Demonstration of Innovative Applications of Technology for the CT-121 FGD Process
A DOE Assessment

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Executive Summary

The U.S. Department of Energy's (DOE) Clean Coal Technology (CCT) Program seeks to furnish the energy marketplace with more efficient and environmentally benign coal utilization technologies through demonstration projects. This document is a post-project assessment (PPA) of one of the demonstration projects selected in Round II of the CCT Program, "Demonstration of Innovative Applications of Technology for the CT-121 FGD Process."

In April 1990, Southern Company Services, Inc. (SCS) entered into a cooperative agreement with DOE to demonstrate Chiyoda Corporation's Thoroughbred-121 (CT-121) advanced flue-gas desulfurization (FGD) process. The project was sited at Georgia Power Company's Plant Yates, located near Newnan, Georgia. Plant Yates consists of seven units with total nameplate generating capacity of about 1,250 MWe. The CCT demonstration project was installed on the entire flue-gas flow from Unit 1, a 110-MWe, pulverized-coal-fired boiler. The purpose of this project was to demonstrate innovative improvements to CT-121's Jet Bubbling Reactor® (JBR) designed to significantly reduce capital and operating costs, while producing an easily disposable by-product that might have beneficial uses. DOE provided 49 percent of the $43.1 million total project funding.

The objectives of this project, as stated in the cooperative agreement, were to demonstrate the following:

- Modifications to the CT-121 process would significantly reduce FGD capital and operating costs.
- A full-scale CT-121 system could meet New Source Performance Standards (NSPS) for Sulfur dioxide (SO_2) control.
- CT-121 operating costs were the lowest of current state-of-the-art FGD systems.
- The by-product gypsum/fly-ash could be readily stored/disposed of in an environmentally safe way, including beneficial uses.

Thus, the goal was to demonstrate that the CT-121 FGD scrubber was one of the most efficient and cost-effective scrubbers for reducing SO_2 and particulate emissions from coal-fired power plants. Principal team members included SCS as project manager; Georgia Power Company as host site provider; and the Electric Power Research Institute (EPRI), co-funder. Consulting team members consisted of Radian Corporation, environmental and analytical consultant; Ershigs, Inc., fiberglass fabricator; Composite Construction and Equipment, fiberglass sustainment; Acentech (formerly Dynatech), flow modeling; Ardaman, gypsum stacking; University of Georgia Research Foundation, by-product utilization studies; and the Southern Research Institute (SRI), particulate measurements and air toxics testing.

Primary equipment for the demonstration project included an existing electrostatic precipitator (ESP) to remove particulates from the flue gas, the CT-121 scrubber to desulfurize the flue gas, and facilities for limestone, gypsum, water and treated-flue-gas handling. The CT-121 FGD process uses a novel Jet Bubbling Reactor® to contact flue gas with a limestone slurry to convert the SO_2 it contains into gypsum. Some of the testing was completed with the ESP system de-energized, to measure the CT-121 JBR's particulate removal capabilities.

In normal operation, flue gas passes through the ESP and enters the JBR gas cooling section, where it is cooled by a spray of recycle water and then completely saturated by contact with slurry recycled from the JBR. The flue gas then enters an enclosed chamber, where it is forced through sparger tubes, bubbling beneath the surface of the gypsum/limestone slurry contained in the bottom of the JBR vessel. After bubbling through the slurry, the scrubbed gas flows upward through gas risers into an upper plenum, where it exits the JBR through a horizontal mist eliminator and then passes to a wet chimney. The demonstration project did not have bypass capability; therefore, the CT-121 unit had to be on stream when the boiler was in operation.

Sulfur-dioxide absorption, acid neutralization, oxidation of sulfite to sulfate, and sulfate crystal growth occur in the slurry in the JBR. The JBR reaction zone provides a large surface area for mass transfer of SO_2 and particulates from the flue gas to the slurry; pH is controlled by the amount of limestone fed. Some of the oxygen required to oxidize sulfite to sulfate comes from the flue gas, but most of it comes from air bubbled into the reaction zone. Solids level in the JBR is maintained by removing a slipstream from the reaction zone; this stream is pumped to a transfer tank and then to the gypsum stack.

Two gypsum dewatering and storage stacks were effectively used to manage water so that there was no wastewater that required disposal. Gypsum produced during the demonstration project was wallboard grade, except during tests conducted with the ESP out of service.

A series of short and long term tests was run to evaluate the operability and reliability of the CT-121 FGD unit and to determine the effect of changes in process variables on system performance. During these tests, boiler load was allowed to follow demand to permit evaluation of process stability and to monitor process response to transients over an extended time period. Tests were run with both low and high flue-gas particulate loading to evaluate the ability of the CT-121 unit to simultaneously remove SO_2 and particulates.

During the 19,000-hour demonstration period, the CT-121 scrubber was in operation 73 percent of the time. Most of the downtime was the result of the boiler being down, and only 654 downtime hours (3 percent of the total demonstration period) were due to problems with the scrubber. Problems encountered during low-particulate operation were relatively minor, with somewhat poorer performance for operations with a high-particulate loading.

The JBR was designed to handle flue gas from coal with a maximum sulfur content of 3 percent and a nominal sulfur content of 2.5 percent. However, even at sulfur levels as high as 4.5 percent, 90-percent desulfurization was achieved by a proper choice of operating conditions, illustrating the flexibility of the system.

Sulfur dioxide removal efficiency is a function of slurry pH, pressure drop across the JBR, SO_2 concentration in the inlet flue gas, and boiler load. The main operational parameters are pH and ΔP, with the most important variable being JBR ΔP. In addition to removing SO_2, the JBR can act as a particulate removal device. For low-particulate loading at the JBR inlet (the normal situation with only fugitive ash escaping a fully energized ESP), fly-ash removal efficiency was in the neighborhood of 90 percent, except for low-load (50-MWe) operation, where efficiency dropped to about 70 percent. At higher particulate loadings, removal percentages increased dramatically.

While process performance exceeded expectations and most of the innovations included in the design of the Yates CT-121 installation worked as intended and significantly improved performance, some areas needing improvement were discovered during this project. Although the fiberglass reinforced plastic (FRP) proved to be essentially impervious to corrosion, there were areas where it was not sufficiently erosion resistant. During the course of the project, an erosion resistant coating (Duromix™) was applied to regions where erosion was a problem and worked very well. Other recommended design changes include moving the gas cooling section farther upstream, adding suction screens to the slurry pumps in the JBR, and mounting the sparger tubes so that their tops are flush with the deck surface to prevent buildup of deposits.

The CT-121 FGD Process was designed to comply with all applicable federal, state, and local environmental regulations. The operation of this CCT demonstration project did not increase the volume nor change the composition of any air, water, or solid waste emissions. No problem areas were identified concerning environmental regulations or permit conditions, nor were any toxic pollutants generated due to operation of the CT-121 Project.

The CT-121 process is an effective combined SO_2 and particulate removal system. When high-sulfur coal was burned at maximum boiler load, the CT-121 scrubber exceeded the target 90-percent SO_2 removal efficiency with limestone utilization over 97 percent. The JBR achieved particulate removal efficiencies of 97.7 percent over a load range of 50 to 100 MWe. NO_x emissions were unchanged as a result of the project.

The innovative CT-121 FGD Process, featuring state-of-the-art designs and materials of construction, is a significant improvement over 1970s wet scrubber technology. The JBR eliminates waste-disposal problems by incorporating oxidation of the calcium-sulfite sludge to wallboard-quality gypsum. Large, easily dewatered, gypsum crystals were consistently produced and successfully stacked on site during the project. Gypsum by-product was also used as a soil amendment and received a plant-food license from the State of Georgia.

Because the CT-121 scrubber operates on the flue-gas stream after it leaves the boiler, it is applicable to virtually any type of boiler burning any sulfur-containing fuel (coal, petroleum coke, or fuel oil). The only limitation is that there must be a supply of limestone within economic transport range, and there must be a market for the gypsum or a suitable landfill area nearby. It is difficult to judge the total potential market, because most power plants have already addressed the SO_2 mitigation problem and have either installed scrubbers or switched to low-sulfur fuel, thus reducing the retrofit market. However, its compact design and flexibility should make the CT-121 FDG Process a good candidate for new units.

The capital requirement of the CT-121 unit at Plant Yates was about $255/kW to treat the flue gas from a 110-MWe unit. Allowing for reduced costs as a result of lessons learned from this

CCT project and for economies of scale for installation on larger units, the Participant estimates that the capital cost of the CT-121 process could be \$150/kW or less (1994 dollars). Fixed operation and maintenance (O&M) costs for operation of the JBR at Plant Yates were about \$866,000/yr (1994 dollars). During the test program, this plant required one operator per shift on an around the clock coverage basis. The only variable costs are for electric power and limestone.

Using the capital costs from this project, economic analysis of the CT-121 process (for a 100-MWe plant, 65-percent operating factor) indicates that the CT-121 scrubber adds about 11 mills in current dollars (8 mills in constant dollars) to the cost of a kWh of electricity. On a sulfur-removal basis, the cost is \$582 (current dollars) or \$449 (constant dollars) per ton of SO_2 recovered. These costs compare favorably with costs of other scrubber systems.

These economics are based on results from the Yates CT-121 demonstration installation, since these are the only data available in the final report. These costs are probably higher than costs for a regular operating plant, because of the additional costs of testing, extra instrumentation, data analysis, and other costs related to the CCT project.

If the Participant's estimated capital cost of \$150/kW (\$15 million for a 100-MWe plant) is used, then the cost of the CT-121 process drops to 7.2 mills/kWh (current dollars) and 5.6 mills/kWh (constant dollars). On a pollutant removal basis, costs are \$386/ton of SO_2 recovered, in current dollars (\$297/ton of SO_2 recovered, in constant dollars).

During two years of testing, the CT-121 FGD process performed very well, removing both SO_2 and particulates from the flue gas with efficiencies of 90 percent or better at a variety of operating conditions. The process proved to be reliable and responsive and was able to maintain efficiency while the plant operated in a load-following mode. Specific conclusions are:

- Almost any SO_2 removal level within the design capabilities of the unit can be achieved by adjusting the pH and the pressure differential across the JBR.

- The CT-121 process has proven to be easy to operate and highly reliable, with limestone utilization typically 98 percent or greater.

- The wet chimney proved to be very successful and operated without the need for reheat.

- The FRP proved to be completely impervious to corrosion, being unaffected by the acidic slurry or its high chloride concentration. Erosion was observed at several points in the reactor, but design modifications should obviate this problem in future plants.

I Introduction

The goal of the U.S. Department of Energy's (DOE) Clean Coal Technology (CCT) program is to furnish the energy marketplace with a number of advanced, more efficient, and environmentally responsible coal-utilization technologies through demonstration projects. These projects seek to establish the commercial feasibility of the most promising advanced coal technologies that have developed beyond the proof-of-concept stage.

This document serves as a DOE post-project assessment (PPA) of a project selected in CCT Round II, "Demonstration of Innovative Applications of Technology for the CT-121 FGD Process," as described in a Report to Congress (U.S. Department of Energy 1990). The desire to reduce emissions of sulfur dioxide (SO_2) from a pulverized-coal-fired boiler by 90 percent at a minimum capital expenditure, while producing a usable by-product, prompted Southern Company Services, Inc. (SCS) to submit the proposal for this project. In April 1990, SCS entered into a cooperative agreement with DOE to conduct the study. The project was sited at Georgia Power Company's Plant Yates, located near Newnan, Georgia. The purpose of this CCT project was to demonstrate the reduction of SO_2 emissions by installing Chiyoda Corporation's Thoroughbred-121 (CT-121) advanced flue-gas desulfurization (FGD) process. (See Figure 1.) This process uses a novel Jet Bubbling Reactor® (JBR) to put flue gas in contact with a limestone slurry to convert the SO_2 in the flue gas into gypsum. DOE provided 49 percent of the $43.1 million total project funding.

Plant Yates consists of seven units with total nameplate generating capacity of about 1,250 MWe. The CCT demonstration project was installed on Unit 1, a 110-MWe, pulverized-coal-fired boiler. Construction for the demonstration project was started in August 1990 and completed in October 1992. Test operations were initiated in October 1992 and completed in December 1994. Although the CCT project concluded in December 1994, the Yates CT-121 desulfurization system continues to operate routinely on Plant Yates Unit 1. The independent evaluation contained herein is based primarily on information from the SCS Final Report (Southern Company Services, Inc. 1997), as well as other references cited.

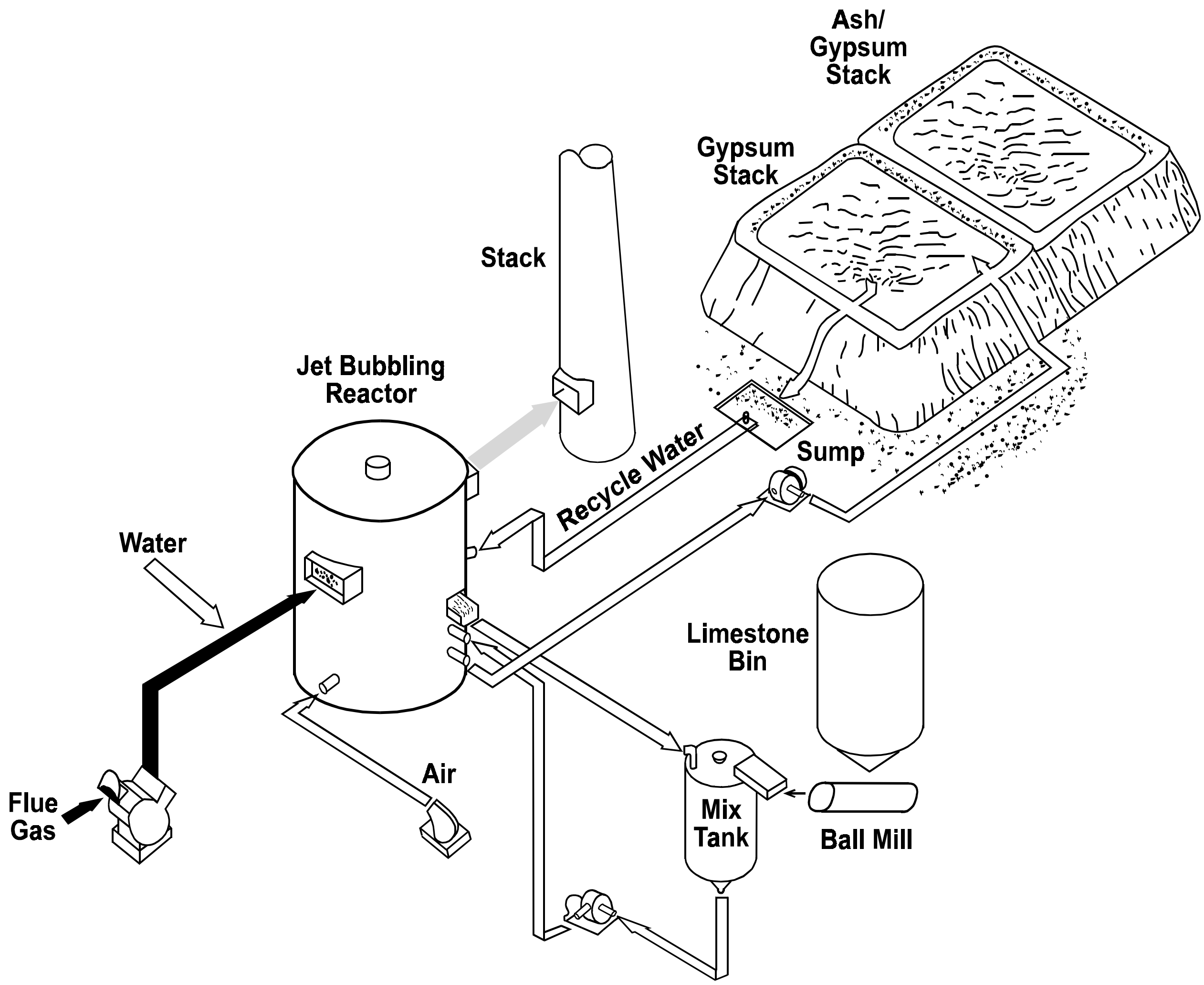

Figure 1. Schematic of CT-121 Installation

II Project/Process Description

II.A Promise of the Technology

The promise of this project was to demonstrate innovative improvements to an existing wet limestone SO_2 scrubbing system, the Chiyoda Thoroughbred-121 (CT-121) Jet Bubbling Reactor® (JBR). This technology is owned by Chiyoda Corporation of Japan. The purpose of the improvements was to significantly reduce capital and operating costs, while producing an easily disposable by-product having potentially beneficial uses.

II.B Project Description

The CT-121 demonstration project was hosted by Georgia Power Company at its Plant Yates site, located about 40 miles southwest of Atlanta, near Newnan, Georgia. Plant Yates consists of seven pulverized-coal-fired units. Units 1 to 5, built in the early 1950's, are housed in a single building and have a combined nameplate capacity of 550 MWe. The flue gas from these units is vented through a two-flue common 825-ft stack. These units use once-through cooling water from the Chattahoochee River and are operated on an intermediate load basis. Units 6 and 7, built in the mid-1970s, are contained in a second building and have a combined nameplate capacity of 700 MWe. The flue gas from these units is vented through a two-flue 800-ft stack. These newer units function on a base-load basis, and each has a cooling tower. All seven Yates units use electrostatic precipitators (ESP) for particulate control. Small quantities of dry fly ash are collected for sale, but the majority of the collected ash is wet-sluiced to disposal ponds.

The CT-121 FGD process was installed to treat the flue gas from Unit 1. All of the flue gas from Unit 1 flows through the JBR, with no bypass provided. Thus, the CT-121 unit must be in operation when the boiler is operating. Treated flue gas from the scrubber is vented through a new wet chimney.

SCS provided the project management and Georgia Power Company provided the host site. Other project team members included the Electric Power Research Institute (EPRI), co-funder; Radian Corporation, environmental and analytical consultant; Ershigs, Inc., fiberglass fabricator; Composite Construction and Equipment, fiberglass sustainment consultant; Acentech (formerly Dynatech), flow modeling consultant; Ardaman, gypsum stacking consultant; and the University of Georgia Research Foundation, by-product utilization studies consultant. Southern Research Institute (SRI) assisted with particulate measurements and air-toxics testing.

II.C Technology Description

The following sections describe the basic facilities involved in this demonstration project, which included the existing ESP, the CT-121 scrubber, and the limestone and gypsum handling facilities. Figure 2 presents a schematic of the CT-121 project showing the primary equipment.

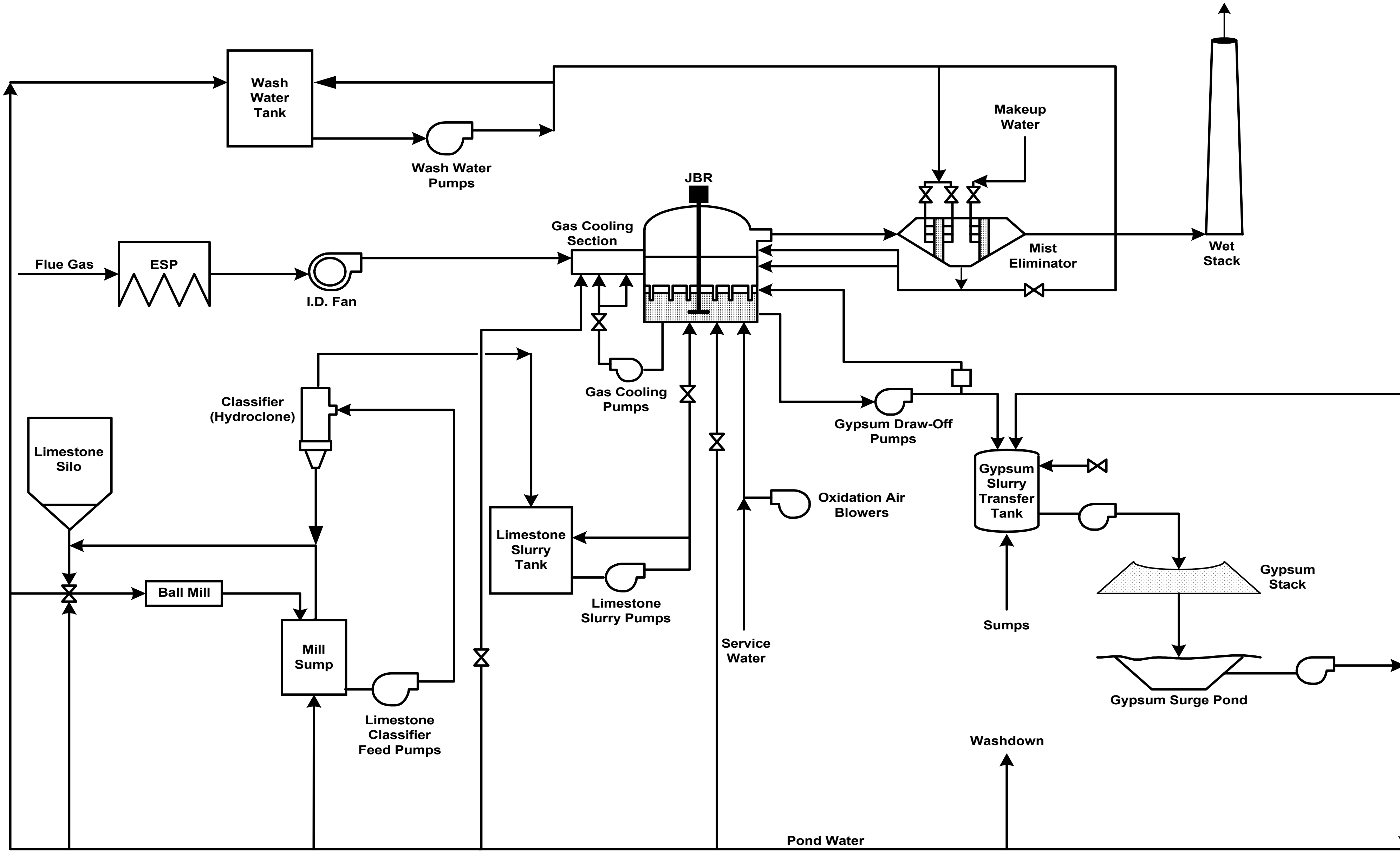

Figure 2. Schematic of the CT-121 CCT Project

II.C.1 Electrostatic Precipitator

Flue gas from Unit 1 passes through an ESP for particulate removal before being sent to the CT-121 scrubber. The ESP has three fields (see Figure 3), powered by four electrical cabinets. One of the variables studied during this demonstration project was the particulate loading in the flue gas to the scrubber. For low-particulate loading in the flue gas, the ESP was operated normally, but for medium- or high-particulate loading, individual cabinets were partially or fully de-energized to achieve the target ash level. Selectively de-energizing fields allowed ash to escape the ESP and flow through to the JBR.

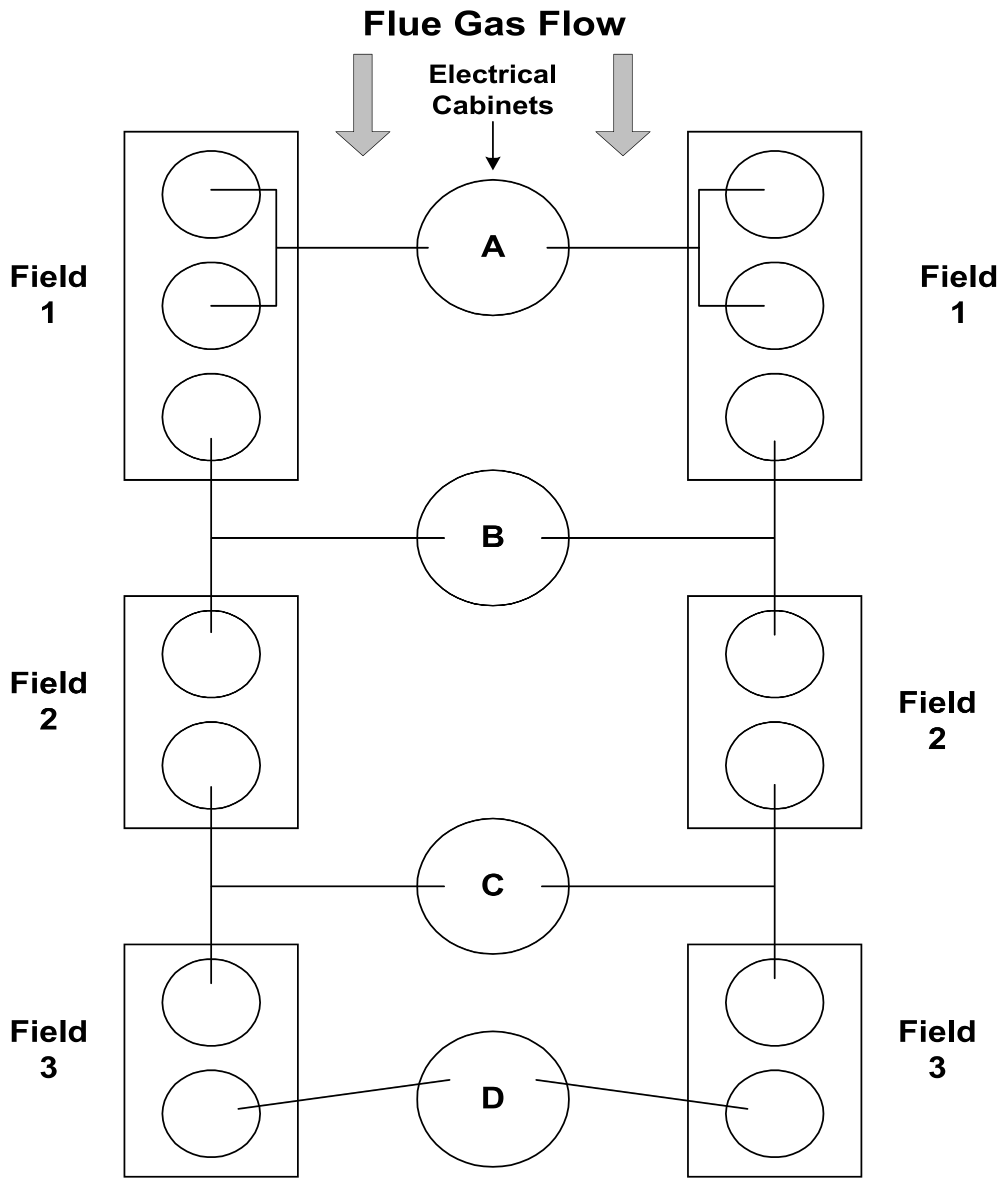

Figure 3. Plant Yates Unit 1 ESP Configuration

II.C.2 Flue-Gas Cooling System

Flue gas from the ESP flows to the single-boiler induced-draft/scrubber booster fan, which provides the pressure required for the gas to flow through the remainder of the CT-121 system. From the fan, the flue gas enters the gas cooling section (transition duct), where the gas is cooled by a spray of water from the recycle water pond at an injection rate of 0.25 gal/1000 acf of flue gas. Following the water spray, the flue gas is completely saturated with water by contact with slurry recycled from the JBR. Two pumps spray the slurry into the gas at a rate of approximately 10 gal/1000 acf. The suction for these pumps is located near the bottom of the JBR, and screens are provided to prevent solid material from entering the pump and plugging the spray nozzles. Saturating the flue gas before it enters the JBR prevents dry surfaces from occurring in the JBR with resultant deposit formation.

II.C.3 CT-121 Wet FGD System

Flue gas leaving the cooling section flows to the JBR (see Figures 4 and 5), which is the heart of the CT-121 process. The gas enters an enclosed chamber, formed by upper and lower deck plates. The flue gas is forced downward through sparger tubes mounted in the lower deck plate into the slurry contained in the bottom of the JBR vessel, exiting below the surface of the slurry reservoir. After bubbling through the slurry, the cleaned gas flows upward through gas risers that connect the lower and upper deck plates. Due to a dramatic velocity reduction, entrained slurry droplets disengage in the plenum above the upper deck plate, and the cleaned gas flows to the mist eliminator.

Two distinct zones exist in the JBR slurry phase: the jet bubbling (froth) zone near the surface at the exit level of the spargers and the reaction zone, which is the bulk of the slurry below the jet bubbling zone in the JBR. Sulfur dioxide absorption occurs in the froth zone, while neutralization, sulfite oxidation, and crystal growth occur in both the froth and reaction zones. Froth is produced by the untreated gas accelerating through hundreds of sparger tubes and bubbling beneath the surface of the slurry to a depth of 8 to 20 inches. The froth-zone depth depends upon the length of the sparger tubes, the slurry level in the JBR and the velocity of the gas through the spargers.

The bubbles rising through the froth zone provide a large surface area for mass transfer of SO_2 and particulates from the flue gas to the slurry. Changing the JBR slurry level, which changes the flue-gas injection depth, varies the amount of interfacial area. As gas injection depth is increased, both the interfacial area for mass transfer and the gas/slurry contact time are increased. Both these effects increase SO_2 removal.

Pressure drop across the JBR is the primary control variable used to adjust SO_2 removal to the desired level. The gas side pressure differential between the inlet and outlet plenums is composed of two components, static head and dynamic head. The JBR slurry level determines the static head, and the velocity of the gas flowing through the sparger tubes and risers generates the dynamic head. Thus, increasing the slurry level in the JBR increases both pressure drop and SO_2 removal.

Some of the oxygen necessary to convert calcium sulfite to calcium sulfate comes from oxygen in the flue gas, but most of it comes from air bubbled into the JBR reaction zone. Air from the blowers, saturated with water to prevent a wet/dry interface, is introduced near the bottom of the JBR. The air forms bubbles that rise and mix with the flue-gas bubbles in the slurry reservoir.

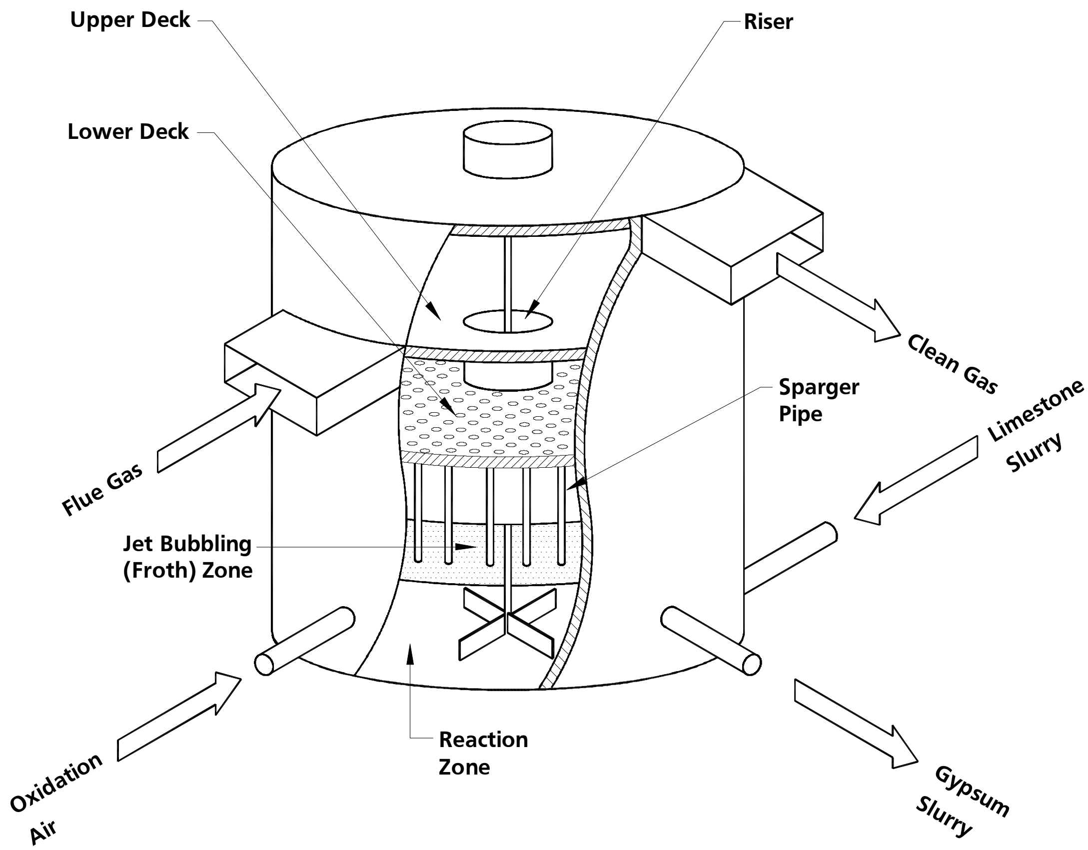

Figure 4. Simplified Schematic View of Jet Bubbling Reactor

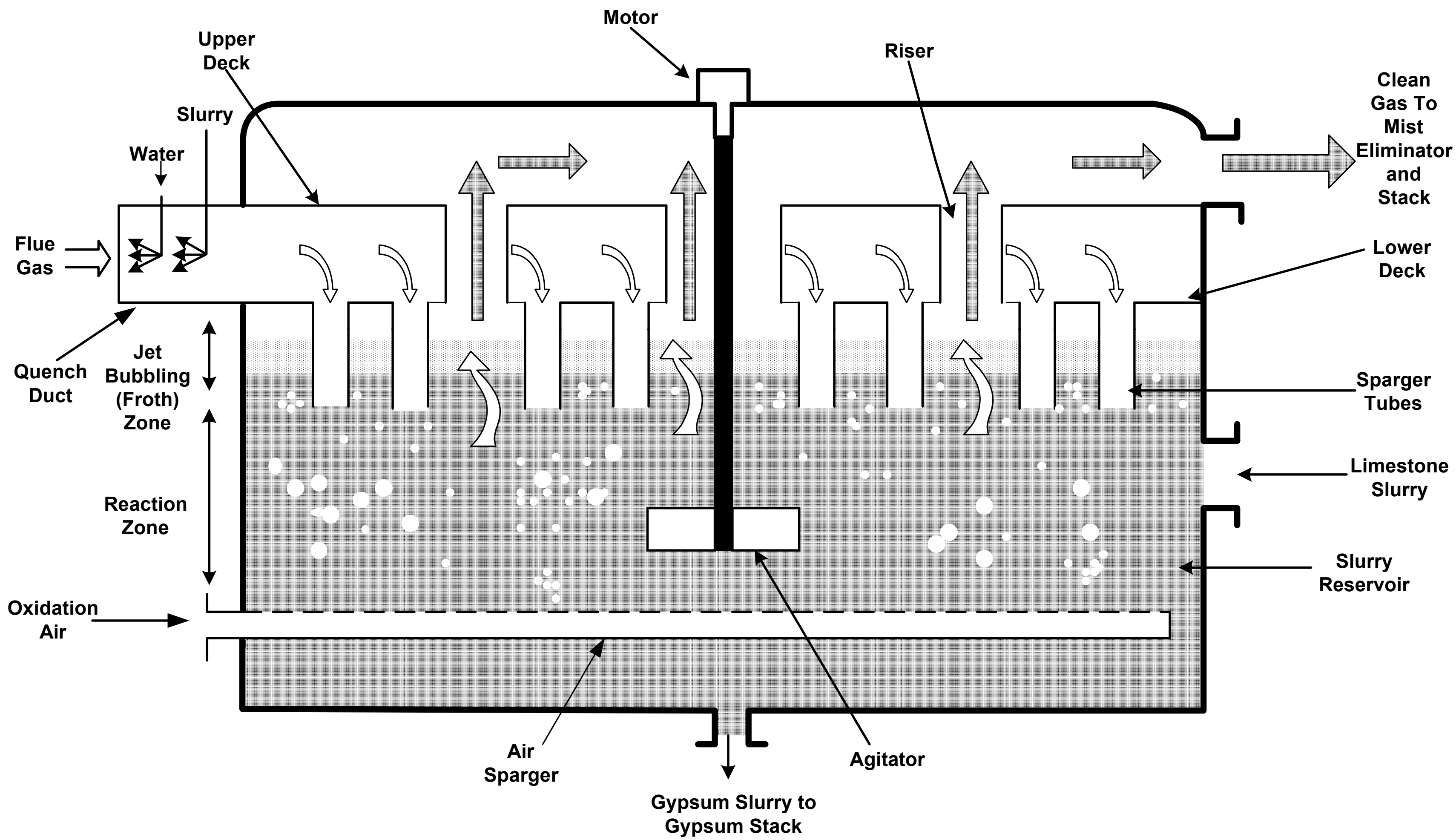

Figure 5. Cross Section View of Jet Bubbling Reactor

SO_2 removal can also be increased by raising the pH of the slurry in the froth zone. A higher pH results in higher slurry alkalinity and more rapid neutralization of the absorbed SO_2. (However, this is true only up to a point, as other issues, discussed below, come into effect.) The pH can be controlled by the amount of limestone fed to the JBR reaction zone. An increased limestone feed rate increases the pH in both the reaction and froth zones. Limestone feed rate can be controlled either by "feed-forward" pH trim or by direct pH feedback. Feed-forward control is accomplished by setting the limestone feed rate based on the SO_2 content and flow rate of the flue gas to the JBR. Feedback control is achieved by setting the limestone feed rate based solely on the JBR slurry pH. Feed-forward control can provide smoother operation, but its implementation requires development of a process model based on data gathered over a range of operating conditions.

Solids concentration in the JBR is maintained by continuously removing a slipstream of slurry from the bottom of the reaction zone and pumping it to a gypsum slurry transfer tank, where it is diluted with pond water before being pumped to the gypsum stack. The density of the slipstream is used to determine the limestone slurry flow-rate required to maintain a constant JBR solids concentration. When slurry is drawn off for solids concentration control, water is added to maintain the JBR level. Water is also added to the JBR during deck washing and mist eliminator washing. To maintain a solids balance, solids must be drawn off at a rate equal to the rate at which they are produced. When burning low-sulfur coal, SO_2 adsorption is decreased and less gypsum is produced; however, the amount of water added is not similarly decreased. Therefore, a lower equilibrium solids concentration is dictated by low-sulfur coals. During the course of the demonstration project, solids content was typically 22 to 24 percent but dropped as low as 15 percent when low-sulfur coal was used.

The chemical reactions occurring in the JBR are:

$$SO_2 + CaCO_3 \text{----->} CaSO_3 + CO_2 \tag{1}$$

$$CaSO_3 + \tfrac{1}{2}O_2 \text{----->} CaSO_4 \tag{2}$$

$$CaSO_4 + 2H_2O \text{----->} CaSO_4 \bullet 2H_2O \tag{3}$$

II.C.4 Mist Eliminator and Wet Chimney

From the plenum above the upper deck plate, the scrubbed flue gas passes through a horizontal mist eliminator. (See Figure 6.) The mist eliminator is a horizontal-gas-flow, two-stage chevron design. During the demonstration project, gypsum pond return water was used to wash the upstream and downstream faces of the first stage for one minute every eight hours. This frequency was increased (doubled) during the course of the project. The upstream face of the second stage was washed with make-up water for one minute every 24 hours, while the downstream face of the second stage was not washed.

From the mist eliminator, the flue gas passes to a wet chimney. Since the gas enters the chimney saturated with water, any heat loss results in gas cooling and, thus, condensation downstream. Preconstruction flow modeling on a scale model of the Yates unit indicated that, to prevent carryover of condensed water droplets, an impact structure and a system of gutters should be attached to the inside of the chimney to collect and return condensate directly back to the JBR by gravity flow. Fiberglass reinforced plastic (FRP) grating sections in the elbow of the chimney provide the impact structure dead zone in the gas path. This dead zone allows collected condensate to drain to the JBR without being re-entrained in the flue-gas stream.

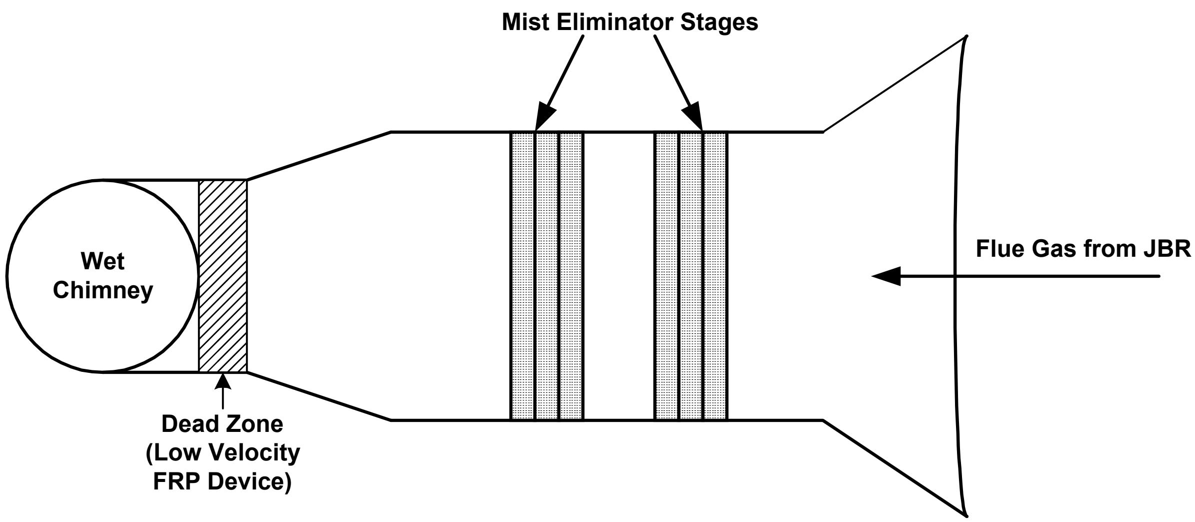

Figure 6. Mist Eliminator

II.C.5 Limestone Preparation Circuit

Limestone (3/4 inch by 0 size range) is delivered by truck and moved by front-end loaders and a conveyor to a day silo from which it is fed to a wet ball mill, along with gypsum pond water and recycled limestone slurry. First-run slurry from the mill is held in a mill sump tank. Slurry from the mill sump tank is pumped to a hydroclone, where the coarse and fine limestone particles are separated. The fine limestone stream is sent directly to the limestone-slurry storage tank, while coarse material is either returned to the mill inlet for regrinding or recycled to the mill sump. From the storage tank, the limestone slurry is pumped to the JBR as required to maintain the reservoir pH. The target limestone grind size for the demonstration project was 90 percent through 200 mesh, but other grind sizes were also tested, as were limestones from several sources.

II.C.6 Gypsum Stack

Figure 7 shows a schematic of the gypsum stacking area consisting of two gypsum by-product dewatering and storage stacks and a recycle water pond. During the low-particulate test period, the slurry from the gypsum-slurry transfer tank was sent to the smaller of the two stacks (the gypsum stack). During the high-particulate test period, a larger gypsum/fly ash stack was placed into service. The gypsum/fly ash stack had to be larger because it had to dewater and store gypsum by-product with a high ash content (a larger volume than the relatively pure gypsum in the gypsum stack). Dewatering relied on sedimentation by gravity.

The stacking technique involves filling a diked area with slurry and allowing the water to drain. The filled area is then partially excavated, with the excavated material used to increase the height of the containment dikes. The process of sedimentation, excavation, and raising the height of the perimeter dikes continues on a regular basis during the active life of the stack. Process water is decanted, stored in the gypsum recycle-water pond, and then returned to the process as described below. The entire stack area was underlaid with a 60-mil polypropylene liner with heat-sealed seams.

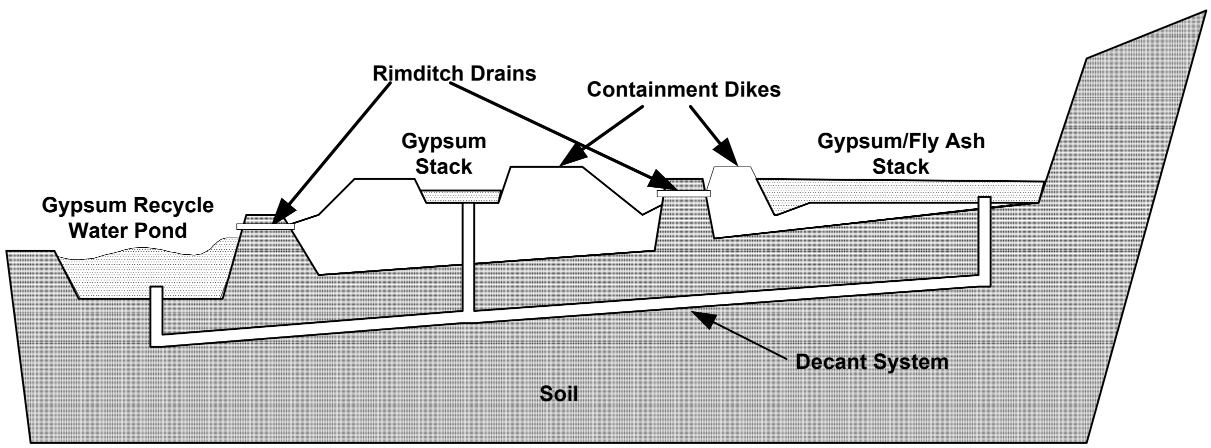

Figure 7. Schematic of the Gypsum Stacking Area

II.C.7 Water Management

In this project, water was managed in a way that required no wastewater disposal. The main reservoir for water was the gypsum water pond, shown in Figure 7. Pond water was reused in the CT-121 process for several purposes including recycle to the JBR, cooling the flue gas in the gas cooling section, providing water to the limestone slurry preparation area and providing wash water to clean the mist eliminators. Makeup water was used to clean one of the surfaces of the mist eliminator and as little as possible was added to the JBR along with the oxidation air.

II.D Project Objectives and Statement of Work

The objectives of this project, as stated in the cooperative agreement, were to demonstrate the following:

- Four modifications to the CT-121 process would significantly reduce capital and/or operating costs. They are (1) use of FRP for construction of the scrubber to replace more costly alloys; (2) elimination of a spare scrubber; (3) elimination of reheating of the scrubbed flue gas by modifications to the ductwork and stack; and (4) achieving both SO_2 and particulate control in a single unit, thus eliminating the need for a separate particulate control device.

- A full-scale CT-121 system could meet New Source Performance Standards (NSPS) for SO_2 control (90 percent removal on a rolling 30-day average basis).

- CT-121 operating costs could be the lowest of current state-of-the-art FGD systems.

- The gypsum/fly-ash by-product could be readily stored/disposed of in an environmentally safe way, and several options could be found for beneficial use of this by-product.

Thus, the goal of this project was to demonstrate, that the CT-121 FGD scrubber was one of the most efficient and cost effective scrubbers for reducing SO_2 and particulate emissions from coal-fired power plants. The project was designed to confirm performance of the novel aspects of the project and to develop correlations permitting computer-based control of the system.

The Cooperative Agreement states that the Participant is responsible for all aspects of project performance. The project was conducted in three phases: Phase I—Permitting and Preliminary Engineering; Phase II—Detailed Design, Construction, and Startup; and Phase III—Operation, Testing, and Disposition. This post-project assessment is concerned mainly with Phase III and deals only minimally with Phases I and II. However, one important aspect of Phase II was the development of a test plan to ensure that all necessary data were generated to allow a full evaluation of the cost-reduction design features. The test plan was to specify operating conditions for the following four test periods:

- Test Period 1 ─ Low fly-ash loading, precooler in service.
- Test Period 2 ─ Low fly-ash loading, precooler bypassed.
- Test Period 3 ─ High fly-ash loading, precooler in service.
- Test Period 4 ─ High fly-ash loading, precooler bypassed.

Although the Cooperative Agreement mentions that tests would be done with the precooler in service, as well as bypassed, the precooler was eliminated as a process improvement to save capital and operating costs, and the test plan was modified to eliminate references to the precooler.

The Statement of Work for Phase III required the Participant to do the following:

- Operate and maintain the CT-121 process during the demonstration project.
- Be responsible for performing all aspects of the CT-121 process evaluation, including evaluation of the following specific areas: (1) process chemistry, (2) SO_2 removal performance, (3) particulate control performance, (4) reliability, (5) corrosion of alloys, (6) FRP performance, and (7) the no-flue-gas-reheat operation.

- Conduct an extensive solid by-product disposal and reuse evaluation program to demonstrate that CT-121 gypsum can be disposed of in an environmentally acceptable manner or can be reused for agricultural or other purposes.

- Conduct groundwater monitoring and environmental data management and reporting.

- Provide analysis of the collected data and correlate relevant parameters to ensure meaningful use of all information.

- Monitor operating costs, income, and savings resulting from the process innovations installed for this project and perform an economic analysis.

- Provide required reports.

III Technical And Environmental Assessment

This section discusses the operating and environmental results of the various test programs run during the CT-121 demonstration.

III.A Technical Results

III.A.1 Description of Test Program

A major objective of the CT-121 demonstration was to evaluate the operability and reliability of the CT-121 FGD unit. Another objective was to determine the effect of changes in process variables on system performance. In order to generate data permitting correlation of operating parameters with system performance, it was initially planned to run two complete factorial tests, one at low-particulate loading and one at high-particulate loading. However, as the test program proceeded, the test plans were refined somewhat to gather the data that was felt to be the most useful.

The three major operating parameters that were varied were pH of the JBR slurry reservoir, pressure drop across the JBR, and boiler load. Limestone grind was also varied in a few tests. Table 1 lists the planned levels for the parameters varied during this test series.

Table 1. Planned Parameter Values for Factorial Tests

	Low-Particulate Loading	High-Particulate Loading
Overflow pH	4, 4.5, 5	3.5, 3.75, 4, 4.5
JBR ΔP, in. H_2O	8, 12, 16	10, 13, 16
Boiler Load, MWe	50, 75, 100	50, 75, 100

For most of these tests, the limestone grind size was 90 percent through 200 mesh; however, a few tests were conducted using a coarser grind of 70 percent through 200 mesh. When early test results indicated that limestone utilization was not affected by grind size, no further grind size tests were performed, and the remainder of the operation used medium grind limestone. Several limestone sources were tested with similar results.

Following completion of the factorial short-term test series, a set of conditions was selected for long-term tests. During these tests, boiler load was allowed to follow demand. This permitted evaluation of process stability and process response to operational transients over an extended time period. The long-term test conducted with low-particulate loading was carried out between

May 28 and September 10, 1993; pH was 4.5, and pressure drop across the JBR was 14 inches of water. Target SO_2 removal during this test was 95 percent.

Between June 7 and August 28, 1994, a long-term test was conducted using a high-particulate loading in the flue gas. The objective of this test was to evaluate the ability of the CT-121 process to operate in a load-following mode at elevated particulate levels as might be encountered with a marginally performing ESP. Operating conditions for the ESP were adjusted to produce approximately 90-percent particulate removal efficiency. The higher ash loading in the slurry resulted in an elevated dissolved aluminum fluoride concentration in the JBR. Below a pH of 4.5, this operation was successful. However, at a pH set point of 4.5, the dissolution of limestone declined due to "limestone blinding." To overcome this problem, the pH set point was changed back to 4.0. Pressure drop across the JBR was set for 14 inches of water.

Supplemental to the tests described above were auxiliary test blocks conducted with both low- and high-particulate loadings. Each test block consisted of the following test periods, each approximately one month long: (1) high-SO_2 removal, (2) alternative coal, and (3) alternative limestone. The purpose of the high-SO_2 removal test was to evaluate system performance at maximum SO_2 removal rate. To accomplish this, pH and pressure drop across the JBR were set at maximum practical levels. For the low-particulate tests, pH was set at 4.8 and ΔP at 18 inches of H_2O; for the high-particulate tests, pH was 4.0 and ΔP was 20 inches of H_2O. Boiler load was allowed to vary during these tests. Coal sulfur level was approximately 2.5 percent for the low-particulates test and 1.2 percent for the high-particulates test. The lower sulfur content during the high-particulate loading test was because of the possibility of switching to low-sulfur coal on a plant-wide basis. The purpose of the alternative limestone test was to determine if limestone variations affected limestone utilization, SO_2 removal or by-product gypsum dewatering. The purpose of the alternative coal test was to evaluate system performance during use of coal with a sulfur content (3.5 to 4.5 wt %) well beyond the design limit.

A series of particulate removal tests was also conducted. The purpose of these tests was to measure the CT-121's performance as a simultaneous FGD unit and particulate removal device.

III.A.2 Discussion of Results

The total length of the demonstration period was 19,000 hours (27 months). During this period, the CT-121 scrubber was in operation 13,811 hours, or 73 percent of the time. Most of the downtime was the result of the boiler's being down, either because of mechanical problems or low electrical demand. Only 654 downtime hours (3 percent of the total demonstration period) were caused by problems associated with the scrubber. CT-121 scrubber reliability and availability were 98 percent during low-particulate operation and 95 percent during high-particulate operation.

Problems encountered during low-particulate operation were relatively minor, resulting either from deliberately operating outside the preferred pH range, which resulted in some scale formation, or from equipment failures due to improper initial installation or initial faulty design. Neither of these effects would cause problems during normal operations after initial shakedown.

The somewhat poorer performance observed during operations with high-particulate loading was due to several factors, including increased maintenance and inspection requirements associated with the high-ash loading in the flue gas entering the scrubber. The difficulties associated with operation under high-particulate loading include the potential for aluminum fluoride inhibition of limestone dissolution, gypsum/ash plugging of the sparger tubes, and erosion damage to internal process components. This high-ash condition was well outside the original design parameters and was intended to increase knowledge of CT-121 operations.

Effect of Limestone Source: Three different limestones were evaluated during the performance-testing period. These limestones were supplied by (1) Martin Marietta Aggregates from their Leesburg, Georgia, quarry; (2) Dravo Lime Company from their Saginaw, Alabama, quarry; and (3) Florida Rock from their Rome, Georgia, quarry. Typical analyses of these three limestones are given in Table 2.

Table 2. Typical Limestone Analyses

Limestone Supplier	Martin Marietta	Dravo	Florida Rock
Component	wt %		
$CaCO_3$	97.5	97.3	94.3
$MgCO_3$	0.4	1.9	1.7
Inerts	2.1	0.8	4.0

Except for a small difference in $MgCO_3$ concentration and inerts, the Martin Marietta and Dravo limestones analyses were similar. Although performance of these two limestones in the scrubber was equivalent, there was a significant difference in the nature of the gypsum crystals formed. The gypsum formed from the Dravo limestone had larger crystals and in lab tests filtered much more easily. The limestone from Florida Rock behaved similarly to the Dravo limestone, although the gypsum particles appeared to be somewhat smaller. This work showed the important effect limestone source has on scrubber performance. However, it is not clear exactly what property of the limestone contributes to producing large crystals.

Limestone utilization during the project was generally high (over 97 percent), when the pH was maintained below 5.0. At higher pH levels however, utilization dropped precipitously. At a pH of 5.5, limestone utilization was reduced to about 60 percent. (See Figure 8.) Consequently, following this test the pH set point was kept lower than 5.0 for the remainder of the project.

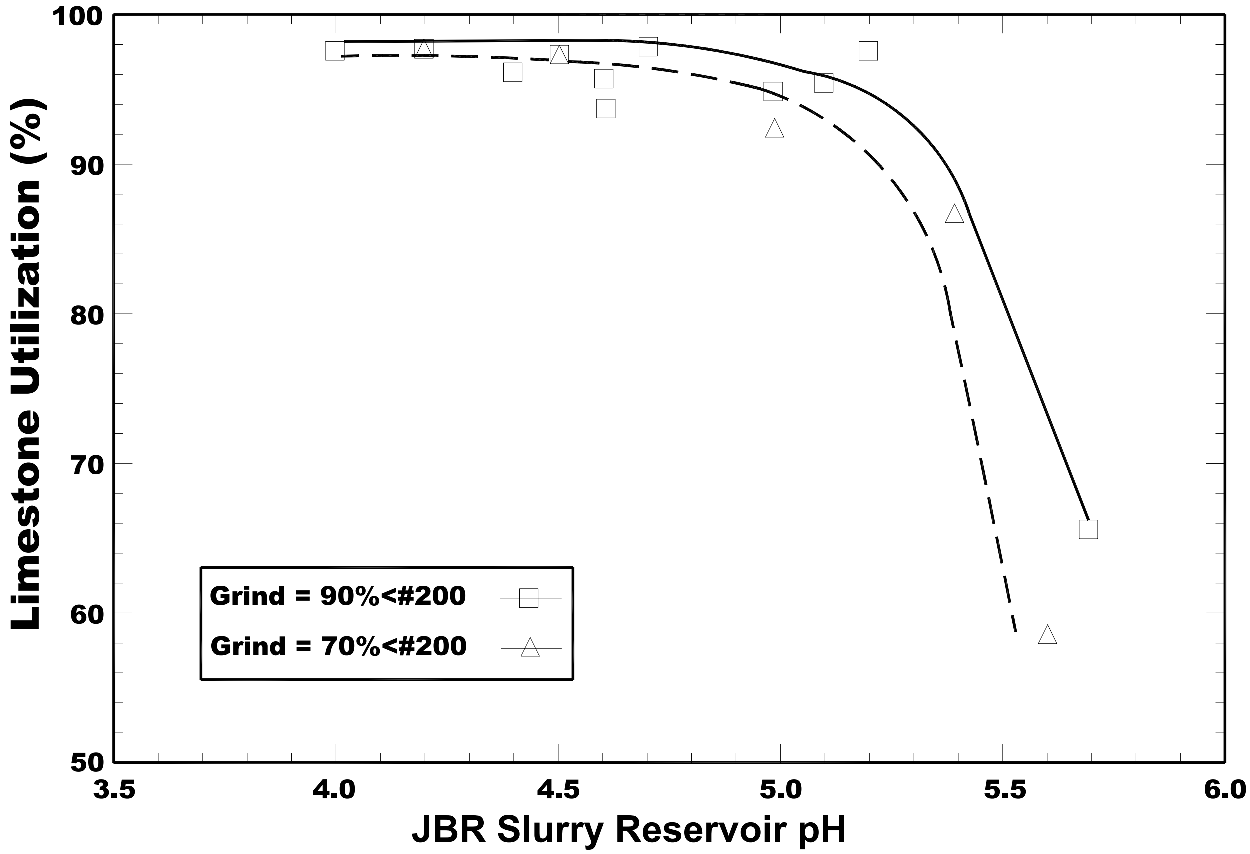

Figure 8. Effect of pH on Limestone Utilization

Effect of Coal Sulfur Content: The JBR was designed to handle flue gas from burning coal with a maximum sulfur content of 3 percent and a nominal sulfur content of 2.5 percent. Most of the operating period was run burning the baseline coal (2.5 percent sulfur), but short periods were also run burning coals with sulfur contents of 1.2 percent, 3.0 percent, 3.4 percent, and 4.3 percent. The effect of coal sulfur content on JBR performance is shown in Figure 9. At a given pressure drop across the JBR, SO_2 removal efficiency increases with decreasing sulfur level. However, even at the two sulfur levels above the design value, 90-percent desulfurization can still be maintained by a proper choice of operating conditions. This ability to exceed design coal sulfur level of 3.0 percent and still operate satisfactorily illustrates the flexibility of the CT-121 system.

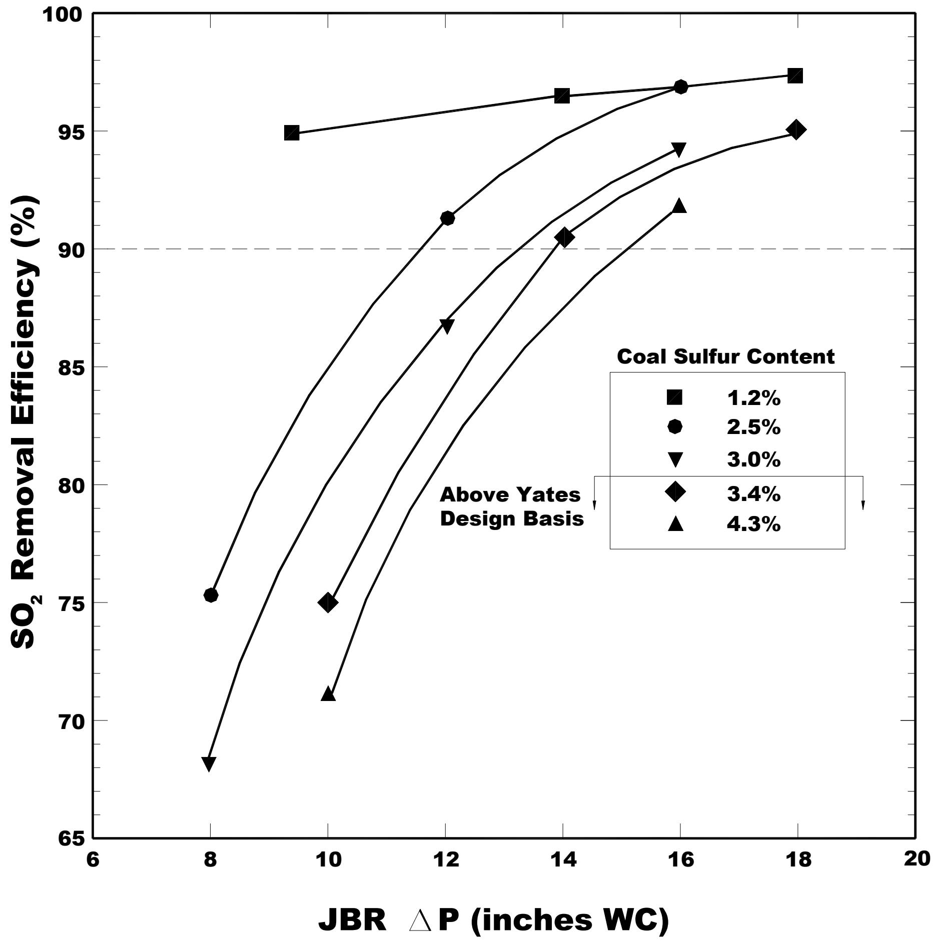

Figure 9. Effect of Coal Sulfur Content on Sulfur Dioxide Removal

Sulfur Dioxide Removal Efficiency: Sulfur dioxide removal efficiency is a function of slurry pH, pressure drop across the JBR, SO_2 concentration in the inlet flue gas, and boiler load. Removal efficiency increased with increasing pH or increasing pressure drop and decreased with increasing SO_2 concentration or increasing boiler load. Since SO_2 concentration and boiler load are not directly controllable variables, the main operational control parameters are pH and ΔP.

The most important variable by far was JBR ΔP. The increase in SO_2 removal with increasing JBR ΔP is the result of increasing the gas/liquid interfacial area as the slurry level above the bottom of the sparger tubes is increased (deeper sparging provides more time for bubble submersion). Increasing pH from 4.0 to 4.5 also had a substantial effect on SO_2 removal, but further increasing pH to 5.0 showed little improvement. Furthermore, during operation with high ash it was necessary to keep pH at 4.0 or below to maintain high limestone utilization and prevent limestone blinding.

As expected, as boiler load increased with other variables remaining unchanged, SO_2 removal efficiency decreased. Two effects contributed to this result. First, because of the inherent increase in pressure drop resulting from the greater flue-gas flow through the JBR at higher load, the level in the JBR had to be lower to maintain a given overall ΔP. This reduced SO_2 removal efficiency, as there was less bubble/liquid contact time. Second, the quantity of SO_2 entering the JBR increases in proportion to the load. Although more total SO_2 is removed at the higher loading levels, efficiency (expressed on a percent-removal basis) begins to decline as the liquid side chemistry begins to be upset.

Tests showed that pH is important for controlling fouling of the lower JBR deck and the sparger tubes. Fouling can result from a pH greater than 5.2, resulting in restricted limestone utilization. At low utilization, excess limestone in the slurry sprayed on the lower deck and sparger tubes by the gas cooling pumps reacts with SO_2 in the flue gas to form gypsum scale on slurry-wetted surfaces.

It was also found that it was important to maintain the oxygen-to-SO_2 ratio in the flue gas above a critical value to ensure complete oxidation of gypsum and to maintain slurry chemistry. When burning a 2.5 percent sulfur coal, this critical ratio was found to be about five to one.

Tests conducted at moderate-to-high-ash loadings, achieved by partially or completely de-energizing the ESP, showed that fouling and plugging can result from high ash levels. At low loads (50 to 55 MWe), SO_2 removal efficiency was about as expected, but at high loads (90 to 105 MWe), efficiency was much lower than with low-ash operation. Furthermore, at high ash levels, it was necessary to operate at lower pH (4.0) to avoid the contribution of the ash to the problem of dissolved aluminum fluoride blinding of the limestone particles, which leads to incomplete dissolution and declining limestone utilization.

Particulate Removal Efficiency: In addition to removing SO_2, the JBR can act as a particulate removal device. For very low-particulate loading at the JBR inlet (approximately 0.1 lb/MBtu, typical of operations with the ESP fully energized), removal efficiency of the particles entering the JBR was approximately 90 percent, except for low-load (50 MWe) operation, where efficiency dropped to about 70 percent. At low load, the ESP efficiency increases, so that the particulate load to the JBR is reduced, with resulting lower removal efficiency. There is a particular size fraction that defies collection, so its proportional impact on removal is greater when ash loading to the JBR declines. The JBR also reduces sulfuric acid mist by 25 to 35 percent.

Testing was also performed with the ESP either fully or partially de-energized. Under these conditions there was a high-particulate loading to the JBR (about 5.0 lb/MBtu). However, 98- to 99-percent particulate removal efficiency was obtained across the JBR. In general, the JBR removed over 99.9 percent of particles larger than 10 µm, but only 69 to 85 percent of particles less than 1 µm. Particles from 1 µm to 10 µm were removed with an efficiency of 97.3 to 99.6 percent.

Regression Model: In order to permit development of feed-forward computer control algorithms, a mathematical model relating SO_2 removal efficiency to system operating variables was developed. Regression analysis, used to develop the model, was based on four independent variables: pH in the JBR froth zone (pH), pressure drop across the JBR in inches of water (ΔP), SO_2 concentration in the inlet flue gas in ppm (at 3-percent oxygen) (SO_2), and boiler load in MWe (load). Several models were developed for various operating scenarios to obtain a higher model fit (R^2), i.e. mathematical confidence level, but the regression model spanning the widest parameter range had the following form:

$$NTU = A + B(Load) + C(SO_2) + D(Load)(SO_2) + E(\Delta P) + F(pH) + G(pH)^2 + H(\Delta P)(pH) \qquad (4)$$

NTU is the number of transfer units for SO_2 removal and the other variables are as identified above. This model is valid over a pH range of 3.75 to 5.0, a ΔP range of 8 to 18 inches of water, an SO_2 inlet rate of 1,000 to 3,500 lb/hr, and a load range of 50 to 100 Mwe, With the following values for the coefficients: A equals 3.556, B equals 0.00687, C equals -9.21×10^{-5}, D equals -8.82×10^{-6}, E equals -0.409, F equals -0.1483, G equals -0.0949, and H equals 0.1406. R^2 has a value of 0.935. SO_2 removal efficiency is related to NTU by the following equation:

$$SO_2 \text{ removal efficiency, percent} = 100(1 - e^{-NTU}) \qquad (5)$$

In addition to its potential for control purposes, the model can also be used to normalize data by bringing all the data to a common inlet SO_2 concentration. Normalization makes it easier to compare performance at different operating conditions.

Equipment Performance: Process performance exceeded expectations and most of the innovations included in the design of the Yates CT-121 installation worked as intended, significantly improving performance. However, some additional areas for improvement were identified during this project. These areas are discussed below.

Although the FRP proved to be impervious to corrosion, there were areas where it was not sufficiently erosion resistant. As the project proceeded, an erosion resistant coating (Duromix™) was applied to regions experiencing erosion. This material worked very well, and such a coating is recommended for future CT-121 designs.

The gas-cooling spray in the Yates facility was only 18 feet upstream of the JBR inlet plenum, due to late design changes that eliminated the precooler. This lead to two problems: erosion damage to the inlet plenum and solids buildup on the lower deck. To alleviate these problems in future designs, the gas cooling section should be moved farther upstream. This would allow slurry to fall to the duct floor well upstream of the JBR, thus reducing deposits and allowing more design flexibility to avoid slurry spray impingement.

Operations showed that suction screens needed to be added to the slurry pump intakes within the JBR. The style that proved to be satisfactory was a "hockey net" arrangement. These screens were sufficiently large to allow adequate flow without any areas of high-velocity slurry flow. The screens were made of FRP and PVC for corrosion resistance. Screen hole size was 3/8 inch, small enough to allow anything that passed through the screen to also pass through the cooling spray header nozzle openings. Finally, the total area of the screen was large, so there was little chance of blinding. Therefore, cleaning was required only during scheduled outages.

Keeping the JBR lower-deck inlet plenum and sparger tubes free of solids is critical to ensuring consistent CT-121 scrubber performance. A wash system was provided to help keep the deck clean. However, in the Yates JBR, the tops of the sparger tubes were designed to protrude 4 inches above the surface of the deck. This design permits buildup of solids around the sparger tube array, particularly during high-particulate loading operations. In future installations, the mounting of the sparger tubes should be modified so that the tops are flush with the deck surface. This would permit each sparger tube to also act as a drain during washing of the deck, thus helping to prevent buildup of solids.

Since level control of the slurry reservoir in the JBR is important, it is necessary to have a reliable device to measure JBR pressure drop (ΔP). The differential pressure cell initially used in the Yates installation proved to be unsatisfactory due to plugging of small diameter sensing lines. Therefore, alternative diaphragm-type instruments or instruments with purged lines were installed at Yates, with marginal improvement. Multiple pressure drop instruments, as used at Yates, are recommended to improve measurement reliability.

The pH probe needs to be of simple and durable design and must be able to be removed during operation, so that it can be cleaned and calibrated. Recommended preventive maintenance practice includes in-situ calibration checks at least twice daily, weekly cleaning, bimonthly probe replacement, and control system comparison readings using at least two redundant pH probes. These redundant probes should be positioned near one another to minimize effects of pH variations across the JBR, and pH probes should be placed at least one foot below the bottom of the sparger tube openings to provide more stable pH readings. The schedule of calibration, checking, cleaning and replacement should follow a strict regimen, as a failing pH probe can give deceptively consistent control output values that may fool a less experienced operator.

III.B Environmental Performance

The CT-121 FGD Process was designed to comply with all applicable federal, state, and local environmental regulations. As a consequence, the operation of this CCT demonstration project did not increase the volume or change the composition of any air, water, or solid waste emissions. No problem areas concerning environmental regulations or permit conditions were identified, nor were any toxic pollutants generated due to operation of the CT-121 Project.

III.B.1 Air Emissions

The CT-121 process is an effective combined SO_2 and particulate removal system. When high-sulfur coal was burned at maximum boiler load at plant Yates, the CT-121 scrubber exceeded the target 90-percent SO_2 removal efficiency at SO_2 inlet concentrations of 1,000 to 3,500 ppm with limestone utilization over 97 percent. SO_2 removal was approximately 98 percent when burning 2.2-percent sulfur coal, and about 95 percent with 3.5-percent sulfur coal. The JBR achieved particulate removal efficiencies of 97.7 percent for mass inlet loadings of 0.303 to 1.392 lb/MBtu over a load range of 50 to100 MWe. System flexibility is achieved by adjusting the submergence depth of the flue-gas spargers (by raising or lowering the depth of the slurry reservoir) to compensate for higher sulfur content. NO_x emissions were unchanged as a result of the project.

III.B.2 Solid Waste

The innovative CT-121 scrubber, featuring state-of-the-art designs and materials of construction, is a significant improvement over 1970s wet-scrubber technology. The JBR eliminated waste disposal problems by incorporating oxidation of the calcium sulfite sludge to produce wallboard quality gypsum (calcium sulfate). Large, easily dewatered, gypsum crystals were consistently produced and successfully stacked on site during the project. Two types of gypsum slurries were produced, one with the ESP in operation and one without the ESP in service. Gypsum stacks were used to store and dewater the solids by gravitational force, with clarified, decanted process water being collected in the common pond area and recycled to the process. Gypsum by-product was also used as a soil amendment and was granted a Plant Food Permit from the state of Georgia that allowed unrestricted use of ash-laden and ash-free gypsum for agricultural purposes.

III.B.3 Air Toxics

The project included an adjunct investigation into potential air toxic emissions as a late project testing opportunity (Radian Corporation 1994). Hazardous Air Pollutant testing of the JBR showed the following capture rates: greater than 95 percent for hydrogen chloride and hydrogen fluoride gases, 80 to 98 percent for most trace metals, less than 50 percent for mercury and cadmium, and less than 50 percent for selenium. However, this was perhaps the first attempt to test a wet scrubber for air-toxics removal potential, and it may not meet the rigorous procedural demands of measurements taken by today’s standards.

IV Market Analysis

IV.A Market Size

Because the CT-121 scrubber operates on the flue-gas stream after it leaves the boiler, it is applicable to virtually any type of boiler burning any sulfur containing fuel (petroleum coke, coal or fuel oil). The only limitation is that there must be a supply of limestone within economic transport range and there must be a market for the gypsum or a suitable landfill area nearby. It is difficult to judge the potential market, because most power plants have already addressed the SO_2 mitigation problem and have either installed scrubbers or switched to low-sulfur fuel, thus reducing the retrofit market. However, the compact design and operational flexibility of the CT-121 FGD process should make it a good candidate for new units.

IV.B Economics

IV.B.1 Capital Cost

Reported capital costs (adjusted to 1994 dollars) for installation of the JBR at Plant Yates are given in Table 3.

Table 3. Capital Costs for JBR Installation at Plant Yates

Plant Area	Capital Cost, $ million
Limestone Preparation	2.4
Sulfur Dioxide Control	6.2
Waste Disposal	1.8
Flue-Gas Handling	4.6
Balance of Plant	5.9
Installed Equipment Cost	20.9
Engineering and Home Office	7.2
Total Capital Requirement	28.1

Unit 1 has a rated capacity of 110 MWe. Therefore, the total capital requirement of the JBR at Plant Yates was about $255/kW. Allowing for reduced costs due to lessons learned from this CCT project and for economies of scale for installation on larger units, the Participant estimates that the capital cost of the CT-121 process could be $150/kW, or less (1994 dollars).

IV.B.2 Operating Cost

Reported operating costs were based on operation of the JBR at Plant Yates. This plant required one operator per shift on an around-the-clock-coverage basis. Table 4 shows reported fixed operation and maintenance (O&M) costs, on a 1994 dollars per year basis.

Table 4. Fixed O&M Costs

O&M Cost Area	Cost, $/yr
Operating Labor	512,000
Maintenance Labor	257,000
Maintenance Material	47,000
Administration and Support Labor	50,000
Total Fixed O&M	**866,000**

The only variable costs are for electric power and limestone. For a 100-MWe unit with a heat rate of 10,000 Btu/kWh, and burning coal with 2.5-percent sulfur content, 8-percent ash content, and a heat of combustion (moisture and ash free) of 14,500 Btu/lb, about 1.95 tons of SO_2 are generated per hour. At a recovery rate of 90 percent, about 1.75 tons of SO_2 are recovered per hour. Based on reported results, approximately two tons of limestone are required to remove one ton of SO_2. At $15/ton, limestone cost amounts to $30/ton of SO_2 removed. The cost of incremental power (power required above that used before installation of the CT-121 facility) is about $14/ton of SO_2 removed.

Based on the above values and an operating factor of 65 percent, limestone cost is about $300,000/yr, and power cost is about $140,000/yr. Thus, the total variable operating cost is $440,000/yr.

IV.B.3 Economics

Economics for the CT-121 process, based on a 100-MWe plant with a 65-percent operating factor and other factors as indicated above, are given in Table 5 on both a current dollar and constant dollar basis.

Table 5. Economics for the CT-121 Process (1994 dollars)

Levelized Cost of Power, mills/kWh	Base, $\$10^6$	Current Dollars		Constant Dollars	
		Factor	**Mills/kWh**	**Factor**	**Mills/kWh**
Capital Charge	28.1	0.160	7.9	0.124	6.1
Fixed O&M	0.866	1.314	2.0	1.000	1.5
Variable O&M	0.440	1.314	1.0	1.000	0.8
Total			**10.9**		**8.4**
Levelized Cost, \$/ton SO_2 Recovered					
Capital Charge	28.1	0.160	421	0.124	327
Fixed O&M	0.866	1.314	107	1.000	81
Variable O&M	0.440	1.314	54	1.000	41
Total			**582**		**449**

From Table 5 it is seen that the CT-121 scrubber adds about 11 mills on a current dollars basis or 8 mills on a constant dollars basis to the cost of a kWh of electricity. On a sulfur removal basis, the cost is \$582 (current dollars) or \$449 (constant dollars) per ton of SO_2 recovered. These costs compare favorably with costs of other scrubber systems.

These economics are based on results for the Yates CT-121 demonstration installation, since these are the only data available in the final report. These costs are probably higher than they would be for a regular operating plant, because of the extra costs of testing, extra instrumentation, data analysis, etc. related to the CCT project.

If a capital cost of \$150/kW (\$15 million for a 100-MWe plant), estimated by the Participant, is used, then the cost of the CT-121 process drops to 7.2 mills/kWh (current dollars) and 5.6 mills/kWh (constant dollars). On a pollutant removal basis, costs are \$386/ton SO_2 recovered (current dollars) and \$297/ton SO_2 recovered (constant dollars).

V Conclusions

During two years of testing, several novel features of the CT-121 FGD process as installed for this project were investigated. In general, the process performed very well, removing both SO_2 and particulates from the flue gas with efficiencies of 90 percent or better over a variety of operating conditions. The process proved to be reliable and responsive and was able to maintain SO_2 removal efficiency while operating in a load-following mode. Plant personnel referred to the CT-121 unit as "robust" for its forgiving nature and ability to operate successfully well outside its design basis. Overall, this was a successful project. The innovative features being demonstrated performed as expected. Minor problems encountered were either satisfactorily overcome or can be eliminated by redesign in a new plant. Specific conclusions follow.

Almost any SO_2 removal level within the operating capabilities of the unit can be achieved by adjusting the pressure differential across the JBR (Jet Bubbling Reactor®), by adjusting the JBR slurry reservoir level. The pH can be adjusted to give high limestone utilization. These two factors combine to give an optimum cost of compliance. The Project also demonstrated that a full-scale CT-121 system can meet New Source Performance Standards for SO_2 control.

- The CT-121 process functioned effectively as a combined SO_2 and particulate control system.

- The CT-121 process has proven to be easy to operate with high reliability. Reliability and availability were both 97 percent during the project period. Reliability was 98 percent for low-particulate operation compared with 95 percent for high-particulate operation.

- Limestone utilization was typically 98 percent or greater during low-particulate operations at pH values up to 5.2. With high-particulate loadings, aluminum fluoride blinding of the limestone was a problem at pH levels above 4.5. The CT-121 FDG unit operated successfully at unexpectedly low pH set points.

- Although it did not affect performance of the JBR, the source of the limestone had a significant effect on the particle size and dewatering characteristics of the gypsum particles. The property of the limestone responsible for this effect could not be unequivocally determined.

- The wet chimney proved to be very successful and operated without the need for reheat. No precipitation (acid rainout) from the stack was observed at any operating condition.

- The FRP (fiberglass-reinforced plastic) proved to be impervious to corrosion, being unaffected by the acidic slurry or its high chloride concentration. However, some erosion occurred in the gas cooling transition duct and the JBR inlet plenum, where slurry spray directly impacted FRP surfaces, due to the high superficial velocity of the gas and the high solids content of the slurry used for gas cooling. Design modifications for future plants have been identified to obviate this problem.

- Solids buildup on the lower deck of the JBR was somewhat of a routine maintenance problem. Again, design changes to mitigate this problem have been identified.

- The CT-121 FGD technology is economically competitive with other wet FGD processes. Its ability to produce wallboard grade gypsum is an advantage. In addition to its potential for use in wallboard, CT-121 gypsum has been approved as a soil additive.

- Gypsum stacking eliminates the need for any dewatering equipment or energy expenditure, as it relies solely on gravity.

- Closed-loop FGD operation (no blowdown, no wastewater treatment) is possible with the use of corrosion-impervious materials like FRP.

The fact that the Yates CT-121 FDG unit continues to operate satisfactorily is a strong indication of the success of this project.

Abbreviations

CT-121	Chiyoda Corporation's Thoroughbred-121
CCT	Clean Coal Technology
DOE	Department of Energy
ESP	electrostatic precipitator
EPRI	Electric Power Research Institute
FRP	fiberglass-reinforced plastic
FGD	flue-gas desulfurization
JBR	Jet Bubbling Reactor®
NSPS	New Source Performance Standards
O&M	operation and maintenance
PPA	post-project assessment
SCS	Southern Company Services, Inc
SO_2	Sulfur dioxide
SRI	Southern Research Institute

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