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THE BABCOCK & WILCOX COMPANY

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**SO<sub>x</sub>-NO<sub>x</sub>-ROX BOX™ FLUE GAS CLEANUP  
DEMONSTRATION PROJECT**



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

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**JUNE 1999**

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ENVIRONMENTAL CONTROL DEVICES

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# SO<sub>x</sub>-NO<sub>x</sub>-Rox Box™ FLUE GAS CLEANUP DEMONSTRATION PROJECT

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**The SNRB™ process offers a compact, highly flexible means of controlling SO<sub>2</sub>, NO<sub>x</sub>, and particulate matter. The system provides a high degree of turndown to match performance to compliance requirements and minimize operating costs with variable fuel supply characteristics.**

## OVERVIEW

A compact, highly flexible multi-pollutant control device, The Babcock & Wilcox Company's SO<sub>x</sub>-NO<sub>x</sub>-Rox Box™ (SNRB™) process, successfully completed demonstration at Ohio Edison's R.E. Burger Plant in Dilles Bottom, Ohio.

The project is part of the U.S. Department of Energy's Clean Coal Technology Demonstration Program (CCTDP) established to address energy and environmental concerns related to coal use. Cost-shared partnerships with industry were sought through five nationally competed solicitations to accelerate commercialization of the most advanced coal-based power generation and pollution control technologies. The CCTDP, valued at nearly \$6 billion, has leveraged federal funding twofold through the resultant partnerships encompassing utilities, technology developers, state governments, and research organizations. This project was one of 16 selected in May 1988 from 55 proposals submitted in response to the program's second solicitation.

The SNRB™ process integrates newly developed high temperature fabric filter bags, dry sorbent injection, and selective catalytic reduction (SCR) into a pulsed jet baghouse to achieve high-percentage capture of SO<sub>2</sub>, NO<sub>x</sub>, and particulate matter. All performance objectives were achieved, including combined 70–90 percent SO<sub>2</sub> removal, 90 percent NO<sub>x</sub> reduction, 99.9 percent particulate matter removal; long-term operability; and the potential for improved boiler efficiency. Although operated on a 5-MWe slipstream, SNRB™ components were commercial scale and manufactured to commercial specifications. Parametric testing along with numerous cold starts at R.E. Burger Unit 5 combined to create far harsher conditions than expected in commercial service, yet the SNRB™ system endured them extremely well.

The flexibility of the system to adjust to a wide range of pollutant control requirements at lower costs than a combination of conventional systems makes it an attractive compliance option. SO<sub>2</sub> and NO<sub>x</sub> controls can be added incrementally, lowering the initial capital cost. The SO<sub>2</sub> control component can accommodate abrupt changes in coal sulfur content reflective of the range of low sulfur to high sulfur coals that might be used. The process can be operated with or without the SCR component that is inserted as a separate assembly inside the filter bags. The SCR catalyst can be designed for any level of NO<sub>x</sub> emission reduction sought. Recent "soot and smog" environmental rulings place a premium on NO<sub>x</sub> and particulate matter control, which enhances the attractiveness of the SNRB™. The SNRB™ process is particularly applicable to boilers in the 50–150 MWe range.

# THE PROJECT

Key to project success was effective performance of newly developed filter bags at temperatures up to 900 °F, as well as the performance of an SCR catalyst designed to fit inside the bags. Pilot testing of three different filter bag fabrics and two different SCR catalyst forms preceded actual demonstration. Evaluated were Nextel™ ceramic fiber, S2-Glass fiberglass fiber, and Silontex filter bags. Based on cleaning and strength characteristics at elevated temperatures, Nextel™ was chosen as the design baseline bag material with S2-Glass as an alternate to be tested, as well. Extruded and pellet forms of Norton's non-toxic zeolite NC-300™ catalyst were tested. The extruded form was chosen because of resistance to plugging and ease of installation and inspection.

The demonstration unit was a 5-MWe equivalent, hot pulsed-jet fabric filter baghouse with six compartments housing commercial scale bags (6-1/4 inches in diameter, 20 feet long). Each compartment contained 42 bags. Five compartments used Nextel™ bags and the other used S2-Glass bags. The unit was operated off a flue gas slipstream taken from the economizer. Provision was made for heating the flue gas entering the unit to support parametric testing and to sustain the elevated temperatures needed.

*Screening Tests* were run to optimize SO<sub>2</sub>, NO<sub>x</sub>, and particulate matter (PM) control with respect to the primary operating conditions that influence SNRB™ performance. *Continuous Tests* were conducted to examine the secondary effects of baghouse operating conditions and bag cleaning techniques on SNRB™ performance. *System Response Tests* assessed the effects of boiler fluctuations on SNRB™ performance and served to develop commercial controls. Alternate sorbents were also evaluated before initiating *Performance Tests* at selected optimum conditions and configurations to obtain steady-state data. An *Air Toxics Emissions Testing Program* was added at the end of the *Performance Tests*.

## Project Sponsor

The Babcock & Wilcox Company

## Additional Team Members

Ohio Edison Company — cofunder/ host  
Ohio Coal Development Office — cofunder  
Electric Power Research Institute — cofunder  
Norton Company — cofunder/ SCR catalyst supplier  
3M Company — cofunder/filter bag supplier  
Owens Corning Fiberglas Corporation — cofunder/  
filter bag supplier

## Location

Dilles Bottom, Belmont County, OH  
(Ohio Edison Company's R.E. Burger Plant,  
Unit No. 5)

## Technology

The Babcock & Wilcox Company's  
SO<sub>x</sub>-NO<sub>x</sub>-Rox Box™ (SNRB™) Process

## Plant Capacity

5-MWe equivalent slipstream from a 156-MWe boiler

## Coals

Bituminous coal blend, 3.7% sulfur average

## Demonstration Duration

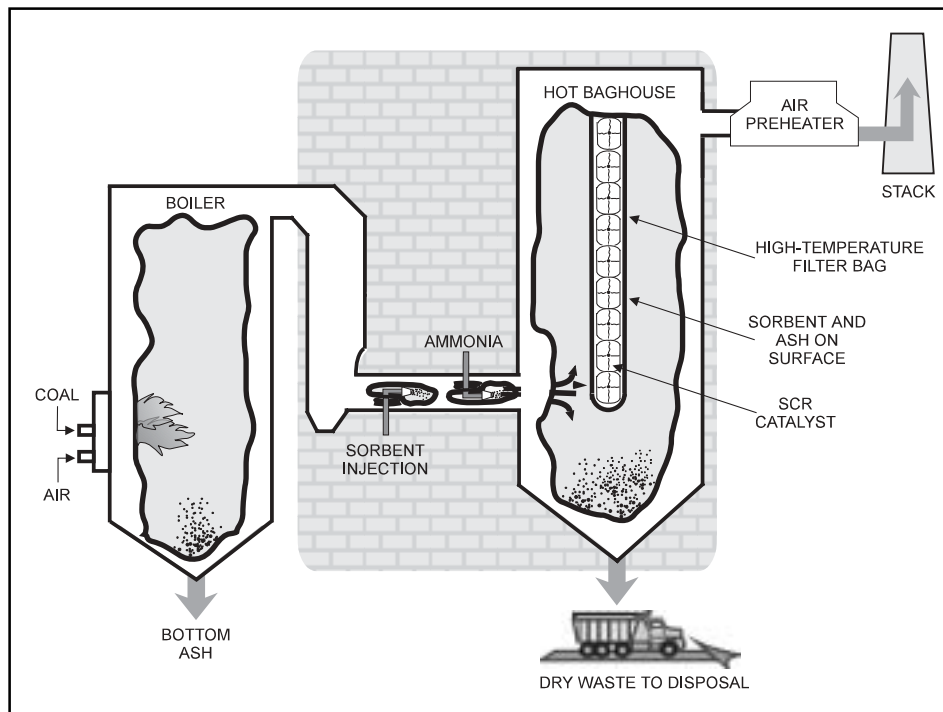
May 1992—May 1993

## Project Funding

Total Project Cost	\$13,271,620	100%
DOE	\$6,078,402	46%
Participant	\$ 7,193,218	54%



# THE TECHNOLOGY



The technology is essentially integrated into a pulsed-jet fabric filter baghouse. The only external components are sorbent and ammonia injection nozzles in the ductwork immediately upstream of the baghouse and sorbent/ammonia storage and delivery. Key elements of the technology are newly developed high temperature fabric filter bags and a zeolite NC-300™ SCR catalyst extruded in a circular configuration to fit inside the bags. The anhydrous ammonia and dry sorbent storage and injection systems used have an extensive history of commercial power plant application.

A high temperature baghouse regime, ultimately determined to be optimal at 800–850 °F, was chosen to provide efficient SO<sub>2</sub> and NO<sub>x</sub> capture and enhance boiler efficiency. Heat recovery is enhanced by removing acid gases that otherwise preclude optimal heat transfer downstream in the air heater. In a commercial configuration, the SNRB™ would be located between the economizer and the air heater.

In the baseline SNRB™ process, a hydrated lime is injected by a single nozzle at 200-250 ft/sec to provide effective particle size distribution and mixing with the flue gas. The injection temperature is approximately 900 °F. SO<sub>2</sub> absorption begins immediately in the ductwork, continues in a gaseous mixing mode in the baghouse chambers, and concludes as the flue gas passes through a sorbent filter cake on the bag surfaces. The elevated temperatures and the sorbent filter cake combine to make SO<sub>2</sub> control efficient, yet simple (no humidification used). The sorbent injection also is effective in removing chloride and fluoride acid gases. The degree of SO<sub>2</sub> capture is controlled by the sorbent injection rate to achieve a certain calcium to sulfur molar ratio (Ca/S). The response time for such adjustments is very quick, permitting a high degree of flexibility in fuel use.

NO<sub>x</sub> control is achieved by injecting ammonia (NH<sub>3</sub>) upstream of the baghouse through a grid designed to provide uniform distribution. In the temperature range chosen, the ammonia does not react with the SO<sub>2</sub>. Upon contact with the SCR catalyst, the ammonia and NO<sub>x</sub> in the flue gas react to form nitrogen and water. Little oxidation of SO<sub>2</sub> to the acid precursor SO<sub>3</sub> occurs, which is characteristic of zeolite catalysts. SCR catalyst placement inside the filter bags creates a very low dust, low acid gas environment conducive to high performance and long life.

## DEMONSTRATION RESULTS

- SO<sub>2</sub> removal efficiency of greater than 80% was achieved with commercial-grade lime at a calcium-to-sulfur molar ratio (Ca/S) of 1.8 and temperature of 830–850 °F.
- SO<sub>2</sub> removal efficiency of greater than 80% was achieved with sodium bicarbonate at a sodium-to-sulfur normalized stoichiometric ratio (Na<sub>2</sub>/S) of 1.0 and temperature of 425 °F.
- SO<sub>2</sub> emissions were reduced to less than 1.2 lb/10<sup>6</sup> Btu with 3–4% sulfur coal and a Ca/S as low as 1.5 or Na<sub>2</sub>/S of less than 1.0.
- NO<sub>x</sub> emissions reduction of 90% was readily achieved with ammonia (NH<sub>3</sub>) slip limited to less than 5 ppm at NH<sub>3</sub>/NO<sub>x</sub> ratios of 0.85 and above.
- Sodium bicarbonate injection provides for modest levels of NO<sub>x</sub> removal (15–25%) over a baghouse temperature range of 450–600 °F without ammonia injection and Na<sub>2</sub>/S of 1.0.
- Overall baghouse particulate matter collection efficiency averaged 99.89%, resulting in average measured emissions of 0.018 lb/10<sup>6</sup> Btu.
- HAPS testing showed reduction of all trace metals except mercury by an average of 95%, reduction of hydrogen chloride by 96%, and reduction of hydrogen fluoride by 84%.
- Calcium utilization was 40–45% for SO<sub>2</sub> removals of 85–90%.
- NC-300™ zeolite catalyst showed no appreciable physical degradation or change in catalyst activity over the course of operation.
- No excessive wear or failures occurred with 3M's Nextel™ or Owens Corning Fiberglas's S2-Glass filter bags.
- Capital cost for a 150-MWe retrofit was \$253/kW (constant 1994 dollars), assuming baseline SO<sub>2</sub>, NO<sub>x</sub>, and particulate matter emissions of 4.31 lb/10<sup>6</sup> Btu (2.8% sulfur), 1.02 lb/10<sup>6</sup> Btu, and 4.78 lb/10<sup>6</sup> Btu, respectively.

## ENVIRONMENTAL PERFORMANCE

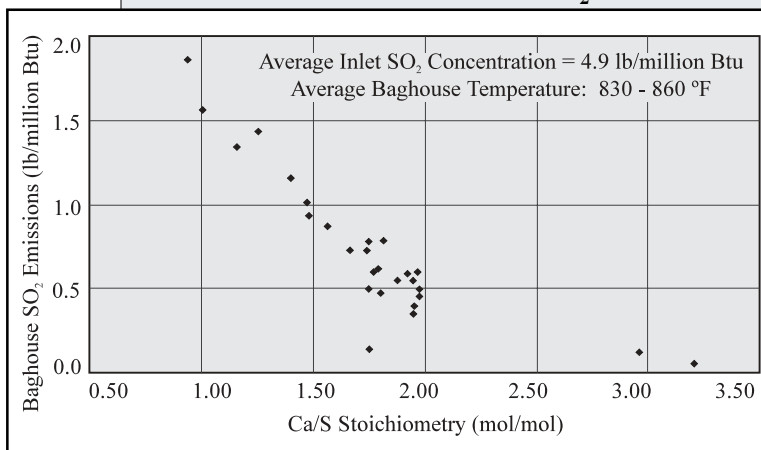
### SO<sub>2</sub> CONTROL

In evaluating SO<sub>2</sub> control for the baseline design, an assessment was made of the effects of Ca/S, sorbent injection temperature and location, and baghouse temperature on performance to establish optimum operating conditions. During these *screening tests*, inlet SO<sub>2</sub> concentrations ranged from 2,000 to 3,000 ppm. Air-to-cloth ratios, the volumetric flow rate of flue gas per square foot of filter bag surface, was maintained at about 4 ft/min. The bag cleaning cycle was about 45 minutes.

### EFFECTS OF CA/S

At baghouse temperatures of 830–860 °F, SO<sub>2</sub> removal increased from about 60 percent at a Ca/S of 1.0 to greater than 80 percent at a Ca/S of 1.8. Lime utilization ranged from 60 percent at a Ca/S of 1.0 to 44 percent at a Ca/S of 1.8. Based on overall laboratory analysis of solid waste and field test data, calcium utilization was determined to be 40–45 percent for SO<sub>2</sub> removal efficiencies of 85–90 percent. *Figure 1* shows the effect of Ca/S on SO<sub>2</sub> emissions at an average inlet SO<sub>2</sub> concentration of 4.9 lb/10<sup>6</sup> Btu and a baghouse temperature of 830–860 °F.

FIGURE 1. EFFECT OF CA/S RATIO ON SO<sub>2</sub> EMISSIONS



## EFFECTS OF SORBENT INJECTION TEMPERATURE AND LOCATION

To examine the effects of sorbent injection temperature/location, five injection locations were provided and controls incorporated to examine temperatures in the range of 700–1,200 °F. Four of the injection locations were significantly upstream of the baghouse to provide residence times of 2–4 seconds, and the remaining injection point was immediately upstream of the baghouse. A set of high temperature (1,000–1,200 °F) tests were run with the four injection locations farthest upstream of the baghouse. Average baghouse temperatures were 820–850 °F and Ca/S ranged from 1.95–2.3. It was found that SO<sub>2</sub> removal dropped off sharply around 1,050 °F. Flue gas residence time had negligible effect. The drop off in removal efficiency was attributed to sorbent sintering, a surface effect severely impacting sorbent reactivity. Maximum SO<sub>2</sub> removal efficiency was found to occur with injection temperatures of 850–900 °F at the injection point immediately upstream of the baghouse. Beyond 900 °F, SO<sub>2</sub> removal efficiency began to decline. This was found to be due to an abrupt rise in sorbent carbonation reactions at the expense of sorbent sulfation (the reaction that captures SO<sub>2</sub>). Once the CO<sub>2</sub> present in the flue gas causes the sorbent surface to be coated with carbonates, the SO<sub>2</sub> cannot penetrate to react. Carbonation conversion above 900 °F was measured at nearly double the sulfation conversion.

The ability to obtain high SO<sub>2</sub> capture efficiency with injection near the baghouse had significant positive capital cost ramifications, particularly for retrofits, because the system was made even more compact than originally anticipated. The short residence time (0.5 seconds) before entering the baghouse was sufficient when combined with the residence time in the baghouse chambers and intimate SO<sub>2</sub>/sorbent contact achieved as the flue gas passes through the filter cake on the bag surfaces. The differential between sorbent injection and baghouse temperatures was about 25 °F.

## EFFECTS OF BAGHOUSE TEMPERATURE

The impact of baghouse temperature on SO<sub>2</sub> removal was as shown in Figure 2. There was a clear trend of increasing SO<sub>2</sub> removal with an increase in baghouse operating temperature. SO<sub>2</sub> removal efficiencies below 50 percent were observed in the temperature range of 700–750 °F, while greater than 80 percent SO<sub>2</sub> removal was achieved at temperatures above 800 °F.

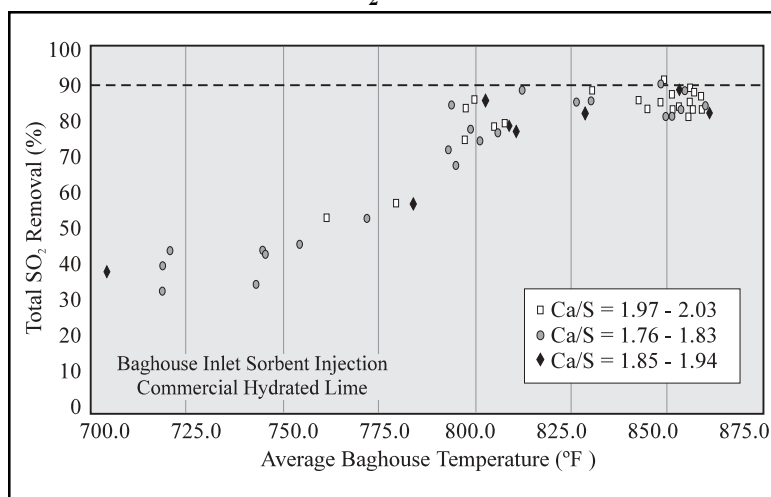
This suggested an optimal operating range of 800–860 °F for commercial service with hydrated lime.

## SECONDARY EFFECTS

Secondary effects on SO<sub>2</sub> removal were also examined. Air-to-cloth ratios over the range of 3.0–4.5 ft/min had no measurable effect on SO<sub>2</sub> removal. Sorbent particle size was reduced to increase sorbent concentration, but no effect on SO<sub>2</sub> removal was detected for the narrow band of SO<sub>2</sub> concentrations that existed (2,100–2,700 ppm). As indicated from earlier pilot testing, sorbent injection velocities of 200–250 ft/sec were sufficient to produce the needed fine sorbent particulate matter and flue gas mixing with commercial grade lime (13.8 m<sup>2</sup> / gram surface area [BET method], 5.4 micron mass mean diameter, 3.2 micron sauter mean diameter). Ammonia injection did not effect SO<sub>2</sub> removal in the temperature range used for hydrated lime injection. The minimum baghouse pressure needed for uniform cleaning along the 20 foot bag length was established at 30–40 psi and was maintained at this value throughout testing.

SO<sub>2</sub> removal was affected by bag cleaning. A drop in removal of about 5 percent accompanied each compartment cleaning, but the effect was temporary and removal quickly returned to its former level. This spike in SO<sub>2</sub> removal was the result of filter cake dispersal upon cleaning. For the demonstration baghouse with five operational compartments, cleaning one compartment removed the sorbent from 20 percent of the filter bags in service. For commercial applications, a significantly lower fraction of the filter bags would be cleaned at any one time and the effect on SO<sub>2</sub> removal would be dampened.

FIGURE 2. EFFECT OF BAGHOUSE TEMPERATURE ON SO<sub>2</sub> REMOVAL





Boiler load fluctuations did not appear to affect SO<sub>2</sub> removal when the Ca/S stoichiometry was maintained through automatic control at the set point. The hydrated lime feed system was able to follow changes in the system SO<sub>2</sub> concentration and flue gas flow rate to eliminate boiler operating fluctuation impacts on SO<sub>2</sub> removal. However, severe temperature swings, not observed at the demonstration, would impact SO<sub>2</sub> removal performance.

### ***PERFORMANCE TESTING***

Performance testing of the baseline SNRB™ system over 108 hours of continuous operation resulted in an average SO<sub>2</sub> removal efficiency of 86.6 percent at a Ca/S of 2.0 and baghouse temperature of 855 °F. SO<sub>2</sub> emissions averaged 0.54 lb/10<sup>6</sup> Btu. Greater than 96 percent hydrogen chloride and 84 percent hydrogen fluoride removal were also attained. Phase II of the Clean Air Act Amendments of 1990 (CAAA) that come into effect in 2000 will require control to only 1.2 lb/10<sup>6</sup> Btu. This could be achieved with a Ca/S of only 1.5.

### ***ALTERNATE SORBENT TESTING***

Alternate sorbents were also evaluated. For the baseline SNRB™ operating mode, two modified lime hydrates were tested — a sugar hydrated lime (SHL) and a calcium lignosulfonated lime (CLS). The additives were reported to increase porosity and reduce the particle size distribution. Analysis showed that the SHL had the smallest mass mean diameter. However, the alternate sorbents had available surface areas smaller than the commercial hydrate (BET method). Particle size distributions did not vary significantly.

Results of the modified hydrate testing showed that SO<sub>2</sub> removal efficiency was enhanced by over 5 percent at a Ca/S of 2.0 and baghouse temperature of about 850 °F. Of the two alternate sorbents, SHL provided slightly better performance.

Testing was also conducted with a sodium bicarbonate sorbent (NaHCO<sub>3</sub>), but at significantly lower operating temperatures than the baseline SNRB™. Historically, dry NaHCO<sub>3</sub> injection had provided higher sorbent utilization than hydrated lime as well as a moderate NO<sub>x</sub> reduction potential. Testing was conducted over a baghouse temperature range of 450–850 °F and normalized Na to SO<sub>2</sub> stoichiometric ratios of 0.5–2.0. The normalized stoichiometric ratio (NSR) took into account that two moles of Na were required to capture one mole of SO<sub>2</sub>. The NSR, essentially Na<sub>2</sub>/SO<sub>2</sub>, was determined by dividing the moles of Na injected by the moles of SO<sub>2</sub> present in the flue gas and dividing this number by 2.



**Workers lower one of the catalyst holder tubes into a mounting plate in the penthouse of the high-temperature baghouse.**



**Bottom of baghouse where ash is removed and sent to storage silo with catalyst holder tube in foreground.**

Baghouse temperatures above 450 °F decreased SO<sub>2</sub> removal efficiency to varying degrees dependent on the NSR. Temperatures below 450 °F could not be evaluated because of test apparatus limitations, but it was postulated that temperatures down to 300 °F would be effective.

At a baghouse temperature of 450 °F and an NSR of 1.0, an 85 percent SO<sub>2</sub> removal efficiency was achieved, corresponding to a sorbent utilization of 85 percent. At a 0.5 NSR, 100 percent sorbent utilization was attained, but only 50 percent SO<sub>2</sub> removal. Ammonia injection at these temperatures mitigated SO<sub>2</sub> removal somewhat, due to adsorption on the sorbent, dropping the 85 percent removal efficiency to about 80 percent. Phase II CAAA SO<sub>2</sub> requirements of 1.2 lb/10<sup>6</sup> Btu could be met with an NSR of less than 1.0.

Sodium bicarbonate injection for SO<sub>2</sub> control also resulted in modest levels of NO<sub>x</sub> reduction without the use of ammonia injection. NO<sub>x</sub> reduction dropped off as temperatures increased above 450 °F, and was found to increase with increasing NSR at a constant temperature. At about 450 °F, NO<sub>x</sub> reduction was approximately 20 percent with an NSR of 1.0 and 32 percent with an NSR of 2.0. Ammonia injection enhanced NO<sub>x</sub> reduction and suppressed formation of nitrous oxide (NO<sub>2</sub>), a side effect of sodium injection that can cause opacity problems. Injecting ammonia (NH<sub>3</sub>) at a NH<sub>3</sub>/NO<sub>x</sub> ratio of 0.5, while maintaining an NSR of 1.0, resulted in a NO<sub>x</sub> reduction of 43 percent. Increasing the NH<sub>3</sub>/NO<sub>x</sub> ratio to 0.8 at an NSR of 1.0 reduced NO<sub>x</sub> by 50 percent.

The relatively low baghouse temperature characteristic of SNRB™ operation with sodium bicarbonate allows for locating the sorbent injection and baghouse downstream of the economizer in commercial application. This simplifies integration with existing boiler system components and allows for the use of more conventional filter bag fabrics. The lower temperature limits the degree of NO<sub>x</sub> reduction achievable, but used in conjunction with low-NO<sub>x</sub> burners may be sufficient for many applications.

## NO<sub>x</sub> CONTROL

In evaluating NO<sub>x</sub> control for the baseline design, the primary parameters that varied in establishing optimum conditions were the NH<sub>3</sub>/NO<sub>x</sub> stoichiometry, catalyst temperature, and catalyst space velocity (ratio of volumetric gas flow to total volume of catalyst). Ammonia slip and SO<sub>3</sub> levels were monitored along with NO<sub>x</sub> emissions in establishing the optimum operating conditions. Inlet NO<sub>x</sub> concentrations ranged from 350–490 ppm.

### EFFECTS OF NH<sub>3</sub>/NO<sub>x</sub> STOICHIOMETRY

The NH<sub>3</sub>/NO<sub>x</sub> stoichiometry was the operating parameter having the greatest impact on NO<sub>x</sub> removal. As shown in *Figure 3*, the project goal of 90 percent NO<sub>x</sub> reduction was achieved with operation above an NH<sub>3</sub>/NO<sub>x</sub> ratio of 0.85 and baghouse temperatures in the range of 790–865 °F. The concentration of NO<sub>x</sub> in the flue gas did not appear to influence significantly the rate of NO<sub>x</sub> conversion. The average inlet NO<sub>x</sub> concentration was approximately 0.63 plus or minus 0.09 lb/10<sup>6</sup> Btu. NO<sub>x</sub> emissions were reduced to 0.05 lb/10<sup>6</sup> Btu with operation at NH<sub>3</sub>/NO<sub>x</sub> ratios of 0.85–0.92 and catalyst temperatures of 790–870 °F. Ammonia slip at the 90 percent NO<sub>x</sub> reduction was consistently

less than 5 ppm. SO<sub>3</sub> levels were approximately 0.8 ppm higher than at the baghouse inlet, corresponding to an SO<sub>2</sub> oxidation rate of about 0.32 percent. Generally, SO<sub>2</sub> oxidation to SO<sub>3</sub> must be kept below 1.0 percent to avoid problems. Turndown capability for tailoring the degree of NO<sub>x</sub> reduction by varying the rate of ammonia injection was 50–95 percent.

### EFFECTS OF CATALYST TEMPERATURE

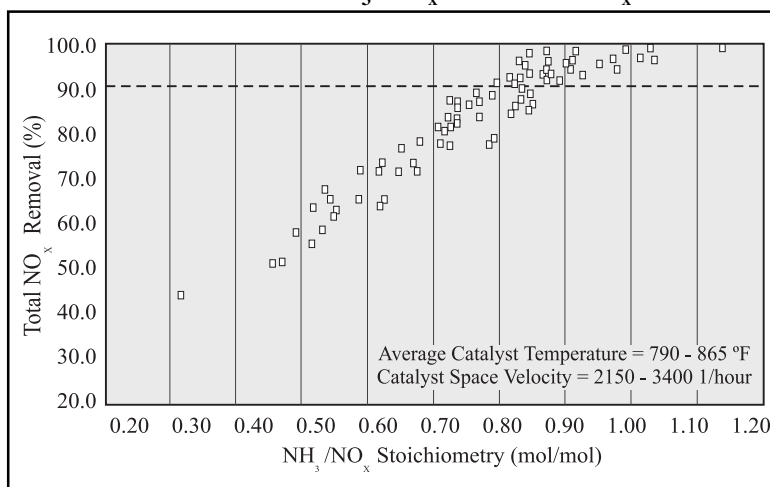
NO<sub>x</sub> removal also increased with catalyst temperature, with optimum removal achieved in the range of 800–900 °F. The Norton NC-300™ catalyst was designed for optimal performance between 700–900 °F. This overlaps the optimum temperature range for SO<sub>2</sub> removal (800–850 °F) with hydrated lime sorbent. The catalyst space velocity was found to have a minimal effect on NO<sub>x</sub> removal over the range of flue gas flow rates evaluated.

### SECONDARY EFFECTS

A secondary catalysis reaction in the baghouse may have been a significant contributor to the overall NO<sub>x</sub> reduction observed. This was attributed to either the flyash or metal surface area of the bag retainers serving as a catalyst.

A slight increase in NO<sub>x</sub> removal was observed with reduction in boiler load. This was attributed to a somewhat slow response of the ammonia flow controller, and the catalyst acting as a reservoir for ammonia. Baghouse cleaning (45 minute cycle) also caused a slight brief decline in NO<sub>x</sub> removal due to either removal of reactive flyash or catalyst temperature drop.

**FIGURE 3. EFFECT OF NH<sub>3</sub>/NO<sub>x</sub> RATIO ON NO<sub>x</sub> REMOVAL**



## PARTICULATE MATTER CONTROL

Control of particulate matter emissions was demonstrated over a wide range of baghouse operating conditions. Overall baghouse particulate matter collection efficiency averaged 99.89 percent, for an average emission rate of 0.018 lb/10<sup>6</sup> Btu.

Performance tests with an air-to-cloth ratio of 3.7 ft/min and 45 minute cleaning cycle resulted in a collection efficiency of 99.86 percent at an average baghouse pressure drop of 11.9 plus or minus 0.35 inches of H<sub>2</sub>O. Inlet loadings were 16.7 lb/10<sup>6</sup> Btu (9.3 grains per scf) and outlet emissions were 0.023 lb/10<sup>6</sup> Btu (0.013 grains /scf). *Figure 4* shows the particle size distribution. Baghouse opacity was generally less than 2 percent.

Variation in baghouse outlet particulate matter emissions could not be correlated with air-to-cloth ratio, lime injection rate, baghouse pressure drop, bag cleaning frequency, or the combination of compartments in service. Emission testing with and without the SCR catalyst installed revealed no apparent difference in collection efficiency, demonstrating that the catalyst was not serving as a particulate matter trap. Particulate matter emissions were independent of sorbent type, but the coarser sodium bicarbonate produced a lower baghouse pressure drop.

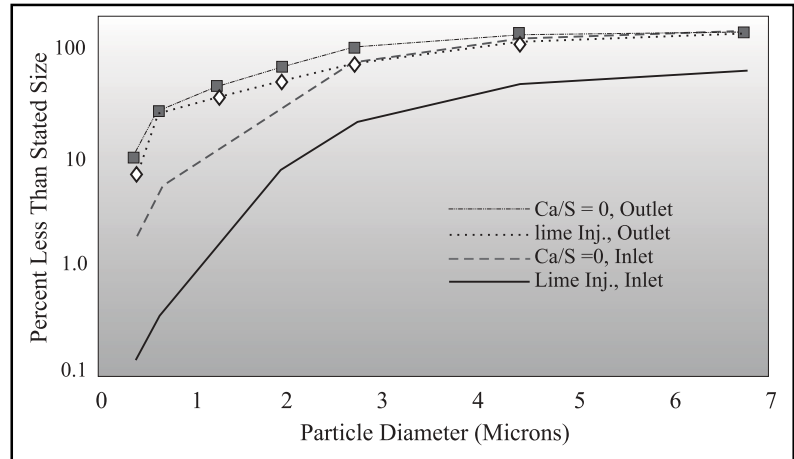
## SOLID WASTE CONTROL

The baghouse byproduct solids were non-corrosive and non-hazardous. The pH was consistently less than 12.5, permitting landfill disposal; and Toxicity Characteristics Leaching Procedure (TCLP) analysis for heavy metals showed levels routinely below detection limits (except for selenium, which was still well below allowable limits). Ammonia was not detected in the byproduct solids. Furthermore, the byproduct solids showed potential for application as an additive to cement, a soil amendment, and soil stabilizer.

## HAPs CONTROL

Operation of the baseline SNRB<sup>TM</sup> system reduced emissions of all trace metals except mercury by over 95 percent (mercury remained in the vapor state). As indicated previously, hydrogen chloride and hydrogen fluoride capture efficiencies were 96 percent and 84 percent, respectively.

FIGURE 4: PARTICULATE MATTER SIZE DISTRIBUTION



## OPERATIONAL PERFORMANCE

The low acidic composition of the flue gas exiting the baghouse indicated that the air heater could operate with lower exit gas temperatures and potentially increase boiler efficiency. However, the capability to realize such efficiency enhancements would be site specific, and longer term corrosion testing would be needed to support the supposition.

The packaged ammonia and sorbent storage and supply systems, based on commercial designs, performed with minimal downtime as anticipated. The critical high temperature filter bags and SCR catalyst, the focus of the demonstration, were designed and manufactured to commercial specifications to lend credence to the demonstration. Their ultimate successful performance, therefore, firmly established the commercial feasibility of SNRB<sup>TM</sup>.

Based on performance measures including bag cleanability, particulate matter capture, and pressure drop, both the Nextel<sup>TM</sup> and S2-Glass fabric filter bags were determined to be suitable for commercial applications. The replacement rate for the Nextel<sup>TM</sup> bags was well within the normal guarantee range of commercial suppliers. Most Nextel<sup>TM</sup> bag damage occurred during installation, not operation. No damage to the S2-Glass bags was observed from either installation or operation. Residual strength for both bag fabrics, following extended high temperature service, was more than adequate. TCLP analysis of the bag material validated the acceptability of the bags for landfill disposal as a non-hazardous material.

The SCR catalyst, stacked on hangers, was easy to install and remove for replacement or inspection. It contributed about 5.5 inches of H<sub>2</sub>O pressure drop to the nominal 13.0 inches of H<sub>2</sub>O for the SNRB™ system. The SNRB™ system pressure drop was comparable to a combination of conventional ESP/wet scrubber/SCR. The filter bags effectively protected the SCR catalyst. There was no sign of catalyst channel plugging or erosion, suggesting little particulate matter contact; and there were no adverse effects of frequent passage through the water and acid dewpoints caused by start-up and shutdown cycles.

The SCR catalyst displayed neither appreciable physical nor catalyst activity degradation over the demonstration period. Because parametric testing allowed acid gases to contact the catalyst (during periods of no sorbent injection) and frequent outages occurred, operations were harsher than anticipated in normal commercial service. No poisoning by compounds commonly found in the flyash, sorbents, or flue gas was found. TCLP analysis confirmed the lack of metals build-up in the catalyst, so that it remained non-hazardous for disposal. A ten-year catalyst life was projected, comparable to gas-fired turbine SCR applications (typical catalyst life guarantee for high dust coal-fired applications is 2–3 years).



**Lime sorbent injector port set in flange plate slip stream in flue gas duct.**

## ECONOMIC PERFORMANCE

The base case economic analysis was on a 150-MWe baseline design SNRB™ retrofit application. This was chosen because SNRB™ economics are most competitive in the 50–150 MWe range and 65 percent of the U.S. coal-fired boiler population without SO<sub>2</sub> emissions controls, as yet, fall in the ≤ 200 MWe range. The cost was based on a commercial n<sup>th</sup> plant. The cost estimating technique was believed to have an accuracy of plus or minus 20 percent. All cost data is provided in 1994 constant dollars.

Key retrofit assumptions were as shown in *Table 1*. Also of note were the following:

- Replaces existing particulate matter control;
- Provides for ID fan upgrade and new combustion air heater;
- Increases capacity of flyash handling system;
- Includes 25 percent retrofit factor, 10 percent technology contingency factor, and 25 percent project contingency factor; and

**TABLE 1. KEY RETROFIT ASSUMPTIONS**

<b>—Economic—</b>	
Construction period	2 years
Construction downtime	30 days
Remaining life of plant	15 years
<b>—Retrofit—</b>	
Coal burn rate	58 tons/hr
Power plant capacity factor	65%
Net power generation	150 MWe
Flue gas flow rate	303,200 SCFM
Uncontrolled emissions	
SO <sub>2</sub>	4.31 lb/10 <sup>6</sup> Btu
NO <sub>x</sub>	1.02 lb/10 <sup>6</sup> Btu
Particulate matters	4.78 lb/10 <sup>6</sup> Btu
<b>—Design—</b>	
Baghouse air-to-cloth ratio	4.0 Ft/min
Baghouse temperature	850 °F
Ca/S stoichiometry	1.8
SO <sub>2</sub> removal efficiency	85%
NH <sub>3</sub> /NO <sub>x</sub> stoichiometry	0.95%
NO <sub>x</sub> reduction	90%
On-site reagent storage	7 days

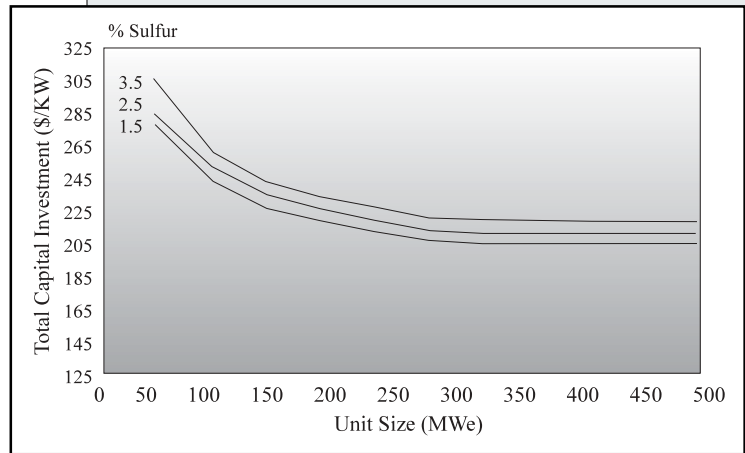
- Does not provide for an auxiliary economizer, sale of byproduct, recovery of additional heat from the cleaned gas, or sale of SO<sub>2</sub> emission allowances.

Based on the above, the total capital cost requirement was \$253/kW. Total operating and maintenance costs (fixed and variable) were \$5.6 million/yr—\$2.0 million fixed and \$3.6 million variable. The SO<sub>2</sub> sorbent costs represent about 46 percent of the operating and maintenance costs. The levelized cost for SO<sub>2</sub>, NO<sub>x</sub>, and particulate matter control was \$12.09 million/kWh or \$270/ton of pollutant removed. The levelized cost for SO<sub>2</sub> and NO<sub>x</sub> reduction alone was \$553/ton.

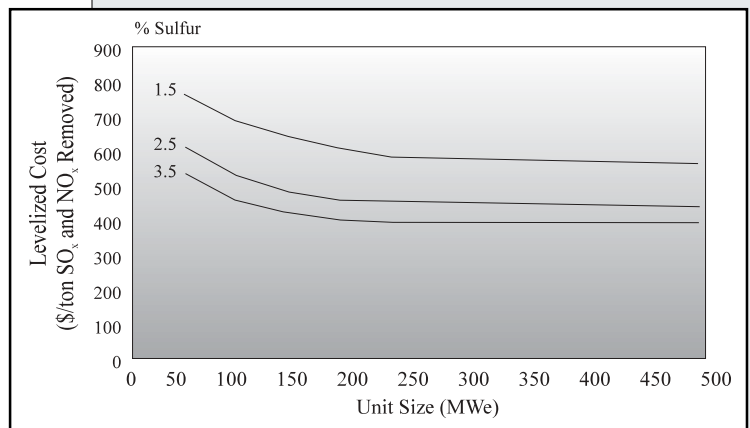
The effect of unit size on capital cost for three different coal sulfur compositions was projected as shown in *Figure 5*. The same assumptions as used in the base case apply except for use of a more optimistic construction schedule and downtime for retrofit. Levelized costs were also projected for the same set of conditions for SO<sub>2</sub> and NO<sub>x</sub> alone as shown in *Figure 6*. The capital charge leveling factor was based on 10 percent interest over 15 years. For generating capacities above 100–150 MWe, the levelized cost per ton of pollutant removed was relatively insensitive to unit size. For a given unit size, the cost per ton of pollutant removed is less sensitive to coal sulfur content as the sulfur content increases. This reflects the significance of the fabric filter costs in the total capital cost.

SNRB™ costs for a new plant were also estimated. The assumptions differed from the retrofit case only in that a 100-MWe plant with a capacity factor of 85 percent was chosen and no retrofit factor was applied. A new plant, of course, did not require replacement of the air heater, or modification of existing flues and ducts, but did include the full cost of the solids handling and storage. The capital cost was estimated to be \$221/kW with the particulate matter portion accounting for 70 percent of the total, NO<sub>x</sub> control 21 percent, and SO<sub>2</sub> control 9 percent. The levelized costs for new units for three different coal sulfur compositions were as shown in *Figure 7*. Cost comparisons were made between SNRB™ and combinations of commercial technologies as shown in *Table 2*.

**FIGURE 5: EFFECT OF UNIT SIZE ON CAPITAL COST**



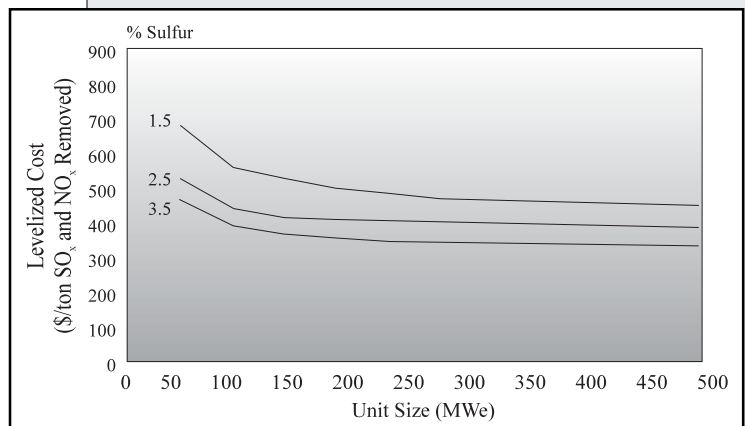
**FIGURE 6: LEVELIZED COSTS IN CONSTANT DOLLARS**



**TABLE 2: COST OF CONVENTIONAL SYSTEM COMBINATIONS**

Combination	Capital Costs \$/kW	Removal Costs \$/tons SO <sub>2</sub> and NO <sub>x</sub>
WFGD/SCR/ESP	245 - 535	195 - 3050
WFGD/LNBOA/ESP	185 - 435	480 - 730
DFGD/SNCR/FF	275 - 445	1950 - 3150
DFGD/SNCR/FF	205 - 350	850 - 1400
SNRB™	253	553

**FIGURE 7: SNRB™ SYSTEM LEVELIZED COSTS  
– NEW PLANT –**



## COMMERCIAL APPLICATIONS

There are a number of features that make SNRB™ attractive as a compliance option, as outlined below:

- High efficiency, multiple emissions control in a single component compatible with all coal-fired boiler types;
- Low plan area space requirement;
- Operating simplicity;
- Flexibility for optimal overall control economics, *e.g.*, can compliment fuel switching for SO<sub>2</sub> control and adjust to high sulfur coal use, and compliment low-NO<sub>x</sub> burners;
- Ability to implement emissions reduction in phases, mitigating initial capital investment;
- Lower capital and operating costs than a combination of conventional systems with comparable control efficiencies for small utility and industrial scale boilers
- Dry, solid by-product, requiring no processing for potential use or disposal; and
- Control of acid gas emissions and other HAPs.

The potential domestic retrofit market for SNRB™ is extensive. Most units affected by Phase I of the CAAA for SO<sub>2</sub> control complied by fuel switching. Additional means may be required for SO<sub>2</sub> compliance with Phase II. SNRB™ can compliment Phase I measures or be used with higher sulfur coals to meet the Phase II requirements. SNRB™ can also compliment NO<sub>x</sub> control measures required for wall-fired and tangentially-fired boilers instituted under Phase I of the CAAA. Phase II of the CAAA lowers emission limits for wall- and tangentially-fired boilers and imposes limits on the balance of boiler types. But more importantly, EPA rulings addressing ozone nonattainment and fine particulate matter place far more stringent requirements on NO<sub>x</sub>, SO<sub>2</sub>, and particulate matter emissions.

Domestically, there are currently 482 boilers in the ≤ 200 MWe range without SO<sub>2</sub> controls installed before 1971, representing 41,354 MWe of capacity. (The post 1971 boilers are probable candidates for wet scrubbers.) The 272 boilers in the ≤ 100 MWe range without SO<sub>2</sub> controls would be the initial market for SNRB™ (11,647 MWe). Industrial coal-fired boilers are a strong potential market as well, representing an estimated 10,000 MWe equivalent generating capacity in this sector. Internationally, the opportunities are great with particulate matter control being emphasized in prime markets such as China and Thailand.



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