw	scfm	306.9	28.0
F(SCA)	SCA Flw	scfm	169.1	20.5
F(TAIR)	TCA Flw	scfm	510.5	25.6
F(FG,BH)	BH Flw	scfm	610.6	4.1
F(TFG)	TFG Flw	scfm	610.6	4.1
W(SR)	Recirc Rt	lbs/hr	11205	1416.7

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	301	10.6
W(S)	LS Fd Rt	lbs/hr	0	0.0
V(FG)	FG SGV	ft/sec	16.0	0.7
V(S,C)	Comb SGV	ft/sec	14.3	0.6
V(S,EHX)	EHX SGV	ft/sec	1.8	0.4
FT18003	CHX Flow	gpm	18.5	0.5
FT19003	EHX Flow	gpm	14.4	0.3
PT15081	Comb dP	in. H2O	42.6	3.6
Q(CA)	CA Heat in	KBtu/hr	106.7	6.9
Q(CHX)	CHX HtRmv	KBtu/hr	638.4	33.7
Q(EHX)	EHX HtRmv	KBtu/hr	752.2	75.8
Q(EHX,IN	E FG Ht in	KBtu/hr	2.5	0.7
Q(F)	Fuel Enrg in	KBtu/hr	2670.9	99.9
Q(FG)	FG Enrg out	KBtu/hr	296.2	2.2
Q(IN)	Tot Enrg in	KBtu/hr	2779.7	100.9
Q(OUT)	Tot Enrg out	KBtu/hr	2100.8	84.7

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	697	42.6
TC13132	AFPE-F6"	907	33.7
TC13133	AFPE-B6"	699	50.8
TC13134	AFPE-F10"	338	56.8
TC13231	AFPW-F2"	730	37.5
TC13232	AFPW-F6"	902	27.1
TC13233	AFPW-B6"	635	32.1
TC13234	AFPW-F10"	779	39.2
DOORS	CHXs On	12	0
COILS	EHXs On	12	0
BH A/C		2.3	0.0
A/SRATIO		1.7	0.0
Feed Air	scfm	18.9	
DC Air	scfm	5.1	
Purge Air	scfm	15.5	

21-Nov-91

CFB-BT1-0891 — TEST 4

(1130-1235)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1589	5.7
TC11021	AFS Ex	°F	1469	6.1
TC15001	C Plenum	°F	617	5.0
TC15004	C 1-1'	°F	1503	7.9
TC15005	C 1-2'	°F	1485	9.2
TC15006	C 1-3'	°F	1511	6.8
TC15007	C 1-4'	°F	1479	7.0
TC15008	C 1-4'	°F	1494	7.5
TC15009	C 1-4'	°F	1480	7.1
TC15012	C 2-6'	°F	1513	6.9
TC15013	C 2-8'	°F	1553	6.5
TC15022	C 3-11'	°F	1528	5.4
TC15023	C 3-14'	°F	1531	5.0
TC15024	C 3-14'	°F	1527	4.7
TC15025	C 3-14'	°F	1548	4.5
TC15032	C 4-17.5'	°F	1533	4.5
TC15042	C 5-22.5'	°F	1548	3.7
TC15052	C 6-27.5'	°F	1558	3.3
TC15053	C 6-27.5'	°F	1559	3.4
TC15054	C 6-27.5'	°F	1529	3.6
TC15062	C 7-32.5'	°F	1545	3.5
TC15071	C 8-37.5'	°F	1557	3.4
TC15073	C 9-41'	°F	1602	3.7
TC15999	Ambient	°F	78	1.0
TC16001	EHX Plenm	°F	129	4.0
TC16012	EHX 0.5'	°F	1339	15.5
TC16013	EHX 1.5'	°F	1314	15.9
TC16014	EHX 2.7'	°F	1320	17.0
TC16015	EHX 3.8'	°F	1331	9.7
TC16017	EHX 5.3'	°F	1280	6.6
TC16018	EHX Exit	°F	1314	7.7
TC16021	Crc A in	°F	1573	5.2
TC16031	DC 8-36'	°F	1570	7.4
TC16032	DC 6-28'	°F	1553	7.7
TC16033	DC 4-18'	°F	1512	29.3
TC16034	DC3-9.5'	°F	1540	29.0
TC16035	DC3-8.5'	°F	1513	31.9

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 10

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	42	126	1553	3.70	155018	20.9	29811
3NE,SW	14	42	133	1535	3.70	167958	23.0	32300
4SE,NW	17.5	44	141	1533	4.00	194635	26.9	37430
5E	22.5	44	155	1548	1.80	100208	27.7	38541
6NE	27.5	44	115	1549	1.90	67227	18.0	25856
7SE,NW	32.5	44	114	1545	3.90	136052	18.3	26164
8	37.5	144	413	1557	0.00	0	0.0	0
	Overall	44	130	1532	17.54	748664	20.5	28795
			From Data Sheets=>		19.00			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-7,9-12	11	41	156	1324	13.79	790674	82.0	95839
			From Data Sheets=>		15.20			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	128	59.3	SO2-A	ppm	119	53.1
SO2-AE	lb/MM Btu	0.22	0.1				
SO2-B	ppm	123	51.2	SO2-B	ppm	105	43.8
SO2-BE	lb/MM Btu	0.21	0.1				
CO	ppm	11	7.6	CO	ppm	10	7.0
CO2	%	17.80	0.3	CO2	%	16.69	0.1
N2O	ppm	32	4.2	N2O	ppm	30	3.9
N2OE	lb/Mm Btu	0.04	0.0				
NOx	ppm	136	9.9	NOx	ppm	128	11.6
NOxE	lb/Mm Btu	0.17	0.0				
O2-A	%	1.72	0.4				
O2-B	%	1.80	0.4				

Tag	Desc	Units	Average	Std Dev
T(A,C)	Comb Temp	°F	1532	4.7
T(A,EHX)	EHX Temp	°F	1324	16.0
EA	Excess Air	%	8.8	2.1
SR	S Reten	%	73.7	11.8
R(PCA)	% Flw PCA	%	60.4	1.7
R(SCA)	% Flw SCA	%	39.6	1.7
R(Q,IN)	% Enrg in	%	74.4	2.3
R(CHX)	CHX Ratio	%	43.1	1.1
R(EHX)	EHX Ratio	%	56.9	1.1
F(PCA)	PCA Flw	scfm	235.7	18.3
F(EHX)	EHX Flw	scfm	60.3	0.9
F(TPA)	TPCA Flw	scfm	291.5	16.8
F(SCA)	SCA Flw	scfm	156.2	5.2
F(TAIR)	TCA Flw	scfm	482.2	16.2
F(FG,BH)	BH Flw	scfm	598.8	9.9
F(TFG)	TFG Flw	scfm	598.8	9.9
W(SR)	Recirc Rt	lbs/hr	13478	938.1

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	315	11.7
W(S)	LS Fd Rt	lbs/hr	15	0.0
V(FG)	FG SGV	ft/sec	15.8	0.5
V(S,C)	Comb SGV	ft/sec	14.1	0.5
V(S,EHX)	EHX SGV	ft/sec	2.2	0.0
FT18003	CHX Flow	gpm	17.5	0.1
FT19003	EHX Flow	gpm	13.8	0.0
PT15081	Comb dP	in. H2O	41.2	2.0
Q(CA)	CA Heat in	KBtu/hr	100.1	4.8
Q(CHX)	CHX HtRmv	KBtu/hr	600.0	34.2
Q(EHX)	EHX HtRmv	KBtu/hr	790.7	21.0
Q(EHX,IN	E FG Ht in	KBtu/hr	3.1	0.2
Q(F)	Fuel Enrg in	KBtu/hr	2801.6	104.0
Q(FG)	FG Enrg out	KBtu/hr	296.7	4.7
Q(IN)	Tot Enrg in	KBtu/hr	2904.8	102.5
Q(OUT)	Tot Enrg out	KBtu/hr	2164.2	50.9

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	793	41.3
TC13132	AFPE-F6"	998	27.8
TC13133	AFPE-B6"	804	36.8
TC13134	AFPE-F10"	418	66.8
TC13231	AFPW-F2"	821	32.1
TC13232	AFPW-F6"	1000	26.0
TC13233	AFPW-B6"	721	29.2
TC13234	AFPW-F10'	879	34.4
DOORS	CHXs On	10	0
COILS	EHXs On	11	0
BH A/C		2.2	0.4
A/SRATIO		5.5	0.1
Feed Air	scfm	19.1	
DC Air	scfm	5.1	
Purge Air	scfm	15.5	

20-Nov-91

CFB-BT1-0891 — TEST 5

(0745-0925)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1554	6.6
TC11021	AFS Ex	°F	1421	7.8
TC15001	C Plenum	°F	571	5.4
TC15004	C 1-1'	°F	1522	8.9
TC15005	C 1-2'	°F	1505	8.8
TC15006	C 1-3'	°F	1529	9.0
TC15007	C 1-4'	°F	1497	7.8
TC15008	C 1-4'	°F	1511	8.8
TC15009	C 1-4'	°F	1497	9.0
TC15012	C 2-6'	°F	1531	7.8
TC15013	C 2-8'	°F	1572	6.3
TC15022	C 3-11'	°F	1540	5.1
TC15023	C 3-14'	°F	1544	6.1
TC15024	C 3-14'	°F	1539	5.1
TC15025	C 3-14'	°F	1558	4.0
TC15032	C 4-17.5'	°F	1539	5.2
TC15042	C 5-22.5'	°F	1555	3.4
TC15052	C 6-27.5'	°F	1567	3.6
TC15053	C 6-27.5'	°F	1568	3.9
TC15054	C 6-27.5'	°F	1521	4.9
TC15062	C 7-32.5'	°F	1553	3.3
TC15071	C 8-37.5'	°F	1558	3.2
TC15073	C 9-41'	°F	1611	4.8
TC15999	Ambient	°F	76	1.8
TC16001	EHX Plenm	°F	119	3.1
TC16012	EHX 0.5'	°F	1356	12.3
TC16013	EHX 1.5'	°F	1322	10.2
TC16014	EHX 2.7'	°F	1339	11.8
TC16015	EHX 3.8'	°F	1312	10.3
TC16017	EHX 5.3'	°F	1232	7.1
TC16018	EHX Exit	°F	1301	10.5
TC16021	Crc A in	°F	1573	5.1
TC16031	DC 8-36'	°F	1567	4.2
TC16032	DC 6-28'	°F	1551	4.0
TC16033	DC 4-18'	°F	1543	4.9
TC16034	DC3-9.5'	°F	1574	3.2
TC16035	DC3-8.5'	°F	1534	27.4

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 10

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	42	133	1572	3.60	164078	21.9	31553
3NE,SW	14	43	135	1547	3.65	167326	22.8	32178
4SE,NW	17.5	43	169	1539	4.45	281428	39.5	54121
5E	22.5	45	153	1555	1.80	97385	26.7	37456
6NE	27.5	43	118	1552	1.80	67591	18.1	25997
7SE,NW	32.5	45	131	1553	1.80	77498	10.5	14903
8E,W	37.5	45	115	1558	1.90	66105	8.8	12712
	Overall	42	140	1545	17.56	859971	23.6	33076
		From Data Sheets=>			19.00			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-2,5-7,	8	42	157	1339	10.07	580405	81.9	96734
10-12		From Data Sheets=>			11.00			

EMISSIONS DATA

As Measured: Tag	Units	Average	Std Dev	Corrected to 3% O2: Tag	Units	Average	Std Dev
SO2-A	ppm	135	60.0	SO2-A	ppm	135	55.4
SO2-AE	lb/MM Btu	0.25	0.1				
SO2-B	ppm	119	54.8	SO2-B	ppm	102	47.0
SO2-BE	lb/MM Btu	0.22	0.1				
CO	ppm	7	2.6	CO	ppm	7	2.6
CO2	%	16.19	0.5	CO2	%	16.39	0.2
N2O	ppm	N/A	N/A	N2O	ppm	N/A	N/A
N2OE	lb/Mm Btu	N/A	N/A				
NOx	ppm	156	13.0	NOx	ppm	159	18.7
NOxE	lb/Mm Btu	0.21	0.0				
O2-A	%	3.85	0.6				
O2-B	%	3.22	0.7				

Tag	Desc	Units	Average	Std Dev
T(A,C)	Comb Temp	°F	1545	5.2
T(A,EHX)	EHX Temp	°F	1339	11.6
EA	Excess Air	%	22.5	4.5
SR	S Reten	%	69.6	12.5
R(PCA)	% Flw PCA	%	60.0	5.6
R(SCA)	% Flw SCA	%	40.0	5.6
R(Q,IN)	% Enrg in	%	78.4	2.8
R(CHX)	CHX Ratio	%	52.3	1.9
R(EHX)	EHX Ratio	%	47.7	1.9
F(PCA)	PCA Flw	scfm	237.1	27.0
F(EHX)	EHX Flw	scfm	48.3	1.4
F(TPA)	TPCA Flw	scfm	292.0	29.4
F(SCA)	SCA Flw	scfm	160.1	27.7
F(TAIR)	TCA Flw	scfm	486.8	17.3
F(FG,BH)	BH Flw	scfm	586.8	5.0
F(TFG)	TFG Flw	scfm	587.0	5.1
W(SR)	Recirc Rt	lbs/hr	9320	499.4

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	277	6.9
W(S)	LS Fd Rt	lbs/hr	6	1.2
V(FG)	FG SGV	ft/sec	15.9	0.6
V(S,C)	Comb SGV	ft/sec	14.2	0.5
V(S,EHX)	EHX SGV	ft/sec	1.8	0.0
FT18003	CHX Flow	gpm	17.6	0.2
FT19003	EHX Flow	gpm	10.1	0.1
PT15081	Comb dP	in. H2O	47.0	1.2
Q(CA)	CA Heat in	KBtu/hr	99.8	3.8
Q(CHX)	CHX HtRmv	KBtu/hr	636.6	50.3
Q(EHX)	EHX HtRmv	KBtu/hr	578.6	14.8
Q(EHX,IN	E FG Ht in	KBtu/hr	2.1	0.2
Q(F)	Fuel Enrg in	KBtu/hr	2473.3	75.9
Q(FG)	FG Enrg out	KBtu/hr	291.1	3.1
Q(IN)	Tot Enrg in	KBtu/hr	2575.2	74.4
Q(OUT)	Tot Enrg out	KBtu/hr	1999.9	87.7

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	739	41.1
TC13132	AFPE-F6"	947	31.2
TC13133	AFPE-B6"	740	34.5
TC13134	AFPE-F10"	356	49.1
TC13231	AFPW-F2"	774	39.2
TC13232	AFPW-F6"	942	27.7
TC13233	AFPW-B6"	645	30.8
TC13234	AFPW-F10"	813	38.1
DOORS	CHXs On	10	0
COILS	EHXs On	8	0
BH A/C		2.2	0.0
A/SRATIO		3.5	0.3
Feed Air	scfm	18.6	
DC Air	scfm	0.0	
Purge Air	scfm	15.5	

22,23-Nov-91

CFB-BT1-0891 — TEST 7

(2100-0130)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1518	8.9
TC11021	AFS Ex	°F	1384	8.7
TC15001	C Plenum	°F	505	3.9
TC15004	C 1-1'	°F	1537	15.9
TC15005	C 1-2'	°F	1519	15.3
TC15006	C 1-3'	°F	1544	15.2
TC15007	C 1-4'	°F	1513	14.8
TC15008	C 1-4'	°F	1530	15.7
TC15009	C 1-4'	°F	1515	14.9
TC15012	C 2-6'	°F	1545	15.7
TC15013	C 2-8'	°F	1587	16.1
TC15022	C 3-11'	°F	1540	14.3
TC15023	C 3-14'	°F	1530	11.9
TC15024	C 3-14'	°F	1530	12.0
TC15025	C 3-14'	°F	1549	13.1
TC15032	C 4-17.5'	°F	1511	8.9
TC15042	C 5-22.5'	°F	1534	9.0
TC15052	C 6-27.5'	°F	1535	8.8
TC15053	C 6-27.5'	°F	1535	9.5
TC15054	C 6-27.5'	°F	1480	7.4
TC15062	C 7-32.5'	°F	1493	5.8
TC15071	C 8-37.5'	°F	1531	9.6
TC15073	C 9-41'	°F	1579	10.7
TC15999	Ambient	°F	68	2.0
TC16001	EHX Plenm	°F	113	3.1
TC16012	EHX 0.5'	°F	1172	17.2
TC16013	EHX 1.5'	°F	1159	18.5
TC16014	EHX 2.7'	°F	1156	16.6
TC16015	EHX 3.8'	°F	1136	11.9
TC16017	EHX 5.3'	°F	1089	7.6
TC16018	EHX Exit	°F	1125	11.1
TC16021	Crc A in	°F	1551	10.2
TC16031	DC 8-36'	°F	1529	13.4
TC16032	DC 6-28'	°F	1508	11.7
TC16033	DC 4-18'	°F	1454	32.8
TC16034	DC3-9.5'	°F	1480	45.5
TC16035	DC3-8.5'	°F	1494	28.5

T(A,C)	Comb Temp	°F	1536	11.6
T(A,EHX)	EHX Temp	°F	1162	17.3
EA	Excess Air	%	23.5	4.4
SR	S Reten	%	77.7	15.1
R(PCA)	% Flw PCA	%	78.6	4.8
R(SCA)	% Flw SCA	%	21.4	4.8
R(Q,IN)	% Enrg in	%	76.8	4.0
R(CHX)	CHX Ratio	%	60.0	2.0
R(EHX)	EHX Ratio	%	40.0	2.0
F(PCA)	PCA Flw	scfm	261.9	27.7
F(EHX)	EHX Flw	scfm	57.3	1.4
F(TPA)	TPCA Flw	scfm	317.0	25.0
F(SCA)	SCA Flw	scfm	51.5	22.0
F(TAIR)	TCA Flw	scfm	403.9	31.2
F(FG,BH)	BH Flw	scfm	485.3	5.8
F(TFG)	TFG Flw	scfm	485.3	5.8
W(SR)	Recirc Rt	lbs/hr	4093	410.9

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 10

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	43	123	1587	3.60	144243	19.0	27739
3NE,SW	14	42	128	1537	3.60	155455	21.2	29895
4SE,NW	17.5	44	135	1511	4.30	195570	27.3	37610
5E	22.5	44	127	1534	2.10	87274	23.9	33567
6NE	27.5	43	107	1517	1.80	57681	15.7	22185
7SE,NW	32.5	44	106	1493	3.80	116851	16.2	22471
8	37.5	128	226	1531	0.00	0	0.0	0
	Overall	43	122	1536	17.51	699893	19.0	26919
			From Data Sheets=>		19.20			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-4,8,9,	8	42	100	1162	12.47	357685	56.1	59614
13-14			From Data Sheets=>		13.70			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	98	68.3	SO2-A	ppm	112	89.1
SO2-AE	lb/MM Btu	0.19	0.1				
SO2-B	ppm	12	11.4	SO2-B	ppm	10	9.7
SO2-BE	lb/MM Btu	0.02	0.0				
CO	ppm	7	2.6	CO	ppm	7	2.7
CO2	%	15.98	0.6	CO2	%	17.84	2.0
N2O	ppm	35	1.4	N2O	ppm	39	4.4
N2OE	lb/Mm Btu	0.05	0.0				
NOx	ppm	177	18.1	NOx	ppm	198	29.3
NOxE	lb/Mm Btu	0.24	0.0				
O2-A	%	4.00	0.6				
O2-B	%	4.73	1.4				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	229	10.5
W(S)	LS Fd Rt	lbs/hr	4	0.0
V(FG)	FG SGV	ft/sec	13.0	1.0
V(S,C)	Comb SGV	ft/sec	11.8	1.0
V(S,EHX)	EHX SGV	ft/sec	1.9	0.0
FT18003	CHX Flow	gpm	17.5	0.3
FT19003	EHX Flow	gpm	12.5	0.1
PT15081	Comb dP	in. H2O	36.3	2.4
Q(CA)	CA Heat in	KBtu/hr	74.3	7.6
Q(CHX)	CHX HtRmv	KBtu/hr	542.0	38.1
Q(EHX)	EHX HtRmv	KBtu/hr	360.5	18.1
Q(EHX,IN	E FG Ht in	KBtu/hr	2.6	0.2
Q(F)	Fuel Enrg in	KBtu/hr	2031.8	94.6
Q(FG)	FG Enrg out	KBtu/hr	240.8	2.9
Q(IN)	Tot Enrg in	KBtu/hr	2110.5	95.5
Q(OUT)	Tot Enrg out	KBtu/hr	1616.7	54.5

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	679	54.0
TC13132	AFPE-F6"	900	42.6
TC13133	AFPE-B6"	686	56.6
TC13134	AFPE-F10"	323	64.8
TC13231	AFPW-F2"	719	44.5
TC13232	AFPW-F6"	904	34.6
TC13233	AFPW-B6"	622	40.0
TC13234	AFPW-F10'	773	50.1
DOORS	CHXs On	10	0
COILS	EHXs On	8	0
BH A/C		1.9	0.0
A/SRATIO		2.9	0.1
Feed Air	scfm	19.3	
DC Air	scfm	5.3	
Purge Air	scfm	15.5	

22-Nov-91

CFB-BT1-0891 — TEST 8

(0945-1415)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1526	8.9
TC11021	AFS Ex	°F	1407	7.2
TC15001	C Plenum	°F	559	4.5
TC15004	C 1-1'	°F	1529	14.2
TC15005	C 1-2'	°F	1512	14.1
TC15006	C 1-3'	°F	1537	13.8
TC15007	C 1-4'	°F	1507	13.3
TC15008	C 1-4'	°F	1522	14.5
TC15009	C 1-4'	°F	1507	13.7
TC15012	C 2-6'	°F	1529	13.2
TC15013	C 2-8'	°F	1576	13.1
TC15022	C 3-11'	°F	1542	12.2
TC15023	C 3-14'	°F	1537	12.6
TC15024	C 3-14'	°F	1529	10.6
TC15025	C 3-14'	°F	1553	12.1
TC15032	C 4-17.5'	°F	1527	11.3
TC15042	C 5-22.5'	°F	1546	10.1
TC15052	C 6-27.5'	°F	1553	10.0
TC15053	C 6-27.5'	°F	1551	10.8
TC15054	C 6-27.5'	°F	1509	10.2
TC15062	C 7-32.5'	°F	1524	10.0
TC15071	C 8-37.5'	°F	1549	10.6
TC15073	C 9-41'	°F	1592	12.4
TC15999	Ambient	°F	72	2.2
TC16001	EHX Plenm	°F	120	3.7
TC16012	EHX 0.5'	°F	1382	14.5
TC16013	EHX 1.5'	°F	1371	14.7
TC16014	EHX 2.7'	°F	1382	15.1
TC16015	EHX 3.8'	°F	1366	13.6
TC16017	EHX 5.3'	°F	1312	10.6
TC16018	EHX Exit	°F	1332	18.4
TC16021	Crc A in	°F	1559	10.1
TC16031	DC 8-36'	°F	1545	13.1
TC16032	DC 6-28'	°F	1530	10.7
TC16033	DC 4-18'	°F	1500	33.3
TC16034	DC3-9.5'	°F	1540	32.8
TC16035	DC3-8.5'	°F	1521	23.5

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 10

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft^{2}hr°F	Heat Flux Btu/ft^{2}hr
2E,W	8	42	123	1576	3.58	144523	19.1	27793
3NE,SW	14	43	131	1539	3.62	159058	21.7	30588
4SE,NW	17.5	45	141	1527	4.28	205267	28.5	39474
5E	22.5	44	134	1546	2.06	92829	25.3	35703
6NE	27.5	43	116	1538	1.78	65311	17.7	25120
7SE,NW	32.5	44	114	1524	3.78	130801	17.8	25154
8	37.5	134	320	1549	0.00	0	0.0	0
	Overall	42	127	1540	17.45	742817	20.2	28570
		From Data Sheets=>			19.10			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft^{2}hr°F	Heat Flux Btu/ft^{2}hr
1-4,8	5	42	139	1378	7.45	362426	78.0	96647
13-14		From Data Sheets=>			8.36			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	10	6.5	SO2-A	ppm	12	8.0
SO2-AE	lb/MM Btu	0.02	0.0				
SO2-B	ppm	12	7.1	SO2-B	ppm	10	6.1
SO2-BE	lb/MM Btu	0.03	0.0				
CO	ppm	4	2.2	CO	ppm	5	2.8
CO2	%	13.97	0.6	CO2	%	17.26	0.3
N2O	ppm	33	3.8	N2O	ppm	41	4.8
N2OE	lb/Mm Btu	0.05	0.0				
NOx	ppm	205	7.3	NOx	ppm	254	18.2
NOxE	lb/Mm Btu	0.32	0.0				
O2-A	%	6.34	0.6				
O2-B	%	6.43	0.6				

Tag	Desc	Units	Average	Std Dev
T(A,C)	Comb Temp	°F	1540	11.0
T(A,EHX)	EHX Temp	°F	1378	14.5
EA	Excess Air	%	43.5	6.2
SR	S Reten	%	97.4	1.7
R(PCA)	% Flw PCA	%	60.3	2.5
R(SCA)	% Flw SCA	%	39.7	2.5
R(Q,IN)	% Enrg in	%	74.6	4.1
R(CHX)	CHX Ratio	%	60.4	1.5
R(EHX)	EHX Ratio	%	39.6	1.5
F(PCA)	PCA Flw	scfm	241.9	27.7
F(EHX)	EHX Flw	scfm	58.3	1.2
F(TPA)	TPCA Flw	scfm	300.3	26.3
F(SCA)	SCA Flw	scfm	162.1	9.3
F(TAIR)	TCA Flw	scfm	496.8	27.4
F(FG,BH)	BH Flw	scfm	594.5	10.4
F(TFG)	TFG Flw	scfm	594.5	10.4
W(SR)	Recirc Rt	lbs/hr	7542	781.8

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	246	13.0
W(S)	LS Fd Rt	lbs/hr	7	0.3
V(FG)	FG SGV	ft/sec	16.1	0.9
V(S,C)	Comb SGV	ft/sec	14.6	0.8
V(S,EHX)	EHX SGV	ft/sec	2.2	0.1
FT18003	CHX Flow	gpm	17.5	0.2
FT19003	EHX Flow	gpm	7.5	0.1
PT15081	Comb dP	in. H2O	36.4	2.3
Q(CA)	CA Heat in	KBtu/hr	101.0	6.2
Q(CHX)	CHX HtRmv	KBtu/hr	556.0	26.4
Q(EHX)	EHX HtRmv	KBtu/hr	363.5	11.0
Q(EHX,IN	E FG Ht in	KBtu/hr	2.8	0.2
Q(F)	Fuel Enrg in	KBtu/hr	2186.8	123.0
Q(FG)	FG Enrg out	KBtu/hr	295.1	5.8
Q(IN)	Tot Enrg in	KBtu/hr	2290.4	122.2
Q(OUT)	Tot Enrg out	KBtu/hr	1692.1	33.1

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	737	41.5
TC13132	AFPE-F6"	945	33.7
TC13133	AFPE-B6"	744	49.6
TC13134	AFPE-F10"	377	55.3
TC13231	AFPW-F2"	771	36.9
TC13232	AFPW-F6"	948	27.8
TC13233	AFPW-B6"	672	32.5
TC13234	AFPW-F10"	827	40.0
DOORS	CHXs On	10	0
COILS	EHXs On	5	0
BH A/C		2.3	0.0
A/SRATIO		3.9	0.1
Feed Air	scfm	19.3	
DC Air	scfm	5.2	
Purge Air	scfm	15.5	

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(2125-2315)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1637	11.3
TC11021	AFS Ex	°F	1502	12.5
TC15001	C Plenum	°F	626	4.8
TC15004	C 1-1'	°F	1629	15.4
TC15005	C 1-2'	°F	1611	15.4
TC15006	C 1-3'	°F	1640	14.9
TC15007	C 1-4'	°F	1606	14.5
TC15008	C 1-4'	°F	1621	15.1
TC15009	C 1-4'	°F	1605	13.5
TC15012	C 2-6'	°F	1625	14.1
TC15013	C 2-8'	°F	1660	14.6
TC15022	C 3-11'	°F	1627	11.4
TC15023	C 3-14'	°F	1628	12.0
TC15024	C 3-14'	°F	1620	11.7
TC15025	C 3-14'	°F	1642	12.4
TC15032	C 4-17.5'	°F	1627	10.9
TC15042	C 5-22.5'	°F	1643	10.8
TC15052	C 6-27.5'	°F	1652	10.4
TC15053	C 6-27.5'	°F	1651	11.5
TC15054	C 6-27.5'	°F	1618	9.5
TC15062	C 7-32.5'	°F	1634	10.0
TC15071	C 8-37.5'	°F	1649	11.0
TC15073	C 9-41'	°F	1691	13.9
TC15999	Ambient	°F	76	1.6
TC16001	EHX Plenm	°F	124	3.5
TC16012	EHX 0.5'	°F	1557	13.4
TC16013	EHX 1.5'	°F	1528	13.2
TC16014	EHX 2.7'	°F	1544	12.9
TC16015	EHX 3.8'	°F	1533	12.5
TC16017	EHX 5.3'	°F	1482	7.6
TC16018	EHX Exit	°F	1527	9.3
TC16021	Crc A in	°F	1639	12.9
TC16031	DC 8-36'	°F	1640	10.4
TC16032	DC 6-28'	°F	1633	10.9
TC16033	DC 4-18'	°F	1622	12.0
TC16034	DC3-9.5'	°F	1650	11.8
TC16035	DC3-8.5'	°F	1608	12.9

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 10

C-HX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E,W	8	43	137	1660	3.60	169931	21.5	32679
3NE,SW	14	43	147	1630	3.60	188146	24.4	36182
4SE,NW	17.5	45	163	1627	4.20	248428	32.6	47775
5E	22.5	43	156	1643	2.00	112538	29.1	43284
6NE	27.5	42	131	1640	1.80	79948	20.4	30749
7SE,NW	32.5	43	131	1634	3.80	165944	21.2	31912
8	37.5	145	475	1649	0.00	0	0.0	0
	Overall	42	145	1637	17.23	884241	22.8	34009
			From Data Sheets=>		19.00			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-2,8,9	4	41	147	1543	6.32	333508	79.6	111169
			From Data Sheets=>		7.10			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	38	24.5	SO2-A	ppm	42	26.2
SO2-AE	lb/MM Btu	0.08	0.0				
SO2-B	ppm	55	21.1	SO2-B	ppm	47	18.1
SO2-BE	lb/MM Btu	0.11	0.0				
CO	ppm	6	0.7	CO	ppm	6	0.8
CO2	%	14.98	0.4	CO2	%	16.75	0.3
N2O	ppm	22	1.2	N2O	ppm	24	1.9
N2OE	lb/Mm Btu	0.03	0.0				
NOx	ppm	227	6.4	NOx	ppm	254	12.4
NOxE	lb/Mm Btu	0.33	0.0				
O2-A	%	4.88	0.4				
O2-B	%	4.90	0.4				

T(A,C)	Comb Temp	°F	1637	12.4
T(A,EHX)	EHX Temp	°F	1543	13.0
EA	Excess Air	%	30.1	3.3
SR	S Reten	%	90.7	5.8
R(PCA)	% Flw PCA	%	59.9	1.7
R(SCA)	% Flw SCA	%	40.1	1.7
R(Q,IN)	% Enrg in	%	73.4	2.1
R(CHX)	CHX Ratio	%	66.9	0.8
R(EHX)	EHX Ratio	%	33.1	0.8
F(PCA)	PCA Flw	scfm	241.9	14.4
F(EHX)	EHX Flw	scfm	53.8	1.1
F(TPA)	TPCA Flw	scfm	293.0	15.8
F(SCA)	SCA Flw	scfm	161.3	4.6
F(TAIR)	TCA Flw	scfm	488.9	14.2
F(FG,BH)	BH Flw	scfm	601.6	7.0
F(TFG)	TFG Flw	scfm	601.1	6.8
W(SR)	Recirc Rt	lbs/hr	15535	2204.1

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	272	11.1
W(S)	LS Fd Rt	lbs/hr	15	0.0
V(FG)	FG SGV	ft/sec	16.9	0.5
V(S,C)	Comb SGV	ft/sec	15.1	0.4
V(S,EHX)	EHX SGV	ft/sec	2.2	0.1
FT18003	CHX Flow	gpm	17.2	0.1
FT19003	EHX Flow	gpm	6.3	0.0
PT15081	Comb dP	in. H2O	35.9	1.6
Q(CA)	CA Heat in	KBtu/hr	103.8	3.4
Q(CHX)	CHX HtRmv	KBtu/hr	673.8	19.4
Q(EHX)	EHX HtRmv	KBtu/hr	333.5	7.8
Q(EHX,IN	E FG Ht in	KBtu/hr	2.6	0.2
Q(F)	Fuel Enrg in	KBtu/hr	2419.1	99.0
Q(FG)	FG Enrg out	KBtu/hr	302.1	3.8
Q(IN)	Tot Enrg in	KBtu/hr	2525.8	98.2
Q(OUT)	Tot Enrg out	KBtu/hr	1864.9	46.6

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	1024	54.7
TC13132	AFPE-F6"	1177	42.4
TC13133	AFPE-B6"	1053	62.2
TC13134	AFPE-F10"	678	71.8
TC13231	AFPW-F2"	1033	48.9
TC13232	AFPW-F6"	1166	39.4
TC13233	AFPW-B6"	895	43.3
TC13234	AFPW-F10"	1086	52.1
DOORS	CHXs On	10	0
COILS	EHXs On	4	0
BH A/C		2.3	0.0
A/SRATIO	-	6.3	0.2
Feed Air	scfm	16.6	
DC Air	scfm	5.1	
Purge Air	scfm	15.5	

APPENDIX E

ASIAN LIGNITE TEST RESULTS

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TEST MATRIX

The matrix of test parameters is shown in Table E-1. The coal and limestone feed rates were established in Test 1 to result in an upper combustor velocity of 18.0 feet per second, 90% sulfur retention, and 20% excess air. The coal feed rate was then held steady for the three remaining tests. The limestone feed rate, which was set to achieve 90% sulfur retention during Test 1, was held constant for Tests 2 and 3. Combustion air flow rates were also held steady for the entire run; the superficial gas velocity varied with temperature during Tests 2 and 3. The bed temperature was increased or decreased in these tests by removing or adding heat-transfer surface in the combustor and external heat exchanger. The target excess air level was 20%, and the ratio of primary to secondary combustion air was 60:40 for all tests. Bed material was periodically drained to maintain a pressure drop across the bed of about 40 inches of water. Solids samples from the coal and limestone hoppers, combustor bed, baghouse, and secondary cyclone were taken every two hours during test periods. Samples of bed material and downcomer ash were taken routinely as specified between test periods.

COAL AND LIMESTONE PROPERTIES

The coal and limestone, which were loaded into 2000-lb (1000-kg) supersacks, were shipped overseas from the source mine in Asia to Hong Kong to Seattle, Washington, and by rail from Seattle to West Fargo, North Dakota. The supersacks were then loaded onto three trucks for shipping to Grand Forks, North Dakota. Two trucks arrived on Saturday, August 3, and the third arrived on Monday, August 5. A total of approximately 100,000 pounds of coal and 20,000 pounds of limestone were scheduled for delivery. Ten sacks of limestone and 41 sacks of coal were received.

The as-received coal consisted of a very high percentage of fines. The larger lumps crumbled easily into fines. The coal was dumped on the ground and mixed with a front-end loader prior to entering the coal preparation system. The as-received limestone was of good consistency--the majority of the material was between 3/4 and 3/8 inch. Samples were taken of the as-received and the as-prepared coal and limestone for size distribution analyses. The size distributions of the prepared coal used for each of the four tests is shown in Figure E-1. Figure E-2 contrasts the size distributions of the as-received and as-prepared limestone which was used throughout the run.

TABLE E-1

Test Matrix

Test #	Temp., °F	Ca/S	Gas Vel., ft/sec	Test Length, hr
1	1550	As req. for 90% ret.	18.0	6
2	1450	Same as Test 1	18.0 (–)	4
3	1650	Same as Test 1	18.0 (+)	4
4	1550	Zero Limestone Feed	18.0	4

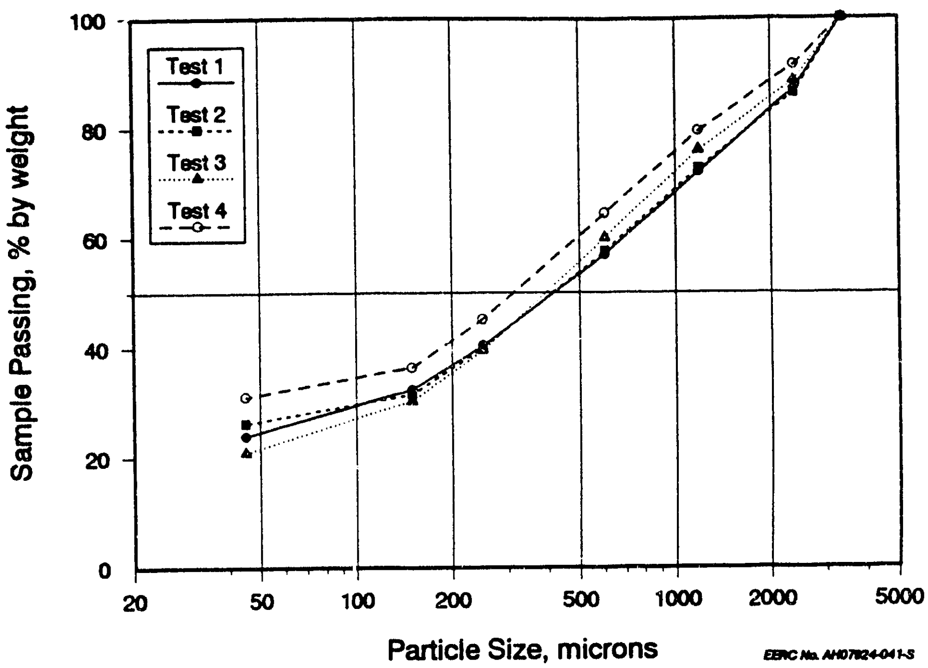

Figure E-1. Size distributions of the coal.

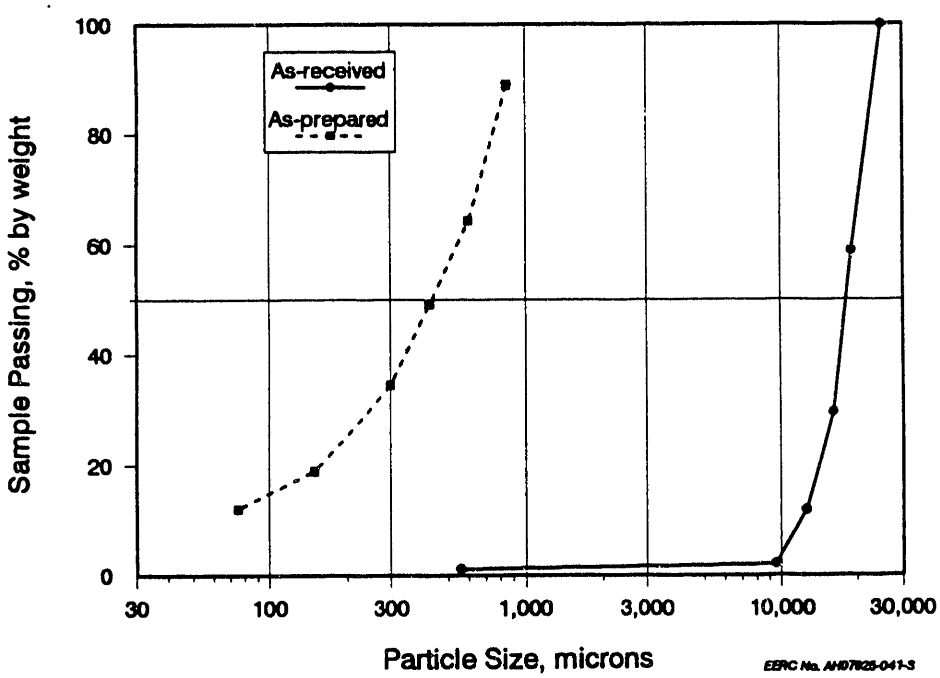

Figure E-2. Size distributions of limestone.

Very little crushing was required for this coal. A few large pieces of rock were found that clogged the surge bin above the crusher; these pieces, probably overburden, were removed from the crusher and discarded. The size distribution of the as-crushed sample is shown in Figure E-1. Note that it is almost the same as the as-received sample.

Limestone was crushed separately using the Williams hammer-mill crusher and double-screened to -16-mesh (1.2-mm or 1200-μm) + 100-mesh (150-μm) size distribution. The limestone crushed well once-through, with only a small amount greater than 16 mesh (separated into barrels for additional crushing) and not many fines. The size distribution for an as-crushed limestone sample is shown in Figure E-3. About 12% was less than 200 mesh (75 μm); 90% was less than 20 mesh (850 μm) with what appears to be a good distribution. The d_{50} of 420 μm was slightly larger than that specified for the test (250 μm).

The sized coal and limestone from final screening were routed into 2-ton capacity coal totes which were on standby waiting to be transferred by forklift and crane to storage hoppers having net capacities of approximately 3500 pounds and 1000 pounds for the coal and limestone, respectively.

Proximate and ultimate analyses of the coal and XRFA of the coal ash and limestone were performed. Results of the coal analyses for each test period are shown in Table E-2, and the limestone analysis is shown in Table E-3. The coal is consistent with what was expected from the Asian lignite, with high levels of ash, sulfur, and calcium and low levels of sodium and potassium. The moisture level of the coal received (~17%) was less than the mine average of ~27%.

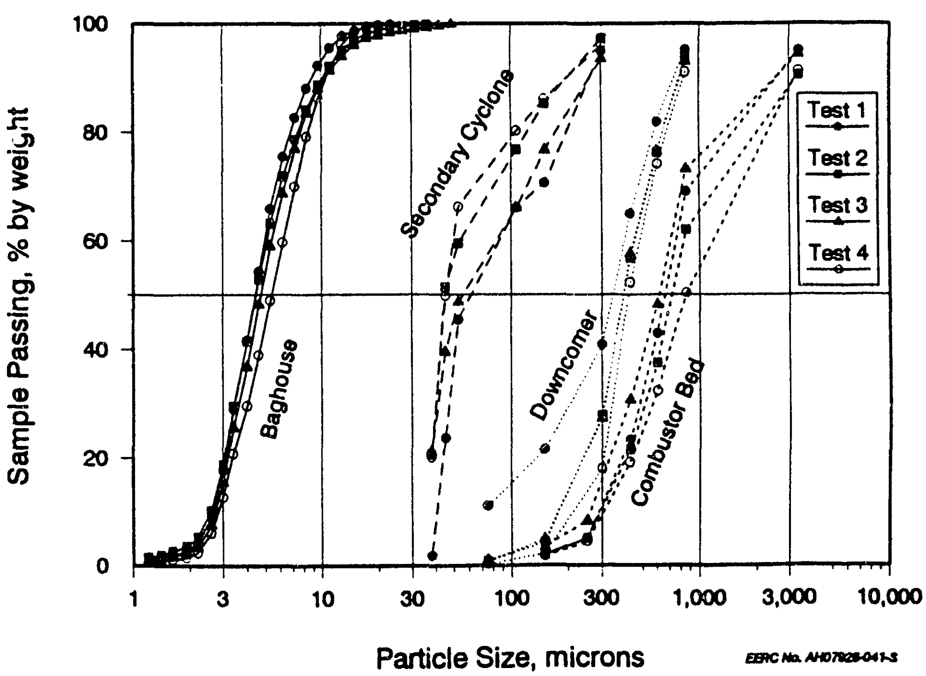

Figure E-3. Downcomer, secondary cyclone, and baghouse ash size distributions.

TABLE E-2

Coal Analyses

	Test 1	Test 2	Test 3	Test 4
Proximate Analysis, as-received, wt%				
Moisture	17.0	17.6	16.1	17.4
Volatile Matter	38.0	37.4	37.0	37.3
Fixed Carbon	6.4	6.7	8.6	8.7
Ash	38.7	38.4	38.3	36.7
Ultimate Analysis, as-received, wt%				
Carbon	24.6	24.6	25.1	25.6
Hydrogen	4.3	4.2	4.2	4.3
Nitrogen	0.6	0.6	0.7	0.7
Sulfur	5.9	6.0	6.0	6.3
Oxygen	25.9	26.2	25.7	26.4
Ash	38.7	38.4	38.3	36.7
Ash Composition, as oxides, wt%				
Calcium, CaO	23.8	19.0	18.0	18.8
Magnesium, MgO	3.2	3.1	3.3	3.4
Sodium, Na_2O	0.2	0.3	0.3	0.3
Silica, SiO_2	26.8	35.9	31.4	28.2
Aluminum, Al_2O_3	11.3	12.7	13.1	12.5
Ferric, Fe_2O_3	13.2	11.5	14.6	15.3
Titanium, TiO_2	0.2	0.2	0.2	0.2
Phosphorous, P_2O_5	0.6	0.5	0.5	0.6
Potassium, K_2O	1.0	1.2	1.2	1.2
Sulfur, SO_3	19.7	15.6	17.4	19.6
High Heating Value, moisture-free, Btu/lb	4608	4582	4676	4925
High Heating Value, as-received, Btu/lb	3824	3777	3922	4068

TABLE E-3

Average Limestone Analysis (% as oxides)

Component	Average
Silica	1.75
Aluminum	0.00
Iron	0.25
Titanium	0.03
Calcium	54.26
Magnesium	0.61
Sodium	0.06
Potassium	0.26
Sulfur	0.15

OPERATIONAL PERFORMANCE

General Operability

Week 1

Operation of the unit to obtain steady-state conditions for the test matrix was not successful during the first week of testing. The first 24 to 32 hours were spent trying to maintain a consistent coal feed rate. Flowability of the coal was extremely poor. Ratholing was observed in the storage hopper, making the transfer of coal to the weigh hopper difficult. During coal transfer, it was necessary to rod out the storage hopper, using a 3/8-inch tube with air flowing through it. The same phenomenon was apparently occurring in the weigh hopper as well, making steady coal feed difficult. Some success was achieved by adding an aeration port to the weigh hopper and making sure there was a good level of material in the weigh hopper. This was supplemented with banging on the hoppers and feed pipes.

When the coal feed problems had been adequately dealt with, anomalies in the operating conditions were observed. The operating conditions were characterized by high levels of oxygen and carbon monoxide in the flue gas, low bed temperature, low air flow and velocity in the combustor, and high flue gas flow rate. These conditions were discovered to be caused by a leak in the flue gas-to-air shell-and-tube heat exchanger. Air was leaking directly to the flue gas piping rather than passing through the combustor. This was verified by sampling flue gas prior to the air heater, for comparison with the O_2 sample measured downstream of the air heater. As soon as the leak was verified, shutdown was initiated so that repairs could be made to the air heater.

The bed drain rate was quite high. The ash in the fuel appeared to be concentrated in the coarser fraction. There was a great deal of ¼"-½" "rocks" observed in the material drained from the bed and in the material remaining on the distributor plate following shutdown. The coal was separated into two size fractions, greater than and less than 600 microns. A Btu analysis of these samples showed no preferential segregation of the ash in the fuel. The high bed drain rate was due, in part, to having both cyclones recirculating material back to the downcomer.

There was no evidence of any sintering of the bed due to its chemical composition, or any deposits of any kind or significance on the air distributor and loop seal nozzles, combustor refractory, cyclone and ducts, or the ash-fouling section. The coal that was received contained very low ash alkali (Na_2O, K_2O), which explains the absence of fouling. In spite of the erratic conditions under which the unit was operated during this 40-hour period on coal, there was no evidence of any tendencies toward ash-related agglomeration, slagging, or fouling problems. This is extremely significant, since reducing conditions at high temperature existed in the combustor, cyclone, and fouling section at various times during the run.

There was only about a 2 to 3 hour period on Tuesday morning of the first week of testing that corresponded to general Test 1 conditions. An average data set calculated for that period was:

Average Combustor Temperature, °F	1543
Primary Air, scfm	199
Secondary Air, scfm	174
Flue Gas Flow, scfm	507
Superficial Gas Velocity, ft/sec	15
Coal Feed Rate, lb/hr	550
Limestone Feed Rate, lb/hr	76
Bed Pressure Drop, in. H_2O	45-50
Excess Air, %	29
Sulfur Retention, % (Based on 5.9% Coal S)	92
NO_x, ppm (Corrected to 3% O_2)	51
SO_2, ppm (Corrected to 3% O_2)	1365
CO, ppm (Corrected to 3% O_2)	71

These data, coupled with visual inspection of the fly ash, showed that the fuel burns very well. Inherent SO_2 capture by the coal ash is excellent (probably around 70%).

Week 2

The second week of testing was successful in meeting the project goals. In addition to repairing the leak in the air-to-flue gas heat exchanger, more air purge lines were added to the coal weigh hopper to keep the coal flowing smoothly. There were still coal feed problems, resulting in fluctuations in emissions and occasional temperature drops of up to 100°F, but, in most cases, the system stabilized near the desired conditions in a matter of minutes. Another significant change between Weeks 1 and 2 of testing was that the material collected in the secondary cyclone was reinjected during Week 1, but collected to a barrel in Week 2.

Summary of Results

Upon completion of the run, data for each of the steady-state test periods were averaged. A summary of the process data for each test is presented in Table E-4. The four test periods correspond to those presented in the test matrix listed in Table E-1. Summaries of the run data are presented at the end of this appendix.

Recirculation Rates and Size Distributions

The solids recirculation rate was determined by calculating a heat balance around the external heat exchanger. The average solids recirculation rates for each test are shown in Table E-5. The recirculation rates were lower compared to those calculated from previous runs (7,660 to 15,750 lb/hr), but this is not surprising, since 169 to 215 pounds of secondary cyclone ash which had previously been recycled to the downcomer was removed during this run. The relative recirculation rates for the four tests were consistent with the operating conditions for each test. The coal and limestone feed rates were essentially the same for the first three tests; the difference in recirculation rates for those three tests was due to the difference in average combustor temperature and, consequently, superficial gas velocity during Tests 2 and 3. At the lower velocity in Test 2, a smaller maximum particle size was carried out of the combustor, resulting in a lower recirculation rate. Similarly, the higher velocity in Test 3 carried larger particles out of the combustor, resulting in a higher recirculation rate. The velocity in Test 4 was essentially the same as that in Test 1; the lower recirculation rate in Test 4 was due to the fact that no limestone was being added during that test, so the amount of solids in the bed was less.

TABLE E-4

Summary of Process Data

Test Number:	Test 1	Test 2	Test 3	Test 4
Time:	0030-0840	1230-1630	2030-0045	1245-1845
Date:	8/14/91	8/14/91	8/14-15/91	8/15/91
Coal Feed Rate, lb/hr	488	479	479	479
Limestone Feed Rate, lb/hr	141.4	141.9	145.4	0.0
Solids Recirculation Rate, lb/hr	3830	3335	4269	3447
Combustor dP, in. H_2O	45.8	50.0	46.1	43.3
Combustion Air				
EHX Flow, scfm	47	45	47	48
Primary Air, scfm	216	184	216	203
Secondary Air, scfm	176	188	179	174
Feed Assist Air, scfm	19	19	19	19
DC Aeration Air, scfm	12.2	12.1	12.0	12.1
Purge Air, scfm	15.5	15.5	15.5	15.5
Total Air, scfm	485	464	489	472
PA/SA, %	60	55	60	59
Excess Air, %	24.4	24.4	24.2	26.6
FG SGV, ft/sec	16.6	15.2	17.3	16.1
EHX SGV, ft/sec	1.7	1.4	1.8	1.6
Flue Gas				
Flow Rate, scfm	536	507	519	517
Oxygen, %	4.06	4.05	4.03	4.37
SO_2, ppm	1481	1852	2172	4399
CO, %	0.0076	0.0082	0.0020	0.0080
NO_x, ppm	122	80	143	97
N_2O, ppm	56	108	31	75
CO_2, %	16.8	16.9	17.5	16.0
Ash				
Bottom Ash Discharge Rate, lb/hr	94	127	85	12
Bottom Ash Unburned Carbon, %	1.07	7.63	0.70	0.22
Cyclone Ash Discharge Rate, lb/hr	203	197	215	169
Cyclone Ash Unburned Carbon, %	0.78	1.81	0.54	0.00
Baghouse Ash Discharge Rate, lb/hr	28.4	9.7	9.5	12.1
Baghouse Ash Unburned Carbon, %	0.50	0.82	0.19	0.42
Total Ash (meas.), lb/hr	325	333	309	192
Total Ash (calc.), lb/hr	321	315	324	175
Bottom Ash/Total Ash (meas.) %	28.8	38.0	27.4	6.1

continued...

TABLE E-4 (continued)

Test Number:	Test 1	Test 2	Test 3	Test 4
Time:	0030-0840	1230-1630	2030-0045	1245-1845
Date:	8/14/91	8/14/91	8/14-15/91	8/15/91
Air and Gas Temperatures (°F)				
Combustor Temperatures				
Plenum	609	547	639	592
Section 1	1516	1423	1608	1518
Section 2	1556	1465	1646	1563
Section 3	1591	1506	1675	1603
Section 4	1574	1490	1689	1584
Section 5	1611	1522	1690	1622
Section 6	1594	1497	1686	1589
Section 7	1600	1476	1655	1560
Section 8	1597	1470	1647	1548
Section 9	1588	1511	1674	1598
PCD Exit	1619	1509	1678	1597
Average	1565	1471	1650	1564
EHX Temperatures				
Plenum	132	144	145	138
0.5' above Distributor Plate	1316	1062	1603	1152
1.5' above Distributor Plate	1283	1026	1353	1120
2.7' above Distributor Plate	1268	1021	1365	1148
3.8' above Distributor Plate	1057	845	1180	954
5.3' above Distributor Plate	911	738	1022	825
Average	1289	1036	1373	1140
Downcomer Temperatures				
Section 3	1574	1467	1653	1538
Section 4	1577	1468	1639	1567
Section 6	1598	1493	1660	1590
Section 8	1621	1513	1678	1613
Cyclone Exit	1612	1497	1662	1597
Baghouse Inlet	411	389	378	402
Baghouse Outlet	337	326	319	336
ID Fan Inlet	281	269	277	280
Ambient	88	100	99	97

Primary cyclone collection efficiency is defined as one minus the ratio of fly ash collected to recirculation rate. The increased fly ash removal, as opposed to recirculation, from the secondary cyclone was the cause of the relatively low cyclone efficiency.

The particle-size distributions throughout the run were fairly consistent. Figure E-3 shows the particle-size distributions for the downcomer, secondary cyclone ash, and baghouse ash for all four tests.

TABLE E-5

Solids Recirculation and Heat-Transfer Data

Test	Temperature (°F)	Ca/S	Excess Air (%)	Primary Air (%)	Solids Recirculation (lb/hr)	DC[1] d_{50} (μm)	H_o[2]	Heat Flux (Btu/hr-ft²)	Cyclone Efficiency (%)	Recirculation Ratio
1	1,565	2.3	24.4	60	3,830	348	14.6	24,021	93.97	11
2	1,471	2.2	24.4	55	3,335	396	14.8	19,986	93.81	10
3	1,650	2.1	24.2	60	4,269	394	15.7	23,926	94.74	12
4	1,564	0.6	26.6	59	3,447	417	15.8	22,597	94.76	20

[1] Downcomer.
[2] Heat-transfer coefficient (Btu/hr-ft²-°F)

Bottom Ash/Total Ash Split

The ash balance for each test period, along with the averages for the entire run, are presented in Table E-6. Ash input to the system was composed of calculated quantities of coal and limestone ash, based on their respective analyses and feed rates. The limestone-derived ash was further broken down into estimates of the sorbent which was either calcined or had undergone sulfation. The output was composed of measured quantities of bottom ash (drained from the combustor bed), fly ash removed from the secondary cyclone, and fly ash removed from the baghouse.

The ratios of bottom ash-to-total ash, as well as the percent closure, are included in Table E-6. The average closure for all tests was about 93%. The bottom-to-total ash split ranged from about 27% to about 39% for the tests with limestone feed. The elimination of limestone feed for Test 4 resulted in a slower accumulation of bed material; the minimal bed drain required to maintain the desired pressure drop of 40" H_2O in the combustor resulted in a very low bottom ash/fly ash split of 6% for this test.

Ash/Limestone Split

Table E-7 presents data on the makeup of the bed material, the secondary cyclone drain, and the baghouse catch. A material balance was performed using alumina as a tracer, since it was present in relatively large quantities in the coal ash, but nonexistent in the limestone. This material balance was used to determine the split of ash and limestone at each solids removal point and is shown in Table E-8. The material balance closure is listed as a measure of possible error and is based on coal ash only. Also presented in Table E-7 is the percentage of ash fed into the combustor, calculated as the total ash in with the coal divided by the total ash in with the coal plus the sorbent equivalent mass inputs (CaO and $CaSO_4$).

For the tests with limestone, the contribution of the coal ash to the fly ash streams ranged from 59% to 68%. This was similar to the ratio of the coal ash to limestone inputs, which was 62%, indicating that both the coal ash and limestone were being elutriated at similar rates. The bed material drains for these tests indicated a buildup of material from the coal ash for Tests 1 and 2 (72% and 80%) and a depletion in Test 3 (35%). The buildup of ash could be attributed to the large clay inclusions that were left after the coal was burned out. The low number obtained for the percentage of ash for

TABLE E-6

Ash Balance

	Test 1	Test 2	Test 3	Test 4
Input, lb/hr				
Ash	200	192	198	175
Sorbent*				
CaO	49	47	48	0
$CaSO_4$	74	78	80	0
Total Solids In	323	318	326	175
Output, lb/hr				
Bed Material	94	127	85	12
Cyclone Ash	203	197	215	169
Baghouse Ash	28	10	10	12
Total Solids Out	325	333	309	192
Closure, %	100.5	104.8	94.7	109.9
Bottom Ash/Total Ash, %	28.8	38.0	27.4	6.1

* The CaO and $CaSO_4$ mass inputs are included to express sorbent equivalent mass inputs.

TABLE E-7

Material Derived from Coal Ash and Limestone Based on an Aluminum Material Balance (%)

	Test 1		Test 2		Test 3		Test 4	
	Ash	Limestone	Ash	Limestone	Ash	Limestone	Ash	Limestone
Feed, %	62	38	61	39	61	39	100	0
Bed Drain, %	72	28	80	20	35	65	88	12
Secondary Cyclone Drain, %	64	36	68	32	63	37	82	18
Baghouse Catch, %	60	40	65	35	59	41	63	37
Aluminum Balance Closure, %	107		125		86		89	

Test 3 may be a sampling artifact, where the larger particles may not have been included in the sample. The limestone feed was stopped for Test 4. This is reflected by the higher percentage of coal ash in the bed (88%) and secondary cyclone ash (82%). If the bed had been completely turned over to an ash bed, these numbers would be 100%. This indicates that some residual limestone was present in the bed during this test. The baghouse catch for Test 4 indicated only 63% of the material was derived from the coal ash. This indicates that the residual limestone in the bed was breaking up and producing fines in a greater proportion than fine ash derived from the coal.

TABLE E-8

Aluminum Material Balance

	Test 1	Test 2	Test 3	Test 4
Coal Ash Feed Rate, lb/hr	200.2	192.3	197.7	175.1
Al_2O_3 in Coal Ash, %	11.3	12.7	13.1	12.5
Secondary Cyclone Ash Out, lb/hr	202.7	196.8	214.8	168.5
Al_2O_3 in Secondary Cyclone Ash, %	7.2	8.6	8.2	10.2
Ash from Coal, %	64.1	67.6	62.9	81.7
Ash from Coal, lb/hr	129.9	133.1	135.1	137.6
Baghouse Ash Out, lb/hr	28.4	9.7	9.5	12.1
Al_2O_3 in Baghouse Ash, %	6.8	8.3	7.7	7.9
Ash from Coal, %	59.9	65.0	59.0	62.9
Ash from Coal, lb/hr	17.0	6.3	5.6	7.6
Bed Material Out, lb/hr	93.7	126.6	84.7	11.8
Al_2O_3 in Bed Material, %	8.1	10.1	4.6	11.0
Ash from Coal, %	71.9	79.5	35.3	88.0
Ash from Coal, lb/hr	67.3	100.7	29.9	10.4
Total Ash from Coal, lb/hr	214.2	240.1	170.6	155.7
Closure, %	107.0	124.9	86.3	88.9

THERMAL PERFORMANCE

Energy and Material Balance

The measured and theoretical fuel and flue gas flow rates are presented in Tables E-9 and E-10, respectively. The theoretical fuel feed rate was calculated using theoretical fuel characteristics, measured combustion air, and measured O_2 and CO_2 concentrations in the flue gas. The theoretical flue gas rates were calculated using the actual coal feed rate and excess air level for each test. The measured fuel feed rates were all higher than the theoretical values based on the measured combustion air flow. The measured flue gas flows were lower than theoretical values based on the measured coal feed rate.

The energy balances for the four tests are presented in Table E-11, both as Btu/hr and percentages. The energy input was made up of the energy potential of the fuel, the primary and secondary combustion air, the external heat exchanger fluidizing air, and the energy released from the sulfation of the sorbent. Measurable heat loss sources were the combustor heat exchange doors, the external heat exchanger cooling coils, the flue gas, the unburned carbon in the ash removed, the heat contained in the ash drained from the system, and the energy absorbed during calcination of the sorbent. Flue gas losses include a correction for leakage. The unmeasurable heat loss due to convection and radiation is based upon a correlation developed from previous testing that takes into account the average operational combustor temperature and the solid recirculation rate. The energy balance closure was good for all tests.

TABLE E-9

Fuel Balance

	Test 1	Test 2	Test 3	Test 4
Fuel Feed Rate, meas., lb/hr	488	479	479	479
Fuel Feed Rate, theor., lb/hr	517	501	516	477
Difference, %	-6.1	-4.5	-7.8	0.5

meas. = Feed rate calculated by linear regression performed on coal feed hopper weight loss over time.
theor. = Theoretical feed rate calculated on the basis of the coal analysis, the combustion air, and excess air for each test period.

TABLE E-10

Flue Gas Balance

	Test 1	Test 2	Test 3	Test 4
Stack Gas Flow, meas., scfm	536	507	519	517
Stack Gas Flow, theor., scfm	558	534	560	541
Difference, %	-4.1	-5.2	-7.9	-4.6

meas. = The flue gas flow measured during the run through an orifice located just upstream of the ID fan.
theor. = Theoretical flue gas flow calculated on the basis of the coal analysis and the theoretical coal feed rate for each test period.

The material balances for the four test periods are presented in Table E-12. The material balance inputs consist of combustion air, coal, and limestone feed rates. Outputs are flue gas (including a correction for leaks), drained bed material, baghouse ash, and secondary cyclone ash. The closures for all tests were fairly good.

Combustion Efficiency

The combustion efficiencies for each test are presented in Table E-13 and shown graphically in Figure E-4. The combustion efficiencies for the four tests ranged from about 89% (Test 2) to nearly 100% (Test 4). The unburned carbon was determined by the difference between loss on ignition (LOI), and for some tests, the carbon from carbonate (expressed as CO_2). Carbonate analyses were not performed for Tests 3 and 4. The results of the unburned carbon calculations are shown in Table E-14. The data indicate that carbon burnout drops significantly for the Asian lignite at low operating temperatures. Combustion efficiencies also decreased with sorbent addition due to increased bed material drain requirements to maintain proper solids inventory. The combination of relatively high concentrations of unburned carbon in the ash streams and high drain rates during Test 2 resulted in the low reported combustion efficiency.

TABLE E-11

Energy Balance

	Test 1	Test 2	Test 3	Test 4
Input, Btu/hr				
Coal	1,874,141	1,788,165	1,924,948	1,842,565
Primary Air	124,684	91,492	129,650	111,760
Secondary Air	101,609	93,129	107,353	95,548
EHX Air	2,295	2,223	2,392	2,217
Sorbent Sulfation	117,531	123,862	126,968	0
Total	2,220,260	2,098,871	2,291,310	2,052,090
Input, %				
Coal	84.4	85.2	84.0	89.8
Primary Air	5.6	4.4	5.7	5.4
Secondary Air	4.6	4.4	4.7	4.7
EHX Air	0.1	0.1	0.1	0.1
Sorbent Sulfation	5.3	5.9	5.5	0.0
Total	100.0	100.0	100.0	100.0
Output, Btu/hr				
Flue Gas (sens.)	1,076,276	948,007	1,117,927	1,018,263
Ash (sens.)	129,079	122,815	128,920	75,941
Ash (chem.)*	38,584	187,638	24,954	1,085
Combustor	249,819	311,779	186,625	411,272
EHX	348,304	423,657	359,456	336,072
Sorbent Calcination	108,312	108,695	111,376	0
Conduction and Radiation Losses	215,363	166,029	259,331	214,613
Total	2,165,739	2,268,620	2,188,589	2,057,245
Output, %				
Flue Gas (sens.)	49.7	41.8	51.1	49.5
Ash (sens.)	6.0	5.4	5.9	3.7
Ash (chem.)*	1.8	8.3	1.1	0.1
Combustor	11.5	13.7	8.5	20.0
EHX	16.1	18.7	16.4	16.3
Sorbent Calcination	5.0	4.8	5.1	0.0
Conduction and Radiation Losses	9.9	7.3	11.8	10.4
Total	100.0	100.0	100.0	100.0
Closure	97.5	108.1	95.5	100.3

* The heat of combustion coefficient for pure carbon is an average of values found in *Perry's Chemical Engineering Handbook*, Perry et al. (1984) and the *Standard Handbook for Mechanical Engineers*, Baumeister and Marks (1967).

TABLE E-12

Material Balance

	Test 1	Test 2	Test 3	Test 4
Input, lb/hr				
Combustion Air	2007	1910	2025	1948
Additional Air	215	214	212	214
Coal Feed	517	501	516	477
Sorbent Feed	141	142	145	0
Total Mass In	2880	2767	2899	2639
Input, %				
Combustion Air	69.7	69.0	69.8	73.8
Feed Assist Air	7.5	7.7	7.3	8.1
Coal Feed	18.0	18.1	17.8	18.1
Sorbent Feed	4.9	5.1	5.0	0.0
Total Mass In	100.0	100.0	100.0	100.0
Output, lb/hr				
Measured Flue Gas	2455	2327	2392	2366
Flue Gas Leaks	101	121	189	108
Ash Out				
Bed Material	94	127	85	12
Baghouse	28	10	10	12
Cyclone Ash	203	197	215	169
Total Mass Out	2881	2781	2890	2667
Output, %				
Measured Flue Gas	85.2	83.7	82.8	88.7
Flue Gas Leaks	3.5	4.3	6.5	4.1
Ash Out				
Bed Material	3.3	4.6	2.9	0.4
Baghouse	1.0	0.3	0.3	0.5
Cyclone Ash	7.0	7.1	7.4	6.3
Total Mass Out	100.0	100.0	100.0	100.0
Closure	100.0	100.5	99.7	101.0

Boiler Efficiency

Boiler efficiencies were calculated for each test period using a modified version of ASME PTC 4.1. The modifications to PTC 4.1 are those recommended in EPRI's "Atmospheric Fluidized-Bed Combustion Performance Guidelines." Basically, the modification is a method to account for the heat losses and gains associated with calcination and sulfation of the sorbent.

Table E-15 summarizes the results of the boiler efficiency calculations for each test. Boiler radiation and convective losses were assumed to be 0.4% of the heat input from the coal. Although these losses were much higher for our pilot plant, 0.4% was chosen to be representative of a full-scale system. An exit gas temperature of 300°F was used in the calculations.

TABLE E-13

Combustion Efficiency

	Test 1	Test 2	Test 3	Test 4
Input				
Coal Feed Rate, lb/hr	517.4	500.8	516.1	477.1
Coal Carbon, %	24.6	24.6	25.1	25.6
Carbon Feed Rate, lb/hr	127.3	123.2	129.5	122.1
Total, lb/hr	127.3	123.2	129.5	122.1
Output				
Bottom Ash Discharge Rate, lb/hr	94	127	85	12
Unburned Carbon, %	1.07	7.63	0.70	0.22
Bottom Ash Carbon Discharge Rate, lb/hr	1.01	9.67	0.59	0.03
Secondary Cyclone Discharge Rate, lb/hr	203	197	215	169
Unburned Carbon, %	0.78	1.81	0.54	0.00
Secondary Cyclone Carbon Discharge Rate, lb/hr	1.59	3.57	1.16	0.00
Baghouse Discharge Rate, lb/hr	28	10	10	12
Unburned Carbon, %	0.50	0.82	0.19	0.42
Baghouse Carbon Discharge Rate, lb/hr	0.14	0.08	0.02	0.05
Total, lb/hr	2.74	13.32	1.77	0.08
Combustion Efficiency, %	97.85	89.19	98.63	99.94

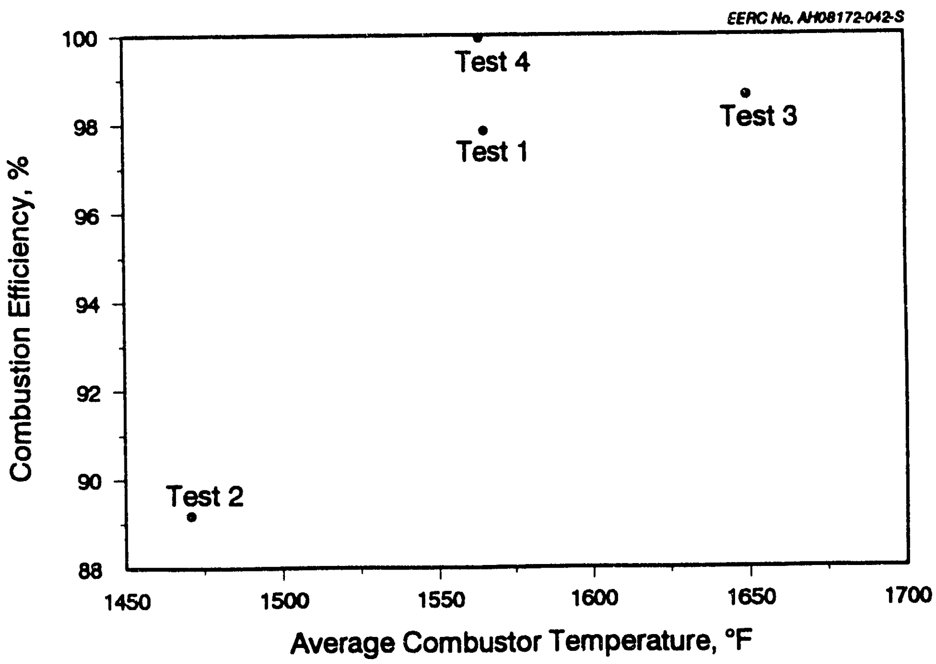

Figure E-4. Combustion efficiency as a function of average combustor temperature.

TABLE E-14

Unburned Carbon (%)

	Test 1	Test 2	Test 3	Test 4
Combustor Bed Material				
Loss on Ignition	1.30	10.70	0.70	0.22
Carbonate (as CO_2)	0.83	11.24	ND[1]	ND
Unburned Carbon	1.07	7.63	0.70	0.22
Secondary Cyclone Ash				
Loss on Ignition	0.94	2.54	0.54	0.00
Carbonate (as CO_2)	0.57	2.66	ND	ND
Unburned Carbon	0.78	1.81	0.54	0.00
Baghouse Ash				
Loss on Ignition	0.50	0.93	0.19	0.42
Carbonate (as CO_2)	ND	0.39	ND	ND
Unburned Carbon	0.50	0.82	0.19	0.42

[1] Not determined.

TABLE E-15

Boiler Efficiency

	Test 1	Test 2	Test 3	Test 4
Assumed Flue Gas Exit Temp., °F	300	300	300	300
Losses, Btu/hr				
Dry Gas	132,387	126,908	134,127	128,523
Water in Fuel	104,809	105,027	99,011	98,919
Comb. of Fuel Hydrogen	14,803	13,394	14,643	13,682
Unburned Carbon	38,584	187,638	24,954	1,085
Sorbent Calcination	108,312	108,695	111,376	0
Radiation and Convection*	7,914	7,566	8,097	7,763
Discharged Solids	129,079	122,815	128,920	75,941
Sorbent Sulfation	-117,531	-123,862	-126,968	0
Total	418,359	548,181	394,161	325,913
Losses, %				
Dry Gas	7.1	7.0	7.1	6.6
Water in Fuel	5.6	5.8	5.3	5.1
Comb. of Fuel Hydrogen	0.8	0.7	0.8	0.7
Unburned Carbon	2.1	10.4	1.3	0.1
Sorbent Calcination	5.8	6.0	5.9	0.0
Radiation and Convection*	0.4	0.4	0.4	0.4
Discharged Solids	6.9	6.8	6.9	3.9
Sorbent Sulfation	-6.3	-6.8	-6.8	0.0
Total	22.4	30.3	21.0	16.7
Boiler Efficiency, %	77.6	69.7	79.0	83.3

* Assumes 0.4% radiative and convective losses.

Boiler efficiencies with this coal were very low, 70% - 83%, compared to the 85% - 90% efficiencies calculated for other coals tested on this unit. The loss due to unburned carbon was greater than 10% for Test 2, the low-temperature test. Boiler efficiency losses due to dry flue gas was about 7% for all four tests; the moisture in the coal accounted for 5% - 6% of the losses. The loss due to the removal of hot solids from the system was almost 7% for Tests 1 through 3, and 4% for Test 4; the difference is that no limestone was added during Test 4, so less material had to be removed to maintain solids inventory.

Heat-Transfer Coefficient and Heat Flux

During testing, combustor heat exchange surface used for heat removal included the doors in Sections 2, 3, 4, 6, 7, and 8. Flow rates and temperatures of the cooling water used in these heat exchange surfaces were monitored to allow calculation of heat-transfer coefficients and heat flux as a function of position in the combustor. In the external heat exchanger, the number of cooling coils used to control temperature ranged from 6 to 11. Heat-transfer coefficient and heat flux are calculated for the EHX as a whole. The average values of heat-transfer coefficient and heat flux for each combustor section which contains one or more heat exchange doors, and for the external heat exchanger, have been calculated for each of the four tests and are presented in Tables E-16 and E-17. Table E-18 presents the average heat-transfer coefficient and heat flux in the combustor for the entire run, along with the average pressure drop across each combustor section containing a heat exchange door. These data are also summarized in Table E-5 to facilitate comparison to test conditions. The heat fluxes calculated for this run ranged from 19,986 Btu/hr-ft^2 for Test 2 to 24,021 Btu/hr-ft^2 for Test 1. These values are lower than the 24,500 to 35,800 Btu/hr-ft^2 observed in previous runs on this unit. The heat flux in the external heat exchanger ranged from 53,122 Btu/hr-ft^2 for Test 2 to 80,362 Btu/hr-ft^2 for Test 3. These values are relatively low compared to EHX heat flux for other coals burned in this unit; while Center, Black Thunder, and Blacksville all had full-load tests with heat flux as low as 55,000, the same runs had maximum heat flux of 123,000, 111,000, and 98,000, respectively. Like the low solids recirculation rates observed in this run, the low heat-transfer coefficients and heat flux in the combustor are due to the removal, rather than recirculation, of secondary cyclone ash.

There was not a lot of variability in combustor heat flux between tests. Test 4 had the lowest heat flux, probably because no limestone was being added during this test, resulting in a decrease in the amount of fine solids in the bed. In the EHX, however, both solids feed and operating temperature appear to affect heat flux, since the flux for Tests 2 and 4 are very similar.

Pressure and Temperature Profiles

The pressure and temperature profiles for Tests 1 through 4 are presented in Figures E-5 and E-6, respectively. Figure E-5 shows the dense phase in the lower portion of the combustor, similar to a bubbling fluidized bed, and the dilute phase in the rest of the combustor. The temperature profiles are quite uniform; areas of lower temperature are caused by heat-transfer doors in those sections of the combustor.

TABLE E-16

Individual Heat-Transfer Coefficients (Btu/hr-ft^2-°F)

Combustor Section	Test 1	Test 2	Test 3	Test 4	Average	Combustor Height
2	23.4	21.6	off	20.0	21.7	7.5
3	off	off	off	17.1	17.1	12.5
4	14.0	12.6	off	14.2	13.6	17.5
6	15.2	13.6	off	15.0	14.6	27.5
7	off	11.7	14.1	13.0	12.9	32.5
8	14.6	12.3	15.3	13.9	14.0	37.5
Overall	16.9	14.8	15.7	15.8	15.8	
EHX	59.3	58.4	63.9	55.2	59.2	

TABLE E-17

Individual Heat Flux (Btu/hr-ft^2)

Combustor Section	Test 1	Test 2	Test 3	Test 4	Average	Combustor Height
2	33,115	28,928	off	29,066	30,370	7.5
3	off	off	off	25,090	25,090	12.5
4	20,213	17,350	off	20,637	19,400	17.5
6	22,088	18,662	off	21,821	20,857	27.5
7	off	15,927	21,673	18,556	18,719	32.5
8	21,215	16,581	23,194	19,636	20,157	37.5
Overall	24,021	19,986	23,926	22,597	22,633	
EHX	67,811	53,122	80,362	56,012	64,327	

TABLE E-18

Average Heat-Transfer Coefficient and Heat Flux

Section	dP (in. H_2O)	H_o	Flux
2	31.9	21.7	30,370
3	2.1	17.1	25,090
4	1.4	13.6	19,400
6	1.0	14.6	20,857
7	0.8	12.9	18,719
8	0.8	14.0	20,157
1-8	55.6	15.8	22,633

[1] Heat-transfer coefficient (Btu/hr-ft^2-°F).

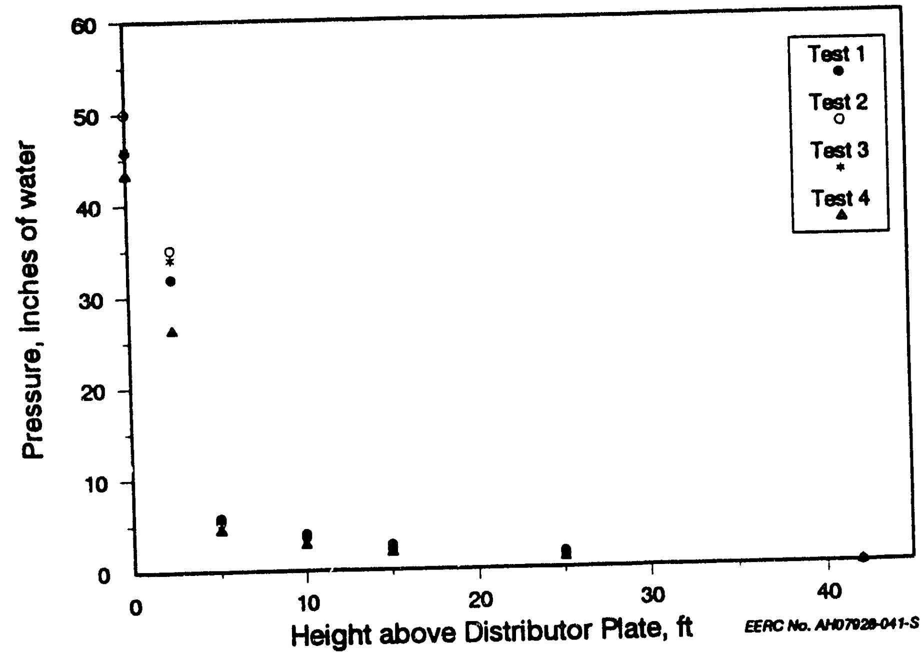

Figure E-5. Combustor pressure profiles.

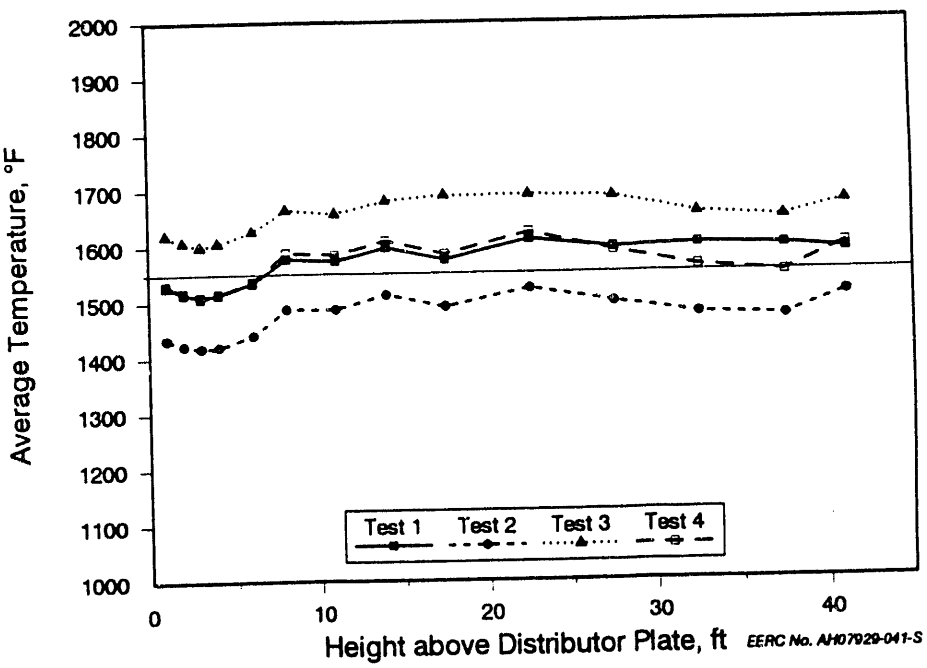

Figure E-6. Combustor temperature profiles.

ENVIRONMENTAL PERFORMANCE

Average flue gas emissions for each of the four steady-state test periods are presented in Table E-19 and discussed in the following sections. All of the emissions are represented graphically as functions of average combustor temperature. The temperature was varied by adjusting the total amount of heat-transfer surface in use from one test period to another. The combustion air supply was held constant throughout the test burn, and, as such, the lower furnace and flue gas velocities were allowed to drift in response to higher or lower combustor temperatures. The trends noted in all cases were the same as expected based on previous experience.

TABLE E-19

Emissions Data

	Test 1	Test 2	Test 3	Test 4
O_2, %	4.06	4.05	4.03	4.37
CO Content, ppm	76	87	20	94
CO Content,[1] ppm	81	82	22	101
CO Emission, lb/MM Btu	0.059	0.06	0.01	0.076
CO_2 Content, %	16.8	16.9	17.5	16.0
CO_2 Content, %	17.8	17.9	18.5	17.3
NO_x Content, ppm	122	80	143	97
NO_x Content,[1] ppm	130	84	151	105
NO_x Emission, lb/MM Btu	0.18	0.12	0.20	0.15
N_2O Content, ppm	56	108	31	75
N_2O Content,[1] ppm	59	114	32	81
N_2O Emission, lb/MM Btu	0.078	0.152	0.041	0.107
SO_2 Content, ppm	1481	1852	2172	4399
SO_2 Content,[1] ppm	1573	1966	2304	4761
SO_2 Emission, lb/MM Btu	3.02	3.77	4.26	9.42
SO_2 Retention (calc.),[2] %	90.3	88.1	86.2	70.1
Ca/S Ratio (ls[3] only)	1.3	1.3	1.4	0.0
Ca/S Ratio (total)	2.21	2.02	2.01	0.63
Ca Utiliz. (ls[3] only)	68.4	66.5	63.7	0.0
Ca Utiliz. (total)	40.9	43.7	42.9	111.8
Alkali-to-Sulfur (total)	2.34	2.17	2.12	0.63
Alkali Utilization (total)	38.7	40.6	40.6	110.4
Average Combustor	1565	1471	1650	1564
Temperature, °F	14.4	14.2	13.9	13.9
Moisture in Flue Gas, vol%	29.6	29.8	29.9	31.0
Moist-Free Coal Carbon, %	7.16	7.30	7.18	7.60
Moist-Free Coal Sulfur, %				

1 Corrected to 3% O_2.
2 Moisture-free coal carbon and sulfur values used in the sulfur retention calculation.
3 limestone.

SO_2 Emissions

The average concentration of SO_2 in the flue gas (corrected to 3% O_2) varied from 1570 to 4760 ppm (3.02 to 9.22 lb/MM Btu), depending upon the operating temperature and ratio of calcium-to-sulfur in the system. Figure E-7 shows that the lowest SO_2 emissions occurred under Test 1 conditions, during which the average combustor temperature was 1565°F.

Figure E-8 is a plot of the measured sulfur retention versus total calcium-to-sulfur (Ca/S) ratio expressed on a molar basis. The plot shows that the Ca/S ratio was slightly higher during Test 1 than it was for Tests 2 and 3. However, the effect of temperature on SO_2 retention is evident from the figure. At similar Ca/S ratios, sulfur retention was lowest at a temperature of 1650°F, was somewhat higher at 1470°F, and was greatest at 1565°F. Overall, a Ca/S ratio of approximately 2.1 (1.3 from limestone, 0.8 inherent with coal) was needed to achieve a SO_2 retention of between 87% and 91% at all combustor temperatures tested. Test 4 was conducted without sorbent feed at an average combustor temperature of 1564°F. As shown in Figure E-8, the alkali inherent in the coal ash was sufficient to achieve 70% SO_2 retention. A calculated calcium utilization of 111% for this test indicates residual limestone was responsible for some of the sulfur capture on Test 4.

The higher Ca/S ratio used during Test 1 may have resulted in slightly greater SO_2 retention and likely resulted in lower SO_2 flue gas concentrations than if it were performed at the exact same Ca/S as Tests 2 and 3. Only a minor change in retention and emission numbers from those reported would be expected if the test were performed at a Ca/S of 2.01 rather than 2.21.

NO_x Emissions

Flue gas emissions of NO_x (corrected to 3% O_2) ranged from 84 to 151 ppm (0.12 to 0.20 lb/MM Btu). The effect of temperature on NO_x emissions is shown in Figure E-9, with NO_x increasing with increasing temperature. NO_x emissions were approximately 25 ppm higher for Test 1 compared to Test 4, due to the catalytic effect of the limestone.

N_2O Emissions

N_2O emissions (corrected to 3% O_2) ranged from 32 to 114 ppm (0.4 to 0.15 lb/MM Btu). Figure E-10 shows how N_2O decreases with increasing combustor temperature. Unlike NO_x emissions, for which the addition of limestone resulted in higher emissions levels, N_2O emissions were lower during Test 1 with limestone feed than during Test 4 without limestone.

CO Emissions

The as-measured emissions of CO varied from 20 to 94 ppm during Week 2 steady-state testing, as shown in Figure E-11. In general, the CO concentrations decreased as the average operating temperature increased. One deviation from that trend was that the highest steady-state CO value resulted from Test 4 operation at an intermediate combustor temperature and zero sorbent feed.

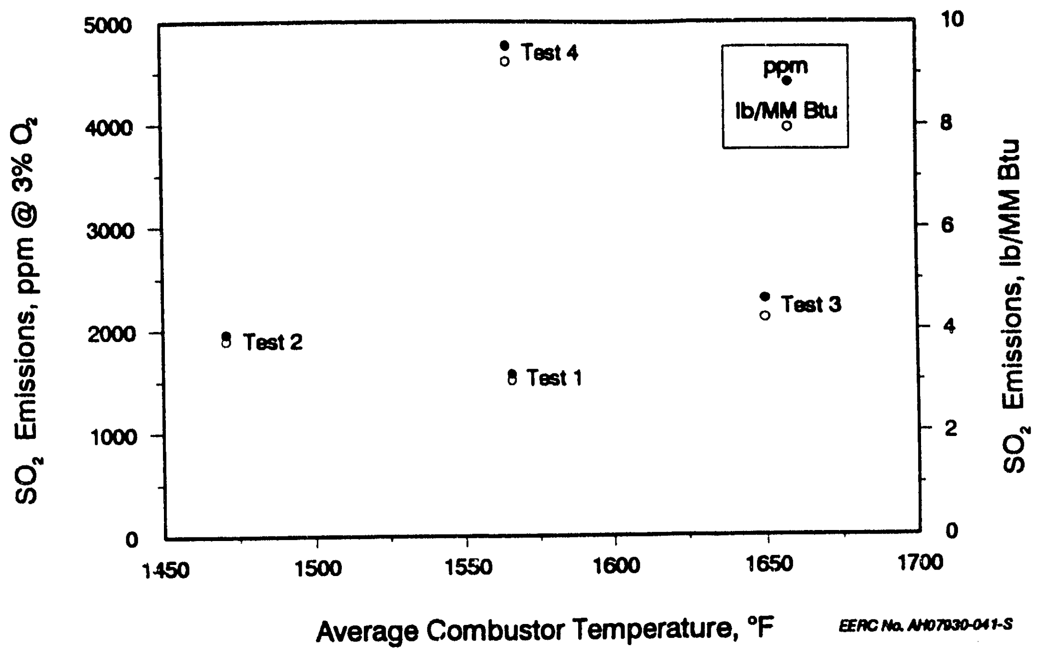

Figure E-7. SO_2 emissions as a function of average combustor temperature.

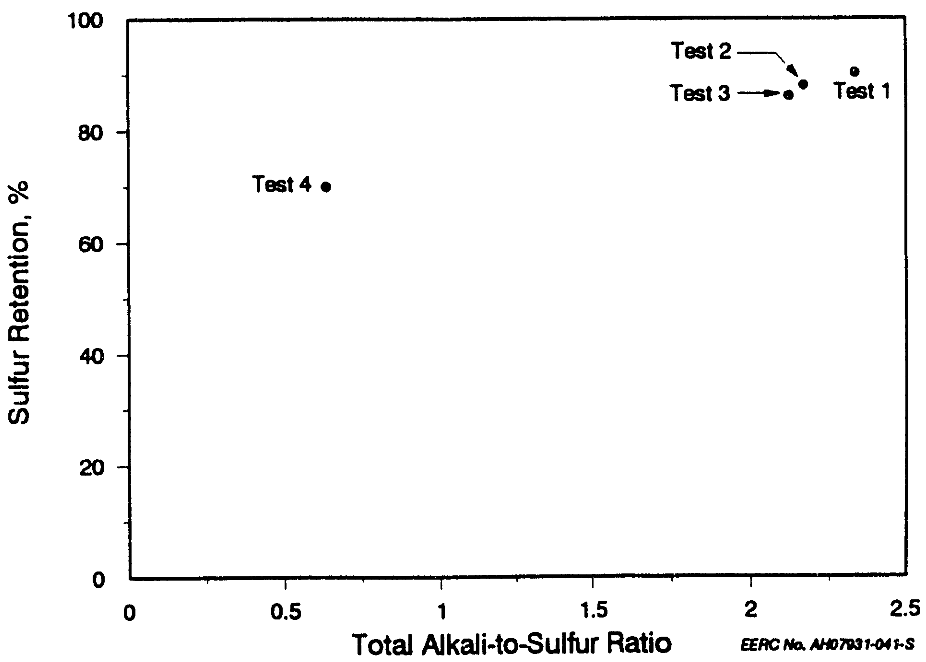

Figure E-8. SO_2 retention as a function of calcium-to-sulfur molar ratio.

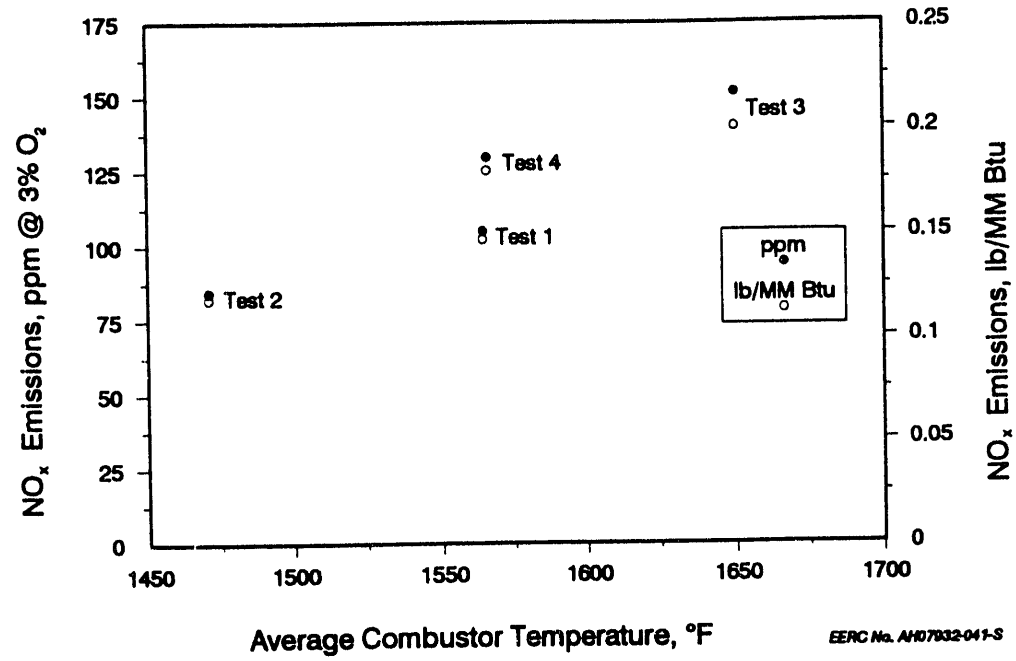

Figure E-9. NO_x emissions as a function of average combustor temperature.

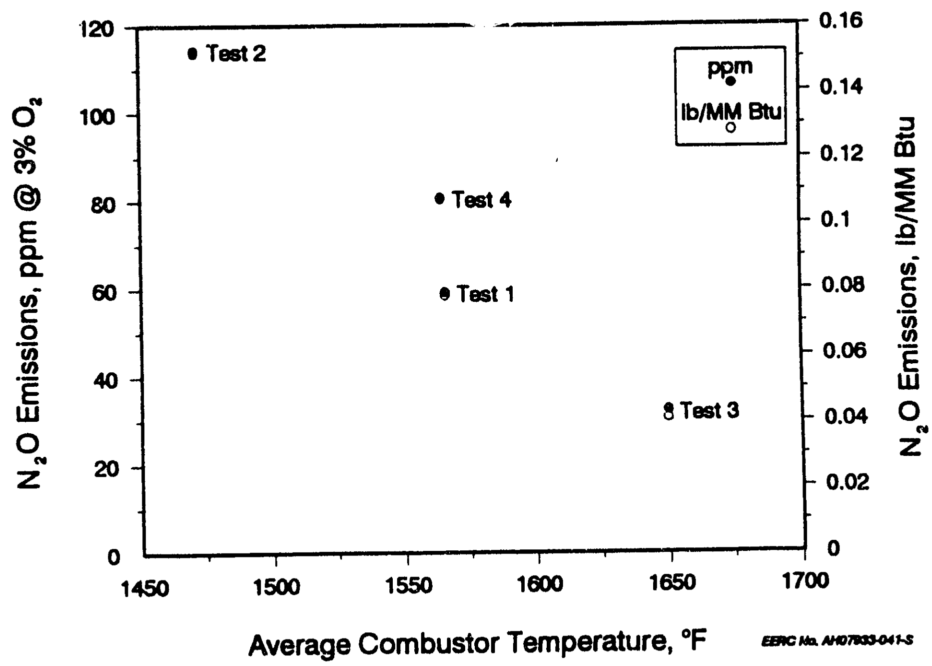

Figure E-10. N_2O emissions as a function of average combustor temperature.

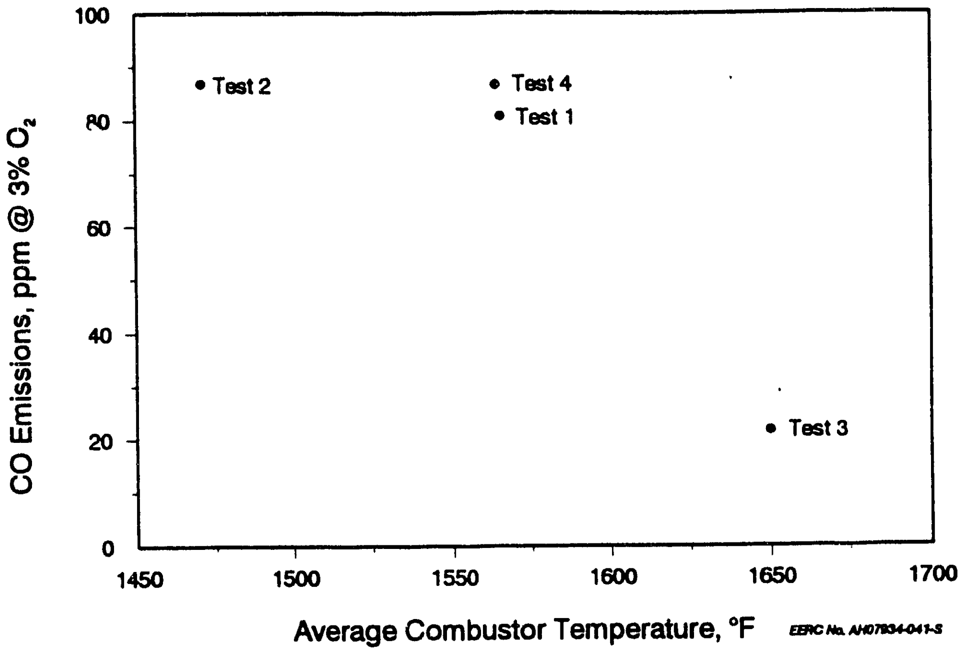

Figure E-11. CO emissions as a function of average combustor temperature.

The flue gas CO emissions measured during Week 1 were much more erratic and, on the average, much higher. This was due to the problems experienced with the air heater leaks, resulting in periods of time when reducing conditions were likely present within the combustor.

SINTERING, AGGLOMERATION, AND DEPOSIT EVALUATION

Although FBCs typically operate at relatively low temperatures, evidence from pilot, industrial, and utility boilers indicates that certain ash components can cause ash-related problems. These ash-related problems can manifest themselves as agglomeration and sintering of bed material, or as deposition on the heat exchange tube surfaces and refractory walls. These ash-related phenomena have been shown to cause a loss in steam temperature; operating difficulties; and, in some cases, unplanned shutdowns. Experience at the EERC has shown fuels with high sodium and potassium levels to be the most troublesome, particularly with bed agglomeration. Agglomerates the size of small cars have been reported by the user of a high-sodium North Dakota lignite (12% NaO in the ash). High calcium and sulfur in the fuel have also been demonstrated to produce ash-related problems. Because of the nature of the ash from the source mine and experience burning this fuel in pc-fired systems, an important goal of this feasibility study was to determine the nature of any ash-related problems.

Bed Material Sintering and Agglomeration Potential

No evidence of bed material agglomeration or ash deposition in the combustor, downcomer, or external heat exchanger was noted during either week of testing. Based on the low sodium and potassium content in the Asian lignite received and tested in the

EERC CFB pilot plant, it was expected that agglomeration would not be a concern. If lignite containing a higher alkali (Na plus K) concentration is utilized, there could possibly be some occurrence of agglomeration. However, if 90% sulfur capture is required, the high bed drain rate that is required when feeding limestone would likely minimize any potential for agglomeration by the constant purge of the alkali from the bed. At the limestone feed rates used during this test, it is expected that the Asian lignite tested could be burned without agglomeration problems.

There were several upsets in operational conditions during the two weeks of testing that are more favorable for the formation of agglomerates, based on past experience at the EERC. At the end of the first week of testing, due to the leak in the air heater, conditions in the combustor were highly reducing, and, immediately before shutdown, there was a temperature excursion up to approximately 1720°F. There were three separate occasions that forced a hot slump of the bed during the first week of testing. The last two hot slumps occurred without sufficient time available for the carbon present in the bed to completely burn out.

During the second week of testing, there was one intentional hot bed slump to retain heat in the combustor until a coal plug could be remedied. Several bed slumps were required during a short period of time on the final day of testing to restart the induced-draft blower, which tripped for electrical reasons. Despite all of these considerable process interruptions, as well as operation of the combustor at greatly reduced bed drain rates during the final 24 hours of Week 2, agglomeration was not a problem and is not expected to be a problem when firing this fuel in a full-scale unit.

A significant quantity of large bed material particles accumulated within the combustor during testing. It is likely that this was an accumulation of clay or rock that was fed into the combustor along with the coal. It is possible that an additional coal-cleaning step might remove these impurities. If that is not feasible, consideration should be given to the design of a bed material drain system to remove large particles selectively.

Backpass Tube-Fouling Potential

Two air-cooled probes located at the exit of the cyclone are used to investigate the degree of ash deposition or slagging that could be expected at the leading edge of the convective pass region of a circulating fluidized-bed boiler. Air flow to the probes was controlled to maintain a probe surface temperature of approximately 1000°F. A thin layer of ash, less than 1 mm thick, was present on the probes at the conclusion of the run.

Postrun inspection of system components revealed a deposit which had formed on top of the shell-and-tube air-to-flue gas heat exchanger located at the exit of the ash-fouling section. The deposit is a very fine-grained matrix, with most of the particles less than one micron. A few larger particles (1 to 10 microns) were found intermixed in the fine-grained matrix. The flow of the flue gas and possible erosion from larger ash particles produced a hill- and valley-like terrain on the deposit. The flue gas temperature entering the heat exchanger is approximately 1400°F. An analysis of the deposit is given in Table E-20. The elemental analyses show that the deposit is primarily composed of calcium and sulfur, with a relatively large amount of iron. This composition differs from both the coal and the limestone analyses, showing an enrichment in the calcium, iron, and sulfur. Further analysis of this deposit using scanning electron microscopy point

TABLE E-20

Analysis of Deposit from the Shell-and-Tube Heat Exchanger

Oxides	wt%
SiO_2	5.9
Al_2O_3	3.3
Fe_2O_3	15.1
TiO_2	0.0
P_2O_5	0.9
CaO	35.6
MgO	4.7
Na_2O	0.1
K_2O	0.3
SO_3	34.1
Minerals	Identified by XRD
Anhydrite ($CaSO_4$)	Major Phase
Maghemite (Fe_2O_3)	Minor Phase
Hematite (Fe_2O_3)	Minor Phase

count identified calcium sulfate as the primary phase. The most likely mechanism for the formation of this deposit is deposition of fine-grained calcium oxide on the face of the tube sheet. Sulfation of the calcium oxide and subsequent sintering of the particles produce a very hard, tenacious deposit. Some of the ash particles appear to have stuck to the deposit; however, it is unlikely that any of the constituents in these ash particles caused the deposit to form or gave it strength. The iron inclusions are probably from fine-grained pyrite being preferentially carried out of the combustor and deposited with the calcium oxide.

A similar phenomenon has been noted in pc-fired boilers firing high-calcium western United States subbituminous coals. In these systems, calcium sulfate-based deposits are found primarily in the reheat section of the boiler where flue gas temperatures range from 1650° to 1200°F. These deposits are very tenacious and difficult to remove using conventional soot blowers if they are allowed to build up and develop strength over time. It is recommended for any FBC built to burn this type of Asian lignite that a conservative design be used in the back pass ensuring adequate soot-blowing coverage to prevent buildup of calcium sulfate-based deposits.

SUMMARIES OF TEST DATA

This section contains the summaries of test data for each test period, including averages and standard deviations of many of the data points recorded by the computerized data acquisition system.

14-Aug-91

CFB-TL2-0691 — TEST 1

(0030-0840)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1612	12.2
TC11021	AFS Ex	°F	1411	8.5
TC15001	C Plenum	°F	609	6.7
TC15004	C 1-1'	°F	1529	16.1
TC15005	C 1-2'	°F	1516	14.6
TC15006	C 1-3'	°F	1511	14.7
TC15007	C 1-4'	°F	1508	14.5
TC15008	C 1-4'	°F	1520	15.1
TC15009	C 1-4'	°F	1515	14.5
TC15012	C 2-6'	°F	1535	16.0
TC15013	C 2-8'	°F	1578	14.2
TC15022	C 3-11'	°F	1574	14.1
TC15023	C 3-14'	°F	1588	13.6
TC15024	C 3-14'	°F	1603	14.6
TC15025	C 3-14'	°F	1599	14.8
TC15032	C 4-17.5'	°F	1574	11.8
TC15042	C 5-22.5'	°F	1611	13.0
TC15052	C 6-27.5'	°F	1607	12.2
TC15053	C 6-27.5'	°F	1610	13.2
TC15054	C 6-27.5'	°F	1566	11.4
TC15062	C 7-32.5'	°F	1600	12.6
TC15071	C 8-37.5'	°F	1597	10.8
TC15073	C 9-41'	°F	1588	13.0
TC15999	Ambient	°F	88	3.3
TC16001	EHX Plenm	°F	132	4.3
TC16012	EHX 0.5'	°F	1316	22.7
TC16013	EHX 1.5'	°F	1283	20.2
TC16014	EHX 2.7'	°F	1268	21.3
TC16015	EHX 3.8'	°F	1057	24.0
TC16017	EHX 5.3'	°F	911	15.5
TC16018	EHX Exit	°F	1169	19.0
TC16021	Crc A In	°F	1619	10.6
TC16031	DC 8-36'	°F	1621	13.1
TC16032	DC 6-28'	°F	1598	12.0
TC16033	DC 4-18'	°F	1577	14.3
TC16034	DC3-9.5'	°F	1600	21.0
TC16035	DC3-8.5'	°F	1548	22.7

T(A,C)	Comb Temp	°F	1565	12.7
T(A,EHX)	EHX Temp	°F	1289	21.1
EA	Excess Air	%	24.4	6.0
SR	S Reten	%	90.4	1.3
R(PCA)	% Flw PCA	%	59.6	2.6
R(SCA)	% Flw SCA	%	40.4	2.6
R(Q,IN)	% Enrg in	%	68.9	4.4
R(CHX)	CHX Ratio	%	41.4	1.5
R(EHX)	EHX Ratio	%	58.6	1.5
F(PCA)	PCA Flw	SCFM	215.6	21.5
F(EHX)	EHX Flw	SCFM	47.0	2.2
F(TPA)	TPCA Flw	SCFM	260.7	23.6
F(SCA)	SCA Flw	SCFM	175.7	7.4
F(TCA,F)	TCA Flw	SCFM	436.5	23.7
F(FG,BH)	BH Flw	SCFM	535.6	14.8
F(TFG)	TFG Flw	SCFM	535.6	14.8
W(SR)	Recirc Rt	lbs/hr	3830	402.3

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 4

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E	8	68	162	1578	1.83	86100	23.4	33115
2	14	148	189	1597	0.00	0	0.0	0
4SE	17.5	67	129	1574	1.69	52554	14.0	20213
6NE	27.5	68	139	1594	1.63	57429	15.2	22088
7	32.5	149	198	1600	0.00	0	0.0	0
8E	37.5	69	141	1597	1.52	55159	14.6	21215
	Overall	67	143	1565	6.56	249819	16.9	24021
			From Data Sheets=>		6.67			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-4,10-12	7	67	147	1289	8.76	348304	58.1	66344
			From Data Sheets=>		8.95			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	1481	242.7	SO2-A	ppm	1569	218.7
SO2-AE	lb/MM Btu	3.02	0.4				
SO2-B	ppm	1576	217.3	SO2-B	ppm	1686	181.9
SO2-BE	lb/MM Btu	3.18	0.5				
CO	ppm	76	21.6	CO	ppm	80	21.5
CO2	%	16.76	0.7	CO2	%	17.8	0.3
N2O	ppm	56	6.7	N2O	ppm	60	9.3
N2OE	lb/MM Btu	0.08	0.0				
NOx	ppm	122	9.2	NOx	ppm	130	14.5
NOxE	lb/MM Btu	0.18	0.0				
O2-A	%	4.06	0.8				
O2-B	%	4.21	0.8				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	487.5	37.7
W(S)	LS Fd Rt	lbs/hr	141.4	3.6
V(FG)	FG SGV	ft/sec	16.8	0.9
V(S,C)	Comb SGV	ft/sec	13.1	0.7
V(S,EHX)	EHX SGV	ft/sec	1.7	0.1
FT18003	CHX Flow	gpm	6.6	0.1
FT19003	EHX Flow	gpm	8.8	0.1
PT15081	Comb dP	in. H2O	45.8	3.6
Q(CA)	CA Heat in	KBtu/hr	97.7	5.8
Q(CHX)	CHX HtRmv	KBtu/hr	245.6	11.9
Q(EHX)	EHX HtRmv	KBtu/hr	347.4	14.1
Q(EHX,IN	FG Ht in	KBtu/hr	2.0	0.2
Q(F)	Fuel Enrg in	KBtu/hr	1603.2	119.2
Q(FG)	FG Enrg out	KBtu/hr	265.9	7.3
Q(IN)	Tot Enrg in	KBtu/hr	1702.9	118.6
Q(OUT)	Tot Enrg out	KBtu/hr	1164.7	24.2

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	951	39.9
TC13132	AFPE-F6"	1027	27.0
TC13133	AFPE-B6"	710	33.5
TC13134	AFPE-F10"	730	71.4
TC13231	AFPW-F2"	924	31.3
TC13232	AFPW-F6"	1086	24.9
TC13233	AFPW-B6"	747	26.4
TC13234	AFPW-F10'	995	33.3
DOORS	CHXs On	4	0
COILS	EHXs On	7	0
BH A/C		2.0	0.1
A/SRATIO		2.1	0.1
Feed Air	scfm	19.3	
DC Air	scfm	12.2	
Purge Air	scfm	15.5	

14-Aug-91

CFB-TL2-0691 — TEST 2

(1230-1630)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1497	19.1
TC11021	AFS Ex	°F	1300	17.6
TC15001	C Plenum	°F	547	19.1
TC15004	C 1-1'	°F	1435	20.1
TC15005	C 1-2'	°F	1423	18.6
TC15006	C 1-3'	°F	1418	18.4
TC15007	C 1-4'	°F	1416	17.9
TC15008	C 1-4'	°F	1425	18.4
TC15009	C 1-4'	°F	1421	19.1
TC15012	C 2-6'	°F	1441	19.8
TC15013	C 2-8'	°F	1488	19.9
TC15022	C 3-11'	°F	1487	18.1
TC15023	C 3-14'	°F	1503	17.0
TC15024	C 3-14'	°F	1517	17.9
TC15025	C 3-14'	°F	1516	19.0
TC15032	C 4-17.5'	°F	1490	16.6
TC15042	C 5-22.5'	°F	1522	16.6
TC15052	C 6-27.5'	°F	1510	16.6
TC15053	C 6-27.5'	°F	1515	17.9
TC15054	C 6-27.5'	°F	1466	16.6
TC15062	C 7-32.5'	°F	1476	17.1
TC15071	C 8-37.5'	°F	1470	17.8
TC15073	C 9-41'	°F	1511	18.0
TC15999	Ambient	°F	100	0.0
TC16001	EHX Plenm	°F	144	3.1
TC16012	EHX 0.5'	°F	1062	46.5
TC16013	EHX 1.5'	°F	1026	45.2
TC16014	EHX 2.7'	°F	1021	43.0
TC16015	EHX 3.8'	°F	845	41.3
TC16017	EHX 5.3'	°F	738	28.1
TC16018	EHX Exit	°F	971	33.9
TC16021	Crc A In	°F	1509	17.4
TC16031	DC 8-36'	°F	1513	19.4
TC16032	DC 6-28'	°F	1493	17.9
TC16033	DC 4-18'	°F	1468	19.5
TC16034	DC3-9.5'	°F	1485	29.6
TC16035	DC3-8.5'	°F	1448	27.1
T(A,C)	Comb Temp	°F	1471	17.1
T(A,EHX)	EHX Temp	°F	1036	44.6
EA	Excess Air	%	24.4	5.8
SR	S Reten	%	87.9	1.3
R(PCA)	% Flw PCA	%	54.7	3.9
R(SCA)	% Flw SCA	%	45.3	3.9
R(Q,IN)	% Enrg in	%	79.7	5.5
R(CHX)	CHX Ratio	%	44.3	2.7
R(EHX)	EHX Ratio	%	55.7	2.7
F(PCA)	PCA Flw	SCFM	184.4	28.2
F(EHX)	EHX Flw	SCFM	45.1	2.3
F(TPA)	TPCA Flw	SCFM	228.7	27.2
F(SCA)	SCA Flw	SCFM	187.7	8.5
F(TCA,F)	TCA Flw	SCFM	416.4	25.4
F(FG,BH)	BH Flw	SCFM	507.3	18.8
F(TFG)	TFG Flw	SCFM	507.7	18.5
W(SR)	Recirc Rt	lbs/hr	3335	348.1

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 6

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E	8	70	146	1488	2.00	75212	21.6	28928
3	14	144	189	1512	0.00	0	0.0	0
4SE	17.5	69	114	1490	2.00	45109	12.6	17350
6NE	27.5	71	120	1497	1.95	48522	13.6	18662
7SE	32.5	71	113	1476	1.95	41409	11.7	15927
8E,W	37.5	72	117	1470	3.80	86220	12.3	16581
	Overall	69	121	1471	11.97	311779	14.8	19986
			From Data Sheets=>		11.70			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-8,10-12	11	69	126	1036	14.84	423657	56.4	51352
			From Data Sheets=>		15.35			

EMISSIONS DATA

As Measured Tag	Units	Average	Std Dev	Corrected to 3% O2 Tag	Units	Average	Std Dev
SO2-A	ppm	1852	192.7	SO2-A	ppm	1966	182.7
SO2-AE	lb/MM Btu	3.77	0.4				
SO2-B	ppm	2052	205.2	SO2-B	ppm	2213	205.2
SO2-BE	lb/MM Btu	4.18	0.4				
CO	ppm	82	10.5	CO	ppm	87	10.0
CO2	%	16.85	1.2	CO2	%	17.9	0.6
N2O	ppm	108	14.6	N2O	ppm	115	20.9
N2OE	lb/MM Btu	0.15	0.0				
NOx	ppm	80	8.6	NOx	ppm	85	12.6
NOxE	lb/MM Btu	0.12	0.0				
O2-A	%	4.05	0.8				
O2-B	%	4.30	0.8				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	479.2	44.4
W(S)	LS Fd Rt	lbs/hr	141.9	2.5
V(FG)	FG SGV	ft/sec	15.3	0.9
V(S,C)	Comb SGV	ft/sec	11.8	0.8
V(S,EHX)	EHX SGV	ft/sec	1.4	0.1
FT18003	CHX Flow	gpm	12.0	0.2
FT19003	EHX Flow	gpm	14.8	0.2
PT15081	Comb dP	in. H2O	50.0	3.9
Q(CA)	CA Heat in	KBtu/hr	87.0	7.7
Q(CHX)	CHX HtRmv	KBtu/hr	336.9	20.7
Q(EHX)	EHX HtRmv	KBtu/hr	423.8	31.5
Q(EHX,IN	FG Ht in	KBtu/hr	1.9	0.2
Q(F)	Fuel Enrg in	KBtu/hr	1573.8	138.5
Q(FG)	FG Enrg out	KBtu/hr	243.9	9.6
Q(IN)	Tot Enrg in	KBtu/hr	1663.4	137.9
Q(OUT)	Tot Enrg out	KBtu/hr	1309.1	45.7

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	934	40.7
TC13132	AFPE-F6"	984	27.3
TC13133	AFPE-B6"	702	31.6
TC13134	AFPE-F10"	739	71.8
TC13231	AFPW-F2"	898	34.2
TC13232	AFPW-F6"	1044	28.2
TC13233	AFPW-B6"	729	26.4
TC13234	AFPW-F10"	969	34.8
DOORS	CHXs On	6	0
COILS	EHXs On	11	0
BH A/C		1.9	0.1
A/SRATIO		2.2	0.1
Feed Air	scfm	19.3	
DC Air	scfm	12.1	
Purge Air	scfm	15.5	

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CFB-TL2-0691 — TEST 3

(2040-0045)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1662	16.3
TC11021	AFS Ex	°F	1449	15.2
TC15001	C Plenum	°F	639	8.6
TC15004	C 1-1'	°F	1621	11.7
TC15005	C 1-2'	°F	1608	12.4
TC15006	C 1-3'	°F	1600	11.8
TC15007	C 1-4'	°F	1600	12.3
TC15008	C 1-4'	°F	1612	11.6
TC15009	C 1-4'	°F	1606	12.7
TC15012	C 2-6'	°F	1627	11.5
TC15013	C 2-8'	°F	1665	11.9
TC15022	C 3-11'	°F	1658	11.0
TC15023	C 3-14'	°F	1678	10.6
TC15024	C 3-14'	°F	1680	10.6
TC15025	C 3-14'	°F	1683	10.4
TC15032	C 4-17.5'	°F	1689	11.8
TC15042	C 5-22.5'	°F	1690	10.8
TC15052	C 6-27.5'	°F	1690	11.6
TC15053	C 6-27.5'	°F	1695	11.7
TC15054	C 6-27.5'	°F	1674	12.5
TC15062	C 7-32.5'	°F	1655	11.7
TC15071	C 8-37.5'	°F	1647	11.7
TC15073	C 9-41'	°F	1674	13.1
TC15999	Ambient	°F	99	1.8
TC16001	EHX Plenm	°F	145	3.6
TC16012	EHX 0.5'	°F	1403	22.1
TC16013	EHX 1.5'	°F	1353	20.2
TC16014	EHX 2.7'	°F	1365	19.6
TC16015	EHX 3.8'	°F	1180	17.6
TC16017	EHX 5.3'	°F	1022	14.1
TC16018	EHX Exit	°F	1299	16.2
TC16021	Crc A In	°F	1678	11.1
TC16031	DC 8-36'	°F	1678	13.7
TC16032	DC 6-28'	°F	1660	13.8
TC16033	DC 4-18'	°F	1639	18.4
TC16034	DC3-9.5'	°F	1667	22.2
TC16035	DC3-8.5'	°F	1639	24.4

T(A,C)	Comb Temp	°F	1650	10.9
T(A,EHX)	EHX Temp	°F	1373	19.8
EA	Excess Air	%	24.2	3.0
SR	S Reten	%	86.4	1.5
R(PCA)	% Flw PCA	%	59.5	1.9
R(SCA)	% Flw SCA	%	40.5	1.9
R(Q,IN)	% Enrg in	%	66.7	3.3
R(CHX)	CHX Ratio	%	32.5	1.6
R(EHX)	EHX Ratio	%	67.5	1.6
F(PCA)	PCA Flw	SCFM	216.3	16.3
F(EHX)	EHX Flw	SCFM	46.8	1.2
F(TPA)	TPCA Flw	SCFM	263.3	17.6
F(SCA)	SCA Flw	SCFM	179.1	3.7
F(TCA,F)	TCA Flw	SCFM	442.3	16.2
F(FG,BH)	BH Flw	SCFM	519.2	10.4
F(TFG)	TFG Flw	SCFM	519.2	10.4
W(SR)	Recirc Rt	lbs/hr	4269	394.9

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service==> 3

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2	8	161	255	1665	0.00	0	0.0	0
3	14	156	202	1681	0.00	0	0.0	0
4	17.5	150	190	1689	0.00	0	0.0	0
6	27.5	158	268	1686	0.00	0	0.0	0
7SE	32.5	70	122	1655	2.20	56350	14.1	21673
8E,W	37.5	71	129	1647	4.20	120607	15.3	23194
	Overall	70	126	1650	6.58	186625	15.7	23926
			From Data Sheets=>		6.40			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-4,8,9	6	69	115	1373	15.56	359456	63.5	79879
			From Data Sheets=>		15.65			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	2172	249.9	SO2-A	ppm	2306	241.7
SO2-AE	lb/MM Btu	4.26	0.5				
SO2-B	ppm	2290	274.4	SO2-B	ppm	2478	258.8
SO2-BE	lb/MM Btu	4.49	0.5				
CO	ppm	20	9.2	CO	ppm	21	9.4
CO2	%	17.46	0.3	CO2	%	18.5	0.3
N2O	ppm	31	3.2	N2O	ppm	33	3.7
N2OE	lb/MM Btu	0.04	0.0				
NOx	ppm	143	6.0	NOx	ppm	151	8.1
NOxE	lb/MM Btu	0.20	0.0				
O2-A	%	4.03	0.4				
O2-B	%	4.27	0.4				

Tag	Desc	Units	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	478.7	21.6
W(S)	LS Fd Rt	lbs/hr	145.4	6.1
V(FG)	FG SGV	ft/sec	17.8	0.7
V(S,C)	Comb SGV	ft/sec	13.7	0.5
V(S,EHX)	EHX SGV	ft/sec	1.8	0.1
FT18003	CHX Flow	gpm	6.6	0.1
FT19003	EHX Flow	gpm	15.6	0.4
PT15081	Comb dP	in. H2O	46.1	2.9
Q(CA)	CA Heat in	KBtu/hr	98.8	4.7
Q(CHX)	CHX HtRmv	KBtu/hr	173.2	10.0
Q(EHX)	EHX HtRmv	KBtu/hr	360.1	14.9
Q(EHX,IN	FG Ht in	KBtu/hr	2.1	0.1
Q(F)	Fuel Enrg in	KBtu/hr	1560.1	82.8
Q(FG)	FG Enrg out	KBtu/hr	267.6	25.3
Q(IN)	Tot Enrg in	KBtu/hr	1655.9	95.7
Q(OUT)	Tot Enrg out	KBtu/hr	1105.5	34.7

Tag	Desc	Average	Std Dev
TC13131	AFPE-F2"	1091	22.9
TC13132	AFPE-F6"	1075	18.0
TC13133	AFPE-B6"	766	16.7
TC13134	AFPE-F10"	1004	41.1
TC13231	AFPW-F2"	1026	21.4
TC13232	AFPW-F6"	1164	20.1
TC13233	AFPW-B6"	758	17.0
TC13234	AFPW-F10'	1108	22.4
DOORS	CHXs On	3	0
COILS	EHXs On	6	0
BH A/C		2.0	0.0
A/SRATIO		2.1	0.1
Feed Air	scfm	19.0	
DC Air	scfm	12.0	
Purge Air	scfm	15.5	

15-Aug-91

CFB-TL2-0691 — TEST 4

(1245-1845)

Tag	Desc	Units	Average	Std Dev
TC11011	PCD Ex	°F	1597	10.4
TC11021	AFS Ex	°F	296	5.9
TC15001	C Plenum	°F	592	3.8
TC15004	C 1-1'	°F	1532	13.8
TC15005	C 1-2'	°F	1518	13.0
TC15006	C 1-3'	°F	1508	12.7
TC15007	C 1-4'	°F	1510	13.1
TC15008	C 1-4'	°F	1522	13.4
TC15009	C 1-4'	°F	1516	13.5
TC15012	C 2-6'	°F	1537	13.7
TC15013	C 2-8'	°F	1588	12.5
TC15022	C 3-11'	°F	1584	9.2
TC15023	C 3-14'	°F	1600	9.0
TC15024	C 3-14'	°F	1616	8.7
TC15025	C 3-14'	°F	1611	9.7
TC15032	C 4-17.5'	°F	1584	9.3
TC15042	C 5-22.5'	°F	1622	8.9
TC15052	C 6-27.5'	°F	1606	9.7
TC15053	C 6-27.5'	°F	1609	9.8
TC15054	C 6-27.5'	°F	1553	9.5
TC15062	C 7-32.5'	°F	1560	9.0
TC15071	C 8-37.5'	°F	1548	9.8
TC15073	C 9-41'	°F	1598	9.9
TC15999	Ambient	°F	97	1.5
TC16001	EHX Plenm	°F	138	3.0
TC16012	EHX 0.5'	°F	1152	26.9
TC16013	EHX 1.5'	°F	1120	25.4
TC16014	EHX 2.7'	°F	1148	25.7
TC16015	EHX 3.8'	°F	954	21.1
TC16017	EHX 5.3'	°F	825	13.8
TC16018	EHX Exit	°F	1090	21.1
TC16021	Crc A In	°F	1597	8.7
TC16031	DC 8-36'	°F	1613	10.6
TC16032	DC 6-28'	°F	1590	10.7
TC16033	DC 4-18'	°F	1567	12.9
TC16034	DC3-9.5'	°F	1580	22.5
TC16035	DC3-8.5'	°F	1495	28.7

T(A,C)	Comb Temp	°F	1564	10.4
T(A,EHX)	EHX Temp	°F	1140	25.7
EA	Excess Air	%	26.6	6.5
SR	S Reten	%	69.9	1.0
R(PCA)	% Flw PCA	%	59.1	2.0
R(SCA)	% Flw SCA	%	40.9	2.0
R(Q,IN)	% Enrg in	%	78.8	5.8
R(CHX)	CHX Ratio	%	54.7	1.8
R(EHX)	EHX Ratio	%	45.3	1.8
F(PCA)	PCA Flw	SCFM	203.4	17.4
F(EHX)	EHX Flw	SCFM	48.2	1.4
F(TPA)	TPCA Flw	SCFM	251.7	18.4
F(SCA)	SCA Flw	SCFM	173.9	3.2
F(TCA,F)	TCA Flw	SCFM	425.5	17.9
F(FG,BH)	BH Flw	SCFM	517.0	5.3
F(TFG)	TFG Flw	SCFM	517.2	5.4
W(SR)	Recirc Rt	lbs/hr	3447	269.5

HEAT-TRANSFER COEFFICIENTS

—Combustor— Number of Doors in Service===> 7

CHX Location	Height (ft)	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
2E	8	70	137	1588	2.25	75572	20.0	29066
3NE	14	71	143	1609	1.80	65234	17.1	25090
4SE	17.5	70	131	1584	1.75	53655	14.2	20637
6NE	27.5	71	136	1589	1.75	56735	15.0	21821
7SE	32.5	71	128	1560	1.68	48246	13.0	18556
8E,W	37.5	72	131	1548	3.43	102110	13.9	19636
	Overall	70	134	1564	12.77	411272	15.8	22597
		From Data Sheets=>			12.66			

—EHX—

Coils Used	No. of Coils	Temp In °F	Temp Out °F	Bed Temp °F	Flow gpm	Q Btu/hr	U Btu/ft²hr°F	Heat Flux Btu/ft²hr
1-8	8	70	124	1140	12.28	336072	55.2	56012
		From Data Sheets=>			12.50			

EMISSIONS DATA

As Measured				Corrected to 3% O2			
Tag	Units	Average	Std Dev	Tag	Units	Average	Std Dev
SO2-A	ppm	4399	82.4	SO2-A	ppm	4770	175.6
SO2-AE	lb/MM Btu	9.42	0.3				
SO2-B	ppm	4696	96.6	SO2-B	ppm	5102	176.0
SO2-BE	lb/MM Btu	9.89	0.2				
CO	ppm	94	16.3	CO	ppm	102	19.5
CO2	%	16.01	0.7	CO2	%	17.3	0.3
N2O	ppm	75	5.1	N2O	ppm	81	8.2
N2OE	lb/MM Btu	0.11	0.0				
NOx	ppm	97	9.4	NOx	ppm	106	14.6
NOxE	lb/MM Btu	0.15	0.0				
O2-A	%	4.37	0.9				
O2-B	%	4.41	0.8				

Tag	Desc	Units	Average	Std Dev	Tag	Desc	Average	Std Dev
W(C)	Coal Fd Rt	lbs/hr	479.3	44.9	TC13131	AFPE-F2"	944	34.5
W(S)	LS Fd Rt	lbs/hr	0.0	0.1	TC13132	AFPE-F6"	1003	21.3
V(FG)	FG SGV	ft/sec	16.4	0.7	TC13133	AFPE-B6"	695	26.9
V(S,C)	Comb SGV	ft/sec	12.6	0.5	TC13134	AFPE-F10"	721	64.2
V(S,EHX)	EHX SGV	ft/sec	1.6	0.0	TC13231	AFPW-F2"	909	31.5
FT18003	CHX Flow	gpm	12.8	0.1	TC13232	AFPW-F6"	1077	24.1
FT19003	EHX Flow	gpm	12.3	0.1	TC13233	AFPW-B6"	734	24.3
PT15081	Comb dP	in. H2O	43.3	2.2	TC13234	AFPW-F10'	986	31.3
Q(CA)	CA Heat in	KBtu/hr	92.8	4.2	DOORS	CHXs On	7	0
Q(CHX)	CHX HtRmv	KBtu/hr	405.9	18.5	COILS	EHXs On	8	0
Q(EHX)	EHX HtRmv	KBtu/hr	336.8	17.9	BH A/C		2.0	0.0
Q(EHX,IN	FG Ht in	KBtu/hr	1.9	0.2	A/SRATIO		0.6	0.0
Q(F)	Fuel Enrg in	KBtu/hr	1571.6	138.3	Feed Air	scfm	19.3	
Q(FG)	FG Enrg out	KBtu/hr	254.4	2.5	DC Air	scfm	12.1	
Q(IN)	Tot Enrg in	KBtu/hr	1663.5	139.6	Purge Air	scfm	15.5	
Q(OUT)	Tot Enrg out	KBtu/hr	1300.6	31.3				

APPENDIX F

DESIGN, CONSTRUCTION, AND SYSTEM MODIFICATIONS

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LIST OF FIGURES

DESIGN, CONSTRUCTION, AND SYSTEM MODIFICATIONS

DESIGN AND CONSTRUCTION

Combustor

Figures F-1 and F-2 show the configuration of the system at the completion of shakedown in October 1989. As the project progressed, it was determined that, from a scaling point of view, it was desirable to construct the combustor as large as possible. The fluid dynamics of a full-scale system are more closely simulated as the pilot-scale size increases. A combustor with circular cross section was selected to have the smallest ratio of surface area to volume, resulting in the least amount of heat loss and the least amount of wall surface to affect the fluid dynamics for a given combustor cross-sectional area.

The final size determination of the CFB system was subject to the following additional constraints: cost of construction, space limitations of the construction site, and operational costs. As the combustor cross section increases, the size of auxiliary equipment increases proportionally, as do fuel requirements. The cost of operation increases somewhat, but is not a significant factor. Over the range of sizes considered (12-inch to 20-inch inside diameter), manpower requirements needed to operate the system were not expected to vary significantly. A combustor with an inside diameter of 20 inches was selected as the upper size limit that could be constructed based upon budget constraints, EERC coal-handling capabilities, and structural constraints.

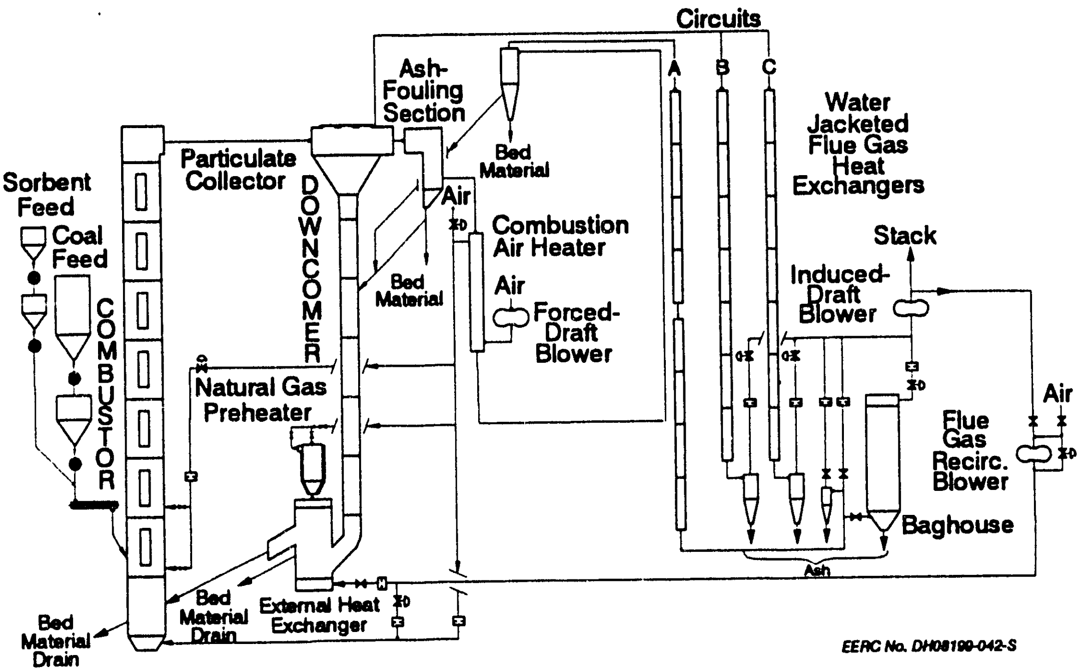

Figure F-1. Original configuration of the EERC CFB system.

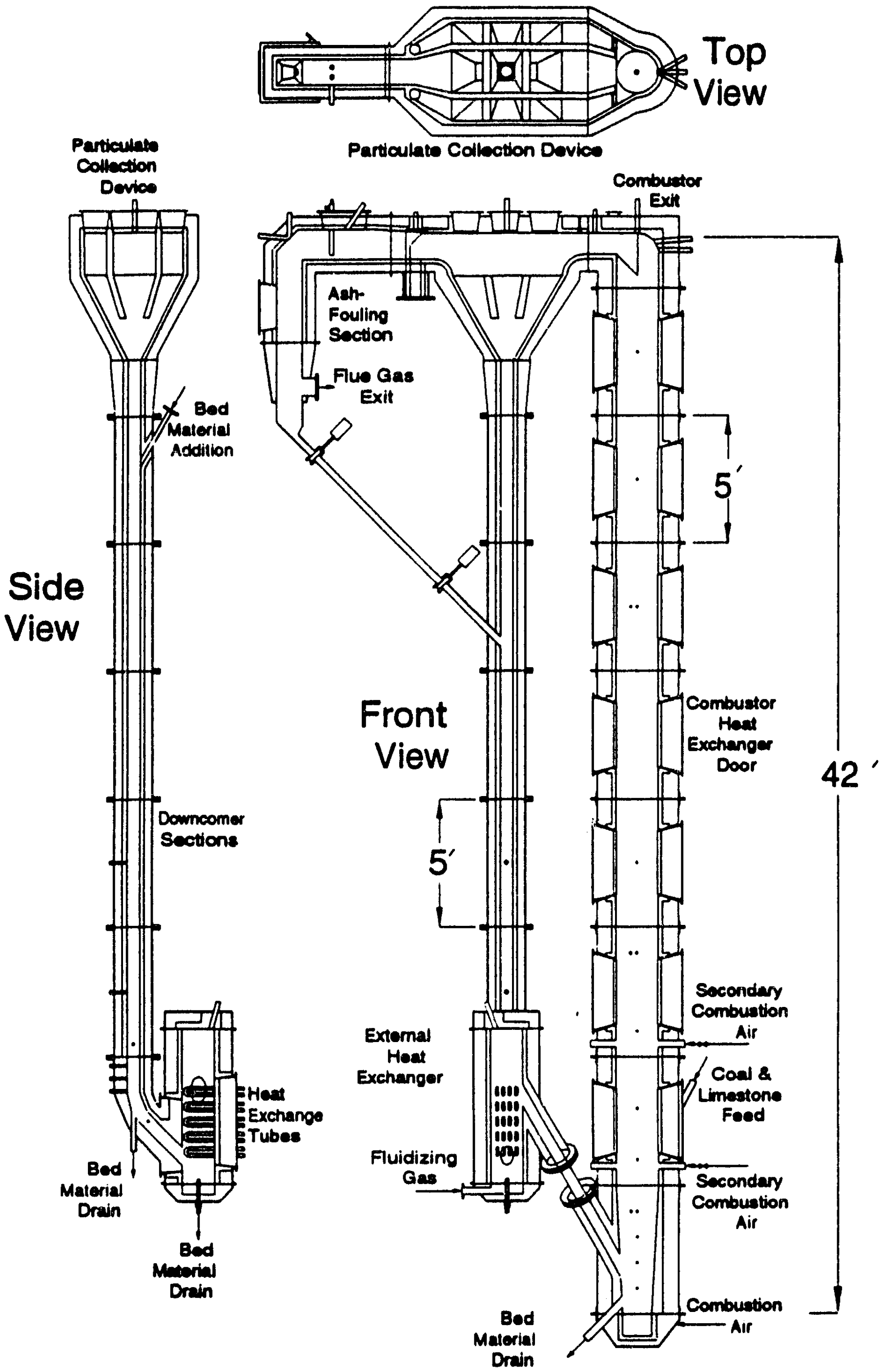

Figure F-2. Cross-sectional views showing details of construction for the combustor sections, particulate collection device, ash-fouling section, downcomer sections, and the external heat exchanger.

The height of the combustor needed to be adequate for any physical and/or chemical reactions to occur. The combustor height also had to be sufficient to allow for the required amount of heat-transfer surface area to obtain a representative temperature profile throughout the combustor which would be comparable to a large-scale system. When operating at velocities similar to a large-scale system, height is the only factor affecting gas residence time. The height and diameter affect solids residence time in the combustor when operating at similar velocities and with the same bed particle-size distribution. Solids residence time affects heat transfer, sulfur capture, and carbon combustion efficiency. During operation there is a high concentration of solids along the combustor walls with a much more dilute phase in the core of the combustor. As the combustor cross section increases, the wall surface area to combustor volume ratio decreases, resulting in a corresponding decrease in overall solids density. In other words, there are more wall effects with a smaller combustor. So, to obtain similar overall solids density in a smaller system over its entire height, it is necessary to have a decreased height.

No acceptable mathematical criterion was found to determine what the appropriate height should be. The temperature distribution throughout the length of a pilot-scale CFPC is related to the amount of refractory insulation and the arrangement of heat-transfer surface. A height of 42 feet from distributor plate to the top of the combustor exit was selected as sufficient for installation of adequate heat-transfer surface and as a reasonable compromise of gas residence time and solids distribution in the combustor.

Combustor sections were fabricated from 5-foot by 10-foot sheets of ⅜-inch-thick carbon steel resulting in an outside shell diameter of 38½ inches for each 5-foot-high section. Two inches of abrasion-resistant refractory, along with seven inches of insulating refractory, result in an operational skin temperature for the combustor of less than 200°F. Similar refractory installation was used for all other refractory-lined components. The refractory used was supplied by Premier Refractories and Chemicals, Inc. Secondary air addition was designed to be introduced at three separate levels through combustor Sections 1, 2, or 3. It is introduced normal to the combustor gas stream through four 3-inch ports. Although it would be a significant modification, the combustor was designed so it is possible to alter the height by the removal or addition of combustor and downcomer sections.

Combustor Heat Exchangers

In some CFB boilers, only the waterwall heat-transfer surface extracts the heat generated in the combustor. Load is managed by varying bed temperatures, velocities, and excess air levels and, in some systems, by controlling the solids recirculation ratio. Other CFB boilers incorporate an external heat exchanger to provide added operational flexibility at the expense of additional initial capital expenditure. Design objectives were to have sufficient heat-transfer surface in the combustor and external heat exchanger to operate over the specified range of design conditions and, under certain conditions, have the option to operate with or without the use of external heat exchange.

To provide the required heat transfer in the combustor over the design conditions selected, it was calculated that a maximum of 14 water-cooled heat-transfer panels would be adequate. The water-cooled combustor heat exchangers used, as shown in Figure F-3, have a geometry similar to that of a waterwall surface. Heat-transfer surface in the

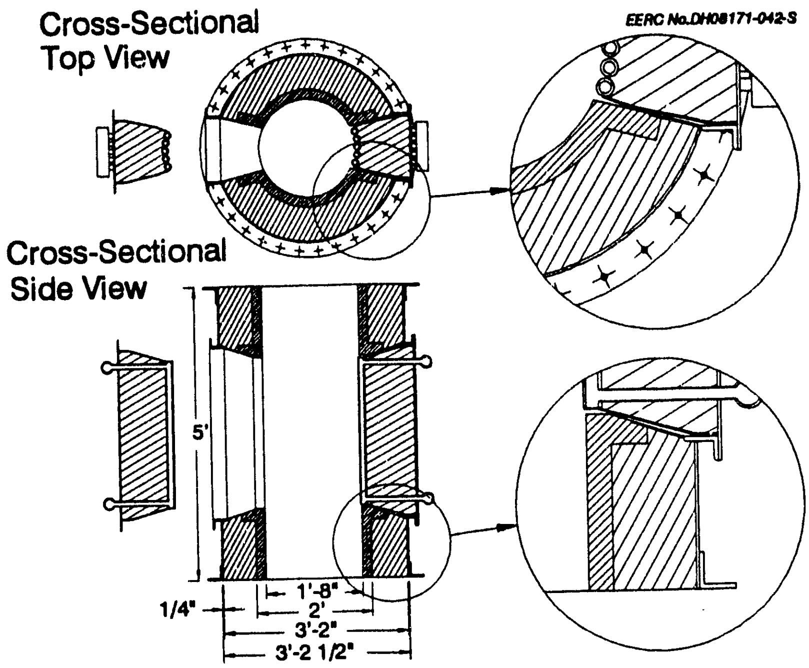

Figure F-3. Details of construction for installation of removable water-cooled heat exchangers in refractory-lined combustor sections.

combustor is controlled by regulating the flow of water through the heat-transfer panels. Air is used to cool the panels prior to the introduction of water to reduce thermal shock. The inlet and exit water temperatures for each panel are monitored and used to determine individual heat-transfer rates. Total water flow to the heat exchangers in the service is monitored with a turbine flowmeter. The water flow to individual heat exchange panels is controlled by globe valves and measured with rotameters.

Each heat exchange panel consists of five 2½-foot-long tubes with 1½-inch outside diameters. Type 304 stainless steel tubes were used with a standard 0.120-inch tube wall thickness. An alternate material considered was type 310 stainless steel, which is better suited to high-temperature operation, but significantly more expensive. Thus far, the 304 stainless steel has performed adequately. Parallel flow (as opposed to series flow) through the tubes of an individual panel was selected to result in less pressure drop when using cooling fluids other than water. Type 304 stainless steel inlet manifolds were designed and installed to supply uniform distribution of either air or water to the heat-transfer tubes. Type 304 stainless steel headers connect the inlet air/water piping to the inlet manifolds. Each inlet header contains an internal cylinder into which two sets of diametrically opposed holes have been drilled along its length. The holes on one side of the cylinder are 1-inch in diameter and allow air to flow into the heat-transfer tubes with as little restriction as possible. When the internal cylinder is rotated 180°, a set of ⅛-inch-diameter orifices line up with the manifold and ensure uniform water distribution to each of the five heat exchange tubes in the panel. The exit header is 2-inch schedule 40, type 304 stainless steel pipe.

For the installation of heat-transfer surface in a circulating fluidized-bed system, consideration must be given to the potential for erosion and the penetration of particulates into almost any size opening. The particulate, after cycles of heating and cooling, can crack and fracture the refractory surfaces that it has penetrated. The heat exchange panels were designed so that the back side of the tubes are totally sealed from the inside combustor environment. There are 1/8-inch gaps between each heat-transfer tube in a panel which are welded shut. The outer metal frame around the tubes is composed of thin gage stainless steel sheeting and is welded to the tubes and outer door flange. When installed, the outer edges of the panel are approximately ½ inch away from the inside refractory, opening into the combustor on all four sides. The stainless steel panel frame is constructed such that the ½-inch gap at the heat exchange panel (inner surface of the combustor) is reduced to approximately 1/8 inch within a distance of about 3 inches from the inside combustor wall. Based upon input from Premier Refractories and Chemicals, Inc., this is a large enough gap so that particulates that do penetrate tend to fall back out and not cause problems. Pourable insulation is installed behind the tubes. The tube panels are slightly recessed in the doors to limit their exposure to erosion.

Shakedown and initial operation was with eight water-cooled heat exchange panels. The initial heat exchange configuration used was two heat exchange panels in each of combustor Sections 2 and 8 and a single panel in each of Sections 3, 4, 6, and 7 on the same side of the combustor. Blank refractory doors were installed in the other six locations.

External Heat Exchanger/Loop Seal

The option to remove additional heat in the external heat exchanger was installed to simulate CFB boilers that incorporate that type of heat removal. The external heat exchanger was designed to serve the dual purpose of heat removal and recirculating solids back into the combustor. It is refractory-lined with inside dimensions of 15 inches square by six feet high and is a bubbling fluidized bed with an operational superficial gas velocity of about 1.5 ft/sec. The external heat exchanger was sized so it would be large enough for the installation of adequate heat-transfer surface and small enough so that excessive amounts of fluidizing gas would not be required.

Solids from the downcomer enter the external heat exchanger/loop seal near the bottom of the 15-inch-square fluidized bed at an angle of 45 degrees. The recirculating solids are fluidized upward past the heat-transfer tubes which are described in detail below. The solids return line to the combustor is located 3 feet above the external heat exchanger distributor plate, has an inside diameter of 5 inches, and slopes down at 60° into combustor Section 1. There is an additional three feet of freeboard above the bubbling fluidized bed.

The heat exchange tubes are of a U-tube type configuration constructed out of 1-inch schedule 40, type 304 stainless steel pipe. They are installed in a removable door, so that they can be periodically replaced if required. The amount of heat removal is controlled by regulating the flow of water to the water-cooled heat exchange tubes. As originally designed and installed, twenty heat exchange tubes were arranged in the following configurations: two using a single tube, two with two tubes in series, two with three tubes in series, and two with four heat exchange tubes connected in series. There is a single inlet thermocouple in the inlet manifold, individual exit thermocouples for each of the eight sets of heat-transfer tubes, and also an exit thermocouple in the outlet manifold. Total water flow is measured with an in-line turbine flowmeter, and individual flow rates to each of the eight groups of tubes are controlled by globe valves and measured with rotameters.

Natural Gas-Fired Preheater

A means of preheating the combustor was required to bring the bed material to a sufficiently high temperature so that the coal would ignite when introduced into the combustor. Natural gas was selected for preheat due to its availability at the installation site. The preheater was sized to supply 600,000 Btu/hr of energy. The preheater has inner and outer cylindrical shells constructed of type 304 stainless steel sheeting. The natural gas burner is bolted to the top of the external heat exchanger and fires downward. Air circulates through the outer, baffled cooling jacket to prevent the inner shell from overheating. The hot combustion gas from the burner combines with the cooling jacket air as it flows into the top of the external heat exchanger at approximately 1200°F. The hot gas then flows downward through the solids return into the combustor. The bed material present in the external heat exchanger is not fluidized during preheat to prevent any of the hot preheat gas from flowing upward through the downcomer. The solids in the combustor are preheated to at least 800°F before coal feed is initiated.

Air is supplied to the natural gas-fired preheater through a 4-inch bypass line from the forced-draft blower. A butterfly valve is used to isolate the preheater on the inlet side when not in use. A knife gate valve between the preheater and the external heat exchanger isolates the exit side. Two additional butterfly valves are installed in the lines to the burner and to the cooling jacket for control purposes. Natural gas flow is measured and controlled with a rotameter. A flame safety system is present to shut off the flow of natural gas if any of the following situations occur: 1) a flame is not present in the preheater, 2) combustion air is not being supplied to the preheat burner or cooling jacket, or 3) the burner air pressure is greater than the natural gas pressure being supplied to the preheater.

Coal and Sorbent Feed Systems

The EERC has on-site facilities for the preparation and storage of coal and sorbent brought in by truck or rail. Coal and sorbent can be crushed and sized as required before the start of a test and placed in transportable storage hoppers or in storage tote bins. From a survey by Burns & McDonnell Engineering Company, the highest estimated coal size for use in a CFB system is 2 inches. This would be too large for most CFB systems, but is likely the size that Riley Stoker uses in its multisolids combustor. The lowest estimated coal size is 0.25 inches. The estimated size range for limestone varied from 0.0059 inches to 0.125 inches.

The coal feed system was designed to handle at least 1000 lb/hr of up to minus 3/4-inch coal, and the sorbent feed system was designed for a maximum feed rate of 500 lb/hr of material sized to minus 1/4 inch. Limestone is generally the sorbent of choice for use as both a bed material and for sulfur capture. Some systems considered for controlling and measuring feed rates included various types of weigh belt feeders and loss-in-weight systems incorporating screw feeders. A more cost-effective method was selected for controlling and measuring feed rates. Feed hoppers suspended from load cells measure weight loss, and rotary valves, regulated by electronic speed controllers, govern feed rates.

Coal and limestone are transported to the system in movable storage hoppers. The coal storage hoppers have net capacities of 3000 pounds. The two sorbent storage hoppers have 1000-lb net capacities. Coal is transferred through a 6-inch knife gate valve into the coal weigh hopper, and limestone is transferred through a 4-inch rotary valve into the sorbent weigh hopper. There is one 6-inch and one 4-inch rotary valve located below the coal and sorbent weigh hoppers, respectively, for controlling the coal and limestone feed rates. Each of the rotary valves is connected to electronic speed controllers.

The coal and limestone feed into a common 6-inch-square duct. A 3-inch-diameter stainless steel auger transports the coal/sorbent mixture horizontally to a 4-inch pipe. The top 2 feet of the 4-inch pipe is oriented vertically and then slopes into the combustor at an angle of 60 degrees. The feed pipe enters the combustor in Section 2 at a level of 6-feet above the combustor distributor plate. The gravity feed into the combustor has a pneumatic assist to help prevent plugging of the inclined section of 4-inch pipe.

Particulate Collection Device

The primary design objective for the particulate collection device was to collect solids of a representative cut point (the size of particles for which 50% of the median diameter of particles collected would be collected) similar to commercial systems. The size of the solids retained in the system is dependent upon the efficiency of the collection device used. A design cut point of 20 to 30 microns was calculated as the initial operational target for the pilot plant system such that the capture would be comparable to a full-scale system.

In general, small pilot plant cyclones are much more efficient in relation to the large cyclones used in full-scale CFB boilers, when compared at similar operating conditions, due to geometric factors. Operation of a pilot-scale CFB with a more efficient collector should result in higher combustion efficiency and better sulfur capture than is possible with a full-scale system. It was decided to design a collector that would be flexible enough to operate over a wide range of operational velocities and have the potential for adjusting the cut size of the particulate collected by the use of different geometries within the collector. The design selected was a particle impaction device, and an illustration of a typical set of collectors, as constructed and used, is shown in Figure F-4.

There were three ducts, referred to as Ducts A, B, and C, in the collector for parallel use when operating at either low, intermediate, or high velocities, respectively. Three removable doors were placed in the top of each of the three ducts to permit the placement of impaction plates for the collection of solids. A cut point of 200 microns was calculated for operation with no obstructions in the ducts. Different internal configurations could be installed in the ducts to allow various cut points to be collected. Slide valves at the entrance of Ducts B and C were in place to isolate those ducts when not in use. The center duct (Duct A) was the primary duct used at low-to-intermediate combustor velocities. Ducts B and C could be brought on-line one at a time as flows were increased in the combustor for different test conditions. Collector performance, modifications to the collector, and the subsequent replacement with a cyclone are discussed in later sections.

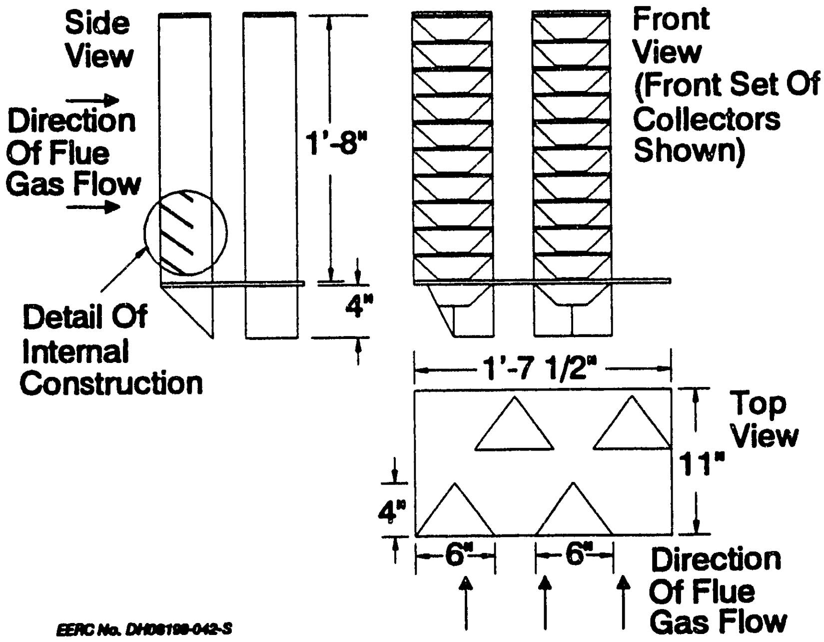

Figure F-4. A schematic of chevron impaction collector configuration.

Downcomer

Solids collected by the particulate collection device enter the downcomer, where they travel downward into the external heat exchanger. Downcomer sections were constructed from 18-inch schedule 10 carbon steel pipe, are refractory-lined with an inside diameter of 6 inches, and are 5 feet in length. There is a 2-inch layer of abrasion-resistant refractory on the inside, with 3¾ inches of insulating refractory between the hard refractory and the pipe. Aeration can be added at various heights in the downcomer, if required, to keep the solids moving more uniformly into the external heat exchanger. An inclined pipe is located in the top section of the downcomer for the addition of bed material at the start of the run and also during operation, if required.

Convective Pass Section

The operating temperatures of CFB boilers are generally below the temperatures for which ash deposition, fouling, and/or slagging occur for most coals. Operation of a CFB on coals with alkaline ash properties may cause convective pass ash deposition. The CFBC pilot plant ash-fouling section was designed to indicate the potential for ash deposition in the convective pass region of a CFB boiler. The geometry of the ash-fouling section is based upon experience gained from operation of the EERC pulverized coal-fired ash-fouling furnace. The ash-fouling section has a carbon steel shell, is refractory-lined, and was installed at the exit of Duct A of the particulate collection device.

Ash-fouling probes were designed for installation into the ash-fouling hopper to simulate boiler tube surface. The probes were air-cooled to maintain surface temperatures typical of convective pass boiler tubes, and the metal surface temperatures were monitored by thermocouples. The first pair of probes were designed for installation in a removable door in the horizontal portion of the ash-fouling section (25- to 30-ft/sec nominal gas velocity) and were to be used for assessing potential ash deposition of sticky particles. The vertical portion of the ash-fouling section was designed for the installation of three pair of probes in a removable door to assess the tendency for ash to accumulate as a result of convective pass geometry. Pressure drop across the probe bank would be monitored to assess ash buildup during operation. Initial operation was with no ash-fouling probes in place (blank doors installed). A collection hopper is located at the bottom of the vertical duct of the ash-fouling section just upstream of the horizontal flue gas exit pipe. Due to the abrupt change in gas direction at the flue gas exit, some ash particles leave the gas stream and are collected in the ash-fouling section hopper.

Flue Gas System

The flue gas system was divided into three circuits, A, B, and C, to have the flexibility to operate over a wide range of operational velocities (13 to 23 ft/sec) at operational combustion temperatures up to 1650°F. Circuit A is the primary circuit that remains in operation during all periods. It includes a shell-and-tube heat exchanger (combustion air heater) to preheat combustion air to approximately 500°F, eight water-jacketed heat exchangers to reduce the flue gas temperature to 250° to 400°F before entering the baghouse, and a pulse-jet baghouse for particulate emissions control. The combustion air heater operates only on the flue gas exiting the ash-fouling section, approximately 40 percent of the original design maximum gas flow. That is a sufficient quantity of flue gas to preheat the combustion air over all operating conditions.

A pulse-jet baghouse is in place to accommodate all of the Circuit A flue gas flow. Flue gas temperature into the baghouse is maintained from 250° to 400°F during operation. Typical operation is at an air-to-cloth ratio of between 2 to 3. Due to the confined area available for installation, a very compact baghouse, with inside dimensions of 2-foot 6-inch, by 3-foot 1-inch plan area and 15 feet high was designed. The baghouse contains 20 woven fiberglass bags five inches in diameter by 10 feet long. The bags are divided up into four sets of five bags each for pulse-cleaning purposes. Pulse duration and the interval between pulses is controlled by the data acquisition system. A bypass around the baghouse is used during start-up when preheating on natural gas to ensure that moisture will not condense out on the bags. An 18-inch-diameter stainless steel cyclone in the bypass section removes particulates when the baghouse bypass is open.

Circuits B and C each have seven water-jacketed heat exchangers to cool the flue gas and a 14-inch-diameter stainless steel cyclone for particulate removal. Some control of the exit flue gas temperature from any of the flue gas circuits is possible by turning water flow on or off to the water-jacketed sections. The amount of flue gas flow through an individual circuit is controlled by the use of 4-inch flow control valves in Circuits B and C. All of the flue gas then combines into a single duct constructed of 8-inch stainless steel tubing and flows into the induced-draft blower, a positive displacement rotary blower. The rotational speed of the induced-draft blower is regulated by an electronic speed controller. A zero pressure balance point near the exit of the combustor is used as control for the speed of the induced-draft blower.

SYSTEM MODIFICATIONS

Numerous modifications have been made to the system based on experiences with different coals, limestones, and operating conditions. The modifications made to each system are described below.

Solids Recirculation

Two initial modifications were made to the solids recirculation system. First, the capability of adding solids from the ash-fouling section hopper back into the downcomer was added. Then, the 18-inch baghouse bypass cyclone was relocated to recycle additional fines back into the downcomer. Both of these recycle loops contain two pneumatically actuated knife gate valves to prevent the bypass of flue gas from the downcomer.

Based upon results obtained during shakedown tests, cold-flow testing was performed to evaluate various impaction collection device configurations. Chevron collectors with internally sloped deflector plates were selected to be used in the particulate collection device during the Salt Creek test. The chevron collectors feature a geometry, illustrated in Figure F-4, that helps force the particulate to the back of the collectors. An opening along the back of each collector allows particulates to flow downward into the collection hoppers that feed into the downcomer. Three stages of collectors were utilized in Duct A during this test, shown in Figure F-5. The first two stages were intended to capture the majority of the particulates, while the third stage was designed to capture smaller particles. The first stage used four chevron collectors, two in

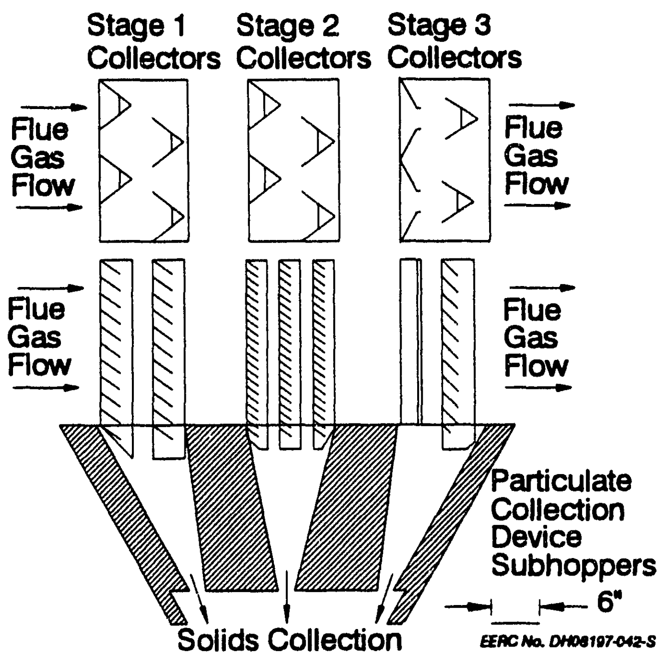

Figure F-5. Collector configuration used for Salt Creek bituminous testing.

each of two rows. The second stage had a total of twelve chevron collectors, four in each of three rows. The third stage had a single row of four chevron collectors, each with a ventury-type configuration as an inlet to accelerate the flow into the collectors. Additional hard refractory was also installed in the Duct A hoppers to reduce the potential for flue gas to bypass between the various stages of chevron collectors.

At the conclusion of the two weeks of testing, the three sets of collectors were removed for inspection. It appeared that all four collectors in stage one had been operating properly. In the second stage, the four collectors in the back row were plugged with fine bed material, while the first two rows appeared to have been operating with some slight blockages at the top and bottom. The third stage of collectors were entirely plugged with bed material fines. The outer two inlet venturies on stage three had also warped, blocking much of the flow to the two outside collectors. It appears that a combination of factors caused the blinding of the back row of stage two and all of the stage three collectors. All of the stage two and stage three collectors were one-half the size of the ones used in stage one, resulting in a smaller exit to the collection hoppers. All of the individual collectors that drained onto the back slope of the hopper plugged off. There did not appear to be sufficient spacing between the collector drains and the refractory to allow solids to flow through. The stage three inlet venturies funneled all of the remaining fines into four collectors, overloading this stage with more material than could be handled.

Operational temperatures in the downcomer remained high throughout the testing, indicating good collector performance even though half of the chevron collectors were probably plugged off for most of the test. The design used for this test was not able to handle the large amount of recirculating fines. The recycle of the secondary cyclone catch to the downcomer may have influenced the plugging problems noted above. Some of the plugging problems encountered during this test were specific to the limestone used: it was a smaller size than had been originally specified for operation with this pilot facility and was extremely cohesive.

A modified configuration was used for Center lignite testing, shown in Figure F-6, to alleviate some of the problems that had been encountered. The stage one collectors did not change from the original design and were retained for use. Newly constructed stage two and stage three chevron collectors were slightly larger than the stage one collectors and had larger openings in the back for collected material to drain through, and the chevron deflector plates were positioned at a steeper angle (50°, compared to 35° in the original design) to help reduce plugging. Stage two used the same layout as stage one with a total of four chevron collectors arranged in two rows of two. Stage three had the flow funneled through venturies into two chevron collectors.

At the conclusion of the first part of testing on Center lignite (following Test 6) all three sets of collectors were removed for inspection. In stage one, there was one chevron collector totally plugged and the remaining three were partially plugged to the degree that they did not appear to be capable of capturing solids for recirculation. Although the hopper directly below stage two was plugged, three of the four collectors from stage two were in good condition and appeared to have been available for particulate collection. It is not known if the hopper plugged off as a result of shutdown, or if this condition had occurred earlier in the run. Both of the collectors in stage three were totally plugged with bed material fines, as had occurred in the previous test. The stage three venturies were

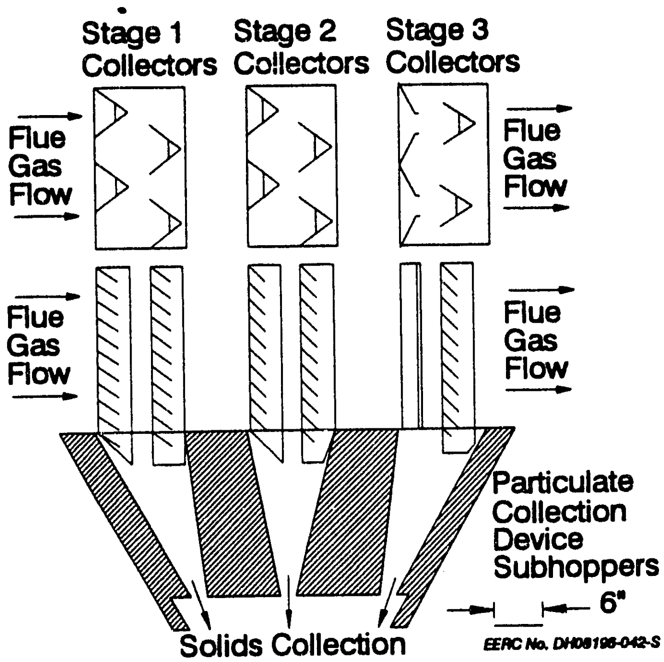

Figure F-6. Chevron collector configuration used for Center lignite testing.

designed to force the majority of the remaining uncollected fines into the stage three collectors. This likely overloaded the stage three collectors with more fines than could be handled under the operating conditions which were used.

Operational temperatures in the downcomer remained high throughout the Center lignite test, indicating good collector performance. However, visual inspection of the particulate collection device at the end of the run indicated that the only operational collectors were in stage two, and these were feeding into a plugged hopper. Some material was collected in the ash-fouling hopper and by the 18-inch secondary cyclone and was reintroduced into the downcomer. Downcomer temperatures, and solids samples which were taken, indicated that the material from the ash-fouling hopper and secondary cyclone was only a small proportion of the total bed material collected for recirculation. Some of the plugging problems encountered were likely related to the coal ash generated from the combustion of a high-alkaline-ash lignite coal. Minor plugging of the type encountered during the Center lignite test would not be significant when using a large-scale cyclone for particulate collection.

A number of simple modifications to the particulate collection device were considered to allow for more long-term, reliable operation. It was decided at this point that a more prudent way to proceed was to replace the particulate collection device with a refractory-lined cyclone collector. The cyclone which was designed, shown incorporated into the system in Figure F-7, had a calculated cut point of 10 μm at nominal operating conditions of 16.0 ft/sec and 1550°F. The actual operational cut point was significantly larger than the predicted value, as was seen with the secondary cyclone. The main features of the cyclone are a main body inside diameter of 25 inches, inlet dimensions of

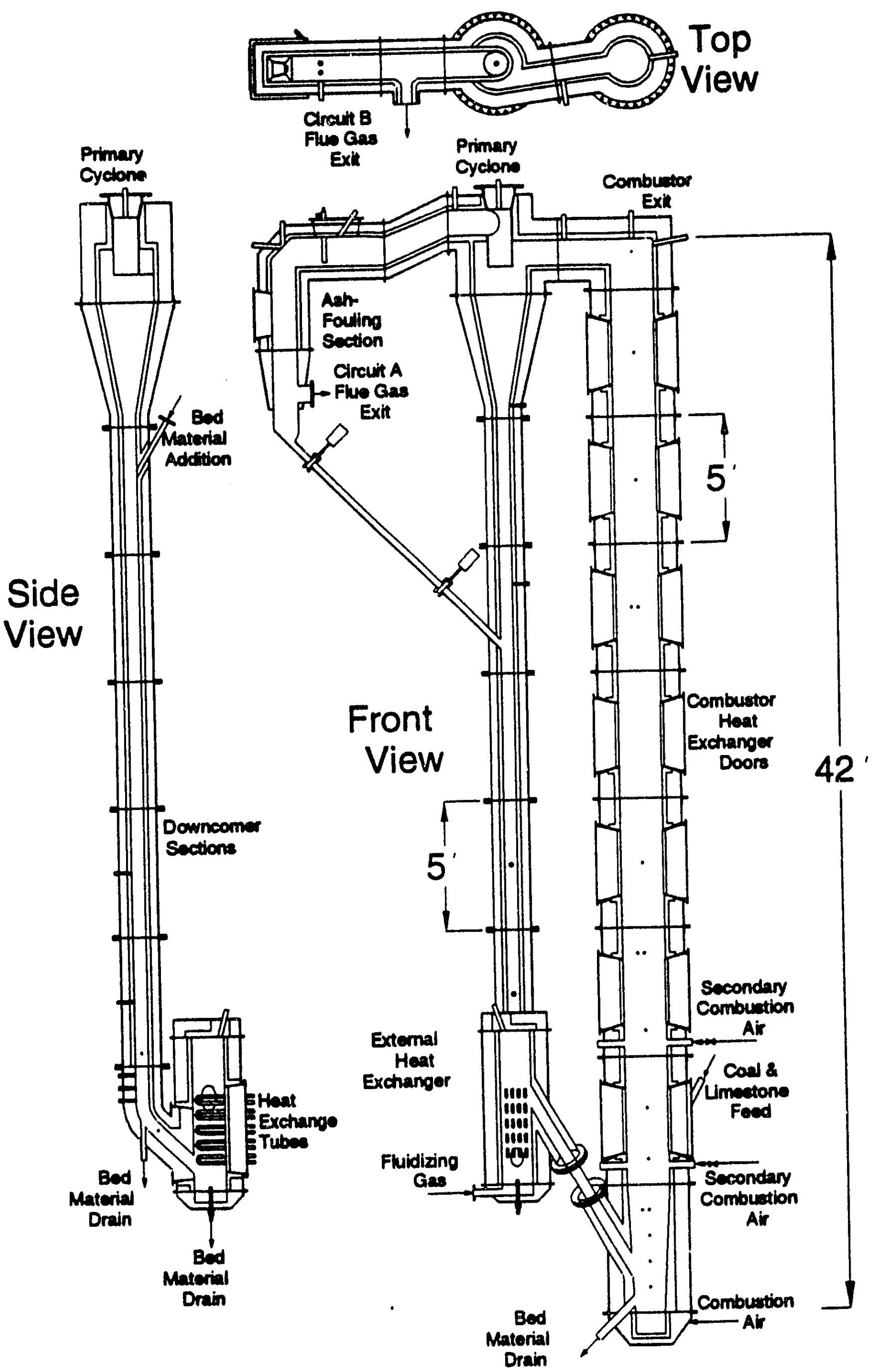

Figure F-7. Cross-sectional views showing details of construction for the combustor section, primary cyclone, ash-fouling section, downcomer section, and external heat exchanger.

8 inches wide by 12 inches high, and a 12-inch diameter type 310 stainless steel vortex finder. Operation with the 25-inch primary cyclone was very successful. Operation was both with and without secondary cyclone catch recycle, depending upon the coal and limestone used. Further details are available in the individual test summaries located in the appendix.

Visual inspections after each test consistently showed the refractory in the combustor and in the newly installed cyclone sections to be in very good shape. The type 310 stainless steel vortex finder in the primary cyclone shows no detectable warping or erosion.

Pressure Measurements

Pressure measurements are taken at various locations in the combustor, downcomer, external heat exchanger, and throughout the flue gas piping. Initially, 3/8-inch stainless steel tubes were installed as pressure probes through the refractory components. The probes at the bottom of the combustor and external heat exchanger would tend to plug off. Some initial success was obtained using a stainless steel screen welded to the ends of the probes, but soon the screens would blind so severely they could not be cleaned. During the Center lignite test, an air purge system was installed on all of the critical pressure tap locations in the combustor, downcomer, and external heat exchanger. The use of the continuous air purges turned out to be extremely successful in providing accurate pressure readings.

Ash-Fouling Section Probes

Two identical ash-fouling probes were designed for installation through the top removable door on the ash-fouling section. A detailed drawing of one of the probes and its relation to the ash-fouling duct is shown in Figure F-8. The ash-fouling probes were installed before the final week of testing with the Center lignite. The ash-fouling probes are air-cooled to maintain an outer skin temperature of approximately 1000°F, as measured by four thermocouples in each probe. There are three thermocouples installed along the upstream side and a single thermocouple on the downstream side of each probe.

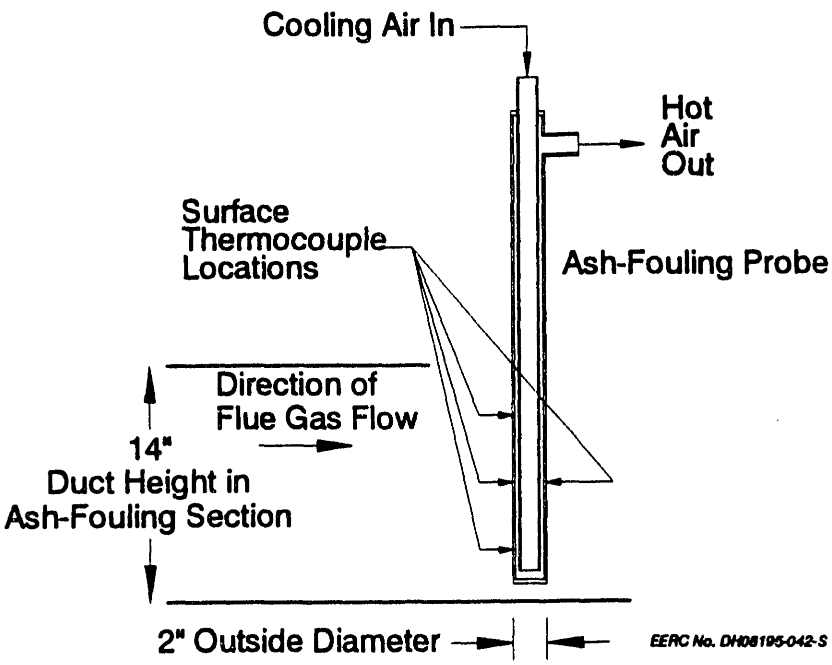

Figure F-8. Details of construction for ash-fouling probes located in the ash-fouling section.

Coal Feed Modifications

Prior to testing with the Center lignite, a rotary seal valve was installed below the coal and limestone feed valves to limit the flow of flue gas from the combustor back into the feed system. This significantly reduced coal plugs that were occurring in the gravity feed line into the combustor.

Some temporary modifications were made on the coal feed hopper during testing with the Asian lignite. Numerous pressure taps were installed for purging around the bottom of the coal feed hopper. A series of timed purges about every 15 seconds at three different heights resulted in a sufficiently stable feed rate to complete the testing. Based upon the results of this testing, it was decided to modify the coal and limestone feed hoppers. The slope of the bottom sections was increased from 60 degrees to 75 degrees. Additionally, soft rubber sides were installed on the coal hopper to more easily collapse the coal in the hopper when it would bridge or rathole. This change was successful in reducing plugs in the hopper and allowed the identification of one final problem area. The pockets in the rotary valve used to meter the coal feed rate tended to become plugged over time, depending upon the characteristics of the coal being fed. To maintain stable coal feed rates, the rotational speed of the valve had to be periodically increased to compensate for the reduced rotary valve capacity. An air line was installed at the bottom of the rotary valve during Black Thunder testing to provide high-pressure pulses as needed. This was sufficient to open the rotary valve pockets as they plugged.

Downcomer Modifications

While testing with the Center lignite, using the newly installed 25-inch primary cyclone, a plug in the downcomer forced an early shutdown. Postrun inspection revealed a plug consisting of loosely packed fines in the downcomer and in the bottom cone of the cyclone. It appeared that with proper aeration, flow could have been maintained through the 6-inch-diameter downcomer. A manifold that allowed aeration to any of four different locations in the downcomer and at the bottom of the primary cyclone entrance was installed.

Flue Gas Piping

The initial system design required the ability to split the flue gas into three separate circuits. This was based upon the range of velocities over which the system was expected to operate and the calculation of superficial gas velocity from combustion air input. As a result of discussions at the sponsors meetings, the design range of operation remained the same, but it was decided to base the target superficial gas velocities on the total flue gas flow rate. This would result in the same actual velocity through the combustor regardless of the fuel being used. This also eliminated the need for the third flue gas circuit.

When the 25-inch primary cyclone was installed, both flue gas Circuits B and C were removed. Figure F-9 shows the current configuration of the entire CFB system. The capability to reinstall Circuit B still exists if required for testing at operational velocities greater than 18 ft/sec.

Heat-Transfer Surface

Prior to the Blacksville testing, four additional combustor heat exchange doors were fabricated and installed in the CFB. The added heat exchange capacity was installed in anticipation of the higher heat load which would be placed on the CFB during operation on the Blacksville bituminous coal. The new combustor heat exchange panels were added to Sections 3, 4, 5, and 7. Each of the new heat exchange doors were equipped with the same auxiliary hardware as the original doors.

During testing on the Blacksville coal, it was discovered that it was extremely difficult to bring the four-tube-in-series heat exchange coils in the external heat exchanger into service. The combination of high total pressure drop through the four coils and the relatively large amount of hot tube surface area would cause the initial flow of water to turn to steam, which would then reduce water flow and further increase the amount of steam generated. This usually resulted in the inability to successfully bring the heat exchanger on-line. The excessive steam which was generated would occasionally back up into the rotameters and also caused some breaks at soldered sweat fittings which were used at the time. Both situations were identified as safety hazards. All sweat fittings were subsequently replaced with stainless steel pipe and high-pressure compression fittings. The top four heat exchange tubes which made up one circuit were disconnected, since it was decided that they were located in the freeboard of the external heat exchanger and thus had a minimal effect on heat removal. The remaining four-tube-in-series heat exchanger was split into two sets of two-tube-in-series heat exchangers.

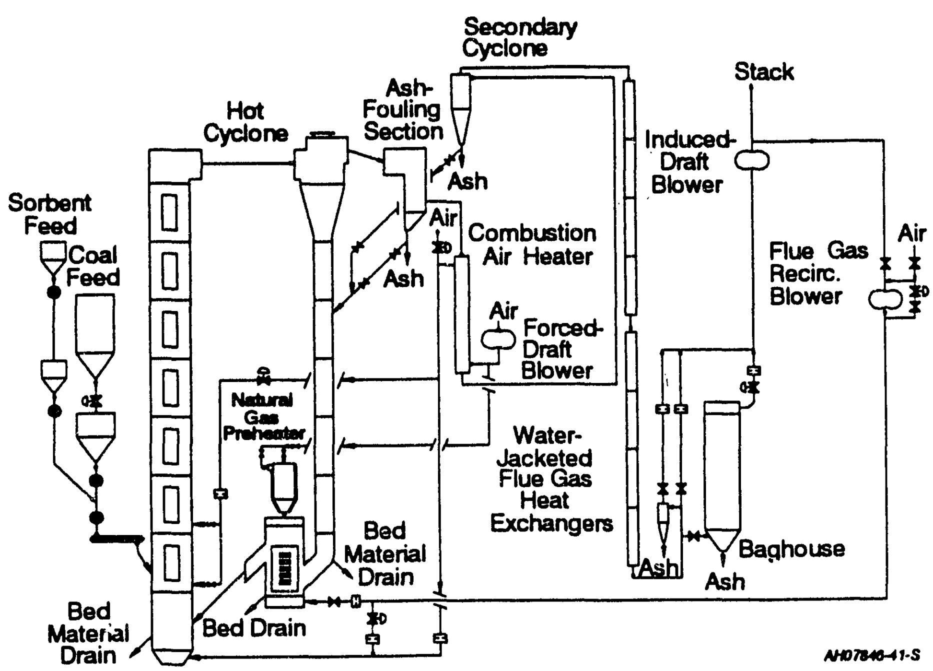

Figure F-9. Current configuration of the EERC CFB system.

APPENDIX G

CALCULATIONS

TABLE OF CONTENTS

The following calculations are grouped according to the Table in which they appear in Appendices A through E. Several equations appear on more than one Table; these will be referenced back to their first occurrence.

SUMMARY OF PROCESS DATA

1. Coal Feed Rate (lb/hr)

The measured coal feed rate is based on the change in weight of the coal weigh hopper over a given period of time. The weigh hopper is suspended from a load cell which measures the weight of the hopper and any coal it holds. The data acquisition system receives a signal from the load cell every two seconds. The difference in hopper weight is calculated from values received 15 minutes apart. The weight difference for each 15-minute interval is divided by the time period and multiplied by 60, and the average feed rate for each test period is presented. Intervals during which the initial hopper weight is less than the final hopper weight (as when the weigh hopper is filled) are not included in the average.

$$\text{Coal Feed Rate} = \frac{\text{Hopper Weight @ Time t (min)} - \text{Hopper Weight @ Time (t+15) (min)}}{\text{Time Interval (min)}} \times 60\ \frac{\text{min}}{\text{hr}}$$

2. Limestone Feed Rate (lb/hr)

The equation used for the limestone feed rate depends upon the limestone feed system in place. For the Salt Creek, Center, Blacksville, and Asian tests, a weigh hopper similar to that used for the coal was used. For the final Blacksville test and all the Black Thunder tests, an Accurate screw feeder was used. Hourly calibrations of the Accurate feeder were performed; calibrations consisted of collecting limestone exiting the screw feeder for a timed interval. The limestone collected in this manner was added to the combustor after it was weighed.

3. Solids Recirculation Rate (lb/hr)

The solids recirculation rate is determined from a heat balance around the external heat exchanger.

$$\text{Solids Recirculation Rate} = \frac{\text{EHX Heat Removal} + \text{EHX Wall Losses} - \text{EHX Heat In}}{\text{Heat Capacity of the Solids} \times (\text{EHX Inlet Temperature} - \text{EHX Exit Temperature})}$$

Where EHX heat removal is given in Equation 37
EHX wall losses are assumed to be 35,000 Btu/hr
EHX heat in is given in Equation 31
EHX inlet temperature is measured by thermocouple DC Sec 3 - 8.5'

Heat capacity of the solids (C_p)(Btu/lb-°F) is given by:

$$C_p = \left\{0.757 + 6 \times 10^{-4}\left[\left(\frac{T-32}{1.8}\right) + 273\right] - 1.68 \times 10^{4}\left[\left(\frac{T-32}{1.8}\right) + 273\right]^{-2}\right\} \times 0.23884$$

for 0°F < T < 1067°F, and

$$C_p = \left[0.762 + 3.83 \times 10^{-4}\left(\frac{T-32}{1.8} + 273\right)\right]$$

for 1067 °F < T < 2912°F

Where T is the average solids temperature in °F

4. Combustor Pressure Drop (dP) (inches of water)

Pressure taps are located throughout the system. The combustor pressure drop is the difference in pressure between the pressure tap located just above the distributor plate and the pressure tap located in the combustor exit.

5. Air and Flue Gas Flow Rates (scfm)

Most of the air and gas flow rates are measured with orifice plates, using the following equation to determine flow rates in scfm:

$$\text{Flow Rate} = \text{Constant}\left(\frac{ft^3 in^2 \sqrt{°R}}{lb\ min}\right) \times \sqrt{\frac{dP\ (in.\ H_2O) \times P_{static}(psia)}{Temperature(°F) + 460°R}}$$

Constants:		
	Primary Combustion Air	894.19
	Secondary Combustion Air	558.87
	Baghouse Flue Gas	971.25
	Secondary Cyclone Flue Gas	971.25
	10" Cyclone Flue Gas	238.34
	EHX Flow from FGR Blower	123.24
	Combustor FGR Flow	221.82

The coal feed assist air, downcomer aeration air, and pressure tap purge air are measured with flowmeters, which measure acfm. This value is corrected to obtain scfm.

$$scfm = acfm \times \sqrt{\frac{\text{Actual Pressure (psig)} + \text{Barometric Pressure (psia)}}{\text{Barometric Pressure (psia)}}}$$

6. Primary-to-Secondary Air Split (PA/SA)

This is the ratio of primary to secondary combustion air. Total primary combustion air is the sum of the primary air (through the combustor distributor plate), EHX air, and downcomer aeration air. Total secondary combustion air consists of secondary air (through the secondary air ports), pressure tap purge air, and coal feed assist air.

7. Excess Air (%)

All flue gas components are in %.

$$\text{Excess Air} = 100 \times \left[\frac{O_2 - (0.5 \times CO)}{0.264 \times (100 - CO_2 - CO - O_2) - O_2 + (0.5 \times CO)}\right]$$

8. Combustor Superficial Gas Velocity (ft/sec)

$$SGV = \frac{[\text{Total Primary Air} + \text{Total Secondary Air (scfm)}] \times [\text{Average Combustor Temperature (°F)} + 460°R]}{520°R \times 2.18\ ft^2 \times 60\ \frac{sec}{min}}$$

9. EHX Superficial Gas Velocity (ft/sec)

$$\text{EHX SGV} = \frac{\text{EHX Flow Rate (scfm)} \times (\text{Average EHX Temperature (°F)} + 460°\text{R}]}{520°\text{R} \times 1.5625\ \text{ft}^2 \times 60\ \frac{\text{sec}}{\text{min}}}$$

10. Bed Material/Cyclone Ash Add Rate (lb/hr)

This is the total amount of each type of material, in pounds, added during a test period, divided by the test duration.

11. Bottom Ash/Cyclone Ash/Baghouse Ash Discharge Rate (lb/hr)

This is the total amount of each type of material, in pounds, removed from the system during a test period, divided by the test duration.

12. Average Combustor Temperature (°F)

The average combustor temperature is the average of fourteen thermocouples located at the following heights in the combustor: 1', 2', 3', 4', 6', 8', 11', 14', 17.5', 22.5', 27.5', 32.5', 37.5', and 41' above the distributor plate.

13. Average EHX Temperature (°F)

The average EHX temperature is the average of three thermocouples located 0.5', 1.5', and 2.7' above the EHX distributor plate.

RECIRCULATION RATES AND SIZE DISTRIBUTIONS

14. Cyclone Efficiency (%)

$$\text{Cyclone Efficiency} = \left(1 - \frac{\text{Cyclone Ash Collected (lb/hr)} + \text{BH Ash Collected (lb/hr)}}{\text{Solids Recirculation Rate (lb/hr)}}\right) \times 100$$

15. Recirculation Ratio

$$\text{Recirculation Ratio} = \frac{\text{Recirculation Rate}}{\text{Coal Feed Rate} \times \frac{\text{\% Coal Ash}}{100} + \text{Sorbent Feed Rate}}$$

ASH BALANCE

16. Coal Ash Input (lb/hr)

$$\text{Ash Input} = \text{Coal Feed Rate} \times \frac{\text{\% Coal Ash}}{100}$$

17. Sorbent CaO and $CaSO_4$ (lb/hr)

$$\text{Sorbent CaO} = \frac{56}{100} \times \text{Sorbent Feed Rate} \times \left(1 - \frac{\text{\% Total Alkali Utilization}}{100}\right)$$

$$\text{Sorbent CaSO}_4 = \frac{136}{100} \times \text{Sorbent Feed Rate} \times \frac{\text{\% Total Alkali Utilization}}{100}$$

18. Ash Balance Closure (%)

$$\text{Closure} = \frac{\text{Total Solids Out (lb/hr)}}{\text{Total Solids In (lb/hr)}} \times 100$$

19. Bottom Ash/Total Ash Split (%)

$$\text{Bottom Ash/Total Ash} = \frac{\text{Bed Material Out (lb/hr)}}{\text{Total Solids Out (lb/hr)}} \times 100$$

MATERIAL DERIVED FROM COAL ASH/ALUMINUM BALANCE

20. Coal Ash Feed Rate (lb/hr)

$$\text{Ash Input} = \text{Coal Feed Rate} \times \frac{\text{\% Coal Ash}}{100}$$

21. Ash from Coal (%)

$$\text{Ash from Coal} = \left(\frac{Al_2O_3 \text{ in Bottom, Cyclone, or Baghouse Ash}}{Al_2O_3 \text{ in Coal Ash}}\right) \times 100$$

22. Ash from Coal (lb/hr)

$$\text{Ash from Coal} = \left(\frac{\text{Ash from Coal(\%)} \times \text{Bottom, Cyclone, or Baghouse Ash (lb/hr)}}{100}\right)$$

23. Solids Input from the Limestone in the Bed Material/Cyclone Ash/Baghouse Ash

These values are obtained by subtracting the percentage input from the coal for each ash stream from 100.

24. Total Ash from Coal (lb/hr)

$$\text{Total Ash from Coal} = \Sigma \text{ Bottom, Cyclone, and Baghouse Ash from Coal}$$

25. Closure (%)

$$\text{Closure} = \frac{\text{Total Ash from Coal}}{\text{Coal Ash}} \times 100$$

FUEL AND FLUE GAS BALANCES

These values are determined using a computer program which calculates products of combustion. The inputs are the coal analysis (in percent), the percentage of excess air, and the combustion air flow rate.

26. Theoretical Fuel Feed Rate (lb/hr)

$$\text{Theoretical Air} = \left(\frac{\text{lb C}}{\text{lb Coal}} \times 11.53\frac{\text{lb Air}}{\text{lb C}}\right) + \left(\frac{\text{lb } H_2}{\text{lb Coal}} \times 34.34\frac{\text{lb Air}}{\text{lb } H_2}\right) + \left(\frac{\text{lb S}}{\text{lb Coal}} \times 4.29\frac{\text{lb Air}}{\text{lb S}}\right) - \left(\frac{\text{lb } O_2}{\text{lb Coal}} \times 4.32\frac{\text{lb Air}}{\text{lb } O_2}\right)$$

$$\text{Total Air Required}\left(\frac{\text{lb Air}}{\text{lb Coal}}\right) = \text{Theoretical Air} \times \left(1 + \frac{\text{\% Excess Air}}{100}\right)$$

$$\text{Total Air Required}\left(\frac{\text{scf}}{\text{lb Coal}}\right) = \text{Total Air Required}\left(\frac{\text{lb Air}}{\text{lb Coal}}\right) \times 13.2\frac{\text{ft}^3}{\text{lb Air}}$$

$$\text{Theoretical Fuel Feed} = \left(\frac{\text{Actual Air Flow Rate [scfm]}}{\text{Total Air Required } \frac{\text{scf}}{\text{lb Coal}}}\right) \times 60\frac{\text{min}}{\text{hr}}$$

27. Theoretical Flue Gas Flow Rate (scfm)

$$\text{Theoretical FG Flow Rate} = \Sigma \text{ Combustion Products} \left(\frac{\text{lb}}{\text{lb Coal}}\right) \times \left(\frac{380 \frac{\text{ft}^3}{\text{lb}}}{60 \frac{\text{min}}{\text{hr}}}\right) \times \text{Theoretical Coal Feed Rate}$$

28. Combustion Products (lb/lb coal)

$$CO_2 = \frac{\text{lb C}}{\text{lb Coal}} \times 3.66 \frac{\text{lb } CO_2}{\text{lb C}}$$

$$H_2O = \left(\frac{\text{lb } H_2}{\text{lb Coal}} \times 8.94 \frac{\text{lb } H_2O}{\text{lb Coal}}\right) + \frac{\text{lb } H_2O}{\text{lb Coal}} + \left(\text{Total Air Required} \left(\frac{\text{lb Air}}{\text{lb Coal}}\right) \times 0.013 \frac{\text{lb } H_2O}{\text{lb Coal}}\right)$$

$$O_2 = (\text{Total Air Required} - \text{Theoretical Air}) \left(\frac{\text{lb Air}}{\text{lb Coal}}\right) \times 0.2313 \frac{\text{lb } O_2}{\text{lb Air}}$$

$$N_2 = \frac{\text{lb } N_2}{\text{lb Coal}} + \text{Total Air Required} \left(\frac{\text{lb Air}}{\text{lb Coal}}\right) \times 0.7685 \frac{\text{lb } N_2}{\text{lb Coal}}$$

29. Closure (%)

$$\text{Closure} = \frac{\text{Measured Feed Rate} - \text{Theoretical Feed Rate}}{\text{Theoretical Feed Rate}} \times 100$$

ENERGY BALANCE

Inputs

30. Coal (Btu/hr)

$$\text{9Energy in from Coal} = \text{HHV (as-received)} - 1040 \frac{\text{Btu}}{\text{lb}} \times \left[\frac{\text{lb } H_0}{\text{lb Coal}} + \frac{\text{lb } H_2}{\text{lb Coal}} - \frac{\left(\frac{\text{lb } H_2O}{\text{lb Coal}}\right)}{9 \frac{\text{lb } H_2O}{\text{lb } H_2}}\right] \times \text{Coal Feed Rate}$$

31. Primary/Secondary/EHX Air (Btu/hr)

$$\text{Energy in from PA} = 0.60 \frac{\text{Btu}}{\text{ft}^3\ {}^\circ\text{F}} \times \text{PA Flow} \times (\text{Combustor Plenum Temperature} - \text{Ambient Temperature}) \times 60 \frac{\text{min}}{\text{hr}}$$

$$\text{Energy in from SA} = 0.60 \frac{\text{Btu}}{\text{ft}^3\ {}^\circ\text{F}} \times \text{SA Flow} \times (\text{Combustor Plenum Temperature} - \text{Ambient Temperature}) \times 60 \frac{\text{min}}{\text{hr}}$$

$$\text{Energy in from EHX} = 1.01 \frac{\text{Btu}}{\text{ft}^3\ {}^\circ\text{F}} \times \text{EHX Flow} \times (\text{EHX Plenum Temperature} - \text{Ambient Temperature}) \times 60 \frac{\text{min}}{\text{hr}}$$

Assumes 600°F PA and SA inlet temperatures and 110°F EHX inlet temperature.

32. Ash (chem.) (Btu/hr)

$$\text{Ash(chem.)} = 14{,}091\ \frac{\text{Btu}}{\text{lb C}} \times \left[\left(\frac{\text{Cyclone Ash Added}\left(\frac{\text{lb}}{\text{hr}}\right)}{\frac{\text{lb C}}{\text{lb Cyclone Ash}}}\right) + \left(\frac{\text{Bed Ash Added}\left(\frac{\text{lb}}{\text{hr}}\right)}{\frac{\text{lb C}}{\text{lb Bed Ash}}}\right)\right]$$

33. Sorbent Sulfation (Btu/hr)

$$\text{Sorbent Sulfation} = 2150\ \frac{\text{Btu}}{\text{lb Limestone}} \times \text{Limestone Feed Rate} \times \frac{\left(\frac{\text{Sulfur Retention}}{\text{Total Alkali/Sulfur}}\right)}{100}$$

Outputs

34. Flue Gas (sensible) (Btu/hr)

$$\text{Flue Gas Energy Out} =$$

$$C_{p(\text{wet FG})}\left(\frac{\text{Btu}}{\text{lb °F}}\right) \times \text{FG Flow Rate (scfm)} \times \text{Density}_{(\text{wet FG})}\left(\frac{\text{lb}}{\text{ft}^3}\right) \times (\text{FG Exit Temperature} - \text{Ambient Temperature}) \times 60\ \frac{\text{min}}{\text{hr}}$$

35. Ash (sensible) (Btu/hr)

$$\text{Solids} = 0.269\ \frac{\text{Btu}}{\text{lb °F}} \times \text{Total Ash Discharge Rate} \times (\text{Average Temperature} - \text{Ambient Temperature})$$

Where Total Ash = Bed Material Drain + Secondary Cyclone Ash + Baghouse Ash in lb/hr

36. Ash (chem.) (Btu/hr)

$$\text{Ash (chem.)} =$$

$$14{,}091\ \frac{\text{Btu}}{\text{lb C}} \times \left[\left(\text{BH Discharge} \times \frac{\text{lb C}}{\text{lb BH Ash}}\right) + \left(\text{Cyclone Discharge} \times \frac{\text{lb C}}{\text{lb Cyclone Ash}}\right) + \left(\text{Bed Discharge} \times \frac{\text{lb C}}{\text{lb Bed Ash}}\right)\right]$$

37. Combustor and EHX Heat Exchangers (Btu/hr)

$$\text{Heat Removal} =$$

$$8.34\ \frac{\text{Btu}}{\text{gal °F}} \times \text{Water Flow Rate (gpm)} \times (\text{Water Temperature Out} - \text{Water Temperature In}) \times 60\ \frac{\text{min}}{\text{hr}}$$

38. Sorbent Calcination (Btu/hr)

$$\text{Sorbent Calcination} = 766\ \frac{\text{Btu}}{\text{lb}} \times \text{Limestone Feed Rate}\left(\frac{\text{lb}}{\text{hr}}\right)$$

39. Conduction and Radiation (Btu/hr)

$$\text{Conduction and Radiation} = (\text{Average Combustor Temperature} \times \text{Slope}) + \text{Constant}$$

For Tests SC and CL: Slope = 482.65
Constant = -304,825

For Tests BT, BV, TL: Slope = 520.95
Constant = -600,132

40. Closure (%)

$$\text{Closure} = \frac{\text{Energy In}}{\text{Energy Out}} \times 100$$

MATERIAL BALANCE

Inputs

41. Combustion/Additional Air (lb/hr)

$$\text{Combustion Air} = 0.076312 \ \frac{\text{lb}}{\text{ft}^3} \times 60 \ \frac{\text{min}}{\text{hr}} \times (\text{Primary} + \text{Secondary} + \text{EHX Air}) \ (\text{scfm})$$

$$\text{Additional Air} = 0.076150 \ \frac{\text{lb}}{\text{ft}^3} \times 60 \ \frac{\text{min}}{\text{hr}} \times (\text{Feed Assist} + \text{Downcomer Assist} + \text{Purge Air}) \ (\text{scfm})$$

42. Bed Material/Cyclone Ash, Coal and Sorbent Feed Rates (lb/hr)

These values are the actual measured amounts, averaged over the length of the test period. The coal feed rate used here is the theoretical coal feed rate.

Outputs

43. Measured Flue Gas (lb/hr)

$$\text{Flue Gas Out} = \text{Actual FG Flow Rate (scfm)} \times \text{Density}_{(\text{wet FG})} \left(\frac{\text{lb}}{\text{ft}^3}\right) \times 60 \ \frac{\text{min}}{\text{hr}}$$

44. Flue Gas Leaks (lb/hr)

$$\text{Flue Gas Leaks} = (\text{Theoretical FG Flow Rate} - \text{Actual FG Flow Rate}) \ (\text{scfm}) \times \text{Density}_{(\text{wet FG})} \left(\frac{\text{lb}}{\text{ft}^3}\right) \times 60 \ \frac{\text{min}}{\text{hr}}$$

45. Bottom Ash/Cyclone Ash/Baghouse Ash Out (lb/hr)

These values are the actual measured amounts, averaged over the length of the test period.

46. Closure (%)

$$\text{Closure} = \frac{\text{Material Out}}{\text{Material In}} \times 100$$

COMBUSTION EFFICIENCY

Inputs

47. Coal/Bed Material/Cyclone Ash Carbon Feed Rates (lb/hr)

$$\text{Coal Carbon Input} = \text{Coal Feed Rate}\left(\frac{\text{lb}}{\text{hr}}\right) \times \frac{\text{lb C}}{\text{lb Coal}}$$

$$\text{Bed Ash Carbon Input} = \text{Bed Ash Add Rate}\left(\frac{\text{lb}}{\text{hr}}\right) \times \frac{\text{lb C}}{\text{lb Bed Ash}}$$

$$\text{Cyclone Ash Carbon Input} = \text{Cyclone Ash Add Rate}\left(\frac{\text{lb}}{\text{hr}}\right) \times \frac{\text{lb C}}{\text{lb Cyclone Ash}}$$

Outputs

48. Bottom Ash/Cyclone Ash/Baghouse Ash Carbon Discharge Rate (lb/hr)

$$\text{Bottom Ash Carbon} = \text{Bottom Ash Drain Rate}\left(\frac{\text{lb}}{\text{hr}}\right) \times \frac{\text{lb C}}{\text{lb Bottom Ash}}$$

$$\text{Cyclone Ash Carbon} = \text{Cyclone Ash Drain Rate}\left(\frac{\text{lb}}{\text{hr}}\right) \times \frac{\text{lb C}}{\text{lb Cyclone Ash}}$$

$$\text{BH Ash Carbon} = \text{BH Ash Drain Rate}\left(\frac{\text{lb}}{\text{hr}}\right) \times \frac{\text{lb C}}{\text{lb BH Ash}}$$

49. Combustion Efficiency (Carbon Basis) (%)

$$\text{Combustion Efficiency} = \left(\frac{\text{Total Carbon In} - \text{Total Carbon Out}}{\text{Total Carbon In}}\right) \times 100$$

BOILER EFFICIENCY

50. Dry Gas Loss (Btu/hr)

Dry Gas =

$$C_{p(\text{dry FG})}\left(\frac{\text{Btu}}{\text{lb }^\circ\text{F}}\right) \times \text{FG Flow Rate (scfm)} \times \text{Density}_{(\text{dry FG})}\left(\frac{\text{lb}}{\text{ft}^3}\right) \times \left(\frac{\text{lb Moisture}}{\text{lb FG}}\right) \times (\text{FG Exit Temperature} - \text{Ambient Temperature}) \times 60\frac{\text{min}}{\text{hr}}$$

51. Water in the Fuel Loss (Btu/hr)

Water in Fuel =

$$\text{Coal Feed Rate} \times \frac{\text{lb H}_2\text{O}}{\text{lb Coal}} \times [1089\,\frac{\text{Btu}}{\text{lb H}_2\text{O}} + 0.46\,\frac{\text{Btu}}{\text{lb H}_2\text{O }^\circ\text{F}} \times (\text{FG Exit Temperature} - \text{Ambient Temperature})]$$

52. Combustion of Fuel Hydrogen Loss (Btu/hr)

Fuel H =

$$\text{Coal Feed Rate} \times \left[\frac{\text{lb } H_2}{\text{lb Coal}} - \frac{\left(\frac{\text{lb } H_2O}{\text{lb Coal}}\right)}{\left(\frac{9 \text{ lb } H_2O}{\text{lb } H_2}\right)} \right] \times [1089 \frac{\text{Btu}}{\text{lb } H_2O} + 0.46 \frac{\text{Btu}}{\text{lb } H_2O\ ^\circ F} \times (\text{FG Exit Temperature} - \text{Ambient Temperature})]$$

53. Unburned Carbon Loss (Btu/hr)

UnburnedCarbon =

$$14{,}091 \frac{\text{Btu}}{\text{lb C}} \times \left[\left(\text{BH Discharge} \times \frac{\text{lb C}}{\text{lb BH Ash}}\right) + \left(\text{Cyclone Discharge} \times \frac{\text{lb C}}{\text{lb Cyclone Ash}}\right) + \left(\text{Bed Discharge} \times \frac{\text{lb C}}{\text{lb Bed Ash}}\right)\right]$$

54. Sorbent Calcination Loss (Btu/hr)

$$\text{Sorbent Calcination} = 766 \frac{\text{Btu}}{\text{lb}} \times \text{Limestone Feed Rate} \left(\frac{\text{lb}}{\text{hr}}\right)$$

55. Radiation and Convection Loss (assumes 0.4% heat loss) (Btu/hr)

$$\text{Radiation and Convection} = 0.004 \times \text{Coal Feed Rate} \times \text{HHV (as-received)}$$

56. Solids Loss (Btu/hr)

Solids =

$$0.269 \frac{\text{Btu}}{\text{lb } ^\circ F} \times \text{Total Ash Discharge Rate} \left(\frac{\text{lb}}{\text{hr}}\right) \times (\text{Average Temperature} - \text{Ambient Temperature})$$

Where Total Ash = Bed Material Drain + Secondary Cyclone Ash + Baghouse Ash in lb/hr

57. Sorbent Sulfation Loss (Btu/hr)

$$\text{Sorbent Sulfation} = -2150 \frac{\text{Btu}}{\text{lb Limestone}} \times \text{Limestone Feed Rate} \times \frac{\left(\frac{\text{Sulfur Retention}}{\text{Total Alkali/Sulfur}}\right)}{100}$$

58. Boiler Efficiency Losses (%)

Each boiler efficiency loss calculated with Equations 50 through 57 is converted to a percentage of the heat in from the fuel with the following equation:

$$\text{Loss (\%)} = \frac{\text{Loss} \left(\frac{\text{Btu}}{\text{hr}}\right) \text{(from Equations 50 - 57)}}{\text{HHV (as-received)} \times \text{Coal Feed Rate}}$$

59. Boiler Efficiency (%)

$$\text{Boiler Efficiency} = 100 - \Sigma \text{ Boiler Efficiency Losses (\%)}$$

HEAT-TRANSFER COEFFICIENTS

60. Combustor Heat Transfer Coefficient (Btu/hr-ft^2-°F)

$$HTC = \frac{\text{Energy Out (Equation 37)} \left(\frac{Btu}{hr}\right)}{2.6 \frac{ft^2}{Door} \times (\text{\# Doors}) \times (\text{Water Temperature Out} - \text{Water Temperature In})}$$

61. EXH Heat Transfer Coefficient (Btu/hr-ft^2-°F)

$$HTC = \frac{\text{Energy Out (Equation 37)} \left(\frac{Btu}{hr}\right)}{0.75 \frac{ft^2}{Coil} \times (\text{\# Coils}) \times (\text{Water Temperature Out} - \text{Water Temperature In})}$$

HEAT FLUX

62. Combustor Heat Flux (Btu/hr-ft^2)

$$\text{Combustor Heat Flux} = \frac{\text{Energy Out (Equation 37)} \left(\frac{Btu}{hr}\right)}{2.6 \frac{ft^2}{Door} \times (\text{\# Doors})}$$

63. EHX Heat Flux (Btu/hr-ft^2)

$$\text{EHX Heat Flux} = \frac{\text{Energy Out (Equation 37)} \left(\frac{Btu}{hr}\right)}{0.75 \frac{ft^2}{Coil} \times (\text{\# Coils})}$$

EMISSIONS

64. $CO/CO_2/NO_x/N_2O/SO_2$ Emissions Corrected to 3% O_2

$$\text{Corrected Concentration} = \text{Measured Concentration} \times \left(\frac{3\% - 21\% \text{ in Air}}{O_2 \text{ Concentration} - 21\% \; O_2 \text{ in Air}}\right)$$

65. $CO/NO_x/N_2O/SO_2$ Emissions in lb/MM Btu

$$CO\left(\frac{lb}{MM\ Btu}\right) = \frac{2.33\ \frac{lb\ CO}{lb\ C}}{Coal\ HHV\left(\frac{Btu}{lb}\right)} \times \frac{\left(\frac{Coal\ C}{100} \times CO\ (ppm)\right)}{\left(\frac{CO_2\ (\%) + CO\ (\%)}{100}\right)}$$

$$NO_x\left(\frac{lb}{MM\ Btu}\right) = \frac{3.83\ \frac{lb\ NO_x}{lb\ C}}{Coal\ HHV\left(\frac{Btu}{lb}\right)} \times \frac{\left(\frac{Coal\ C}{100} \times NO_x\ (ppm)\right)}{\left(\frac{CO_2\ (\%) + CO\ (\%)}{100}\right)}$$

$$N_2O\left(\frac{lb}{MM\ Btu}\right) = \frac{3.66\ \frac{lb\ N_2O}{lb\ C}}{Coal\ HHV\left(\frac{Btu}{lb}\right)} \times \frac{\left(\frac{Coal\ C}{100} \times N_2O\ (ppm)\right)}{\left(\frac{CO_2\ (\%) + CO\ (\%)}{100}\right)}$$

$$SO_2\left(\frac{lb}{MM\ Btu}\right) = \frac{5.33\left(\frac{lb\ SO_2}{lb\ C}\right)}{Coal\ HHV\left(\frac{Btu}{lb}\right)} \times \frac{\left(\frac{Coal\ C}{100} \times SO_2\ (ppm)\right)}{\left(\frac{CO_2\ (\%) + CO\ (\%)}{100}\right)}$$

66. SO_2 Retention (%)

$$SO_2\ Retention = 100 - \frac{0.0267 \times SO_2\ (ppm) \times \%\ C\ in\ Coal}{[CO_2\ (\%) + CO\ (\%)] \times \%\ S\ in\ Coal}$$

67. Ca/S Ratio (sorbent only)

$$Ca/S = \frac{Sorbent\ Feed\ Rate \times \frac{\%\ CaO\ in\ Sorbent}{56\ \frac{lb}{mol}}}{Coal\ Feed\ Rate \times \frac{\%\ S\ in\ Coal}{32\ \frac{lb}{mol}}}$$

68. Ca/S Ratio (total)

$$Total\ Ca/S = \frac{\left(Sorbent\ Feed\ Rate \times \frac{\%\ CaO\ in\ Sorbent}{56\ \frac{lb}{mol}}\right) + \left(Coal\ Feed\ Rate \times \%\ Coal\ Ash \times \frac{\%\ CaO\ in\ Coal\ Ash}{56\ \frac{lb}{mol}}\right)}{Coal\ Feed\ Rate \times \frac{\%\ S\ in\ Coal}{32\ \frac{lb}{mol}}}$$

69. Calcium Utilization (%)

$$Calcium\ Utilization = \frac{SO_2\ Retention}{Ca/S\ (total)}$$

END

DATE FILMED

6 / 29 / 93