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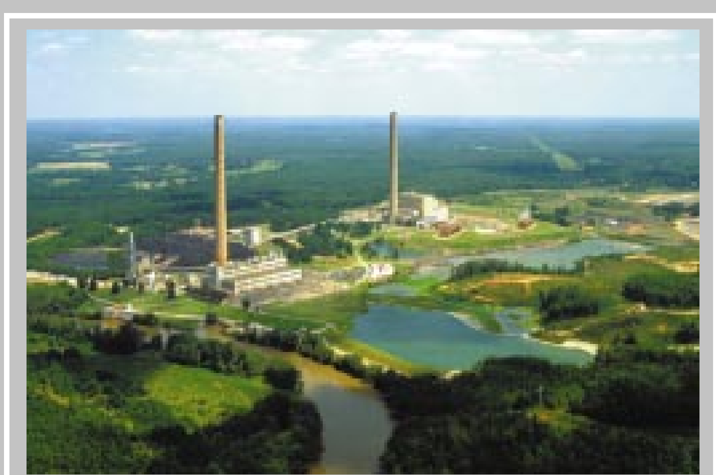
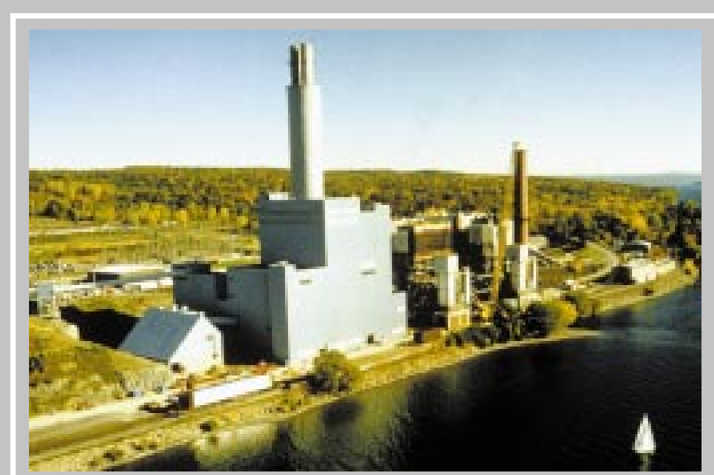
CLEAN COAL TECHNOLOGY





Advanced Technologies for the Control of Sulfur Dioxide Emissions from Coal-Fired Boilers

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A report on three projects conducted under separate cooperative agreements between:

The U.S. Department of Energy and
- Pure Air
- Southern Company Services
- New York State Electric & Gas Corporation

Pure Air

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CLEAN COAL TECHNOLOGY

Advanced Technologies for the Control of Sulfur Dioxide Emissions from Coal-Fired Boilers

Cover image: Plant Views of Bailly, Yates, and Milliken Stations

Executive Summary

The Clean Coal Technology (CCT) Program is a government and industry cofunded effort to demonstrate a new generation of innovative coal utilization processes in a series of "showcase" facilities built across the country. These projects are carried out on a scale sufficiently large to demonstrate commercial worthiness and to generate data for design, construction, operation, and technical/economic evaluation of full-scale commercial applications.

The goal of the CCT Program is to furnish the U.S. energy marketplace with a number of advanced, more efficient coal-based technologies meeting strict environmental standards. These technologies will mitigate the economic and environmental impediments that limit the full utilization of coal as a continuing viable energy resource.

To achieve this goal, beginning in 1985, a multiphased effort consisting of five separate solicitations was administered by the U.S. Department of Energy's (DOE) Federal Energy Technology Center (FETC). Projects selected through these solicitations have demonstrated technology options with the potential to meet the needs of energy markets while satisfying relevant environmental requirements.

Part of this program is the demonstration of technologies, referred to as flue gas desulfurization (FGD) processes, designed to reduce sulfur dioxide (SO_2) emissions from coal-fired power plants. Emissions of SO_2, a precursor of acid rain, are regulated under the provisions of the 1990 Clean Air Act Amendments (CAAA).

This Topical Report discusses three completed CCT projects that successfully demonstrated SO_2 emissions reductions via innovative FGD processes. The goal of all three projects was to achieve greater than 90% SO_2 removal. This goal was achieved, with SO_2 removals as high as 98% being demonstrated. High particulate removal efficiencies were also achieved. In addition, these processes demonstrated the capability of producing wallboard-quality gypsum, a marketable by-product, thereby eliminating the need for FGD sludge disposal, a major problem for many conventional FGD processes.

- *Advanced Flue Gas Desulfurization (AFGD)* was demonstrated at Northern Indiana Public Service Company's Bailly Station, near Gary, Indiana. The project was conducted by Pure Air on the Lake, L.P., a company formed by the process developer, Pure Air, which is a partnership between Air Products and Chemicals, Inc. and Mitsubishi Heavy Industries America, Inc. The scrubber was of unique design, incorporating cocurrent flow of gas and liquid. Coal sulfur content varied between 2.3% and 4.5%, typical of high-sulfur bituminous coals. A total of 210,000 tons of high-quality gypsum was produced during the demonstration and sold to a wallboard manufacturer.
- *Innovative Applications for the CT-121 FGD Process* was demonstrated at Georgia Power's Plant Yates, Newnan, Georgia, using a novel scrubber called a jet bubbling reactor. This single process vessel replaces the usual spray tower/reaction tank/thickener arrangement. The fiberglass-reinforced plastic used as the construction material proved highly corrosion resistant. Coal sulfur content ranged from 1.2% to 4.3%. In addition to SO_2 removal, the system also was highly efficient in removing hazardous air pollutants from the flue gas.
- *Milliken Clean Coal Technology* was demonstrated at New York State Electric & Gas Corporation's (NYSEG) Milliken Station at Lansing, New York. On May 14, 1999, NGE Generation, an affiliate of NYSEG, completed the sale of its coal-fired power plants in New York State, including Milliken Station, to The AES Corporation. The FGD technology demonstrated at Milliken uses the Saarberg-Holter-Umwelttechnik (S-H-U) process, which incorporates a unique cocurrent/countercurrent flow path plus formic acid for enhanced absorption of SO_2. The Stebbins tile-lined, reinforced concrete absorber exhibited superior corrosion and abrasion resistance. FGD availability during the test period was 99.9%. Coal sulfur content averaged 3.2%.

The technologies described in this report are capable of high levels of SO_2 removal and have proven to be very reliable. Through the use of efficient, compact absorber equipment and the elimination of spare reactors, these technologies offer costs significantly lower than those of previous wet FGD processes. As a result, higher standards for FGD performance and economics have been set. With increasingly stringent air quality regulations, these innovative FGD technologies should find numerous commercial applications.

Through these CCT demonstrations and related projects, significant experience has been gained by U.S. suppliers of FGD systems and system components. This expertise includes operating techniques, equipment designs, and selection of materials of construction. These CCT projects have demonstrated advanced features, several of which have been adopted by commercial FGD suppliers, thereby accruing substantial cost savings to U.S. electric utilities and their customers. This has led to cost-effective answers to design challenges for equipment such as reaction vessels, pumps, and a wide variety of other items.

Advanced Technologies for the Control of Sulfur Dioxide Emissions from Coal-Fired Boilers

Background

History

The Clean Coal Technology (CCT) Program, sponsored by the U.S. Department of Energy (DOE), is a government and industry cofunded technology development effort conducted since 1985 to demonstrate a new generation of innovative coal-utilization processes.

The CCT Program involves a series of "showcase" projects, conducted on a scale sufficiently large to demonstrate commercial worthiness and generate data for design, construction, operation, and economic/technical evaluation of full-scale commercial applications. The goal of the CCT Program is to furnish the U.S. energy marketplace with advanced, more efficient coal-based technologies meeting strict environmental standards. These technologies will mitigate some of the economic and environmental impediments that inhibit the full utilization of coal as an energy source.

Environmental Regulations

Concurrent with the development of the CCT Program by DOE, the U.S. Environmental Protection Agency (EPA) has promulgated regulations under the 1990 Clean Air Act Amendments (CAAA) controlling emissions from a variety of stationary sources, including coal-burning boilers. The CCT Program has opened a channel to policy-making bodies by providing data from cutting-edge technologies to aid in formulating regulatory decisions. For example, results from several CCT projects have been provided to EPA to help establish achievable nitrogen oxides (NOx) emissions targets for coal-fired boilers subject to CAAA compliance.

Control of SO_2 Emissions

A major goal of the CCT Program is the demonstration of technologies designed to reduce emissions of sulfur dioxide (SO_2) from coal-fired utility boilers. Many U.S. coals have a sufficiently high sulfur content to cause SO_2 emissions to exceed air quality regulations. For operators of boilers

Loading FGD by-product gypsum for transport to wallboard plant.

burning such coals, three major compliance options are available:

- Switch fuels (low-sulfur coal or natural gas)
- Purchase SO_2 credits (allowances) on the open market
- Employ flue gas desulfurization (FGD) technologies.

Use of low-sulfur coals is quite common, but may result in reduced boiler output, since these fuels frequently have a lower heat content. Natural gas is more expensive than coal and may not be available at the site. Since the price of SO_2 allowances is rising, FGD is becoming the choice for more and more boiler owners.

Types of FGD Processes

FGD processes can be categorized as (a) wet and (b) dry or semidry systems. In most wet FGD systems, SO_2 is removed from the flue gas by reaction with a calcium-based sorbent in an aqueous solution or slurry. A relatively high degree of SO_2 removal is usually achieved, with a high level of sorbent utilization. In addition, wet FGD systems generally achieve excellent particulate removal because of intimate contact between the gas and liquid phases.

Dry and semidry FGD systems involve injecting a solid sorbent (dry), usually limestone, or a sorbent slurry (semidry), usually lime, into the furnace or flue gas duct; the by-product solids are collected in a dry form along with the flyash from the boiler in the existing particulate removal equipment. Compared with wet FGD systems, SO_2 removal efficiency and sorbent utilization are usually lower.

This report reviews the results of demonstrations of three innovative wet FGD processes conducted under the auspices of the CCT Program.

Emissions Standards

The Clean Air Act was originally passed in 1970. It was amended in 1977 and most recently in 1990. The CAAA authorized EPA to establish new standards for a number of atmospheric pollutants, including SO_2 and NOx. Periodic review of the emissions standards every five years is mandated.

SO_2 Emissions Standards

Under Phase II of Title IV, the CAAA impose significant reductions in SO_2 emissions from existing boilers by 2000 and place an annual cap on emissions beyond 2000. The Phase II allowable SO_2 emissions rate is 1.2 lb/million Btu input, down from 2.5 lb/million Btu in Phase I.

The CAAA provide for SO_2 emissions allowances (each allowance permits the emission of 1 ton of SO_2). As part of a trading program, allowances can be bought and sold on the open market. To date, allowance prices have been relatively low, with the result that many utilities have opted to purchase allowances instead of installing FGD systems. However, SO_2 allowance prices have been increasing recently, thereby providing the potential for development of a large-scale retrofit market for FGD technologies.

To meet forthcoming emissions regulations, especially when burning high-sulfur coals, it is essential to achieve high levels of SO_2 removal, usually 90% or higher. Even higher levels of SO_2 removal can be beneficial, since this is a way to generate emissions allowance credits.

Sorbent recirculation system at Bailly Station.

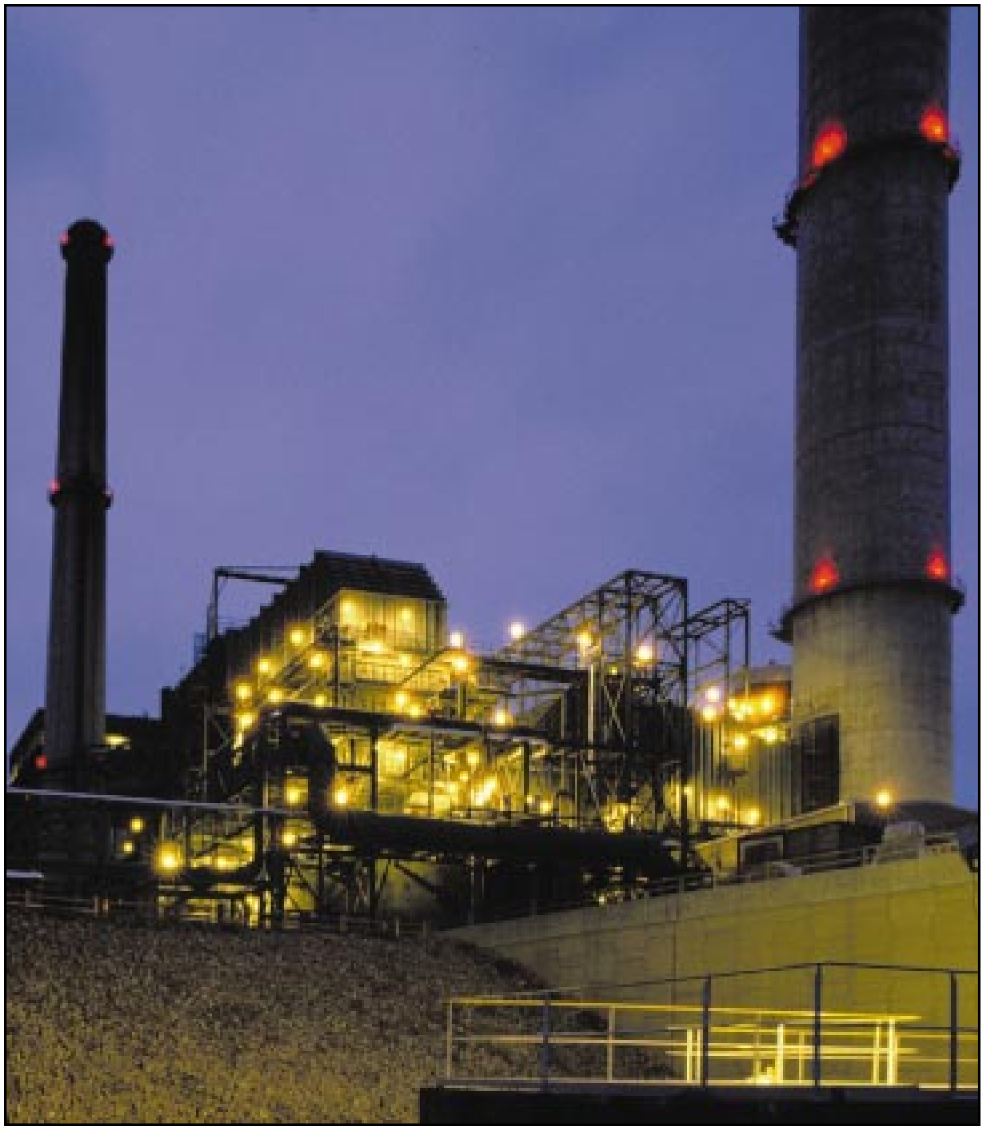
Clean Coal Technology Wet FGD Demonstration Projects

This report discusses three CCT projects involving innovative wet FGD technologies:

- Advanced Flue Gas Desulfurization (AFGD) Demonstration Project
- Demonstration of Innovative Applications of Technology for the CT-121 FGD Process
- Milliken Clean Coal Technology Demonstration Project

Each of the technologies demonstrated uses limestone ($CaCO_3$) as a sorbent and is capable of producing wallboard-grade gypsum as a by-product. A major goal of these projects was to demonstrate greater than 90% SO_2 removal at a cost substantially lower than that of conventional wet FGD processes.

Advanced Flue Gas Desulfurization (AFGD) Demonstration Project



Night view of Bailly Generation Station.

Project Description

This project was selected during Round II of DOE's CCT Program. In December 1989, Pure Air on the Lake, L.P. entered into an agreement to conduct this demonstration project. Pure Air on the Lake is a company formed to carry out this project by Pure Air, a general partnership between Air Products and Chemicals, Inc. and Mitsubishi Heavy Industries America, Inc.

The host site was the Bailly Generating Station of Northern Indiana Public Service Company (NIPSCO), located about 12 miles northeast of Gary, Indiana. The site is immediately adjacent to the Indiana Dunes National Lakeshore, along the southern edge of Lake Michigan. The demonstration was conducted between June 1992 and June 1995, treating the combined flue gases from two boilers (Units No. 7 and 8) having a total nameplate capacity of 616 MWe. Total project cost was $152 million, of which DOE provided $64 million, or 42%.

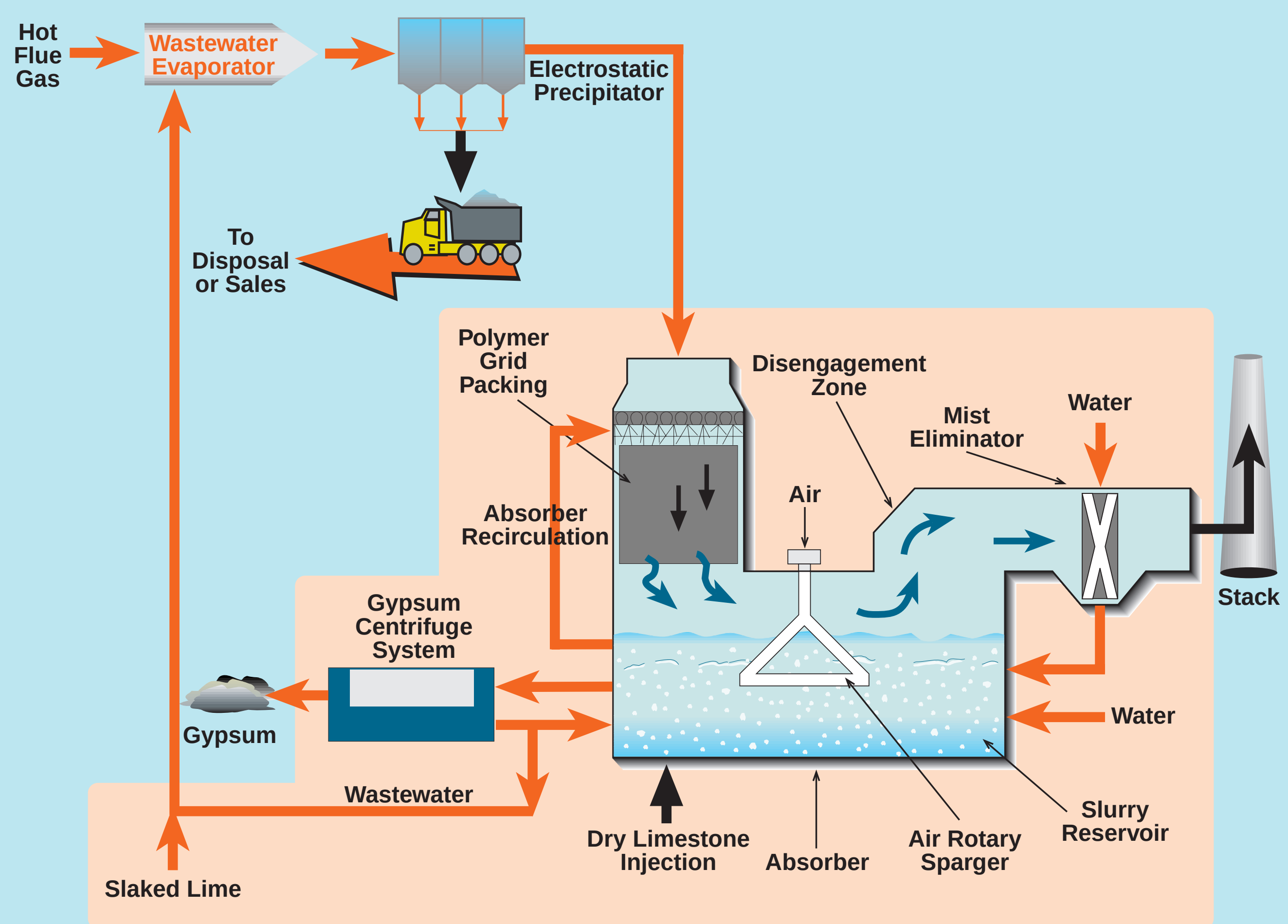
The project consisted of installing a scrubber of unique design involving co-current flow of gas and liquid, an air rotary sparger (ARS) located within the base of the absorber, and a novel wastewater evaporation system (WES). The project also included a gypsum agglomeration process known as PowerChip®, which enhances the handling and transportability characteristics of the by-product gypsum. The result is a stable, densely agglomerated, semidry flake with handling properties equivalent to natural gypsum rock.

Adding PowerChip® technology expands the potential market for the gypsum by-product. Gypsum made at the Bailly Station is sold to United States Gypsum Company for wallboard manufacture at its East Chicago, Indiana, plant. The East Chicago plant is the first facility in North America to produce wallboard from 100% FGD gypsum.

Process Description

The AFGD process accomplishes SO_2 removal in a single absorber which performs three functions: prequenching the flue gas, absorption of SO_2, and oxidation of the resulting calcium sulfite to wallboard-grade gypsum.

Description of the Advanced Flue Gas Desulfurization (AFGD) Demonstration Unit at Bailly Station



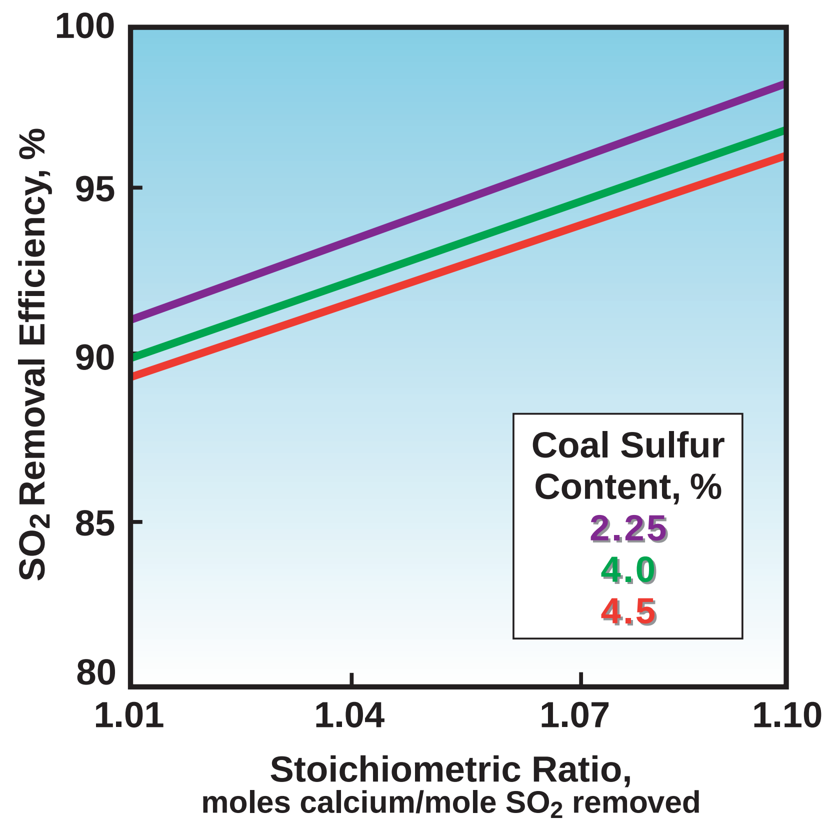
Incoming flue gas is cooled and humidified with process water sprays before passing to the absorber. In the absorber, two tiers of fountain-like sprays distribute reagent slurry over polymer grid packing that provides a large surface area for gas/liquid contact. The gas then enters a large gas/liquid disengagement zone above the slurry reservoir in the bottom of the absorber and exits through a horizontal mist eliminator.

After contacting the flue gas, slurry falls into the slurry reservoir where any unreacted acids are neutralized by limestone injected in dry powder form into the reservoir. The primary reaction product, calcium sulfite, is oxidized to gypsum by the air rotary spargers, which both mix the slurry in the reservoir and inject air into it. Fixed air spargers assist in completing the oxidation. Slurry from the reservoir is circulated to the absorber grid.

A slurry stream is drawn from the tank, dewatered, and washed to remove chlorides and produce wallboard quality gypsum. The resultant gypsum cake contains less than 10% water and 20 ppm chlorides. The clarified liquid is returned to the reservoir, with a slipstream being withdrawn and sent to the wastewater evaporation system for injection into the hot flue gas ahead of the electrostatic precipitator. Water evaporates and dissolved solids are collected along with the flyash for disposal or sale.

Important features of the AFGD project technology are:

- The use of cocurrent flow to permit high flue gas velocities (up to 20 feet per second) and compact design
- A non-pressurized slurry distribution system that requires approximately 30% less recirculation pump power than conventional countercurrent scrubbers
- Fountain-like flow that doesn't generate a fine mist, thereby reducing mist eliminator loading by as much as 95% compared to countercurrent designs
- Use of a dry pulverized limestone direct injection system, eliminating the need for ball mills, tanks, pumps, and other equipment associated with onsite wet grinding systems
- Use of an ARS, combining agitation and oxidation, that significantly enhances scrubber performance
- Incorporation of WES to control chlorides without creating a new waste stream
- Use of the PowerChip® system, incorporating a compression mill operating at an optimum compacting pressure and cure time/temperature relationship to change the physical structure of the gypsum



SO_2 removal performance at Bailly Station (76% of design liquid-to-gas flow ratio).

Results

The AFGD unit successfully achieved the target of removing more than 90% of the SO_2 from the flue gas. Five Midwestern bituminous coals, having sulfur contents between 2.25% and 4.5%, were burned during this demonstration. SO_2 removal efficiency averaged 94%, with a maximum of over 98%. The facility was operated for 26,300 hours during the demonstration, with system availability of 99.5%. High availability eliminates the need for a spare absorber.

Variables studied in the test program included the sulfur content of the coal, the slurry recirculation rate, the ratio of calcium injected to SO_2 in the flue gas, and the liquid-to-gas ratio in the absorber.

U.S. Gypsum has taken the entire by-product gypsum output from the Bailly AFGD unit. During the three-year demonstration, gypsum production exceeded 210,000 tons, with an average purity of 97.2%.

Business Arrangement

An important innovation with the AFGD project was a business arrangement whereby Pure Air owns and operates the FGD system on behalf of NIPSCO, thus relieving the utility of day-to-day operating and maintenance responsibilities.

Emissions Standards

History

The Clean Air Act of 1970 established a major air regulatory role for the federal government. The Act was extended by amendments in 1977 and most recently in 1990. The 1990 CAAA is one of the most complex and comprehensive pieces of environmental legislation ever written. It authorizes EPA to establish standards for a number of atmospheric pollutants, including sulfur dioxide (SO_2).

SO_2 Emissions Standards

SO_2 is formed through the combustion of sulfur contained in coal. Burning typical medium- and high-sulfur coals produces SO_2 emissions that exceed the allowable limits under the CAAA. Two major portions of the CAAA relevant to SO_2 control are Title I and Title IV. Title I establishes National Ambient Air Quality Standards (NAAQS) for six criteria pollutants, including SO_2. The 24-hour average ambient air standard for SO_2 under Title I is 0.14 ppm.

Title IV addresses controls for specific types of stationary boilers, including those found in coal-fired power plants. Title IV is often referred to as the Acid Rain Program. The overall goal of Title IV is to achieve environmental and public health benefits through reductions in emissions of SO_2 as well as reduced nitrogen oxides (NOx) and particulates emissions.

Title IV uses a two-phase SO_2 control strategy. Phase I began in 1995 and affects 263 units at 110 mostly coal-burning electric utility plants located in 21 Eastern and Midwestern states. An additional 182 units joined the program as substitution or compensating units, bringing the total of Phase I affected units to 445.

Phase II, which begins January 1, 2000, tightens annual emissions limits and also sets restrictions on smaller plants fired by coal, oil, and gas. The Title IV Phase I SO_2 emissions limit is 2.5 lb/million Btu of heat input to the boiler. This decreases to 1.2 lb/million Btu in Phase II.

Title IV allows sources to select their own compliance strategies. To reduce SO_2 emissions an affected source may repower, use cleaner burning fuel, reassign some of its energy production from dirtier to cleaner units, or reduce fuel consumption by improving efficiency. In general, no prior approval is required, allowing sources to respond quickly to market conditions.

The SO_2 Trading Allowance Program

The Acid Rain Program represents a dramatic departure from traditional regulatory methods that establish specific, inflexible, emissions limits with which all affected sources must comply. Instead, the program introduces an allowance trading system that harnesses the incentives of the free market to reduce pollution. Affected utility units have been allocated allowances based on their historic fuel consumption. Each allowance permits a unit to emit one ton of SO_2; for each ton of SO_2 emitted, one allowance is retired.

Allowances may be bought, sold, or banked. Anyone may acquire allowances and participate in the trading system. However, regardless of the number of allowances held, a source may not emit pollutants at levels that would violate federal or state limits set under Title I of the CAAA to protect public health.

In Phase II, the CAAA set a permanent ceiling (or cap) of 8.95 million annual allowances allocated to utilities. This cap firmly restricts SO_2 emissions and ensures that environmental benefits will be achieved and maintained.

The allowance trading system contains an inherent incentive for utilities to reduce pollution, since for each ton of SO_2 that a utility avoids emitting, one fewer allowance must be retired. Utilities that reduce emissions below their allowance allocation are able to sell, transfer, or bank their surplus allowances.

Title IV includes an optional program involving voluntary reduction of SO_2 emissions. This program allows sources not regulated under Title IV the opportunity to participate on a voluntary basis, reducing their emissions and, thereby, receiving SO_2 allowances.

EPA invited broad input into the development of Title IV by consulting with representatives from various stakeholder groups and is maintaining this open-door policy as it implements the program. The Acid Rain Program is viewed as a prototype for tackling emerging environmental issues. The allowance trading system capitalizes on the power of the marketplace to reduce SO_2 emissions in the most cost effective manner.

Costs

Pure Air developed cost estimates for commercial implementation of the AFGD technology, covering a range of plant capacities and coal sulfur contents. For a 500-MWe power plant firing a 3% sulfur coal and operating at 90% SO_2 emissions reduction, the capital cost is estimated at $94/kW. For a 15-year project life, the levelized cost on a current dollar basis is 6.5 mills/kWh, which is equivalent to $302/ton of SO_2 removed. These costs are about one-half those of a conventional wet FGD process.

The advanced design features of the AFGD technology result in a comparatively smaller scrubber, one that requires less plot area, less material to construct, and has much lower capital and operating costs than conventional scrubbers.

Awards

The Bailly AFGD project received a 1992 Outstanding Engineering Achievement Award from the National Society of Professional Engineers and Power magazine's 1993 Powerplant Award.

Conclusions

This project shows that a single absorber can provide flue gas desulfurization for a power plant of at least 600-MWe capacity and that no spare absorber is required. It also shows that pulverized limestone can be successfully injected directly into an absorber.

Wastewater evaporation in the flue gas duct eliminates the need for liquid waste disposal, and use of the gypsum by-product for wallboard manufacture eliminates the need to dispose of solid waste.

A unique own-and-operate business arrangement successfully handles the processing of flue gas, relieving the host utility of these responsibilities. The Bailly AFGD scrubber continues to operate commercially under a long-term agreement between NIPSCO and Pure Air.

Limestone and lime silos for AFGD Demonstration Project, adjacent to Indiana Dunes National Lakeshore.

The Indiana Dunes

Adjacent to the Pure Air project site, only about 300 feet away, are the Indiana Dunes National Lakeshore and the Indiana Dunes State Park. The State Park was established in 1926, followed by establishment of the adjacent National Lakeshore in 1996. Together, these two parks span about 20 miles along the southern shore of Lake Michigan.

The Indiana Dunes consist of large sand dunes at the lake's edge, behind which is an area of dunes whose plant cover has evolved to mature forests. With 1,445 native plant species present, the area is a botanist's dream with variety exceeded in the United States only by the Grand Canyon and Great Smoky Mountains National Parks. Overlapping ranges of plant species converge at the dunes, where plants usually found in warmer climates (orchids, cacti, and carnivorous plants) grow alongside species more typical of Canadian forests and the tundra (Arctic bayberry, jack pine, and northern rose).

This unusual diversity of plant life serves to attract a wide variety of wildlife to the area. For example, nearly 350 species of birds have been sighted in the dunes, ranging from waterfowl (geese, ducks, and swans) to raptors (hawks, falcons, and eagles). The National Lakeshore staff even manages a nearby heron rookery.

From 1895 to 1934, the Indiana Dunes served as the laboratory for Henry C. Cowles, a professor at the University of Chicago who was eulogized as being America's first professional ecologist. At the Indiana Dunes, Dr. Cowles studied the effects of geological formations on plant communities and the transformation of habitat by those communities.

Amidst the kaleidoscope of plant communities found at the dunes, Cowles recognized some patterns. As the habitat changed, proceeding inland from beachfront to forested dunes, he observed a succession of plant communities—ranging from grasses that colonize the beachfront dunes to increasingly complex cottonwood, pine, oak, and beech-maple forests. This principle of ecological succession is important enough that when ten European botanists were asked what sites they wanted to see on their trip to America in 1913, they responded, "The Grand Canyon, Yosemite, and the Indiana Dunes." Scientific investigations are still performed at the Indiana Dunes, largely under the auspices of a staff of scientists at the National Lakeshore.

It is fitting that the AFGD demonstration project is located in the midst of this environmentally sensitive area. In addition to such features as reduced SO_2 emissions, production of commercial gypsum instead of sludge, and wastewater evaporation, the project includes extensive environmental monitoring.

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

Project Description

In April 1990, Southern Company Services entered into an agreement with DOE to conduct this project, which was selected during Round II of DOE's CCT Program. The demonstration was hosted at Georgia Power Company's Plant Yates, Unit 1, located at Newnan, Georgia. This unit is a 100-MWe (net) pulverized-coal fired boiler. Total project cost was $43 million, of which DOE provided $21 million, or 49%.

The project involved installation of the Chiyoda CT-121 FGD process, that includes a specially designed absorber known as a Jet Bubbling Reactor® (JBR), made of fiberglass-reinforced plastic (FRP). A primary objective was to demonstrate reliable, long-term operation of the JBR. Coal sulfur content ranged from 1.2% to 4.3%.

Process Description

A major innovative feature of the CT-121 process is the use of a single absorber vessel — Chiyoda's patented JBR — in place of the spray tower/reaction tank/thickener arrangement used in conventional FGD systems. The JBR combines SO_2 absorption in a limestone slurry, oxidation of sulfite to sulfate, and gypsum crystallization.

Much of the undesirable crystal attrition and secondary nucleation associated with the large centrifugal pumps used for slurry recirculation in conventional FGD systems is eliminated in the CT-121 design. The result is that large, easily dewatered, gypsum crystals are consistently produced. The CT-121 design also significantly reduces the potential for gypsum scale growth, a problem that frequently occurs in conventional FGD systems.

The gypsum storage area at Plant Yates has three separate cells: a "clean" gypsum stack area, a gypsum/flyash stack area, and a recycle water pond. The stacks are used to store and dewater the solids, with clear, decanted process water being collected in the common pond area and returned to the process.

Aerial view of Yates Electric Station.

SO_2 Emissions Control Technologies

Overview

Most SO_2 control technologies involve the addition of a calcium-based sorbent to the system. Under the proper conditions, this material reacts with SO_2 to form calcium sulfite ($CaSO_3$), which is then oxidized to calcium sulfate ($CaSO_4$). Because of their low cost, limestone and lime are the most frequently used sorbents.

In the majority of applications, the sorbent is dissolved in, or slurried with, water; flue gas contacts the solution or slurry in a scrubber. Alternatively, the sorbent is injected directly into the furnace or flue gas duct.

Historical Note

The notion of scrubbing SO_2 from coal-derived flue gas dates back to the 1920s and 30s, when the first scrubbers were built in Great Britain. These facilities were shut down during World War II so that the British power plants would not be detected by aircraft that could follow the vapor plumes. Interestingly, even these first scrubbers were capable of removing 90% of the SO_2. Scrubber technology continued to evolve through the 1960s, with installations in Europe, Japan, and the United States. However, widespread application in the United States did not occur until enactment of the Clean Air Act of 1970.

In the United States, a number of coal-fired power plants were equipped with scrubbers during the 1970s and early 1980s. These scrubbers were, for the most part, installed at newly constructed power plants, because existing plants were exempt under the law. When domestic power plant construction decreased in the 1980s, the market for scrubber technology moved overseas, where improvements were made. With the advent of acid rain controls for older units under the 1990 Clean Air Act Amendments (CAAA), a new market for scrubber technology began to emerge in the United States. Technology developments continue to improve performance and reduce costs.

Dry and Semidry Sorbent Injection

A reactive calcium- or sodium-based sorbent is injected into the economizer or flue gas duct, where the particles react with SO_2 and are subsequently removed along with flyash by the boiler's particulate control device. The two most common calcium-based sorbents are limestone, $CaCO_3$, and slaked lime, $Ca(OH)_2$. Limestone, which generally requires a higher reaction temperature, is usually injected as a dry powder. Lime, on the other hand, is usually handled as a slurry that dries as soon as it is injected into the hot flue gas.

This is referred to as semidry scrubbing, which dominates the sorbent injection market. All commercial semidry systems in the U.S. use lime and recycled fly ash as sorbent. These systems account for 8-10% of the installed FGD capacity in the U.S.

Sulfuric Acid Production

Although less commonly used, another approach is to oxidize the SO_2 to SO_3 over a catalyst and absorb it in water to form sulfuric acid, which can be sold for a variety of uses, such as metals pickling.

Conventional Wet FGD Technology

Conventional wet FGD systems are typically designed for SO_2 removal efficiencies of about 90%, a level required to meet air quality standards when burning high-sulfur coals.

The processing scheme for most wet FGD systems is essentially as follows. Flue gas from the particulate collector flows to the SO_2 absorber, the energy necessary to overcome the FGD system pressure drop being provided by the boiler induced draft (ID) fans. In the absorber, a variety of technology specific devices achieve intimate contact of the flue gas with the sorbent slurry. Gas flow per unit cross sectional area, which determines scrubber diameter, must be low enough to minimize entrainment. Mass transfer characteristics of the system determine absorber height. Absorber vessels tend to be quite large in practice.

Following contact with the slurry, the scrubbed flue gas passes through mist eliminators, which remove entrained slurry droplets. Periodic washing using fresh water keeps the mist eliminators clean and provides make-up water to the FGD system.

In the absorber, SO_2 reacts with limestone, forming calcium sulfite. Limestone is supplied either as a dry solid or a slurry. The sulfite is subsequently oxidized in a separate reaction tank to form calcium sulfate, which crystallizes as gypsum ($CaSO_4 \cdot 2H_2O$). The residence time of solids in the reaction tank is generally in the range of 15 to 25 hours. This extended residence time, coupled with proper reaction tank design and operation, provides an environment conducive to gypsum crystal growth.

In some processes, pumps recirculate slurry from the reaction tank to the scrubber to provide the volume of slurry necessary to maintain good gas/slurry contact and ensure high SO_2 removal efficiency. The slurry in the recycle tank is agitated to maintain the solids in suspension and prevent solids buildup on the tank bottom.

A small slipstream of slurry is sent to a primary dewatering system, which recovers solids (gypsum and flyash). The dewatering system is designed to concentrate the gypsum crystals to an ultimate solids content of 85% to 90% (dewatered gypsum has the consistency of wet sand). The gypsum is conveyed to an on-site waste disposal landfill or shipped to a processing facility where the by-product gypsum is utilized for wallboard or cement manufacture.

Recovered process water is returned to the absorption and reagent preparation systems.

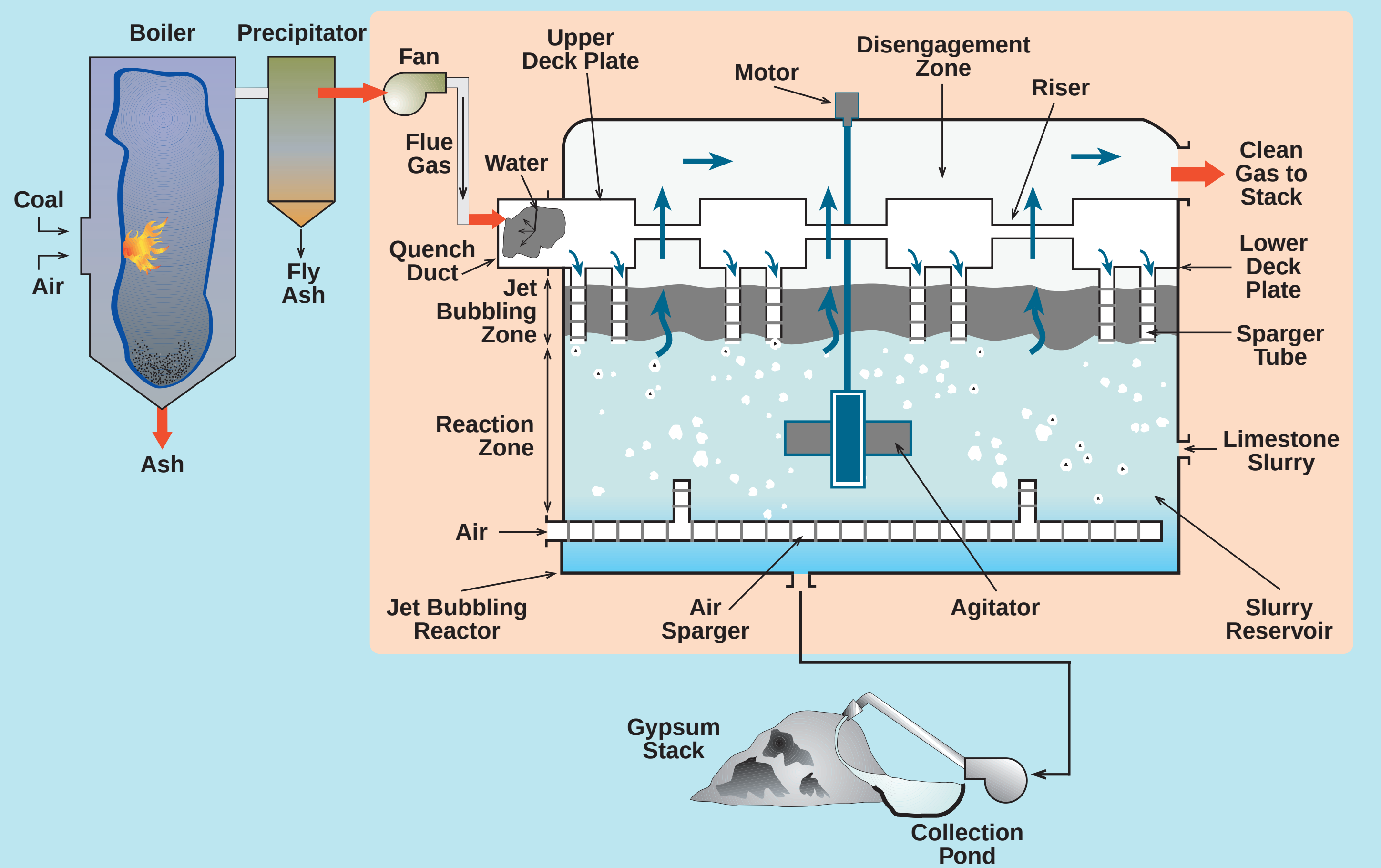
Over its life, a 500-MWe coal-fired power plant with a conventional wet scrubber produces enough sludge to fill a 500-acre disposal pond 40 feet deep. Early scrubbers were plagued by poor reliability, often requiring the installation of spare modules as back-up to ensure continuous flue gas cleanup.

Innovative Wet FGD Technology

The innovative scrubbers described in this report are a significant improvement over 1970s wet scrubber technology, featuring state-of-the-art designs and materials of construction. Highly efficient, compact, and less expensive to construct and operate, these scrubbers eliminate waste disposal problems by incorporating oxidation of the calcium sulfite sludge to wallboard-grade gypsum. Because of high process reliability, spare scrubber modules are not required.

Advanced features developed in these CCT projects have been widely adopted by scrubber vendors and, more importantly, the U.S. electric utility industry. These demonstration projects have resulted in increased competition, pointing the scrubber market toward fewer but larger absorber vessels, salable by-products, and better equipment guarantees. The resultant savings to U.S. electricity customers amount to billions of dollars in reduced costs for CAAA compliance.

Description of the CT-121 Process Demonstration Unit at Plant Yates



Flue gas enters the scrubber inlet gas cooling section downstream of the boiler's ID fan, which also serves as the scrubber's booster fan. In the gas cooling section, the flue gas is cooled and saturated using diluted Jet Bubbling Reactor™ (JBR) slurry. From the gas cooling section, the flue gas enters an enclosed plenum chamber in the JBR, formed by the upper and lower deck plates.

Sparger tubes mounted in the floor of the inlet plenum conduct the flue gas below the level of the slurry reservoir in the jet bubbling zone (froth zone) of the JBR. After bubbling through the slurry, the gas flows upward through large gas riser tubes that bypass the inlet plenum.

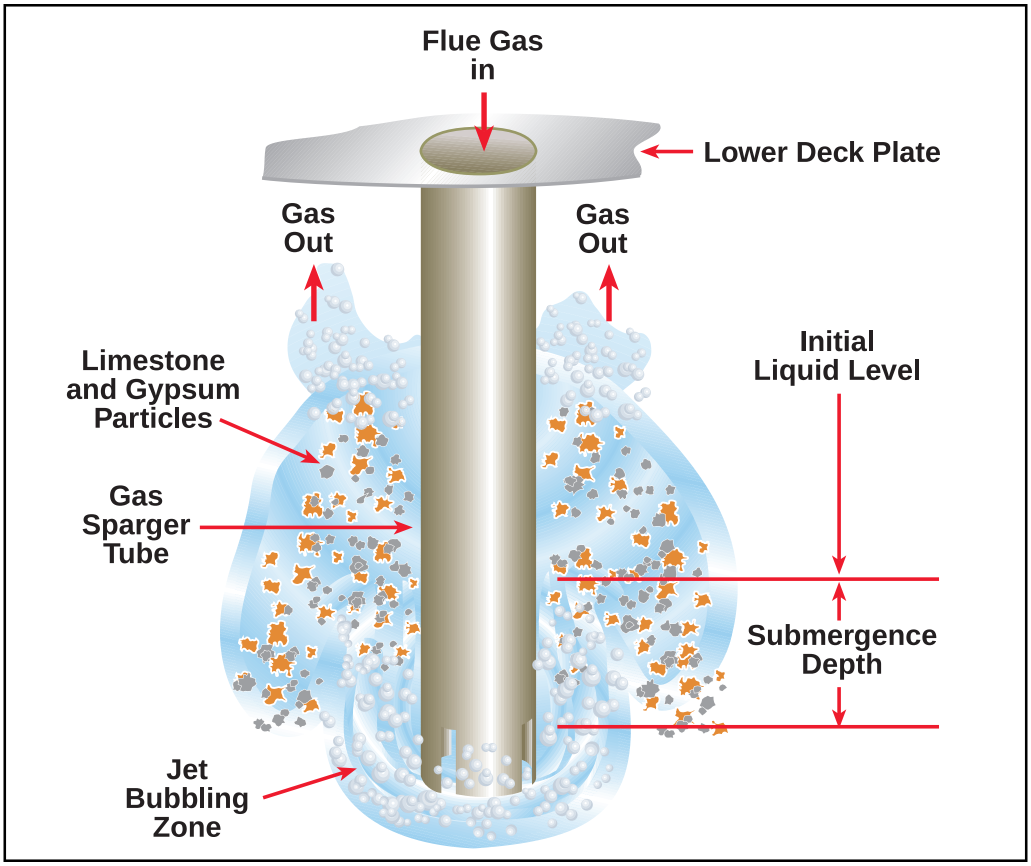
The cleaned gas enters a second plenum above the upper deck plate, where, because of a large decrease in velocity, entrained liquor is disengaged. The cleaned gas passes to a two-stage, chevron-style, horizontal-flow mist eliminator, then on to a wet fiberglass-reinforced plastic chimney.

A closed-circuit, wet ball mill limestone preparation system is used to grind raw (≤ 3/4") limestone to a particle size small enough (90% through a 200-mesh screen) to ensure rapid reaction and minimize the amount of unreacted limestone in the JBR.

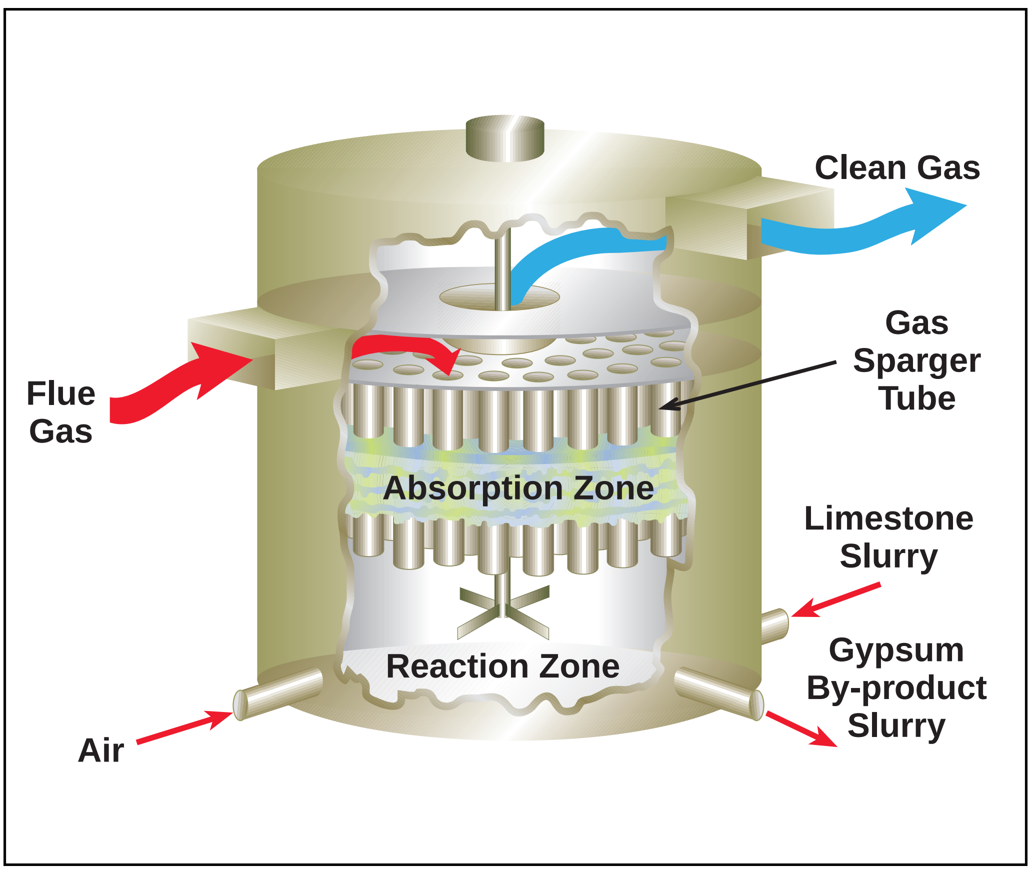
The JBR slurry reservoir provides about 36 hours of solid-phase residence time, depending on the SO_2 absorption rate. For JBR slurry level and density control, slurry from the JBR is pumped intermittently to a gypsum slurry transfer tank. It is then diluted for pumping to a Hypalon®-lined gypsum (or gypsum/ash) stacking area for gravity dewatering and storage.

Gypsum stacking involves filling a lined, diked area with slurry for gravity sedimentation. Over time, this area fills with settled solids. The filled area is then partially excavated, with the excavated material used to increase the height of the containment dikes. The repetitive cycle of sedimentation, excavation, and raising of perimeter dikes continues on a regular basis during the active life of the stack. Process water is decanted, stored in a surge pond and then returned to the CT-121 process.

The amount of SO_2 removed from the flue gas is controlled by varying the slurry pH or the depth of submergence of the flue gas spargers in the JBR. Higher liquid levels result in increased SO_2 removal because of increased contact time between the flue gas and the slurry.



Detail of gas sparger tube.



Schematic of Chiyoda's Jet Bubbling Reactor with gas sparger action.

SO_2 Formation and Removal

Combustion

All coals contain sulfur. Some of this sulfur, known as organic sulfur, is intimately associated with the coal matrix. The rest of the sulfur, in the form of pyrites or sulfates, is associated with the mineral matter. High-sulfur bituminous coals contain up to about 4% sulfur, whereas low-sulfur Western coals may have a sulfur content below 1%.

Upon combustion, most of the sulfur is converted to SO_2, with a small amount being further oxidized to sulfur trioxide (SO_3).

$S(Coal) + O_2 \text{---->} SO_2$
$SO_2 + {}^1/_2\, O_2 \text{---->} SO_3$

Because, in the absence of a catalyst, the formation of SO_3 is slow, over 98% of the combusted sulfur is in the form of SO_2.

Effective January 1, 2000, the SO_2 emissions limit for coal-fired power plants is 1.2 lb/million Btu. To comply with this regulation without FGD, the maximum sulfur content for a coal having a higher heating value of 12,000 Btu/lb is 0.72% by weight, assuming 100% conversion of sulfur to SO_2.

Wet FGD

The major reactions occurring in wet FGD processes are shown by the following equations:

Absorption

$SO_2 + H_2O \text{---->} H_2SO_3$
$SO_3 + H_2O \text{---->} H_2SO_4$

Neutralization

$CaCO_3 + H_2SO_3 \text{---->} CaSO_3 + CO_2 + H_2O$
$CaCO_3 + H_2SO_4 \text{---->} CaSO_4 + CO_2 + H_2O$

Oxidation

$CaSO_3 + {}^1/_2\, O_2 \text{---->} CaSO_4$

Crystallization

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

Results

When high-sulfur coal was burned at maximum boiler load at Plant Yates, the CT-121 scrubber exceeded the target 90% SO_2 removal efficiency and demonstrated excellent availability. Limestone utilization was greater than 97%. Maximum SO_2 removal was about 98% when burning 2.2% sulfur coal, and about 95% with 3.5% sulfur coal. Since removal efficiency is controlled by adjusting the depth of submergence of the flue gas spargers, it is relatively simple to compensate for the higher sulfur content, thereby maintaining SO_2 removal efficiency.

Materials of Construction

As indicated previously, one of the novel aspects of the CT-121 design is the use of fiberglass-reinforced plastic to avoid the corrosion damage associated with traditional closed-loop FGD systems. Both the JBR and the inlet transition duct, where flue gas is cooled prior to contacting the sparger tubes, are made completely of FRP. A distinct advantage of this construction is that it eliminates the need for a flue gas prescrubber, traditionally included in FGD systems to remove chlorides that cause serious corrosion in alloys.

Exposed surfaces at Plant Yates were coated with homogeneous filler materials (Duromar® and Duromix®) to protect against erosion. The use of FRP was very successful; this material proved to be durable both structurally and chemically. The chimney resisted corrosion from condensates in the wet flue gas, thereby precluding the need for flue gas reheat. The high reliability verified that a spare absorber is not necessary.

Particulate Removal

In 1993, the Yates CT-121 Project was chosen by DOE as one of eight coal-fired sites for a study of hazardous air pollutants (HAPs) conducted on EPA's behalf. The project investigated the fate of HAPs at a number of plants that utilize a variety of air pollution control technologies.

At all tested conditions, the JBR exhibited excellent particulate removal efficiency, ranging from 97.7% to 99.3%. The JBR also removed from 40% to 95% of HAPs. Since much of the HAPs of interest are associated with the particulate phase, removal of particulates effectively removes the HAPs. Additional testing in 1994 confirmed that the Chiyoda CT-121 JBR is highly efficient at HAPs removal.

Gypsum Quality

The gypsum was of wallboard quality except for high chloride content, which would require washing for removal.

In 1996, Georgia Power received a Plant Food Permit from the State of Georgia that allows the unrestricted sale of ash-free gypsum from the Yates project for agricultural purposes. This market exceeds 1 million tons/yr in Georgia alone.

Costs

Projected capital costs for commercial implementation of the CT-121 process are in the range of \$80-\$95/kW. Levelized cost estimates are not available.

Awards

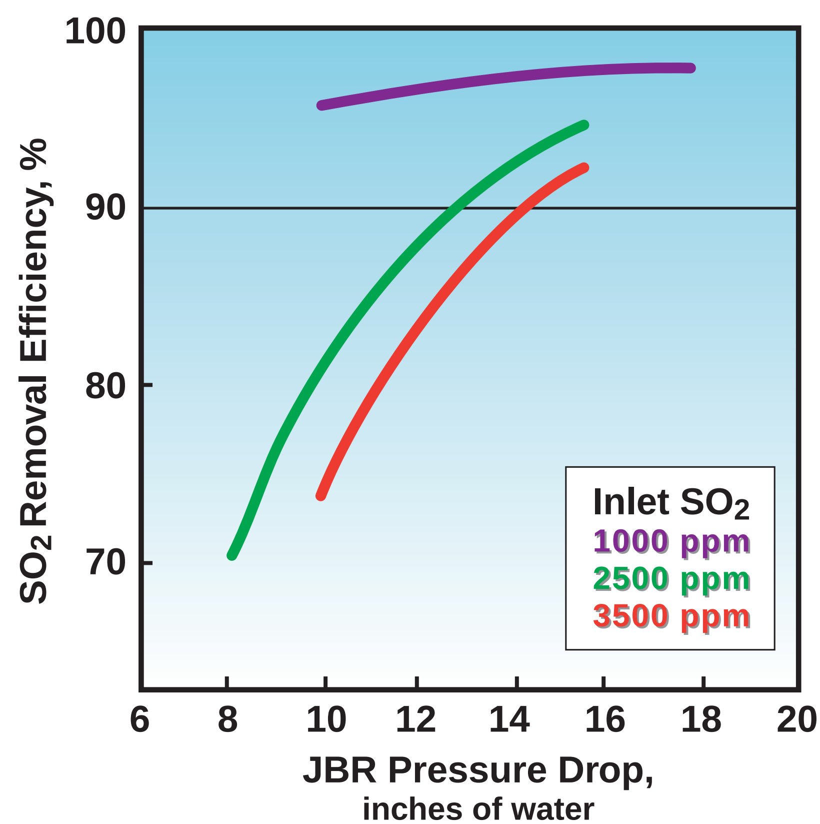
The Yates CT-121 project received Power magazine's 1994 Powerplant Award, the Society of Plastic Industries' 1995 Design Award, and environmental awards from the Air & Waste Management Association and the Georgia Chamber of Commerce.

Hazardous Air Pollutants

Hazardous air pollutants (HAPs), also referred to as toxic air pollutants or air toxics, are generally defined as atmospheric pollutants that are known or suspected to cause serious health problems. HAPs are emitted by motor vehicles and a variety of industrial sources and may exist as particulate matter or as gases. HAPs include metals and other particulates, gases adsorbed on particulates, and certain vapors, such as benzene, from fuels and other sources.

For coal-fired power plants, the HAPs of most concern are metals such as arsenic, cadmium, mercury, selenium, and vanadium, present in trace quantities in the mineral matter in coal. There is also concern over certain other elements such as fluorine.

DOE conducted on EPA's behalf a study to investigate the fate of HAPs at a number of coal-fired plants utilizing a variety of air pollution control technologies. The objective was to see how effective these technologies are for removing HAPs from flue gas. The CCT Program has made a significant contribution to this study through the participation of a number of its projects.



SO_2 removal performance at Plant Yates.

Benefits of U.S. Experience in SO_2 Removal

The United States has the largest number of FGD installations in the world, with over 260 units installed on coal-fired power plants having a total capacity of over 85,000 MWe. As a consequence of the extensive work on CCT demonstrations and other projects, vast experience has been gained by U.S. suppliers of FGD systems and system components, including expertise in operating techniques, equipment design, and construction materials. Examples include the use of Warman pumps, made in Milwaukee, Wisconsin, for circulating the slurry in the AFGD Demonstration Unit, and the use of Stebbins tile, made in Watertown, New York, as a corrosion resistant liner in the S-H-U absorber at Milliken Station.

Taken together, these projects have demonstrated advanced features, several of which have been adopted by FGD suppliers, thereby accruing substantial cost savings to U.S. electric utilities and their customers. This has led to cost-effective answers to design challenges for equipment such as reaction vessels, pumps, and a wide variety of other items.

When the CAAA were promulgated, many operators of high-sulfur coal mines expressed concern that their markets would be significantly reduced. Development of innovative, economic FGD technologies has provided new opportunities for continued use of high-sulfur Eastern coal.

Limestone unloading conveyor, slurry tank, and hopper at CT-121 Demonstration Unit.

Gypsum stack impoundment at CT-121 Demonstration Unit.

Conveying by-product gypsum.

Milliken Clean Coal Technology Demonstration Project

View of Milliken Station on the shores of Cayuga Lake.

This project was selected during Round IV of DOE's CCT Program. In October 1992, the New York State Electric & Gas Corporation (NYSEG) entered into an agreement with DOE to conduct this demonstration. The project was hosted at NYSEG's Milliken Station, Units 1 and 2, located at Lansing, New York. The plant is in an environmentally sensitive area on the shores of one of the famous Finger Lakes. Units 1 and 2 are 150-MWe (net) pulverized-coal fired units built in the 1950s by Combustion Engineering. Total cost of the CCT project was $159 million, of which DOE provided $45 million, or 28%.

The project involved installing a combination of technologies to control both SO_2 and NOx emissions, including a wet limestone scrubber, low-NOx burners, and a heat-pipe combustion air preheater.

Because low-NOx burners are, to a great extent, developed technologies and are covered in other Topical Reports, this report is limited to discussion of the innovative SO_2 removal technology tested at Milliken, namely the Saarberg-Holter-Umwelttechnik (S-H-U) FGD process. The project goals were to demonstrate SO_2 emissions reduction of greater than 90%, improved boiler efficiency, minimum solid waste production through by-product utilization, and zero wastewater discharge.

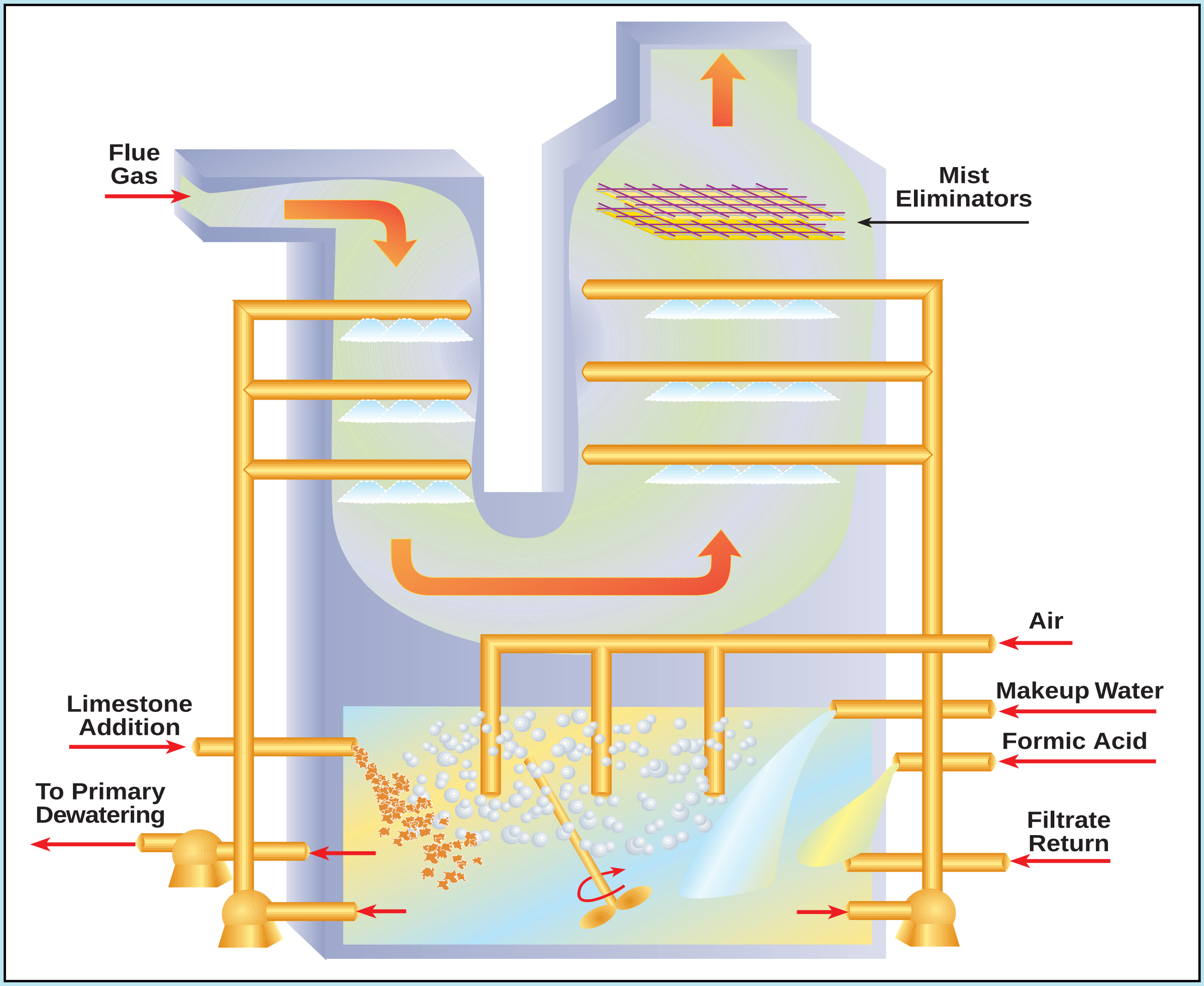
The S-H-U process was installed on both Units 1 and 2 at Milliken. A single two-compartment absorber was used, providing separate absorber sections for each unit within a single vessel. The Milliken FGD system has been in operation since 1995. Performance testing was concluded in 1998.

Process Description

In the S-H-U process, flue gas is scrubbed with a limestone slurry in a space-saving cocurrent/countercurrent absorber vessel. The process is designed specifically to take advantage of the benefits of organic acid enhanced absorption by utilizing a low concentration of formic acid additive in the scrubbing liquid.

Formic acid acts as a buffer in the absorber. Formic acid addition improves both the rate of limestone dissolution and the solubility of calcium in the scrubbing liquid, thereby enhancing SO_2 absorption efficiency, reducing limestone consumption, improving energy efficiency, improving by-product gypsum quality, and reducing wastewater production.

Description of the FGD Demonstration Unit at Milliken Station



Flue gas from the boiler ID fans is ducted to the top of the absorber and flows cocurrently downward with scrubbing liquid sprayed into the flue gas through an array of spray nozzles. The sprayed liquid is collected in a reservoir at the bottom of the absorber, while the partially scrubbed flue gas makes a 180-degree turn and flows upward through the countercurrent stage of the absorber. Here, additional scrubbing liquid is sprayed into the flue gas to complete SO_2 absorption.

Mist eliminators are mounted in the roof of the vessel to remove entrained liquid droplets before the flue gas is discharged to the stack.

Spent scrubbing liquid from both absorption stages collects in a common reservoir in the base of the absorber. Air blown into this reservoir oxidizes calcium sulfite to gypsum. Oxidation is enhanced by agitation of the liquid, which also prevents gypsum particles from settling to the bottom of the reservoir. Reagent limestone is added to the reservoir along with makeup formic acid as required to maintain stable operation.

A slurry slipstream is pumped from the reservoir to the gypsum dewatering system, where solid gypsum particles are recovered before the liquid is returned to the scrubbing vessel. A small liquid bleed stream is removed from the gypsum dewatering system to control the chloride concentration in the slurry.

Hydrocyclone in gypsum dewatering system at Milliken Station.

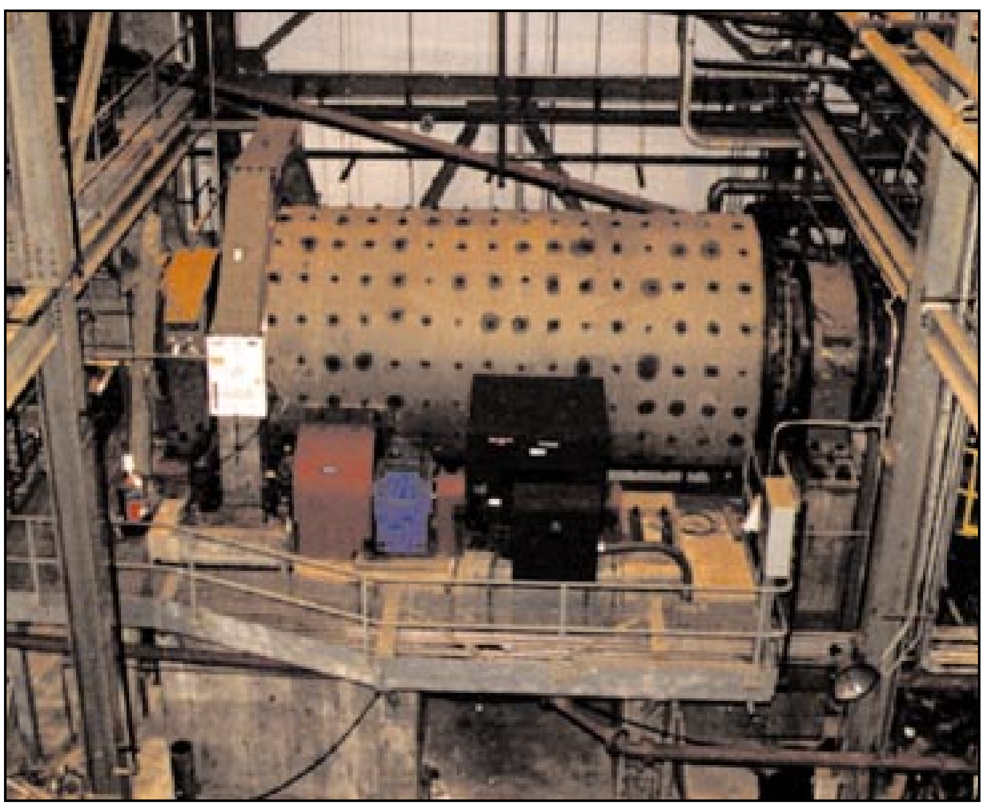
By-product gypsum storage prior to wallboard manufacture.

Operation at low pH provides the benefit of producing soluble calcium bisulfite as a reaction product, rather than the less soluble calcium sulfite. This greatly increases the ease of oxidation to gypsum and essentially eliminates the potential for sulfite scaling within the absorber, thus reducing maintenance costs.

The by-product gypsum is trucked to a wallboard manufacturer located in Mississauga, Ontario.

Results

Operating variables studied include formic acid concentration, coal sulfur content, limestone grind size, and flue gas velocity within the absorber vessel. In addition, FGD efficiency was examined as the number and location of operating spray headers were varied. SO_2 removal efficiency as high as 98% was demonstrated, exceeding the target value of 90%. A high degree of reliability was achieved.



Limestone ball mill at Milliken Station.

Performance testing has demonstrated the beneficial effect of formic acid enhanced operation. In one series of tests, SO_2 removal efficiency increased from 83% without formic acid to 95% with formic acid. At the same removal efficiency, using formic acid results in a 75% reduction in energy required for circulating the sorbent slurry.

Materials of Construction

Special consideration was given to the materials of construction of the absorber to minimize erosion and corrosion, which have caused problems with some conventional FGD systems. The absorber shell is constructed of reinforced concrete with an integral, cast-in-place liner made of Stebbins ceramic tile. This tile has superior abrasion and corrosion resistance compared to rubber and alloy linings and is expected to last for the life of the plant.

Costs

Projected economics for commercial implementation of the S-H-U process have been prepared by NYSEG. For a 300-MWe power plant burning 3.2% sulfur coal, the total capital requirement for an S-H-U retrofit with 95% SO_2 removal is $300/kW. Assuming a 15-year project life, the levelized cost on a current dollar basis is 12.0 mills/kWh, which is equivalent to $534/ton of SO_2 removed.

Aerial view of Milliken Station.

Conclusions

The demonstration phase for the projects described in this report has been completed. The AFGD, CT-121, and S-H-U facilities continue to operate on a commercial basis, attesting to the success of these demonstration projects and the technical and economic viability of the technologies.

During the demonstrations, all of the projects exceeded their goals with respect to SO_2 removal efficiency and proved to be easily maintained and economical to operate. As a result of these efforts, the utility industry has several new technology choices to enable continued use of coal, our most abundant fuel, in an economical and environmentally sound manner. In addition, because of high levels of particulate removal, these technologies are very effective at removing HAPs.

The FGD processes demonstrated in these CCT projects feature compact scrubbers which operate at high levels of reliability, thereby eliminating the need for spare reactors. All three technologies offer high SO_2 removal efficiency at costs significantly lower than conventional wet FGD. As a result of these projects, improved standards for FGD performance and economics have been set.

Another important benefit of the innovative FGD systems demonstrated in the CCT Program is the production of wallboard-quality gypsum, thus eliminating the sludge disposal problem common to conventional wet FGD processes. According to recent trade announcements, several facilities for manufacture of wallboard from FGD gypsum waste are planned or under construction. Because of its uniform high quality, synthetic gypsum, produced as an FGD by-product, has become the preferred feedstock for wallboard manufacture.

With implementation of increasingly stringent air quality regulations, there should be a significant market, both in the United States and abroad, for innovative wet FGD processes such as those presented in this report. In the past, many utilities have chosen other options, including fuel switching and purchasing SO_2 allowances, but these new wet FGD technologies that offer lower costs, high reliability, and low maintenance should result in many more power producers opting for FGD.

Loading finished wallboard for use in construction industry.

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The Clean Coal Technology Program

The Clean Coal Technology (CCT) Program is a unique partnership between the federal government and industry that has as its primary goal the successful introduction of new clean coal utilization technologies into the energy marketplace. With its roots in the acid rain debate of the 1980s, the program has met its objective of broadening the range of technological solutions available to eliminate acid rain concerns associated with coal use.

Moreover, the CCT Program has evolved and been expanded to address the need for new, high-efficiency power-generating technologies that will allow coal to continue to be a fuel option well into the 21st century.

Begun in 1985 and expanded in 1987 consistent with the recommendation of the U.S. and Canadian Special Envoys on Acid Rain, the CCT Program has been implemented through a series of five nationwide competitive solicitations. Each solicitation has been associated with specific government funding and program objectives. After five solicitations, the CCT Program comprises a total of 40 projects located in 18 states with a capital investment value of nearly $6 billion. DOE's share of the total project costs is about $2 billion, or approximately 34% of the total. The projects' industrial participants (i.e., the non-DOE participants) are providing the remainder — nearly $4 billion.

Technologies being demonstrated under the CCT Program are establishing a technology base that will enable the nation to meet more stringent energy and environmental goals. Most of the demonstrations are being conducted at commercial scale, in actual user environments, and under circumstances typical of commercial operations. These features allow the potential of the technologies to be evaluated in their intended commercial applications. Each application addresses one of the following four market sectors:

- Advanced electric power generation
- Environmental control devices
- Coal processing for clean fuels
- Industrial applications

Given its programmatic success, the CCT Program serves as a model for other cooperative government/industry programs aimed at introducing new technologies into the commercial marketplace.

Yates CT-121 scrubber in the early stages of fabrication.

To Receive Additional Information

To be placed on the Department of Energy's distribution list for future information on the Clean Coal Technology Program, the demonstration projects it is financing, or other Fossil Energy Programs, contact:

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List of Acronyms and Abbreviations

AFGD	Advanced Flue Gas Desulfurization
ARS	Air rotary sparger
Btu	British thermal unit
CAAA	Clean Air Act Amendments of 1990
$CaCO_3$	Calcium carbonate (limestone)
CaO	Calcium oxide (lime)
$Ca(OH)_2$	Calcium hydroxide (slaked lime)
$CaSO_3$	Calcium sulfite
$CaSO_4$	Calcium sulfate
$CaSO_4 \bullet 2H_2O$	gypsum
CCT	Clean Coal Technology
CO_2	Carbon dioxide
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ESP	Electrostatic precipitator
FETC	Federal Energy Technology Center
FGD	Flue gas desulfurization
FRP	Fiberglass-reinforced plastic
HAPs	Hazardous air pollutants
ID	Induced draft
JBR	Jet Bubbling Reactor®
H_2SO_4	Sulfuric acid
kW	kilowatt
kWh	kilowatt hour
MWe	Megawatts of electric power
NAAQS	National Ambient Air Quality Standards
NIPSCO	Northern Indiana Public Service Company
NOx	Nitrogen oxides
NSPS	New Source Performance Standards
NYSEG	New York State Electric & Gas Corporation
ppm	parts per million
S-H-U	Saarberg-Holter-Umwelttechnik
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide
SR	Stoichiometric ratio
WES	Wastewater evaporation system