DOE/FE-0394

PURE AIR ON THE LAKE

ADVANCED FLUE GAS DESULFURIZATION DEMONSTRATION PROJECT

PROJECT PERFORMANCE SUMMARY
CLEAN COAL TECHNOLOGY DEMONSTRATION PROGRAM

JUNE 1999

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ENVIRONMENTAL CONTROL DEVICES

Advanced Flue Gas Desulfurization Demonstration Project

Overview

The Pure Air scrubber has received worldwide acclaim for its contributions to the power generating industry and the environment. The project earned the Bailly Generating Station *Power Magazine's* 1993 Powerplant Award. In 1992, it was named an Outstanding Engineering Achievement by the National Society of Professional Engineers.

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 16 selected in May 1988 from 55 proposals submitted in response to the Program's second solicitation.

A major step forward in technology and business approach was taken with the Pure Air AFGD demonstration at Northern Indiana Public Service Company's 528-MWe Bailly Generating Station. Under a unique own-and-operate arrangement, Pure Air constructed a single 600-MWe module absorber to process flue gas at the full plant capacity produced from units No. 7 and 8 as a contracted service to the facility. The demonstration covered the first three years of a 20-year commercial arrangement between Northern Indiana Public Service Company (NIPSCO) and Pure Air. Through this project, NIPSCO's Bailly Station became the first power plant to meet new SO_2 limits set for Phase I of the Clean Air Act Amendments of 1990 (CAAA).

With the largest capacity module at the time, the project sought to prove that single absorber modules of advanced design could process large volumes of flue gas and provide the required availability and reliability without the usual spares. Major performance objectives were achieved. These included achieving 95 percent or greater SO_2 control with high sulfur coals (up to 4.5 percent), significantly reducing capital costs and space requirements relative to conventional wet scrubbers, and creating no new waste streams.

Over the three year demonstration, Pure Air's AFGD accumulated 26,280 hours of operation with an availability of 99.5 percent. Approximately 237,000 tons of SO_2 were removed, with capture efficiencies of 95 percent or more, and over 210,000 tons of saleable gypsum were produced. The AFGD continues in commercial service, which includes sale of all the by-product gypsum to U.S. Gypsum's East Chicago, Indiana wallboard production plant.

The Project

With NIPSCO's Bailly Station targeted for SO_2 reduction under Phase I of the Clean air Act Amendments of 1990, the decision was made to scrub the flue gas rather than fuel switch. To avoid historic problems associated with this undertaking, a unique business arrangement was used to place the burden of scrubber operation on a third party, and advanced technology was applied to mitigate cost and performance concerns. Under an own-and-operate agreement, NIPSCO pays a monthly Base Facility Charge for flue gas processing services. Pure Air is responsible for the turnkey, financing, operating and maintenance risks as well as AFGD performance. AFGD technology reduces cost and space requirements by using a single, highly efficient and reliable absorber module that achieves 95 percent or more SO_2 reduction, produces a saleable by-product, and generates no new waste streams. Conventional systems on the other hand require spare absorber modules and fail to adequately oxidize calcium sulfite to sulfate. Calcium sulfate/sulfite sludges result which are difficult to handle, cause severe scaling and plugging, and require high land use for disposal.

Over the three year demonstration, the AFGD system was operated on coals with varying ranges of sulfur content. In 1992, tests were run on the standard coal with sulfur content ranging from 3.0–3.5 percent. During 1993, tests were conducted on coals ranging from 3.5–4.0 percent sulfur and 2.5–3.0 percent sulfur. In 1994, tests were completed on coals with 4.0–4.5 percent sulfur and 2.0–2.5 percent sulfur. In addition, five coals were selected for parametric tests. Variables were coal sulfur content, boiler load, calcium to sulfur stoichiometric ratio (SR) as moles of calcium in reagent to moles of SO_2, gallons of liquid (sorbent slurry) per 1,000 ft^3 of flue gas (L/G). In addition to SO_2 levels, hydrogen chloride, hydrogen fluoride and sulfuric acid mist emissions were measured. Trace element analyses were conducted to determine how the trace elements in the coal partition upon combustion to plant output streams (bottom ash, flyash, gypsum product, blowdown and stack gas).Tests were also conducted on a Wastewater Evaporation System (WES), focusing on effective nozzle performance; and on a PowerChip™ system, characterizing and validating product handling.

Project Sponsor

Pure Air on the Lake, LP (a project company of Pure Air which is a general partnership between Air Products and Chemicals, Inc., and Mitsubishi Heavy Industries America, Inc.)

Additional Team Members

Northern Indiana Public Service Company—cofunder & host
Mitsubishi Heavy Industries—process designer
United Engineers & Constructors (Stearns-Roger Division)—facility designer
Air Products & Chemicals, Inc.—constructor and operator

Location

Chesterton, Porter County, IN
(NIPSCO's Bailly Generating Station, Units No. 7 and 8)

Technology

Pure Air's flue gas desulfurization (AFGD) process

Plant Capacity

528-MWe

Coal

Indiana & Illinois Basin bituminous coal—2–4.5% Sulfur

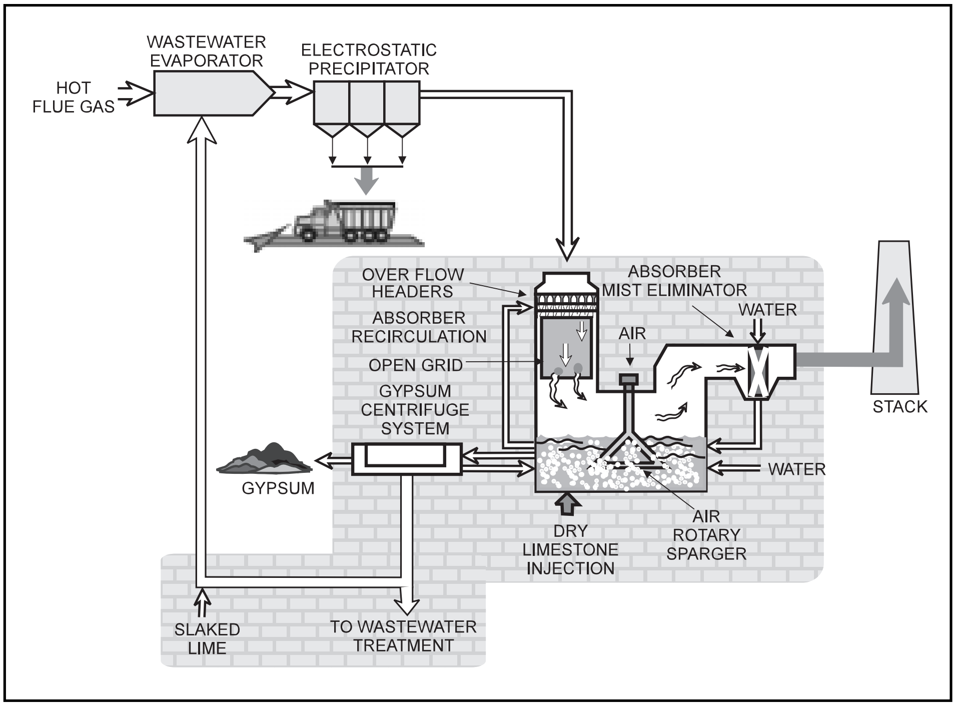
Demonstration

June 1992–June 1995

Project Funding

Total project cost	$151,707,898	100%
DOE	63,912,200	42%
Participant	87,794,698	58%

THE TECHNOLOGY



In the AFGD, incoming flue gas is cooled and humidified with process water sprays before passing into an absorber grid. Two tiers of fountain like sprays distribute reagent slurry to a polymer grid packing to provide a large surface area for gas/liquid contact. The gas enters a large gas-liquid disengagement zone above the absorber tank and passes out through a horizontal mist eliminator. Reacted slurry falls to the absorber tank where acids are neutralized and calcium sulfite is oxidized to calcium sulfate. Limestone injected in dry powder form into the tank performs the neutralization and produces gypsum—calcium sulfate dihydrate. Primary oxidation is achieved by three rotary air spargers which both mix and inject air into the absorber tank. Fixed air spargers assist in completing the forced oxidation. Neutralized reagent in the absorber tank is recirculated back to the absorber grid.

A gypsum slurry is drawn from the tank, dewatered and washed to remove chlorides. The resultant gypsum cake contains less than 10 percent water and 120 ppm chlorides. Solids (gypsum/flyash) are removed from the gypsum process water (filtrate) and are either mixed with gypsum product or sent to wastewater treatment. Some filtrate passes to the Wastewater Evaporation System (WES) for injection into the hot flue gas ahead of the electrostatic precipitator (ESP) where dissolved solids are collected. Hydrated lime is used to neutralize any flyash buildup in the filtrate that could impede limestone reactivity.

To increase the range of the market for the gypsum, handling and transportability characteristics of the AFGD derived gypsum were enhanced to that of natural gypsum by incorporation of a PowerChip™ system. PowerChip™ uses a compression mill at an optimum compacting force and exclusive cure time/temperature relationship to change the physical structure. The result is a stable, densely agglomerated, semi-dry flake with handling properties equivalent to natural rock gypsum.

AFGD differs from conventional wet scrubbers in combining several functions in a single module (pre-quenching, absorption, and oxidation) and using co-current flow to permit relatively high flue gas velocities (up to 20 feet per second), allowing the system to be more compact. Non-pressurized slurry spays reduce power requirements by 30 percent and mist generation by 95 percent. The air rotary sparger, combining agitation and oxidation, significantly enhances performance. Incorporation of a WES controls chlorides without creating a new waste stream. Processing a portion of the flyash gypsum sludge with the by-products reduces solid waste. Adding PowerChip™ technology expands the market for the gypsum by-product.

DEMONSTRATION RESULTS

- AFGD design enables a single 600–MWe absorber module without spares to remove 95 percent or more SO_2 at availabilities of 99.5 percent when operating with high sulfur coals.
- AFGD's use of co-current high velocity flow, integration of functions, and use of a unique air rotary sparger make it a highly effective, compact scrubber which produces wallboard grade gypsum.
- The own-and-operate contractual arrangement whereby Pure Air took on the turnkey, financing, operating and maintenance risks through performance guarantees was deemed successful.
- Sales of commercial grade gypsum to a wallboard manufacturer were made.
- The need for on-site wet grinding systems was eliminated by injecting as purchased, dry pulverized limestone into the AFGD absorber.
- The WES mitigated expected increases in wastewater generation associated with gypsum production and showed the potential for achieving zero wastewater discharge. (Only a partial capacity WES was installed for the demonstration.)
- Hook-up of multiple boilers to a single absorber module was achieved.
- PowerChip™ successfully demonstrated low cost conversion of typical wet scrubber derived gypsum (with the handling properties of wet sand) to a product with the handling characteristics of natural rock gypsum.
- Most of the AFGD innovations introduced in this demonstration have been adopted in current wet scrubber designs.
- Capital costs and space requirements for the AFGD were approximately half that of contemporary wet scrubbers.

Ductwork being installed with stack in the background and absorber module in lower right corner

Worker inspecting ductwork

Environmental Performance

Expected emissions from the Bailly Station with and without AFGD control for typical operating parameters are outlined in *Table 1* and *Table 2*. They reflect coal consumption of 5,000 tons per day, a load factor of 85 percent, availability of 85 percent, and coal with 3.2 percent sulfur, 10 percent ash, and 0.07 percent chlorine. Assumptions are that 95 percent SO_2 and 99.5 percent particulate reductions are achieved.

The 71,600 tons per year of SO_2 is captured and recycled in the 97 percent pure gypsum used either in the wallboard or cement industry. The 650 tons per year additional flyash captured ends up in the gypsum by-product. Chlorides that would have been released to the air are captured and potentially become a wastewater problem. This is mitigated by addition of the WES, demonstrated as part of the project. Greater than 99 percent of the hydrogen fluoride generated is removed by the AFGD. For the base case 3.2 percent sulfur coal, low levels of sulfuric acid gas ranging from 14 to 33 ppm at the AFGD inlet were reduced to 9 to 20 ppm. Low levels of sulfuric acid gas at the AFGD inlet are due in part to the injection of 15 ppm of ammonia (NH_3) at each ESP inlet to control SO_3.

Table 1. No AFGD In Operation Tons/Year

Components in Flue Gas	Generated by Combustion	Recycle	*Discharge* Land	Air	Water
SO_2	84,400	———	*8,440*	*75,960*	*Nil*
Ash	132,000	65,350	*65,350*	*1,300*	*Nil*
HCl	950	———	*Nil*	*950*	*Nil*

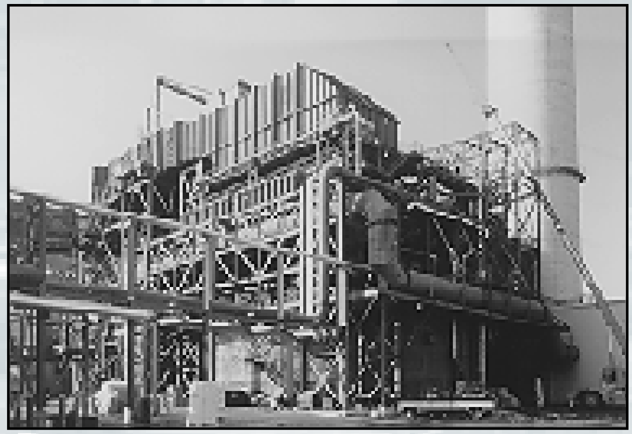
Table 2. AFGD In Operation Tons/Year

Components in Flue Gas	Generated by Combustion	Recycle	*Discharge* Land	Air	Water
SO_2	84,400	71,600	*8,440*	*3,800*	*Nil*
Ash	132,000	65,350	*65,350*	*650*	*Nil*
HCl	950		*Nil*	*Nil*	*950*

The WES takes a portion of the wastewater stream with high chloride and sulfate levels and injects it into the ductwork upstream of the ESP. The hot flue gas evaporates the water and the dissolved solids are captured in the ESP. The resultant increase in solids is slight. Only about 230 lb/hr of chloride removal is needed to keep the absorber system in chemical balance. Temperatures in the flue gas entering the ESP are kept well above the sulfuric acid dew point of 285 °F. Problems were experienced early on with the WES nozzles failing to provide adequate atomization and plugging as well. This was resolved by replacing the original single fluid nozzles with dual fluid systems employing air as the second fluid.

Trace elements within the coal were measured and an assessment made as to where they ultimately resided within the plant streams subsequent to combustion. The locations (output streams) chosen to determine the fate of the trace elements were bottom ash, ESP ash (flyash), gypsum product, blowdown and stack gas. The trace elements addressed included antimony, arsenic, barium, beryllium, boron, cadmium, manganese, mercury, molybdenum, nickel, selenium and vanadium. *Figure 1* summarizes the results of the analysis. The bulk of the trace elements wound up in either the bottom or ESP ash. (For the unit No. 7 and 8 cyclone boilers, 63 percent of the ash is bottom ash and 37 percent flyash.) Only boron, mercury and selenium were evidenced in the stack gas.

Testing over the three year period clearly established that AFGD operating within its design parameters (without additives) could consistently achieve 95 percent SO_2 reduction or more with 2.0–4.5 percent sulfur coals. The design range for calcium to sulfur stoichiometric ratio (SR) was 1.01–1.07 with the upper value set by gypsum purity requirements (amount of unreacted reagent allowed in the gypsum). Another key control parameter was the ratio of the amount of reagent slurry injected into the absorber grid (gallons) to 1,000 cubic feet of flue gas (L/G). The design L/G range was 50–128 gal/1000 ft^3. The lower end was determined by solids settling rates in the slurry and the requirement for full wetting of the grid packing. The high end was determined by where performance leveled-out.



Overview of process water distribution system

Interconnection of absorber module and stack

Figure 1. Trace elements in output streams —Bailly Station—

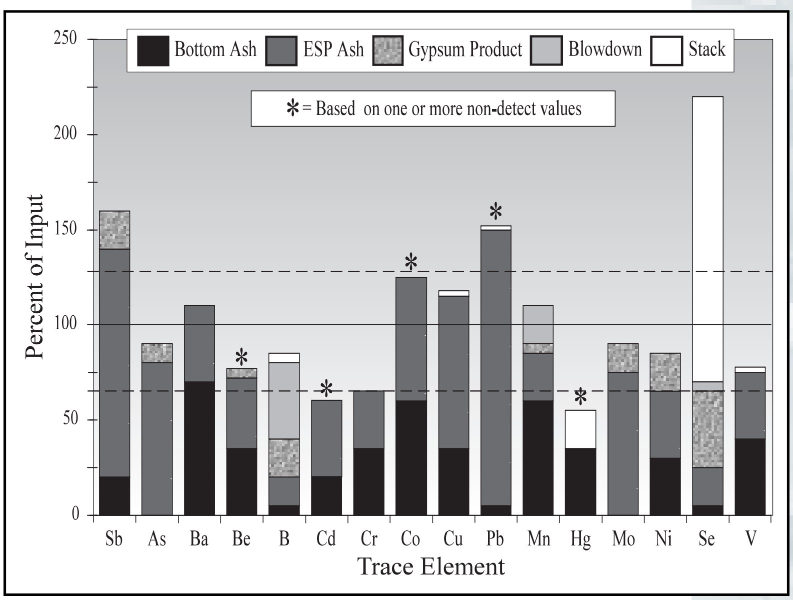


TABLE 3. SO_2 REMOVAL PERFORMANCE (100% BOILER LOAD)

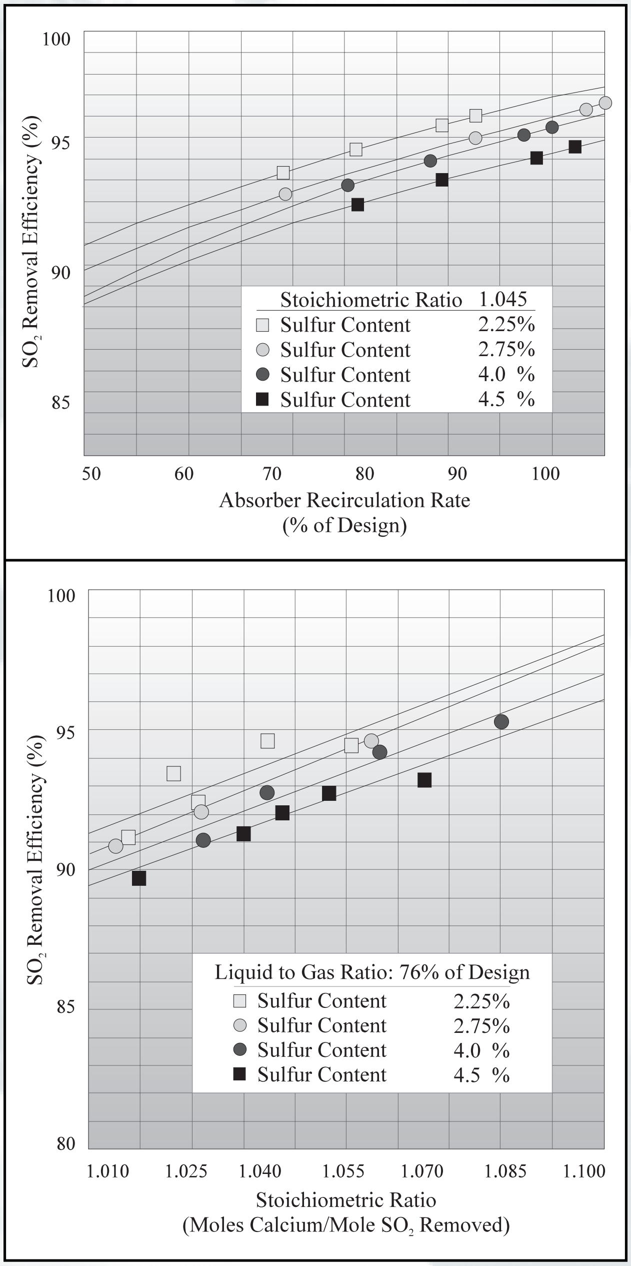


TABLE 4. FULL LOAD SR & L/G REQUIREMENTS FOR 95% SO_2 REDUCTION

2.25% S Coal SR–L/G	2.75% S Coal SR–L/G	3.1% S Coal SR–L/G	4.0% S Coal SR–L/G	4.5% S Coal SR–L/G
1.055–70 to 75	1.064–80	1.090–72	1.060–82	1.068–76
1.039–86	1.055–88 to 92	1.046–82	1.050–92	1.050–93 to 95
1.017–100	1.040–100	1.030–97	1.043–100	

Five coals with differing sulfur contents were selected for parametric testing to examine SO_2 removal efficiency as a function of load, sulfur content, SR and L/G. Loads tested were 33, 67 and 100 percent. High removal efficiencies, well above 95 percent, at 33 and 67 percent loads was possible with low to moderate SR and L/G settings even for 4.5 percent sulfur coal. *Table 3* summarizes the results of parametric testing. *Table 4* provides data points taken from parametric testing to show combinations of SR and L/G settings necessary to achieve 95 percent SO_2 removal for the five selected coals at full load. L/G is expressed as a percentage of the maximum 128 gal/1000 ft^3.

Commercial grade gypsum quality was maintained throughout these tests even at the lower sulfur concentrations where the ratio of flyash to gypsum increases due to lower sulfate availability. With 2.25 percent sulfur coal, gypsum purity ranged from 96.7– 99.7 and with 4.5 percent sulfur coal, the purity ranged from 95.6 –99.7 percent.

The primary importance of producing a commercial grade gypsum is avoidance of the environmental and economic consequences of disposal. The marketability of the gypsum is dependent upon whether users are in range of economic transport and whether they can handle the gypsum by-product. For these reasons, PowerChip™ technology was developed and demonstrated as part of the project. This technology takes the highly cohesive gypsum cake produced from the AFGD and converts it into a flaked product with handling characteristics equivalent to natural rock gypsum. The process avoids use of binders, pre-drying or pre-calcining normally associated with briquetting and is 30–55 percent cheaper at $2.50–$4.10 per ton.

The problem with wet scrubber gypsum, which has the properties of wet sand, is in handling the material. This finely divided moist material is very cohesive, tends to stick to most handling or storage surfaces and will bridge over outlets in chutes, bins and hoppers. Transportation of conventional wet scrubber gypsum with bottom discharge railcars has been unsuccessful (moisture in 6 to 15 percent range). PowerChip™ uses a roll press (like those used in metal rolling) to produce a stable, densely agglomerated, semi-dry flake 1/8 –1/4" thick and 3/8" to 1–1/4" long/wide. Flake density is 90 lb/ft^3 and bulk density is 60–65 lb/ft^3. Tests showed consistent flow from feed bins and silos to belt feeders, through rotary rock feeders, and out of bottom discharge railcars. Product was tested in 8 wallboard and 12 cement plants with most finding handling acceptable without adjustments. Some required adjustment for a tendency to flood (flow too freely). Weathering tests showed the product to be durable but warranting a shed to prevent some fines generation.

Operational Performance

Availability over the three year operating period averaged 99.5 percent while maintaining an average SO_2 removal efficiency of 94 percent. This is attributable to the simple, effective design. Use of co-current rather than conventional counter-current flow results in lower pressure drops across the absorber and affords the flexibility to increase gas flow without an abrupt drop in removal efficiency. AFGD SO_2 capture efficiency with limestone is comparable to wet scrubbers using lime which is far more expensive. Twenty-four-hour power consumption was 5,275 kW, or 61 percent of expected consumption, and water consumption was 1,560 gallons per minute, or 52 percent of expected consumption.

A detailed "fault tree" analysis conducted in the design phase to evaluate impacts of process upsets identified loss of power as the most significant event. Loss of power causes loss of flue gas quench and slurry circulation, resulting in temperature buildup and damage to the absorber grid and resin absorber tank liner. To counter such an event, an emergency quench system was incorporated to engage the pre-quench water spray system ahead of the absorber grid. A careful review of the facility to improve potential reliability identified the following spare equipment requirements:

Electric Power	Dual High Voltage Feeders
Sump Pumps	One installed spare pump
Centrifuges	One installed spare centrifuge
Circulation Pumps	One installed spare pump
Limestone system	One installed spare system

Some modifications were made to the AFGD and auxiliaries over the course of the demonstration. Shute angles had to be increased and air cannons added to address handling problems with the highly cohesive gypsum coming out of the dewatering system. Filtrate tanks had to be sealed to prevent unacceptably high humidity in the water processing plant. Agitators had to be added to the absorber tank to prevent buildup of gypsum in dead spots identified. A larger access door was installed to permit entry of maintenance vehicles. The alloy wallpaper construction in the absorber tower wet/dry interface was replaced with a C-276 alloy over carbon steel clad material to reduce maintenance costs. As mentioned previously, the original single fluid WES spray nozzles were replaced by dual fluid (air assisted atomization) nozzles to achieve the desired performance and PowerChip™ was introduced to expand the gypsum market.

Absorber module with flue gas inlet ductwork and process water and sorbent slurry lines

Water (top) and sorbent recycle (bottom) injection lines above absorber grid packing

TABLE 5. ESTIMATED COSTS FOR AN AFGD SYSTEM (1995 CURRENT DOLLARS)

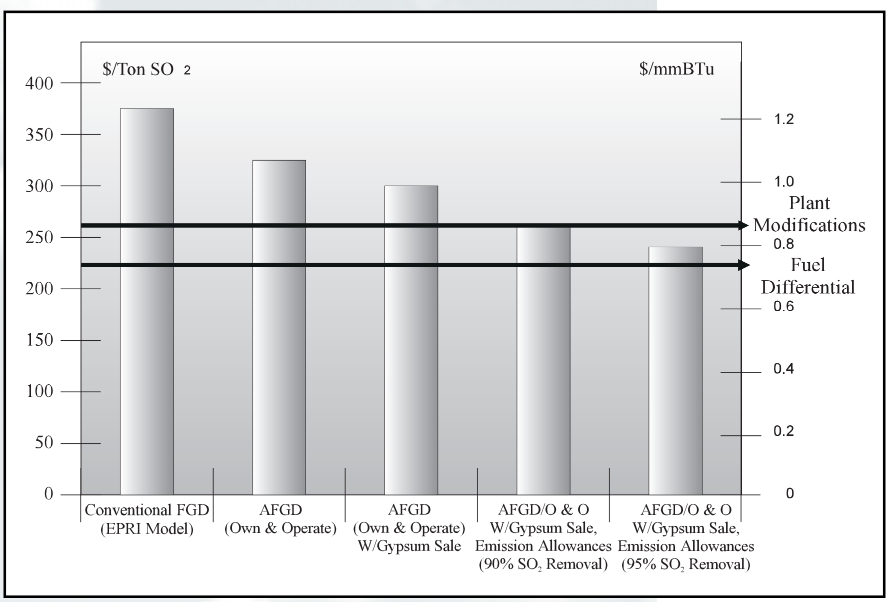
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
Plant Size (MWe)	100	100	100	300	300	300	500	500	500
Coal Sulfur Content (%)	1.5	3.0	4.5	1.5	3.0	4.5	1.5	3.0	4.5
Capital Cost ($/kW)	193	210	227	111	121	131	86	94	101
Levelized Cost ($/ton SO_2)									
—15 year life	1,518	840	603	720	401	294	536	302	223
—20 year life	1,527	846	607	716	399	294	531	300	223
Levelized Cost (mills/kWh)									
—15 year life	16.39	18.15	19.55	7.78	8.65	9.54	5.79	6.52	7.24
—20 year life	16.49	18.28	19.68	7.73	8.62	9.52	5.74	6.48	7.21

ECONOMIC PERFORMANCE

Table 5 summarizes capital and levelized current dollar cost estimates for nine cases with varying plant capacity and coal sulfur content. A capacity factor of 65 percent and a sulfur removal efficiency of 90 percent were assumed. The calculation of levelized cost follows guidelines established in the Electric Power Research Institute's Technical Assessment Guide.

The incremental benefits of own and operate, by-product utilization, and crediting the value of emission allowances were also evaluated. *Figure 2* depicts the relative costs of a hypothetical 500-MWe generating unit in the Midwest burning 4.3 percent sulfur coal with a base case conventional FGD system and incremental cases of AFGD own & operate, AFGD own & operate with gypsum sales ($2/ton), AFGD own & operate with gypsum sales and emission allowance credits at $300/ton (90 percent SO_2 removal), AFGD own & operate with gypsum sales and emission allowance credits at $300/ton (95 percent SO_2 removal). Further, *Figure 2* shows the range of costs for a fuel switching option. The lower bar is the cost of fuel delivered to the hypothetical Midwestern unit and the upper bar allows for some plant modification to accommodate the compliance fuel. Building and operating a conventional FGD system would be more than 50 percent higher than an AFGD with all the incremental savings considered. On the other hand, all the incremental savings would have to be realized to compete with fuel switching.

FIGURE 2. FLUE GAS DESULFURIZATION ECONOMICS
500 MW PLANT–30 YEAR LEVELIZED COSTS ALLOWANCE VALUE = $300/TON



Commercial Applications

The CAAA will impose significant reductions in SO_2 emissions from existing boilers by year 2000 under Phase II of Title IV and place a cap on emissions beyond year 2000. In Phase II, emissions constraints on Phase I units will be tightened and restrictions will be set for the remaining plants at an emission rate of 1.2 pounds per million Btu, down from 2.5 pounds per million Btu for Pre-New Source Performance Standards plants. As a result, the Energy Information Agency expects that allowance prices will increase significantly after 2000, and thereby provide a regulatory push to retrofit almost 32-GWe of capacity by 2010 with more than 30-GWe of retrofit occurring in the five-year period between 2005 and 2010. AFGD also has application to a vast worldwide market as coal-based power consumption grows from 52.8 quads in 1996 to 78.3 quads in 2020, and pressure increases to reduce pollutant emissions.

The CAAA and Energy Policy Act of 1992 have done much to change the environmental control arena from one of "command and control" to "least cost" emphasis. Approaches chosen will be those with the least cost over the life of the generating unit. Compliance may be achieved by the use of low sulfur fuels, the purchase or transfer of SO_2 emission allowances, and many other alternatives. The historic requirement for installation of pollution control systems is absent. Although cost is the primary driving force, the level of risk associated with each compliance strategy comes into play as well. For example, the risk of building an AFGD versus the availability/reliability and price volatility associated with fuel switching must be weighed. Other environmental requirements such air toxics emissions and solid waste disposal must also be considered.

AFGD is positioned well to compete in the pollution control arena of year 2000 and beyond. AFGD has markedly reduced cost and demonstrated the ability to compete with fuel switching under certain circumstances even with a first generation system. Advances in technology, e.g., in materials and components, should improve costs for AFGD. The own-and-operate business approach has done much to mitigate risk on the part of prospective users. High SO_2 capture efficiency places an AFGD user in the possible position of trading allowances or applying credits to other units within the utility. WES and PowerChip™ mitigate or eliminate otherwise serious environmental concerns. AFGD effectively deals with most hazardous air pollutants.

Sorbent recycle injection system inside absorber module

One million gallon gypsum storage silo with flyash hopper (right) and stack (left)

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James U. Watts, FETC, (412) 892-5991

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U.S. DEPARTMENT OF ENERGY

ASSISTANT SECRETARY FOR FOSSIL ENERGY

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