DOE/FE-0392

TRI-STATE GENERATION AND TRANSMISSION ASSOCIATION, INC.

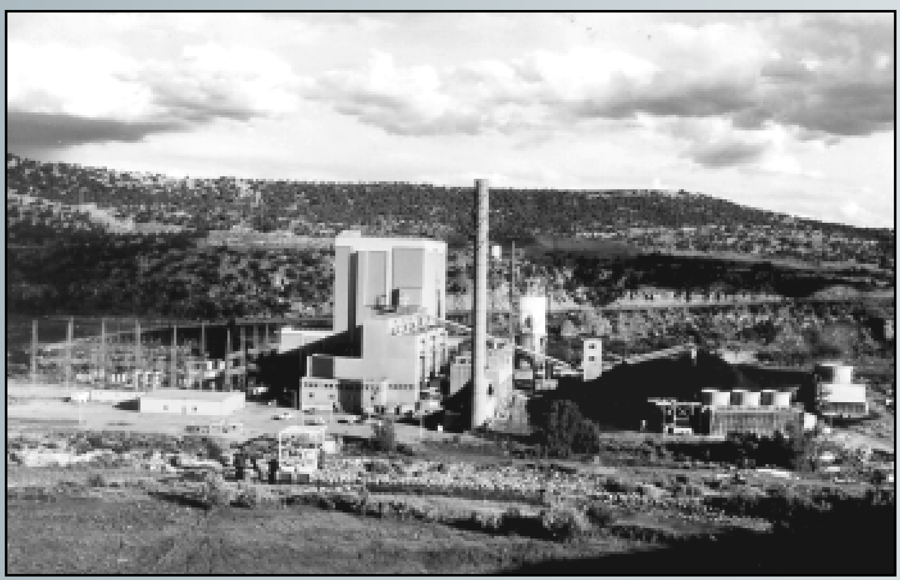
# NUCLA ACFB DEMONSTRATION PROJECT

## PROJECT PERFORMANCE SUMMARY
## CLEAN COAL TECHNOLOGY DEMONSTRATION PROGRAM

JUNE 1999

Tri-State Generation and Transmission association, Inc.

# Nucla ACFB Demonstration Project



## Project Performance Summary
## Clean Coal Technology Demonstration Program

Advanced Electric Power Generation

# Nucla ACFB Demonstration Project

## Overview

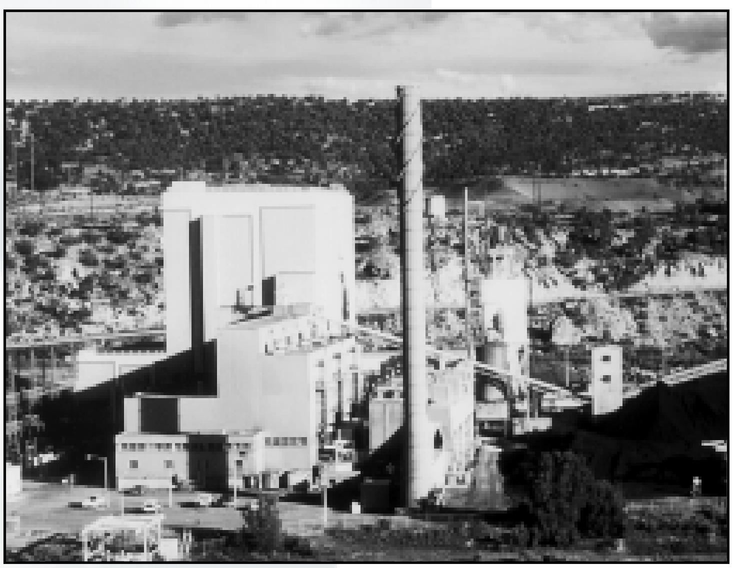
**Nucla, the first utility-scale ACFB project, achieved the following results:**

- **Validated consistent low-$NO_x$ emissions far below the regulated level and the ability to achieve greater than 90 percent $SO_2$ reduction through the combustion process rather than adding external controls**
- **Accelerated introduction of ACFB by 3 years and provided the design basis for more efficient and larger commercial units**

The project is part of the U.S. Department of Energy's Clean Coal Technology Demonstration Program (CCTDP) established to address energy and environmental concerns related to coal use. Cost-shared partnerships with industry were sought through five nationally competed solicitations to accelerate commercialization of the most advanced coal-based power generation and pollution control technologies. The CCTDP, valued at nearly $6 billion, has leveraged federal funding twofold through the resultant partnerships encompassing utilities, technology developers, state governments, and research organizations. This project was one of 17 selected in July 1986 from 51 proposals submitted in response to the Program's first solicitation.

The Nucla atmospheric circulating fluidized-bed (ACFB) project showed that the technology could be scaled from small industrial units to a 110-MWe utility power plant. In 1988, when Nucla's boiler was repowered, the ACFB unit installed was not only the largest in the world, it was more than 40 percent larger than any of the others.

The ability of the ACFB to remove up to 95 percent of the $SO_2$ and to far exceed $NO_x$ standards was successfully demonstrated during the 15,700 hours of operation. The project saved almost 3 years in establishing a commercial line of utility ACFB systems backed by performance guarantees. The plant continues to be operated by Tri-State Generation and Transmission Association, Inc., which took over ownership in 1992.



The Nucla project significantly advanced the environmental, operational, and economic potential of ACFB, precipitating a large number of orders. The project's comprehensive ACFB database remains the most comprehensive, available resource in the ACFB technology area and continues to be used in the design of larger and more efficient systems.

# THE PROJECT

Burdened with low efficiency and high operating costs at its Nucla Station, the Colorado-Ute Electric Association (subsequently purchased by Tri-State) evaluated options for upgrading their 36-MWe net stoker fired unit. The option selected was to retrofit the plant with a 925,000 lb/hr API ACFB and a new 74–MWe steam turbine. By tying in the three existing 12.5–MWe turbines through interstage extraction, the plant capacity was increased to 100–MWe net, 110-MWe total electric output. Extensive use of existing equipment was made, including coal receiving, preparation and storage equipment, baghouses, feedwater system, condensers, and 12.5–MWe turbines. Advantages realized beyond enhanced plant capacity were a station heat rate improvement of 15 percent, reduced fuel costs due to the inherent fuel flexibility of ACFB, lower emissions than that required by New Source Performance Standards, and a plant life extension of 30-years.

Department of Energy (DOE), Electric Power Research Institute, and Technical Advisory Group (potential users) interest and participation in the project was on the basis of evaluating ACFB potential for broad utility application through a comprehensive test program. Over a 2½ year period, 72 steady state performance tests were conducted and 15,700 hours logged.

**Sorbent receiving area in foreground and storage and distribution system in background**

**Project Sponsor**
Tri-State Generation and Transmission Association, Inc.
(formerly Colorado-Ute Electric Association)

**Additional Team Members**
Foster Wheeler Energy Corporation (formerly Pyropower Corporation)—technology supplier
Technical Advisory Group (potential users)—cofunder
Electric Power Research Institute—technical support

**Location**
Nucla, Montrose County, CO
(Nucla Station)

**Technology**
Foster Wheeler's atmospheric circulating fluidized-bed (ACFB) combustion system

**Plant Capacity**
110-MWe (gross); 100-MWe (net)—2:1 scale-up from previously demonstrated capacity

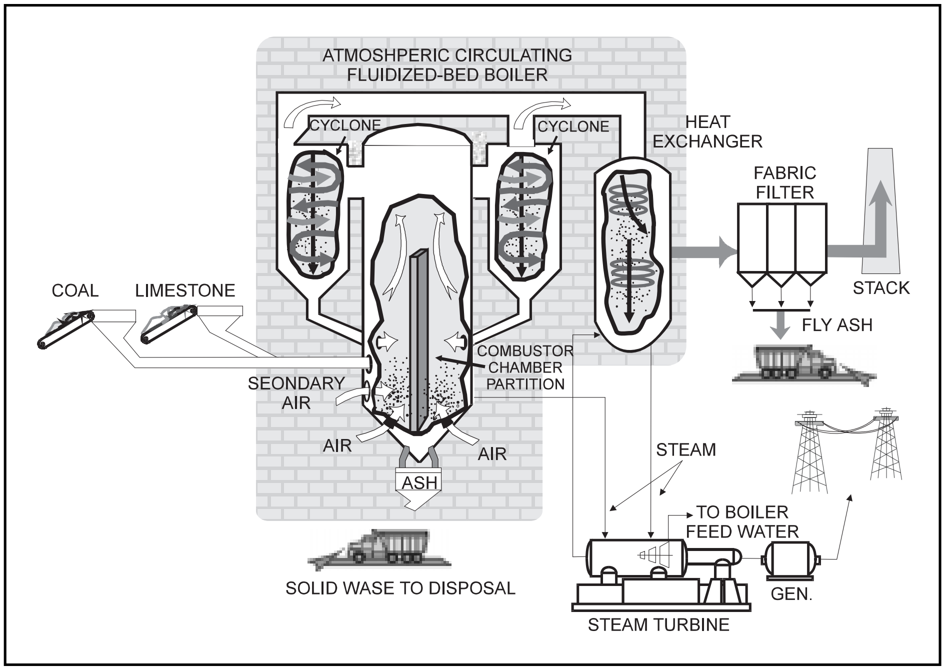
**Coals**
Western Bituminous—
Salt Creek, 0.5% Sulfur, 17% Ash
Peabody, 0.7%, Sulfur, 18% Ash
Dorchester, 1.5% Sulfur, 23% Ash

**Demonstration Duration**
15,700 hours
April 1988–January 1991

**Project Funding**

| | | |
|---|---|---|
| Total project cost | $46,512,678 | 100% |
| DOE | 17,130,411 | 37% |
| Participants | 29,382,267 | 63% |

# THE TECHNOLOGY




Fluidized beds, using a gas such as air to entrain solids, were first used in the chemical industry. The effective gas/solid mixing that is induced enhances chemical reaction and heat transfer. Fluidized-bed combustion (FBC) evolved from efforts to find a combustion process conducive to controlling pollutant emissions without external controls. FBC enables efficient combustion at temperature of 1400–1700 °F, well below the thermal $NO_x$ generation temperature (2500 °F), and high $SO_2$ capture efficiency through effective sorbent/flue gas contact. Two parallel paths were pursued in FBC development — bubbling and circulating beds. Bubbling beds use a dense fluidized bed and low fluidization velocity (3–4 ft/sec) to affect good heat transfer and mitigate erosion of an in-bed heat exchanger. Circulating fluidized-beds (CFB) use a relatively high fluidization velocity (6–8 ft/sec) in conjunction with hot cyclones to separate and recirculate the particulate from the flue gas before it passes to a heat exchanger. Both use water walls in the combustor to extract heat.

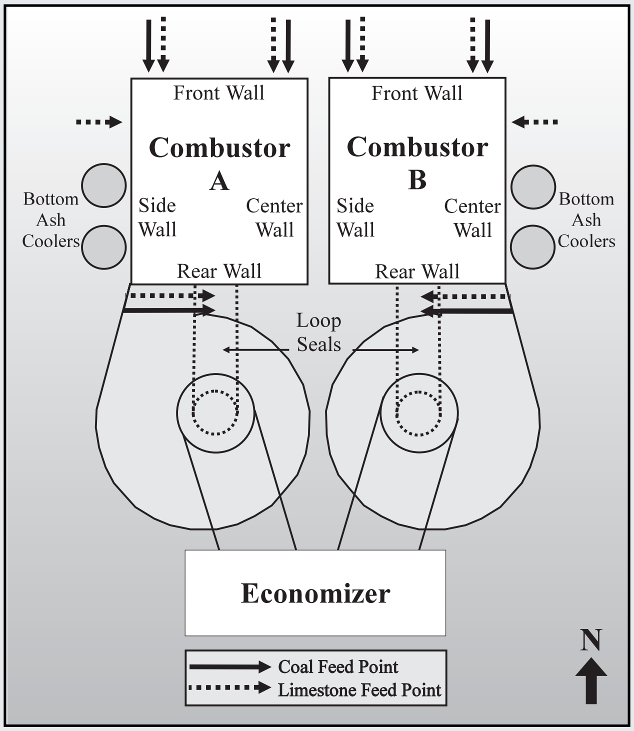
The continuous circulation of coal char and sorbent particles is the unique aspect of CFB. Fluidization velocities used in CFBs entrain the bed materials, which are then separated and recirculated, allowing extensive gas/solid contact time. Although both systems have advantages, CFB advantages over bubbling beds are purported to be: (1) lower coal crushing costs, (2) simpler coal feed system, (3) higher $SO_2$ capture and combustion efficiency, and (4) less likelihood of heat exchanger tube erosion.

In the Foster Wheeler atmospheric circulating fluidized bed (ACFB) system, crushed coal (1/4") and powdered limestone are injected into the lower portion of the combustor and fluidized along with recirculated bed material by preheated primary air. Only 5 to 10 percent of the bed material is unreacted limestone and unburned coal. The large volume of recirculated material is used to control bed temperature. Sulfur in the form of $SO_2$ generated during combustion is captured by the limestone sorbent and ultimately removed with the ash. Secondary air is introduced in stages to mitigate $NO_x$ formation while ensuring complete combustion. The demonstration ACFB used twin combustion chambers each with a hot cyclone separator and return loop with U-shaped seal. The 925,000 lb/hr of steam was generated by wrap-around radiant superheaters in the upper furnace section and a heat exchanger downstream of the cyclones.

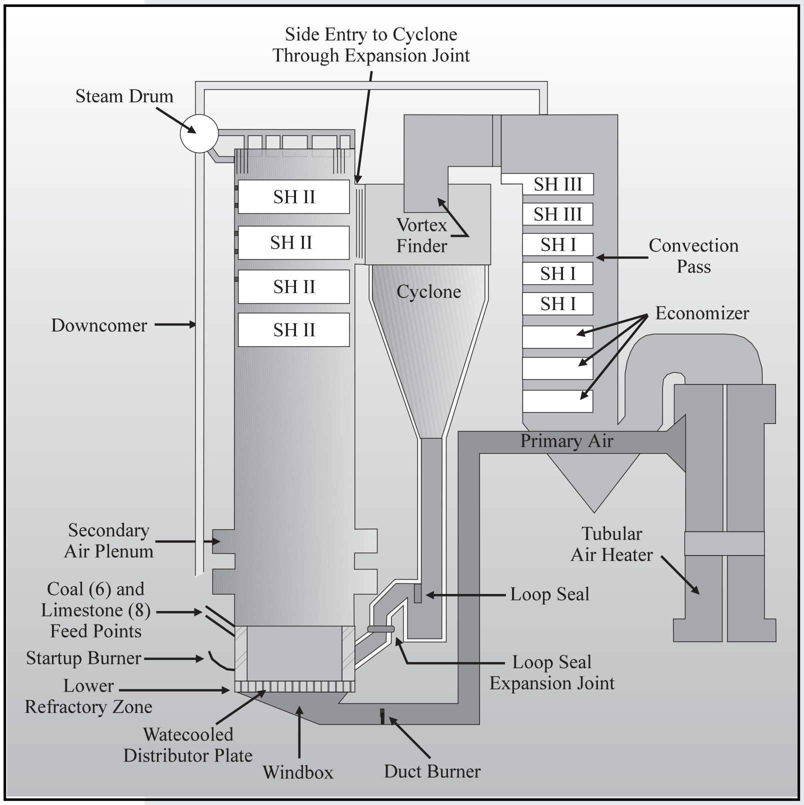
# Demonstration Results

- Bed temperature had the greatest effect on boiler efficiency and pollutant emissions.
- At bed temperatures below 1,620 °F, sulfur capture efficiencies of 70 and 95 percent were achieved at calcium to sulfur molar ratios (Ca/S) of 1.5 and 4.0 respectively.
- During all tests, $NO_x$ emissions averaged 0.18 lb/$10^6$ Btu and did not exceed 0.34 lbs/$10^6$ Btu.
- CO emissions varied between 70 and 140 ppmv.
- Particulate emissions ranged from 0.0072 to 0.0125 lb/$10^6$ Btu, corresponding to a removal efficiency of 99.9 percent.
- The solid waste was essentially benign and showed potential as an agricultural soil amendment, soil/road bed stabilizer, or landfill cap.
- Boiler efficiency ranged from 85.6 to 88.6 percent and combustion efficiency ranged from 96.9 to 98.9 percent.
- A 3:1 boiler turndown capability was demonstrated.
- Heat rate was 11,600 Btu/kWh at full load and 12,400 Btu/kWh at half load.
- The capital cost for the Nucla retrofit was $1,123/kW and operating costs averaged 64 mills/kWh

**Plant Layout with Coal and Limestone Feed Locations**




**Side view of CUEA's 110-MWe CFBC**



## Approach

The test program examined the effects of load, excess air, primary-to-secondary air ratios, unit operating temperature, coal and limestone feed configuration, and coal type and size distribution on unit operational, economic and environmental performance. Also assessed were boiler start-up and dynamic response characteristics, heat transfer in the combustion and air heater, and gas/solid mixing effectiveness in the combustor. Three western bituminous coals with varying sulfur and ash contents were used. Because of its relatively homogeneous nature, Salt Creek coal, with a sulfur and ash content of 0.5 and 17 percent respectively, served as the baseline coal (used in 62 of the 72 tests). Eight tests were run on local Peabody coal with a high variability in sulfur and ash (average 0.7 percent sulfur, 18 percent ash); and two tests were run on a Dorchester coal (1.5 percent sulfur, 23 percent ash). In addition, a comprehensive Environmental Monitoring Plan was developed and implemented as required by DOE to assess all relevant air, aqueous and solid waste emission and discharges.

## Operational Performance

Between July 1988 and January 1991, the plant operated with an average availability of 58 percent and an average capacity factor of 40 percent. (Industry averages for commercial operation are 83.9 percent availability and 49.7 percent capacity factor.) The lower values achieved during the demonstration were caused by both technical and financial factors. Nucla's availability and capacity factors were reduced by part-load testing and numerous outages attributed to "first-generation" ACFB equipment and component design. In addition, the utility was plagued by financial difficulties throughout the demonstration, which prevented it from making some of the capital improvements that could have enhanced the plant's reliability. However, toward the end of the demonstration, most of the technical problems had been overcome. During the last 3 months of the demonstration, average availability was 97 percent and the capacity factor, 66.5 percent.

The major contributors to ACFB related outages were: (1) secondary superheater tube erosion, (2) primary air fan upgrades 3) bubble cap replacement, (4) refractory damage, (5) tube erosion at refractory/waterwall interface (lower furnace), (6) bottom ash disposal system upgrade, (7) limestone feed system upgrade, and (8) limestone feed system modifications.

The secondary superheater tube erosion was corrected by addition of 6-inch shelves over the top row of one panel subjected to downward particulate flow. Upgrades to the primary air fan eventually proved to be adequate. Improvements were made to the bubble caps on the primary air injection nipples designed to prevent backsifting of bed material into the windbox. However, some backsifting persisted as did erosion at loop seal returns and ash cooler interfaces. Refractory failures were alleviated by improvements in refractory material (and installation procedures) and avoidance of severe thermal transients. Tube erosion at the refractory/waterwall interface was handled by periodic addition of welded hard facing. Enhancement of pneumatic transport capacity and addition of water sprays resolved the bottom ash handling problem. A series of modifications corrected the limestone handling system problems.

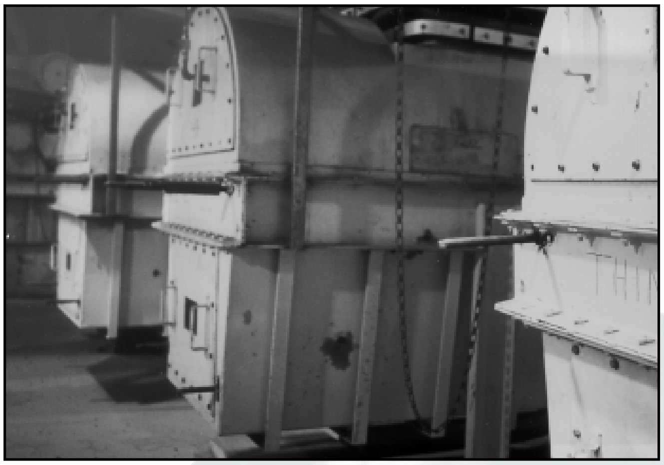
Controlling bed temperature remained a problem throughout the demonstration. This made parametric testing difficult, particularly in view of the fact that bed temperature was the most influential parameter on ACFB performance. Having twin beds with persistent temperature differentials exacerbated the problem. However, accommodations were made and all parametric testing was completed with the exception of evaluating the effect of sorbent and coal size on performance. The sorbent and coal feed systems simply would not provide the size ranges sought.

Combustion efficiency, a measure of the quantity of carbon that is fully oxidized to $CO_2$, ranged from 96.9 to 98.9 percent. Of the four exit sources of incompletely burned carbon, the largest was carbon contained in the fly ash (93 percent). The next largest (5 percent) was carbon contained in the bottom ash stream, and the remaining carbon loss (2 percent) was incompletely oxidized CO in the flue gas. The fourth possible source, hydrocarbons in the flue gas, was measured and found to be negligible.

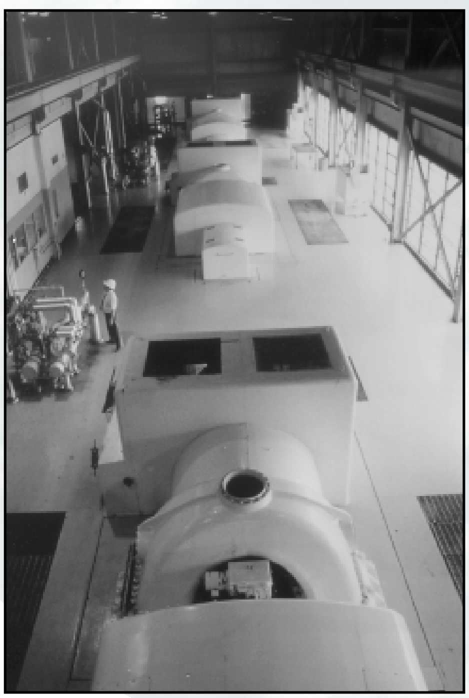
Boiler efficiencies for 68 performance tests varied from 85.6 to 88.6 percent. The contributions to boiler heat loss were identified as unburned carbon; sensible heat in dry flue gas; fuel and sorbent moisture; latent heat in burning hydrogen; sorbent calcination; radiation and convection; and bottom ash cooling water.

Net plant heat rate decreased with increasing boiler load, from 12,400 Btu/kWh at 50 percent of full load to 11,600 Btu/kWh at full load. The lowest value achieved during a full-load steady-state test was 10,980 Btu/kWh. These values were affected by the absence of reheat, the presence of the three older 12.5-MWe turbines in the overall steam cycle, the number of unit restarts, and part-load testing.

At the conclusion of the demonstration, the unit began commercial operation with an availability below industry standard. Using the experience and knowledge gained through the demonstration program, Tri-State successfully upgraded the plant. During a 3-month outage, the boiler was modified, the generator rewound, and about 150 other modifications were implemented to improve heat rate, overall efficiency, and reliability. Since the upgrades and repairs made during the 1993 outage, the unit experienced a major improvement in reliability. Over a 20-month period following the outage, average availability was 85 percent and the capacity factor, 77 percent.



**Three of six coal feeder units are shown here (three per combustion chamber)**



**Shown here are the three older 12.5-MWe turbines.**

## Key Operational Performance Results

- Boiler efficiency of 85.6–88.6%; contributions to boiler heat loss—
  - Unburned carbon
  - Sensible heat in dry flue gas
  - Fuel and sorbent moisture
  - Latent heat in burning hydrogen
  - Sorbent calcination
  - Radiation and convection
  - Bottom ash cooling water
- Combustion efficiency of 96.9–98.9%
  - Measured by quantity of carbon fully oxidized
  - Loss mechanisms—
    - Carbon carry-over in fly ash (93%)
    - Carbon contained in bottom ash (5%)
    - CO in flue gas (2%)
- Heat rate—
  - 11,600 Btu/kWh at 100% load
  - 12,400 Btu/kWh at 50% load
  - Lowest achieved was 10,980 Btu/kWh
  - Heat rate values affected by—
    - Absence of preheat
    - Use of 3 older 12.5-MWe turbines
    - Numerous restarts
    - Part-load testing

## Environmental Performance

***Sorbent Utilization.*** As indicated above, bed temperature had the greatest impact on ACFB performance, including pollutant emissions. *Figure 1* shows the effect of bed temperatures on the Ca/S requirement for 70 percent sulfur retention. Ca/S molar ratios were calculated based on the calcium content of the sorbent only and do not account for the calcium content of the coal. While a Ca/S of about 1.5 was sufficient to achieve 70 percent sulfur retention in the 1,500 °F to 1,620 °F range, the Ca/S requirement jumped to 5.0 or more at 1,700 °F or greater.

*Figure 2* shows the effect of Ca/S molar ratio on sulfur retention at average bed temperatures below 1,620 °F. Salt Creek and Peabody coals contain 0.5 and 0.7 percent sulfur, respectively. To achieve a 70 percent $SO_2$ reduction, a Ca/S molar ratio of approximately 1.5 was required. At full load, a 70 percent $SO_2$ reduction equates to an $SO_2$ emission rate of 0.26 lb/$10^6$ Btu with the baseline Salt Creek coal. To achieve an $SO_2$ reduction of 95 percent, a Ca/S molar ratio of approximately 4.0 was necessary. At full load, a 95 percent $SO_2$ reduction equates to an $SO_2$ emission rate of 0.05 lb/$10^6$ Btu with Salt Creek coal. Dorchester coal, averaging 1.5 percent sulfur content, required a somewhat lower Ca/S for a given retention.

Coal feed configuration had some effect on the Ca/S requirement at full load with the effect becoming more pronounced at elevated temperatures. A balanced coal feed (all coal injectors feeding at equal rates) yielded the lowest Ca/S requirements, suggesting additional coal feeders would enhance emission performance. The Nucla coal feed configuration used two injectors on the front wall and one on the rear wall for each combustion chamber.

Ca/S requirements were insensitive to limestone feed configuration. At bed temperatures below 1,680 °F, excess air did not appear to influence calcium requirements. Neither secondary air to primary air ratio (SA/PA) nor CO concentration had any effect on calcium requirements.

***$NO_x$ Emissions.*** $NO_x$ emissions measured throughout the demonstration were less than 0.34 lb/$10^6$ Btu, which is well below the regulated value of 0.5 lb/$10^6$ Btu. The average level of $NO_x$ emissions for all tests was 0.18 lb/$10^6$ Btu. $NO_x$ emissions indicate a relatively strong correlation with temperature, as shown in *Figure 3*, increasing from 40 ppmv (0.06 lb/$10^6$ Btu) at 1,425 °F to 240 ppmv (0.34 lb/$10^6$ Btu) at 1,700 °F.

**Figure 1. Effect of Bed Temperature on Ca/S Requirement**

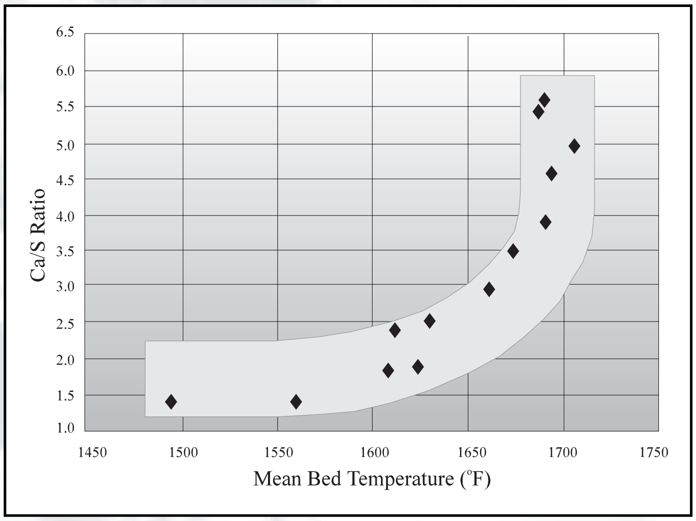



**Figure 2. Calcium Requirements and Sulfur Retentions for Various Fuels**

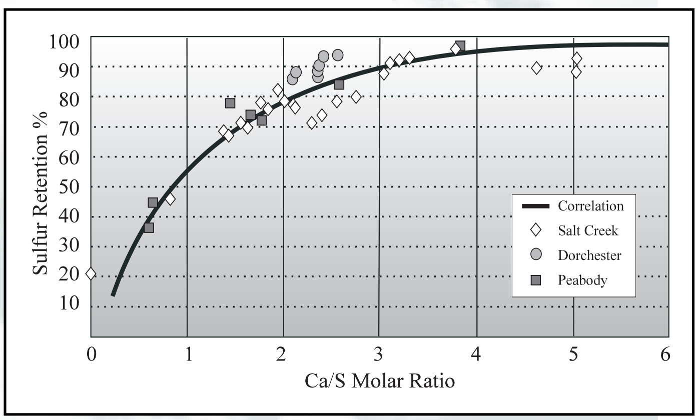
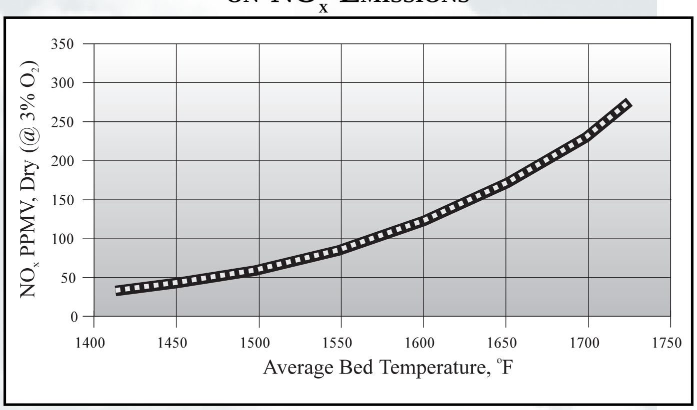


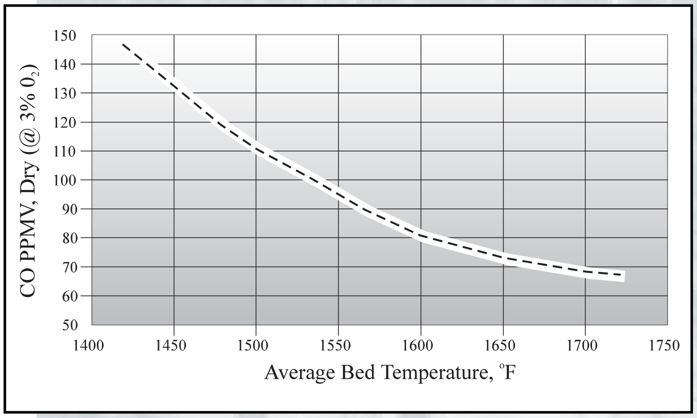

**Figure 3. Effect of Bed Temperature on $NO_x$ Emissions**



Limestone feed rate was also identified as a variable affecting $NO_x$ emissions, i.e., somewhat higher $NO_x$ emissions resulted from increasing calcium to nitrogen (Ca/N) molar ratios. The mechanism was believed to be oxidation of volatile nitrogen in the form of ammonia ($NH_3$) catalyzed by calcium oxide. Coal type also affected $NO_x$ emissions somewhat but was thought to be attributed largely to Ca/N. Coal feed configuration impacted on $NO_x$ emissions only as it impacted Ca/N. Excess air did not appear to have a significant effect on $NO_x$ emissions over the range tested. However, the range was somewhat limited. Limestone feed configuration, SA/PA ratio, and CO concentration were found to have no measurable effect on $NO_x$ emissions.

***CO Emissions.*** As shown in *Figure 4*, CO emissions decrease as temperature increases. Coal feed configuration and coal type had some effect on CO emissions. Excess air affected CO levels only slightly over the range tested. But data suggested that with low excess air values, CO levels would begin to increase. SA/PA ratios had no influence on CO emissions.

**Figure 4. Effect of Bed Temperature on CO Emissions**




***Particulate Emissions.*** At full load, the hot cyclones removed 99.8 percent of the particulate. The balance of particulate seen by the baghouse was an average 6.28 gr/std $ft^3$ for Peabody Coal and 8.85 gr/std $ft^3$ for Salt Creek Coal. Removal efficiencies achieved on Peabody and Salt Creek Coals were 99.905 and 99.959 percent respectively. This equated to emission levels of 0.0125 lb/$10^6$ Btu for Peabody coal and 0.0072 lb/$10^6$ Btu for Salt Creek coal, well below the required 0.03 lb/$10^6$ Btu. The mean median diameter of inlet particulate was 7.1 microns (as measured by BACHO analyzer) and 8.0 microns for the outlet particulate, indicating a higher collection efficiency on smaller particles. This was supported by finding that the Salt Creek coal ash had a smaller median mean diameter than the Peabody coal.

***Other Environmental Considerations.*** Unanticipated plant downtime prevented completion of the environmental characterization of trace metal, semi-volatile and volatile organic compound emissions. Aqueous discharge analyses are presented in reference 1, covering pH, total suspended solids, oil and grease, total copper, total iron, total chromium, total zinc and total dissolved solids. A special test was conducted to characterize the solid as applied to a landfill situation and the results are presented in reference 2.

ACFB solid waste has showed potential as an agricultural soil amendment, for use in stabilizing soils or roadbeds, or in capping landfills.

### Economic Performance

The final capital costs associated with the engineering, construction, and start-up of the Nucla ACFB system were \$112.3 million (construction started in November 1984 and was completed in May 1987). This represented a capital cost of \$1,123/net kW. Total power costs associated with plant operations between September 1988 and January 1991 were approximately \$54.7 million, resulting in a normalized cost of power production of 64 mills/kWh. The average monthly operating cost over this period was about \$1,888,000. Fixed costs represent about 62 percent of the total and include interest (47 percent), taxes (4.8 percent), depreciation (6.9 percent), and insurance (2.7 percent). Variable costs represent more than 38 percent of the power production costs and include fuel expenses (26.2 percent), non-fuel expenses (6.8 percent), and maintenance expenses (5.5 percent).

On average, 43 staff were required on site to operate the Nucla ACFB system during the demonstration project. Adjusting for the demonstration program would result in a staffing requirement of 41 under normal utility operating conditions.

**Shown here is the new stack required for the ACFB Unit.**

# Commercial Applications

### Commercial Configuration and Performance

Data from the Nucla demonstration confirms the predicted performance of ACFB and provides a basis for design of commercial ACFB power plants. DOE commissioned the design of a 400-MWe Reference Plant (greenfield, not retrofit) featuring mature ACFB technology based on Nucla project experience. A reasonable extension of state-of-the-art ACFB technology was assumed. The plant configuration chosen consisted of two 200-MWe ACFB combustors that supply steam to a 400-MWe turbine generator operating on a single reheat power cycle of 2,400 $lb/in^2$ (gauge) at 1,000 ºF. A summary of the performance of the Reference Plant follows:

- Operational performance (at 100 percent load)

– Net efficiency—34.4 percent (HHV)

– Net heat rate—9,930 Btu/kWh (HHV)

- Environmental performance

– $NO_x$ emissions—0.2–0.45 $lb/10^6$ Btu

– $SO_2$ reduction—92 percent at a Ca/S molar ratio of 2.5, or less than 0.371 $lb/10^6$ Btu

- Economic performance (30-yr plant life; 65 percent capacity factor; EPRI TAG methodology; 1991 constant dollars)

– Capital cost—\$1,380/kW

– Levelized busbar cost of electricity—85.1 mills/kWh

### Attributes

- All types of coal or coal wastes can be used, including high-ash coals, because ACFB is relatively insensitive to feedstock.
- No special feedstock-handling is needed other than the addition of limestone or other sorbent to the feeding system.
- The fluid-like motion of the solids in the combustion chamber promotes turbulent mixing that improves combustion efficiency and sulfur capture.
- The turbulent mixing permits combustion at substantially lower and more evenly distributed temperatures, thus reducing the formation of $NO_x$.

- Combustion occurs at temperatures below the ash melting point so that solids accumulation and boiler tube erosion and corrosion are minimized.
- Efficiencies comparable with conventional pulverized coal-fired plants without emissions controls can be achieved with normal heat recovery processes and the use of reasonably efficient steam turbines.
- Average availability and capacity factors for ACFB plants are now comparable to those of pulverized coal-fired plants with emissions controls.
- The wastes generated are dry, benign solids that can be disposed of easily or usefully employed.

## Market Applications

Nucla continues in commercial service. Today, every major boiler manufacturer offers an ACFB system in its utility product line. After the demonstration, commercial sales of units greater than 100 MWe had reached 29 by the end of 1998, representing 6.2 gigawatts of capacity and nearly $6 billion. The fuel flexibility and ease of operation make it a particularly attractive power generation option for the burgeoning power market in developing countries.

**Shown here are the bed ash (foreground) and flyash (background) silos.**

## CONTACTS

Stuart Bush
(303) 452-6111
(303) 254-6066 (Fax)
Tri-State Generation and Transmission Association, Inc.
P.O. Box 1149
Montrose, CO 81402

George Lynch
DOE/HQ, (301) 903-9434
Nelson F. Rekos
FETC, (304) 285-4066

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U.S. Department of Energy

Assistant Secretary for Fossil Energy

Washington, DC 20585