TOPICAL REPORT NUMBER 4

APRIL 1995

CLEAN COAL TECHNOLOGY

SO_2 Removal Using Gas Suspension Absorption Technology

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A report on a project conducted jointly under a cooperative agreement between:

The U.S. Department of Energy and AirPol Inc.

CLEAN COAL TECHNOLOGY

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Cover image: An illustration of the GSA nozzle injecting lime slurry into boiler flue gas at the inlet to the reactor.

Introduction and Executive Summary

The Clean Coal Technology (CCT) Demonstration Program is a government and industry co-funded technology development effort designed to demonstrate a new generation of innovative coal utilization processes in a series of full-scale, "showcase" facilities built across the country. These demonstrations are on a scale sufficiently large to generate data for design, construction, operation, technical/economic evaluation, and future commercialization of each process.

The goal of the program is to furnish the U.S. energy marketplace with a number of advanced, more efficient, and environmentally responsive coal-utilizing technologies. These technologies will reduce and/or eliminate the economic and environmental impediments that limit the full utilization of coal as a continuing viable future energy resource.

To achieve this goal, a multi-phased effort consisting of five separate solicitations was administered by the U.S. Department of Energy (DOE). Projects selected through these solicitations have demonstrated technology options with the potential to meet the needs of energy markets and respond to relevant environmental considerations.

In response to the third of these solicitations, AirPol Inc., with the assistance of the Tennessee Valley Authority (TVA), has demonstrated the Gas Suspension Absorption (GSA) technology in a CCT project titled "10 MW Demonstration of Gas Suspension Absorption." AirPol performed this demonstration under a Cooperative Agreement awarded by DOE in October 1990.

The host site for this project was the Center for Emissions Research (CER), located at TVA's Shawnee Fossil Power Plant near Paducah, Kentucky. Over the past 25 years, the CER has served as a test ground for several different flue gas desulfurization (FGD) technologies. Before the GSA demonstration program, two other semi-dry processes, one of which was a 10 MWe spray dryer/electrostatic precipitator (ESP), were tested at the facility. The GSA system was retrofitted upstream of the existing ESP and the test period began in November 1992.

The GSA process was initially developed as a calciner for limestone in cement production. It has been used successfully to clean gases from commercial waste-to-energy plants in Denmark, primarily to capture chloride emissions. For FGD applications, the GSA system removes sulfur dioxide (SO_2) by bringing coal combustion gases into contact with a suspended mixture of solids, including lime. After the lime reacts with the SO_2, most of the solids are separated from the flue gas in a cyclone and recycled for additional SO_2 absorption. The flue gas, cleaned of the acid gas components, is sent through a dust collector for particulate removal before being released into the atmosphere.

The key to the system's superior performance is the recirculation of solids back to the reactor. Typically, a solid particle will be recirculated about 100 times before being discharged. Another advantage of the GSA system is that it requires only a single, simple, dual-fluid nozzle to inject fresh lime slurry into the reactor.

The major objectives of the demonstration were successfully achieved:

- The GSA system removes greater than 90 percent of the SO_2 with a low level of lime consumption.
- The GSA process operates with a high degree of reliability.
- The capital cost for a GSA system is about 30 percent less than that for a comparable wet limestone FGD system.
- The GSA process removes substantially all of the trace metals from the flue gas.

The GSA FGD system is a promising technology that will aid U.S. utilities and other industries in achieving an effective, economic, and space-efficient solution to the SO_2 emissions problem. The state of Ohio, in conjunction with the Ohio Coal Development Office, has awarded the city of Hamilton a grant to install GSA technology in the city's municipal power plant. This will allow the city to meet environmental regulations while using high-sulfur Ohio coal for power generation.

Present commercialization activities for GSA include installations at 1) an iron ore sintering plant in Sweden having a flue gas flow rate equivalent to that of a 135 MWe power plant boiler, and 2) a cogeneration project in Asia. For both of these applications, the success of the CCT demonstration program at TVA was a major factor in the decision to employ GSA technology.

SO_2 Removal Using Gas Suspension Absorption Technology

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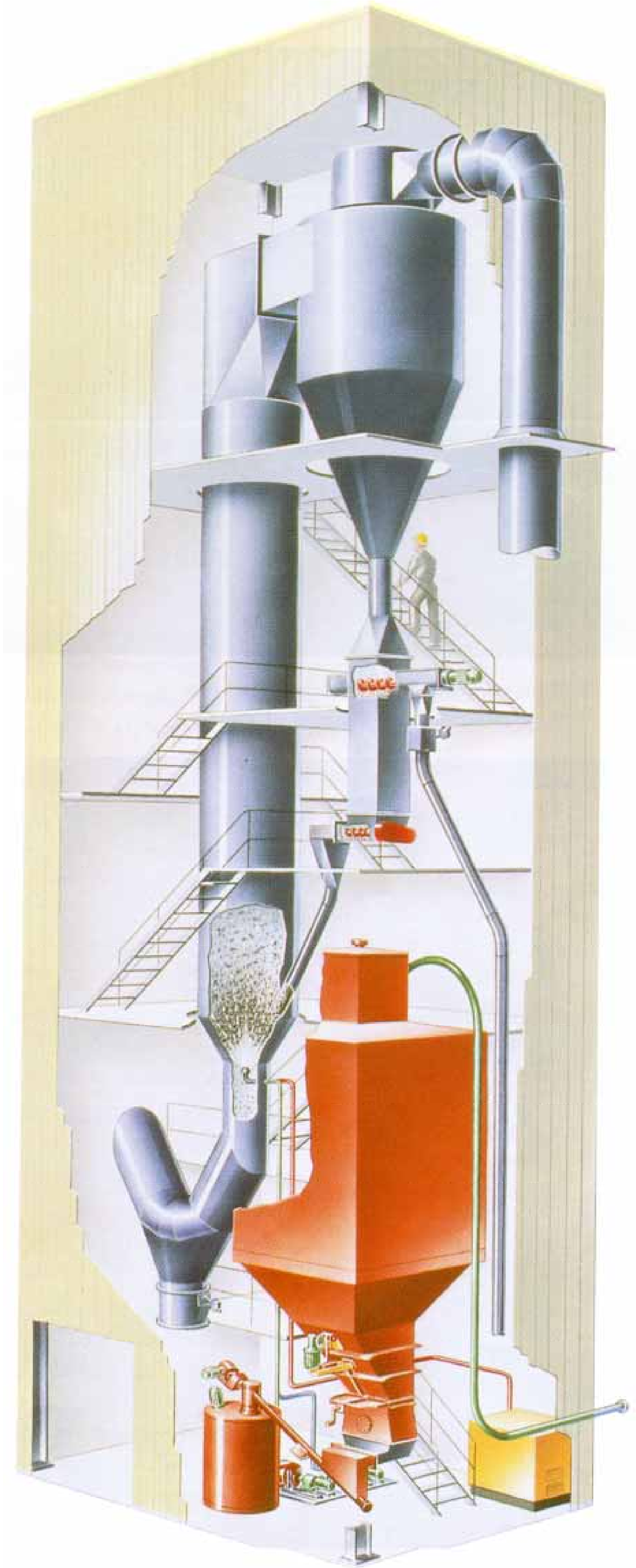
Definition of Technology

Combustion of coal results in the generation of flue gas containing sulfur dioxide (SO_2). Many U.S. coals have a sufficiently high sulfur content to cause SO_2 emissions to exceed environmental standards. Thus, some form of flue gas desulfurization (FGD) is generally required. These FGD processes are usually categorized as wet or dry systems. In wet FGD systems, flue gas is contacted with sufficient solution or slurry consisting of a sorbent in an aqueous medium, such that the flue gas is cooled to the adiabatic saturation temperature. The sorbent and the byproduct in the process are in slurry form, with the byproduct slurry subsequently being dewatered for disposal. Dry FGD systems usually involve injecting a solid sorbent into the furnace or flue gas duct, and the byproduct solids are collected in a dry form along with the fly ash from the boiler.

Several wet FGD systems have been developed and are in commercial use, including a variety of scrubbing processes involving lime or limestone slurries. Sulfur dioxide removal efficiency is high, generally 90 percent or greater. Dry FGD systems include a number of spray drying or sorbent injection processes using lime, limestone, or sodium-based sorbents. The dry FGD, systems based on lime also can achieve high SO_2 removals. However, some of these dry FGD systems that use limestone exhibit lower SO_2 removal efficiencies, about 50 percent, because of the lower reactivity of the limestone and the short contact time between the flue gas and the sorbent.

Gas Suspension Absorption (GSA) is an innovative semi-dry FGD technology based on lime sorbent. Flue gas is contacted with an atomized slurry containing fresh lime, resulting in absorption of the SO_2. Major products of this reaction are calcium sulfite and calcium sulfate.

A key feature of the GSA process is the recirculation of large amounts of dry solids,



The GSA system.

which are coated with lime slurry in the reactor and act as the reaction medium. The resulting heat and mass transfer characteristics of the system are superior to those in conventional semi-dry technology where lime slurry is sprayed directly into a duct or spray dryer.

A more detailed process description is given subsequently in the section titled *System Description.*

Process Benefits

SO_2 Removal

As discussed above, GSA is a semi-dry FGD process in which the flue gas is contacted with a lime slurry. Essentially all of the water evaporates in the process, leaving a "dry" solid byproduct. The SO_2 removal efficiency of the GSA process is 90 percent or greater, roughly equivalent to that achieved by wet scrubbing. Two main factors account for the superior performance of GSA:

The Clean Coal GSA Demonstration Site at Paducah, Kentucky.

The GSA Reaction Chemistry

$$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 \cdot \tfrac{1}{2} H_2O + \tfrac{1}{2} H_2O$$

$$CaSO_3 + \tfrac{1}{2} O_2 \rightarrow CaSO_4$$

1. The GSA process operates successfully very close to the flue gas adiabatic saturation temperature due to excellent heat transfer characteristics. The injected slurry dries very quickly, allowing short retention time for the flue gas and generating a dry byproduct.

2. The GSA process takes advantage of the large surface area of recycle particles on which the absorption of SO_2 can take place. The lime slurry coats the turbulent bed of dry solids, providing enhanced mass transfer between the lime slurry and the SO_2 laden flue gas.

Operation Near Saturation Temperature

Sulfur dioxide absorption and lime utilization efficiencies increase as the flue gas temperature comes closer to its adiabatic saturation temperature. A key variable is the approach-to-saturation temperature (AST), which is the difference between the temperature of the flue gas leaving the reactor and its adiabatic saturation temperature. A conventional spray dryer system cannot normally operate at an AST below 10 to 11° C (18 to 20° F) without solids build-up problems caused by high moisture levels in the solids.

However, because of the enhanced heat and mass transfer in the GSA reactor, the lime slurry injected into the GSA system dries completely, as evidenced by the fact that the byproduct solids have less than 1 percent moisture, even when operating at an AST as low as 4° C (8° F). Several tests have demonstrated that the GSA system can operate successfully at these low ASTs when the chloride level in the system is low. Thus, for a low-chloride coal application, the GSA system can attain higher SO_2 absorption efficiencies than a conventional spray dryer system at the same lime consumption.

Lime Consumption

The lime reagent ratio is expressed in terms of moles of calcium per mole of SO_2 in the flue gas entering the system. This figure is also referred to as the calcium/sulfur molar ratio. Since the GSA system can operate at low ASTs, it can achieve high SO_2 removal efficiencies with a low level of lime consumption.

Byproduct Generation

The byproduct generated in the GSA system consists mainly of calcium sulfite and calcium sulfate, in addition to fly ash from the boiler. The moisture content is surprisingly low, less than 1 percent. This low moisture content explains why there is little dust build-up on the system walls. Conventional spray dryer systems avoid this potential problem by operating at higher ASTs, but as a consequence, the SO_2 removal efficiencies are not as high as those achieved by the GSA process.

Analysis of the solids from the GSA system supports the theory that the dry recycle solids are coated with a thin layer of fresh lime slurry on each pass through the reactor. Cross-sectional photomicrographs of large particles removed from the recycle stream show a central core surrounded by a series of rings similar to tree rings. Spectral analysis of these layers determined that the central core of this particle is fly ash, while surrounding rings are composed of calcium-sulfur compounds.

The amount of byproduct generated depends on the amount of acid gases entering the system, the capture efficiency of these acid gases, and the amount of lime used.

The byproduct can be disposed of in the same manner as the boiler fly ash. However, converting the byproduct to a marketable material is being considered. One possibility is to convert it to pozzolanic cement, which is a ready-mix product that can be used for non-structural concrete applications, such as sub-base for roadways.

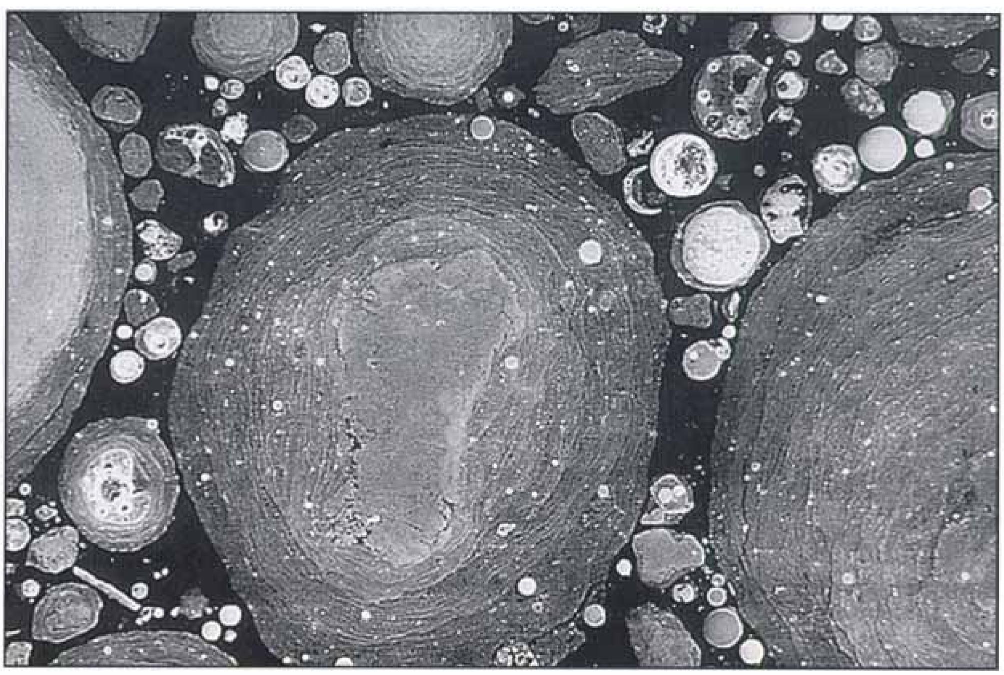
This cement can be made from a mixture of GSA byproduct, fly ash, water, and a small amount of quicklime (pebble lime). Properties of concrete made from pozzolanic cement are quite similar to those of concrete made from Portland cement. The pozzolanic cement has extremely low leachability. If landfilled, it would thus form its own liner and prevent any leaching into the ground. AirPol is studying possible uses of the pozzolanic cement.

Power Consumption

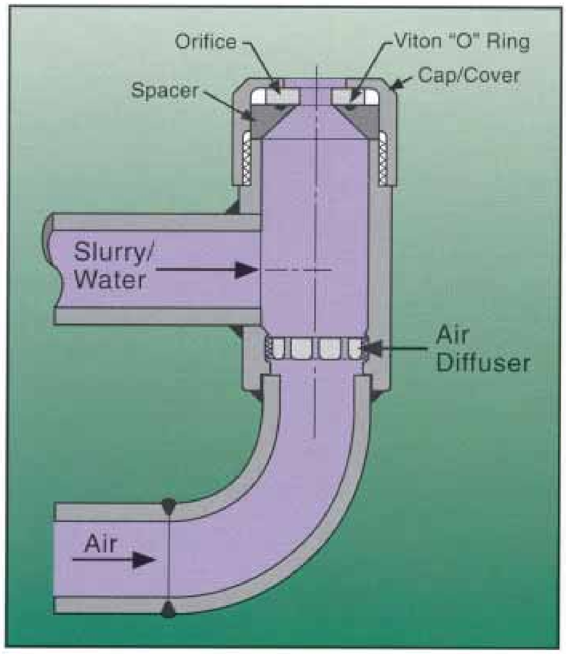
The major power consumption in the GSA system occurs in the induced draft fan and in the compressor for atomization of the lime slurry. The more significant of these is the fan, which is required to overcome the pressure drop in the GSA system. Although the flue gas pressure drop across the GSA system is somewhat higher than in a conventional spray dryer system, the total power consumption is lower because the power for atomization is much less than that for either rotary atomizers or atomizing nozzles used in spray dryer systems.

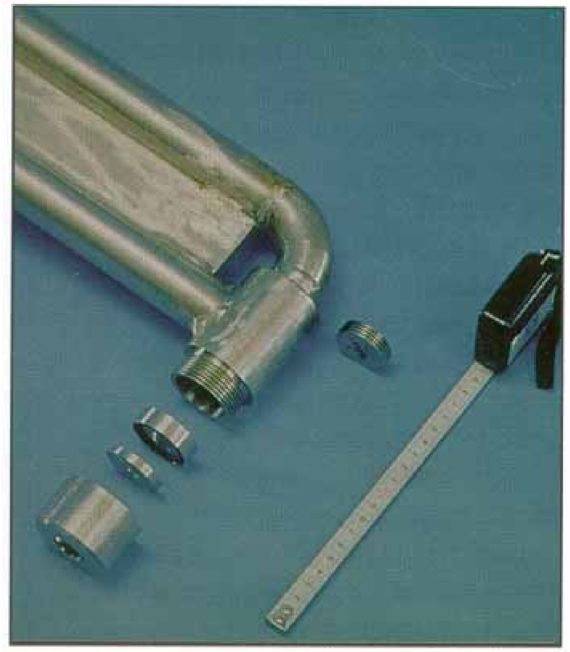
Solids Build-Up

GSA systems in commercial operation were previously installed at municipal solid waste (MSW) incinerators, primarily to remove hydrogen chloride (HCI) from the flue gases. The first MSW application started operating in 1988. None of these GSA installations has experienced difficulties with dust build-up. The approach temperature is higher in MSW applications than in FGD applications of GSA, but the chloride content is also much higher. The MSW byproduct has a very low moisture content,



Cross-section of a large particle removed from the GSA recycle stream.
Magnification x1000.





The GSA nozzle—at left is an engineering design of the nozzle and at right is an exploded view of the actual nozzle.

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 is on the verge of meeting its early objective of broadening the range of technological solutions available to eliminate acid rain concerns associated with coal use. Moreover, the program has evolved and has 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 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 45 projects located in 21 states with a capital investment value of nearly $7 billion. DOE'S share of the total project costs is about $2.37 billion, or approximately 34 percent of the total. The projects' industrial participants (i.e., the non-DOE participants) are providing the remainder-nearly $4.60 billion.

Clean coal 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.

despite the high concentrations of chlorides. It should be noted that incinerator applications are much more susceptible to scaling, corrosion, and dust build-up than coal-fired boilers due to the presence of chlorides. This is the reason for the higher approach temperatures for MSW applications.

Maintenance

Experience shows that the GSA system has very low maintenance requirements. This is due to the simple design with no moving parts in contact with the flue gases. The lime slurry spray nozzle is the only part that is exposed to wear. The spray nozzle assembly is routinely alternated with a spare unit once per week, a procedure that takes less than 5 minutes and is done while the GSA system is in full operation. The orifice washer (a low-cost item) is replaced and the assembly is cleaned and made ready for the following week's replacement.

All components are constructed of carbon steel, which has proven to be corrosion-free in the GSA system.

Of the commercial installations, none has a dedicated maintenance crew for the GSA system. Most of them have no dedicated operator, with the incinerator personnel also operating the GSA system.

Availability and Reliability

Commercial GSA system installations operate reliably around the clock, and have demonstrated availability of close to 100 percent.

The GSA nozzle is easily removed for inspection and service.

The host site for the GSA demonstration is TVA's Shawnee Fossil Power Plant near Paducah, Kentucky.

The Demonstration Project at TVA's Center for Emissions Research

With the increased emphasis on SO_2 emissions reduction by electric utility and industrial plants as required by the Clean Air Act Amendments of 1990 (CAAA), there is a need for a simple and economical FGD process, such as the GSA system, for small to mid-size plants where a wet FGD system may not be the least-cost option.

In the U.S. Department of Energy (DOE) Clean Coal Technology (CCT) Demonstration Program, the third solicitation (issued in 1989) targeted those technologies capable of achieving significant reduction of SO_2 and/or nitrogen oxides (NO_X) emissions from existing facilities. Reduction of these emissions would minimize environmental impacts—such as transboundary and interstate pollution—and/or provide for future energy needs in an environmentally acceptable manner.

In response to this solicitation, AirPol Inc. submitted a proposal for the design, installation, and testing of the GSA system. This project is the first North American demonstration of the GSA FGD system for a coal-fired utility boiler. The purpose of this project was to demonstrate the high SO_2 removal efficiency of the GSA system, as well as its cost effectiveness. GSA is a novel concept developed by FLS miljϕ, a wholly-owned subsidiary of FLS Industries of Copenhagen, Denmark. The GSA system is distinguished in the MSW market by its high SO_2 removal efficiency, low capital cost, and low operating cost.

TVA's Center for Emissions Research

The Center for Emissions Research (CER) is located at TVA's coal-fired Shawnee Fossil Plant. A 10 MWe equivalent flue gas slipstream is pulled from the Unit 9 boiler, which is a 175 MWe (nameplate), Babcock and Wilcox, wall-fired unit. Unit 9 is normally fired with high-sulfur (1.7 to 2.2 kg SO_2/GJ, or 4.0 to 5.0 lb SO_2/Million Btu) western Kentucky bituminous coal, under a variance granted by the state of Kentucky.

The CER had its origins in the early 1970s as an experimental test facility for evaluating alternative technologies for controlling emissions of SO_2 from coal-fired boilers. Some of the first work on dry limestone injection as an FGD technology was completed at this facility. Later, wet limestone scrubbing FGD technology was developed with cofunding support over the years from the Environmental Protection Agency (EPA), the Electric Power Research Institute (EPRI), and the DOE. All aspects of wet limestone scrubbing FGD technology were evaluated, ranging from process and equipment design and operation to byproduct disposal studies.

In the 1980s, after the successful commercialization of wet limestone scrubbing FGD technology, the CER began evaluating other new FGD technologies. One of the innovative FGD technologies being developed-at the time was the spray dryer system, which was beginning to be commercialized for low-sulfur coal and MSW applications. TVA began evaluating the potential of this spray dryer FGD technology for higher sulfur coal applications with the installation of two small, 1 MWe pilot plants at the CER.

Later, in cooperation with EPRI and Ontario Hydro, TVA constructed and operated a 10 MWe spray dryer pilot plant using an ESP for particulate removal.

Because of the apparent advantages of GSA technology, TVA agreed to act as the host site for this CCT demonstration program. The CER operated and maintained the system, developed the test plan, analyzed the test data, and acted as a true partner in the project, including provision of substantial cofunding. In addition, TVA is continuing to test the GSA process at the CER to further expand the database.

Dedication of the completed GSA facility at the Center for Emissions Research.

At the Center for Emissions Research (CER), the flue gas bypassed the existing spray dryer that had previously been installed as a test unit. The experience gained in designing, manufacturing, and constructing the GSA system for this project will be used for future commercialization of the technology. Results of the operation and experimental testing will be used to further improve the GSA design.

The objectives of the GSA demonstration project were to:

- Demonstrate SO_2 removal in excess of 90 percent using high-sulfur U.S. bituminous coal.
- Optimize recycle and design parameters to achieve maximum efficiencies of lime utilization and SO_2 removal.
- Compare removal efficiency and cost with existing FGD technologies.
- Determine the air toxics removal performance.
- Compare the SO_2, particulates, and air toxics removal performance between a GSA system with an electrostatic precipitator and a GSA system with a fabric filter.

Coal Composition

The sulfur content of the western Kentucky coal burned during the demonstration ranged from 1.7 to 2.2 kg SO_2/GJ (4 to 5 lb/million Btu), or about 2.6 to 3.0 percent sulfur by weight. Three different coals were burned separately during the test program. Typical compositions for these coals are shown in the table below.

Ultimate Analyses	Peabody Martwick	Emerald Energy	Andalex
Carbon	72.99	76.26	69.42
Hydrogen	4.92	5.72	5.03
Oxygen	7.65	6.83	9.91
Nitrogen	1.65	1.26	1.39
Sulfur	3.05	2.61	3.06
Chlorine	0.02	0.04	0.04
Ash	9.72	7.28	11.15
Total	100.00	100.00	100.00
Heating Value, MJ/kg			
Wet	29.7	30.0	27.5
Dry	30.5	31.2	28.5
Heating Value, Btu/lb			
Wet	12,800	12,910	12,420
Dry	13,117	13,420	12,870

Analyses: Percent on a dry basis

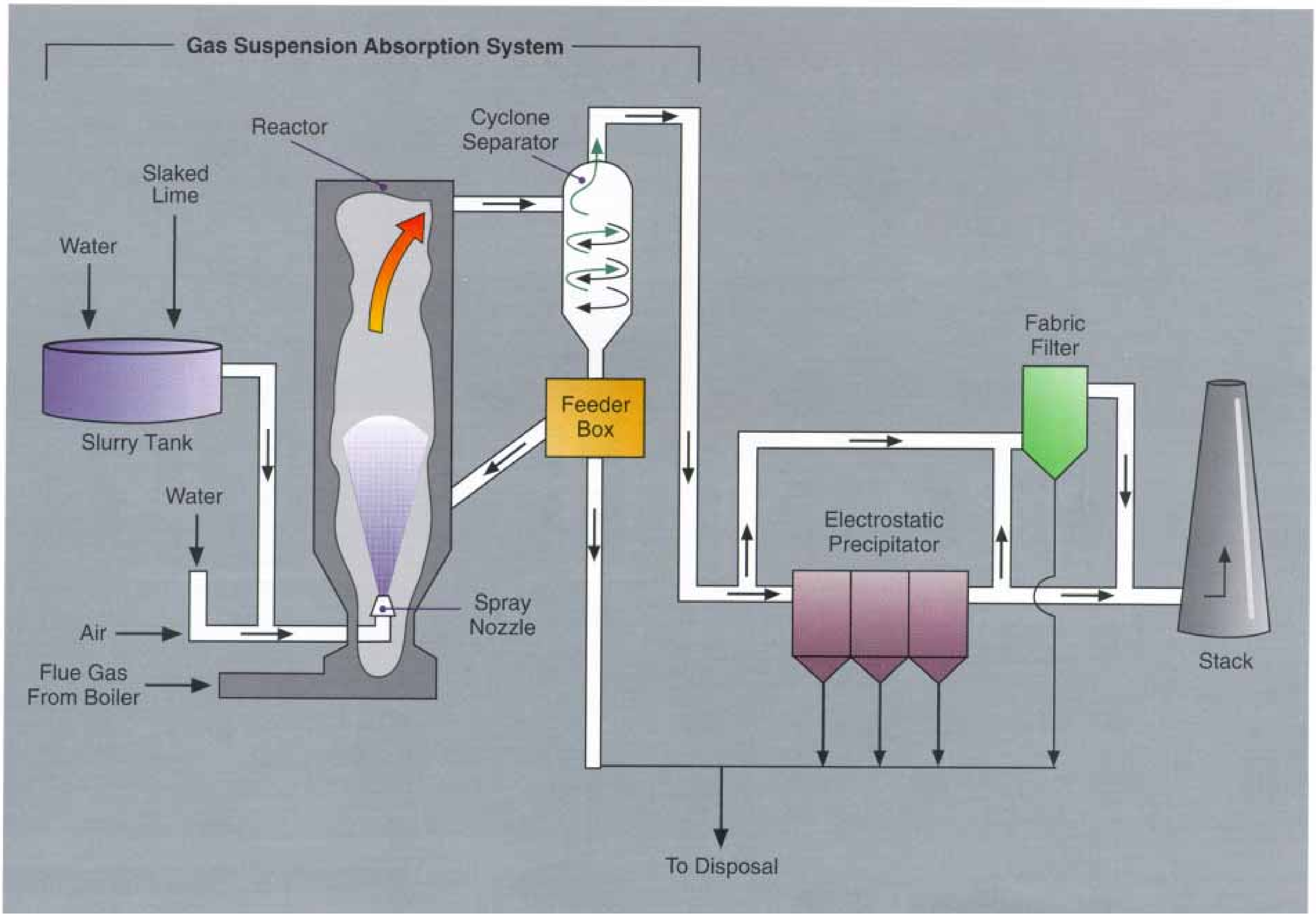
Composition of coals used in the test program.

System Description

The GSA FGD system tested at the CER is composed of:

- An absorption reactor with an injection nozzle for lime slurry.
- A cyclone for separating and recycling material to the reactor.
- A slurry preparation system which converts pebble lime (also referred to as quicklime) to slaked lime needed in the reactor.
- A dust collector which removes fly ash and reaction products from the flue gas stream.

The flue gas from the boiler air preheater enters the bottom of the reactor, where it contacts a suspended bed of recycle solids coated with lime. Fresh lime slurry is fed into the reactor by way of a single, dual-fluid nozzle located in the center of the reactor, and atomized by compressed air. The heat in the flue gas causes the moisture in the slurry to evaporate while an absorption reaction between the lime and the SO_2 in the flue gas takes place.



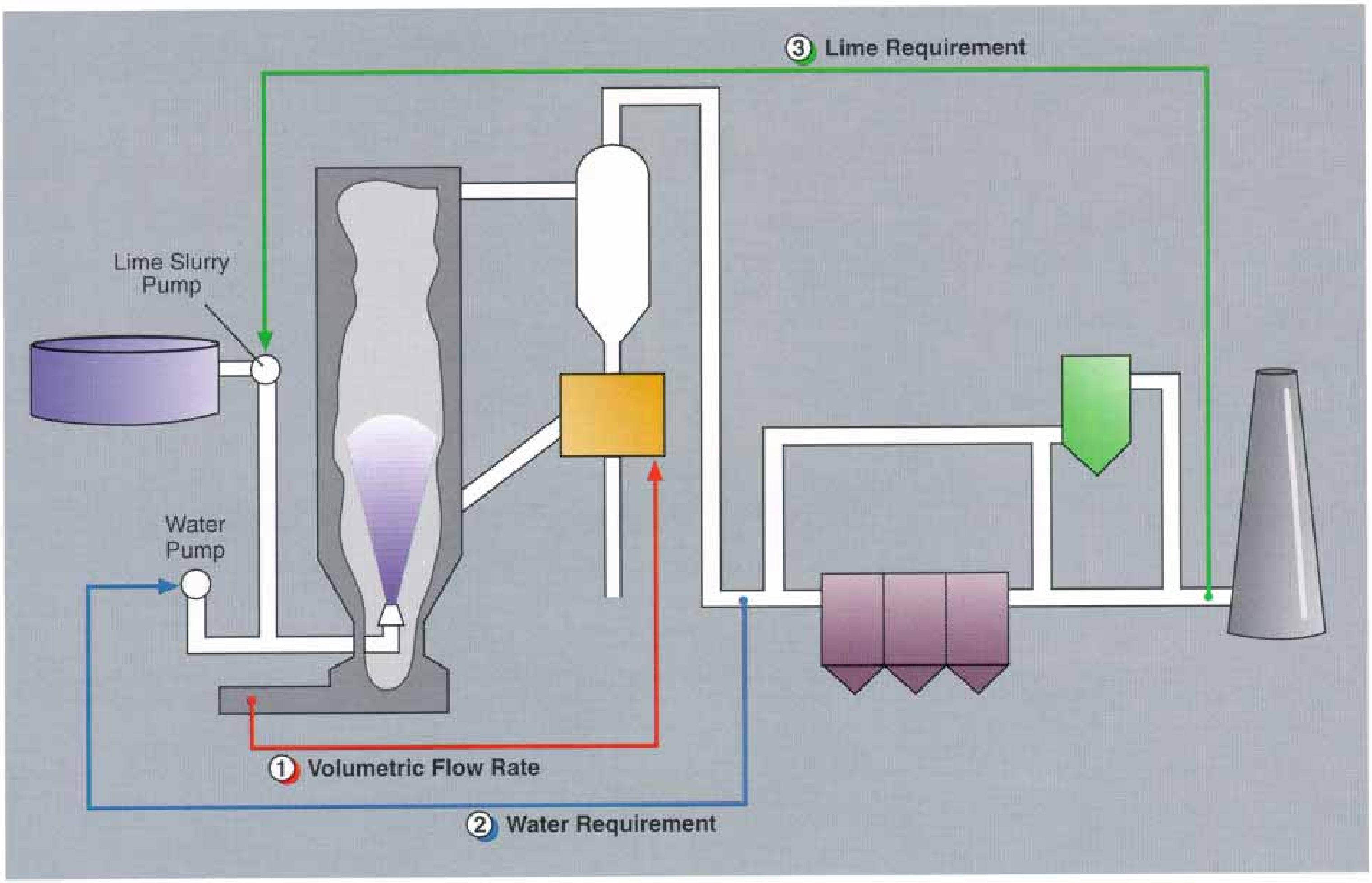
Flow diagram of the GSA demonstration system.

Slurry droplets impact and coat the dry solids, thereby preventing slurry from hitting the wall of the reactor and causing a build-up of solids. Recycle solids further minimize scaling due to a scouring effect on the reactor walls. The solids are suspended in the reactor by the velocity of the flue gas stream flowing up through the reactor. The resulting turbulence provides intimate contact, allowing SO_2 to be absorbed into the lime slurry, which exists as a thin layer coating the solid particles.

The cleaned flue gas and the suspended reaction particles travel upward in the reactor and continue to the cyclone, where most of the solids, containing the calcium salts, fly ash, and unreacted lime, are removed. About 99 percent of the solids are collected in the cyclone and recycled to the reactor. Thus, most of the unreacted lime is available to absorb additional SO_2 from the flue gas, thereby minimizing the consumption of lime.

The remaining 1 percent of the solids entering the cyclone leaves the system with the flue gas. The flue gas leaving the cyclone proceeds to a dust collector for final particulate collection. The cleaned flue gas is released to the atmosphere.

The dust collector can be either an electrostatic precipitator (ESP) or a fabric filter; at the CER, both an ESP and a fabric filter are available for testing. The fabric filter used at the CER is a small, 1 MWe pulse-jet baghouse that treats a slipstream of flue gas.



Control scheme for the GSA system.

Time Schedule

The CCT GSA test program was composed of five parts. The first part was the preliminary tests, which were conducted in November and December 1992. The second part was the factorial tests, performed between January and August 1993. The air toxics testing, which was conducted between mid-September and mid-October 1993, was the third part. The next part was the 28-day GSA/ESP demonstration run, executed in late October and November 1993. The final part was the 14-day fabric filter demonstration run, which was conducted from late February to mid-March 1994. Over the span of the project, the GSA unit operated a total of 7700 hours.

The Peabody Martwick coal was burned during January and February 1993; the Emerald Energy coal was burned during the period of February to July 1993; and the Andalex coal was burned from early September 1993 to the end of the test program in March 1994.

The GSA system is automatically controlled to maintain the required level of acid gas emissions while keeping the lime consumption at a minimum. The system is comprised of three control loops.

1. *Material Recycle.* A sensor in the reactor inlet measures the dynamic pressure and converts it to gas velocity (flow). Based upon the flow, the controller adjusts the speed of the metering screws in the feeder box, thereby controlling the recycle flow of material to the reactor in direct proportion to the gas flow.

2. *Flue Gas Temperature.* A temperature sensor, located between the cyclone and dust collector, controls the speed of the pump directing cooling water to the spray nozzle.

3. *SO_2 Emissions.* An SO_2 emissions monitor in the stack controls the speed of the pump injecting lime slurry into the reactor.

The metering screws in the feeder box, the cooling water pump, and the lime slurry pump are all driven by electric motors provided with variable frequency drives for precise speed control. The pumps are positive displacement hose-type pumps. Unlike a centrifugal pump, where the flow changes with the pressure, the hose pump maintains constant pressure at different flow rates. This is necessary to maintain a constant pressure at the spray nozzle in the reactor.

For more precise and faster response of the acid gas emissions control, especially when the flue gas has large and rapid fluctuations in acid concentration, an additional acid gas sensor is installed in the reactor inlet. This permits control of the lime slurry injection rate by a feed forward/ feedback system.

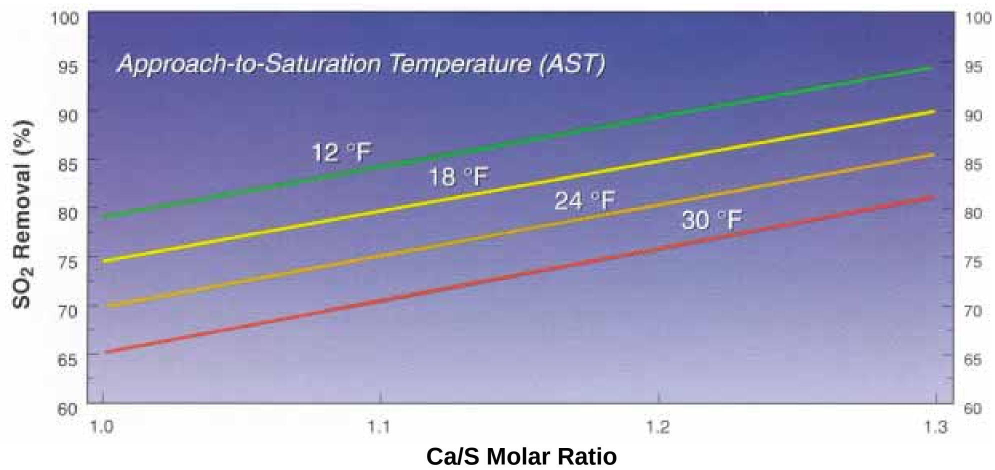
Demonstration Program

Preliminary Testing

After installation of the *GSA* equipment, preliminary tests were performed to establish the operating ranges attainable and confirm the influence of different operating parameters. The test results established that SO_2 removal efficiency has a close relationship to the *AST.*

The tests showed that the *GSA* system can operate successfully without dust build-up at an *AST* as low as 3–6° C (5–10° F). The tests also showed, as expected, that the addition of small amounts of calcium chloride to the recycle dramatically increases the SO_2 removal rate.

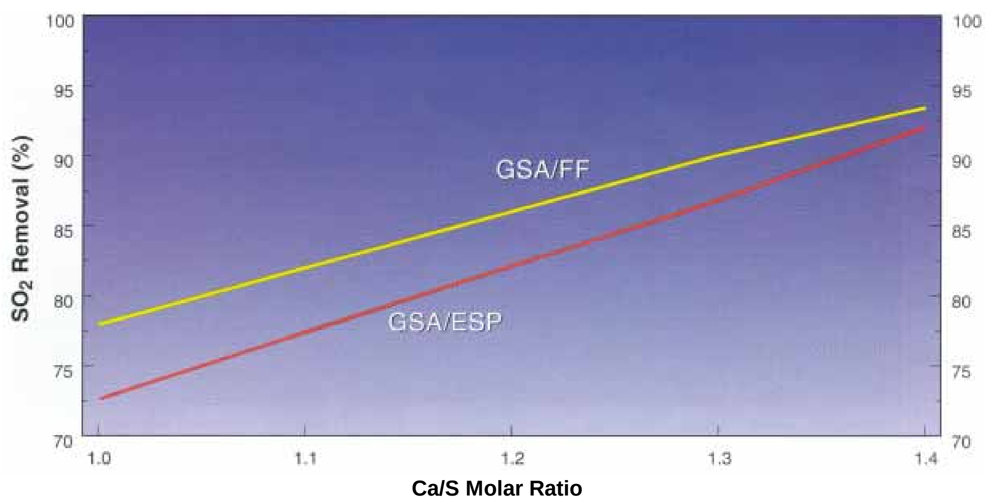
SO_2 Removal Efficiency



Dust loading 2.0 gr/acf.
No chloride addition.

Overall system SO_2 removal efficiency. A model created from data collected during factorial testing demonstrates that SO_2 removal efficiency increases as the calcium/ sulfur molar ratio increases and as the AST decreases.

SO_2 Removal Efficiency
GSA/ESP vs. GSA/FF

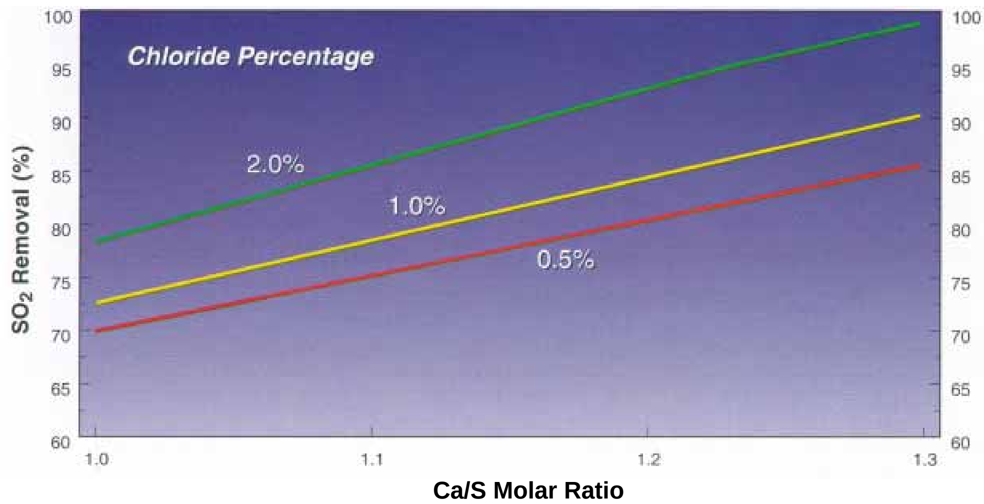


ESP = Electrostatic Precipitator
FF = fabric filter

Comparison Of SO_2 removal efficiencies with GSA/ESP and GSA/FF options. A model created from data collected during the test program shows higher SO_2 removal efficiencies for GSA/FF than for GSA/ESP.

Effect of Chloride on SO_2 Removal

AST = 24 °F



Effect of chloride on SO_2 removal. A model based on data collected during factorial testing with injection of calcium chloride demonstrates that SO_2 removal efficiency increases as chloride content increases. The chloride additions are expressed as percent of lime feed*. Note: The natural chloride content in the Peabody Martwick coal corresponds to 0.5 percent of the lime feed and thus represents the baseline in this graph.*

Trace Metal Removal Efficiency

Test results based on an average of three measurements.

Removal rates for trace metals for the test program GSA/ESP system.

Factorial Testing

Upon completion of the preliminary tests, a statistically designed factorial test program was conducted. The purpose of this factorial testing was to determine the effect of process variables on the operation and SO_2 removal efficiency in the reactor/cyclone and in the subsequent ESP or alternate fabric filter in order to optimize GSA system performance.

Reducing the AST results in a substantial boost in the overall system SO_2 removal efficiency. Sulfur dioxide removal efficiency also increases as the calcium/sulfur molar ratio increases.

The overall system SO_2 removal efficiencies for the factorial tests ranged from 61 to 99 percent, depending on the specific test conditions. Most of the SO_2 removal occurred in the reactor/cyclone. The SO_2 removal efficiency in the ESP was very low, ranging from 1 to 7 percentage points based on the inlet SO_2 concentration to the reactor.

The SO_2 removal efficiency in the GSA/fabric filter system was typically about 3 to 5 percentage points higher than that achieved in the GSA/ESP system at the same test conditions. This higher SO_2 removal efficiency in the GSA/fabric filter system is due to the intimate contact between the residual SO_2 and the still reactive solids in the filter cake on the bags.

One of the important parameters established during the factorial tests was the influence of chlorides. The test results showed that SO_2 removal efficiency improves as chloride content in the system increases.

A surprising result of this testing was the ability of the GSA system to operate close to saturation temperature without incurring any operating problems, while still achieving high SO_2 removal. This is even more impressive given the low flue gas residence time in the reactor/cyclone (3 to 5 seconds).

Air Toxics Testing

The potential impacts of Title III of the CAAA have resulted in increased emphasis by electric utilities on the measurement of air toxics, especially for CCT demonstrations. Air toxics tests, which followed the factorial tests, were conducted to determine the capability of the GSA system to remove hydrogen fluoride (HF), HCI, and trace metals.

The results of the air toxics testing show that the GSA process is capable of removing these components from the flue gas. The removal rate across the GSA system reactor and cyclone appears to be 100 percent for HCI and 99 percent for HF. The GSA/ESP system removal rates for trace metals are surprisingly high, exceeding 98 percent for most metals.

Demonstration Runs

Upon completion of the factorial tests and the air toxics tests, the GSA system was tested in a 28-day continuous demonstration run with the ESP and separately in a 14-day demonstration run with the fabric filter. The demonstration runs began with the boiler burning the high-sulfur, low-chloride Andalex coal and the following test conditions:

Gas Flow Rate	570 Nm^3/min (20,000 scfm)
Inlet Gas Temperature	160° C (320° F)
Fly Ash Loading	4.6 g/m^3 (2.0 gr/acf)
Simulated Coal Chloride Level	0.12%
AST	10° C (18° F)

The cyclone is being moved to the layout area for insulation prior to installation.

The insulated GSA reactor is being lifted into place during construction.

History of GSA Development

The GSA process is an innovative concept for FGD that was developed by AirPol's parent company, FLS miljϕ in Copenhagen, Denmark. The process was initially developed as a cyclone preheater system for cement kiln raw meal (limestone and clay). This system provided both capital and energy savings by reducing the required length of the rotary kiln and lowering the fuel consumption. The GSA system also showed superior heat and mass transfer characteristics and was subsequently used in conjunction with the calcination of limestone, alumina, and dolomite. The GSA process for FGD applications was developed later by injecting lime slurry and recycled solids into the reactor for acid gas removal.

In 1985, a GSA system pilot plant was built to establish design parameters for SO_2 absorption in flue gas from an electric utility power boiler (Stignaes Station of SEAS) in Copenhagen. The power station subsequently managed to meet the emissions code for SO_2 without an FGD system, and thus had no further interest in installing a GSA system.

At the same time, the code requirements for SO_2 and HCI for MSW incinerators were tightened and the pilot unit was moved to an incinerator plant. The first commercial GSA system unit was installed at the KARA Waste-to-Energy Plant at Roskilde, Denmark, in 1988.

The CCT demonstration project was the first U.S. commercial scale test of the GSA process for removing SO_2 from power plant stack gas. It was conducted at TVA's Shawnee Fossil Power Plant, using high-sulfur coal as feed.

The SO_2 control mode was engaged for this run with an overall System SO_2 removal efficiency goal of 91 percent. Due to some problems encountered in obtaining the chosen coal, a switch was made to burning Warrior coal, a higher sulfur (3.5 percent) coal, for about 1 week. The lime consumption averaged 1.40 – 1.45 moles of calcium per mole of SO_2 in the inlet gas.

The following results were achieved in the demonstration program:

- During the 28-day run of the GSA/ESP system, SO_2 removal efficiency exceeded 90 percent, even when the boiler was switched to a higher sulfur coal. This switch to the higher sulfur coal, which necessitated an increase in lime consumption, demonstrated the flexibility of the GSA system over a range of coal sulfur levels.
- The particulate removal efficiency averaged 99.9+ percent. The emissions rate with the ESP remained well below the New Source Performance Standards (NSPS) for particulates (12.9 g/GJ, or 0.03 lb/million Btu) throughout the 28-day run. The particulate emissions were about 6.5 g/GJ (0.015 lb/million Btu), i.e., one-half the NSPS level.
- The GSA system demonstrated its reliability by remaining on-line for the entire 28-day period.
- The 14-day fabric filter demonstration run showed that the GSA/fabric filter system can achieve very high SO_2 and particulate removal efficiencies. Sulfur dioxide removal levels reached as high as 96+ percent.

Particulate Collection

Performance with Electrostatic Precipitator

The ESP used during the demonstration program is a relatively modern, four-field unit with a specific collection area of about 1.44 m^2/m^3/min (440 ft^2/1000 acfm). This is a size similar to several full-scale ESPs installed on the TVA power system. The most important result of this demonstration was that the emissions rate from the ESP was well below the NSPS for particulates at all of the test conditions, with a particulate removal efficiency above 99.9+ percent for most of the tests.

Performance with Fabric Filter

The fabric filter was tested in two modes: treating flue gas from either the GSA system outlet or the ESP outlet during separate phases of the factorial testing. The bags used in this testing were made of polyphenylene sulfide needle felt, having a weight of 542 g/m^2 (16 oz/yd^2). Based on the factorial tests, the SO_2 removal efficiency in the GSA/fabric filter system was typically about 3 to 5 percentage points higher than that achieved in the GSA/ESP system at the same test conditions. This enhanced performance in the fabric filter system was not unexpected given the intimate contact between the SO_2 in the flue gas and the alkaline material collected on the bags.

The particulate removal efficiency in the fabric filter was 99.9+ percent for all of the tests completed with the full dust loading from the GSA system reactor/cyclone. The emissions rate was typically in the range of 4.3 g/GJ (0.01 lb/million Btu), which is well below the NSPS for particulates. The filter cake on the bags was relatively easy to dislodge and no problems were encountered in cleaning the bags.

The particulate emission rates with the fabric filter pulling flue gas from the ESP outlet were extremely low, about 0.9 g/GJ (0.002 lb/million Btu), which is more than an order of magnitude below the NSPS for particulates. If extremely high removal efficiencies are required, then the most effective arrangement may be to install a fabric filter downstream of the GSA unit and the ESP.

Economic Evaluation

As part of the DOE CCT Demonstration Program, an economic evaluation of the GSA process was conducted using the same design and economic premises that were used to evaluate a number of other FGD processes. Economics were estimated for a moderately difficult retrofit 300 MWe boiler burning 2.6 percent sulfur coal. The design SO_2 removal efficiency was 90 percent at a lime feed rate equivalent to 1.30 moles of calcium per mole of SO_2 in the gas inlet stream.

Comparative capital cost estimates for the conventional wet limestone, forced-oxidation scrubbing system and the GSA system show that the total capital requirement for the GSA process is substantially lower ($149/kW vs. $216/kW). The lower capital requirement for GSA is primarily due to lower costs in the SO_2 removal area. The capital cost for the GSA system is also lower than that for a conventional spray dryer system.

Capital Cost Comparison
GSA vs. Wet Limestone Forced Oxidation (WLFO)
300 MWe, 2.6% Sulfur Coal

Area	$/kW (1990 dollars) **GSA**	**WLFO**
Reagent Feed	25	37
SO_2 Removal	38	71
Flue Gas Handling	18	24
Solids Handling	5	7
General Support	1	2
Additional Equipment	4	4
Total Process Capital	**91**	**145**
Total Capital Requirement*	**149**	**216**

* Includes general facilities, engineering and home office fees, contingencies, pre-production costs, etc.

Capital cost comparison, GSA versus WLF0. The total capital requirement for GSA is about 30% lower than that for WLFO.

Operating and Maintenance Experience

The GSA system tested at TVA's CER was remarkably trouble free, and there were no major problems encountered during the entire program. All equipment and control instruments operated as anticipated without extra attention. The GSA system has demonstrated the following advantages:

- The system is a very simple design and is easy to operate and maintain.
- The spray nozzle assembly can be replaced without interrupting the operation.
- None of the systems in operation has had dust buildup requiring shutdown.
- Dedicated maintenance personnel are not required.
- GSA yields a byproduct with less than 1 percent moisture, that can be easily disposed of or converted to a low grade cement.
- There has been no apparent corrosion or erosion after seven years of operation in MSW service.
- All GSA systems in operation show very close to 100 percent availability.

Legislative and Marketplace Incentives

Title IV of the 1990 revisions to the Clean Air Act is intended to reduce SO_2 emissions in order to mitigate acid rain. The 100 largest SO_2 sources are required to reduce SO_2 emissions and implement controls in Phase 1, starting in January 1995. In Phase 11, starting in January 2000, all sources are required to meet more stringent SO_2 control standards.

Title IV controls SO_2 via a system of emission allowances. Each allowance authorizes the utility to emit one ton of SO_2 per year. The EPA will distribute the allowances based on the plant's total annual heat input in the mid-1980s multiplied by an emissions factor, which is 1.1 kg/GJ (2.5 lb/million Btu) for Phase I and 0.52 kg/GJ (1.2 lb/ million Btu) for Phase II. New plants receive no allowances. The SO_2 emission allowances may be bought or sold. Decisions will be made to install SO_2 controls or to buy allowances based on the relative costs in $/ton Of SO_2 emitted.

SO_2 control systems installed will make additional allowances available, which may be sold at the current market price.

Some companies now burn compliance coals, i.e., coals that generate SO_2 emissions which are in compliance with emissions limits. These are low-sulfur coals with either a higher delivered price than high-sulfur coals or characteristics which require significant boiler changes. Thus, utilities must consider the trade-offs between the cost of lower sulfur in the coal feed versus the cost of removing SO_2 from the stack gas.

Commercialization

The GSA system is a low-cost alternative to wet scrubbers and other semi-dry FGD systems, with SO_2 removal efficiencies higher than those for other semi-dry systems. The GSA system meets NSPS requirements for SO_2 and provides significant removal of air toxics.

The patented GSA technology is considered a viable and cost-effective process for controlling air pollution emissions from medium-size boilers fueled with medium- to high-sulfur coal. Particulate control in GSA systems can be achieved by either an ESP or a fabric filter. The ground space requirements for the primary equipment are very small. The GSA system, therefore, lends itself well to retrofit installations, where in many cases an existing ESP can be utilized.

The potential market for GSA includes new coal-fired utility boilers and cogeneration boilers up to 500 MWe. Additionally, in those cases where boilers are fired with compliance coal, use of GSA would permit switching to lower-cost high-sulfur coals.

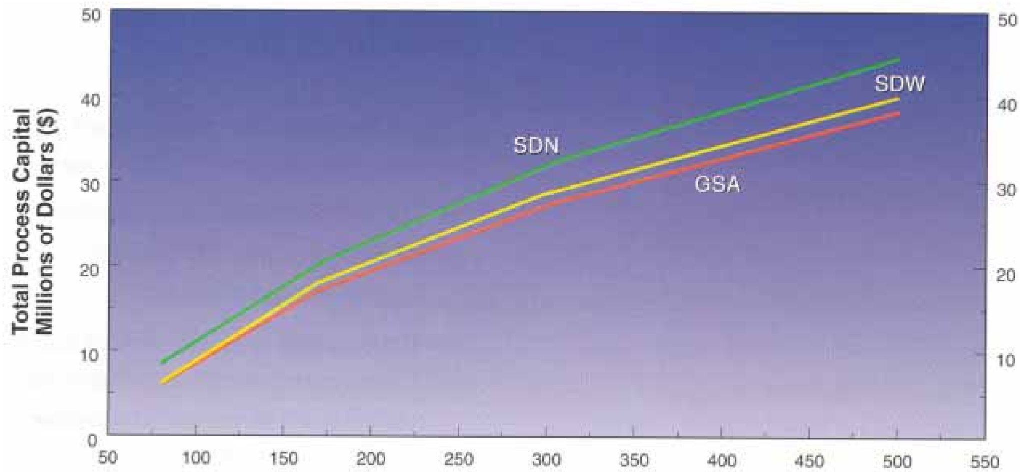
One of the goals of this demonstration project was to design, fabricate, construct, and operate a GSA system that can be commercialized for the benefit of U.S. electric utilities and industries. GSA technology is now ready to be used to comply with Phase II of the Clean Air Act Amendments.

An effort has been made to standardize the process design and equipment sizing so that a commercial unit can be built and installed in a relatively short time. Furthermore, equipment design has been simplified, resulting in reduced material and construction costs. A GSA unit which will accommodate a 100 MWe boiler in a single reactor has also been designed.

Efforts are now being concentrated on the retrofit market. AirPol will supply a GSA system for a 50 MWe municipal boiler burning Ohio coal as its first commercial utility installation in the U.S. The state of Ohio, in conjunction with the Ohio Coal Development Office, awarded the city of Hamilton a grant to install a GSA system in the city's municipal power plant. To meet requirements of the CAAA it has been necessary to burn relatively expensive low-sulfur coal in this plant. After tests on the GSA system are completed, the unit will remain in place, allowing the city of Hamilton to meet environmental regulations while using high-sulfur Ohio coal for power generation.

The next step in development will be to apply GSA to a 100-200 MWe boiler, a conservative scale-up from the 50 MWe system. Since the GSA system consists of modular units, subsequent size increases should be easily accommodated.

Capital Cost Comparison



Note: SDW = Spray Dryer, Wheel Type
SDN = Spray Dryer, Nozzle Type

Capital cost comparison, GSA vs spray dryer. Process capital cost for GSA is lower than that for spray dryer.

Insulated cyclone separator being elevated for placement into the system.

Conclusions

All of the major objectives of the GSA demonstration were successfully achieved:

- The GSA system removes more than 90 percent of the SO_2 with a low level of lime consumption.
- The GSA unit operated without interruption during the 28-day demonstration period. The emissions from the ESP remained well below the NSPS for particulates.
- The capital cost for a GSA system is about 30 percent less than that for a comparable wet limestone FGD system.
- The GSA process in conjunction with dust collection removes substantially all of the HCl, HF, and trace metals from the flue gas.
- The SO_2 removal efficiency of the GSA system using a fabric filter for particulate removal is about three to five percentage points higher than that achieved in a GSA system using an ESP under comparable conditions.

As shown in the demonstration program, the GSA process can be designed to take into account existing site conditions, environmental impacts, and operational concerns, as well as the goal of cost minimization. The GSA process is a viable solution to SO_2 removal in coal-fired boiler plants, and the technology for commercial application in order to meet the Phase II CAAA compliance requirements. The results of this demonstration project show that GSA technology meets the goals of the CCT Program. The GSA process offers a simple, economical means of achieving a high degree of SO_2 removal from boilers burning high-sulfur coals.

Additional GSA Commercial Projects

As a result of the success of the 10 MWe GSA demonstration project, FLS miljϕ has won a major contract for a high performance SO_2 removal GSA system. The $10 million contract, awarded by Swedish company Luossavaara Kirunavaara AB (LKAB), sets a landmark in the application of the GSA process: with a gas volume equivalent to a 135 MWe boiler application, it will be the largest GSA unit built to date.

The GSA unit will be used to remove sulfur from the flue gas of a four million ton per year iron ore reduction plant. According to FLS miljϕ, the Swedish environmental authority suddenly imposed more stringent emissions standards, which raised the required SO_2 removal efficiency from 90 percent to 95 percent at the final stage of contract negotiations. The test results from the GSA demonstration project at TVA convinced LKAB that GSA is capable of achieving such high SO_2 removal efficiencies and led to the contract.

In February 1995, AirPol was awarded a contract for the supply of a GSA system for a 12 MWe oil-fired cogeneration plant in Asia. The GSA system, which is scheduled to be operational by the end of 1995, will be the first GSA, and possibly the first semi-dry scrubber, for an oil-fired boiler application.

Based on their prior experience with a wet scrubber on a similar installation, and their preference for a scrubber that generates dry waste, the company selected a semi-dry scrubber for this application. Among competing technologies from worldwide suppliers, GSA was chosen based on the excellent SO_2 removal performance and the extremely dry characteristics of the GSA waste product as demonstrated at the test unit at TVA.

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List of Acronyms and Abbreviations

acf .... actual cubic feet
AST .... approach-to-saturation temperature
Btu .... British thermal unit
CAAA .... Clean Air Act Amendments of 1990
CCT .... Clean Coal Technology
CER .... Center for Emissions Research
DOE .... U.S. Department of Energy
ESP .... electrostatic precipitator
FGD .... flue gas desulfurization
g .... gram
gr .... grain
GSA .... Gas Suspension Absorption
J .... joule
kW .... kilowatt
MSW .... municipal solid waste
MW, MWe .... megawatt
NSPS .... New Source Performance Standards
scfm .... standard cubic feet per minute
TVA .... Tennessee Valley Authority

Preparation and printing of this document conforms to the general funding provisions of a cooperative agreement between AirPol Inc. and the U.S. Department of Energy. The funding contribution of the industrial participant permitted inclusion of multicolored artwork and photographs at no additional expense to the U.S. Government.