Babcock & Wilcox

SOx
NOx ROx

SOx-NOx-Rox Box™
FLUE GAS CLEAN-UP DEMONSTRATION

FINAL REPORT

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SNRB™ FINAL REPORT

1.0 EXECUTIVE SUMMARY

Babcock & Wilcox's (B&W) SOx-NOx-Rox Box™ process effectively removes SO_x, NO_x and particulate (Rox) from flue gas generated from coal-fired boilers in a single unit operation, a high temperature baghouse. The SNRB™ technology utilizes dry sorbent injection upstream of the baghouse for removal of SO_x and ammonia injection upstream of a zeolitic selective catalytic reduction (SCR) catalyst incorporated in the baghouse to reduce NO_x emissions. Because the SO_x and NO_x removal processes require operation at elevated gas temperatures (800° - 900°F) for high removal efficiency, high-temperature fabric filter bags are used in the baghouse. A schematic of the SNRB™ process is presented in Figure 1-1. The process advantages include compact integration of emission control technologies in a single module and dry materials handling.

The SNRB™ Flue Gas Cleanup Demonstration Project was cooperatively funded by the U.S. Department of Energy (DOE), the Ohio Coal Development Office (OCDO), B&W, the Electric Power Research Institute (EPRI), Ohio Edison, Norton Chemical Process Products Company and the 3M Company. The SNRB™ technology evolved from the bench and laboratory pilot scale to be successfully demonstrated at the 5-MWe field scale. Development of the SNRB™ process at B&W began with pilot testing of high-temperature dry sorbent injection for SO_2 removal in the 1960's. Integration of NO_x reduction was evaluated in the 1970's. Pilot work in the 1980's focused on evaluation of various NO_x reduction catalysts, SO_2 sorbents and integration of the catalyst with the baghouse. This early development work led to the issuance of two US process patents to B&W - #4,309,386 and #4,793,981. An additional patent application for improvements to the process is pending. The OCDO was instrumental in working with B&W to develop the process to the point where a larger scale demonstration of the technology was feasible.

This report represents the completion of Milestone M14 as specified in the Work Plan. B&W tested the SNRB™ pollution control system at a 5-MWe demonstration facility at Ohio Edison's R. E. Burger Plant located near Shadyside, Ohio. The design and operation were influenced by the results from laboratory pilot testing at B&W's Alliance Research Center[1]. The intent was to demonstrate the commercial feasibility of the SNRB™ process. The SNRB™ facility, detailed in Figure 1-2, treated a 30,000 ACFM flue gas slipstream from Boiler No. 8. Operation of the facility began in May 1992 and was completed in May 1993.

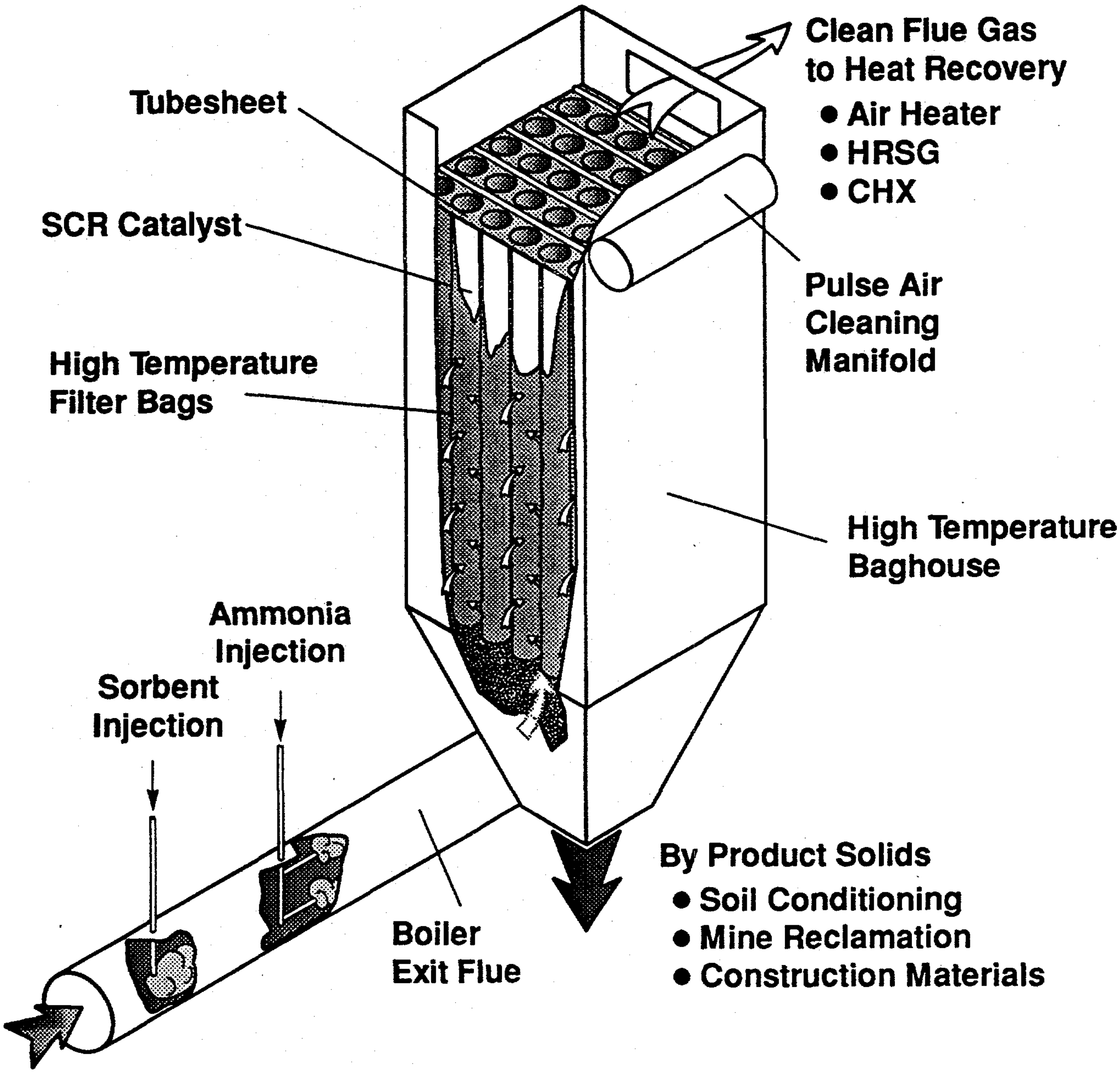


FIGURE 1-1 SCHEMATIC OF SNRB PROCESS

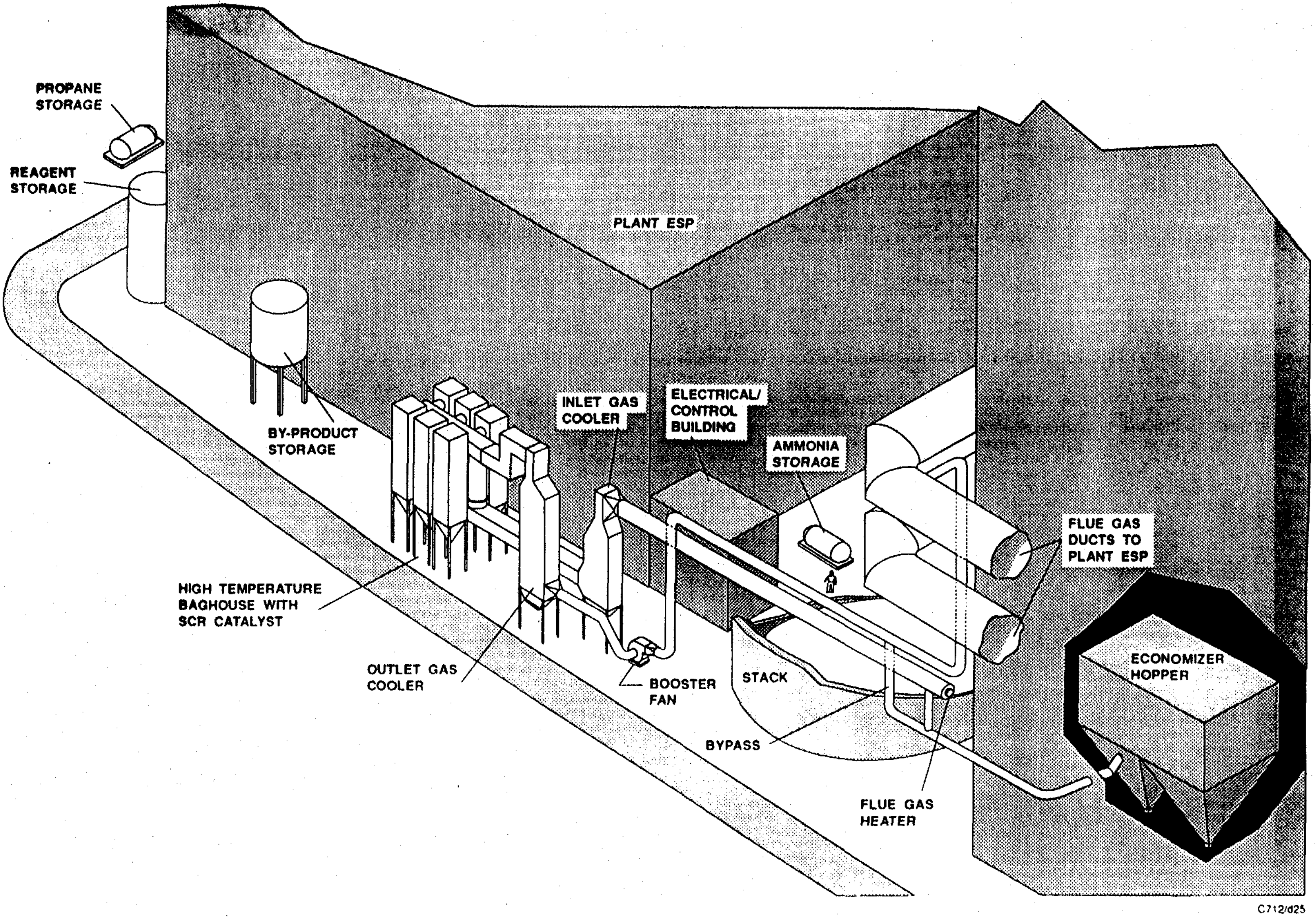


FIGURE 1-2 SNRB DEMONSTRATION FACILITY

About 2,300 hours of high-temperature operation were achieved. The SNRB^{TM} test facility was designed to effectively remove SO_x, NO_x and particulate matter from the slipstream over a range of expected utility operating conditions, to optimize SNRB^{TM} performance and advance commercialization of the SNRB^{TM} process. The main emissions control performance goals of:

- Greater than 70% SO_2 removal using a calcium-based sorbent
- Greater than 90% NO_x removal with minimal ammonia slip
- Particulate emissions in compliance with the New Source Performance Standards (NSPS) of 0.03 lb/million Btu

were exceeded simultaneously in the demonstration program when the facility was operated at optimal conditions. Testing also showed significant reductions in emissions of some hazardous air pollutants (HAP).

1.1 SNRB^{TM} TECHNOLOGY DESCRIPTION

The SNRB^{TM} technology is a post-combustion emission control technology which would be integrated into a power plant or industrial process between the combustion zone and the downstream heat recovery equipment. The incorporation of the SNRB^{TM} baghouse relative to a coal-fired boiler and the boiler's combustion air heater dictates the selection of either a calcium- or sodium-based sorbent. One possible commercial arrangement featuring a calcium-based sorbent as applied to a utility boiler system is detailed in Figure 1-3. The process involves locating the high-temperature baghouse directly downstream of the economizer section of the boiler and upstream of the air heater. The optimal baghouse operating temperature range of 800° - 900°F for the calcium-based system requires the use of a high-temperature fabric and a high-temperature SCR catalyst for reliable operation at these elevated temperatures. A heat recovery steam generator (HRSG) or condensing heat exchanger (CHX) may be integrated into the system downstream of the baghouse to enhance thermal efficiency.

The use of sodium bicarbonate ($NaHCO_3$) injection for SO_x removal reduces the operating temperature requirements of the SNRB^{TM} process. Operation with $NaHCO_3$ over the baghouse temperature range of 300° - 600°F may eliminate the need for the more expensive high-temperature filter bags. Whereas some economizer modifications may be required for calcium-based applications, none would be required to incorporate a sodium-based SNRB^{TM} system into the plant cycle. This lower temperature system may be applicable when high NO_x reduction efficiency is not required.

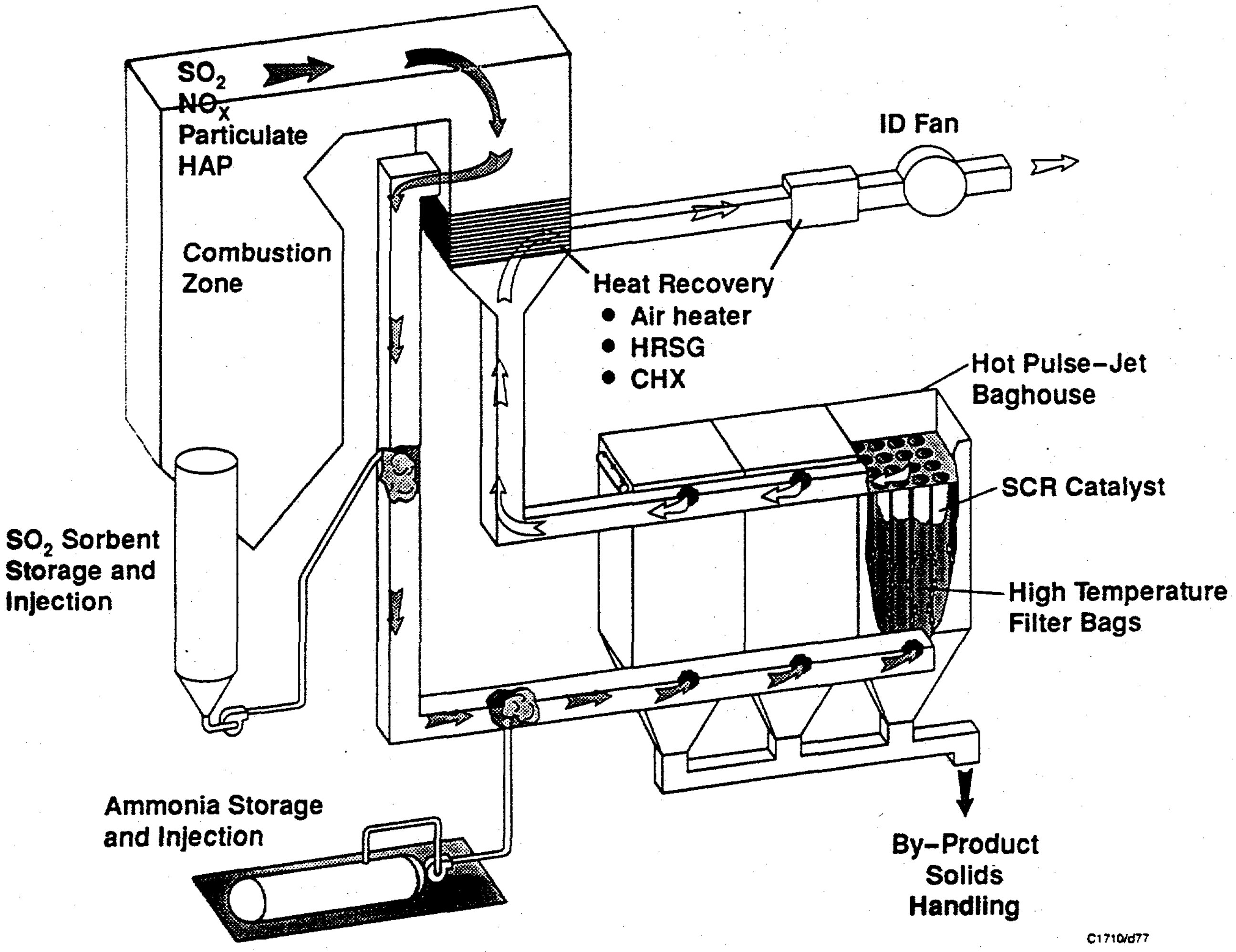


FIGURE 1-3 SNRB™ ARRANGEMENT FOR CALCIUM-BASED SORBENTS

Adsorption of SO_2 is achieved through injection of the fine, dry alkali sorbent into the fluework upstream of the baghouse. Simultaneous dehydration and sulfation of the sorbent begins immediately upon injection in the fluework and continues as the flue gas passes through the fluework forming calcium sulfite ($CaSO_3$) and calcium sulfate ($CaSO_4$). Additional SO_2 removal is obtained as the flue gas passes through the filter cake residing on the bags which is composed of unreacted sorbent, fly ash, and reaction products. By-products from the reaction between $NaHCO_3$ and SO_2 include sodium sulfite (Na_2SO_3) and sodium sulfate (Na_2SO_4)

The SNRB™ process utilizes SCR for high-efficiency, post-combustion NO_x control. In the presence of the SCR catalyst, NO_x reacts with NH_3 to form N_2 and H_2O. The commercial, non-toxic NC-300™ series zeolite catalyst from Norton Company was used in the demonstration. The SNRB™ process design avoids common operating problems associated with promoted SCR catalysts in power plant SCR applications. These operating problems include:

1) catalyst deactivation by adsorption of heavy metals in fly ash and sulfur species in the flue gas
2) ammonium sulfate salt formation and subsequent deposition on steel surfaces
3) catalytic oxidation of SO_2 to SO_3 and increased equipment corrosion due to SO_3 generation
4) erosion or pluggage of the catalyst by fly ash

These problems have been avoided in the SNRB™ process through the use of a non-toxic, zeolitic SCR catalyst and incorporation of the catalyst into each filter bag downstream of both SO_x and particulate removal. By the time the flue gas reaches the catalyst, the SO_2 concentration has been reduced by more than 70% and particulate loading reduced to trace levels.

The SNRB™ process includes several innovative characteristics which provide for a unique, high efficiency combined emissions control process. Operation of a pulse-jet baghouse at high temperatures requires that the filter bags be made of a fabric which can withstand exposure to flue gas at 800° to 900°F while maintaining high particulate collection efficiency and flexibility. Integration of the SCR catalyst to minimize unreacted ammonia emissions and permit bag cleaning using conventional pulse-jet technology required development of a cylindrical monolith catalyst. The unique features of the process provide several distinct advantages in comparison with competing emissions control technologies. These general advantages include:

- Multiple emissions control in a single component
- Low plan area space requirements
- Operating simplicity
- Flexibility for optimal overall control economics
- Enhanced SCR operating conditions

- Improved SO_2 sorbent utilization
- Dry materials handling

In certain applications, the SNRB^{TM} system capital costs are lower than a combination of conventional systems for comparable emissions control.

1.2 PROJECT OBJECTIVES

The overall objective of this project was demonstration of an advanced flue gas cleanup process for the combined removal of SO_2, NO_x, and particulate from a commercial, coal-fired boiler. The success of the 5-MWe field demonstration confirmed the commercial viability of this technology. Specific objectives of the project included demonstration of:

- 70 - 90% SO_2 removal at a cost-effective sorbent/sulfur stoichiometry.
- 90% NO_x removal at a cost-effective NH_3/NO_x stoichiometry.
- 99.9% particulate removal.
- High pollutant removal efficiencies in an integrated single-unit operation.
- Long-term operability of such an unit.
- Potential for improved boiler efficiency.

The Clean Coal Technology Program demonstration was a key component in the SNRB^{TM} technology commercialization effort. The demonstration provided for optimization of the catalyst integration arrangement, evaluation of operating conditions for maximizing simultaneous emissions control, investigation of alternative bag fabrics and evaluation of SO_2 sorbents for enhancing SO_2 removal. The project also permitted an assessment of the bag and catalyst suppliers ability to produce these key components to commercial specifications.

1.3 SNRB^{TM} TEST PROGRAM

The project scope was comprised of four primary test programs:

- Base demonstration project
- Filter fabric assessment
- Alternative bag demonstration
- Air toxics emissions testing

Base Demonstration Project

The base SNRB™ project focused on the engineering, design and construction of the facility at the R.E. Burger Plant for evaluation of the emission control performance and operability of key components of the technology.

Detailed design activity included pilot testing to finalize details of the filter bag and catalyst configurations and to screen operating conditions for the larger facility. Both pellet and honeycomb or monolith SCR catalysts were evaluated in the design stage. The need for a cylindrical monolith catalyst to minimize the potential for emission of unreacted ammonia was identified and provisions were made by Norton Chemical Process Products to extrude cylindrical catalyst sections for the demonstration.

Construction of the facility was completed in November, 1992. A five month start-up and shakedown period followed. The base test program was initiated in May, 1992 and completed in April, 1993.

Filter Fabric Assessment Program

A pilot baghouse was installed at a coal-fired utility to provide extended exposure testing for high-temperature filter bag fabrics. Three alternative fabrics were evaluated in a 1,300 ACFM slipstream pilot installed on Boiler #7 of the City of Colorado Springs Utilities Martin Drake Plant[2]. The baghouse was operated at 600° to 720°F for a total of 3,700 hours over a 12 month period. Each bag experienced approximately 11,200 cleaning pulses.

Filter bags made of Nextel™ ceramic fibers, S2-Glass fiberglass fibers and Silontex were evaluated. The Nextel™ and S2-Glass fabrics demonstrated acceptable cleaning and strength characteristics. The Nextel™ bags were selected as the base filter bag for the 5-MWe demonstration.

Alternative Bag Demonstration

To continue evaluation of the S2-Glass filter bags, which are potentially a lower cost alternative to the Nextel™ bags, one module of the SNRB™ demonstration baghouse was equipped with these fiberglass bags. The bags were exposed to integrated SNRB™ operating conditions for a total of 1,490 hours. The S2-Glass filter bags held up well at operating temperatures of 800 to 900°F through numerous start-ups and exposure to uncontrolled SO_2 and HCl emissions.

Air Toxics Emissions Testing

A comprehensive air toxics emissions characterization test program was performed in which emissions at the inlet and outlet of the SNRB^{TM} baghouse were compared to emissions from the host boiler and the Burger plant ESP[3]. Emissions of targeted air toxics were measured over a six day period in April and May, 1993. The emissions monitored included trace metals, volatile organic compounds (VOCs), semi-volatile organics, aldehydes, halides and radionuclide species.

1.4 SNRB^{TM} DEMONSTRATION FACILITY DESCRIPTION

In the SNRB^{TM} demonstration program, the process treated a slip stream of flue gas from the Burger Plant boiler #8. The gas tie-in was between the economizer and the combustion air heater where the flue gas temperature was approximately 600 to 650°F. This nominal 160-MWe, pulverized coal, wall fired B&W boiler has been in operation since 1955. Ohio Edison fired a blend of bituminous coals in the boiler with an average sulfur content of 3 to 4%. At the SNRB^{TM} process inlet, the flue gas contained 2000 to 3000 ppm SO_2, 350 to 500 ppm NO_x and 3 to 4 grains/scf particulates.

The major components of the 5-MWe Field Demonstration are illustrated in Figure 1-4. The flue gas was heated by a propane-fired burner to approximately 1000°F and passed through refractory-lined fluework equipped with four sorbent injection ports. The burner permitted evaluation of a wide range of sorbent injection temperatures without the need for multiple penetrations in the host boiler. The flue gas was then cooled by a plate-type heat exchanger (inlet cooler) to the desired baghouse operating temperature. The inlet cooler simulated heat transfer in the economizer section of a boiler. An ammonia injection grid and one additional sorbent injection port were located in the fluework between the inlet cooler and the baghouse. After exiting the baghouse, the flue gas was cooled by a second plate-type heat exchanger (outlet cooler) for return to Ohio Edison's electrostatic precipitator via a booster fan. The outlet cooler simulated the heat transfer surface of a combustion air heater to lower the flue gas temperature for evaluation of expected SO_3 concentrations and corrosion potential.

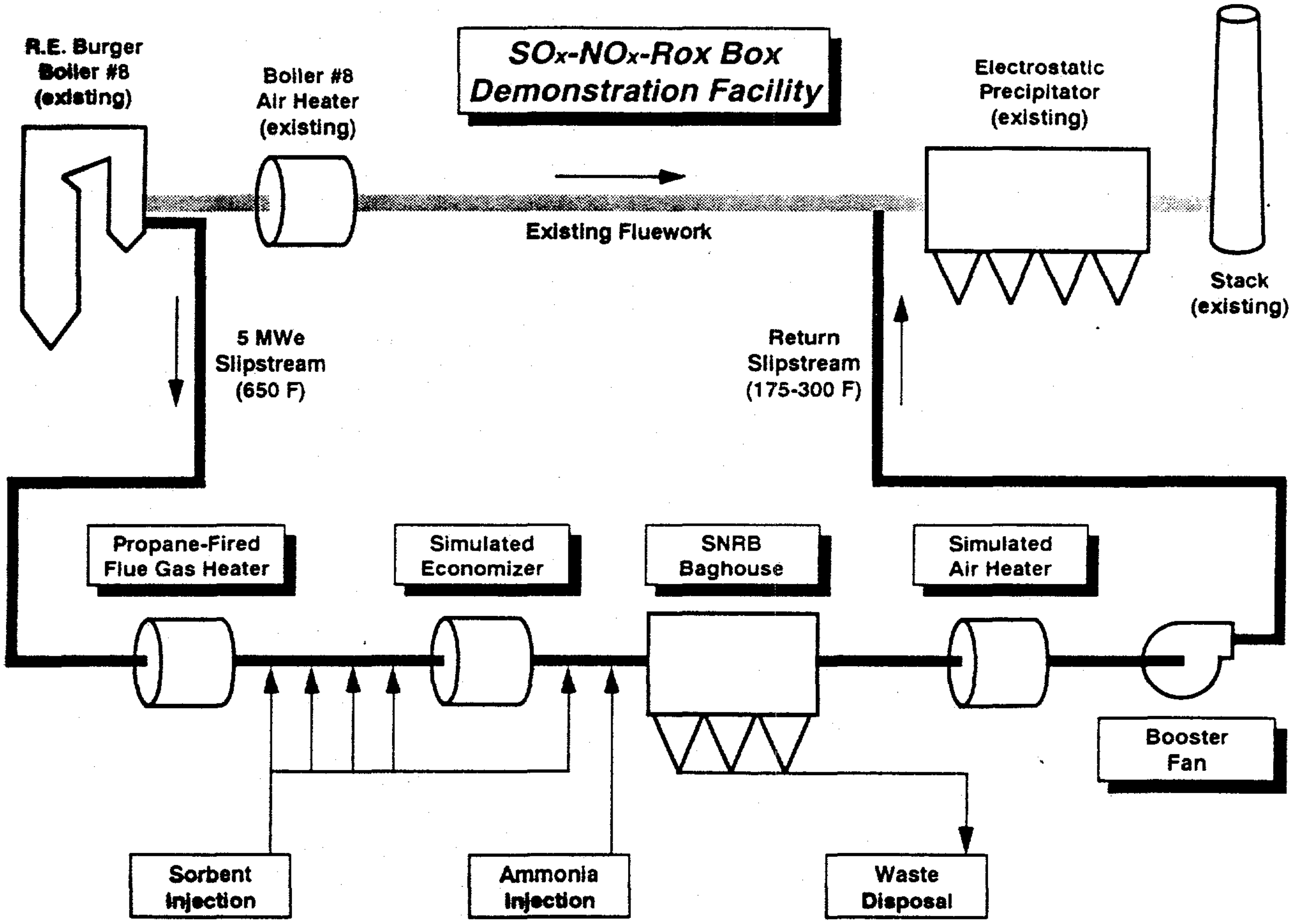


FIGURE 1-4 SNRB 5-MWe FIELD DEMONSTRATION COMPONENTS

The propane burner and flue gas coolers were integral parts of the field demonstration facility that permitted operation over a wide range of temperatures. These components would not be part of a commercial system. The basic components of a commercial application would include the high-temperature baghouse, the ammonia and sorbent feed and storage systems, and ash handling equipment to provide a simple retrofit for simultaneous SO_x, NO_x, and particulate removal.

Key design features of the 5-MWe SNRB™ demonstration facility are summarized in Table 1-1. Design characteristics of the major components are summarized in Table 1-2.

The SNRB™ demonstration facility was operated for approximately 2,300 hours with sorbent and ammonia injection for emissions control. The facility experienced more than 25 cold start-up cycles. Despite these numerous start-ups, no degradation of the catalyst or filter bags was observed. The initial performance goals were exceeded. It is particularly worth noting that significantly higher SO_2 removal was obtained by optimizing the sorbent injection and baghouse operating temperatures and through the use of modified lime hydrates. In three periods of planned continuous operation of over 200 hours each, system availability averaged 99%.

TABLE 1-1 SNRB™ DEMONSTRATION FACILITY
Six Compartment Pulse-Jet Baghouse
Commercial Scale Bag/Catalyst Assemblies
Independent Injection/Baghouse Operation Temperature Control
Pneumatic Materials Handling
Anhydrous Ammonia Storage and Injection

TABLE 1-2 DESIGN SPECIFICATIONS OF KEY COMPONENTS	
PULSE-JET BAGHOUSE	
Flue Gas Flow	30,000 ACFM @ 800°F
Air-to-Cloth Ratio	4:1
Operating Temperature	450-900°F
Filter Bags	20' Long x 6" Diameter
Number of Filter Bags	252 (6 x 42)
Bag Material 3M Owens Corning Fiberglas	 Nextel™ Ceramic Fibers S2-Glass Fiberglass
Cleaning Air Pressure	30-40 psig
Cleaning Air Pulse	80-100 milliseconds
Catalyst Norton	 NC-300 Series Zeolite
SORBENT HANDLING	
Storage	2,350 ft^3
Hydrated Lime	300 to 700 lb/hr
Sodium Bicarbonate	300 to 1300 lb/hr
AMMONIA INJECTION	
Storage	1000 Gallons
Dilution	19:1
Flow Rate	3 to 30 lb/hr

1.5 TECHNICAL RESULTS

1.5.1 SNRB™ Demonstration Performance Highlights

Table 1-3 summarizes performance with commercial grade hydrated lime injection and operation of the baghouse at 855 °F. This data reflects the average of several tests conducted at similar operating conditions at various times throughout the demonstration program. The stoichiometric ratios noted are based on SO_2 and NO_x measurements at the SNRB™ system inlet following the propane burner.

TABLE 1-3 TYPICAL SNRB™ EMISSION CONTROL PERFORMANCE		
	Emissions (lb/10^6 Btu)	
	SNRB™ Inlet	SNRB™ Baghouse
SO_2	4.313	0.544
NO_x	0.660	0.067
Particulate	5.660	0.019
	SNRB™ Operation	
	Ca/S	1.95:1
	NH_3/NO_x	0.84:1

1.5.2 SO_2 Emission Control

SO_2 emission control at the demonstration was optimized through evaluation of the sorbent injection and baghouse operating temperatures, operation over a range of Ca/S stoichiometric ratios and investigation of alternative SO_2 sorbents. A major breakthrough for the technology was the optimization of SO_2 removal when the sorbent was injected directly upstream of the high-temperature baghouse. This translates into an even more compact technology. Incorporation of the baghouse into the power generation cycle is more flexible than envisioned on the basis of earlier pilot tests.

As shown in Figure 1-5, with the baghouse operating above 830°F, outlet SO_2 emissions were reduced to less than 1.2 lb/10^6 Btu using Ca/S ratios of 1.4 and above.

A commercial grade hydrated lime supplied by Dravo Lime Company was used for most of the operation of the SNRB™ demonstration. Approximately 225 tons of hydrated lime were used in the demonstration test program. Dravo also supplied approximately 90 tons of two alternative limes with the potential to improve SO_2 removal. Slight modifications were made to the operation of a commercial hydrator to produce finer mass mean diameter products through the addition of lignosulfonate or a sugar solution the hydrator [4]. At a Ca/S ratio of 2, both alternative hydrates yielded approximately an 8% improvement in performance over the base sorbent, pushing SO_2 removal over 90%.

The use of sodium bicarbonate, $NaHCO_3$, as the SO_2 sorbent provides for SO_2 emission control at a lower baghouse temperature. The observed performance with sodium bicarbonate injection for SO_2 control is summarized in Table 1-4. The system inlet SO_2 concentration ranged from 4 to 5 lb/10^6 Btu.

TABLE 1-4 TYPICAL SO_2 REMOVAL WITH SODIUM BICARBONATE

	SO_2 Emissions	
	% SO_2 Removal	lb/10^6 Btu
Baghouse Operation @ 450-460°F		
Na_2/S 1.0	84	0.78
2.0	98	0.08
Baghouse Operation @ 600-625°F		
Na_2/S 1.0	74	1.01
2.0	92	0.40

Sorbent grade-extra fine $NaHCO_3$ was supplied by Church & Dwight for these tests. The bicarbonate was 98% less than 200 mesh with a surface area of 4.5 m^2/gram. A 95% $NaHCO_3$ purity was measured. In general, the use of $NaHCO_3$ results in a higher sorbent utilization than possible with hydrated lime.

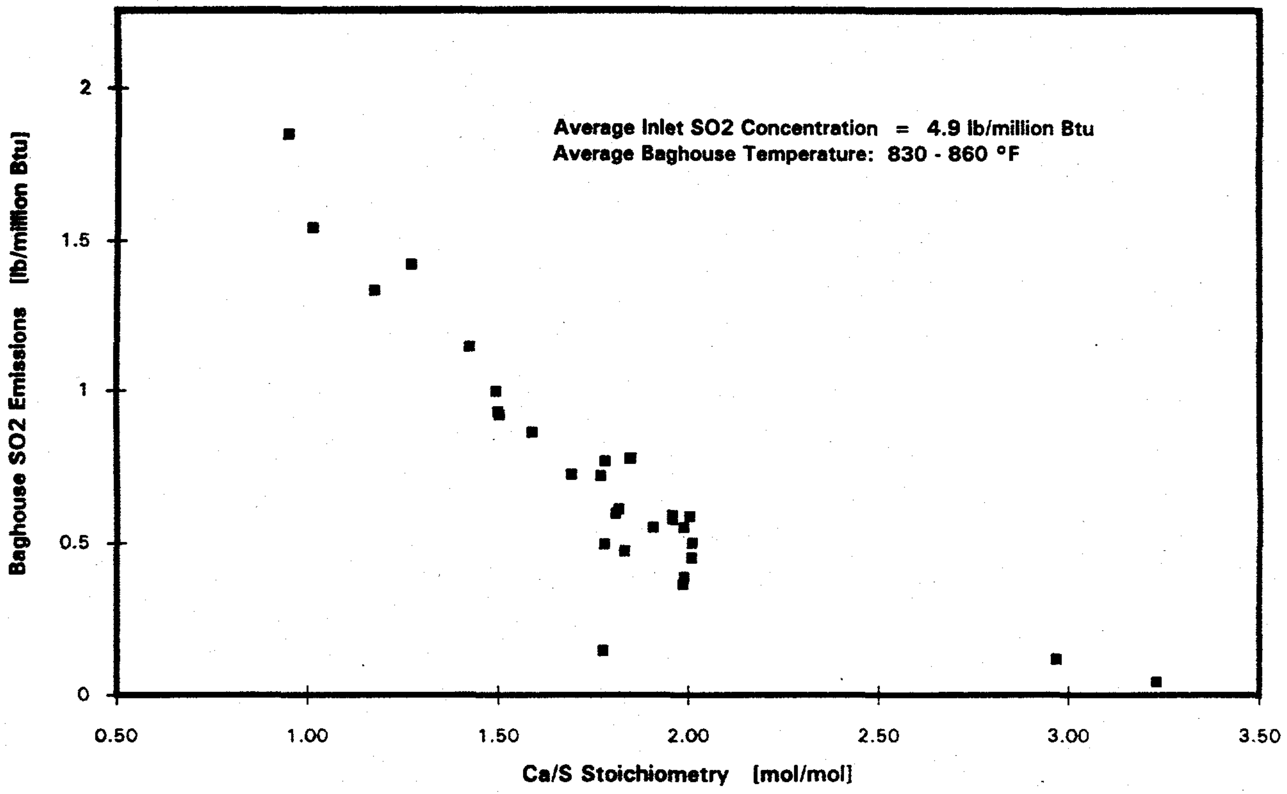


FIGURE 1-5 SNRB SYSTEM SO_2 EMISSIONS

The following key points characterize SNRB^{TM} system SO_2 removal performance in the demonstration test program:

- Injection of the sorbent directly upstream of the baghouse at 825° to 900°F resulted in higher overall SO_2 removal than injection further upstream at temperatures up to 1200°F.
- With the baghouse operating above 830°F, injection of a commercial hydrated lime sorbent injected at Ca/S ratios of 1.8 and above resulted in SO_2 removals over 80%.
- SO_2 removals of 85 to 90% were obtained with Ca utilizations of 40 to 45%. This is significantly higher than the 60% removal, 30% utilization typical of other dry $Ca(OH)_2$ injection processes.
- The use of $NaHCO_3$ as the SO_2 sorbent permitted high removal efficiencies at significantly reduced baghouse operating temperatures.
- SO_2 emissions were reduced to less than 1.2 lb/10^6 Btu with a 3 to 4% sulfur coal with Ca/S ratios as low as 1.5 and Na_2/S ratios less than 1.

1.5.3 Comparison with Alternate SO_x Control Methods

The Clean Air Act Amendments (CAAA) of 1990 specified two phases of SO_2 emissions reduction, with the first phase taking effect in 1995 and the second phase in 2000. Although the CAAA did not advocate particular technologies to meet emission limits, primarily two options were selected by utilities in Phase 1: limestone flue-gas desulfurization (FGD) and fuel-switching. Both options present a higher degree of commercial experience and lower near term risk but address control of only SO_2 emissions. These two options may not be technically or economically feasible for an existing boiler subject to Phase II emission control. The SNRB^{TM} process was developed as an alternative low capital cost, easily retrofitted SO_2 control technology which simultaneously provides efficient NO_x reduction and particulate capture.

Wet FGD systems achieve higher SO_2 removal efficiency than SNRB^{TM}. However SNRB^{TM} is capable of reducing SO_2 emissions to compliance levels for many coal-fired boilers. SNRB^{TM} provides a high degree of turndown flexibility to match performance to compliance requirements and minimize operating costs with variable fuel supply characteristics. Maintenance and byproduct disposal costs for SNRB are expected to be lower than similar wet FGD system costs. The capital cost of a wet FGD systems is higher on a \$/kW basis than the SO_2 sorbent storage and injection fraction of the SNRB^{TM} system costs.

The coal switching option secured a greater share of the Phase I compliance market than anticipated. However, numerous impacts on plant operation may arise from coal switching. Low-rank coals may spontaneously combust in storage areas and pulverizers, leading to the need for extensive fire protection. Appreciable changes in the coal characteristics affect pulverizer capacity, often resulting in a derating of the boiler generating capacity. Changes in the coal ash characteristics will change slagging, fouling corrosion and erosion potential in the boiler, which could affect boiler performance. Ash content can be significantly higher with the new coal and tax the capacity of the ash handling system. Ash from low sulfur coals may become cementitious when exposed to moisture. Coal switching may require overhaul of an existing ESP or employment of flue gas conditioning with SO_3 or NH_3 injection to facilitate fly ash collection.[5] The SNRB™ system permits continued use of local, higher sulfur and potentially lower cost coal without extensive combustion modifications to the boiler. SNRB™ also provides the potential for lower emissions than possible with coal switching.

1.5.4 NO_x Emission Reduction

Nitrogen oxide gases constitute a major portion of the gases responsible for air pollution. The primary component of NO_x emissions is NO which is converted into NO_2 in the atmosphere by photochemical oxidation. The reaction of NO_2 with rain produces nitric acid, one of the components of acid rain. In addition, NO_x is reported to contribute to ozone depletion in the stratosphere and contributes to smog formation. Primary sources of NO_x formation are the combustion of fossil fuels in mobile (automobiles, air traffic, etc.) and stationary (power plants, domestic heating, etc.) energy conversion processes. Stationary sources contribute more than 50% of total NO_x emission from fossil fuel combustion. Selective Catalytic Reduction (SCR) is a widely accepted method of regulating NO_x emission by converting nitrogen oxides gases into N_2 and H_2O through catalytic reduction with NH_3. Other methods of curtailing NO_x emissions are combustion modifications and selective non-catalytic reduction (SNCR).

The North Eastern States for Coordinated Air Use Management (NESCAUM) has drafted a reasonably available control technology (RACT) rule that will require utilities to retrofit boilers with SCR in order to reduce NO_x emissions. When implemented in 2000, this regulation will limit NO_x emissions to about 0.2 lb/million Btu from coal-fired utilities.[7]

Among the different SCR catalysts, V_2O_5/TiO_2 is the most widely used due to its high activity at temperatures between 500° - 800°F. In recent years, zeolite-based SCR catalysts with a wide temperature window of operation (600° - 1100°F) have emerged as an alternative to promoted catalysts containing vanadia or titanium. The ability to operate at temperatures greater than 800°F is especially attractive in some applications. Conventional V_2O_5/TiO_2 catalysts cannot operate in the high temperature range due to excessive, undesired oxidation of ammonia to other species such as N_2O. In high sulfur coal applications, the formation of NH_4HSO_4 resulting from reaction of the SO_2 and NH_3 may be a concern.

The unpromoted, zeolite SCR catalyst installed at the demonstration was formulated for optimal performance at temperatures above 750°F. In this temperature region, outlet NO_x emissions were reduced to less than 0.05 lb/10^6 Btu with NH_3/NO_x ratios of 0.85 and above with the baghouse operating temperature above 800°F. NO_x emission reduction for baghouse operating temperatures of 790° to 865°F is summarized in Table 1-5.

TABLE 1-5 AVERAGE NO_X EMISSIONS AT THE BURGER PLANT DEMONSTRATION

		NO_x Emissions lb/10^6 Btu
SNRB™ Inlet		0.54 to 0.72
SNRB™ Outlet		
NH_3/NO_x Ratio	0.5	0.30
	0.7	0.14
	0.9	0.03

The emission of unreacted ammonia downstream of an SCR unit, ammonia slip, is a primary concern with SCR system operation. Periodic ammonia slip measurements were obtained using a modified EPA Method 5 sample train over a range of operating conditions. Figure 1-6 presents NO_x removal and ammonia slip data obtained by a third party testing contractor, Total Source Analysis.

Ammonia slip levels below 5 ppm are well within the limits typically found for commercial SCR installations. Short term operation of a continuous NH_3 analyzer confirmed the low ammonia slip measured with the flue gas sampling trains.

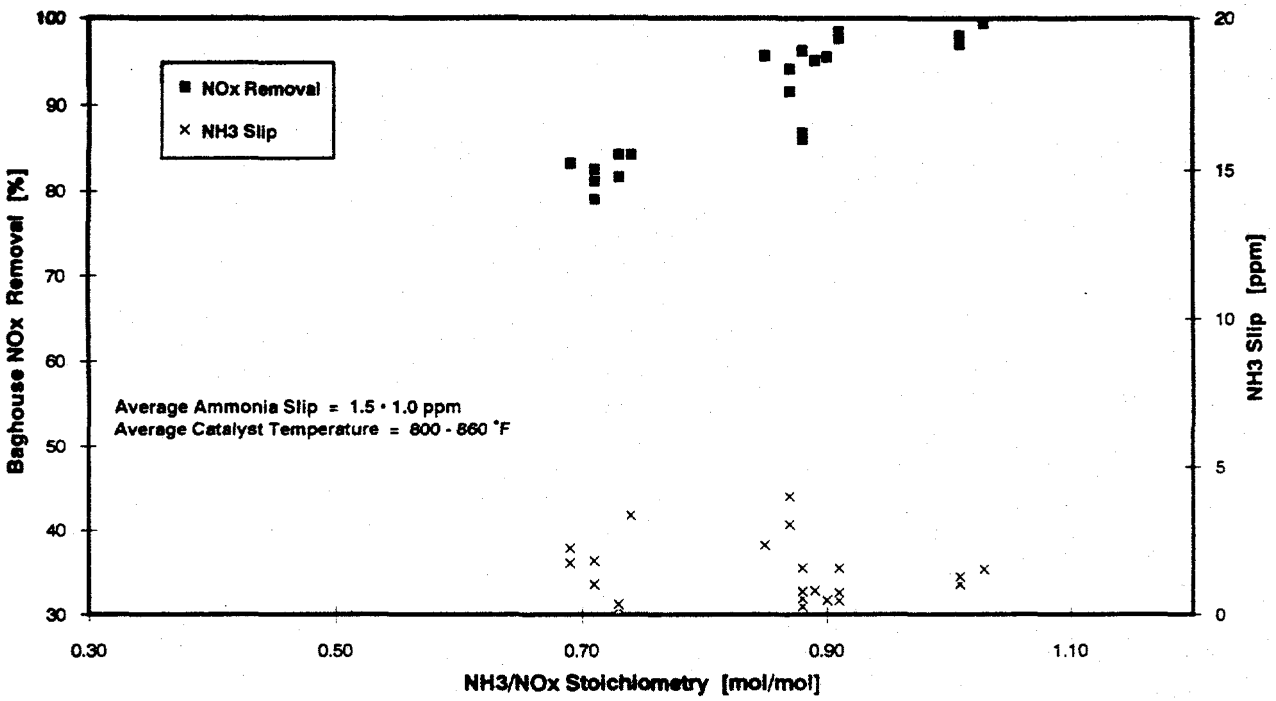


FIGURE 1-6 NO_x EMISSION REDUCTION AND AMMONIA SLIP

Key SNRB™ NO_x reduction observations from the demonstration tests are summarized as follows:

- 90% NO_x emission reduction was readily achieved with ammonia slip limited to less than 5 ppm. This performance reduced NO_x emissions to less than 0.05 lb/10^6 Btu at NH_3/ NO_x ratios of 0.85 and above.

- NO_x reduction was insensitive to temperature over the catalyst design temperature range of 700° to 900°F.

- Variation of catalyst space velocity (volumetric gas flow/catalyst volume) had a minimal effect on NO_x removal over the range evaluated.

- Turndown capability for tailoring the degree of NO_x reduction by varying the rate of ammonia injection was demonstrated for a range of 50 to 95% NO_x reduction.

- No appreciable physical degradation or change in catalyst activity was observed over the duration of the test program.

- The degree of oxidation of SO_2 to SO_3 over the zeolite catalyst appeared to be less than 0.5%. SO_2 oxidation is a concern for SCR catalysts containing vanadia to promote the NO_x reduction reaction.

- TCLP analysis of the catalyst after completion of the field tests confirmed that metal concentrations were well below regulatory limits and the catalyst remained non-hazardous for disposal.

1.5.5 Comparison to Alternate NO_x Control Systems

Other methods of curtailing NO_x emissions are combustion modifications and selective non-catalytic reduction (SNCR). Combustion modifications, which include low-NO_x burners and fuel reburning, redistribute the air and coal to slow the mixing process, reducing the amount of oxygen in the critical NO_x formation zones. Burner modifications generally provide for 20 - 50% NO_x reduction. Gas reburning has been shown to provide greater than 60% NO_x reduction. Some consequences of combustion modification may include higher carbon loss in the fly ash, reducing atmospheres in some regions of the boiler, more frequent sootblowing, difficulty in changing load and mechanical reliability problems.[8] SNCR involves the injection of urea or ammonia into the furnace within the proper temperature window to reduce NO_x to N_2 and H_2O. SNCR is a simple process, yet it is very sensitive to operating conditions. In SNCR, the reactions occur in the gas phase between NO_x and the NH_3 radical, and high temperatures (1600 - 2200 °F) are required. SNCR can achieve 40 - 60% reduction of NO_x at inlet NH_3/NO_x ratios of 1.5 - 2.0 in conventional boilers under favorable conditions (good NH_3 mixing, a 1,600 - 1,900 °F temperature window, and adequate residence time). In large boilers (above 300 - 400 MW) it becomes more difficult to achieve adequate mixing of the injected ammonia. Non-uniformities in flue gas flows and temperature complicate optimization of the process. One consequence of SNCR can be the formation of nitrous oxide, N_2O, which is a greenhouse gas that may lead to chemical destruction of stratospheric ozone. Overall, SNRB™ provides a higher level of emissions reduction with lower sensitivity to boiler operating conditions than the alternatives.

1.5.6 Particulate Emissions

Two types of filter fabrics, Nextel™ and S2-Glass, were exposed to high-temperature, pulse-jet baghouse operation during the field demonstration. Nextel™ is a woven ceramic fabric developed and manufactured by 3M. S2-Glass, manufactured by Owens-Corning Fiberglas, is a formulation of fiberglass with better strength properties at high temperatures than conventional fiberglass bags. As a result of numerous start-up cycles and frequent baseline testing when sorbent was not injected, the fabrics were exposed to environments harsher than anticipated at commercial applications. Visual inspection of the fabrics at the end of the program after 2,300 hours of exposure revealed minimal operational damage.

EPA Method 5 sampling downstream of the baghouse confirmed that particulate emissions were consistently below the NSPS standard of 0.03 $lb/10^6$ Btu. Variations in particulate emissions could not be correlated with the hydrated lime injection rate, air-to-cloth (ATC) ratio, baghouse pressure drop, bag cleaning frequency or the combination of modules in service. The average of over 40 baghouse particulate emission measurements was 0.019 $lb/10^6$ Btu which translated into an average collection efficiency of 99.89%.

The results of cascade impactor sampling of the baghouse inlet and outlet flue gas streams are shown in Figure 1-7. The comparison clearly shows the increased fineness of the solids at the baghouse inlet when hydrated lime is injected at 270 to 420 lb/hour. The size distribution of the baghouse emissions was consistent with and without lime injection. Additional particle size distribution measurements of the baghouse outlet emissions revealed that on average about 80% of the emissions were less than 10 microns and 40% were less than 1 micron.

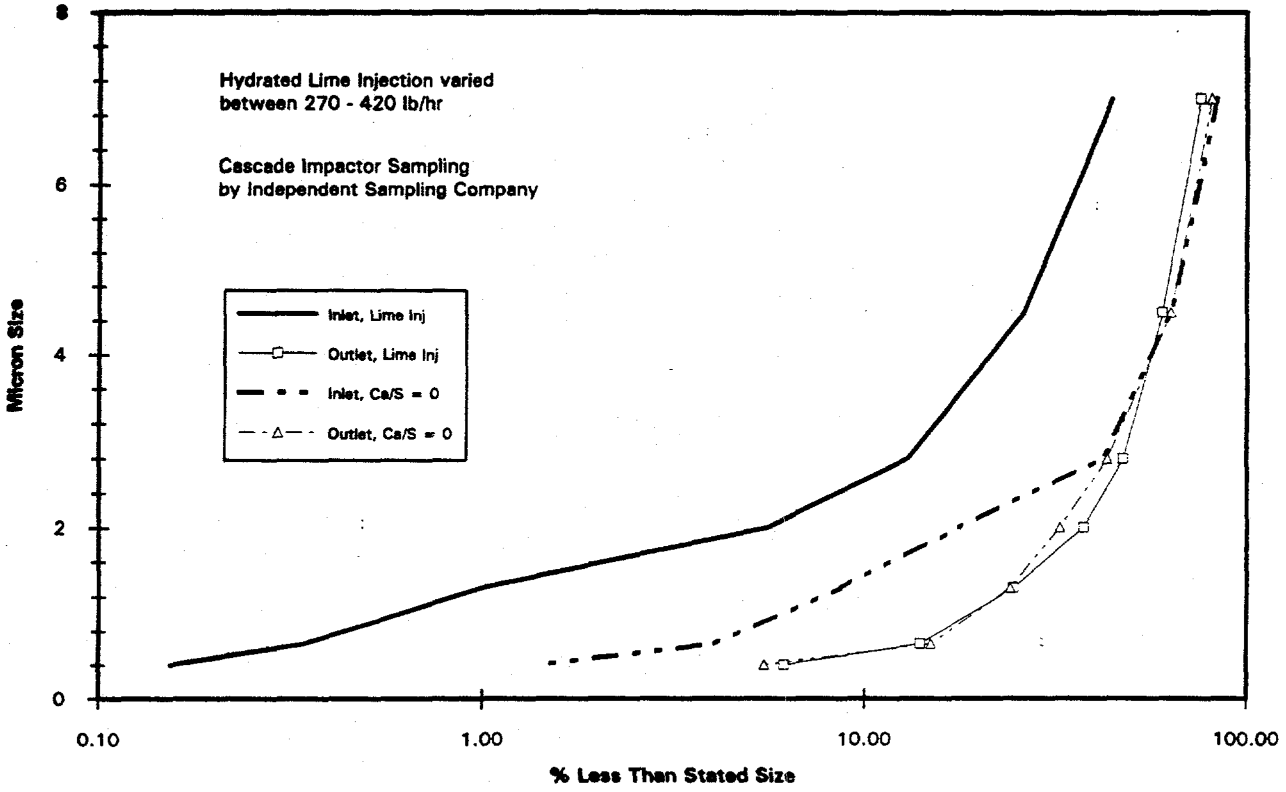


FIGURE 1-7 PARTICLE SIZE DISTRIBUTIONS BAGHOUSE INLET AND OUTLET

Key observations related to particulate collection and baghouse operation at the SNRB™ demonstration include:

- Hydrated lime injection increased the baghouse inlet particulate loading from an average of 5.7 lb fly ash /10^6 Btu to 16.9 lb fly ash and lime reaction products /10^6 Btu (3.3 to 9.6 grains/SCF).
- Emission testing with and without the SCR catalyst installed revealed no apparent difference in collection efficiency.
- On-line cleaning with a pulse air pressure of 30 to 40 psi was sufficient for cleaning the bag/catalyst assemblies.
- Typically, one of the five baghouse modules in service was cleaned every 45 to 90 minutes.
- Baghouse outlet opacity was generally less than 2% at an ATC ratio of 4.0 ft/min.
- Fabric filter performance was relatively insensitive to boiler and SNRB™ system operation.
- The catalyst contribution to the baghouse pressure drop was approximately 5.5" H_2O at an ATC ratio of 4.0 ft/min.
- Baghouse operation at an ATC ratio of 3.5 ft/min produced an average baghouse pressure drop of 12.5" H_20. Operation at an ATC ratio of 4.0 ft/min increased the average pressure drop to 13.0 " H_20.

1.5.7 Comparison to Alternate Fabric Filtration Method

Of the three types of commercially available baghouse technologies, reverse-gas fabric filters (RGFF) have been most successfully applied to utility boilers. Currently, RGFFs are installed on over 20,000-MWe of generating capacity.[9] In a RGFF, the fly ash deposits on the inner surface of the bags. The gentle cleaning method employed in RGFF promotes long bag life and low particulate emissions. Bag life approaches five to seven years. RGFFs have been successfully used in high and low-sulfur coal applications and typically operate at an ATC ratio of 1.8.

Pulse-jet fabric filters (PJFF) have been applied to industrial boilers in Australia, Canada, Europe, Japan and the United States. As of 1991, there were over 300 PJFFs installed on industrial and utility boilers worldwide.[10] In contrast to RGFF, the flue gas in a PJFF passes from the outside of the bags to the inside and exits a tubesheet located in the top of the compartment. A PJFF collects ash on the outer surface of the bag and requires a metal cage to support the bag. PJFF can achieve outlet emissions similar to RGFFs at lower pressure drop. The main advantage of the PJFF is operation at higher ATC ratios which reduces the required filtration area for a given gas flow, resulting in lower space requirements and capital cost savings. One disadvantage of PJFF is that the more energetic cleaning may shorten filter bag life to three to five years. PJFF is used in SNRB™ because the high-temperature, high volume flue gas flow requires operation at a high ATC ratio to minimize the size of the baghouse. The outside-in filtration provides for easy integration of the catalyst after the particulates have been removed from the gas stream.

1.5.8 Byproduct Characterization

Operation of the demonstration generated a total of approximately 830 tons of fly ash and byproduct solids. Approximately 30 tons of this material was used for evaluation of potential commercial uses for the solids. The remaining solids were disposed of in a solid waste landfill.

Table 1-6 provides a typical composition of the baghouse solids with injection of commercial hydrated lime at a Ca/S ratio of 2. The coal contained approximately 3.5% sulfur and 12% ash.

TABLE 1-6 SNRB™ SOLIDS COMPOSITION

Constituent	Weight % of Total
Fly ash	32.8
$CaCO_3$	23.9
$CaSO_4$	20.5
$CaSO_3$	15.4
CaO	7.4

The key characteristics of the solids collected in the SNRB™ baghouse are as follows:

- The moisture content of the baghouse product was typically below 0.5% and the product showed little affinity for picking up moisture even after outdoor storage for several months.
- Leach potential (TCLP) well below regulatory limits for solid waste disposal.
- No ammonia was detected in the baghouse solids.
- The pH of the solids ranged from 10.5 for sodium bicarbonate injection to 12.4 for hydrated lime injection.

A variety of potential uses for the solids have been investigated. Spreadability tests for soil amendment applications were performed with several types of agricultural lime spreaders. These tests indicated the low bulk density and moisture content of the material may require an intermediate pelletizing step for efficient application of the material for agricultural liming. The SNRB™ solids were found to have a pozzolanic activity index above the minimum required for fly ash to be used in concrete. The final compressive strength of a mortar prepared using SNRB™ solids was comparable to that of the base mortar indicating the solids could be used as a partial cement replacement to lower the cost of the concrete. Innovative uses of the byproduct solids in local commercial enterprises will enhance the economics of specific applications of the technology.

1.5.9 Corrosion Study

A concern for application of SCR to coal fired boilers is the oxidation of SO_2 to SO_3. Subcontractor testing indicated the SNRB™ SCR configuration results in minimal, if any, net oxidation of SO_2 to SO_3 which is consistent with commercial applications of the zeolite catalyst. To some extent, the SO_3 content of the flue gas determines the minimum exit temperature at which the combustion air heater can be operated to minimize corrosion of the heat transfer surfaces. This minimum exit temperature influences the net thermal efficiency of the power plant.

An air-cooled deposition probe was installed downstream of the outlet flue gas cooler to expose coupons of carbon steel (A36) and Corten (A588) to flue gas temperatures ranging from 150 to 260°F. The probe was exposed for approximately 300 hours of operation with $Ca(OH)_2$ injection upstream of the baghouse resulting in an average SO_2 emission rate of 1.13 lb/10^6 Btu. The concentration of SO_3 in the flue gas downstream of the baghouse was on the order of 5 to 10 ppm. Analysis of the corrosion rate as a function of probe temperature indicated that operation below approximately 250°F could result in an unacceptable level of corrosion.

1.6 AIR TOXICS STUDY

A comprehensive evaluation of the emission of selected hazardous air pollutants or air toxics was completed as part of the SNRB™ demonstration program. In general, the high particulate collection efficiency of the baghouse resulted in good capture of metals which were condensed on the particulates. The alkaline sorbent significantly reduced emissions of the acid halides HCl and HF.

The SNRB™ system consistently reduced emissions of chromium, barium, cobalt, manganese, vanadium, beryllium, arsenic, lead and selenium by over 92%. Removal efficiencies for cadmium, nickel, and antimony were also high but somewhat less consistent. The test results did not indicate any significant control of mercury emissions across the SNRB™ baghouse as was expected due to the high operating temperature. The SNRB™ system removed 84% of the HF and 95% of the HCl present in the flue gas. Measured emissions of volatile organic compounds and polycyclic aromatic hydrocarbons were very low both before and after SNRB™. No aldehyde emissions were detected.

Attempts to quantify emissions of dioxins, furans and radionuclides did not provide consistent results. Significant variations between repeat tests were observed in measuring these HAPs which may be present in very small trace quantities.

1.7 PROJECTED COMMERCIAL SNRB™ ECONOMICS

A cost model has been used to evaluate the projected capital costs of a SNRB™ system for various utility boiler emission control applications. The projected total capital requirement for a 150 MW retrofit SNRB™ system is $253/kW. The system is designed for 85% SO_2 removal and 90% NO_x reduction. The levelized cost which includes capital charges, fixed O&M and variable operating costs is $553/ton of SO_2 and NO_x removed. For a valid comparison of emission reduction costs with alternative combined technologies, the particulate control costs need to be added to the SO_2 and NO_x system costs. Including the reduction in particulate emissions integral to operation of the process reduces the SNRB™ system levelized cost per ton of emissions reduction to $271/ton. This basis is more representative of the SNRB™ process, since the fabric filter is the main component of the system. This cost basis does not include reduction of HCl and HF emissions which would result in a lower cost per ton of total emissions reduction.

For a 250-Mwe boiler fired with 3.5% sulfur coal and generating 1.2 lbs $NO_x/10^6$ Btu, the projected capital cost of a retrofit SNRB™ system is approximately $233/kW which includes various technology and project contingency factors which reflect the commercial development status of the technology. A combination of a fabric filter, SCR and a wet scrubber for achieving comparable emissions control has been estimated at \$360 to \$400/kw [11]. A comparison of the SNRB™ system with a combination of SCR, dry scrubbing for SO_2 control and a baghouse has indicated SNRB™ system capital costs are competitive with this combination for smaller units burning lower sulfur coal [12]. The capital cost of the SNRB™ system was projected to be 20% less than a SCR/dry scrubber/baghouse combination for a 100-MWe plant burning 1.5% sulfur coal. The levelized costs expressed as \$/ton of SO_2 and NO_x removed were also lower for SNRB™.

SNRB™ system costs for new plant applications on a \$/ton of pollutant removed basis are lower than retrofit system costs for a similar size installation. New plant installations do not require modification of the economizer and air heater heat transfer surfaces or re-routing of existing flue work. The estimated capital cost for a new 150 MW installation would be about \$190/kW or 25% less than the \$253/kW for a similar retrofit application.

Variable operating costs are dominated by the cost of the SO_2 sorbent for a system designed for 85 to 90% SO_2 removal. Fixed operating costs primarily consist of system operating labor and projected labor and materials for the hot baghouse and ash handling systems.

SNRB™ system costs may be optimized by tailoring emissions reduction to achieve the best combination of emissions reduction for compliance operation and generation of marketable SO_2 and NO_x emission allowances. Phased installation of the SO_2 and NO_x control systems may be used to reduce the initial capital costs of the system. The SO_2 system capital costs represent only about 9% of the total cost. The costs associated with the high efficiency NO_x control subsystem account for about 21% of the total new system costs.

1.8 COMMERCIALIZATION

Relatively few long term CAAA compliance decisions such as installing wet scrubbers have been made by utilities. Near term fuel switching provides utilities with time to evaluate the allowance trading market and consider emerging clean coal technologies such as SNRB™ as a future compliance option[13]. SNRB™ can compliment a fuel switching strategy for SO_2 emission compliance by adding the flexibility of variable sorbent injection rates to enhance existing emissions reduction and providing a greater degree of fuel supply flexibility while integrating NO_x emission control and upgrading particulate emission control capability.

B&W is actively exploring potential power generation and industrial coal-fired boiler and other industrial process applications. Activity to date has been focused on smaller units where the cost advantages appear to be greatest. Potential applications to waste-to-energy plant emission control are also being investigated.

For smaller, low-capacity-factor units, the SNRB^{TM} system provides quick on/off sorbent injection flexibility for short term operation with variable coal sulfur contents. The sorbent injection system represents a relatively minor component, projected to be less than 15%, of the total system capital cost. Integration of the SNRB^{TM} system with fuel switching strategies or low NO_x combustion modifications provides a high overall level of emissions reduction with reduced capital and operating costs.

On-going commercialization efforts will benefit from successful installations of pulse-jet fabric filters for controlling particulates and selective catalytic reduction for NO_x emission control in a variety of industrial and utility applications. High-temperature filtration is gaining interest for integrated, combined cycle system designs.

In 1996, the first US pulverized coal fired utility equipped with SCR for controlling NO_x emissions will begin operations [13]. The 440 MW Stanton Unit 2 is owned by the Orlando Utilities Commission. The NO_x control portion of the SNRB^{TM} system capital and operating costs should follow the costs of more conventional SCR systems which have shown a dramatic decline in recent years.

1.9 SUMMARY

The SNRB^{TM} system provides for high efficiency control of the primary emissions from coal-fired boilers. The system is capable of exceeding the SO_2 emission control performance of existing dry sorbent injection technologies. NO_x emission reduction comparable to commercial, conventional SCR systems has been demonstrated. In fact, emissions control at the SNRB^{TM} demonstration exceeded the initial project goals. The comprehensive scope of the demonstration addressed several key questions for commercialization of the technology such as expected filter bag life and air toxics emissions control potential. Commercial-scale components used in the demonstration performed well and the component manufacturers demonstrated the ability to produce the components to commercial specifications. In all of the extended periods of continuous operation, the process achieved a high level of reliability and the operability of the subsystems was clearly demonstrated.

B&W is pursuing commercial application of the technology, using the successful 5-MWe demonstration as proof of the technical feasibility of the process and evaluating the unique requirements of specific new and retrofit applications as opportunities are identified.

2.0 INTRODUCTION

Babcock & Wilcox's (B&W) patented SOx-NOx-Rox Box^{TM} (SNRB^{TM}) process has been developed to provide utilities and large industrial boilers with a cost-effective way to simultaneously control emissions of SO_x, NO_x and particulate matter. The SNRB^{TM} Flue Gas Clean-Up Demonstration Project was selected for funding in the second round of the Clean Coal Technology Program. The $13.3 million project was co-sponsored by the US Department of Energy, the Ohio Coal Development Office, B&W, the Electric Power Research Institute and Ohio Edison. In-kind contributions were provided by 3M, Norton Chemical Process Products and Owens-Corning Fiberglas. DOE provided 45.8% of the total project funding. The Cooperative Agreement with DOE was signed in December, 1989.

2.1 TECHNOLOGY DESCRIPTION

The SOx-NOx-Rox Box^{TM} process consists of ammonia and either calcium- or sodium-based sorbent injection upstream of a "hot" baghouse which employs high-temperature fabric bags and a selective catalytic reduction (SCR) catalyst incorporated in each bag assembly (see Figure 2-1). This advanced SO_x/NO_x removal process would remove SO_x, NO_x, and particulate in a single unit operation - a "hot" baghouse. The reduced overall size of the emissions control system (an integrated baghouse being the only requirement, rather than a combination of separate FGD, SCR, and particulate removal systems) would make the plot plan area requirements smaller.

A possible arrangement for incorporation of the SNRB^{TM} process into the steam cycle of a coal-fired boiler is shown in Figure 2-2. The process involves the use of a high-temperature baghouse between the economizer and the combustion air heater. The economizer section of the boiler is typically the last water-cooled heat transfer surface in the boiler and is used to heat the boiler feed water. The air heater recovers heat from the flue gas to increase the temperature of the primary and secondary combustion air. In a retrofit application, some modification of the heat transfer surfaces in the economizer and air heater may be necessary to optimize overall plant efficiency and emission control performance.

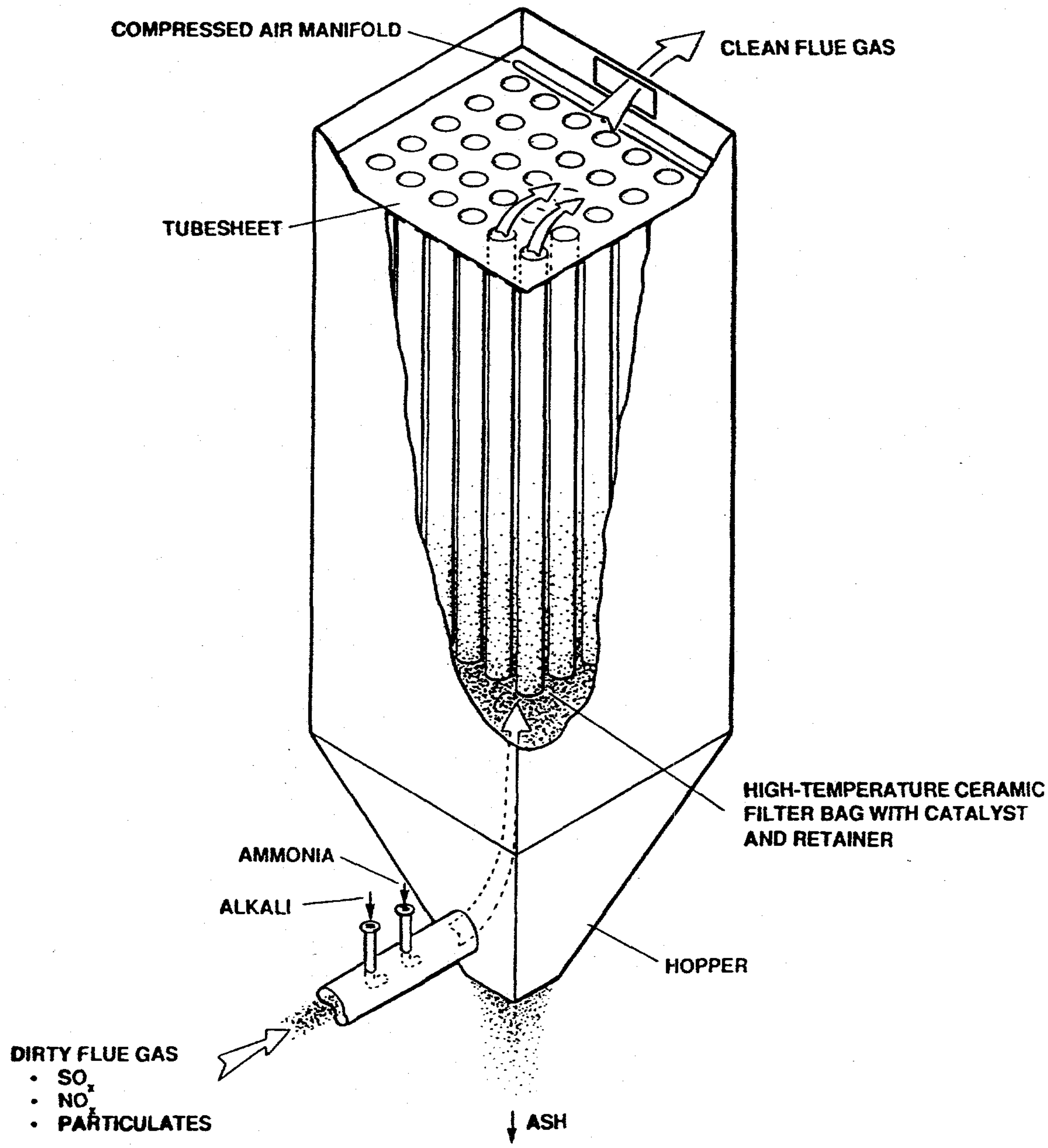


FIGURE 2-1 SNRB™ BAGHOUSE SCHEMATIC

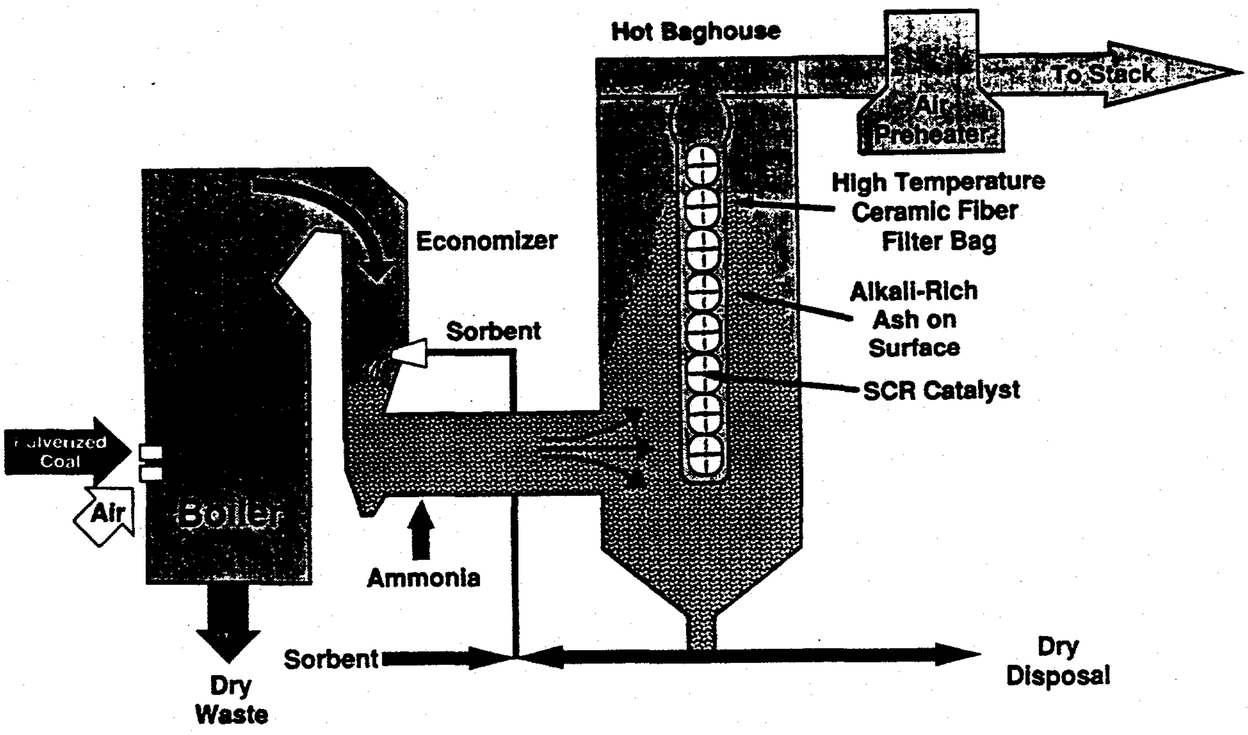


FIGURE 2-2 SNRB™ SYSTEM INTEGRATION

The SNRB™ process combines the removal of SO_2, NO_x, and particulates in a single unit, a high-temperature baghouse. SO_2 removal is accomplished using either a calcium or sodium based sorbent injected into the flue gas. In commercial applications, the choice of sulfur sorbent depends on the site application. NO_x removal is accomplished by injecting NH_3 to selectively reduce NO_x in the presence of a non-promoted selective catalytic reduction (SCR) catalyst. Particulate removal was accomplished with high-temperature filter bags. Since particulate and SO_x removals occur upstream of the air heater, fouling and corrosion potential are substantially reduced, allowing the air heater to potentially operate at lower flue gas outlet temperatures. The additional energy recovery would improve boiler cycle efficiency, compared to a system without SO_2 control. This would make the SNRB™ process one of the few SO_x/NO_x removal processes that could increase, rather than decrease, a power plant's efficiency.

The three simultaneous emission control processes are individually discussed in the following sections.

2.1.1 SO_x Removal Background

A commercial SNRB™ system may be designed for either calcium or sodium sorbents. During the 5-MWe demonstration, commercial hydrated lime ($Ca(OH)_2$), modified hydrated limes and sodium bicarbonate ($NaHCO_3$) were evaluated for SO_2 removal. Objectives of field testing with regard to SO_2 removal over wide range of operating conditions included: cost effective Ca/S ratio, sorbent injection location and temperature which favored reaction with SO_2 over CO_2 and enhanced SO_2 removal with alternate sorbents. The information generated will be used in design of the sorbent injection system, sorbent storage, and optimal sorbent selection for commercial applications.

Upon injection into SO_2 laden flue gas, $Ca(OH)_2$ immediately reacts with SO_2 (Reaction 1) and begins to dehydrate (Reaction 2). During dehydration, the escaping water vapor creates internal pore passages, providing access for SO_2 diffusion into the interior of the $Ca(OH)_2$ particle. The dehydration reaction is much slower than the $Ca(OH)_2$ - SO_2 reaction, and continues in the SNRB™ baghouse. The dehydration product, CaO, also reacts with SO_2 (Reaction 3). In addition, the $CaSO_3$ reaction product may oxidize to $CaSO_4$ (Reaction 4).

$$Ca(OH)_2\,(s) + SO_2\,(g) \rightarrow CaSO_3(s) + H_2O\,(g) \qquad (1)$$

$$Ca(OH)_2\,(s) + \text{heat} \rightarrow CaO\,(s) + H_2O\,(g) \qquad (2)$$

$CaO (s) + SO_2 (g) \rightarrow CaSO_3 (s)$ (3)

$CaSO_3 (s) + 1/2O_2 \rightarrow CaSO_4 (s)$ (4)

The general physical process includes the following steps:

a. Bulk diffusion of SO_2 to the particle surface.

b. Diffusion of SO_2 into the porous particle.

c. Diffusion of SO_2 through the $CaSO_3$ and $CaCO_3$ layer formed on the surface to react with CaO.

The $CaCO_3$ layer is formed from the reaction of the abundant CO_2 present in the flue gas with hydrated lime and CaO:

$Ca(OH)_2 (s) + CO_2 (g) \rightarrow CaCO_3 (s) + H_2O (g)$ (5)

$CaO (s) + CO_2 (g) \rightarrow CaCO_3 (s)$ (6)

These carbonation reactions compete with the SO_2 removal reactions and are undesired because the $CaCO_3$ product will not react further with SO_2 under normal SNRB^{TM} operation conditions. In addition, the $CaCO_3$ may contribute to the formation of an outside product layer which hinders reaction between SO_2 and the $CaO/Ca(OH)_2$ in the interior of the sorbent particle. The competing carbonation reaction appears to be the reason for the existence of an optimum sulfation reaction temperature range. Laboratory studies have shown that the carbonation reaction becomes dominant at temperatures over approximately 900 °F. [14]

The available sorbent will also react with HCl present in the flue gas according to Reactions 7 and 8:

$Ca(OH)_2 (s) + 2 HCl (g) \rightarrow CaCl_2 (s) + 2H_2O (g)$ (7)

$CaO (s) + 2 HCl (g) \rightarrow CaCl_2 (s) + 2H_2O (g)$ (8)

Removal of HCl from the flue gas by these reactions reduces the potential for corrosion downstream of the high-temperature baghouse. High-temperature removal of HCl may also limit the downstream formation of dioxins and furans.[15] For coal-fired applications, HCl is a relatively minor constituent of the flue gas.

The following reactions can occur upon injection of sodium bicarbonate into the flue gas:

$2\ NaHCO_3\ (s)\ +\ SO_2\ (g) \rightarrow Na_2SO_3\ (s)\ +\ H_2O\ (g)\ +\ 2\ CO_2\ (g)$ (9)

$2\ NaHCO_3\ (s)\ +\ \text{heat} \rightarrow Na_2CO_3\ (s)\ +\ H_2O\ (g)\ +\ CO_2\ (g)$ (10)

$Na_2CO_3\ (s)\ +\ SO_2\ (g) \rightarrow Na_2SO_3\ (s)\ +\ CO_2\ (g)$ (11)

$Na_2SO_3\ (s)\ +\ 1/2\ O_2\ (g) \rightarrow Na_2SO_4\ (s)$ (12)

Below 300°F, sodium bicarbonate ($NaHCO_3$) immediately reacts with SO_2 to form Na_2SO_3 via reaction 9. At higher temperatures, $NaHCO_3$ decomposes to sodium carbonate before reacting with SO_2 (Reaction 10). As the decomposition products of water and CO_2 are given off, the sorbent particles newly exposed surface area is available for reaction with SO_2. While CO_2 is a product of the sodium bicarbonate decomposition, the amount generated is minimal compared to that already present in the flue gas generated by coal combustion.

Other strongly favored reactions competing for available sorbent include:

$NaHCO_3\ (s)\ +\ HCl\ (g) \rightarrow NaCl\ (s)\ +\ H_2O\ (g)\ +\ CO_2\ (g)$ (13)

$Na_2CO_3\ (s)\ +\ 2HCl\ (g) \rightarrow Na_2SO_3\ (s)\ +\ CO_2\ (g)\ +\ H_2O\ (g)$ (14)

$NaHCO_3\ (s)\ +\ HF\ (g) \rightarrow NaF\ (s)\ +\ H_2O\ (g)\ +\ CO_2\ (g)$ (15)

Sodium bicarbonate provides an order of magnitude higher removal efficiency for HCl than for SO_2 and has been successfully used for acid gas (HCl and HF) removal at waste-to-energy plants.[16] Similar high HCl removal efficiencies are expected with the SNRB™ emissions control system.

2.1.2 NO_x Removal Background

Generally, coal combustion produces almost twice as much NO_x as burning natural gas or oil. Combustion measures for reduction of NO_x emissions such as low NO_x burners and reburning were first employed in the 1970s. The various demonstrations of combustion modifications to coal-fired boilers reveal NO_x reductions of 20 to 40% and sometimes as high as 50 - 60%[8]. When the limits on NO_x emissions cannot be met by combustion controls, flue gas treatment can be installed. The dominant post-combustion control method currently in use is selective catalytic reduction (SCR).

In SCR, the NO_x concentration in the flue gas is reduced through injection of ammonia (NH_3) in the presence of a catalyst. The desirable reaction products are water and nitrogen. The reaction is selective in that oxidation of NH_3 and SO_2 should not occur. Ammonia reacts with NO and NO_2 as follows:

$$4\ NH_3 + 6\ NO \rightarrow 5\ N_2 + 6\ H_2O \qquad (16)$$

$$8\ NH_3 + 6\ NO_2 \rightarrow 7\ N_2 + 12\ H_2O \qquad (17)$$

When oxygen is present, the corresponding reactions are:

$$4\ NH_3 + 4\ NO + O_2 \rightarrow 4\ N_2 + 6\ H_2O \qquad (18)$$

$$4\ NH_3 + 2\ NO_2 + O_2 \rightarrow 3\ N_2 + 6\ H_2O \qquad (19)$$

Because oxygen is present in flue gas from coal-fired boilers, reactions 18 and 19 are predominant. A theoretical NH_3/NO_x stoichiometry of 1.0 is typically required in a SCR system, where one mole of NH_3 is injected to remove one mole of NO_x. A number of other less desirable reactions can also occur, including SO_2 oxidation to SO_3, ammonia oxidation to NO_x, thermal decomposition of ammonia, and the creation of nitrous oxide.

For high temperature applications (> 700°F), the SNRB™ system employs a non-promoted, zeolite catalyst. Promoted catalyst containing titanium oxide (TiO_2) or vanadium (V_2O_5) may be required to achieve high NO_x removal efficiency and maintain low ammonia slip at temperatures below 700°F.

A side benefit of sodium bicarbonate injection for SO_2 removal is the NO_x emission reduction according to:

$$2\ NaHCO_3 + 2\ NO\ (g) + 1/2\ O_2\ (g) \rightarrow 2NaNO_2\ (s) + H_2O\ (g) + 2\ CO_2\ (g) \qquad (20)$$

$$Na_2CO_3\ (s) + 2\ NO\ (g) + 1/2\ O_2\ (g) \rightarrow 2NaNO_2\ (s) + 2\ CO_2\ (g) \qquad (21)$$

$$NaNO_2\ (s) + 1/2O_2\ (g) \rightarrow NaNO_3 \qquad (22)$$

While the reaction mechanisms with NO_x are not fully understood, field tests have indicated a relationship between increasing SO_2 removal and NO_x removal. A study conducted by KVB concluded that nitrogen oxide can react with sodium carbonate or, at lower temperature, with sodium bicarbonate, but only in the presence of SO_2.[17] However, at temperatures above 575°F, $NaNO_2$ and $NaNO_3$ are not stable and decompose to NO_x. Therefore, sodium injection at operational temperatures above 575°F should not result in appreciable NO_x removal. According to the studies conducted by KVB, sodium nitrate ($NaNO_3$) can react with SO_2 to form NO_2, which can cause a brown plume. Additives such as urea or NH_3, already present in the SNRB™ process, can suppress NO_2 formation.

2.1.3 Particulate Removal Background

Fabric filters are a common method of removing particulate from industrial sources. In this type of dust collection, the particle separation occurs when dust-laden gas is forced through the fabric, allowing the gas to pass, but retaining most of the particulate. In the case of a new fabric, the particles are initially deposited on the fibers of the fabric. With progressive filtration, collection transfers from the fiber to the developing filter cake.

In the case of a pulse-jet fabric filter, the filter medium is in the form of a long bag supported on a metal cage. The gas to be cleaned flows through the bag from the outside, with particle collection on the outside of the bag. The pressure drop increases with time, requiring periodic removal of the filter cake. With pulse-jet filters, this is accomplished by introducing a brief pulse of compressed air into the clean side of the bags, causing an abrupt increase in pressure. As a result, the gas flow is reversed and the bag is fully expanded, causing the filter cake to fall off the surface of the bag.

Cleaning typically occurs with the compartment remaining "on-line" with the flue gas flow through the bags and is classified in terms of the pressure and volume of pulse air used. The three methods of cleaning are: low pressure/high-volume (7.5 - 10 psi), intermediate pressure and volume (15 - 30 psi) and high pressure/low volume (40 - 100 psi).[10] Pulse-jet baghouses generally operate at higher air-to-cloth (ATC) ratios than other available fabric filters. ATC ratio is a primary design factor for fabric filter operation and is a measure of the amount of gas passing through each square foot of fabric in the baghouse. Operation at higher ATC ratios can reduce the required filter surface area resulting in a reduced "footprint" and capital cost savings. One disadvantage of pulse-jet technology is that the high energy cleaning may shorten bag life.

SNRB™ has advanced hot gas filtration as one of the first applications of filter fabrics upstream of the combustion air heater in the boiler cycle. Hot gas filtration offers advantages in the savings or recycling of energy and reduced particulate erosion in the heat exchanger. However, the primary incentive for high-temperature SNRB™ baghouse operation is the temperature requirement for the simultaneous SO_x and NO_x removal processes. One disadvantage of hot gas filtration is the higher bag cost relative to conventional fabrics. A major emphasis of the SNRB™ field testing was the demonstration of a low cost, high-temperature filter fabric. However, the SNRB™ process is not limited to high-temperature operation. The system may be applied at temperatures below 600 °F using $NaHCO_3$ injection for SO_2 removal. More conventional bag fabrics may be used in this temperature region.

In addition to baghouse operation, particulate collection efficiency can be affected by the type of fuel combusted, the resulting particulate characteristics and the particle size distribution (PSD). For application to coal-fired utility boilers, an effective filter fabric must at a minimum, meet the current New Source Performance Standard (NSPS) of 0.03 lb ash/million Btu over a variety of operating conditions. Changes in boiler operation may produce different flue gas conditions in terms of fly ash loading, fly ash particle size, and concentrations of gases that may chemically attack the fabric. Boiler operation cycling through start-up, normal operation and shut-down generates wide variations in the flue gas temperature, moisture content, volatile matter content and excursions through the water and acid gas dewpoints. The SNRB^{TM} sorbent injection system also changes the flue gas conditions at the baghouse inlet and bag cleaning requirements. The performance of the baghouse in meeting acceptable emissions is expected to be relatively insensitive to the properties of the fly ash, the boiler performance and SNRB^{TM} operation.

2.2 SNRB^{TM} PROCESS DEVELOPMENT

Development of the SNRB^{TM} process at B&W began with pilot testing of high-temperature dry sorbent injection for SO_2 removal in the 1960's. Integration of NO_x reduction was evaluated in the 1970's. Pilot work in the 1980's focused on evaluation of various NO_x reduction catalysts, SO_2 sorbents and integration of the catalyst with the baghouse. This early development work led to the issuance of two US Process patents to B&W - #4,309,386 and #4,793,981. An additional patent application for improvements to the process is pending. The Ohio Coal Development Office (OCDO) has been instrumental in working with B&W to develop the process to the point where a larger scale demonstration of the technology was feasible.

2.2.1 Early Development Work

Several pilot baghouse test programs have been conducted by B&W.[18,19,20] The objectives of these programs were to evaluate various calcium-based sorbents, determine the viability of the Norton zeolitic, vanadium-free catalyst, and evaluate the effect of air-to-cloth (ATC) ratio in the SNRB^{TM} process. The facility for these tests consisted of a 2,500 ACFM high- temperature baghouse, 3M Nextel^{TM} woven ceramic bags, and the Norton SCR catalyst integrated into the baghouse downstream of the Nextel^{TM} bags. The primary results obtained during the pilot baghouse tests are summarized as follows:

- SO_2 removal performance improved with increasing injection temperatures up to 1000°F, with a slight decrease in SO_2 removal from 1000-1100°F. SO_2 removals from 80 - 85% were achieved at a Ca/S stoichiometry of 2 and an injection temperature of 1000°F.

- NO_x removals greater than 80% were achieved at a catalyst temperature ranging from 700° - 800°F and an NH_3/NO_x stoichiometry of about 0.9.

- Particulate removals of 99.8+% were measured. However, two of the particulate emissions measured were greater (0.044 and 0.091 lb/million Btu) than the New Source Performance Standards (NSPS) of 0.03 lb/million Btu.

- At higher ATC ratios, baghouse operability was adversely affected. The pressure drop across the baghouse increased, and the length of the bag cleaning cycle decreased. In addition, cleaning of the bags became more difficult and required higher cleaning air pressures.

These early tests, however, were not entirely representative of an anticipated commercial SNRB™ application. First, the laboratory test facility did not simulate sorbent injection upstream of an economizer. In a typical application, the sorbent would experience a sharp change in its residence time/temperature profile when passing through the economizer before entering into the baghouse. Secondly, the test programs did not evaluate a full-size, integrated bag/catalyst arrangement. The bags used were 4-5/8 inches in diameter and 10 feet long, whereas a full-size bag would be approximately 6 inches in diameter and 20 feet long. Thirdly, the ATC ratio was varied by removing bags from service, instead of varying the flue gas flow or the number of compartments. As a result, the gas residence time remained essentially constant over the range of ATC ratios tested. Finally, the SCR catalyst was installed in a fixed bed located in the clean gas plenum of the baghouse rather than incorporated into the bag/cage assembly.

In addition to the early pilot work funded by OCDO and B&W, two additional test programs were conducted to evaluate catalyst integration with the baghouse and the feasibility of sorbent recycle.

Catalyst Integration Tests

The objective of this test program was to integrate the Norton SCR catalyst into the bag filter assembly so to minimize the effect on bag cleanability. Two bag/catalyst arrangements were designed and fabricated by B&W, Norton, and ETS, a baghouse testing firm. Both catalyst arrangements were then tested for bag cleanability using a 1-bag, plexiglass baghouse the ETS facility in Roanoke, Virginia. The two catalyst configurations that were evaluated were (1) a cylindrical bed of catalyst pellets, and (2) a monolith of the catalyst. The tests demonstrated that both the monolith and pellet designs could be effectively cleaned either on-line or off-line. These tests, however, were conducted at ambient conditions to study bag cleaning only. As a result, the tests did not simulate a "hot" baghouse and NO_x removal performance was not evaluated. In addition, the bags tested were 6 inches in diameter but only 8 feet long.

Baghouse Solids Recycle Tests

An additional test program evaluated the feasibility of recycling baghouse solids containing unreacted calcium sorbent to enhance overall sorbent utilization. SNRB^{TM} baghouse solids were re-hydrated using a Littleford pilot pressure hydrator. The re-hydrated solids were then tested for reactivity to SO_2 in a series of bench-scale tests at the University of Texas. The tests determined that the re-hydrated SNRB^{TM} baghouse solids were not highly reactive with SO_2.

2.3 CLEAN COAL TECHNOLOGY DEMONSTRATION PROJECT

The Clean Coal Technology Program demonstration is a key component in the SNRB^{TM} technology commercialization effort. The demonstration provided for optimization of the catalyst integration arrangement, evaluation of operating conditions for maximizing simultaneous emissions control, investigation of alternative bag fabrics and evaluation of SO_2 sorbents for enhancing SO_2 removal. The project also permitted an assessment of the bag and catalyst suppliers ability to produce these key components to commercial specifications.

The project scope was comprised of four primary test programs:

- Base demonstration project
- Filter fabric assessment
- Alternative bag demonstration
- Air toxics emissions testing

The overall project objectives included demonstration of greater than 70% SO_2 removal and 90% or higher reduction of NO_x emissions while maintaining particulate emissions below 0.03 lb/10^6 Btu. A 5-MWe slipstream demonstration of the technology was the focus of the project. The demonstration incorporated commercial scale bag/catalyst assemblies.

Base Demonstration Project

The base SNRB^{TM} project focused on the engineering, design and construction of a facility for evaluation of the emission control performance and operability of key components of the technology. The SNRB^{TM} demonstration facility was constructed at the R.E. Burger Plant of Ohio Edison. The plant is located on the Ohio River south of Shadyside, Ohio.

Detailed design activity included pilot testing to finalize details of the filter bag and catalyst configurations and to screen operating conditions for the larger facility. Both pellet and honeycomb or monolith catalysts were evaluated in the design stage. The need for a cylindrical monolith catalyst to minimize the potential for emission of unreacted ammonia was identified and provisions were made by Norton Chemical Process Products to extrude cylindrical catalyst sections for the demonstration.

Construction of the facility was completed in November, 1992. A five month start-up and shakedown period followed. The base test program was initiated in May, 1992 and completed in April, 1993.

Filter Fabric Assessment Program

A pilot baghouse was installed at a coal-fired utility to provide extended exposure testing for high-temperature filter bag fabrics. Three alternative fabrics were evaluated in a 1,300 ACFM slipstream pilot installed on Boiler #7 of the City of Colorado Springs Utilities Martin Drake Plant.[2] The baghouse was operated at 600 to 720°F for a total of 3,700 hours over a 12 month period. Each bag experienced approximately 11,200 cleaning pulses.

Filter bags made of Nextel ceramic fibers, S2-Glass fiberglass fibers and Silontex were evaluated. The Nextel and S2-Glass fabrics demonstrated acceptable cleaning and strength characteristics. The Nextel bags were selected as the base filter bag for the 5-MWe demonstration.

Alternative Bag Demonstration

To continue evaluation of the S2-Glass filter bags, which are potentially a lower cost alternative to the Nextel bags, one module of the SNRB™ demonstration baghouse was equipped with these fiberglass bags. The bags were exposed to integrated SNRB™ operating conditions for a total of 1,490 hours. The S2-Glass filter bags held up well at operating temperatures of 800° to 900°F through numerous start-ups and exposure to uncontrolled SO_2 and HCl emissions.

Air Toxics Emissions Testing

A comprehensive air toxics emissions characterization test program was performed in which emissions at the inlet and outlet of the SNRB™ baghouse were compared to emissions from the host boiler and the Burger plant ESP.[3] Emissions of targeted air toxics were measured over a six day period in April and May, 1993. The emissions monitored included trace metals, VOCs, semi-volatile organics, aldehydes, halides and radionuclide species. The test results are summarized in Section 7.

2.3.1 Host Site

The SNRB™ demonstration facility occupied approximately 0.22 acre of the two-hundred acre Ohio Edison Company's R.E. Burger Plant, located on the northwest side of the Ohio River, south of Shadyside, Ohio and east of the unincorporated settlement of Dilles Bottom, in Mead Township, Belmont County, Ohio. The power plant is located at River Mile 102.5 (measured from Pittsburgh, Pennsylvania), which is in the section of the river called Hannibal Pool. It is approximately eight miles downstream from Bellaire, Ohio, twelve miles from Wheeling, West Virginia , and almost directly across the river from Moundsville, West Virginia.

There are eight coal-fired boilers supplying five generating units at the R.E. Burger plant. All of the boilers fire bituminous coal with an estimated avenge ash content of 12% and three percent sulfur from the Ohio and northern Appalachian coal-producing areas. The SNRB™ demonstration utilized a 5-MWe equivalent slipstream off of generating Unit No. 5, which was supplied by boiler No. 8. Boiler No. 8 is a pre-New Source Performance Standards, 156-MWe Babcock & Wilcox pulverized coal-fired drum-type boiler (RB-208), equipped with an electrostatic precipitator. Figure 2-3 illustrates the Ohio Edison R.E. Burger Plant.

2.3.2 Project Participants

The SOx-NOx-Rox Box™ Project organization consisted of the U.S. Department of Energy (DOE), Ohio Coal Development Office (OCDO), B&W, the Electric Power Research Institute (EPRI), Ohio Edison, Norton Chemical Process Products Company, 3M Company and Owens-Corning Fiberglas. Team members from B&W represent the Research and Development Division, the Environmental Equipment Division (EED), and the Contract Research Division (CRD). A summary of the overall project organization is as follows:

DOE	Funding co-sponsor
OCDO	Funding co-sponsor
B&W	Prime contractor/technology supplier/project manager/funding co-sponsor
EPRI	Technical advisor and funding co-sponsor
Ohio Edison	Host site utility and funding co-sponsor
Norton	SCR catalyst supplier
3M	Nextel™ high-temperature fabric bag supplier
Owens Corning	S2-Glass high-temperature fabric bag supplier

City of Colorado Springs Utility - Filter Fabric Assessment Program site host

The project team organization is illustrated in Figure 2-4.

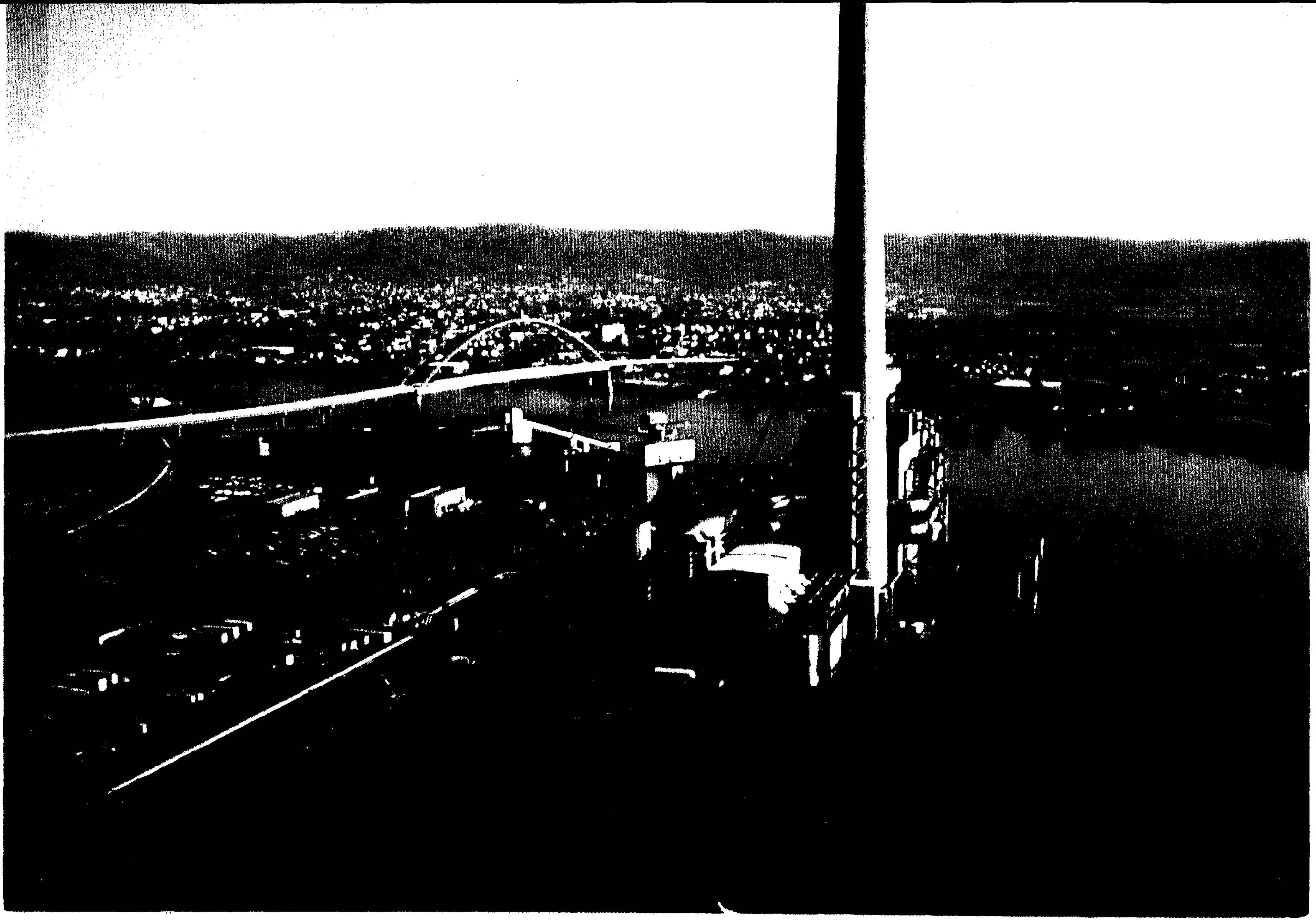


FIGURE 2-3 SNRB^{TM} DEMONSTRATION SITE

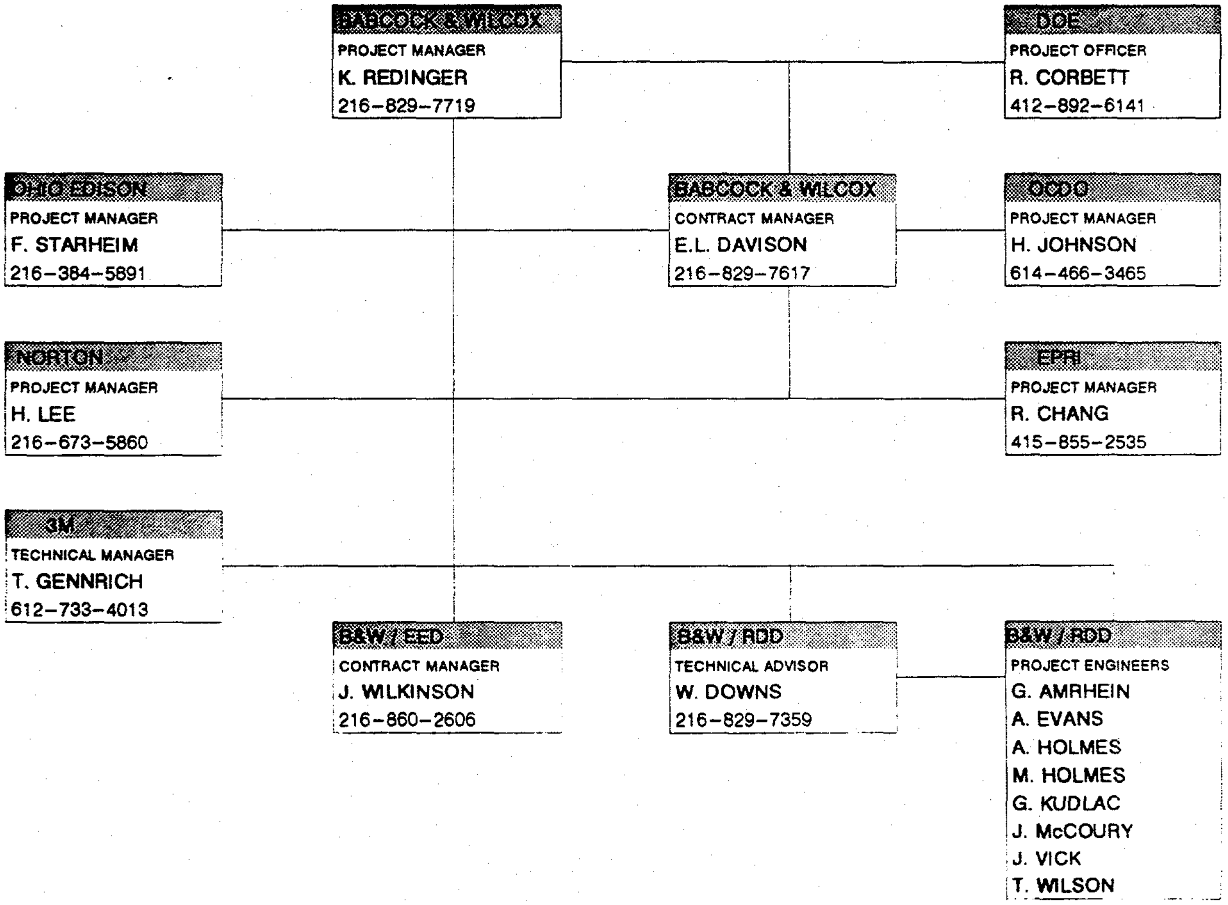


FIGURE 2-4 SNRB™ DEMONSTRATION ORGANIZATION

2.3.3 Base Demonstration Project Phases

The demonstration project was divided into three phases:

Phase I - Design and Permitting (Budget Period I)
Phase II - Long Lead Procurement, Installation, and Start-up (Budget Periods 1 and 2)
Phase III - Operation and Restoration (Budget Period 3)

Phase II was divided into two parts to facilitate completion of the demonstration facility engineering and installation activity:

Phase IIA - Long Lead Procurement (Budget Period 1)
Phase IIB - Installation and Start-up (Budget Period 2)

The overall project work breakdown structure is presented in the following discussion which reflects the total project workscope.

2.4 SNRB™ DEMONSTRATION TASK DESCRIPTION

Phase 1 - Design and Permitting

Task 1 - Project Management (WBS 1.1.1)

This task provided for overall project coordination, leadership, guidance, reporting, and supervision for Phase I of the SNRB™ Project. Objectives of the project management subtasks were to:

1. Document the initial overall scope of work to serve as the basis to direct and manage the project.
2. To coordinate the activities of the project team and to define scope and responsibility for performance of specific tasks in a logical framework.
3. To manage project cost and schedule to allow sound and effective decisions to be made on a timely basis to assure the progress of the project.
4. To produce timely progress reports on project status for use by participating organizations.

Reporting for this phase has included: the Detailed Work Plan, Project Evaluation Plan, Progress Reporting and the QA/QC Plan. The Detailed Work Plan defined the work to be accomplished for the SNRB™ project and was submitted to the DOE on 3/15/90. To provide an evaluation of the SNRB™ project for the project management team, criteria was developed to provide a periodic measure of the technical and cost progress of the SNRB™ project. The Project Evaluation Plan, submitted to the DOE on 6/7/90, identified the specific objectives of Phase I. Progress Reporting consisted of the milestone reports, monthly activity reports and others as specified by the contract. Executive monthly summary reports (form EIA-459E) were issued. In addition to the USDOE, the executive summary reports were also issued to OCDO, Ohio Edison, EPRI, Norton and 3M. Detailed monthly status reports were prepared and issued during the following month. These monthly status reports were issued to the entire project team. Topical reports, in the form of test plans, literature searches, process design packages, and preliminary design documents, were submitted for Phase 1. The QA/QC Plan was submitted as part of the project's Management Plan, dated 12/02/89, and reaffirmed on 5/10/90.

Task 2 - Environmental & Permitting (WBS 1.1.2)

Task 2 specified completion of the Environmental Monitoring Plan Outline (EMPO), Environmental Monitoring Plan (EMP), and permitting for installation and operation of the demonstration. The EMPO which summarized the strategy and philosophy for emissions monitoring at the demonstration facility, was submitted to the DOE on 6/5/90. The EMP detailed the process streams to be monitored, the frequency of sampling and the monitoring procedures to be used. A draft EMP was prepared by B&W and it's environmental contractor, the Environmental Mitigation Group. The draft was reviewed by the DOE and project team. The EMP was approved with the incorporation of several comments and the final revision was issued 1/28/92.

Permitting involved securing all necessary state and local environmental permits required for construction and operation of the facility. The Permit to Install (PTI) the demonstration facility equipment was obtained from the Ohio EPA. A Permit to Operate (PTO) application was filed. Compliance with the PTI was demonstrated. The facility was placed on registration status by the Ohio EPA in July, 1992. It was ruled that a PTO was not required.

Task 3 - Process Design & Design Criteria (WBS 1.1.3)

The Process Flow Schematics specified the major equipment, material used, preliminary PID diagrams, the process control strategy and preliminary process block logic. The Process Flow Schematics were included in the preliminary design review package which was distributed on 2/23/90 with revisions on 4/3/90. The Mass and Energy Balances which specified the composition and quantity of all process streams of the demonstration facility were included in the preliminary design review package.

The Integrated System Design subtask addressed technical concerns and unresolved issues required for successful completion of the demonstration. Under this subtask the following activities were completed: Technology Evaluation, Integrated Baghouse/Catalyst Economic Study, High Temperature Fabric Evaluation, Baghouse Solids Recycle, Pilot Process Evaluation, Boiler Modification Development. The results of these studies were included in the Preliminary Design Review Package. A summary of the pilot process evaluation work is presented in Section 2.5.

Task 4 - Preliminary System Design (WBS 1.1.4)

This task involved all activities required for the design of the 5-MWe demonstration. Development of System & Equipment Technical Specifications was completed 8/24/90. Preparation of technical specifications for subcontractor engineering support for foundation and site improvements and structural steel were completed 8/29/90. The preliminary design package was submitted the DOE on 10/24/90 and project revised cost forecasts were discussed at the 40% review meeting held on 11/9/90. Performance calculations and the operating relationship of the demonstration facility on the boiler were determined by 8/31/90 and were included in the Preliminary Engineering Package. The preliminary site design preparation and foundation design information and required boiler modifications were also included in the Preliminary Engineering Package. The technical and cost status of the project was reviewed by all sponsoring organizations at the 40% Design Review on 11/9/90. Public Report 1A was issued on 12/7/92.

Task 5 - Installation and Detailed Design (WBS 1.1.5)

The Certified Engineering Design Review Package which summarized the civil, structural, mechanical and electrical design information for the demonstration facility was issued in May, 1991. The Mechanical Installation Package which provided the design details required to support erection of the demonstration facility was issued in March, 1991. The Electrical/Instrumentation Installation Design package was issued to potential bidders on 5/28/91. The second DOE Design review was held on 6/14/91 at the demonstration site. During the meeting the results from the Laboratory Pilot tests were presented, proposed facility operation and the project financial status were discussed. No changes to the design were requested. The comprehensive Operations and Maintenance (O&M) manual which assisted field operators with checkout, start-out and operation of the facility was distributed in September, 1991. Then Public Report 1B which summarized the information contained in the Certified Design Review Package and presented at the 90% Engineering Review Meeting was issued December 14, 1992.

Phase 2A and 2B - Procurement, Installation, and Start-up

Task 1 - Project Management and Reporting (WBS 1.2.1)

The project work plan was reviewed and a new work plan for Budget Period 2 was prepared and issued in February, 1991. The Budget Period 2 Evaluation Plan was distributed in December, 1991. Monthly Status reports continued to be issued to the project participants. A review of the Project QA/QC plan did not identify any necessary changes.

Task 2 - Procurement (WBS 1.2.2)

Procurement and delivery of all process equipment for the demonstration facility and boiler modification were completed in Budget Period 2. Project tax exemption documentation was obtained from the State of Ohio. All of the necessary purchase orders and subcontracts were let to complete installation of the general facility equipment. The civil/sitework and foundation installation subcontractor work was awarded in February, 1991. The detailed electrical bid and specification package was distributed and a pre-bid meeting was held on June 6, 1991. The electrical subcontractor work was awarded to Chapman Corporation in July, 1991. Specification packages were prepared for the supply of lime, ammonia and propane and distributed to potential bidders. The purchase order to supply lime to the demonstration facility was awarded to Dravo Lime in November, 1991. The ammonia supply purchase order was given to National Ammonia in October, 1991. A purchase order to supply propane was awarded to Suburban Propane and Petrolane in October, 1991. Calibration gas for the facility was purchased from Ohio Air Products. In October, 1991, a purchase order for solid waste disposal was awarded to Waste Management of North America for transportation of the baghouse solid product and disposal at the Countywide Recycling and Disposal facility located near East Sparta, Ohio.

Fabrication and delivery of all of the major equipment to the demonstration site was completed by June, 1991. The delivery of auxiliary equipment continued through October, 1991.

Task 3 - Demonstration Plant Installation (WBS 1.2.3)

The demonstration facility installation schedule is summarized in Table 2-1. Although the filter bags and catalyst were delivered in December, 1992, installation was delayed by fabrication difficulties with the filter bag retainers.

Facility checkout initiated in August, 1991 continued through April 1992 as a result of the bag retainer fabrication difficulties. The SNRB™ Demonstration Start-Up Plan was issued in January 1992 as a facility checkout guide.

TABLE 2-1 PLANT INSTALLATION ACTIVITY

ACTIVITY	COMPLETION
Boiler Modifications	January, 1991
Foundation Installation	April, 1991
SNRB™ Control Room Erection	May, 1991
Baghouse Installation	August, 1991
Structural Steel Installation	August, 1991
Process Equipment Installation	August, 1991
Piping Systems Installation	August, 1991
Insulation and Lagging Installation	August, 1991
Electrical Installation	September, 1991
Bag and Catalyst Installation	February, 1992

Task 4 - Field Demonstration Operation and Test Plan (WBS 1.2.4)

The field testing and operation goals were developed based on the analysis of the laboratory pilot test results and were reviewed with the project participants at the 90% Design Review on June 14, 1991. Specific test matrices were prepared which detailed the number of tests and the data to be acquired. The specific test matrices and test schedules were incorporated in the draft test plan distributed on October 22, 1991. Comments on the draft plan were received and discussed with the project team through November, 1991. The final test plan was distributed to the project participants in January, 1992.

Task 5 - Start-up and Shakedown (WBS 1.2.5)

Each of the facility sub-systems were operated to ensure the systems functioned according to specifications and to provide the facility operators with some training. Minor operating problems were encountered with several of the subsystems. Vendors were on site to provide training on operation of the baghouse, the opacity monitor, sorbent feeder and ammonia handling system. Shakedown Testing, intended to demonstrate proper operation of the entire facility, was delayed by approximately 3 months. The delay resulted from the necessary remanufacturing of the bag retainers. Improper fit between the bag and retainer is a common cause of premature bag failure. Shakedown testing which emphasized the elimination of leakage in the baghouse was completed in May, 1992.

Phase 3 - Operation and Restoration

Task 1 - Project Management and Reporting (WBS 1.3.1)

This task provided for overall project coordination, guidance, and reporting for Phase 3 of the project. The Project Work Plan was reviewed and updated as appropriate to reflect the current project direction based on progress to date and input from previously completed tasks. The Budget Period 3 Workplan was submitted to the DOE and OCDO on 12/17/91. Regular monthly project status reporting continued.

The Quality Assurance/Quality Control guidelines previously developed as part of the Management Plan in Phase 1 under Subtask 1.1.1.04 was reviewed and it was determined that no revisions were necessary.

Task 2 - Environmental Assessment (WBS 1.3.2)

The Environmental Monitoring Plan (EMP) detailed the planned environmental monitoring activity during operation of the SNRB^{TM} demonstration facility. The solids waste stream was analyzed periodically under this task to support disposal site requirements and commercialization analysis activity.

Task 3 - Demonstration Plant Operation and Testing (WBS 1.3.3)

The planned demonstration plant operation and testing activity are detailed in the Field Operation and Test Plan prepared in Task 2.5. The demonstration test program was scheduled to be completed over a seven-month period. Operation covered the following five test phases:

- Screening
- Continuous
- Sorbent Evaluation
- System Response
- Performance

The emission control performance efficiency was verified using an independent testing agency. Solid wastes from operation of the facility were disposed of according to the plan developed in Subtask 1.2.2.09. B&W supplied the operating and maintenance labor for the demonstration. A review of the facility operation was conducted midway through the test program to highlight the progress achieved, identify potential problem areas, and discuss near term plans for continued test activity.

The information collected during operation of the facility included the flue gas composition (SO_x, NO_x, O_2) at three locations, sorbent feed rate, ammonia feed rate, ammonia slip, baghouse outlet opacity, and key operating temperatures. Samples of the bags and catalyst were removed periodically for evaluation of changes in mechanical and chemical properties resulting from exposure to flue gas, fly ash, ammonia, and lime.

Screening Tests

The objective of this initial test phase was to determine the operating conditions for optimal SO_2 and NO_x removal based on the results of the laboratory pilot tests completed in Subtask 1.1.3.03. The operating variables evaluated included the air-to-cloth ratio, baghouse operating temperature, sorbent injection temperature, injection location, and the NH_3/NO_x stoichiometry. SO_2 removal, NO_x emission reduction, and baghouse collection efficiency were used as the basis for characterizing performance. The optimal operating conditions were used in subsequent test phases which were intended to further evaluate and optimize performance. The demonstration test results were compared with the pilot test data to verify scale-up of the technology. The Screening Tests lasted approximately two months. Initial operation of the facility in the Screening Tests marked the completion of Project Milestone M11.

Continuous Tests

The Continuous Tests provided for examination of the secondary effects of baghouse operating conditions on SNRB™ emission control performance. The primary objectives were the optimization of baghouse operating conditions and development of SNRB™ baghouse performance predictive capabilities. The effect of Ca/S stoichiometry on SO_2 removal and baghouse operation were evaluated. Other operating variables to be examined include sorbent injector design, on-line bag cleaning, and acid deposition probe analysis. The facility was operated semi-continuously over a period of approximately one month during this phase.

Independent Verification Testing

An independent testing organization, Total Source Analysis (TSA) was contracted to verify performance of the demonstration facility and conduct specialty testing to enhance the operating crew capabilities. The testing organization was selected with the assistance of EPRI and Ohio Edison. Parallel continuous emissions monitoring was used to confirm the B&W measurements of NO_x and SO_2 removal efficiencies. TSA monitored particulate emissions, particle size distribution, and ammonia slip. Verification testing was completed over a two week period during the Continuous Tests.

Sorbent Tests

The objective of the Sorbent Tests was to evaluate alternative SO_2 sorbents for maximizing SO_2 removal efficiency. The enhanced performance efficiency target was 80 to 90%. Calcium-based sorbents and sodium bicarbonate were evaluated over a range of injection temperatures, residence times, and baghouse operating temperatures as detailed in the Field Operation and Test Plan. The testing was designed to provide for direct comparison of performance with the alternative sorbents and the base lime at similar operating conditions. The Sorbent Tests were completed over a five-month period.

System Response Tests

The objective of the System Response Tests was to simulate operation of a commercial SNRB™ installation on a cyclic boiler. However, as Ohio Edison routinely dropped load, simulation was not required. During actual load drops, the SNRB™ baghouse inlet flue gas flow rate and temperature were reduced. Variation in fly ash loading, particle size distribution, and composition occurred as a result of the changing boiler operating load. These tests provided information on the required controls and expected performance of SNRB™ in a cyclic boiler retrofit application. The System Response Tests coincided with actual load changes resulting from Ohio Edison operation.

Performance Tests

A one-week period of continuous operation was scheduled to complete the operation activity at the field demonstration site. The optimal operating conditions and sorbent were selected based on the results of the previous test phases. The facility was operated continuously for 270 hours. System availability was 99%. Emission control performance averaged 87% SO_x removal and 89% NO_x emission reduction.

A report was prepared following completion of operations at the facility which summarized the emission control performance over the range of operating conditions evaluated. The report included a summary of operating material usage and byproduct disposal for the demonstration testing. Table 2-2 summarizes material usage and generation.

TABLE 2-2 DEMONSTRATION MATERIAL USAGE AND BYPRODUCT GENERATION	
Ammonia	8,300 pounds
Propane	158,000 gallons
Hydrated Lime	220 tons
Sugar Hydrated Lime	45 tons
Calcium Lignosulfonated Lime	45 tons
Sodium Bicarbonate	50 tons
By-product Disposal	800 tons

Task 4 - Economic and Engineering Evaluation (WBS 1.3.4)

The objective of the economic and engineering evaluation was to use the information generated in the demonstration program to further refine the tools required to support commercialization of the SNRB™ technology. The preliminary cost model was updated and used to project the capital and operating costs of commercial SNRB™ installations. A summary of potential market applications was prepared.

The following existing plant characteristics must be evaluated in assessing potential SNRB™ retrofit sites:

- SO_2 , NO_x and particulate emission limits
- Potential need/market for emission allowances
- Economizer heat transfer surface
- Economizer outlet flue work
- Air-preheated heat transfer surface
- Fan capacity limitations
- Particulate collection equipment
- Ash handling equipment

Balance-of-plant considerations such as the availability of land for the equipment, compressed air quantity and quality, and auxiliary power requirements must be considered. These balance-of-plant considerations are expected to be highly site-specific.

The SNRB™ system cost model was updated using information from the demonstration facility and budgetary equipment cost information. The updated model was used to perform sensitivity analyses for key capital and operating costs in a commercial installation. Key cost factors evaluated included the boiler size, coal sulfur content, plant capacity factor, SO_2 removal requirements, auxiliary power cost and by-product solids disposal costs.

Task 5 - Demonstration Plant Restoration (WBS 1.3.5)

In accordance with the host utility site access agreement, B&W was obligated to restore the demonstration site to a mutually acceptable condition. Efforts were made to minimize the costs associated with the site restoration work. A specification for equipment dismantling and restoration of the site was prepared. The site restoration work was completed by the Babcock & Wilcox Construction Company.

Task 6 - Final Project Report (WBS (1.3.6)

B&W prepared a final project report which summarized the work performed on the project and provided an evaluation of the results achieved. The report summarized the conclusions presented in previously submitted project deliverables and tied the various technical and economic aspects of the project together. A summary of the present technical and potential commercial status of the SNRB™ technology was presented.

2.5 DESIGN VERIFICATION TESTING

Laboratory pilot SNRB™ testing was completed under Subtask 1.1.3.03.05, Integrated Systems Design. The comprehensive findings of the lab testing are documented in "SNRB™ Laboratory Pilot Test Report" completed in March,1992.[1] The purpose of the laboratory pilot tests was to resolve technical issues that would impact the design and operation of the demonstration facility.

The laboratory pilot test facility consisted of a pilot test furnace, high-temperature baghouse, 3M Nextel™ woven ceramic filter bags and Norton NC-300™ series catalyst integrated into each bag filter assembly. The baghouse contained twelve 6-¼ inch diameter, 20 foot long Nextel™ bags providing 375 ft^2 of available collection area. The baghouse was designed to operate over an ATC ratio range of 3 - 6 ft/min.

2.5.1 Field Demonstration Design

The pilot tests were performed at the B&W Alliance Research Center to provide specific design information for the field demonstration facility. Acquisition of the design information at the pilot scale reduced operational risks and limited expenditures at the larger field demonstration. The major design issues addressed included:

- Selection of a preferred catalyst arrangement
- Determination of the feasibility of sorbent recycle for improved utilization
- Evaluation of alternate sorbent injector locations, temperature, and designs
- Verification of the bag length and bag/catalyst assembly cleanability
- Evaluation of the effect of ATC ratio on emission control performance

The test plan, experimental conditions and test schedule developed to address the objectives of the SNRB™ laboratory pilot tests are detailed in the July 20, 1990 B&W SNRB™ Laboratory Pilot Test Plan Report.

Catalyst Design

In previous work under an OCDO contract, B&W and Norton Company developed two catalyst designs that could be incorporated within each bag filter assembly, one with monolith catalyst and the other with pellet catalyst.[20] The criteria for selecting the preferred catalyst design for installation in the field demonstration included NO_x removal efficiency, the effects of particulate matter, ammonia slippage, and costs. Economic considerations included catalyst cost, the ease of catalyst installation and catalyst pressure drop. Extensive testing with the monolith and pellet catalyst arrangements indicated that the monolith design was preferred for the demonstration facility. The 90% NO_x removal goal was achieved with both arrangements under similar operating conditions at a cost-effective NH_3/NO_x stoichiometry. The pellet arrangement resulted in lower ammonia slip and baghouse pressure drop. The higher monolith ammonia slip was attributed to flue gas bypass around the catalyst. The monolith design for the field demonstration was modified to eliminate the bypass. The monolith pitch (distance from channel to channel) was designed for high dust applications which reduced the potential of fly ash pluggage. The pellet bed collected a significant amount of particulate. Installation of the monolith catalyst required only one fourth of the time required for pellet installation. The monolith catalyst provides more design and installation flexibility and allows for inspection and replacement of the catalyst without removing the filter bags. Economic considerations favored the monolith option with the pressure drop and time required for catalyst installation included in the evaluation.

Sorbent Recycle

B&W subcontracted with the University of Cincinnati (UC) to conduct bench-scale tests to evaluate the feasibility of improving the sorbent utilization by recycling the once-through baghouse solids which contain unreacted sorbent. SNRB™ spent sorbent was analyzed to determine the extent of reaction, the reaction products and the available lime. Bench-scale reactor experiments were performed at the UC to determine the extent of Ca/S conversion over a range of reaction temperatures and residence times. Sorbent recycling without intermediate processing did not appear to increase hydrated lime utilization based on the UC bench-scale tests. Due to the formation of a highly carbonated outer shell, the sorbent could not be effectively recycled without thermal treatment.

Sorbent Injection

In addition to the design of the sorbent injection system, SO_2 removal efficiency largely depended on the residence time/temperature profile in the duct and in the baghouse. Pilot-scale testing of the three parameters aided the selection of the sorbent injector nozzle size, the temperature, and the location of sorbent injection for the 5-MWe Field Demonstration. Sorbent injector design affected total SO_2 removal and sorbent utilization by way of the "as-injected" sorbent particle size distribution and sorbent/flue gas mixing. A noticeable improvement in lime utilization occurred as the sorbent injection velocity was increased. The higher sorbent injection velocities promoted a finer sorbent particle size distribution by dispersing agglomerates and enhanced flue gas entrainment due to turbulent mixing. Sorbent injection temperature did not significantly effect SO_2 removal over the 900° - 1050°F temperature range evaluated.

High-Temperature Bag Design

A primary design objective was to confirm that commercial size bags containing the SCR catalyst could be uniformly cleaned along the entire bag length. As the baghouse plot plan area and overall baghouse costs generally decrease as the bag length increases, the longest bag yielding acceptable performance was desired. Bag cleanability was evaluated for the 6-¼" by 20' Nextel™ bags over a range of baghouse operating conditions, cleaning air pressure, on-line and off-line cleaning to determine the suitability of the bags for the demonstration. The tests showed the commercial size 20-foot Nextel™ bags could be uniformly cleaned over a range of SNRB™ operating conditions. The Nextel™ bags were visually observed to be uniformly clean along the entire bag length when housing either the monolith or pellet catalyst arrangement.

The effect of the ATC ratio on performance was evaluated over the limited range of 3.0 - 4.5 ft/min due to I.D. fan limitations and air infiltration into the baghouse. Over this range of ATC ratios, no effect was observed on the overall SO_2 or NO_x removal performance.

2.5.2 Assessment of Operations

The SNRB™ pilot tests were also conducted to identify ranges of key operating conditions for further evaluation at the demonstration and to confirm predicted emission control performance for use in a preliminary economic analysis of the technology. The primary operating and performance objectives included evaluation of:

- Operating conditions required to simultaneously achieve 90% NO_x and greater than 70% SO_x removal
- SNRB™ performance for both eastern and western coal applications (with calcium- and sodium-based sorbents, respectively)
- Effective baghouse operating conditions
- Particulate emissions under integrated SNRB™ operating conditions
- Ammonia emissions (slip) downstream the baghouse

Optimal Operating Conditions

The sorbent injection, baghouse, and catalyst operating temperatures must be compatible to simultaneously optimize SO_2 and NO_x removal efficiencies. Operating temperature compatibility is essential to the commercial application of the SNRB™ technology. The SCR catalyst operating temperature range over which NO_x removal was maximized was examined. Outside of this range, a loss of catalytic activity occurs. Likewise, the duct injection and baghouse operating temperature yielding optimum SO_2 removal were evaluated. At temperatures above and below the optimum range, sorbent sintering or inadequate dehydration of the sorbent may occur which inhibit SO_2 removal. The minimum 70% SO_2 removal and 90% NO_x removal were achieved over a baghouse operating temperature range of 800° to 850°F as illustrated in Figure 2-5. Baghouse and catalyst operating temperatures were compatible for simultaneous SO_x and NO_x removal sufficient to meet the performance criteria. The objectives were met at reagent stoichiometries which appeared to be cost-effective.

SO_2 removal efficiency and lime utilization improved with increased baghouse temperature, with notable improvements occurring at baghouse temperatures greater than 800°F. The performance target of 70% removal was attained at Ca/S stoichiometries of 1.8 mol/mol and above while operating at baghouse temperatures of 800° - 850°F. Above a stoichiometry of 2.5, only a slight improvement in SO_2 removal was

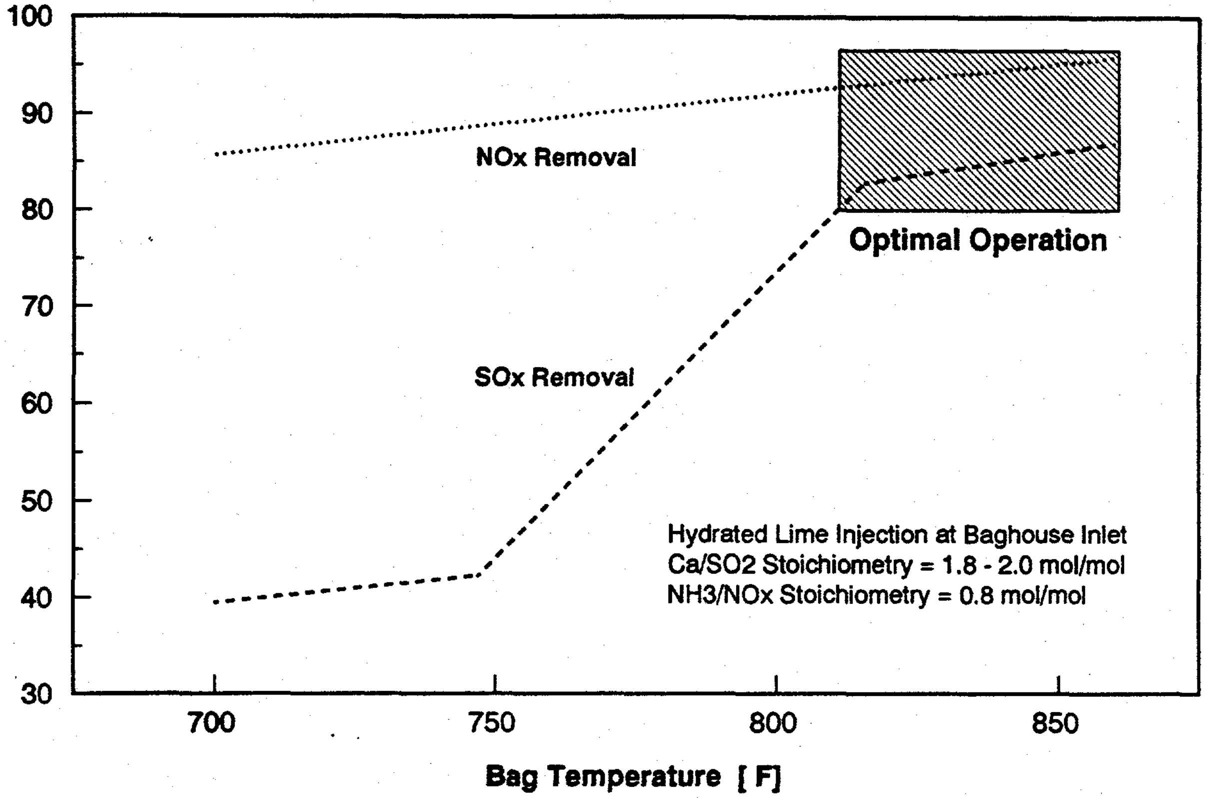


FIGURE 2-5 SIMULTANEOUS OPTIMIZATION OF SO_2 AND NO_x REMOVAL IN SMALL PILOT SCALE TESTING

observed with increasing Ca/S stoichiometry. In-duct $Ca(OH)_2$ utilization increased with increased duct residence time. Approximately 80 to 85% of the total SO_2 removal occurred in the flue work ahead of the baghouse.

The performance target of 90% NO_x removal was achieved at a NH_3/NO_x stoichiometry of 0.95 - 1.05 and an average catalyst temperature of 800 - 850 °F. NO_x removal efficiency leveled off above an NH_3/NO_x stoichiometry of 1.1 and further increases resulted in unacceptable ammonia slip.

Coal Sulfur Content

The majority of the SNRB™ laboratory tests were conducted with an eastern, medium-sulfur bituminous coal. Commercial hydrated lime ($Ca(OH)_2$) was the primary sorbent used in these tests. Low sulfur coal performance was evaluated at the pilot scale by burning a western, sub-bituminous coal with sodium bicarbonate ($NaHCO_3$) as the sorbent. The SNRB™ pilot scale tests were inconclusive as to SNRB™ applicability to low sulfur coal-fired boilers due to the limited operating time on low sulfur coal. Previous B&W pilot scale testing revealed that SO_2 removal with sodium bicarbonate ($NaHCO_3$) required a lower baghouse operating temperature than that needed for optimal NO_x removal. However, an alternative SCR catalyst formulation may be used to achieve 90% NO_x removal at the lower baghouse temperature when $NaHCO_3$ is used as the SO_2 sorbent.

Baghouse Operation

Baghouse operating parameters such as operating temperature, cleaning air pressure, cleaning cycle frequency, tubesheet pressure drop and ATC ratio were evaluated in the laboratory pilot testing to pinpoint operating conditions conducive to efficient SO_2 removal and particulate removal in the field.

Steady-state baghouse operation was achieved over a range of ATC ratios, two catalyst integration arrangements, a range of particulate loadings resulting from variation of the Ca/S stoichiometry, cleaning air pressures and cleaning cycle set-points. Stable baghouse operation with uniform cleaning cycles were obtained with a pulse-jet cleaning pressure of 30 - 40 psig.

Particulate Emissions

The New Source Performance Standard (NSPS) for particulate emissions from coal-fired boilers is 0.03 lb/million Btu. The 3M Nextel™ woven ceramic fabric was previously evaluated for particulate collection efficiency only at the laboratory pilot scale by B&W and the University of North Dakota.[21] Additional testing was necessary to demonstrate Nextel™ compliance to the NSPS and to establish particulate emissions expected at the field demonstration. Particulate emissions less than 0.03 lb/million Btu were obtained with the Nextel™ bags under three test conditions: without catalyst, with the monolith and with the pellets. NSPS compliance was maintained over a range of ATC ratios, reagent stoichiometries, cleaning cycle variations and baghouse pressure drop. Variation in the measured particulate loadings could not be correlated to any of these baghouse operating conditions.

Ammonia Slippage

Ammonia slippage refers to the presence of unreacted ammonia downstream of the high-temperature baghouse. Although ammonia slip is not currently addressed in the Code of Federal Regulations or the 1990 Clean Air Act Amendments, state agencies may require reporting of NH_3 emissions. Ammonia slip may also lead to an undesirable plume formation resulting from reaction between NH_3 and SO_2/SO_3 to form ammonium sulfate salts. The SNRB™ performance target for ammonia slip is based on the SCR system vendor standard of 5 ppm. Ammonia slippage was monitored downstream of the pilot baghouse over a wide range of NH_3/NO_x stoichiometries and catalyst temperatures to establish the potential for NH_3 emissions at the field demonstration. The ammonia slip measured with the pellets was lower than that from the monolith catalyst at a comparable NH_3/NO_x stoichiometry and catalyst temperature. At optimum conditions of a NH_3/NO_x stoichiometry between 0.95 - 1.05 and a catalyst temperature range of 800 - 850°F, ammonia slip with the pellets was less than 5 ppm while slip with the monolith was as high as 20 ppm. The higher NH_3 slip measured downstream of the monolith catalyst was attributed to flue gas leakage around the monolith assemblies. Figure 2-6 compares the irregularly chiselled outer surface of the rectangular monolith catalyst used in the laboratory pilot tests with the circularly extruded monolith catalyst design used in the 5-MWe demonstration. The elimination of the flue gas leakage reduced the NH_3 slippage in the demonstration.

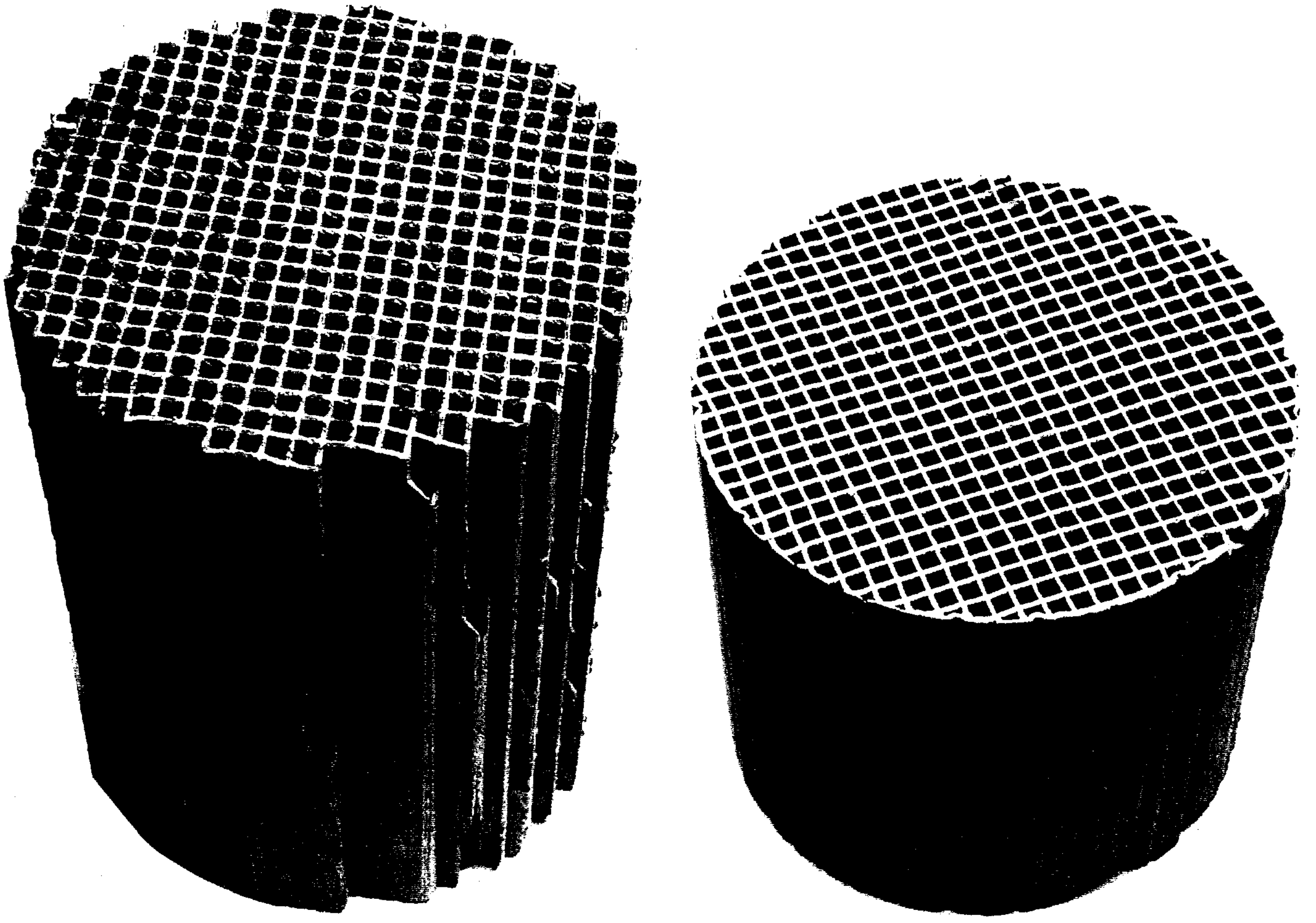


FIGURE 2-6 COMPARISON OF CHISELLED AND EXTRUDED CYLINDRICAL MONOLITH CATALYST SECTIONS

2.5.3 Application of Pilot Results to the Demonstration

Based on NO_x removal performance, ease of installation, reduced pluggage potential, and lower cost, the monolith was selected as the preferred catalyst design for the 5-MWe demonstration. To prevent flue gas bypass, the monolith catalyst was extruded in a circular form and a gasket was added between the catalyst and the catalyst holder. The catalyst holder design was modified to provide support along the entire outer circumference of the monolith to reduce abrasion from vibration of the monolith in the holder.

The effect of residence time and injection temperature on sorbent utilization merited further study. The demonstration facility included five sorbent injection locations that provided a wide range of sorbent residence times in the flue work. The effect of sorbent injection temperature was studied in greater detail in the field demonstration.

A high sorbent injection velocity was recommended to promote flue gas/sorbent mixing and obtain a finer, more effective sorbent particle distribution. Tests to evaluate the effect of the sorbent injection velocity were included in the field demonstration. Interchangeable doors with two different injector diameters were designed to provide for variation of the sorbent injection velocity.

The 20-foot long, 6-¼ inch diameter Nextel™ bags were suitable for use in the field demonstration. Unnecessary handling of the filter bags was avoided to reduce the potential for damage to the ceramic fibers. To minimize flue gas and particulate bypass, a good seal was obtained between the baghouse tubesheet and bag retainers. Gaskets similar to those used in the pilot-scale baghouse which had a significant impact on reducing particulate emissions were used in the field.

A Ca/S stoichiometry of 2.0, a sorbent injection temperature of 920 - 1050 °F and a baghouse temperature between 800° - 850°F were the recommended operating conditions to achieve SO_2 removals greater than 70% in the field demonstration. The maximum SO_2 removal achieved in the laboratory pilot tests with hydrated lime at a cost-effective Ca/S stoichiometry was approximately 75%. To improve SO_2 removal efficiency and cost-effectiveness, alternate calcium-based sorbents in addition to commercial hydrated lime were suggested for evaluation in the demonstration.

To meet the project performance target of 90% NO_x removal during the field demonstration, an NH_3/NO_x stoichiometry of 0.95 - 1.05 and a catalyst operating temperature between 800° - 850°F were recommended.

The recommended pulse-jet cleaning pressure for effective cleaning of the Nextel™ bags was 30 - 40 psig. The baghouse operating conditions evaluated in the laboratory pilot tests were the guidelines for initial baghouse operation during the field demonstration. The EPA Method 17 sample train was recommended for particulate sampling downstream of the baghouse. Operation at ATC ratios over the range of 3.0 - 6.0 ft/min were suggested for the field demonstration.

2.5.4 Filter Fabric Assessment Tests

In a commercial SNRB™ application, the initial and replacement costs of the filter bags could be a significant component of the overall capital and O&M costs. In order to reduce commercial costs, Filter Fabric Durability Tests were conducted at the Martin Drake Plant in Colorado Springs from November, 1991 to December, 1992. The purpose of the tests was to evaluate alternative bag fabrics for an extended period of time for strength degradation and particulate penetration. Those fabrics that demonstrated suitability to the high-temperature, pulse-jet SNRB™ baghouse were potential candidates for further evaluation.

The effect of long-term operation at elevated SNRB™ temperatures was evaluated through installation of three types of filter bags in a baghouse which was previously used in SNRB™ laboratory pilot tests at B&W's Alliance Research Center. The baghouse was relocated to the City of Colorado Springs' Martin Drake plant. A photograph of the overall facility is shown in Figure 2-7. The test facility consisted of a flue tie-in to the boiler economizer outlet flue work, the high-temperature baghouse, a compressed air system, an ID fan, and pneumatic ash return system.

The pulse-jet baghouse contained 12 full-size bag/catalyst assemblies, arranged in a three by four array. On-line bag cleaning with dry, compressed air was initiated by a baghouse pressure differential setpoint of approximately 14 inches H_2O and the pulse duration was 200 milliseconds. A cleaning air pulse pressure of 50 psig was used. The bags were approximately 6-1/4 inches in diameter by 20 feet in length, yielding a total collection area of 375 ft^2.

Two different weaves of the ceramic Nextel™ fabric (16.4 oz/yd^2), distinguished by the number of yarns in the horizontal and vertical directions, and Owens-Corning S-2 Glass (22.0 oz/yd^2) were evaluated. Nextel™ and S-2 Glass fabric bags are also installed in the 5-MWe field demonstration baghouse where acceptable particulate collection efficiencies were achieved. The Nextel™ bags were supported on perforated retainers and attached to the retainers by constant torque clamps at the top and bottom. The S-2 Glass bags were supported on wire cages and perforated retainers and were suspended from the tubesheet with snap rings. In order to evaluate the bags objectively, the bags were installed in a random order to minimize gas flow, temperature, or particulate loading bias.

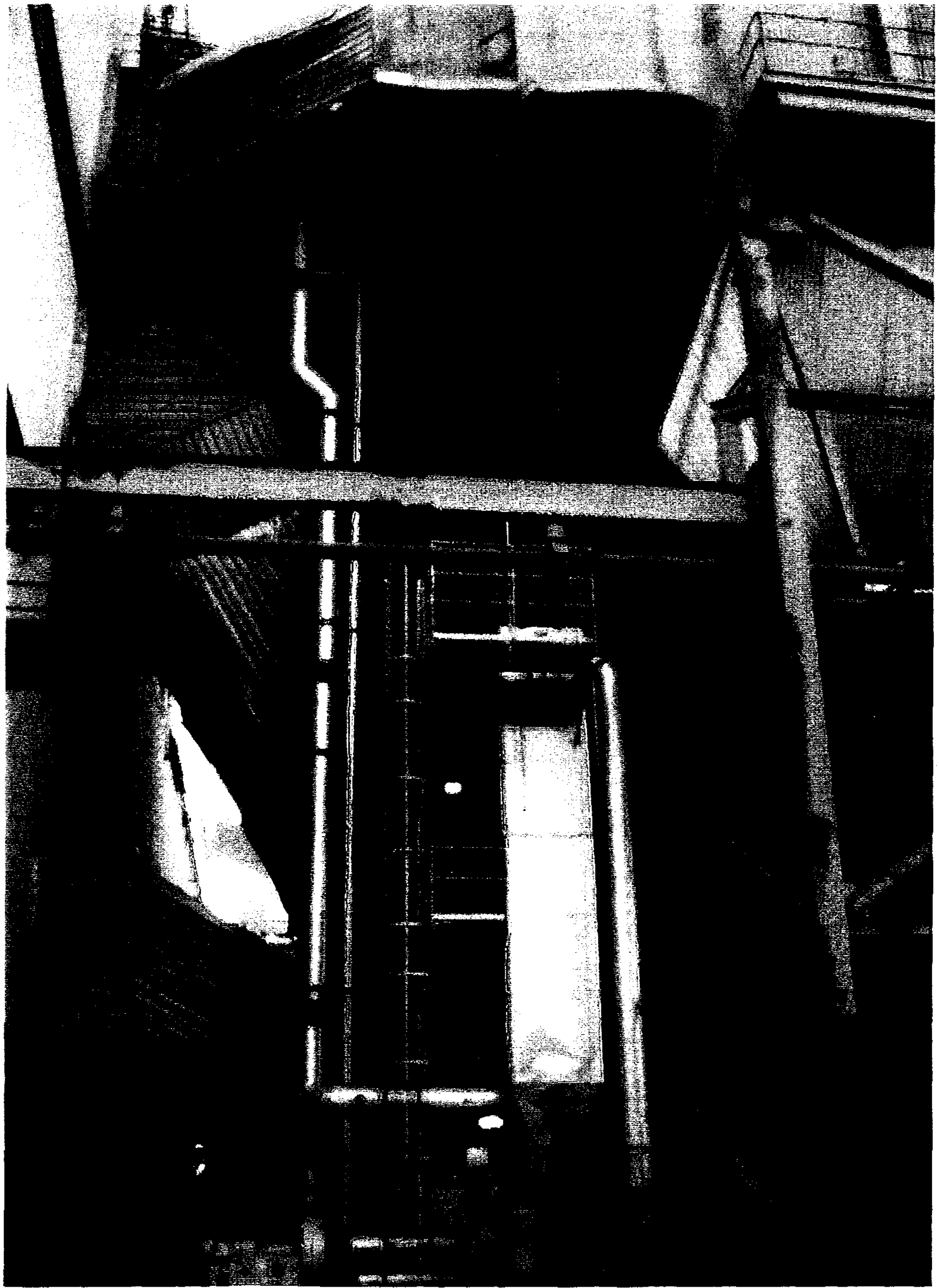


FIGURE 2-7 SNRB™ FILTER FABRIC TEST PILOT

The test facility did not include sorbent or ammonia injection for SO_x and NO_x removal. Since western coal was fired, the SO_2 concentration contacting the bags was comparable to an eastern utility with 80 - 90% SO_2 reduction. The low SO_2 concentration minimized acid attack during baghouse start-up and shut-down.

After 3,700 hours of operation and 11,200 pulse-jet cleanings per bag, the bags were removed from the baghouse at the end of the field tests. No significant damage to the Nextel™ and S-2 Glass bags was noted during visual inspection. Based on visual inspection of the bags at the end of the field tests, the Nextel™ and S-2 Glass fabrics appeared suitable for SNRB™ high-temperature, pulse-jet operation.

2.5.5 Alternate Sorbent Tests

Eight different sorbents were evaluated at the University of Cincinnati to aid in the selection of alternate sorbents to test at the field demonstration. One of the major findings was that the reactivity of the sorbents was more prominent with CO_2 than SO_2 at baghouse temperature higher than 900°F.[14] Another was that the extent of reaction with SO_2 in the drop tube furnace at the tested conditions did not depend on either the original available lime index or the specific surface area of the sorbent. Based on the results, two alternate sorbents, calcium lignosulfonated lime and sugar hydrated lime were selected for evaluation at the demonstration facility.

3.0 5-MWe FIELD DEMONSTRATION

3.1 FACILITY DESCRIPTION

The basic process design criteria as well as general gas and solid flow descriptions for the SNRB™ demonstration facility are discussed in this section. Figure 3-1 presents a schematic of the system. A detailed facility equipment list is provided as Appendix A.

3.1.1 Facility Design Criteria

General criteria used for the design of the SNRB™ demonstration facility are presented in Tables 3-1 through 3-6.

TABLE 3-1 GENERAL DESIGN CRITERIA

Pilot Size	5-MWe
Nominal Capacity	47,667 lb/hr 22,785 ACFM @ 650 F, -8.5" H_2O
Plant Elevation	658'0" above MSL
AMBIENT CONDITIONS	
Temperature, Maximum Dry Bulb	95°F
Temperature, Minimum Dry Bulb	-15°F
Barometric Pressure	29.18 in Hg
Relative Humidity, Minimum	20 %
Relative Humidity, Maximum	100 %
Location of Equipment	Outdoors

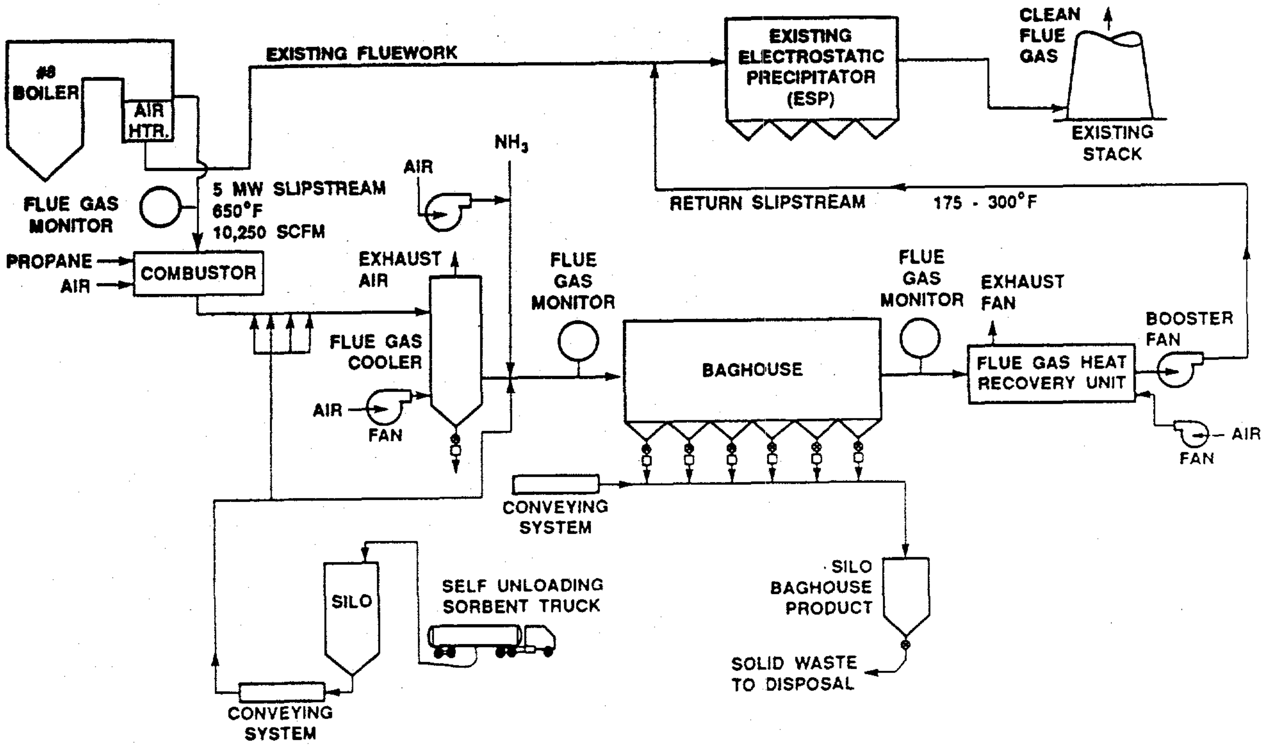


FIGURE 3-1 SNRB™ DEMONSTRATION SCHEMATIC

TABLE 3-2 FUEL CHARACTERIZATION-EASTERN BITUMINOUS COAL			
ANALYSIS	NOMINAL (%)	DESIGN (%)	RANGE (%)
Ash	10.94	11.6	6.6 to 15.0
S	2.19	3.5	0.6 to 3.5
H	5.09	4.4	3.3 to 5.3
C	73.02	65.1	62.0 to 73.5
H_2O	5.24	7.5	4.0 to 1.9
N_2	1.62	1.2	1.0 to 1.9
Cl	less than 0.05	0.05	0.01 to 0.05

TABLE 3-3 FLUE GAS CHARACTERIZATION	
Pressure at System Inlet*	-8.5" H_2O
Temperature at System Inlet*	650°F
Pressure at System Outlet*	-15." H_2O
GAS ANALYSIS (%) N_2	74.11
O_2	2.98
CO_2	13.98
SO_2	0.28
H_2O	8.65
Total	100.00
FLUE GAS COMPOSITION SO_2	500 - 2500 ppm
NO_x	500 - 800 ppm
NH_3	0 - 500 ppm
O_2	3 - 8 %

* For typical full load boiler operation

TABLE 3-4 FLY ASH CHARACTERIZATION

ANALYSIS (% wt.)	NOMINAL (%)	RANGE (%)
SiO_2	47.0	36.2 to 57.0
Al_2O_3	22.6	17.7 to 34.0
Fe_2O_3	22.8	4.8 to 34.2
TiO_2	1.3	0.48 to 2.40
CaO	3.0	0.20 to 5.50
MgO	1.1	0.21 to 5.00
Na_2O	0.3	0.07 to 1.10
K_2O	1.9	0.15 to 5.60

PARTICLE SIZE DISTRIBUTION Particle Size (microns)	% less than
100	100
50	90
20	48
10	20
5	9
2	3

TABLE 3-5 SORBENT CHARACTERIZATION

	HYDRATED LIME	SODIUM BICARBONATE
Composition (by wt)	95 % CaO	95 % $NaHCO_3$
Inerts	5 %	5%
Bulk Density		
Volumetric	30 lb/ft^3	50 lb/ft^3
Loading	100 lb/ft^3	100 lb/ft^3
Angle of Repose	40°	40°
Average Particle Size	5-10 microns	10-20 microns

TABLE 3-6 ANHYDROUS AMMONIA CHARACTERIZATION	
Composition	9 9+% NH_3
Molecular Weight	17.03 lb/mole
Specific Volume	20.78 ft^3/lb
Density, (liquid phase)	4 2.57 lb/ft^3
Relative Density of Vapor	0.597
Viscosity	6.72×10^{-6} lb/ft-s

A flue gas slip stream from the Burger Plant Boiler No. 8 economizer outlet hopper section was the source of the flue gas for the pilot facility. The flue gas was routed through the system where it was first heated by a propane-fired heater to the desired temperature for injection of a calcium or sodium based sorbent for SO_2 removal. After sulfur sorbent injection, the gas stream was cooled by a plate-type heat exchanger to the desired temperature for ammonia injection. The ammonia for this NO_x removal step was supplied by a packaged anhydrous ammonia injection system. The flue gas then entered the hot catalytic baghouse, where additional SO_2 removal occurs, particulates were removed using high temperature bags, and NO_x was selectively reduced by NH_3 in the presence of a catalyst. After exiting the baghouse the gas was cooled in a second plate-type heat exchanger, passed through a booster fan, and was recombined with the Burger Plant outlet flue gas upstream of the Boiler No. 8 electrostatic precipitator.

The solids handling portion of the SNRB^{TM} system consisted of two (2) basic systems: the reagent feed system and the ash removal system. The reagent feed system supplied fresh sorbent at a controlled rate to a pneumatic conveying system that transported the sorbent to one of five (5) injection locations in the flue. Four of these injection locations were between the propane-fired burner and the inlet flue gas cooler. The fifth injection point was located just downstream of the inlet gas cooler. The ash removal system collected ash from each of the baghouse hoppers and transported it via a pneumatic conveying line to an ash storage silo. The ash silo was equipped for truck removal of the ash. Any ash that dropped out into either of the flue gas cooler hoppers was removed manually off-line by adjusting dampers to pull the ash either into the baghouse or into the plant ESP.

3.1.2 Flue Gas Flow

Flues

The SNRB™ demonstration flue work began with a slip stream take-off at the economizer outlet of Boiler No. 8. It was constructed of A-36 carbon steel and sized for a nominal gas velocity of 3,000 feet per minute. A manually operated butterfly damper located at the inlet of the pilot system flue work permitted isolation of the SNRB™ system from the Ohio Edison boiler. A photograph of the primary flues is presented in Figure 3-2. The flues were designed to accommodate a full load slip stream gas flow of 47,667 lb/hr. The flue gas mass flow rate increased slightly throughout the system, primarily as a result of gas heater combustion products and the sorbent and ammonia injection streams.

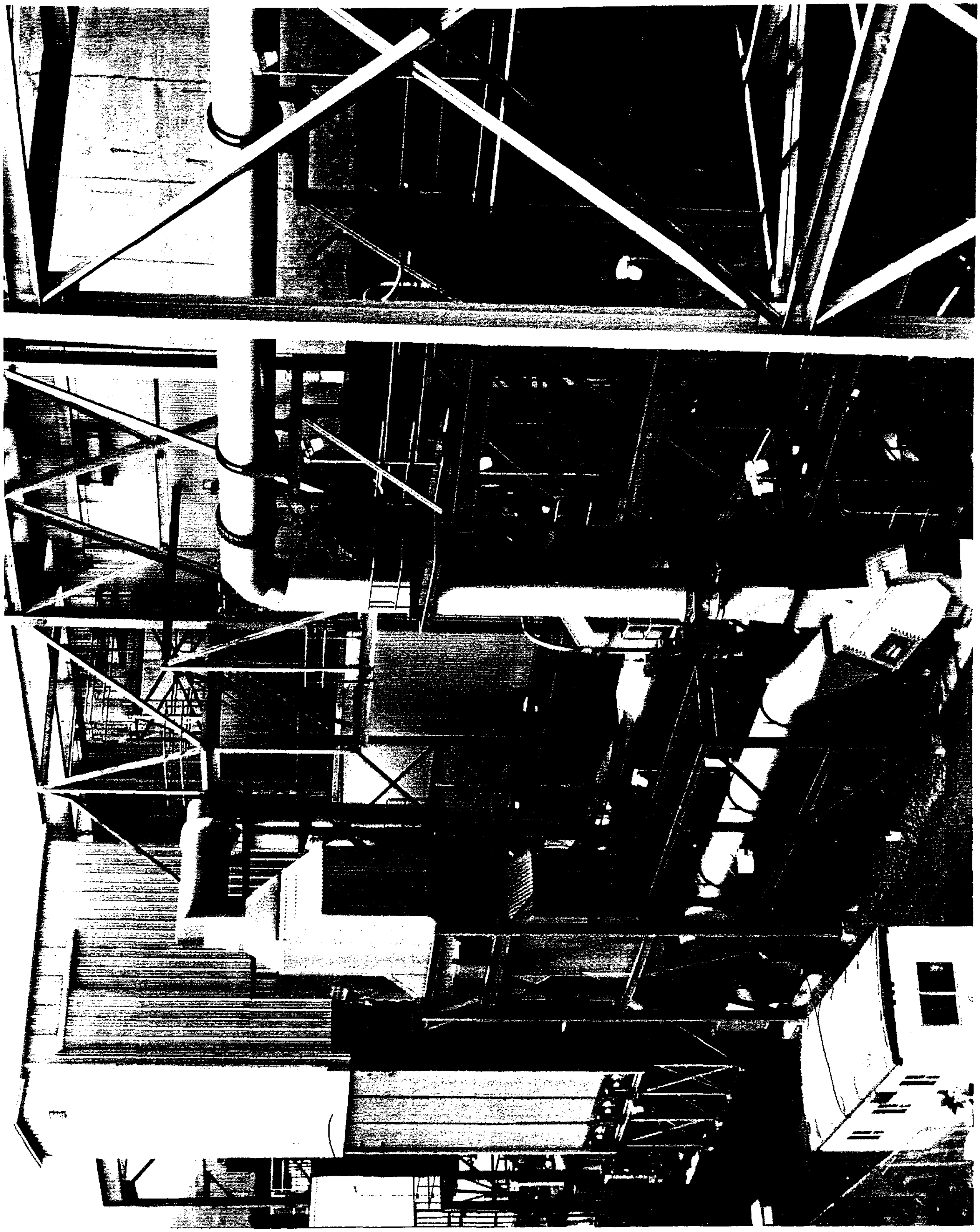
Instrumentation connections for monitoring inlet gas temperature, pressure, and composition were located upstream of the inlet gas flow measurement venturi. One set of additional test connections was also provided. The additional connections were 90 degrees apart to allow for a flue traverse.

A tie-in for a recirculation flue was located downstream of the venturi. This provided for gas recirculation when the pilot system was in a hot stand-by mode. An isolation damper in the recirculation flue prevented gas flow through this section during normal operation.

A propane-fired flue gas heater located on a 90° elbow was used to increase the gas temperature from the boiler economizer outlet temperature (about 650°F) to an approximate range of 900° - 1250°F. The actual downstream temperature was adjustable over this range to provide the desired test conditions. Varying the flue gas temperature at the sorbent injection point provided data on the effect of flue gas temperature on sorbent utilization and overall SO_2 removal efficiency.

A thermocouple grid connection was located downstream of the flue gas heater for temperature control. Two additional thermocouple connections were located just downstream of the burner for use in the heater control logic.

FIGURE 3-2 SNRB™ DEMONSTRATION FACILITY FLUE WORK



The burner chamber and the entire length of the flue work to the inlet flue gas cooler were refractory lined. The burner chamber had an inside diameter greater than that of the flue immediately downstream due to burner requirements. Four sorbent injection points were located along the length of the lined flue between the burner and the inlet flue gas cooler. These injection ports provided for sorbent residence times of approximately 2 s, 1 s, 600 ms, and 200 ms upstream of the baghouse. Thermocouple connections just upstream of each of the latter three injection points were used to measure the gas temperature at the point of injection.

An ammonia injection port was also located in the refractory lined flue, downstream of the burner control thermocouple grid but upstream of the first sorbent injection point. This high temperature region ammonia injection port was not used during the test program.

The inlet flue gas cooler lowered the gas temperature to the desired level for ammonia injection and baghouse operation, usually around 850°F. The temperature of the gas stream could be varied to accommodate a range of operating conditions. A second venturi was located between the inlet flue gas cooler and the baghouse to provide an accurate indication of the gas flow entering the baghouse. Temperature and pressure measurement connections were located between the inlet gas cooler and the venturi. A thermocouple grid was used for correction of the venturi flow measurement as well as for control of the inlet cooler cooling air fan. A flue gas analyzer sampling connection was also located upstream of the venturi.

The flue between the baghouse inlet venturi and the baghouse contained an ammonia injection port, a sorbent injection port, and a gas analyzer connection for SO_2, NO_x, and O_2. An auxiliary test connection was provided downstream of the sorbent and ammonia injection ports for flue gas sampling traverses.

The baghouse was provided with a bypass for protection during start-up and potential upset conditions. Automated dampers at the individual compartment outlets and at the bypass line allowed rapid response to upset conditions. Triboflow dust emission monitors were located at the exit of each of the six baghouse modules to monitor for bag breakage/leaking. Thermocouples located in each module were used for data acquisition and detecting module hopper fires.

The flue exiting the baghouse contained a gas analyzer connection for SO_2, NO_x, and O_2 and an auxiliary sampling port before entering the outlet flue gas cooler. A thermocouple grid connection was located in the flue downstream of the outlet flue gas cooler for control of the outlet cooler cooling air fan.

The heat exchanger cooling air inlet temperature had to be maintained at a 95° F minimum for cold block protection. A recirculation duct from the cooling air exit to the fan inlet was used to control the inlet temperature. A thermocouple measurement at the cooling air fan discharge was used to control the amount of recirculation.

The flue gas exiting the outlet flue gas cooler was routed to the booster fan where the pressure was increased to allow return to the existing Boiler No. 8 flue upstream of the electrostatic precipitator. An auxiliary sampling port was located in the flue between the outlet gas cooler and the fan. An opacity meter was located in the flue to measure the baghouse outlet opacity.

A manually operated butterfly damper for isolation of the pilot system, was located at the tie-in with the Boiler No. 8 flue to the precipitator. The recirculation flue tied in to the SNRB^{TM} system main flue upstream of this damper. The flue sizes and design temperatures varied throughout the pilot facility due to changes in the flue gas conditions. The design specifications for each section of the flue work are presented in Table 3-7.

Dampers

Butterfly dampers were utilized for the isolation of the pilot system from the existing facility, controlling the gas flow rate through the pilot, and for hot stand-by mode operation. Manual isolation dampers were located in the pilot system inlet, outlet, and gas recirculation flues. The flow control damper, located downstream of the booster fan discharge, was modulated using the gas flow measured by the system inlet venturi.

The butterfly dampers, supplied by Damper Design, Inc, were model RSH36/OBYU and 36" in diameter. The manual damper actuators (model #WA20-30), with the exception of the system gas flow control damper, were supplied by Dyna-Torque. The system gas flow control damper actuator was supplied by Accord/Sheffer. The design specifications for the dampers are provided in Table 3-8.

TABLE 3-7 FACILITY FLUE WORK DESCRIPTION					
	FLUE 1	FLUE 2	FLUE 3	FLUE 4	FLUE 5
Gas Flow Rate (lb/hr)	47,667	53,214	53,968	54,466	47,667
Design Pressure ("H_2O)	-35 to +15	-35 to +15	-35 to +15	-35 to +15	-35 to +15
Design Temperature (°F)	750	1250	900	600	600
Operating Pressure ("H_2O)	-8.5	-9.5	-11.5	-30 to -15	-30 to -15
Operating Temperature (°F)	650	650-1250	500-850	170-300	500-600
Inside Diameter (inches)	36	42	40	36	36
Material of Construction	Carbon Steel	Carbon Steel	Carbon Steel	Carbon Steel	Carbon Steel
Linings	None	NARCO-HPX50	None	None	None
Insulation	Yes	Yes	Yes	Yes	Yes

Flue 1: System Inlet Flue to Burner Chamber
Flue 2: Burner Chamber to Inlet Flue Gas Cooler
Flue 3: Inlet Gas Cooler to Outlet Gas Cooler
Flue 4: Outlet Gas Cooler to System Exit Terminal Point
Flue 5: Recirculation Flue

TABLE 3-8 DAMPER DESIGN DESCRIPTION				
	DAMPER 1	DAMPER 2	DAMPER 3	DAMPER 4
Design Pressure ("H_2O)	-35	-35	-35	-35
Operating Pressure: ("H_2O)	-8.3	-15	-5	-13
Design Temperature (°F)	750	750	750	750
Operating Temperature (°F)	650	200	650	200
Leakage at Design Cond. (%)	0.41	0.64	0.20	0.64

Damper 1: Inlet Isolation
Damper 2: Outlet Isolation
Damper 3: Recirculation Flue
Damper 4: System Gas Flow Control Damper

Flue Gas Heater

A propane fired flue gas heater was located in a 90° elbow of the flue, downstream of the system inlet venturi and upstream of the sorbent injection locations. The specifications for the gas heating systems are summarized in Table 3-9. The flue gas heater was used to heat the gas stream to the desired operating temperature and maintain the system temperature during short periods of no testing. The heater typically increased the temperature of the flue gas from about 650°F to 1000° - 1250°F. Gaseous propane was supplied to the burner by an integrated propane storage tank/vaporizer assembly. Liquid propane was pumped from the storage tank to the vaporizer. The vaporized propane was then routed to the burner through the burner's valve train.

In order to ignite the burner, the flue gas flow had to be above a minimum level. The operating burner was tripped if the flue gas flow fell below the minimum level. High flue gas temperature would also trip the burner. A control signal was generated by the Net-90 based on deviation of the flue gas temperature from the set-point. A significant deviation of the flue gas temperature from the set point alerted the operator with an alarm.

The Net-90 control signal was received by the local control panel and directed to the combustion air actuator motor which modulated the combustion air flow. A sensing line downstream of the air control valve was connected to the top of the diaphragm on a ratio regulator to control the flow of the propane. Thus the Net-90 signal controlled combustion air flow and provided near "on-ratio" modulation of the burner.

Inlet Flue Gas Cooler

A plate-type heat exchanger was used to cool the flue gas before the gas entered the ammonia injection section of the flue. The heat exchanger typically cooled the gas to a temperature of 800° -900°F. The inlet flue gas cooler specifications are summarized in Table 3-10.

A control signal from the Net-90 adjusted the cooling air fan inlet vanes based on the set point and the actual gas outlet temperature. The inlet vanes had to be closed to start the cooling air fan and in the event of a fan trip, the inlet vanes closed and an alarm sounded. Each block of the inlet cooler had a thermocouple at its midpoint which was wired directly to the Net-90 for data acquisition.

TABLE 3-9 FLUE GAS HEATING SYSTEMS	
BURNER	
Manufacturer	Eclipse
Model Number	1000RM-IRI-NEMA4
Fuel Type	Propane
Heat Output (BTU/hr)	4.0 X 10^6 Btu @ -10" H_2O press
Combustion Air Fan hp	10
Combustion Air Flow	8625 lb/hr (max)
PROPANE STORAGE AND DELIVERY SYSTEM	
Tank Manufacturer	Plant Systems, Inc.
Fuel Tank Size	Length 41'0" I.D. 9' 0"
Fuel Tank Capacity	18,000 gal
Vaporizer Manufacturer	Sam Dick Industries
Model No.	EQ-160
Capacity	160 gal/hr propane
Propane Pump Manufacturer	Corken
Model No.	C-12
Motor hp	1

TABLE 3-10 INLET FLUE GAS COOLER SPECIFICATIONS	
Manufacturer	North Atlantic Technologies
Type	Plate
Size	24'10" x 18'5" x 8'4"
Design Pressure (gas side)	-35" to 15" H_2O
Design Pressure (air side)	6" H_2O
Max. Inlet Gas Temp	1250°F
Max. Allowable Outlet Gas Temp	900°F
Min. Air Inlet Temp	-15°F
Outlet Air Temp (@ design)	720°F
Overall U	4.0 BTU/hr-ft^2-°F
Fouling Resistance	0.02
Casing Material	Carbon Steel
Heat Transfer Surface Area	4, 019 ft^2
Heat Transfer Surface Material:	
Cold Block	Aluminized Steel
Hot Block	SS304
Cleaning Equipment	Soot Blower Connections
Cooling Air Fan:	
Manufacturer	Buffalo Forge
Model No.	Aerocline 600
Max./Min. Air Flow	60,000/8,800 lb/hr
Pressure Increase	4" H_2O
Brake/Motor hp	12.6/15
Speed	1800 RPM
Motor Frame Size	254T

Baghouse

The baghouse was designed to operate in a hot flue gas environment, typically in a range from 800° - 900°F. The NO_x reduction catalyst was housed in an assembly within each of the filter bags. All baghouse functions were controlled through a vendor supplied control panel. Some of the baghouse operating conditions were transmitted to the Net-90 for data acquisition and monitoring baghouse operation. The baghouse specifications are summarized in Table 3-11.

Hot flue gas entering the baghouse was distributed to each of six compartments through a tapered inlet manifold. Each compartment could have been isolated from the inlet manifold by a manually operated butterfly damper. The inlet manifold contained a thermocouple wired directly to the Net-90 for data acquisition purposes and a temperature switch that alarmed (on the vendor panel) high and low inlet gas temperature. The upstream tap of the baghouse differential pressure transmitter was located in the inlet manifold. The differential pressure transmitter was used to control pressure difference-based cleaning and was alarmed for high and low values.

Each of the six compartments of the baghouse had individual differential pressure gauges for local indication of the module differential pressure. Each compartment also had a thermocouple wired directly to the Net-90 for data acquisition and fire protection. High temperature in any compartment could have caused the Net-90 to send a signal to the baghouse control panel to sound an alarm. Outlet particulate monitors were also provided at the exit of each baghouse module to assist in detecting and locating leaking or broken bags. The ash collection hoppers under each compartment were equipped with locally controlled heating panels and level probes.

A baghouse trip could be caused by high inlet temperature or high differential pressure. In the event of a baghouse trip, the bypass flue isolation damper was opened and the individual compartment outlet dampers were closed. The flue gas was then routed directly to the outlet manifold. A signal indicating the baghouse trip was sent to the Net-90.

The outlet manifold was equipped with a thermocouple and the downstream tap of the differential pressure transmitter. The thermocouple was wired directly to the Net-90 for data acquisition purposes.

The baghouse compartments could be cleaned on-line (with flue gas flow) or off-line (isolated from flue gas flow). In addition, the bags could have been cleaned manually or in an automatic cycle. In the automatic mode the bag cleaning frequency was controlled by baghouse pressure differential, on a timed cycle, or a combined differential pressure/time cycle. The manual mode allowed individual compartments to be cleaned at the operator's discretion.

Outlet Flue Gas Cooler

A plate-type heat exchanger was used to reduce the flue gas temperature exiting the baghouse from 800° - 900°F to 170° - 300°F. Table 3-12 summarizes flue specifications for the outlet flue gas cooler. A control signal from the Net-90 adjusted the cooling air fan inlet vanes based on a comparison of the set point and the actual gas outlet temperature. A control signal from the Net-90 adjusted the recirculation diverter valve so a portion of the exhausted cooling air mixed with the inlet cooling air to maintain a minimum inlet temperature. The adjustment was based on the set point temperature and the actual inlet cooling air temperature. The minimum allowable cooling air inlet air temperature was 95°F to protect the cold block from operating at potential acid deepened temperatures.

The diverter valve and the inlet vanes had to be closed for the fan to start and if the fan tripped off at any time the dampers closed and sounded an alarm. Thermocouples at the midpoint of each block were wired to the Net-90 for data acquisition.

Booster Fan

The booster fan, located downstream of the outlet gas cooler, was used to compensate for the system gas side pressure losses. The fan specifications are summarized in Table 3-13. The control damper had to be closed in order for the fan to start. Thirty seconds after the booster fan was started the control damper was released to open and control gas flow. A booster fan trip would initiate a complete SNRB™ system trip.

TABLE 3-11 BAGHOUSE SPECIFICATIONS

Manufacturer	Amorous, Inc.
Size	19' x 15.5' x 49.3'
Number of Compartments	6 (3 x 2)
Design Pressure	± 35" H_2O
Design Temperature	900°F
Design Gas Flow	54,630 lb/hr
Air to Cloth Ratio	
All compartments in service	3.74
Five compartments in service	4.49
Cleaning air Requirements	84 SCAM @80 psig
Cleaning Type	Venturi
On-line/Off-line Cleaning	Both Available
Bags/Compartment	42 (6 x 7)
Bag Diameter/Length	6"/20'
Effective Cloth Area/Bag	31.75 ft^2
Material of Construction	Carbon Steel
Thickness	3/16"
Insulation Material	Mineral Wood
Insulation Thickness	4"
Lagging Material/Thickness	Aluminum/0.032"
Hopper Storage Capacity	37 ft^3
Hopper Heaters	5 kW/hopper

TABLE 3-12 OUTLET FLUE GAS COOLER SPECIFICATIONS	
Manufacturer	North Atlantic Technologies
Type	Plate
Size	43'2" x 25'6" x 8'6"
Design Pressure (gas side)	-35" to 15"
Design Pressure (air side)	15"
Max. Inlet Gas Temp	900°F
Min. Allowable Outlet Gas Temp	170°F
Min. Inlet Air Temp	95°F
Air Outlet Temp (@ design condition)	415°F
Overall U	4.6 BTU/hr-ft^2-°F
Fouling Resistance Used	0.01
Casing Material	Carbon Steel
Heat Transfer Surface Area	11,716 ft^2
Heat Transfer Surface Material	
Cold Block	Corten/SS304
Hot Block	Carbon Steel
Cleaning Equipment	Soot blower connection Cold block water wash
Cooling Air Fan (FN-102)	
Manufacturer	Buffalo Forge
Model. No.	Aerocline 805
Max./Min. Air Flow	128,500/49,000 lb/hr
Pressure Rise	12"
Brake/Motor hp	72.8/75
Speed	1,417 RPM
Motor Frame Size	365T

TABLE 3-13 FAN SPECIFICATIONS	
Manufacturer	Zurn Industries
Model No.	80 RHM 5540 Series
Air Flow @ design condition.	17,131 ACFM
Pressure Increase @ design	21.5" H_2O
Fan Speed	1,775 RPM
Motor hp	100
Motor Frame Size	405T

3.1.3 Solids Handling Systems

Reagent Feed System

The reagent feed system consisted of a storage silo with bin activator, loss-of-weight feeder, and a pneumatic conveying system with blower, valves, rotary air locks, piping, and all instrumentation necessary to transport sorbent at the desired feed rate to the selected injection point in the flue. The reagent feed system specifications are summarized in Table 3-14. The storage silo stored either hydrated lime or sodium bicarbonate sorbent depending on the sorbent being tested at the time.

The fresh reagent flow rate was controlled by a 4-20 mA signal from the Net-90. The flow rate signal was based on demand calculated from the gas flow rate, the inlet gas SO_2 composition, the pre-selected stoichiometric ratio, and the purity of the sorbent feed stock. The reagent feed system would not operate if the baghouse was in the bypass mode.

The reagent flowed from the storage silo to a loss-of-weight feeder when the silo discharge valve was opened. The loss-of-weight feeder was equipped with a single bag vent filter to control dust emissions. The feeder discharged solids through a rotary airlock into a feed hopper. The feed hopper was equipped with a high level switch and a single bag filter to control dust emissions. If the hopper level was too high, an alarm sounded and the loss-of-weight feeder discharge screw stopped.

TABLE 3-14 REAGENT FEED SYSTEM SPECIFICATIONS	
REAGENT STORAGE SILO	
Manufacturer	Smoot Company
Reagent Material	Hydrated lime / sodium bicarbonate.
Capacity	70,000 lb
Size	
Height	42 ft
Diameter	12 ft
Materials of Construction	carbon steel
REAGENT PNEUMATIC CONVEYING SYSTEM	
Manufacturer	Smoot Company
Design Temperature	70°F
Design Pressure	5.7 psig
Solids/Air Ratio	1.7 (max)
Pick-up Velocity	66.7 ft/s
Discharge Velocity	92.5 ft/s
Conveying Line Size	3.5 in O.D.
Conveying Line Material	carbon steel
Blower Type	positive displacement
Blower Manufacturer	Sutorbilt
Model	6 HL
Blower Motor hp	20
Blower Control	AC variable frequency

A second rotary feeder discharged the reagent into the transport line for conveying to the point of injection. Diverter valves directed the flow to the desired branch of the system for injection into the gas stream.

The reagent silo included a truck unloading station and was sized to hold greater than one standard truck load of material, approximately 35 tons. The silo was equipped with a pulse jet type bin vent filter, a vacuum/pressure relief valve, and access doors. A differential pressure switch on the bin vent filter alarmed a blinded bag condition if a high differential pressure existed for more than 30 seconds.

Reagent level within the silo was monitored by three level switches - high, mid, and low. Each switch lit a light on the local panel to indicate reagent level. In addition, a high level indication sounded an alarm if a fill hose was connected at the truck unloading station.

The pneumatic conveying system utilized a positive displacement blower as the air source. The blower was equipped with an inlet filter and silencer, pressure relief valve, pressure gauge, high pressure switch, discharge silencer, and check valve. An AC variable frequency controller allowed the speed of the blower to be varied to provide different transport air flow rates.

High pressure in the transport system lit an indicating light on the local panel upon initial detection of the high pressure condition. After 2 seconds, the rotary airlocks and loss-of-weight feeder stopped and an alarm horn sounded. The blower shut down if the high pressure condition continued for 15 seconds.

Ash Removal System

Specifications for the ash removal system are summarized in Table 3-15. The ash removal system transported solids collected in the baghouse hoppers to the baghouse product silo. The silo was sized to hold twenty-four (24) hours of by-product solids produced at full flow operation of the pilot.

Ash was discharged from each of the baghouse module hoppers to the transport line through NUVA feeders. Knifegate valves isolated the NUVA feeder from the hopper and the transport line. In operation, the upper knifegate valve first opened for a set time to allow ash to fill the NUVA feeder bottle, then closed to isolate the feeder. Air displaced by the ash was vented to the baghouse hopper. The feeder vessel was then pressurized to a pressure slightly above the transport line pressure by a separate line taken from the transport blower discharge piping. The lower knifegate valve opened to discharge the solids into the conveying line, then closed. Finally, the feeder vessel was vented to the hopper to allow the cycle to repeat.

The six NUVA feeders were activated one at a time, in sequence, to prevent overloading of the transport line with ash. The cycle was continued until a no load condition was sensed. Depending on which of two automatic modes of operation was selected, the conveying cycle would either repeat or the transport line would be purged followed by annunciation of the completion of the conveying cycle.

Discharge of the ash from the storage silo was controlled using a rotary feeder and air slide. Three discharge points on the air slide allowed the discharge point to be varied along the length of the transport trailer. A dedicated blower and heater were provided for the ash silo fluidizing system.

The ash removal system operated independently of the rest of the SNRB™ system. All functions of the ash removal system were controlled by the vendor supplied instrumentation. Interface with the Net-90 system extended only to indication of the ash conveying system's operating status.

3.1.4 Auxiliary Systems

Ammonia System

A complete, skid mounted package system supplied ammonia vapor to the ammonia injection point in the flue downstream of the inlet flue gas cooler. The specifications for the ammonia supply system are summarized in Table 3-16.

The ammonia feed rate was controlled by a signal from the Net-90. The signal was generated based on the measured flue gas flow rate, the system inlet NO_x concentration, and the pre-selected stoichiometric ratio.

Anhydrous ammonia flowed from the storage tank to an electrical resistance heater where the liquid ammonia was vaporized. The ammonia vapor was then directed into the storage tank headspace to maintain a set pressure in the tank. Vapor flow from the tank to the air/ammonia mixer was controlled by a wafer type valve.

Injection air was supplied by a fan at a constant air:ammonia ratio of 19:1. Air flow was controlled based on the ammonia flow rate desired. Air and ammonia were mixed in a low pressure static mixer before the ammonia injection pipe in the flue.

The ammonia supply system could not be started if there was no flue gas flowing through the SNRB™ system or if the baghouse was in the bypass mode. The supply system would trip if the flue gas temperature was not in the specified range for injection, if the flue gas flow dropped below a minimum value or if there was a general SNRB™ system trip.

TABLE 3-15 ASH REMOVAL SYSTEM SPECIFICATIONS	
Manufacturer	United Conveyor Corp.
Design Temperature	850°F
Design Pressure	4.4 psig
Solids/Air Ratio	1.24
Pick-up Velocity	63 ft/s
Discharge Velocity	77 ft/s
Conveying Line Size	3 inch
Conveying Line Material	Sch 80 Carbon Steel
CONVEYING AIR BLOWER	
Manufacturer	Sutorbilt
Model Number	5ML-RHC
Size	7.5' x 2.2' x 8.8'
Capacity	253 ACFM
Discharge Pressure	4.4 psig
Discharge Temp. Increase	64°F
Motor hp	15
Motor Speed	1,750 RPM
BAGHOUSE PRODUCT STORAGE SILO	
Material Density, Volumetric Sizing	30 lb/ft^3
Material Density, Structural Sizing	100 lb/ft^3
Capacity	30,000 lb
Size	
Height	33 ft (total)
Diameter	10 ft
Materials of Construction	A-36 Mild Steel

TABLE 3-16 AMMONIA SYSTEM SPECIFICATIONS	
Manufacturer	Ferguson Industries
Storage Tank Skid Size	16'9" x 5'6"
Storage Tank Capacity	
Total Volume	1000 gal
Liquid Volume	850 gal
Tank Design Pressure	250 psig
Tank Design Temperature	100°F
Vaporizer Capacity	35 lb/hr
Vaporizer Power Draw	20 kW
Ammonia Feed Line Size	1 1/4"
Ammonia Feed Line Pressure	2 psig
Ammonia Feed Rate Range	2-27 lb/hr
Injection Air Pressure	2 psig
Injection Air Temperature	40° - 120°F
Injection Air Flow Rate	1,125 lb/hr (max)
Air/Ammonia Ratio	19:1
Fan Capacity	1,125 lb/hr
Fan HP	5

Compressed Air

A packaged compressed air system supplied the instrument and service air requirements of the pilot system. This included all cleaning air for the baghouse and the silo bin vent filters, as well as instrument quality air for the control valves. Specifications for the compressed air supply system are summarized in Table 3-17.

Two receiver tanks were mounted on a common skid. One receiver tank provided instrument air and the second tank provided the service air. Each tank was equipped with a pressure gauge and drain connection. The header from each tank was equipped with a pressure regulator and pressure gauge. In addition, the baghouse branch of the instrument air line was equipped with a pressure transmitter to provide continuous monitoring of the baghouse cleaning air pressure.

The compressed air system operated independently of the rest of the SNRB™ systems. Interfaces with the Net-90 system were limited to indication of the compressor status and an alarm for low baghouse cleaning air pressure.

Water System

The service water and potable water were provided by branches routed from existing Ohio Edison plant locations. Potable water was provided to the control room, laboratory trailer, and emergency eyewash/shower stations located in the ammonia and hydrated lime storage areas. Service water hose stations were located in the following areas:

- Ammonia Storage - general clean-up
- Product Ash Storage - wetting ash on transfer to trailer
- Baghouse - general clean-up
- Outlet Cooler - cold block flushing

TABLE 3-17 COMPRESSED AIR SUPPLY SYSTEM SPECIFICATIONS	
Manufacturer	Ingersoll-Rand
Compressor Type	Rotary Screw
Model Number	EP-100 SSR
Design Pressure	125 psig
Design Inlet Temperature	95°F
Outlet Temperature (60°F ambient basis	75°F
Dryer Manufacturer	Hankison
Dryer Model Number	DH-60
Dryer Type	Heatless regenerative
Dryer Capacity	60 CFM
Filter Manufacturer	Hankison
Air Filter Model Number	A-100
Air Filter Capacity	100 CFM @100 psig
Oil Removal Filter Model Number	C-100
Oil Removal Filter Capacity	100 CFM @100 psig
Receiver Tank Manufacturer	Roy E. Hanson, Jr.
Instrument Air Receiver Capacity	400 gal
Instrument Air Receiver Size	36" x 98"
Service Air Receiver Capacity	80 gal
Service Air Receiver Size	20" x 63"

3.1.5 Instrumentation and Data Acquisition

The primary instrumentation used to continuously monitor the flue gas characteristics required for emission control calculations are provided in Table 3-18. Table 3-19 summarizes the specifications of the continuous process monitors including the manufacturer, model number, and instrument range.

TABLE 3-18 GASEOUS STREAM CONTINUOUS MONITORING LOCATIONS (TAG ID NUMBERS)

LOCATION	SO_2	NO_x	O_2	OPACITY/ PARTICULATES	TEMP.	PRESSURE	FLOW
SLIPSTREAM LOCATIONS							
System Inlet	A-100	A-100	A-100	-	T-100	P-100	F-100
Burner Outlet	-	-	-	-	T-101	-	-
Baghouse Inlet[a]	A-101	A-101	A-101	-	T-102	P-101	F-101
Baghouse Module Outlets[b]	-	-	-	O-80x	T-x06	-	-
Baghouse Outlet	A-102	A-102	A-102	-	T-109	PD-006	-
Outlet-Cooler Outlet	-	-	-	O-800	T-105	-	-
SIDESTREAM INLETS							
Sorbent Injection[c]	-	-	-	-	T-115,6,7	-	-
Ammonia Injection	-	-	-	-	-	-	F-401
Outlet-Cooler Air Inlet	-	-	-	-	T-108	-	-

[a] Inlet-cooler outlet

[b] Six baghouse modules ('x' – No. 1 to 6)

[c] Five alternate locations

Sensors: A–Analysis, O–Opacity, T–Temperature, P–Pressure, PD–Pressure Difference, F–Flow

TABLE 3-19 GASEOUS STREAM CONTINUOUS MONITORING SPECIFICATIONS

Gas Analyzer	Sensors	Instr. Range	Sensitivity	Manufacturer	Model No.
SO_2	A-100,101,102	0 - 5000 ppm	±50 ppm	Anarad	AR-440
NO_x	A-100,101,102	0 - 1000 ppm	±10 ppm	Thermo Envir.	10A/R
O_2	A-100,101,102	0 - 10%	±0.05%	Teledyne	326RAX
Opacity	O-800 to 806	0 - 100%	±2%	Enviroplan	CEMOP-281
Temperature	T-108,109	0 - 2500°F	±4.0°F	RAM Sensors	250-K-304-I-18"-0-1K(CI-4)
"	T-100	0 - 2500°F	±4.0°F	RAM Sensors	250-K-304-I-26"-0-1K(CI-4)
"	T-115,116,117	0 - 2500°F	±4.0°F	RAM Sensors	250-K-304-I-34"-0-1K(CI-4)
"	T-101,102,105	0 - 2500°F	±4.0°F	RAM Sensors	CI-1TB-200/TB-2521
"	T-x06	0 - 2500°F	±4.0°F	Gordon/Marlin	
Pressure	P-100	-13 to -5" H_2O	±0.25% span	Rosemount	1151DP3E12B1
"	P-101	-21 to -0" H_2O	±0.50% span	Rosemount	1151DP3E12B1
Pres. Diff.	PD-006	0 - 20" H_2O	±1" H_2O	Dwyer	2020
Flue Flow	F-100,101	0 - 11,4730 scfm	±2%	Rosemount	1151DP3E12B1
NH_3 Injection	F-401	0 - 125 ft^3/hr	±1%	Hoffer	HO1/2X1/4-30-B-1MC3PA-MS

'x' - No. 1 to 6 baghouse modules (filters)

Flue Gas Sampling System

The flue gas analyzer system consisted of three independent subsystems to continuously monitor and record the SO_2, NO_x, and O_2 concentrations in the flue gas at the system inlet, baghouse inlet, and baghouse outlet. The analyzer outputs were downloaded to the Net-90 for indication, calculation of the removal efficiencies and control of the ammonia and sorbent injection systems. The major components of each subsystem included an extractive sampling probe, heated sample line, thermoelectric chiller, the SO_2, NO_x and O_2 analyzers, and a chart recorder. The components of the gas sampling system are detailed in Table 3-20.

TABLE 3-20 FLUE GAS SAMPLING SYSTEM

Components of Each System (3)	Anarad SO_2 Analyzer Teco NO_x Analyzer Teledyne O_2 Analyzer Chessel Chart Recorder Fluke Digital Volt Meter Baker Thermoelectric Chiller Dryer Cabinet Enclosure Sample Pump Sample Probe Heated Sample Line Calibration Gas
Design Criteria	
Flow	3-4 liters/min
Temperature	120-200°F
Pressure	3-12 "H_2O

The sampling probe spanned across the 36" or 40" flue work to obtain a representative flue gas sample. The flue gas passed through a 20" ceramic frit designed to filter out particulate. To maintain the sample temperature above the acid deepened, the flue gas passed through a length of heated sample line which connected the probe to the gas conditioner (chiller). The chiller condensed water from the flue gas to protect the analyzers. The dry gas passed from the conditioner to a manifold which routed the sample gas to each of the three analyzers. The extractive sampling system is illustrated in Figure 3-3. The analyzers continually monitored the flue gas composition, unless calibration was in process. Frequent calibrations (at least twice daily) ensured the integrity of the flue gas composition data.

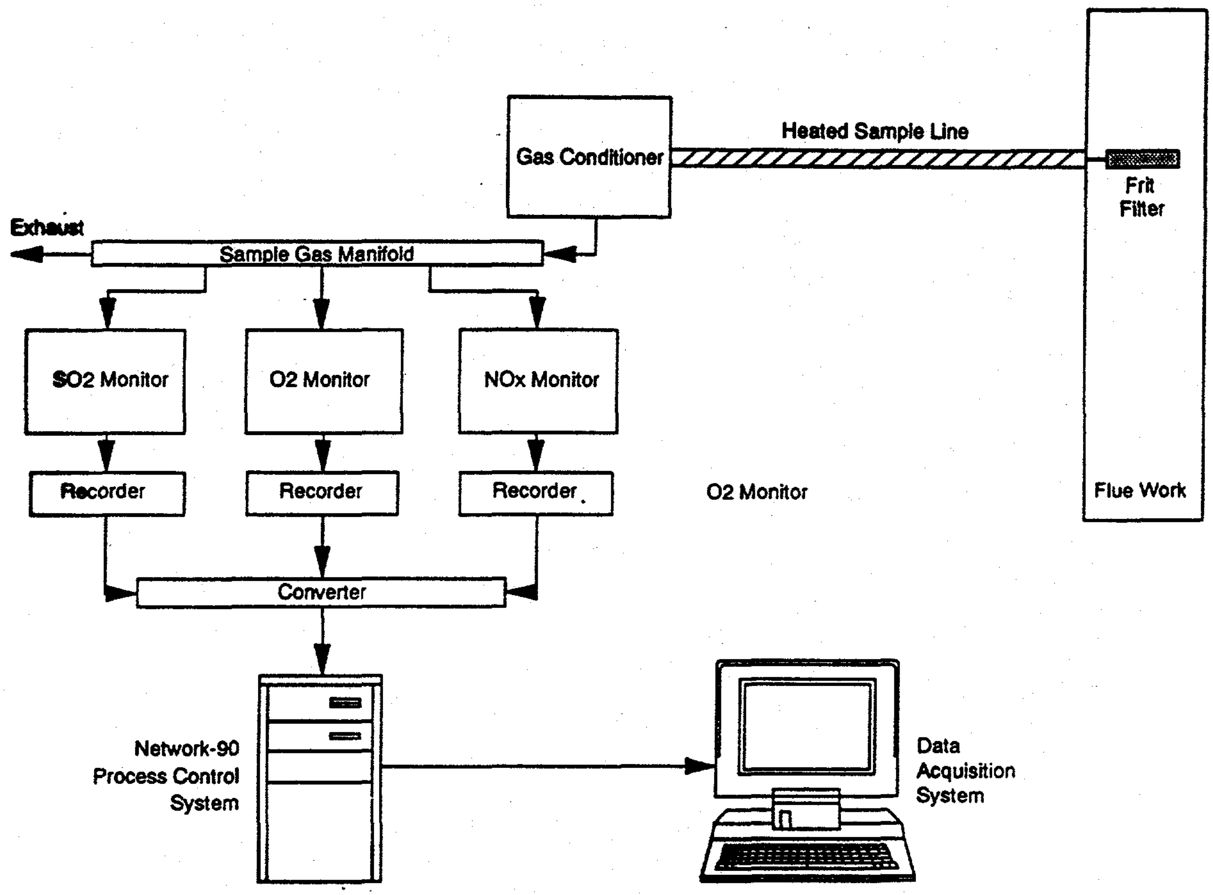


FIGURE 3-3 FLUE GAS SAMPLING SYSTEMS

Data Acquisition System

The Microsoft Windows based data acquisition system (DAS) consisted of the following hardware:

Gateway 2000 486/50DX2 personal computer, 8 MB memory
ATI Graphics Ultra Card
IEEE-488 interface card
NEC MultiSync 4FG Monitor

The DAS was developed by B&W in-house specifically for the SNRB™ field demonstration. SNRB™ operating variables that were continually monitored by the Network-90 control system were transferred to and recorded by the DAS. The DAS output was used to monitor process performance. The emissions control efficiencies were calculated and stored by the DAS. The DAS pathways are illustrated in Figure 3-4. Operation of the DAS is detailed in Section 3.2.3.

3.2 FACILITY START-UP/MODIFICATIONS

Once the construction work was completed, start-up activities formally began on October 2, 1991. Start-up activity at the 5-MWe SNRB™ demonstration was organized into three stages: installation checkout, start-up of individual system packages, and shakedown testing. Planned start-up activities are detailed in the SNRB™ Demonstration Start-Up Plan.[22] Figure 3-5 compares the actual start-up schedule with the projected start-up schedule.

The main contribution to the delay in completion of the shakedown testing was the initial improper fit between the high-temperature bags and the manufactured bag retainers. Bag life and performance are sensitive to the bag fit or "pinch". Remanufacturing of the relatively less expensive bag retainers was selected as the lower cost and most expedient option for reducing the potential for premature filter bag failures.

A complete activity log of the demonstration start-up modifications and routine maintenance are provided in Appendix B. No critical component failures occurred during facility start-up or operation. The facility start-up procedure is also summarized in Appendix B.

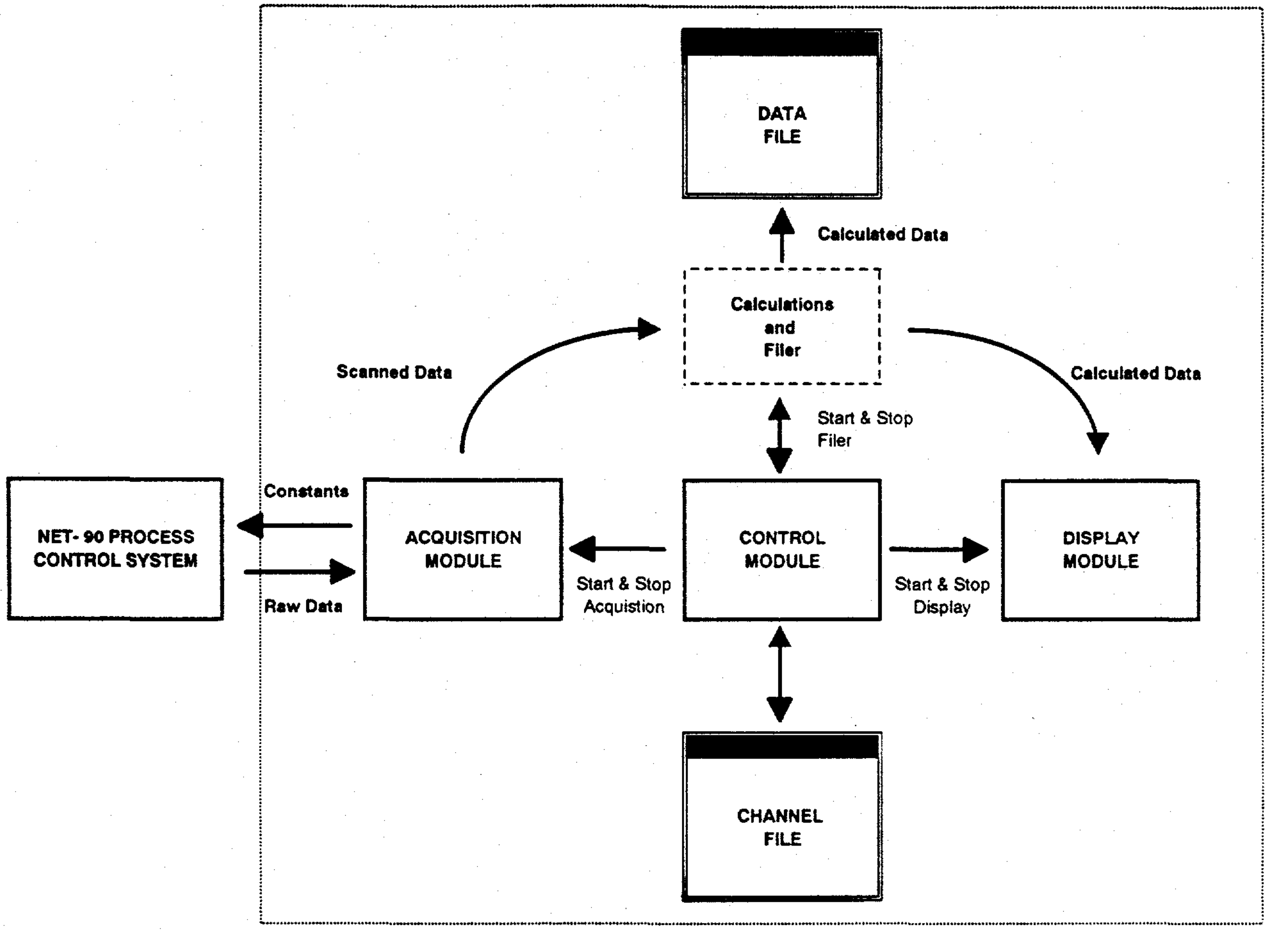


FIGURE 3-4 SNRB™ DATA ACQUISITION SYSTEMS

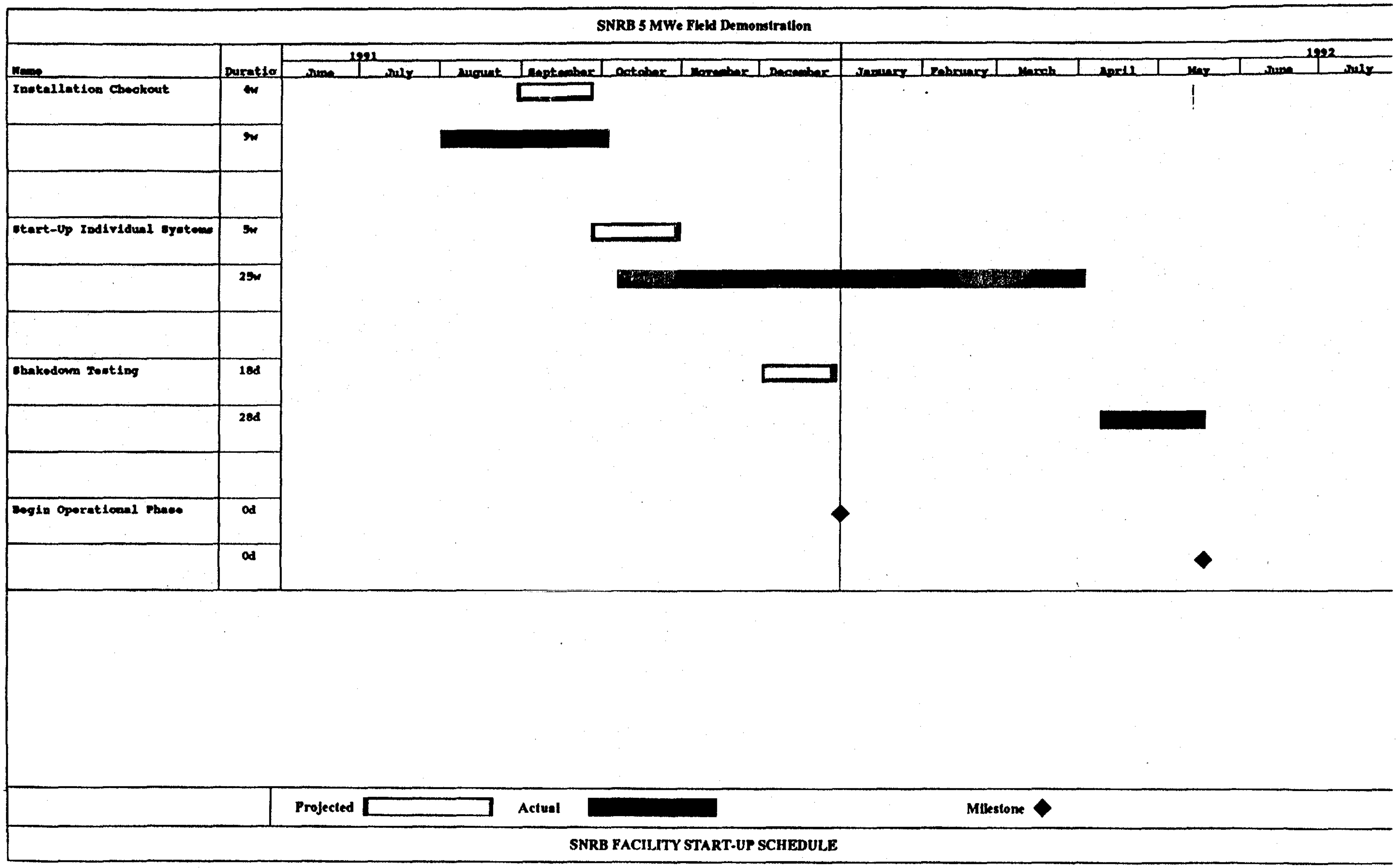


FIGURE 3-5 COMPARISON PROJECTED AND ACTUAL START-UP SCHEDULES

3.2.1 Mechanical and Electrical Checkout

The installation checkout phase was intended to verify the proper mechanical and electrical installation of all equipment, instrumentation and the process control system. Few installation errors were detected during the installation checkout. The only major piece of equipment that required replacement was a defective Siemmens electrical breaker panel which the vendor replaced free of charge. Other minor equipment replacements included a throat heater on one of the baghouse modules.

3.2.2 Start-Up of Individual Systems

The start-up modifications and adjustments are summarized for each system. Only the modifications on systems required for a commercial application of the technology are discussed. Modifications that were performed during subsequent operation which impacted system performance are also included.

Equipment vendors provided training on site for the baghouse, opacity monitor, sorbent feed system, and the ammonia storage and handling system.

Sorbent Injection System

Three vendor visits were required to bring the sorbent injection system up to B&W standards. Initially, a faulty circuit board in the weigh feeder control system was replaced. In order to meet the design capacity of 800 lb/hour of hydrated lime, the existing 2" diameter screw was replaced with a 3" screw. This was necessary since the actual hydrated lime density of 23 lb/ft^3 was less than the design value of 30 lb/ft^3. The major obstacle to meeting sorbent flow within ± 5% was back pressure from the air transport line preventing the sorbent from freely feeding into the transport line. This was remedied by rerouting the back pressure to the atmosphere through the installation of a blower and additional vent lines. Lastly, the original 18" cartridge filter which served to prevent fugitive sorbent emissions was replaced with a larger unit.

Ammonia Injection System

The initial start-up challenge in delivering anhydrous ammonia to the SNRB™ facility was the reduction of the substantial pressure drop in the transport line. The pressure drop was reduced by increasing the transport line diameter from 1.5" to 3" and replacing a 1.5" globe valve with a 3" ball valve. Replacement of an in-line internal static mixer with a straight section further reduced the transport line pressure drop after the existing line length to the injection point was determined to be sufficient for thorough mixing of the air and ammonia. A larger diameter sheave was installed on the dilution air blower to improve the dilution air flowrate.

SNRB™ Ash Transport System

In order to maintain free flowing SNRB™ solids byproduct from the baghouse hoppers, the ash transport system required modification. The SNRB™ product passed through a slide gate from the hopper into the NUVA feeder and pressurized air was used to transport the hot ash product to a storage silo. The hot ash product had a tendency to bridge over in the hopper and agglomerate. The remedy included increasing the time the slide gate remained open and adding air lances to the pressurized NUVA feeder to quickly breakup any product bridging without requiring system shutdown. Adjustments to the baghouse cleaning cycle logic alleviated the operating difficulty by reducing the volume of ash handled during each cleaning.

Baghouse

To further reduce the potential for SNRB™ product to build up in the baghouse compartment hoppers after cleaning the filter bags, one of the baffles used to distribute the flue gas flow uniformly was removed. The baffle was positioned too close to the baghouse wall providing a site for solids to accumulate.

Thermocouples were installed into the center of the baghouse hoppers for monitoring the solids temperature during the bag cleaning cycle. These temperatures were used to identify plugged hoppers.

Flue Gas Sampling System

The flue gas sampling system comprised three SO_2 analyzers, three NO_x chemiluminescence analyzers and three oxygen analyzers used to monitor the flue gas at three locations in the SNRB™ facility. Prior to shakedown testing, two of the SO_2 analyzers and one NO_x analyzer were malfunctioning and required servicing by the manufacturer. The flue gas was analyzed on a dry basis. The chillers used to condense water from the gas samples were found to be undersized and were backed up by iced impinger bottles to prevent water from fouling the analyzers.

Compressed Air System

A malfunctioning circuit board was replaced and the internal thermostat settings were adjusted to keep the condensate discharge line from freezing during cold weather operation. This prevented the blocked condensate line from shutting down the compressor.

3.2.3 Shakedown Testing

High-Temperature Baghouse Evaluation

Shakedown testing, denoted by installation of the high-temperature fabric bags and SCR catalyst, was postponed by the remanufacturing of the original bag retainers. Major activities during shakedown testing included:

- Ensuring that all subsystems functioned as expected and that design flow/capabilities could be attained.
- Establishment of the Net-90 process control responsiveness and fine-tuning the control parameters.
- Calibration of the sorbent loss-of-weight feeder, sorbent and ammonia transport air flows, and the flue gas analysis equipment.
- Verification of the operation and output of the data acquisition system.
- Operator training
- *Documentation of operating procedures.*

The majority of the shakedown testing centered on preparation of the high-temperature baghouse for operation. Installation of the filter bags and catalyst assemblies commenced on February 12, 1992 and the initial passage of flue gas to the baghouse was on April 9, 1992. The shakedown testing was completed on May 17, 1992. The catalyst assemblies were installed in each baghouse compartment following installation of the filter bags. The catalyst was temporarily removed later in the test program enabling baghouse pressure drop measurements without the catalyst.

Bag installation and removal was efficient and was not constrained by the bag length. A pulley was used to maneuver the bag over the tubesheet. The major concern during bag installation and removal was to avoid directing the bag towards the tubesheet at an angle. This would have resulted in contact and possible damage to other bags already suspended from the tubesheet. Damage to the bag in the process of installation was minimized by wrapping the circumference of the sharp tubesheet opening with nalgene tubing.

The primary focus of the shakedown testing was verification of the fabric filter bag installation through a series of leak check procedures as summarized in Table 3-21. Potential sources of leakage were around improperly sealed tubesheet gaskets between the bag retainer and the tubesheet and bags that had been damaged during installation. The majority of baghouse maintenance performed to achieve low particulate emissions consisted of simple gasket replacement. Of the 252 original tubesheet gaskets, 47 gaskets or 18.6% were replaced. These replacements are classified as arising from installation problems rather than operational failure. During the same period 14 Nextel bags (5.6%) were replaced due to damage during installation. For comparison, only 5 Nextel™ bags (2.0%) and 19 tubesheet gaskets required replacement over the entire remaining period of operation.

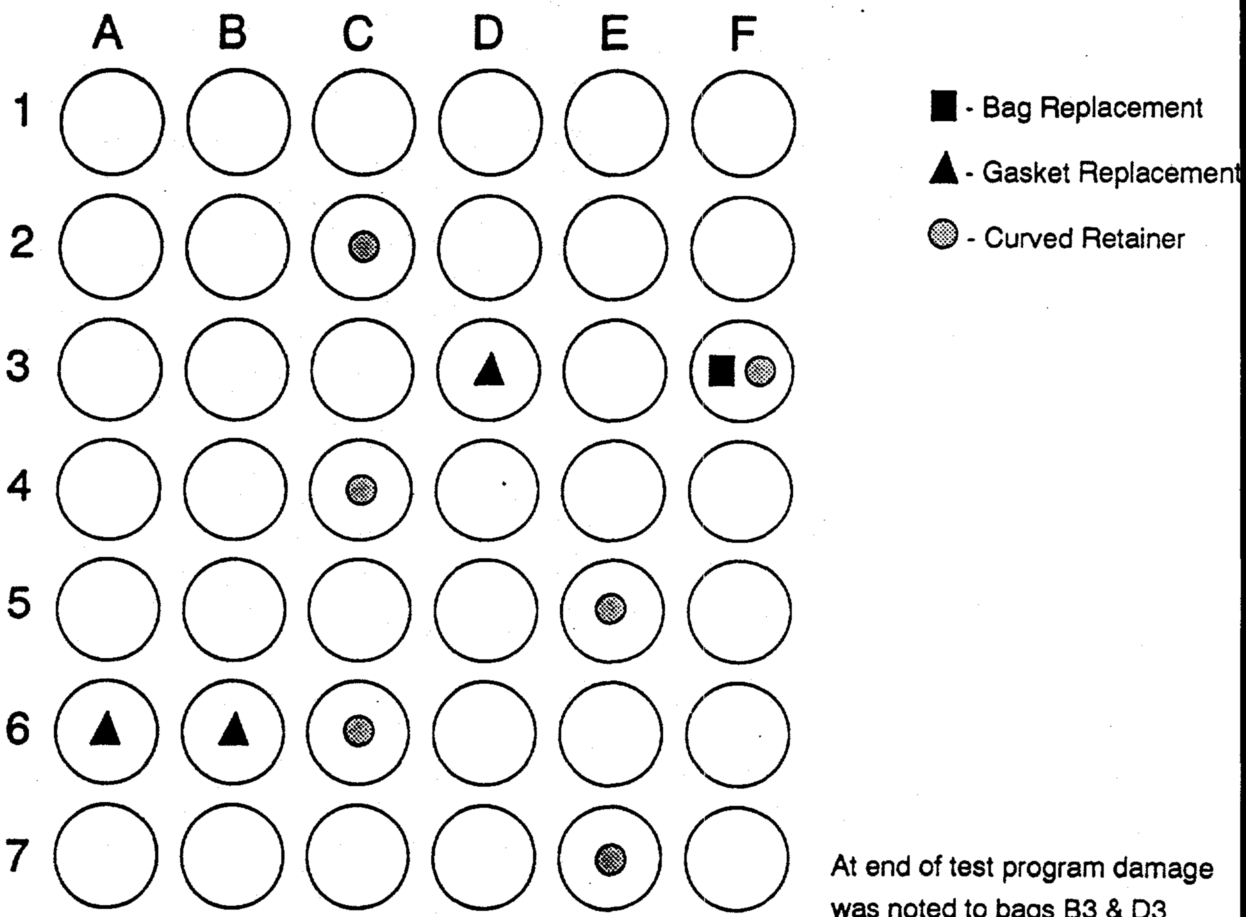
The first method of detecting bag and gasket failures was through cold injection of a fluorescent tracing compound into the compartments followed by visual inspection of the individual compartment tubesheets. As this was time consuming, hydrated lime was injected into the cold compartments and the changes in opacity were monitored as individual compartments were brought in and out of service. This helped to more quickly pinpoint which compartments contained leaks.

TABLE 3-21 BAGHOUSE LEAK CHECKING SEQUENCE
Bag/Catalyst Installation
Pre-coat Bags with Nuetralite
Cold Leak Check Compartments with Fluorescent Compound
Leak Check Compartments with Lime Injection and Opacity Monitor
Cure Catalyst Gasketting Material
Hot Leak Check Compartments On-Line with EPA M5 Sample Train
Cold Leak Check of Compartments with Black Cloths
Investigation of Baghouse Bypass Damper

The final test of the bag and gasket installation was demonstration of compliance with the New Source Performance Standard (NSPS) of 0.03 lb/million Btu. This required operating the baghouse at elevated temperature. The initial heat up of the baghouse was conducted gradually at 100°F/hour to assure even expansion of the catalyst gasketting material. Emission sampling conducted at the baghouse outlet with an EPA Method 5 (M5) sampling train revealed a high particulate emission rate. To verify the source of particulate bypass, black cloths were adhered above the individual tubesheets and hydrated lime was injected into the cold baghouse. This method revealed a few gaskets that were faulty, but could not substantiate the high particulate loading measured by the M5 train. Additional M5 tests verified the initial results. Investigation of the baghouse bypass damper revealed that the backing plate was missing which prevented a tight seal of the flue gas bypass damper. Method 5 tests after installation of a new backing plate demonstrated NSPS compliance.

Once the source of particulate emissions was resolved, a series of short-term performance tests were conducted at elevated SNRB™ operating temperature to measure baseline NO_x and SO_x removal in the absence of ammonia and sorbent injection. Baseline removals are discussed in Section 4.0. Air infiltration into the baghouse was quantified.

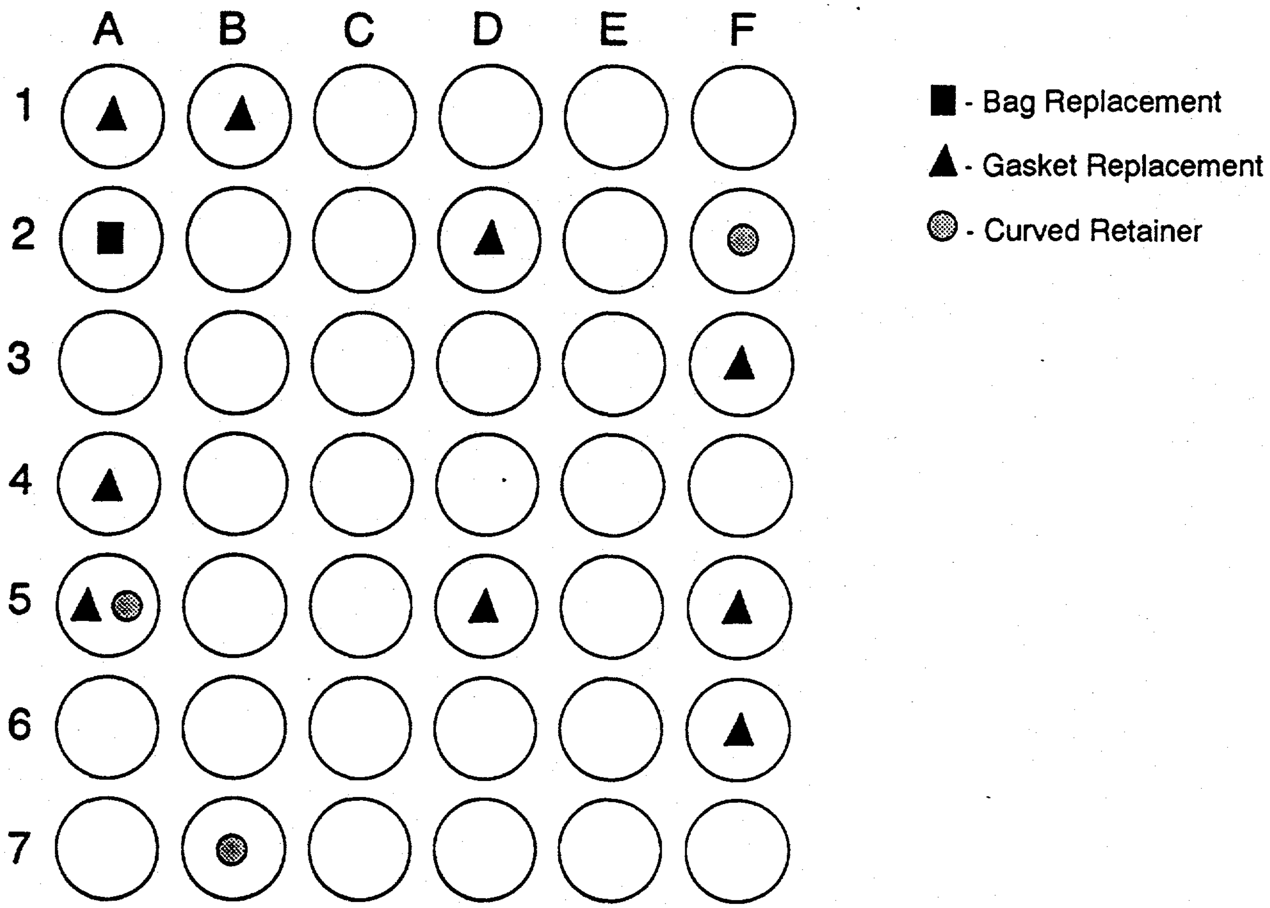
Figures 3-6 through 3-11 detail all of the compartment modifications such as bag and gasket replacement and curved retainer replacement that occurred throughout the entire test period. The majority of the bag and gasket replacement activity was concentrated in the facility shakedown period. Following several hundred hours of high-temperature operation, an inspection revealed that several of the spiral wound perforated bag retainers supporting the Nextel™ fabric filters had begun to curve. Due to the tight spacing between the bags, a few of the curved retainers had rubbed and damaged adjacent bags. The deformation was likely in response to thermal effects during frequent shutdown and start-ups of the baghouse. In order to minimize exposure time at the acid deepened during start-up, the baghouse was brought on-line with fairly high-temperature (>450°F) flue gas. Retainers were replaced as necessary to avoid premature bag failure resulting from the filter bags abrading against each other. The midpoint installation of the S2-Glass bags into compartment 3 provided an opportunity to replace the curved retainers in the other compartments. The Nextel™ bags/retainer assemblies removed from compartment 3 were used as substitutes for the curved bag assemblies. Approximately 30 retainers (11.9%) were affected and replaced midway through the test program.



At end of test program damage
was noted to bags B3 & D3

Bag F3 installed prior to air toxic test

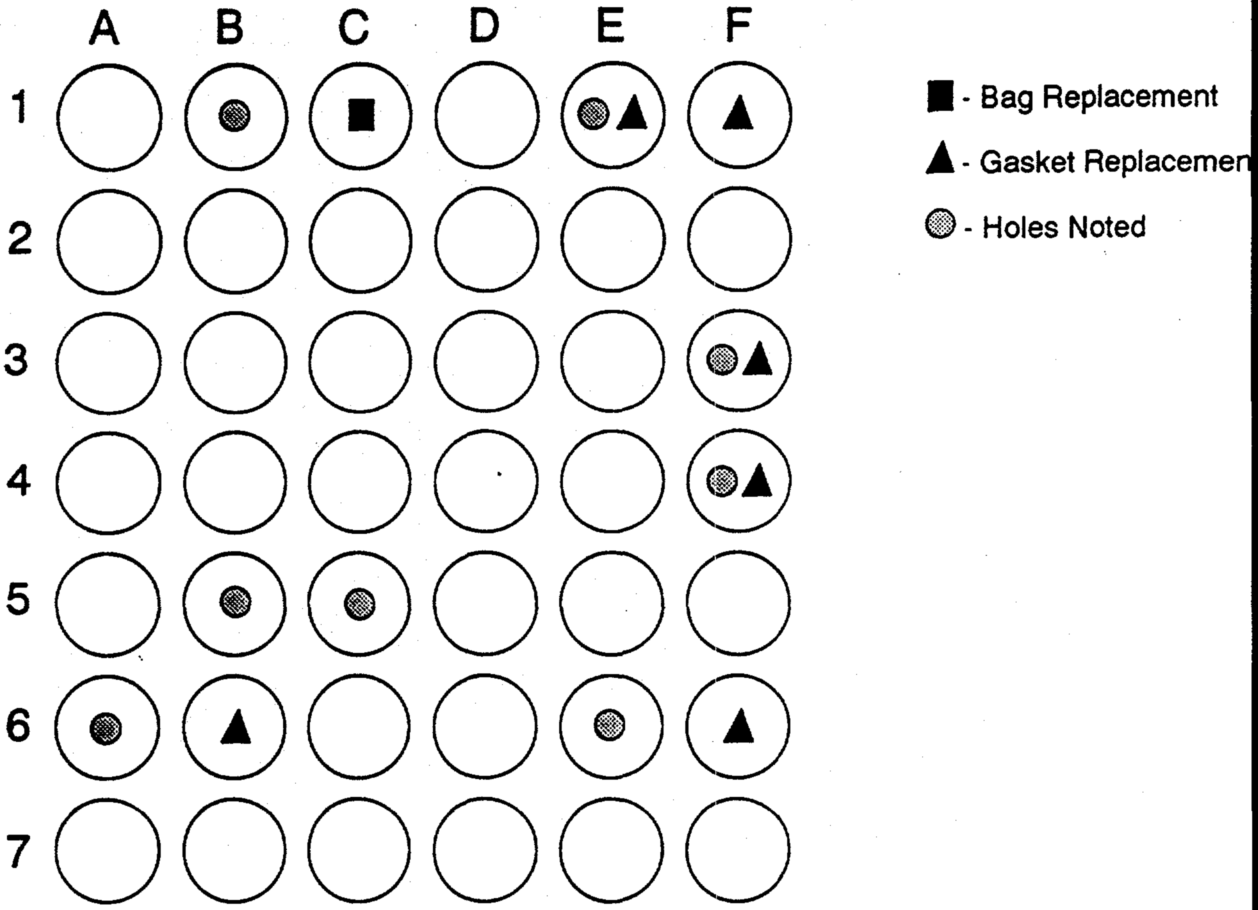
FIGURE 3-6 SNRB™ COMPARTMENT #1 MODIFICATIONS



	A	B	C	D	E	F
1	▲	▲				
2	■			▲		●
3						▲
4	▲					
5	▲ ●			▲		▲
6						▲
7		●				

■ - Bag Replacement
▲ - Gasket Replacement
● - Curved Retainer

FIGURE 3-7 SNRB™ COMPARTMENT #2 MODIFICATIONS



3M Nextel bags removed from Module 3 in Sept 199
and replaced with Owens Corning S2-Glass bags.

FIGURE 3-8 SNRB™ COMPARTMENT #3 MODIFICATIONS

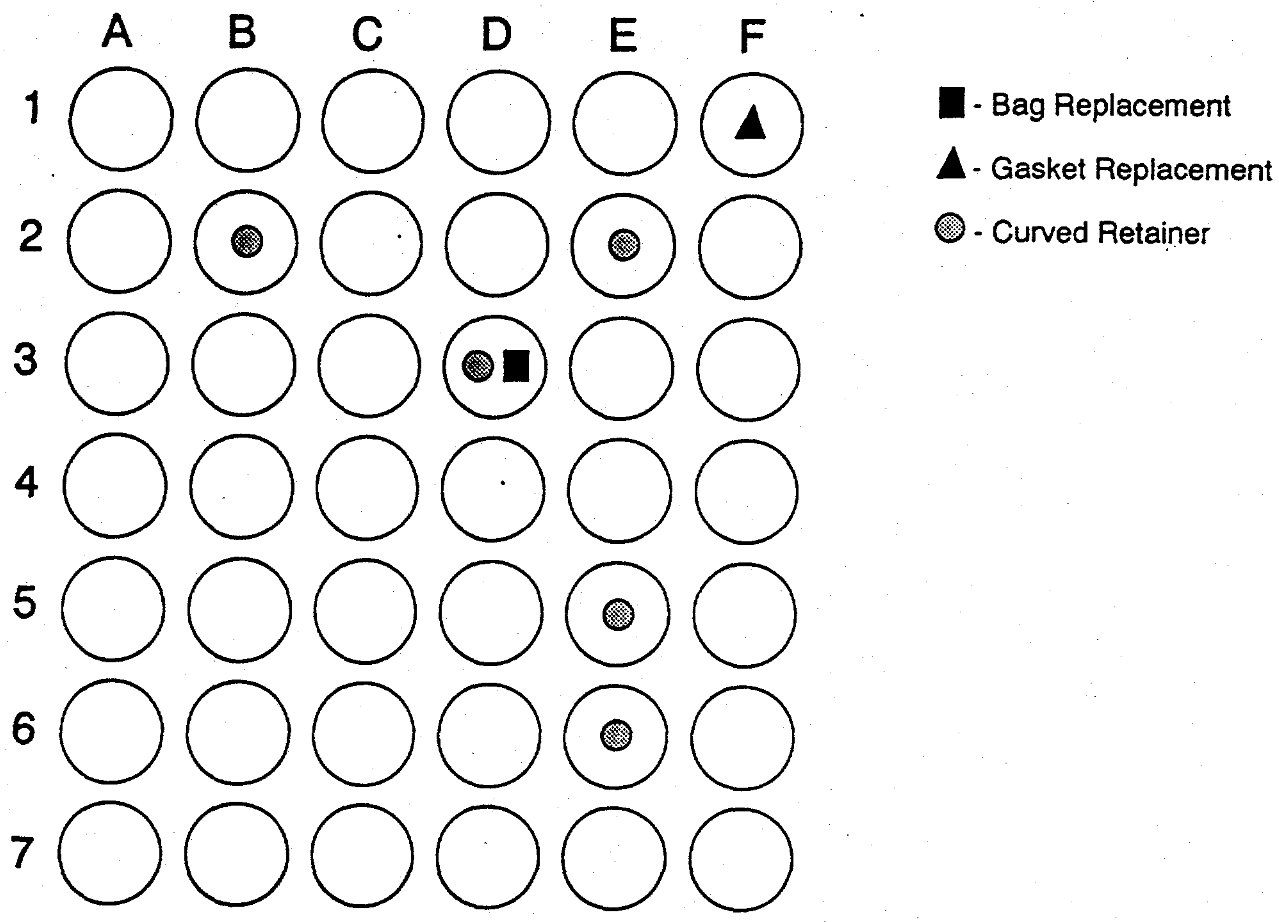


FIGURE 3-9 SNRB™ COMPARTMENT #4 MODIFICATIONS

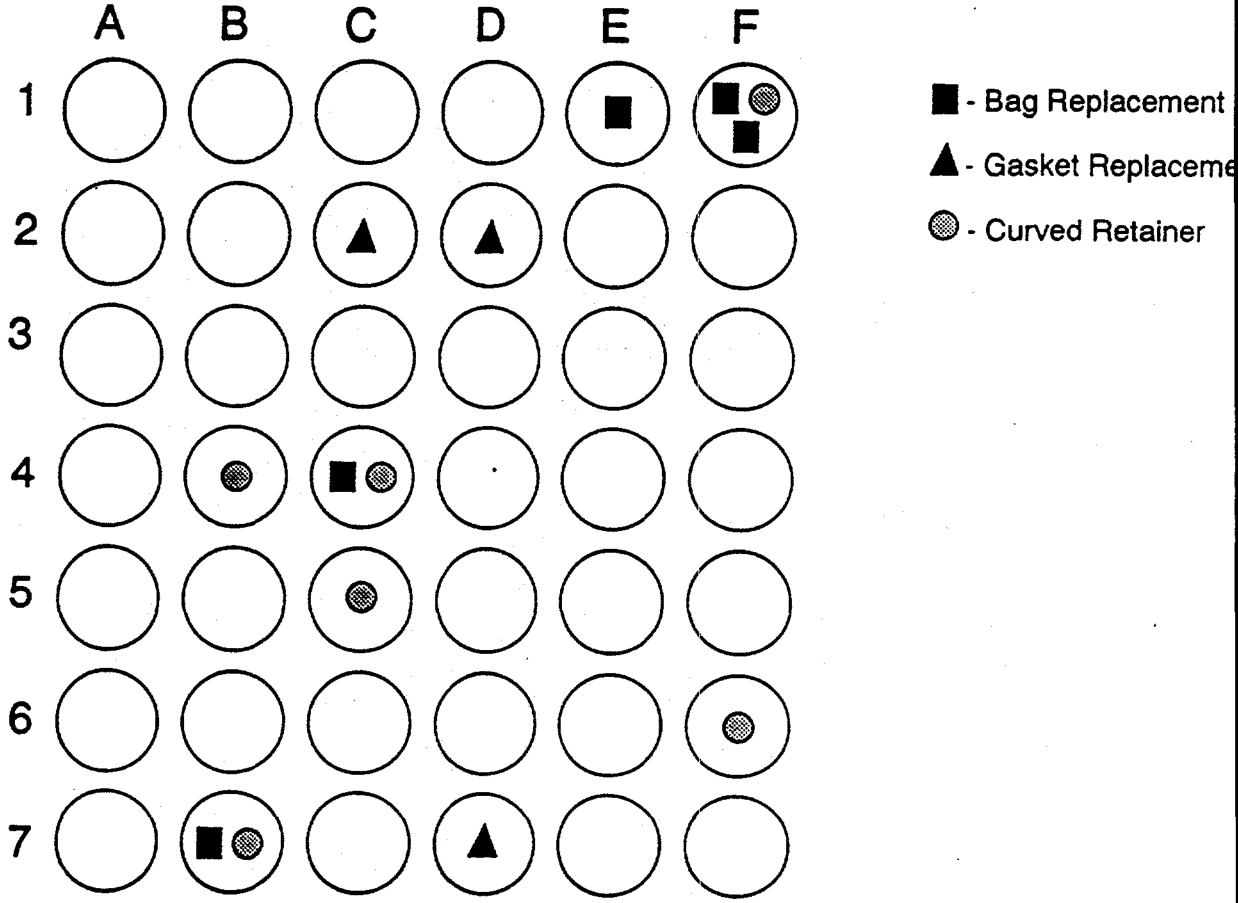
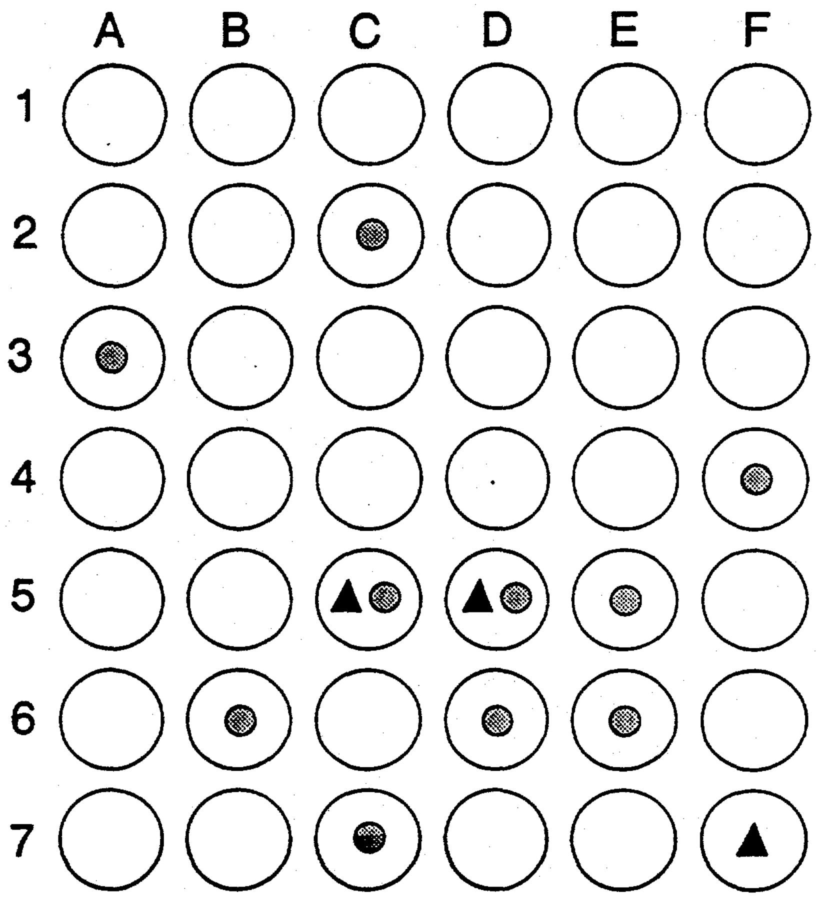


FIGURE 3-10 SNRB™ COMPARTMENT #5 MODIFICATIONS



■ - Bag Replacement

▲ - Gasket Replacement

● - Curved Retainer

At end of test program damage was noted to bags D5 & E7
Four of the bags removed with the curved retainers were damaged.

FIGURE 3-11 SNRB™ COMPARTMENT #6 MODIFICATIONS

Instrumentation Calibration

Flue gas analyzer calibration procedures and documentation were developed during shakedown testing. Calibrations were performed with certified calibration gas traceable to the National Institute of Standards and Technology (NIST). Instrument calibration was performed by using zero and span calibration gases and measuring instrument drift on a regular basis. The integrity of the heated sample lines and sample pumps delivering the flue gas to the analyzers were confirmed by passing calibration gas through the line to recently calibrated instruments. This was performed periodically during the operation of the facility. Other items calibrated in preparation for testing are listed in Table 3-22. Good practice methods developed during start-up were carried on throughout the test phase.

TABLE 3-22 INSTRUMENTATION CALIBRATION

Sorbent Loss-of-Weight Feeder	Pressure Transmitters
Laboratory Balances	Digital Multimeters
Sorbent Air Transport Flows (Orifices)	Chart Recorders
Ammonia Flowrate (Pitot Tube)	Triboflow Dust Emission Monitors
Bailey Net-90 Control System	Baghouse Hopper Level Indicators
System and Baghouse Inlet Flow Venturis	Opacity Monitor
Ammonia Turbine Flow Meter	

Data Acquisition System

During shakedown, the wiring between the Net-90 process control system, the remote instrumentation and the DAS was checked. The DAS was checked out for operability and ability to monitor data. The performance calculations executed by the DAS were hand checked for accuracy. The DAS system designer provided training to potential operators during the start-up period. The reliability of the DAS was tested by unattended overnight operation. On several occasions the system failed. The system failure was traced to a surge in the power supply and was remedied by adding a power protector. In August 1992, the original 286 (12 megahertz) computer was updated to a 486 (50 megahertz) computer to enhance data acquisition capabilities. The computer upgrade enabled rapid acquisition and storage of SNRB^{TM} parameters for longer periods of operation.

3.2.4 Sampling Procedures

The procedures for sampling the various process streams were developed during Shakedown testing. To assure the representativeness of the samples, the samples were collected during stable, well-defined plant and facility operation. Representative samples of the following solid streams were required for data analysis purposes:

Coal feed to Ohio Edison Boiler No. 8
Baghouse inlet and outlet particulate
SNRB^{TM} baghouse product
Fresh sorbent feed

Weekly coal samples were obtained by Ohio Edison personnel from each of the coal pulverizers feeding Boiler No. 8. The coal samples were collected in vacuum packed plastic bags. Baghouse inlet and outlet particulate samples were collected with the EPA M5 sampling train. Table 3-23 specifies the solid sampling schedule developed for the demonstration program in addition to the method of chemical analysis. A comprehensive list of the chemical analysis methods used during the demonstration program is included in Appendix C.

Existing SNRB^{TM} facility equipment was modified to provide "on-line" sampling capabilities. On-line sampling was preferred as the resulting sample could be traced to an exact operating time and hence, operating conditions. The bin which supplied sorbent to the air transport line was modified for sampling purposes. An access port with a ball valve was added to enable sorbent sampling during operation. Access ports/valve assemblies were welded to each of the NUVA feeders enabling SNRB^{TM} byproduct sampling while emptying the baghouse hoppers.

SNRB^{TM} sorbents were collected in pre-cleaned nalgene bottles. The baghouse products, typically at temperatures exceeding 700°F, were collected in pre-cleaned glass containers. All containers were filled as full as possible and tightly sealed to minimize sample contact with air. The sample containers were labelled and documented at the time of collection.

TABLE 3-23 - SOLID STREAM GRAB SAMPLING SCHEDULE

ANALYSIS	FREQUENCY	METHOD
Baghouse By-Product		
Waste Quantity	Every Disposal	Shipment Weight
Ca, Na, Mg, K, S, Al, Si, Fe, Ti	Each Sorbent Type	Inductively Coupled Plasma
SO_3^- , SO_4^-	Each Sorbent Type	Wet Chemistry
TCLP Metals: Ar, Ba, Cd, Cr, Pb, Hg, Se, Ag	First Disposal & Quarterly	40 C.F.R. 261 App. II
Ignitability	First Disposal	40 C.F.R. 261.21
Corrosivity (pH)	Weekly	40 C.F.R. 261.22
Reactivity	First Disposal	40 C.F.R. 261.23
Fresh Sorbent		
Sorbent Usage	Continuously For each Sorbent Type	Sorbent airlock feeder hopper level indicator L-204
Sorbent Purity	Each Sorbent Type	Wet Chemistry B&W Method 701-777
Particle Size	Each Sorbent Type	Microtrac®
BET Surface Area	Each Sorbent Type	BET

3.3 DEMONSTRATION FACILITY COST SUMMARY

The major components of the slipstream demonstration facility are presented in Table 3-24. The installed costs of the demonstration equipment are summarized in Table 3-25. The inlet and outlet flue gas coolers and flue gas heater (items 5, 6 and 7) were an integral part of the demonstration, but would not be included in a commercial plant design. These components permitted evaluation of the process over a broader range of operating conditions than readily available at the host site.

TABLE 3-24 MAJOR EQUIPMENT LIST

MAJOR EQUIPMENT ITEM	Number In Use	 Spare	UNIT CAPACITY	DESIGN CHARACTERISTICS	MATERIALS OF CONSTRUCTION	MANUFACTURER
Instrumentation	NA	NA	NA	Continuous monitoring	Various	Various
Electrical Equipment	NA	NA	NA		Various	Various
ID Fan	1	0	56,000 lb/hr flue gas	16,000 ACFM @ 21.9 in WC, 170 F, 67 Hp	A-514 (Wheel)	Zurn Industries
Compressed Air System	1	0	442 ACFM @ 125 psig, 75 F	Air-cooled, rotary screw, 100 Hp, 1775 RPM	Carbon Steel	Ingersoll-Rand
Inlet Gas Cooler	1	0	54,023 lb/hr flue gas	Recuperative plate, 4,019 ft2, -35 to +15 in WC	Carbon/304 SS	North Atlantic Tech
Outlet Gas Cooler	1	0	54,552 lb/hr flue gas	Recuperative plate, 11,716 ft2, -35 to +15 in WC	Carbon/304 SS	North Atlantic Tech
Propane System/Flue Gas Heater	1	0	18,000 gal / 14 million Btu/Hr	Propane tank 41 ftx9 ft dia, 677 lb/hr fuel @ 1 psi	Carbon/304 SS	Plant System/ Eclipse
Reagent Storage/Feed System	1	0	700 lb/hr hydrated lime	Silo 12 ft dia x 42 ft high, 2,350ft3, 23,000 lbs	Carbon Steel	Smoot
Baghouse and Hardware	1	0	29,934 ACFM @ 800 F	Pulse jet cleaning, 6 modules, 7,719 ft2 filter area	Carbon Steel	Amerex
Ammonia Storage/Injection System	1	0	1,000 gal storage, 18 lb/hr NH3	NH3 tank 23 ft x 6 ft dia, air/NH3 dilution @ 19:1	SA-516-GR70	Ferguson Industries
Filter Bags	252	28	30.63 ft2 filter area per bag	6 in dia x 20 ft long, 280 bags	Nextel	3M
Catalyst Assemblies	252	28	NA	280, 25 cpsi monolith catalyst assemblies	NC-300	Norton
Process Control System	1	0	NA	Microprocessor with digital and analog I/O	Various	Bailey Controls
Ash Handling System	1	0	2,340 lb/hr, 1,021 ft3 storage	Silo 10 ft dia x 15 ft high, 16,500 lbs	A-36/Carbon	United Conveyor
Flues, Venturis, Dampers, Exp Joints	NA	NA	NA		Various	NA Refactory/Others
Steel/Platforms/Building	NA	NA	NA		Carbon Steel	EPI Clevaland
Process Piping, Fittings and Valves	NA	NA	NA		Carbon Steel	Various

Note : Equipment specifications are detailed in the Certified Design Review Package

TABLE 3-25 MAJOR EQUIPMENT COSTS

ITEM #	MAJOR EQUIPMENT ITEM	F.O.B. COST/UNIT	SALES TAX/UNIT	FREIGHT COST/UNIT	INSTALLATION COST/UNIT	TOTAL COST/UNIT	NUMBER OF UNITS	TOTAL COST	YEAR
1	Instrumentation	$163,787	$0	$0	$21,458	$185,245	Lot	$185,245	1991
2	Electrical Equipment	$50,176	$0	$0	$280,689	$330,865	Lot	$330,865	1991
3	ID Fan	$36,200	$0	$0	$523	$36,723	1	$36,723	1990
4	Compressed Air System	$34,855	$0	$0	$523	$35,378	1	$35,378	1990
5	Inlet Gas Cooler	$109,500	$0	$0	$9,617	$119,117	1	$119,117	1990
6	Outlet Gas Cooler	$207,700	$0	$0	$17,859	$225,559	1	$225,559	1990
7	Propane System/Flue Gas Heater	$122,845	$0	$0	$17,990	$140,835	1	$140,835	1990
8	Reagent Storage/Feed System	$171,917	$0	$0	$17,009	$188,926	1	$188,926	1990
9	Baghouse and Hardware	$428,800	$0	$0	$91,064	$519,864	1	$519,864	1990
10	Ammonia Storage/Injection System	$69,892	$0	$0	$4,514	$74,406	1	$74,406	1990
11	Filter Bags	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	280	[redacted]	1991
12	Catalyst Assemblies	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	280	[redacted]	1991
13	Process Control System	$103,300	$0	$0	**	$103,300	1	$103,300	1991
14	Ash Handling System	$198,464	$0	$0	$52,924	$251,388	1	$251,388	1990
15	Flues, Venturis, Dampers, Exp Joints	$280,049	$0	$0	$159,035	$439,084	Lot	$439,084	1991
16	Steel/Platforms/Building	$110,018	$0	$0	$112,456	$222,474	Lot	$222,474	1990
17	Process Piping, Fittings and Valves	$44,278	$0	$0	$181,081	$225,359	Lot	$225,359	1991
		Total Freight		$42,425				$42,425	

* SNRB Project sales tax exemption number 5064 for Air Pollution Control Equipment

** Control system installation included in electrical equipment installation cost

Note: The unit costs of the fiter bags and catalyst are considered proprietary information

The compressed air supply system and the ammonia storage and supply systems were prefabricated, skid mounted units.

The slipstream demonstration facility was operated as a test unit rather than a commercial emissions control facility. Frequent changes of operating conditions to evaluate the impacts of process control variables were common. This method of operation did not provide for quantification of annual operating and maintenance labor and material costs. Typical variable operating costs for the demonstration are summarized in Table 3-26. It should be noted that both the unit costs and usage rates reflect the small quantity, slip stream nature of the demonstration. Note that only one of the three SO_2 sorbents noted in Table 3-26 would be used at any one time. The quantity/hr use rates reflect operation at flue gas conditions typical of the demonstration test program. Propane costs represented approximately 45% of the variable operating costs for the demonstration. Propane fired heating of the flue gas would not be required for a commercial SNRB^{TM} installation.

TABLE 3-26 VARIABLE OPERATING COST SUMMARY

COMMODITY	UNIT	$/UNIT	QUANTITY/HR	COST $/HR
Hydrated Lime	Ton	69.85	0.10	6.98
Alternative Limes	Ton	74.85	0.10	7.45
Sodium Bicarbonate	Ton	268.00	0.50	134.00
Propane*	Gallon	0.425	76.00	32.30
Ammonia	Pound	0.24	5.00	1.20
Waste Disposal	Ton	45.86	0.40	18.34
Total variable operating cost with hydrated lime				58.82
Variable operating cost without propane				26.52

*Required for demonstration only, not for commercial application.

4.0 TECHNICAL PERFORMANCE

4.1 SUMMARY

The primary objectives of the 5-MWe field demonstration were to demonstrate the commercial readiness of the SNRB^{TM} technology, and to develop scale-up procedures necessary for commercial application of the technology. The specific objective of the field demonstration tests was to optimize the SO_x, NO_x and particulate removal efficiencies during extended operation with fully-integrated, commercial-sized components. The performance targets include demonstration of:

- Greater than 70% SO_x removal with a calcium-based sorbent.
- Greater than 90% SO_x removal with a sodium-based sorbent.
- Greater than 90% NO_x removal with minimal ammonia slippage.
- Compliance with the New Source Performance Standards for particulate emissions from coal-fired boilers of 0.03 lb/million Btu

All of the performance targets were met or exceeded during the test program. SO_2 removal efficiencies greater than 80% were consistently achieved with injection of commercially hydrated lime at a cost-effective stoichiometry between 1.8 - 2.0 mol/mol. Injection of alternate calcium-based sorbents resulted in improved SO_2 removal at similar Ca/S stoichiometries and baghouse operating temperatures. Sodium bicarbonate injection attained 85% removal at a normalized Na/S stoichiometry of 1.0 and baghouse temperature of 450°F, corresponding to a sorbent utilization of 85%. Greater than 90% removal was achieved at higher Na/S stoichiometries reduced sorbent utilizations. NO_x removals greater than 90% with ammonia slip less than 5 ppm were realized over a broad range of catalyst temperatures. Particulate emissions downstream of the baghouse were less than 0.03 lb/million Btu. Emissions averaged 0.019 lb/million Btu, corresponding to an average collection efficiency of 99.89%.

This section presents the technical results of the SNRB^{TM} 5-MWe field demonstration. Background pertaining to operation of the facility is discussed in Sections 4.2 - 4.4. SO_x and NO_x emission control are discussed separately in Sections 4.5 and 4.6. Baghouse operation and particulate emission control performance is presented in Section 4.7. Verification of the performance data is provided in Section 4.8 which compares the simultaneous measurements conducted by B&W and an independent testing contractor.

4.2 TEST CHRONOLOGY

The SNRB™ demonstration testing followed the testing guidelines outlined in the Operation and Test Plan issued on January 7, 1992.[23] The Operation and Test Plan provided the rationale behind the selection of the operating parameter ranges investigated over the course of the demonstration program. Test scheduling was designed to promote the progressive acquisition of operating experience towards a final demonstration of the SNRB™ technology at optimized operating conditions. Planned demonstration testing consisted of five phases: Screening Tests, Continuous Tests, Alternate Sorbent Tests, System Response Tests, and Performance Tests. Figure 4-1 compares the proposed and actual test schedules. The difference between the two schedules resides mainly in the remanufacturing of bag retainers which extended the start-up phase by approximately 3 months and a 3 month unscheduled boiler outage later in the program.

The objective of the Screening Tests was to optimize SO_x, NO_x and particulate collection efficiencies with respect to the primary operating conditions that influence SNRB™ process performance: baghouse/catalyst temperature, baghouse air-to-cloth ratio and sorbent injection temperature. Commercial hydrated lime was used as the SO_2 sorbent. Characterization of baghouse performance was emphasized.

The Continuous Tests provided an opportunity to examine the secondary effects of baghouse operating conditions and bag cleaning techniques on SNRB™ system performance. During the Continuous Tests a third party testing company verified the test procedures and methods employed by B&W to characterize SNRB™ process performance.

In the Alternate Sorbent Tests, two enhanced calcium-based sorbents and sodium bicarbonate were evaluated for SO_2 removal. Calcium lignosulfonated lime (CLS) and sugar hydrated lime (SHL) were selected on the basis of bench-scale performance reactor tests conducted at the University of Cincinnati. SO_2 removals and utilizations achievable with CLS and SHL were compared to the base commercial hydrated lime to determine the most cost-effective SO_2 sorbent for commercial applications.

The System Response Tests were conducted to determine the effect of boiler fluctuations on SNRB™ performance and to develop a commercial SNRB™ process control philosophy. The testing tracked actual variations in the host boiler operating load.

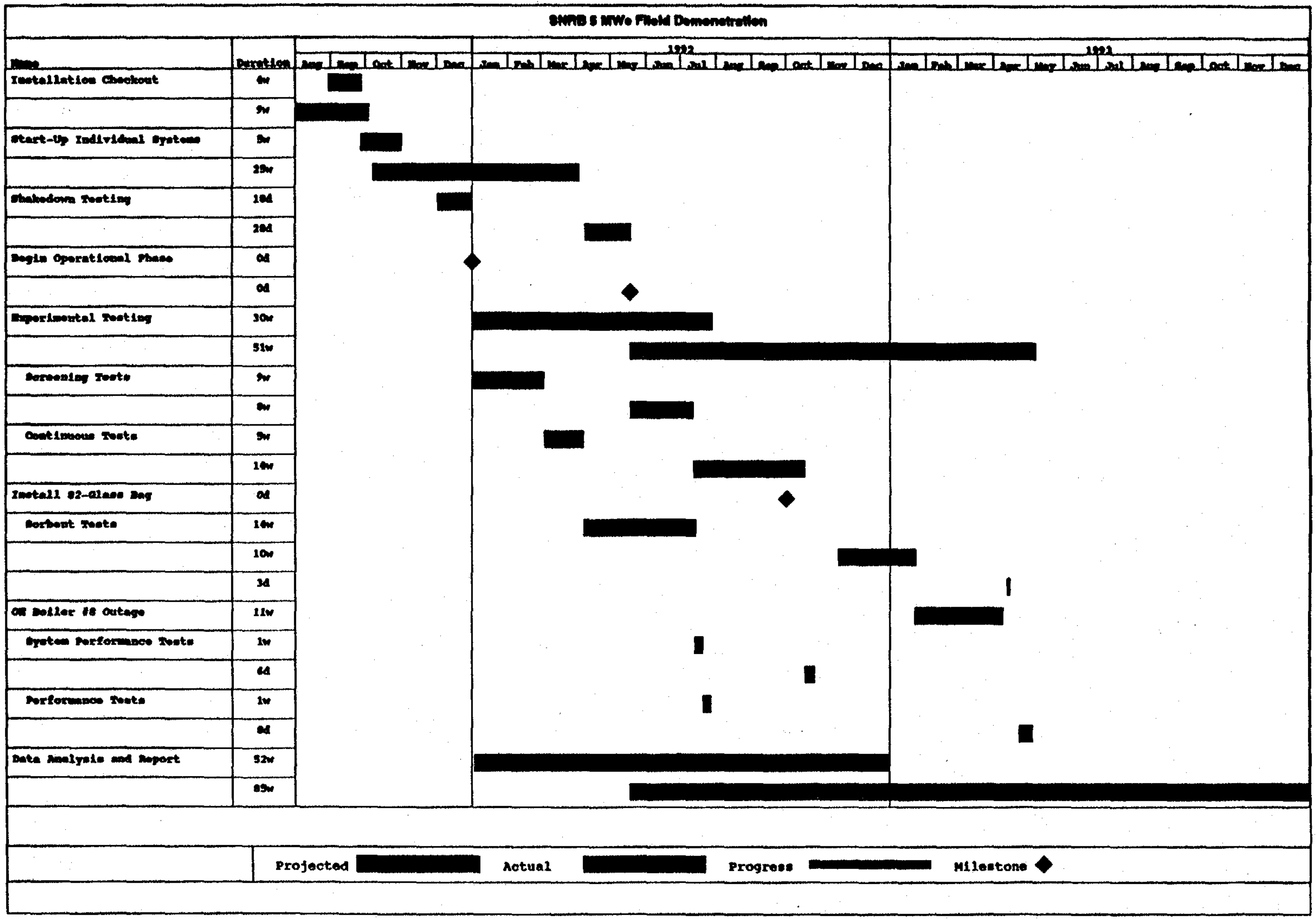


FIGURE 4-1 SNRB FACILITY OPERATION SCHEDULE

Based on the cumulative results of the Screening, Continuous and Alternate Sorbent tests, the SO_2 sorbent and system operating conditions were selected for the Performance Tests. The facility was successfully operated continuously at constant conditions for over 100 hours in the Performance Test.

A few minor tasks outlined in the test plan were not completed. These included cleaning the baghouse compartments off-line and evaluating a wide range of baghouse cleaning air pressures for subtle effects on baghouse operation. The Air Toxics Emissions Testing program conducted during the last week of performance testing was a major addition to the original plan.

The demonstration facility was operated at replicate conditions periodically to measure SNRB^{TM} performance and identify any changes that may indicate possible bag failure, catalyst deactivation, pressure drop creep, or bag blinding with time.

Table 4-1 identifies the ranges of several key SNRB^{TM} process parameters evaluated in the demonstration program.

4.3 FIELD OPERATION

Operation can best be described as semi-continuous. The facility was operated continuously (24 hours/day) for periods of one to two weeks followed by one to two weeks downtime for maintenance, inspections and data reduction. The periods of facility operation are detailed in Figure 4-2. The test plan specified initial half day testing which would have required daily facility start-up and shut-down. Continuous operation was found to be more cost efficient. In addition, the time required to reach steady state conditions exceeded initial estimates. Staffing consisted of two 12-hour shifts with 3 or 4 people/shift. The staff included a test leader, research engineer and at least one technician. Fewer operators would be required to run a commercial operation where the operating conditions would be fairly uniform. The facility processed hot flue gas for approximately 27% of the total demonstration program calendar period.

TABLE 4-1 EVALUATED SNRB$^{\text{TM}}$ PARAMETERS

HYDRATED LIME TESTS	UNITS	RANGE
Ca/S Stoichiometry (based on inlet SO_2)		
Hydrated Lime	[mol/mol]	0.9 - 3.0
Calcium Lignosulfonated Lime	[mol/mol]	1.0 - 5.1
Sugar Hydrated Lime	[mol/mol]	1.0 - 3.0
NH_3/NO_x Stoichiometry (based on inlet NO_x)	[mol/mol]	0.3 - 1.1
Air-to-Cloth Ratio	[ft/min]	2.3 - 5.0
Catalyst Space Velocity	[1/hour]	1900 - 3950
Bag/Catalyst Temperature	[°F]	695 - 900
Sorbent Injection Temperature	[°F]	710 - 1220
Sorbent in Flue Residence Time	[seconds]	0.5 - 4.5
Bag Cleaning Pressure	[psig]	31 - 42
Baghouse Pressure Drop	[" H_2O]	6.0 - 17
Bag Cleaning Cycle	[minutes]	30 - 120
SODIUM BICARBONATE TESTS		
Na_2/S Stoichiometry	[mol/mol]	0.5 - 2.0
Air-to-Cloth Ratio	[ft/min]	2.6 - 3.8
Bag/Catalyst Temperature	[°F]	440 - 850
Sorbent Injection Temperature	[°F]	460 - 1050
Sorbent in Flue Residence Time	[seconds]	0.6 - 3.0

BAG CLEANING ACTIVATION

	DIFFERENTIAL PRESS.	TIME	COMBINATION
On-Line Cleaning	yes	yes	no
Off-Line Cleaning	no	no	no

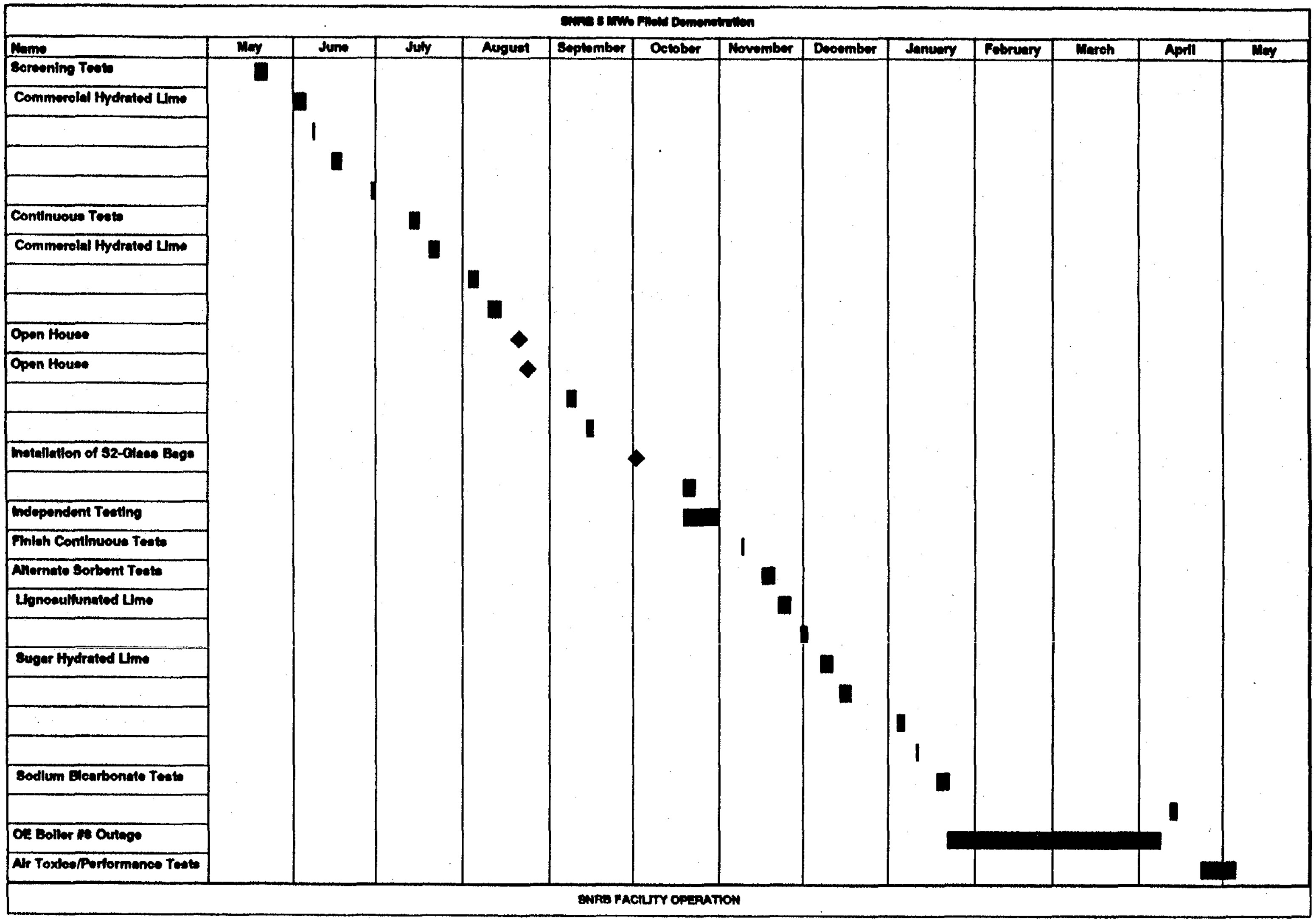


FIGURE 4-2 SNRB™ FACILITY OPERATION

The B&W test crew was supported by the Analytical Chemistry Section at B&W's Alliance Research Center which analyzed samples of fresh sorbent, coal and baghouse product for composition and particle size distribution. Completion of special system maintenance and modifications were handled by general craft labor from B&W Construction. Norton Company and 3M supported the field operation by conducting chemical and physical analysis on the bag fabrics and catalyst removed from the baghouse during inspections, in addition to providing technical advise.

Ohio Edison provided a plant liaison who kept the demonstration project test personnel informed of boiler outages, plant maintenance and other activities that might have affected the operation and performance of the SNRB™ facility.

4.3.1 Emission Sampling

Flue gas was sampled with continuous emission monitors at three locations: the SNRB™ system inlet, the baghouse inlet, and the baghouse outlet. To obtain a representative sample at each location, flue gas passed through a 20 inch long ceramic filter situated in the center of the flue. The flue diameter was 36 inches at the system inlet and 40 inches at both the baghouse inlet and outlet. The frit filters were blown back frequently to remove substances from the frit that could react with the flue gas and lead to incorrect readings. Heated sample lines carried the hot flue gas to a chiller which dropped out the water vapor. To assure that all water was removed from the flue gas, the chillers were backed up by iced impinger bottles. The dry gas then passed through a manifold which routed samples to each analyzer. The flue gas was continuously monitored for SO_2, NO_x, and O_2.

Medium- to high-sulfur coal was burned at the R.E. Burger Plant through out the demonstration program. The coal fired in Boiler No. 8 was from several sources. The general coal characteristics were: 3 - 4% sulfur, 10 to 13% ash, 4 to 8% moisture, and 12,000 Btu/lb on an as-received basis. Coal analyses are provided in Appendix D. The resulting flue gas composition ranged from 2,000 to 3,000 ppm SO_2, 350 to 500 ppm NO_x, and 3.0 to 5.5% O_2. Boiler No. 8 load reduction to base load (150 MWe to 80 MWe) typically decreased the SO_2 and NO_x concentrations by 20% or approximately 450 ppm SO_2 and 95 ppm NO_x. The O_2 concentration usually increased by 45% at the reduced load.

4.3.2 System Responsiveness

Net-90 controllers (burner temperature control, system flue gas flow, inlet cooler temperature, Ca/S stoichiometry, NH_3/NO_x stoichiometry, outlet cooler temperature, outlet cooler cooling air recirculation) were fine tuned for quick response to load fluctuations or intended setpoint changes. Control of the NH_3/NO_x

stoichiometry was not adequate in the event of a sudden and severe load drop (i.e. 150-MWe to 80-MWe). In the event of a sudden load drop, the SCR catalyst would become saturated with NH_3 as the amount of NO_x contacting the catalyst diminished. The NH_3 injection rate was then reduced to allow the excess NH_3 to desorb from the catalyst.

4.3.3 Steady State Operation

The fine tuning of the system controllers provided for stable system operation. On the SNRB™ side, the most frequent interruption was loss of the sorbent feed system, which was typically restored to operation within 5 minutes. The major sources of variation from the host boiler were load changes and loss of one or more coal pulverizers. Boiler fluctuations affected the flue gas composition, flue gas temperature and pressure and the fly ash loading. The effect of boiler fluctuations on SNRB™ performance was evaluated and is discussed in Sections 4.5 to 4.7.

4.4 DATA ACQUISITION AND QUALITY CONTROL

The Microsoft Windows-based data acquisition system used to continually monitor SNRB™ performance was developed by B&W and therefore was specifically designed and tailored for the SNRB™ demonstration. The SNRB™ Data Acquisition System (DAS) accepted 63 channels of SNRB™ data from the Bailey Controls Network-90 input subsystem. The SNRB™ inputs to the DAS are detailed in Appendix E. Performance data were calculated from the raw values received from the Net-90 and were graphically displayed for the operator. Continuous plotting of the performance data allowed the operator to quickly verify steady state operation of the facility and trend key operating and performance parameters. The raw and calculated data were stored for later data reduction. The DAS was simple to operate and could be easily modified. Manual inputs reflected changes in the sorbent type, sorbent injection location and number of baghouse compartments on-line. In addition, the rate of data acquisition could be adjusted to scan the inputs once every 10 to 900 seconds. The calculations used to generate operating and performance data, such as the Ca/S and NH_3/NO_x stoichiometries, are presented in Appendix E.

4.4.1 Quality Assurance

The quality assurance and control procedures presented in the Quality Assurance Program Management Plan submitted to the DOE were observed. The flue gas analyzers were calibrated with certified calibration gas at the beginning and ending of each data set (at least twice daily). Representative solid samples were properly labeled and documented.

After each period of continuous operation, the facility was inspected for ash build up in the flue work and gas coolers which may have affected future operation. The lines leading to the pressure transmitters which measured critical parameters such as flue gas flow and baghouse pressure drop were routinely examined for pluggage with particulate matter. The integrity of flue gas sample lines leading to the analyzers was verified. The opacity monitor alignment was routinely checked. All instrumentation was calibrated on a yearly basis which resulted in two instrument calibrations over the test period.

The baghouse outlet flue gas was periodically sampled using a modified EPA Method 5 to determine particulate loading and ammonia slip. The ammonia samples were split and sent to B&W ARC and the Norton Company for duplicate analysis. Baghouse solid byproduct samples were also periodically taken for laboratory analysis. The laboratory analysis were used to verify sorbent utilizations observed in the field.

Independent testing of the SNRB™ process was conducted by a third party over approximately 240 hours of operation. Independent sampling was intended to serve two purposes. One, it provided an independent source of data for comparison of the SNRB™ process performance measured by the operations crew. In addition, the results of the independent testing verified the accuracy and reliability of the sampling methods used by B&W. The independent testing primarily consisted of EPA-approved continuous emission monitoring and grab sampling techniques. A summary the gaseous streams sampled, the sampling methods used for verification of SNRB™ performance and test results is presented in Section 4.8.

4.4.2 Data Reduction Procedure

The facility was operated at predetermined conditions for a period of 4 to 7 hours to comprise a "data set". In Figures 4-3, 4-4 and 4-5, the primary performance parameters are plotted over time to illustrate a typical data set. Analyzer calibrations usually preceded each data set. The DAS was normally set to scan the facility performance parameters once every minute. At the end of each data set, the DAS automatically downloaded the raw data in the form of Excel spreadsheets to the DAS computer hard drive. The raw data was then imported to an Excel template that generated a number of charts which fully described facility operation during the data set. The charts were reviewed by a B&W engineer to determine an appropriate period of steady operation for obtaining a representative average data set. These averages, adjusted for analyzer drift, constitute the final performance data presented in the following discussions. Examples of the DAS outputs including the continuous data contained in the Excel template, the resulting charts and the data sheet used to record the data set averages are presented in Appendix F.

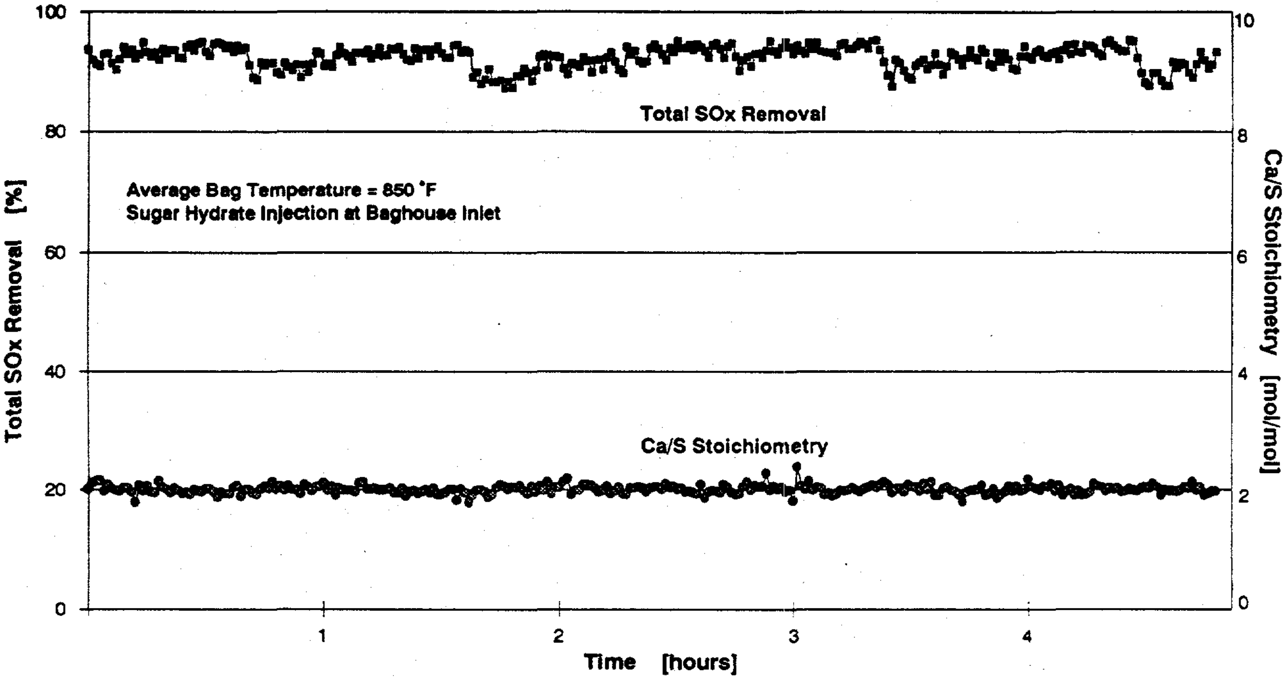


FIGURE 4-3 TYPICAL SO_2 REMOVAL DATA SET

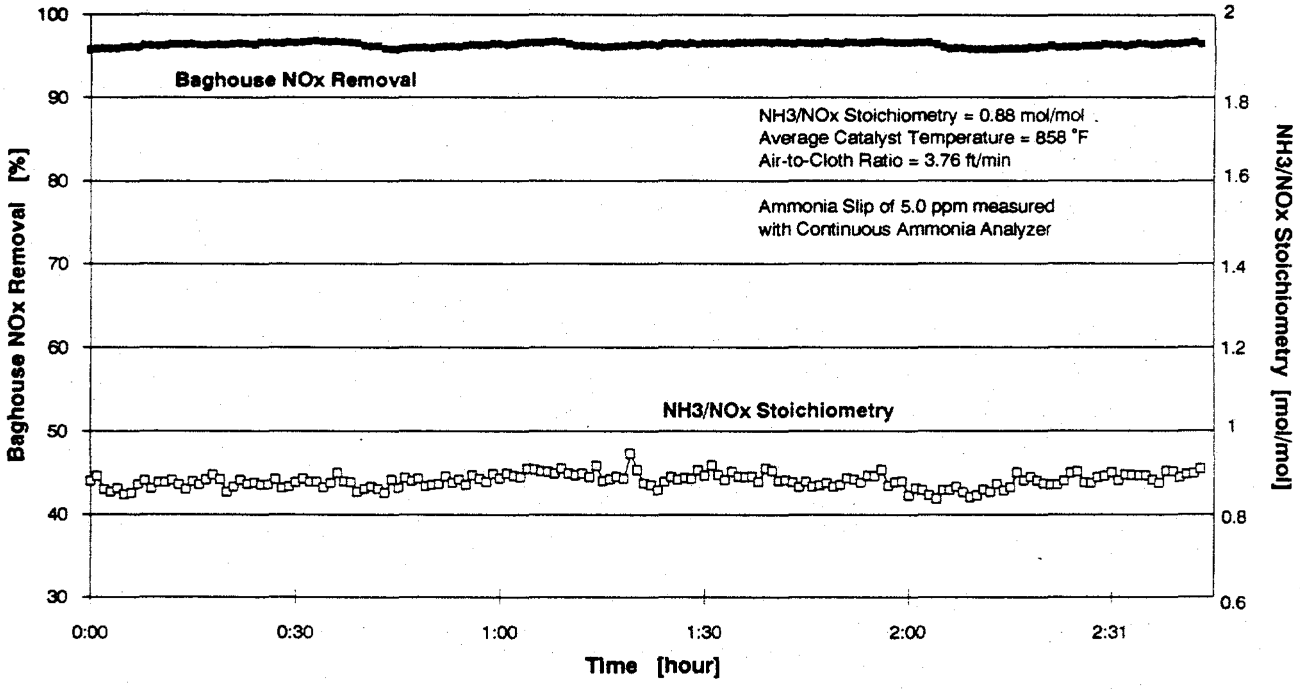


FIGURE 4-4 TYPICAL NO_x REMOVAL DATA SET

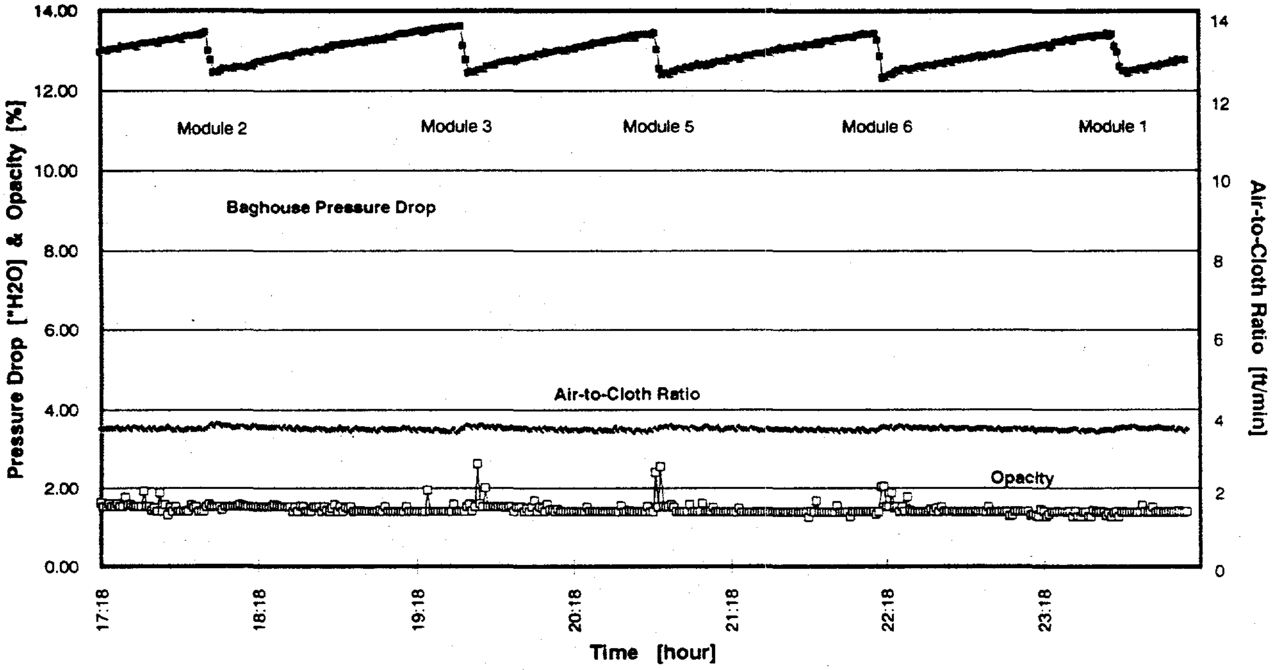


FIGURE 4-5 TYPICAL BAGHOUSE OPERATION DATA SET

4.5 SO_x REMOVAL

4.5.1 Introduction

SO_2 removal performance was influenced by the sorbent characteristics and operating conditions such as the Ca/S stoichiometry, the baghouse operating temperature, and the sorbent injection mechanics. The location of the high-temperature baghouse in the steam cycle of a commercial boiler determines the sorbent injection and baghouse operating temperature. The Ca/S stoichiometry determines the sorbent use rate and therefore impacts the SNRB™ system operating costs. Improved SO_2 removal may be achieved at higher Ca/S stoichiometry, but the increased operating costs may not be acceptable. Sorbent utilization better defines the relationship between SO_2 removal performance and sorbent consumption. Utilization is the percentage of injected sorbent which reacts to remove SO_2. These factors along with the cost of the sorbent and the required SO_2 removal are used to determine the optimum Ca/S stoichiometry for specific commercial applications. Modified hydrated limes were evaluated to obtain data for evaluating the marginal benefits of improved SO_2 removal with a higher cost sorbent.

The SO_x removal performance data is presented in this section according to sorbent type. Initial discussions beginning in Section 4.5.5 focus on test results obtained with the primary test sorbent, commercial hydrated lime. In section 4.5.10, SNRB™ performance obtained with the alternate hydrated lime sorbents is discussed and compared with the base hydrated lime performance. SNRB™ system operation with sodium bicarbonate injection is discussed in Section 4.5.11. Briefly, SO_2 removal efficiency greater that 80% was achieved with injection of the commercial hydrated lime at Ca/S stoichiometries between 1.8 to 2.0 mol/mol. The modified calcium-based sorbents resulted in improved SO_2 removal performance at similar Ca/S stoichiometry and baghouse temperature. Testing with the sodium bicarbonate indicated that SO_2 removals greater than 80% can be achieved over a wide range of baghouse operating temperatures. The demonstration program SO_2 removal test data are summarized by sorbent type in Appendix G.

4.5.2 Sorbent Injection Process Description

Five sorbent injection locations — four upstream of the inlet gas cooler and one between the inlet gas cooler and the baghouse — allowed for testing of the effects of sorbent injection temperature and sorbent residence time in the flue on SO_2 removal. The propane-fired burner was used to increase the flue gas temperature above the host boiler exit at 625 °F to permit testing over a wide range of controlled sorbent injection temperatures. The four high-temperature sorbent injection locations were designated 5, 4, 3, and 2 in the direction of flue gas flow. The flue gas then passed through the inlet gas cooler (which simulated flue gas cooling in the economizer of a commercial unit) to cool the gas to obtain the desired baghouse operating temperature. The baghouse inlet sorbent injection location (#1) was midway between the inlet gas cooler and the baghouse. The baghouse sorbent injection temperature was usually 25 °F higher than the average baghouse temperature. The ammonia was injected into the flue work at the baghouse inlet directly upstream of the sorbent injection point.

The sorbent injection system, shown in Figure 4-6, was supplied as a package unit. The sorbent was stored in a 2,350 ft^3 silo. This silo discharged into a feed hopper coupled to a loss-in-weight feeder used to feed the sorbent at the desired, controlled rate. The weigh feeder controls were linked to the data acquisition and control system to continuously record and control the feed rate to a Ca/S stoichiometry set point based on the inlet flue gas flow rate and SO_2 concentration. The sorbent was transported to the injection point with transport air supplied by a low-pressure blower operating at 2 to 3 psig. The design details of the sorbent feed system are summarized in Table 4-2. A single nozzle was located at each injection point.

TABLE 4-2 SO_2 SORBENT INJECTION SYSTEM
2,350 ft^3 storage silo
Loss-in-weight feeder
300 to 700 lb/hr hydrated lime
300 to 1300 lb/hr sodium bicarbonate
Rotary air lock feeders
Variable speed blower
3-inch transport line
Five flue work injection locations

The sorbent injector design may affect SO_2 removal performance in two ways: 1) by determining the effective sorbent particle size distribution (PSD), and 2) through the injection velocity, which directly influences the rate and degree of sorbent/flue gas mixing. Several sorbent injectors were evaluated in the SNRB^{TM} design verification pilot tests to facilitate injector design for the demonstration. Two injectors were designed to provide injection velocities in the range of 200 to 250 ft/sec which was determined to be sufficient to disperse the sorbent and provide the finest PSD.

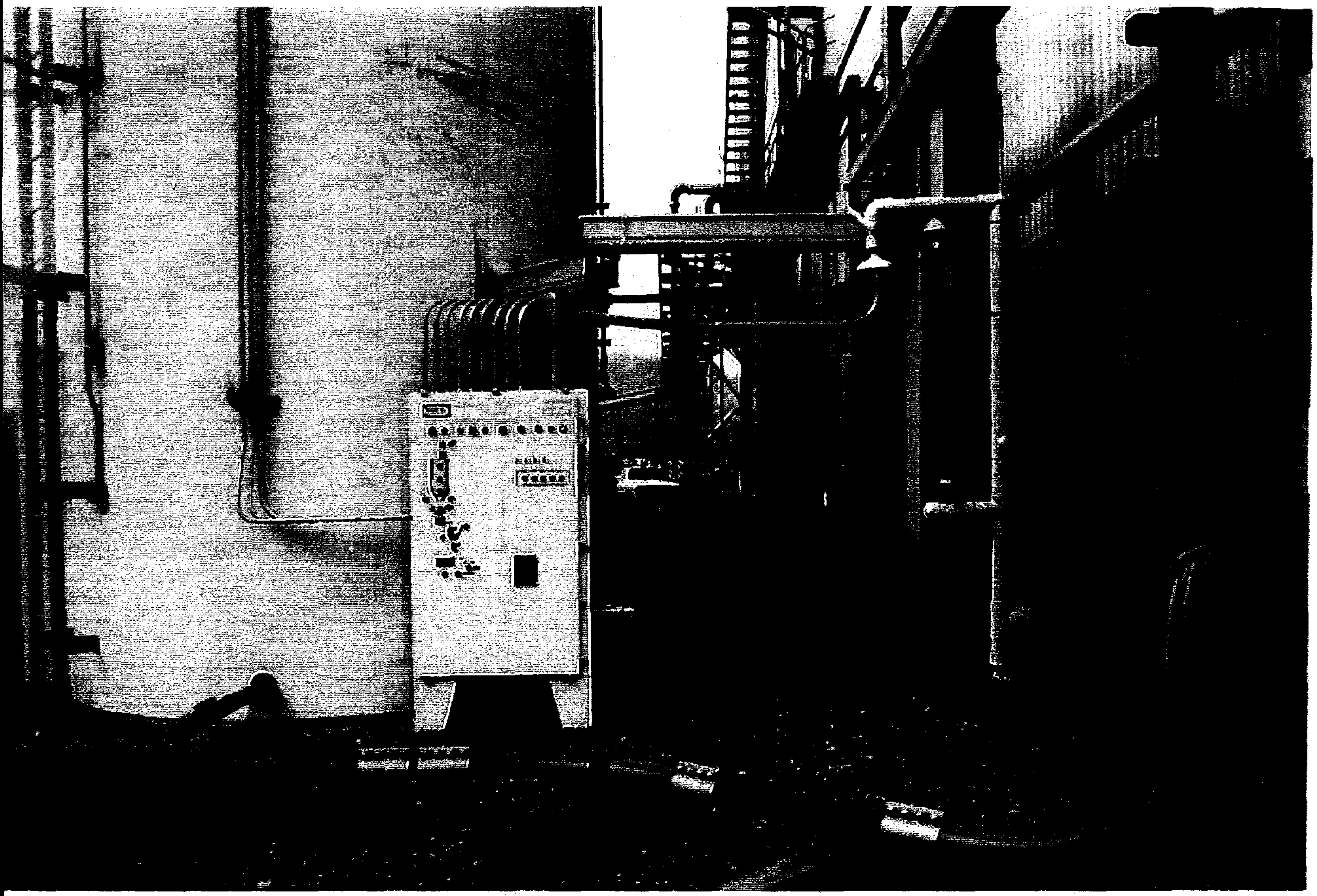


FIGURE 4-6 SORBENT INJECTION SYSTEM

4.5.3 Operations Summary

Performance testing at the 5-MWe demonstration facility began in May 1992 and was completed in May 1993. The SNRB™ system was operated for a total of about 2,300 hours during the demonstration project. Sorbent injection tests were performed for approximately 1,575 hours. A commercially produced hydrated lime supplied by Dravo Lime Company was the primary SO_2 sorbent used in operation of the demonstration facility for 1,005 hours. Average characteristics of the Dravo Black River hydrate are provided in Table 4-3. Testing was also conducted with sugar hydrated lime (240 hours), lignosulfonated lime (215 hours), and sodium bicarbonate (115 hours). The range of operating conditions related to SO_2 removal are summarized in Table 4-4.

TABLE 4-3 AVERAGE LIME HYDRATE SORBENT CHARACTERISTICS

Available lime index (ALI) as % $Ca(OH)_2$	92%
Inerts	1.4%
MgO	1.5%
Surface area (BET)	13.8 m^2/gram
Mass mean diameter	5.4 microns
Sauter mean diameter	3.2 microns

TABLE 4-4 TYPICAL RANGE OF OPERATING CONDITIONS

Inlet SO_2 concentration	2000 to 3000 ppm
Ca/S stoichiometry	1.0 to 3.0
Sorbent injection temperature - high range	1000 to 1200°F
Sorbent injection temperature - baghouse inlet	825 to 900°F
Baghouse operating temperature	800 to 875°F
Air-to-cloth ratio	3.0 to 5.0 acfm/ft^2

The SO_2 concentration in the gas was measured with continuous emission monitors at three locations: the system inlet (upstream of the propane burner), the baghouse inlet (downstream of the inlet flue gas cooler), and the baghouse outlet (upstream of the outlet flue gas cooler). The total SO_2 removals reported in this section are based on the SO_2 concentration measured at the system inlet and the baghouse outlet. The calculated removals account for the flue gas flow increase generated by the propane-fired burner, the sorbent and ammonia transport air and air dilution in the baghouse. The sorbent feed rate was automatically controlled by the Net-90 feedback controller based on real time measurements of the baghouse inlet SO_2 concentration and a operator selected Ca/S stoichiometry setpoint. Sorbent feed was typically within 5% of the setpoint as illustrated in Figure 4-3. The term baghouse temperature refers to the average of the thermocouple measurements made in the center of each of the baghouse compartments on-line. The locations of the thermocouples in the individual compartments are illustrated in Appendix B.

In the high-temperature baghouse the SO_2/sorbent reaction products, unreacted sorbent, and fly ash were collected on the outside of the filter bags. The bags were cleaned with a quick pulse of pressurized air and the solids dropped off the bags and into the collection hoppers. A representative baghouse solids sample was obtained for each data set for laboratory analysis. In the demonstration project, the SNRB™ system solid byproduct was disposed of off-site in a solid waste landfill.

4.5.4 Baseline SO_x Removal

Tests to determine the degree of background SO_2 removal without sorbent injection were performed on each start-up of the facility. Baseline SO_2 removal, measured from the system inlet to the baghouse outlet, usually varied from 0 to 10%. Average baseline SO_2 removal was 3.0% ± 4.7% over the range of conditions tested. The baseline SO_2 removal is believed to be a result of residual, unreacted sorbent on the filter bags. Figure 4-7 presents the measured baseline removal as a function of average baghouse temperature. The level of baseline SO_2 removal did not correlate with baghouse temperature, air-to-cloth ratio, inlet SO_2 concentration or whether on not ammonia was injected. These results compare well with the 6% to 12% SO_2 baseline removal observed in the design verification pilot tests. The SO_2 removals reported in this section have not been adjusted for baseline SO_2 removal. At an inlet SO_2 concentration of 2,500 ppm, SO_2 removal of 80 - 90 % would decrease by less than 1% when accounting for a 3% baseline removal.

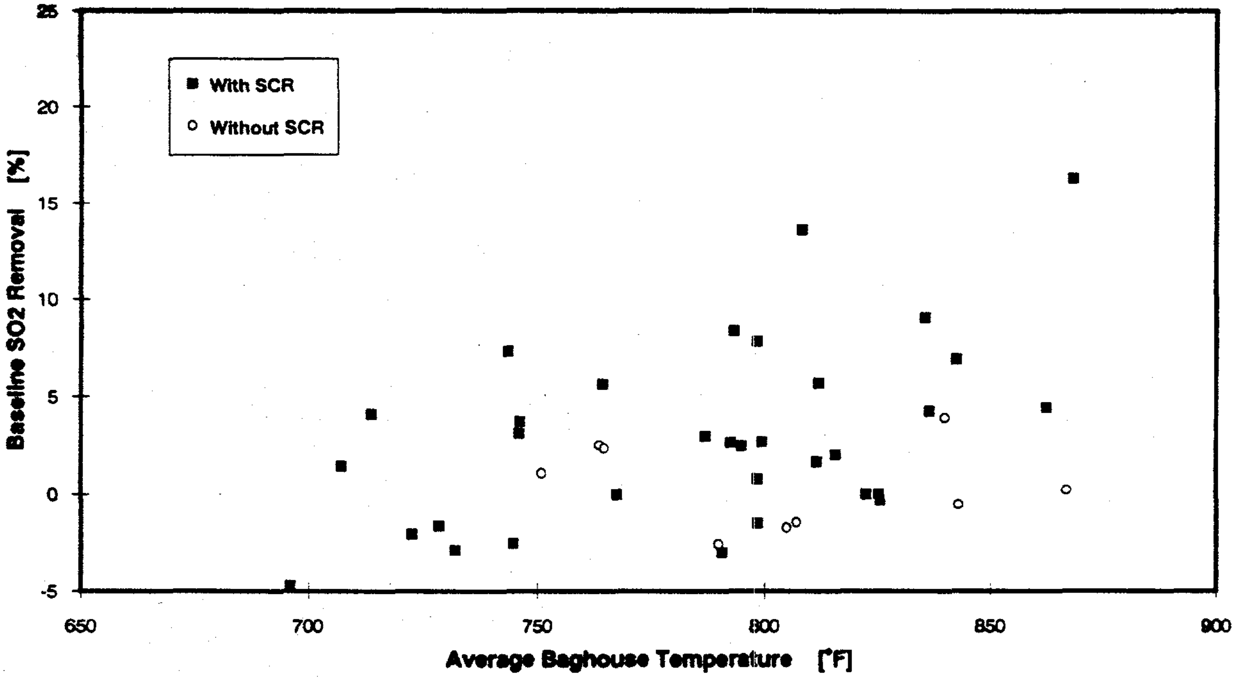


FIGURE 4-7 EFFECT OF BAGHOUSE TEMPERATURE ON BASELINE SO_2 REMOVAL

4.5.5 Effect of Ca/S Stoichiometry

The Ca/S stoichiometry is a significant design parameter because it determines the amount of lime available for reaction with SO_2. The relationship between the SO_2 removal and the Ca/S stoichiometry is quantified by the lime utilization. Lime utilization is defined as the percentage of injected lime that reacts with SO_2 in the flue gas and is determined by dividing the measured SO_2 removal by the Ca/S stoichiometric ratio. The effect of the Ca/S stoichiometry on SO_2 removal and lime utilization is shown in Figure 4-8. The data presented are limited to commercial hydrated lime injection at the baghouse inlet with baghouse operating temperatures of 830°F to 860°F. The general increase in SO_2 removal efficiency associated with increasing Ca/S stoichiometry coincides with decreasing lime utilization. SO_2 removals greater than 80% were achieved at Ca/S stoichiometries of 1.8 and above, correlating to a lime utilization of about 44%. Maximum lime utilization of 60% was obtained at a Ca/S stoichiometry of 1.0. The calcium utilizations achieved in the demonstration are significantly greater than those reported for other dry furnace or duct sorbent injection technologies. As presented in Figure 4-9, outlet SO_2 levels of about 0.7 $lb/10^6$ Btu were attained with operation at a Ca/S stoichiometry of 1.8 and an 850°F baghouse temperature. This performance is well below the current NSPS and CAAA Phase II compliance level of 1.2 $lb/10^6$ Btu for SO_2 emissions.

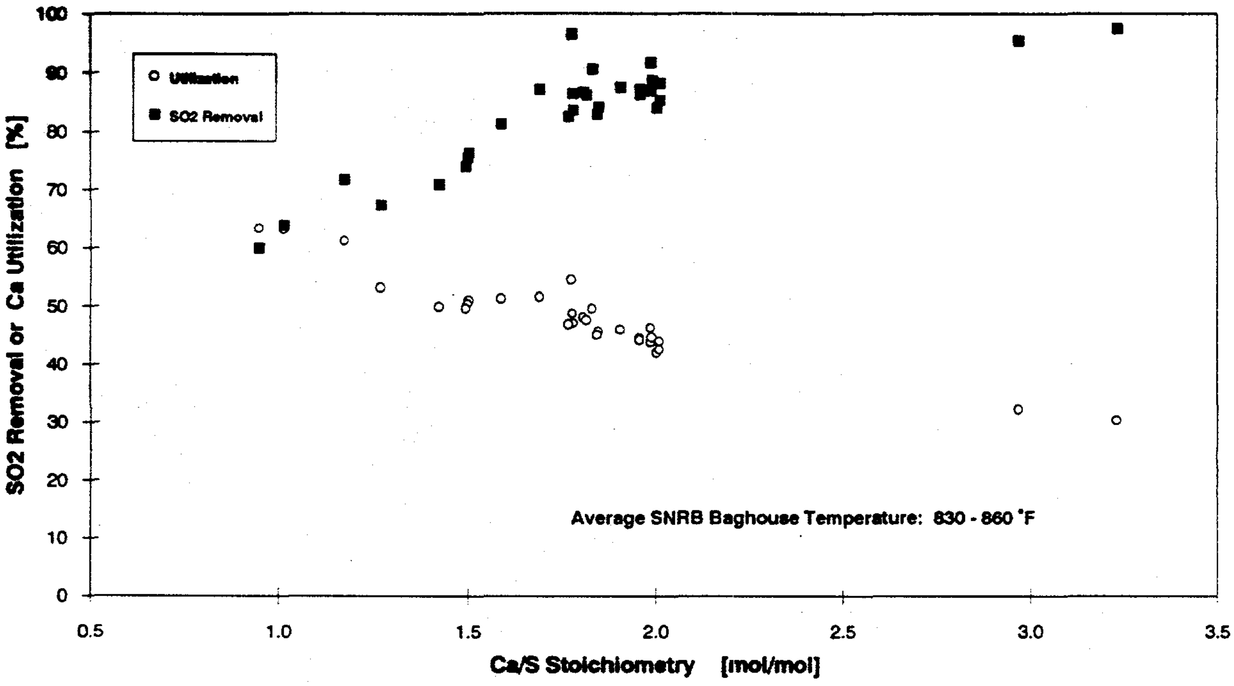


FIGURE 4-8 EFFECT OF Ca/S STOICHIOMETRY ON SO_2 REMOVAL AND Ca UTILIZATION

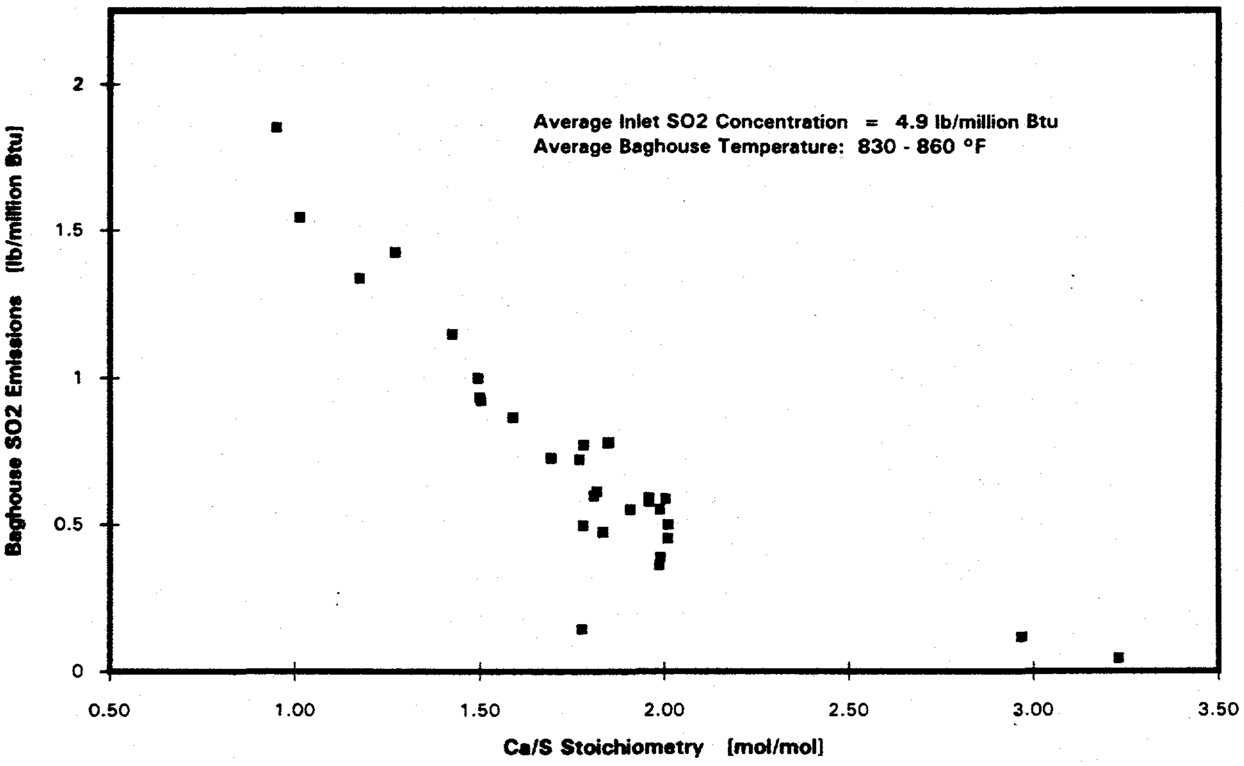


FIGURE 4-9 EFFECT OF Ca/S RATIO ON SO_2 EMISSIONS

4.5.6 Effect of Injection Location

Effect of Sorbent Residence Time

The demonstration facility inlet flue work was equipped with five sorbent injection locations. The different sorbent injection locations were used to determine the effect of sorbent residence time in the flue on SO_2 removal. Injection at the four locations upstream of the inlet flue gas cooler resulted in overall sorbent residence times ahead of the baghouse ranging from 2 to 4 seconds at a gas flow corresponding to an air-to-cloth ratio of 4.0 acfm/ft^2. The use of these different injection locations did not have a significant effect on SO_2 removal, indicating that residence time in the flue is not a major factor at the conditions evaluated. At similar baghouse operating temperatures, the injection temperature was significantly greater at the upstream locations relative to injection at the baghouse inlet. This temperature effect prevented comparison of data from injection at the baghouse inlet with the other four locations.

Effect of Sorbent Injection Temperature

With sorbent injection upstream of the inlet gas cooler, the injection temperature was controlled by varying the propane burner operation. The injection temperature effect on SO_2 removal efficiency was determined while operating the inlet gas cooler to maintain a constant baghouse temperature. Injection temperatures upstream of the inlet cooler ranged from 1000° to 1200°F using the commercially hydrated lime. Figure 4-10 illustrates that over the temperature range evaluated, removal of SO_2 in the flue was higher at lower injection temperature. Above 1050°F, the SO_2 removal started to drop off. This is likely due to sintering of the lime particles, which is known to decrease reactivity. The flue removal measured upstream of the baghouse from the point of sorbent injection is presented to eliminate the impact of baghouse operating temperature. Total system SO_2 removal efficiencies of about 70% were obtained when injecting the sorbent in the temperature range presented in Figure 4-10.

The significant improvement in SO_2 removal achieved when the sorbent was injected directly upstream of the baghouse at temperatures of 825° to 900°F is shown in Figure 4-11. Because sorbent injection at the baghouse inlet achieved higher SO_2 removal, subsequent testing concentrated on injection at this location for optimizing performance.

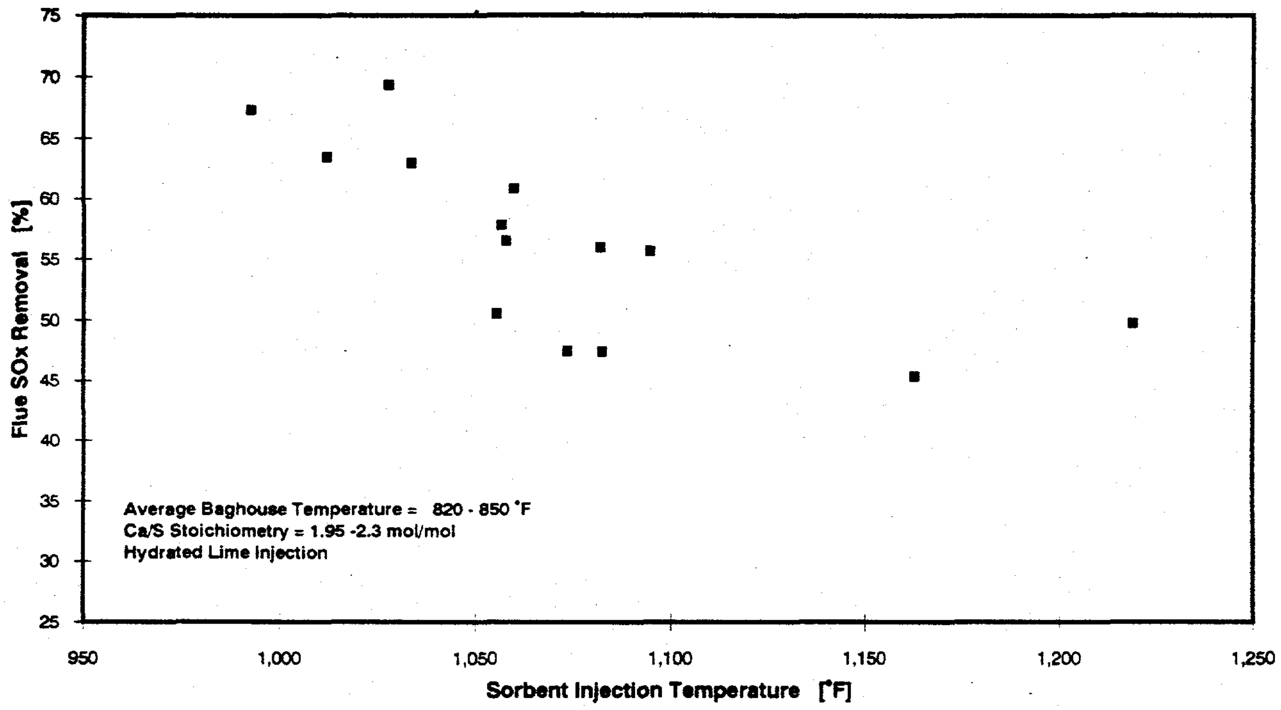


FIGURE 4-10 EFFECT OF SORBENT INJECTION TEMPERATURE ON SO_2 REMOVAL

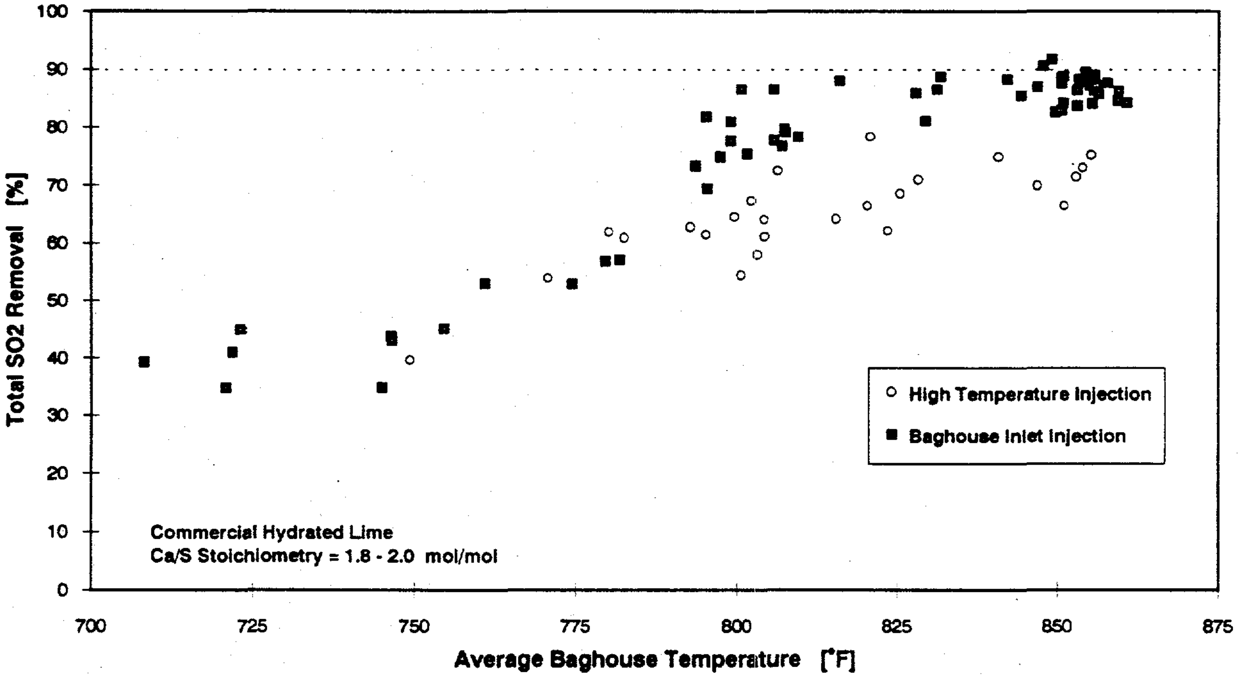


FIGURE 4-11 EFFECT OF SORBENT INJECTION TEMPERATURE

Laboratory reactor studies subcontracted to the University of Cincinnati supported the observation that sorbent injection at lower temperatures resulted in higher SO_2 removal. A drop tube reactor with quick quenching at the reactor outlet was used to conduct fast kinetic experiments with reaction times less than one second. Several reactions using hydrated lime were evaluated: dehydration of $Ca(OH)_2$, carbonation, sulfation, simultaneous sulfation/carbonation reaction and the reactivity of CaO. The following observations were made:

(1) The dehydration reaction of $Ca(OH)_2$ without CO_2 and SO_2 is relatively insensitive to both reaction time and temperature compared to the reaction with the gases.

(2) The carbonation conversion increases continually with the temperature, however, it is insensitive to the reaction time. The carbonation reaction appears to have reached the reaction limit within the first 0.5 second.

(3) Due to the competing carbonation reaction of the sorbent, sulfation conversion with CO_2 present is lower than that without CO_2. Under the conditions in the drop tube reactor, the carbonation conversion is almost twice the sulfation conversion when both CO_2 and SO_2 are present in the flue gas.

(4) The sulfation rate of CaO in the economizer temperature range is lower than that of $Ca(OH)_2$, but it still contributes a significant share to the overall sulfation reaction.

Observation (3) supports the SNRB^{TM} demonstration experience. Figure 4-12 presents the comprehensive effects of simultaneous carbonation and sulfation. Carbonation conversion of $Ca(OH)_2$ increased rapidly at temperatures higher than 900°F. Since the CO_2 concentration is nearly 50 times higher than that of SO_2 in flue gas, and the molar volume of CO_2 is smaller than that of SO_2, CO_2 diffuses through the pores of the sorbent and reacts first. Once the surface is carbonated, it is not available for reaction with SO_2. As illustrated in Figure 4-12, the carbonation conversion above 900°F was measured at nearly double the sulfation conversion.[24] The impact of the dominating carbonation reaction was significantly reduced by operation at temperatures less than 900°F .

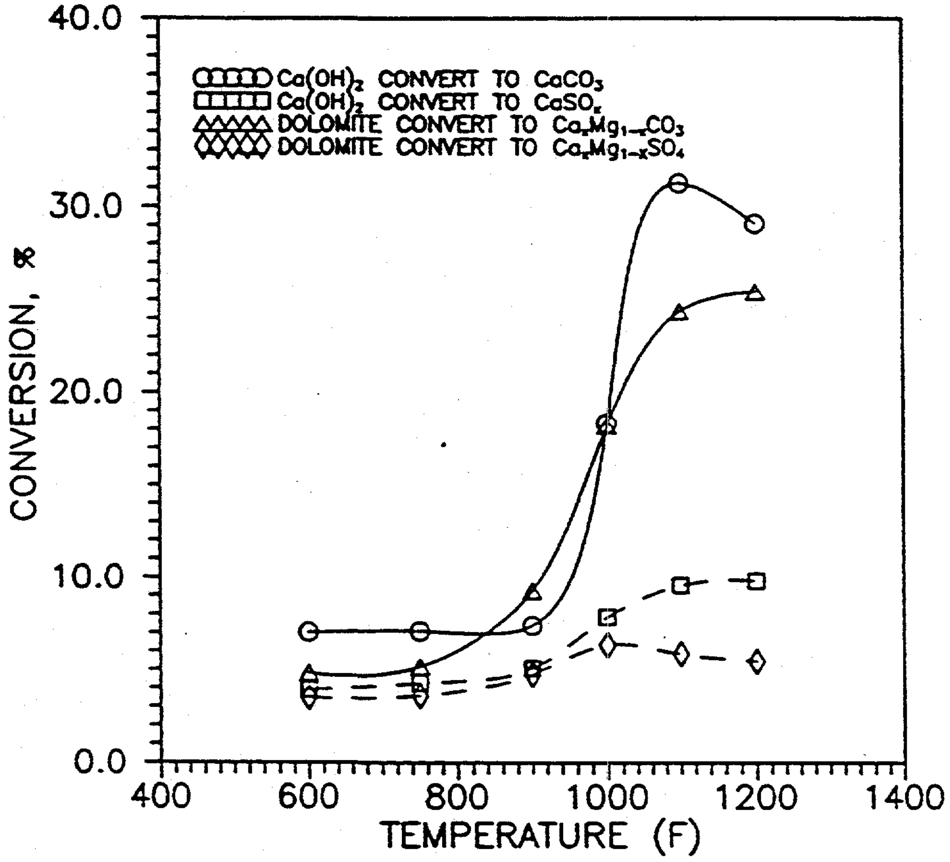


FIGURE 4-12 COMPARISON OF SORBENT SULFATION AND CARBONATION

The SNRB^{TM} baghouse solids were chemically analyzed to compare the extent of the carbonation and sulfation reactions. The SNRB^{TM} demonstration and University of Cincinnati reaction times differed since the SNRB^{TM} solids continued to react with the flue gas in the baghouse. The degree of conversion of the $Ca(OH)_2$ to $CaCO_3$ and $CaSO_x$ is plotted as a function of injection temperature in Figure 4-13. The sulfation reaction was predominate at temperatures below 900°F, however the carbonation conversion increased with increasing sorbent injection temperature. Chemical analysis of the baghouse solids confirmed that the lower sorbent injection temperature favored the sulfation reaction over the carbonation reaction. Higher SO_2 removal efficiencies were consistently achieved with sorbent injection at the baghouse inlet location relative to injection at higher temperatures in the flue work upstream of the baghouse. The baghouse inlet sorbent injection temperature was approximately 25°F higher than the average baghouse operating temperature.

4.5.7 Effect of Baghouse Temperature

The SNRB^{TM} baghouse operating temperature has a notable affect on sorbent utilization since a large portion of the total SO_2 reduction occurs in the baghouse. Discussion of the effect of baghouse temperature on SO_2 removal will focus on performance with sorbent injection at location #1, just upstream of the baghouse. Testing was conducted at baghouse temperatures ranging from 700° to 860°F. The impact of baghouse temperature on SO_2 removal is shown in Figure 4-14. The data points are sorted by Ca/S stoichiometry to identify the impact of this key parameter. A narrow range of Ca/S ratios from 1.7 to 1.9 was selected to minimize the effect of stoichiometry. A clear trend of increasing SO_2 removal with an increase in the baghouse operating temperature is shown. SO_2 removals below 50% were observed in the temperature range of 700° to 750°F, while greater than 80% SO_2 removal was achieved at temperatures above 800°F. This illustrates a significant temperature effect and suggests a baghouse operating temperature between 800° and 860°F for commercial applications with hydrated lime injection.

The same trend of increased SO_2 removal with increased baghouse temperature was also observed over the lower Ca/S stoichiometry range of 1.5 - 1.7 mol/mol as presented in Figure 4-15. At the lower Ca/S stoichiometry, approximately 75% SO_2 removal was achieved at temperatures above 800°F.

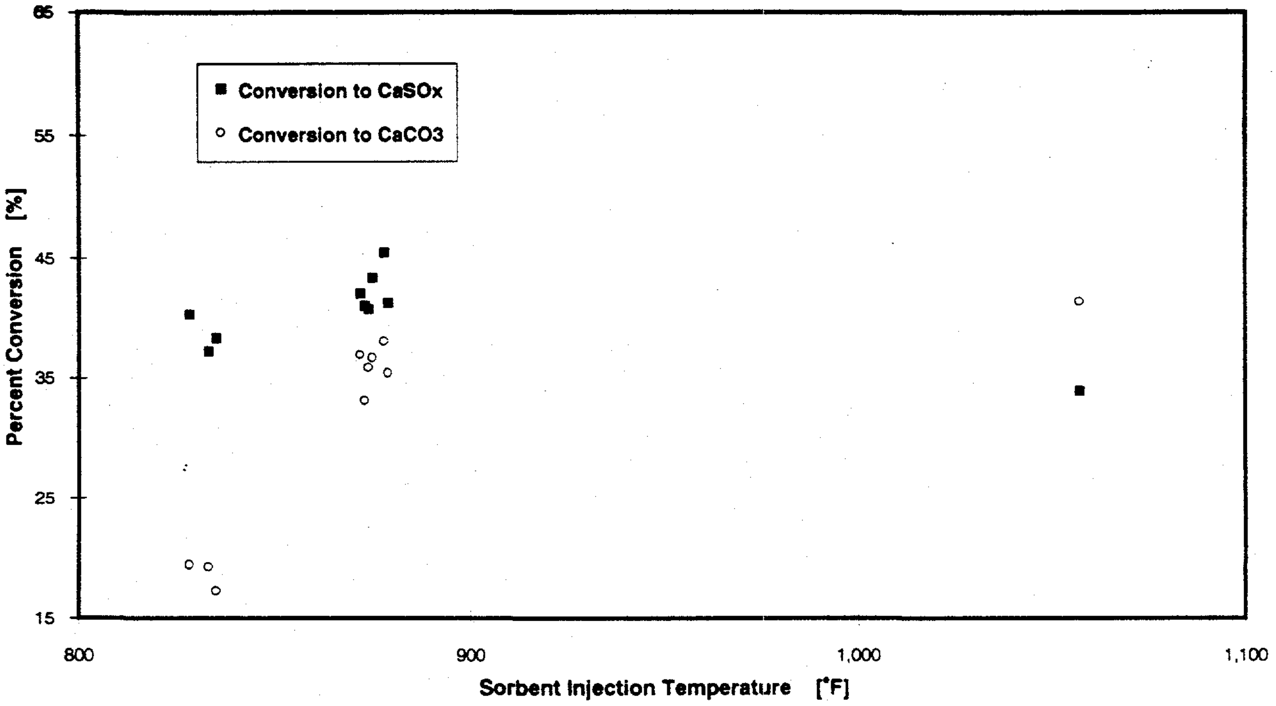


FIGURE 4-13 EFFECT OF TEMPERATURE ON HYDRATED LIME SULFATION AND CARBONATION

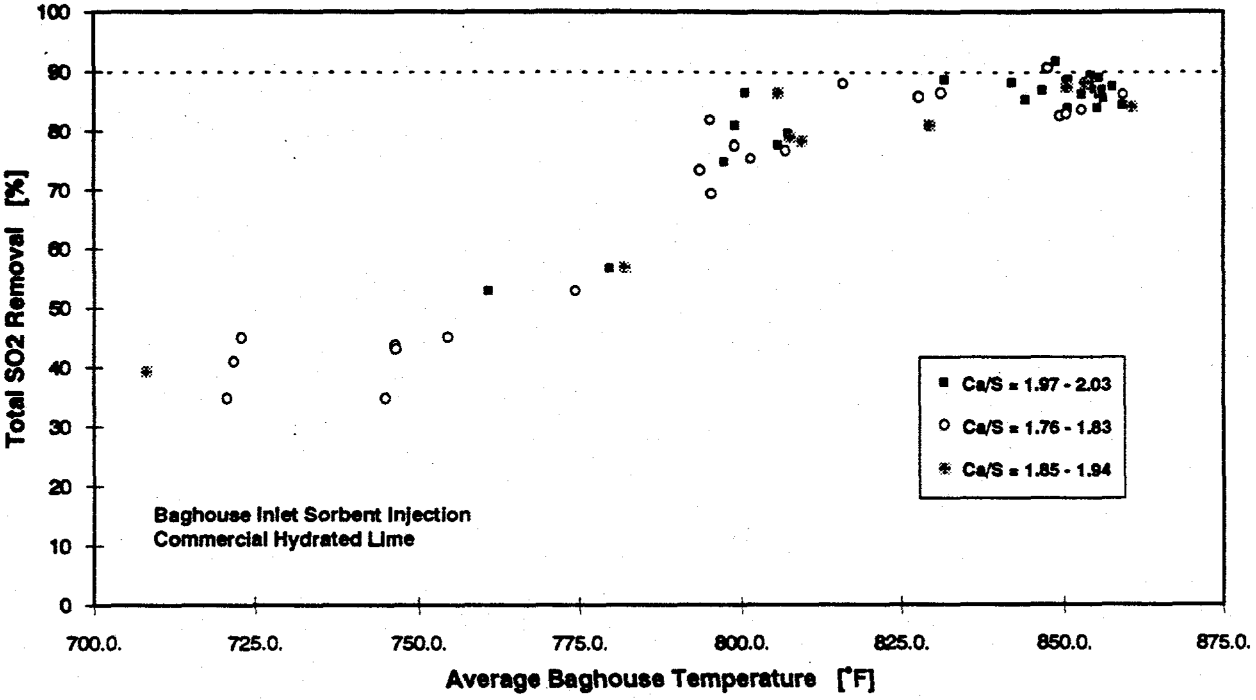


FIGURE 4-14 EFFECT OF BAGHOUSE TEMPERATURE ON SO_2 REMOVAL AT Ca/S RATIOS OF 1.7 TO 1.9

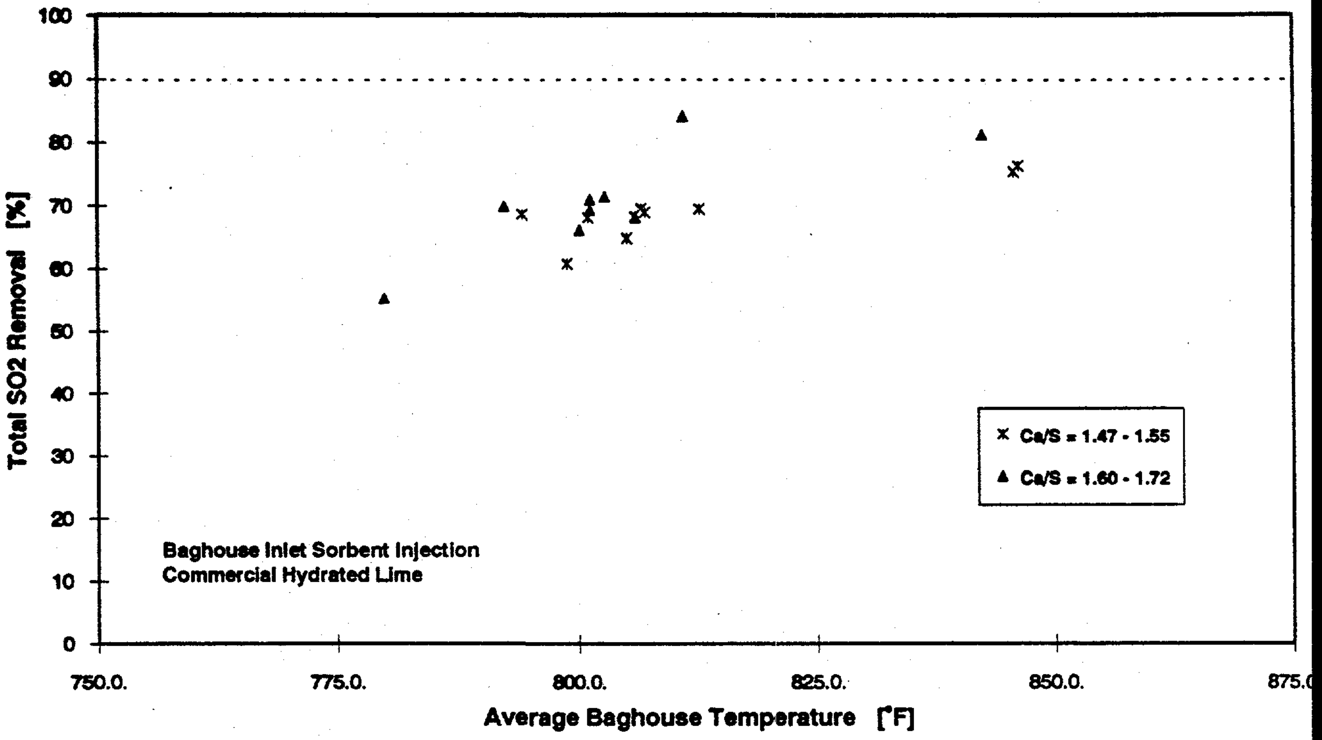


FIGURE 4-15 EFFECT OF BAGHOUSE TEMPERATURE ON SO_2 REMOVAL AT Ca/S RATIOS OF 1.5 TO 1.7

4.5.8 Baghouse Product Laboratory Analysis

Representative samples of the solid byproduct were analyzed by B&W as a check on removal trends observed in the field. These samples were primarily analyzed for total sulfur, total calcium, sulfite sulfur, and total carbonate. The lime or calcium utilization was determined by dividing the moles of total sulfur in the sample by the moles of total calcium. Lime utilization calculated with this method was in good agreement with utilization calculated from on-line field measurements of Ca/S stoichiometry and SO_2 removal. For tests at a Ca/S stoichiometry of 1.8 and a baghouse temperature of 850°F, the laboratory analysis yielded an average utilization of 42.9%. Using field flue gas and hydrated lime feed measurements from the same tests, a utilization of 44.7% was calculated. Differences in individual runs ranged from 0.4 to 3.8% for the four tests used in this comparison. A similar comparison using 15 runs with the modified hydrated lime sorbents resulted in an average utilization based on the laboratory analysis being 0.5% greater than the average utilization determined from the field data. Figure 4-16 compares the sorbent utilization resulting from the measured field parameters and those utilizations determined from analysis of the byproduct solids from operation with commercial hydrated lime injection. A similar comparison of sorbent utilizations for operation with the modified hydrates is provided in Figure 4-17.

The composition of the SNRB™ byproduct solids generated in operation at a Ca/S stoichiometry of 2.0 with commercial hydrated lime and a baghouse temperature of 850°F is provided in Table 4-5. The average free moisture content of the solid byproduct was 0.05%. The coal burned during this period contained approximately 3.5% sulfur and 12% ash. The chemical composition of all the solids samples analyzed are presented in Appendix H.

Table 4-5 SNRB™ SYSTEM SOLID BYPRODUCT COMPOSITION

CONSTITUENT	WEIGHT %
Fly ash	32.8%
$CaCO_3$	23.9%
$CaSO_4$	20.5%
$CaSO_3$	15.4%
CaO	7.4%

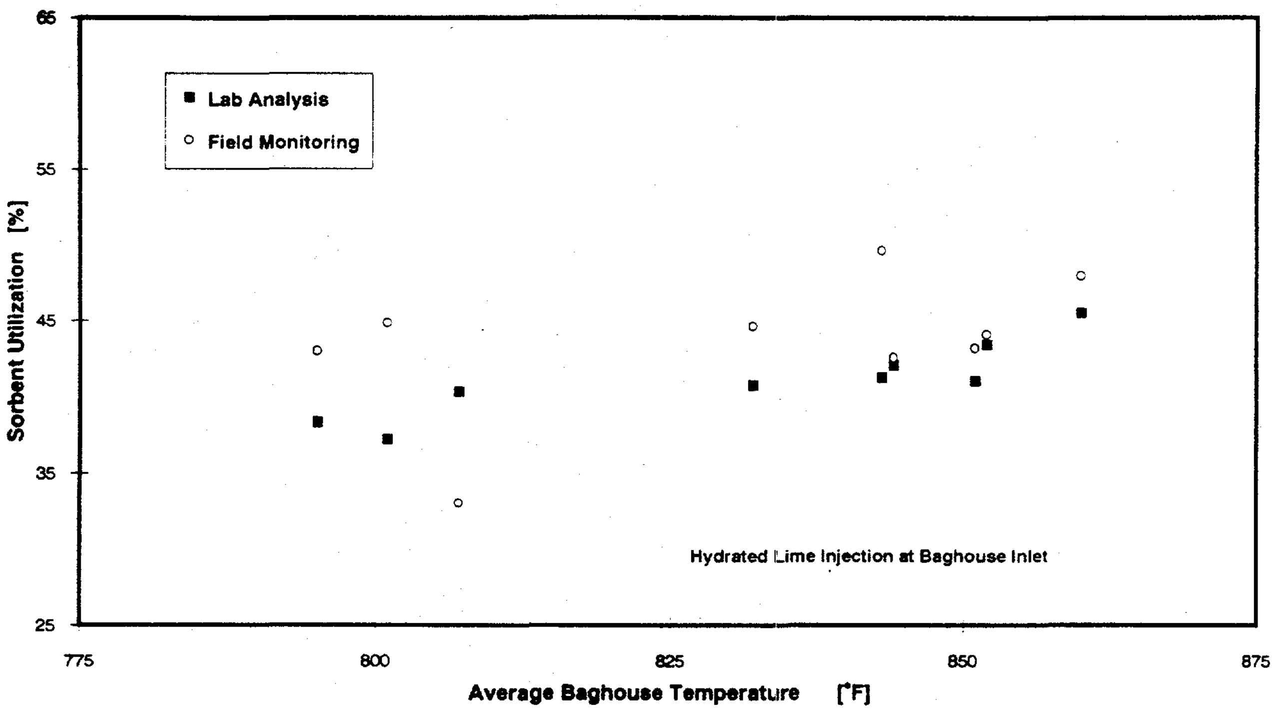


FIGURE 4-16 HYDRATED LIME UTILIZATION COMPARISON

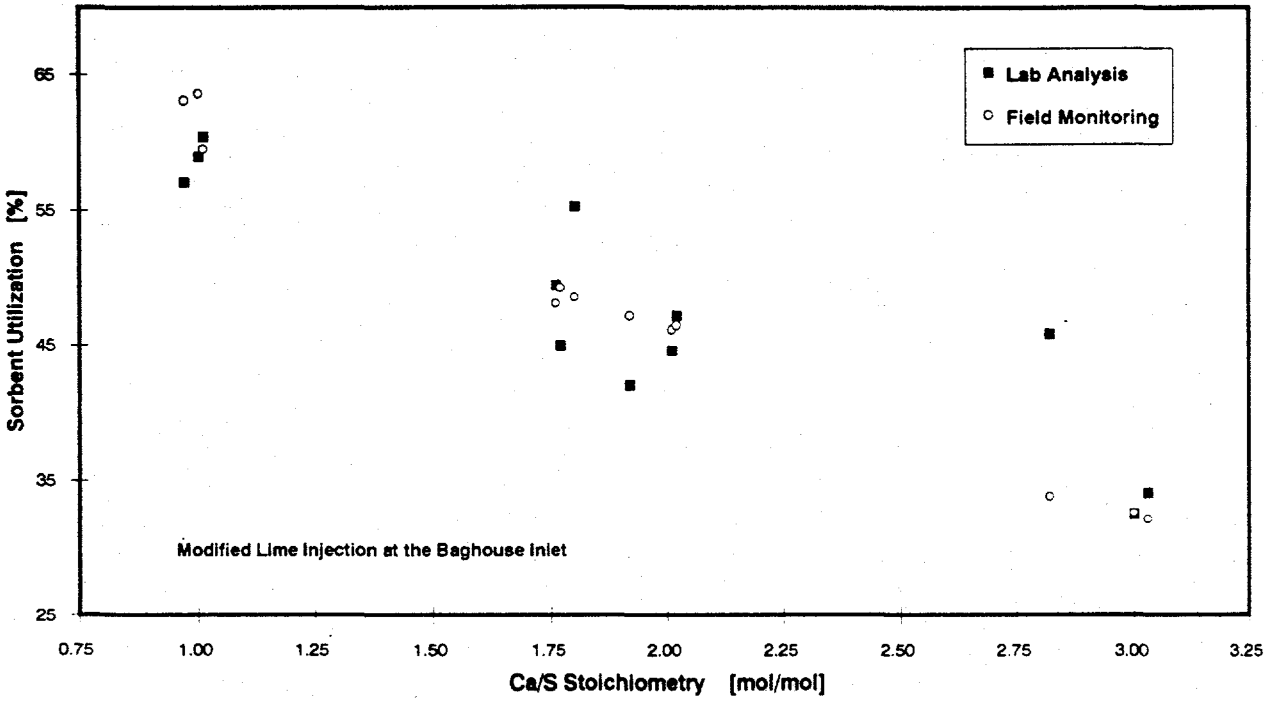


FIGURE 4-17 MODIFIED HYDRATE UTILIZATION COMPARISON

4.5.9 SO_2 Performance Tests

Based on the cumulative results of the screening, continuous and alternate sorbent tests, the optimal SNRB™ operating conditions were selected for the performance tests. In addition to monitoring SO_2 and NO_x removal, gaseous and solid sampling for trace chemical emissions were conducted at the major inlet and outlet streams of the SNRB™ facility to determine the fate of air toxics in the SNRB™ process. Commercial hydrated lime was selected for the performance tests since this was expected to be typical of a commercial operation. SNRB™ performance was continuously monitored 24 hours/day for a period of 5 days at the conditions presented in Table 4-6. Total SO_2 removal averaged 86.6% at a Ca/S stoichiometry of 2.0 mol/mol and baghouse temperature of 855°F. The raw SO_2 removal (not adjusted for analyzer calibration) and the Ca/S stoichiometry monitored over the 108 hours of continuous operation are plotted in Figure 4-18. The spikes in the total SO_2 removal correspond to short periods when the sorbent feed system malfunctioned and the slight dips in SO_2 removal have been traced to analyzer drift. The width of the SO_2 removal band is directly a result of the baghouse cleaning cycle. The effect of the baghouse cleaning cycle on SO_2 control is addressed in Section 4.5.12.

4.5.10 Alternative Calcium-Based Sorbents

Modified lime hydrates were evaluated as a means of enhancing SO_2 removal and lime utilization. Improved SO_2 removal has been generally attributed to the finer mean particle size and increased porosity of the modified hydrates. The alternate sorbent tests were performed to provide on different SO_2 sorbents for potential industrial and utility commercial applications. On the basis of the University of Cincinnati bench-scale Sorbent Screening Studies, sugar hydrated lime (SHL) and calcium lignosulfonated lime (CLS) were selected for evaluation at the demonstration facility. These alternative lime hydrates were produced by slightly modifying the commercial hydration process.[2] To produce the sugar hydrated lime, a sugar solution was used in the hydrating process. Calcium lignosulfonate was added to the hydration water to produce the calcium lignosulfonate hydrate. The additives are reported to increase the sorbent porosity and reduce the particle size distribution. The averaged sorbent characteristics determined by B&W and Dravo are compared to commercial hydrated lime in Table 4-7.

TABLE 4-6 PERFORMANCE TEST CONDITIONS

		RANGE	AVERAGE
GASEOUS INFLUENT System Inlet SO_2	[ppm]	2290 - 2400	2350
Baghouse Inlet NO_x	[ppm]	390 - 410	400
Baghouse Inlet O_2	[%]	4.12 - 4.64	4.38
NH_3 Feed Rate	[lb/hr]	7.4 - 10.2	8.6
NH_3/NO_x Stoichiometry	[mol/mol]	0.80 - 0.98	0.88
Ca/S Stoichiometry	[mol/mol]	1.8 - 2.1	2.0
Sorbent Feed Rate	[lb/hr]	433 - 472	453
Baghouse Inlet Flue Gas Flow	[acfm]	23,450 - 24,002	23,752
Baghouse Inlet Pressure	["H_2O]	-11.3 to -10.7	-11.0
Baghouse Inlet Temperature*	[°F]	875 - 879	877
Flue Gas Moisture Content	[%]	8.0 - 9.2	8.6
Particulate Mass Loading	[gains/scfm]	7.1 - 12.0	9.2
Ammonia Transport Air	[lb/hr]	206 - 223	215
Sorbent Transport Air	[lb/hr]	N/A	1251
GASEOUS EFFLUENT Baghouse Outlet SO_2	[ppm]	170 - 260	210
Baghouse Outlet NO_x	[ppm]	35 - 42	38
Baghouse Outlet O_2	[%]	5.30 - 5.90	5.60
Baghouse Outlet Opacity	[%]	0.5 - 3.2	1.7
Flue Gas Moisture Content	[%]	5.6 - 8.6	7.1
Particulate Mass Emissions	[grains/scfm]	0.009 - 0.016	0.011
Ammonia Slip	[ppm]	1.0 - 5.0	2.6
Baghouse Outlet Flue Gas Flow	[acfm]	25,330 - 25,880	25,600
Baghouse Outlet Pressure	["H_2O]	-23.1 to -22.5	-22.8
Baghouse Outlet Temperature	[°F]	778 - 788	783
BAGHOUSE OPERATION Bag/Catalyst Temperature	[°F]	845 - 860	855
Catalyst Space Velocity	[1/hr]	2900 - 3050	2975
Air-to-Cloth Ratio	[acfm/ft^2]	3.6 - 3.75	3.7
Baghouse Pressure Drop	["H_2O]	11.5 - 12.2	11.8
Cleaning Cycle	[minutes]	43 - 49	46

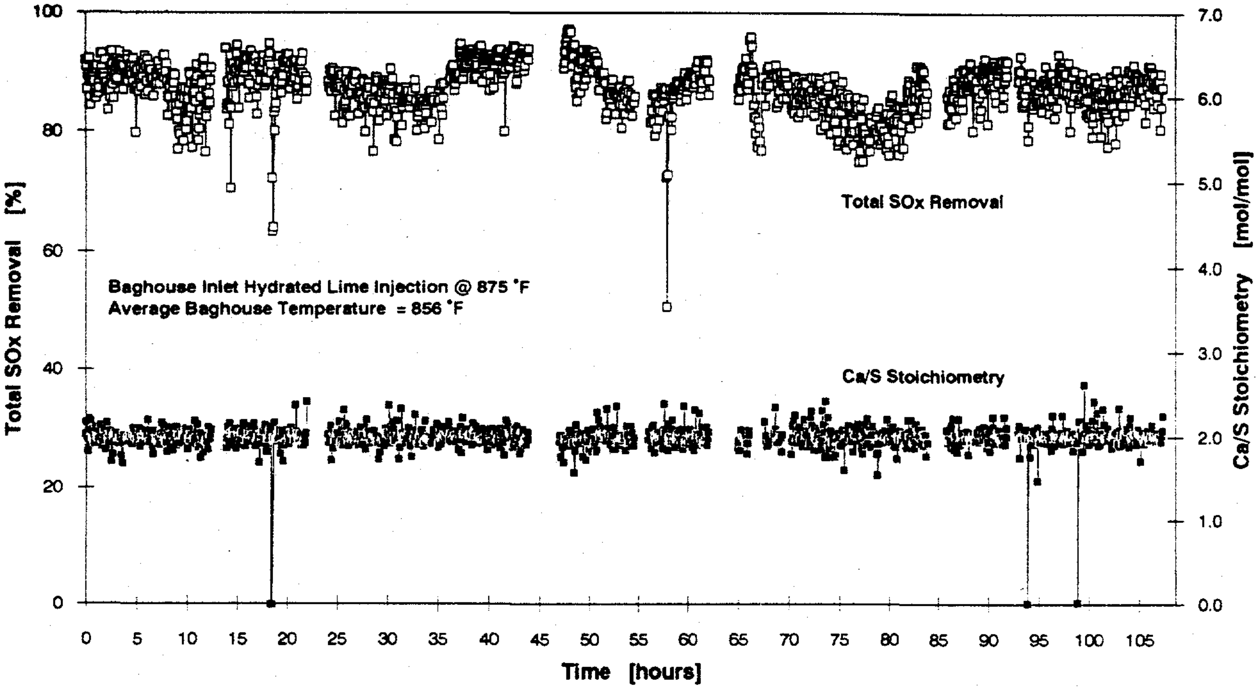


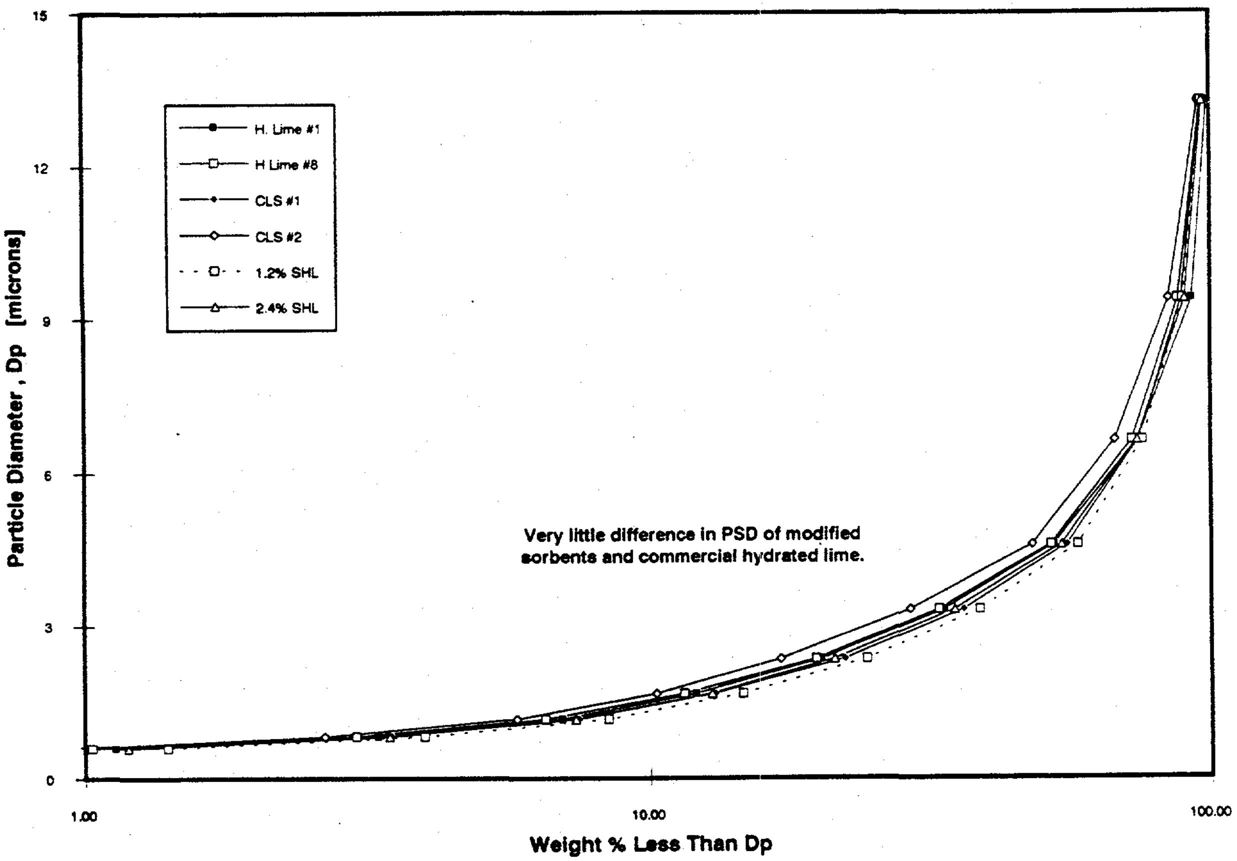
FIGURE 4-18 SNRB™ PERFORMANCE TEST: TOTAL SO_2 REMOVAL

TABLE 4-7 SORBENT CHARACTERISTICS						
	SMD micron	MMD micron	BET [m^2/g]	ALI [%]	Inerts [%]	Additive [%]
DRAVO ANALYSIS						
Hydrated Lime	3.44	4.08	14.9	94.2	N/A	N/A
CLS	3.35	4.00	11.9	93.3	N/A	1.18
SHL	3.05	3.56	10.7	95.1	N/A	1.85
B&W ANALYSIS						
Hydrated Lime	3.21	5.40	13.8	92.0	1.36	N/A
CLS	3.15	5.50	12.2	90.6	1.64	N/A
SHL	2.89	5.09	9.8	90.7	1.84	N/A

The Sauter Mean Diameter (SMD) is the particle diameter based on the equivalent volume-to-surface area. The Mass Mean Diameter (MMD) is the particle diameter for which one half of the particulate mass consists of smaller particle and one half is larger. BET refers to the total surface area available for reaction determined by the method developed by Brunauer-Emmett-Teller using nitrogen at its boiling point as the adsorbate. Available Lime Index (ALI) refers to the % $Ca(OH)_2$ by weight available for reaction.

The sugar hydrated lime had the smallest mass mean diameter. In contrast to expectations, the alternate sorbents had available surface areas smaller than the commercial hydrate and the particle size distributions (PSD) of the sorbents did not vary significantly. The PSD of the sorbents as determined by Microtrac analysis are compared in Figure 4-19. A dispersant is added during Microtrac analysis to break up sorbent agglomerates. The Microtac results represent the finest PSD theoretically possible.

Most of the alternate sorbent tests were performed with injection at the baghouse inlet which had yielded the best results for commercial hydrate injection. Tests conditions were similar to those with commercial lime for data comparisons.



Very little difference in PSD of modified sorbents and commercial hydrated lime.

FIGURE 4-19 COMPARISON OF SORBENT PARTICLE SIZE DISTRIBUTION

Effect of Ca/S Stoichiometry

Results from the use of the modified lime hydrates are presented in Figure 4-20 which illustrates the effect of Ca/S stoichiometry on SO_2 removal with sorbent injection at the baghouse inlet and a baghouse operating temperature of 850°F. Over 90% SO_2 removal was achieved at a Ca/S stoichiometry of 2.0. This compares to about 85% SO_2 removal using the commercial hydrated lime sorbent at the same operating conditions.

Of the two alternate sorbents, the sugar hydrate provided slightly higher SO_2 removal than the calcium lignosulfonate at the conditions tested. This higher performance agreed with previous work by the Dravo Lime Company in a 1 MW test facility in which extensive furnace injection testing demonstrated that sugar hydrates obtained the highest SO_2 removal, best utilization, and were the most economical of all the sorbents tested.[4]

Effect of Baghouse Temperature

The emphasis of the alternate sorbent tests was on comparison to commercial lime at optimum test conditions. Therefore, most tests were conducted at baghouse operating temperatures greater than 800°F. Since the Ca/S stoichiometry strongly influenced performance, the data demonstrating the impact of baghouse temperature in Figure 4-21 is limited to Ca/S ratios of 1.8 - 2.0 mol/mol. The alternate sorbents exhibited the same trend of increased performance with increased baghouse temperature as observed with the base hydrated lime.

Comparison with Commercial Hydrated Lime

The alternate sorbent tests demonstrated that SO_2 emission control could be enhanced through the use of modified hydrates. Sugar hydrated lime provided the lowest SO_2 emissions of the three lime hydrates evaluated. Figure 4-22 presents the SO_2 emissions levels resulting from injection of the three types of hydrated lime over a wide range of Ca/S stoichiometries at similar baghouse operating temperatures. At low stoichiometries, the sugar hydrated lime produced the lowest level of emissions, although the is a significant degree of data scatter. At higher stoichiometries, the better performance of the sugar hydrate is more readily apparent. At a Ca/S stoichiometry of 1.8 mol/mol, sugar hydrated lime injection reduced SO_2 emissions to 0.5 $lb/10^6$ Btu compared to 0.75 $lb/10^6$ Btu with commercial hydrated lime. A similar improvement in SO_2 removal can be observed in Figure 4-22 at a Ca/S stoichiometry of 2.0 mol/mol. Note that the CAAA Phase I compliance level of 2.5 $lb/10^6$ Btu is achieved with Ca/S ratios of 1.0 and the 1.2 $lb/10^6$ Btu Phase II limit is attained with a 1.5 Ca/S ratio.

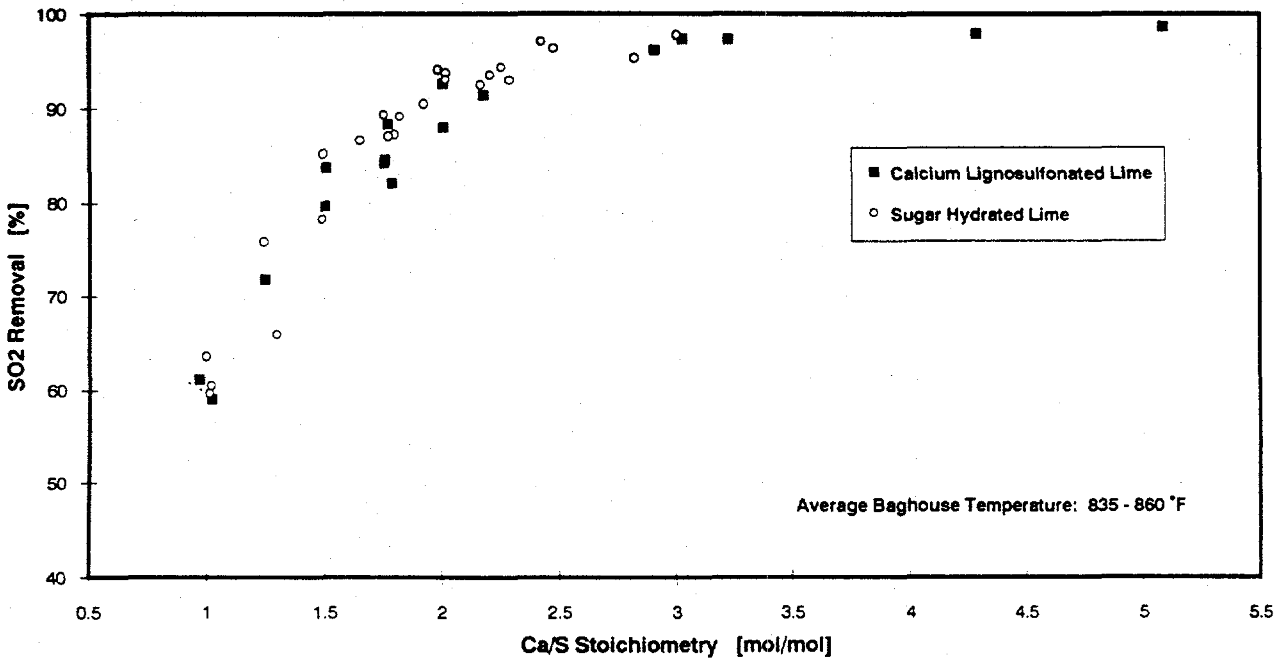


FIGURE 4-20 EFFECT OF MODIFIED HYDRATE Ca/S RATIO ON SO_2 REMOVAL

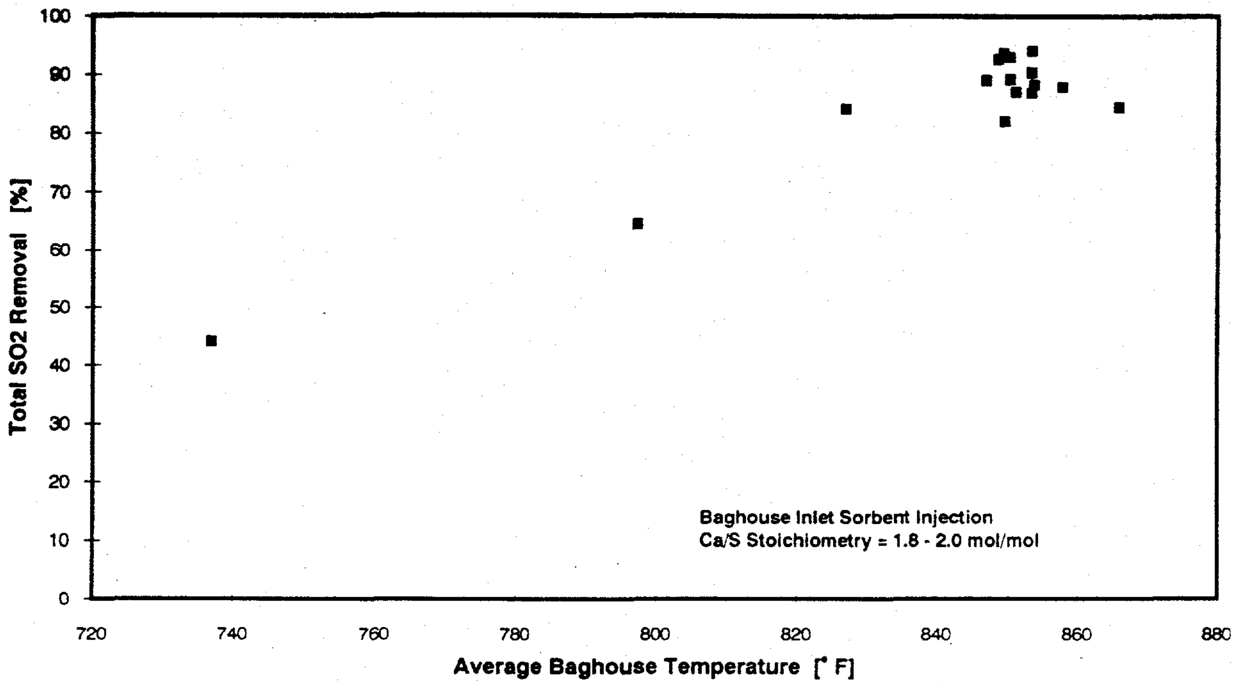


FIGURE 4-21 EFFECT OF TEMPERATURE ON SO_2 REMOVAL WITH ALTERNATE SORBENTS

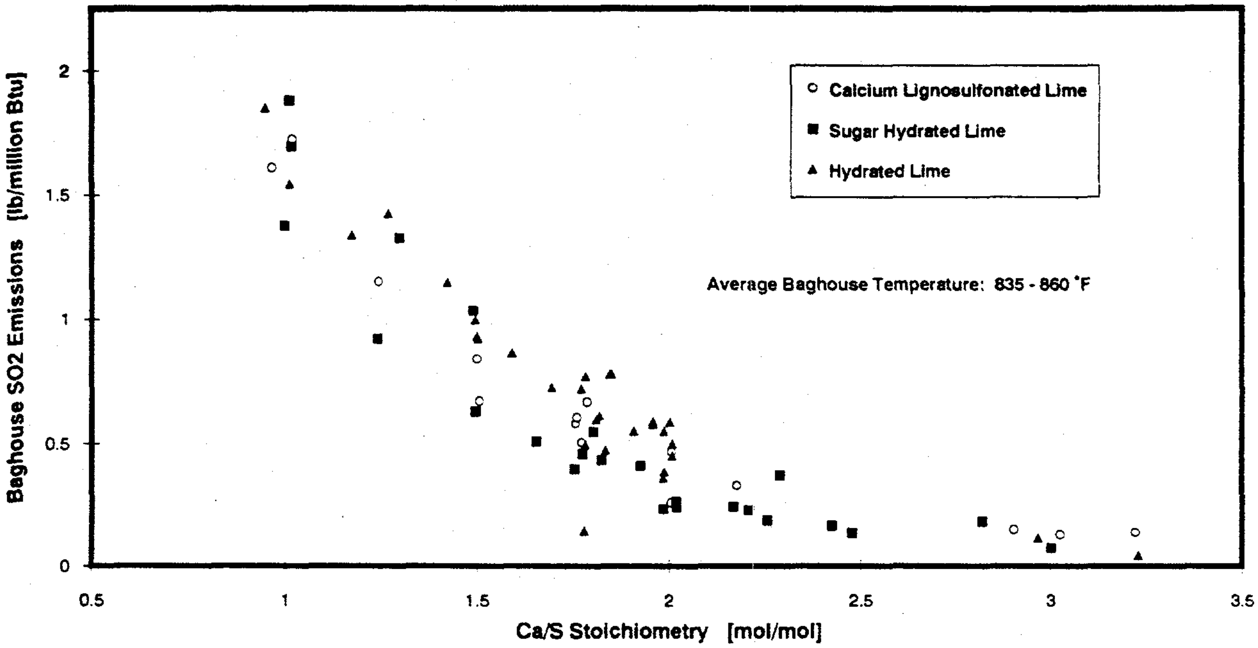


FIGURE 4-22 COMPARISON OF SO_2 REMOVAL WITH ALTERNATIVE HYDRATED LIMES

4.5.11 Sodium Bicarbonate Tests

Dry sodium bicarbonate ($NaHCO_3$) injection has been used commercially at industrial sites for acid gas emissions control since the mid 1980's. $NaHCO_3$ provides a higher sorbent utilization than hydrated lime as well as a moderate NO_x reduction potential. At five full-scale commercial demonstrations at electric coal-fired units equipped with ESPs, up to 75% SO_2 removal and 0 to 40% NO_x reduction have been achieved. Recent slipstream studies have indicated up to 90% SO_2 removal and 25% NO_x removal can be achieved when $NaHCO_3$ injection is followed with particulate collection in a baghouse.[25] Sodium-based SNRB™ technology would be geared to power plants and industrial boilers where $NaHCO_3$ is readily available. $NaHCO_3$ injection is appropriate for lower temperature applications where sorbent injection downstream of the air heater may provide sufficient SO_2 removal.

Commercial, sorbent-grade, extra-fine $NaHCO_3$ was supplied by Church & Dwight for a short test period at the demonstration facility. A summary of chemical and physical analysis of the fresh sorbent by B&W is provided in Table 4-8.

TABLE 4-8 SODIUM BICARBONATE CHARACTERISTICS

Solids	[%]	99.8
Inerts	[%]	0.01
$NaHCO_3$	[%]	95.17
Sulfur	[ppm]	3.50
Chloride	[ppm]	<10
BET Surface Area	[m^2/g]	4.5
MMD	[microns]	34.4
SMD	[microns]	15.2

The relative coarseness of the $NaHCO_3$ sorbent is apparent when compared to the hydrated lime PSD in Figure 4-23 given comparable test conditions with $Ca(OH)_2$.

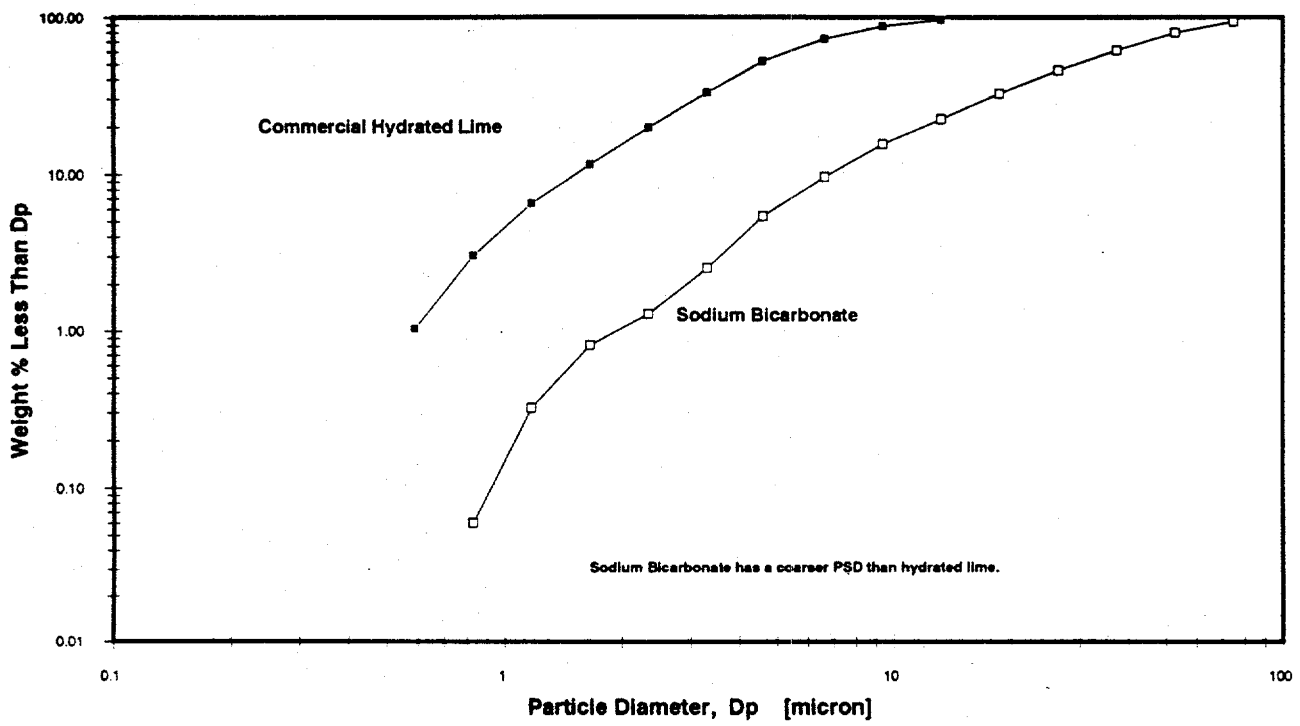


FIGURE 4-23 COMPARISON OF $NaHCO_3$ AND $Ca(OH)_2$ SIZE DISTRIBUTIONS

Effect of Na_2/S Stoichiometry

The theoretical reactions describing SO_2 capture with $NaHCO_3$ indicate two moles of sorbent are required for every mole of SO_2 removed. Test results will be discussed in terms of the normalized stoichiometric ratio (NSR). NSR is defined as the molar ratio of sodium injected to the SO_2 present in the flue gas exiting the boiler, divided by the number of moles of sodium required to theoretically react with one mole of SO_2. In equation form it is expressed as:

$$NSR = \frac{[\text{moles Na injected}]/[\text{moles } SO_2 \text{ in inlet flue gas}]}{2}$$

For sodium sorbent applications, sorbent utilization is defined as the actual SO_2 removal obtained divided by the NSR. $NaHCO_3$ tests were conducted over a baghouse temperature range of 450° to 850°F and NSRs of 0.5 to 2.0 mol/mol. The baghouse temperature of 450°F was the minimum at which the SNRB™ demonstration baghouse could be operated. Sorbent was injected at the baghouse inlet location for all of the tests.

SO_2 removal performance with $NaHCO_3$ injection is summarized in Figure 4-24 which illustrates performance over a range of NSRs with the baghouse operating at 450 °F. At a NSR of 0.5, approximately 100% utilization was obtained. Over 85% SO_2 removal was achieved with a NSR of 1.0. $NaHCO_3$ provides for higher sorbent utilizations than the calcium sorbents evaluated at the demonstration. The maximum sorbent utilization obtained with commercial hydrated lime was approximately 60% at a Ca/S stoichiometry of 1.0 mol/mol. With a NSR of 1.0 the average $NaHCO_3$ utilization was 85%.

In some cases, repeating the tests with NH_3 injection for NO_x reduction resulted in reduced SO_2 removal. Sorbent utilization dropped from 85% to 80% with NH_3 injection at a sodium sorbent NSR of 1.0 mol/mol. Ammonia can adsorb on solid surfaces at 450°F and may have inhibited the SO_2/Na_2CO_3 reaction.

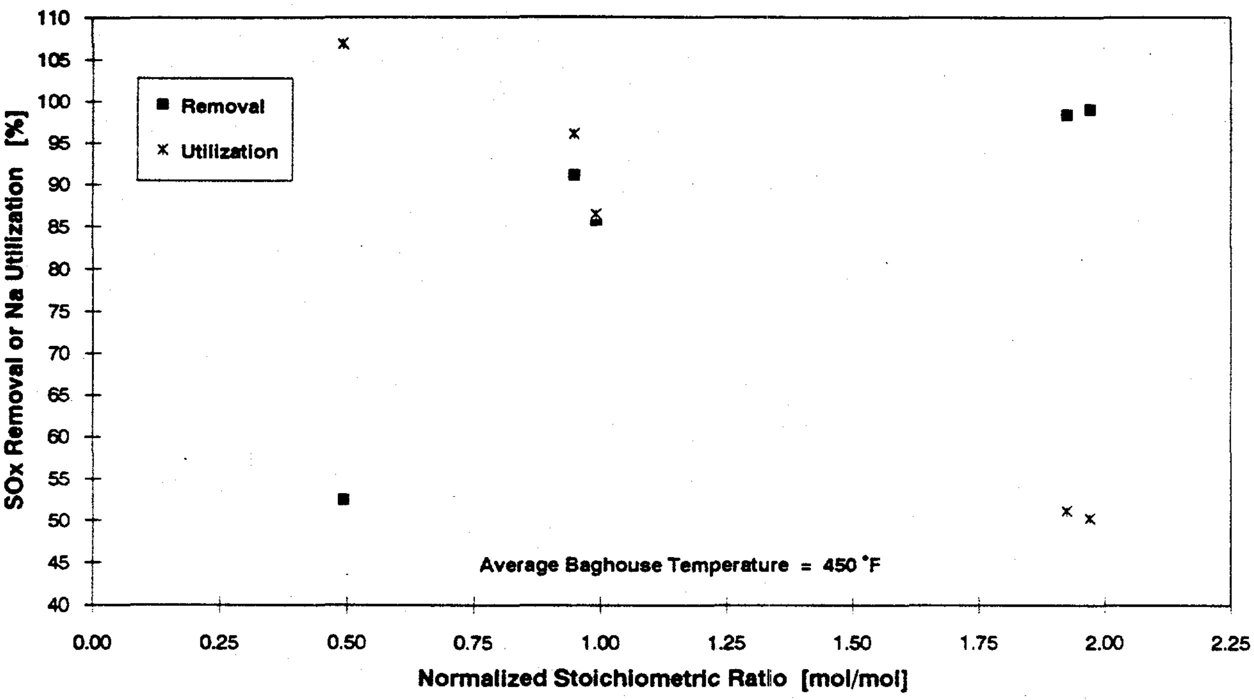


FIGURE 4-24 EFFECT OF Na_2/S RATIO ON SO_2 REMOVAL

Effect of Baghouse Temperature

$NaHCO_3$ provided for high SO_2 removal at relatively low baghouse operating temperatures. Greater than 90% SO_2 removal at a normalized stoichiometry (Na_2/S) of 2.0 was observed over baghouse temperatures ranging from 425° to 875°F. As indicated in Figure 4-25, removal dropped off slightly at temperatures greater than 500°F but remained well above 90%. At a more cost-effective normalized Na_2/S stoichiometry of 1.0, increasing the baghouse temperature from 450°F to 625°F resulted in a decrease in removal efficiency from over 80% to approximately 70%. The impact of temperature on SO_2 removal at a NSR of 1.0 is shown in Figure 4-26. The reduction in $NaHCO_3$ utilization at the higher temperature may be caused by several factors. At too high a temperature, the sorbent may sinter, reducing the available surface area for reaction. In addition, the rate of Na_2SO_3 oxidation to Na_2SO_4 is expected to increase at higher temperatures. This rate-limiting step in the $NaHCO_3/SO_2$ reaction is believed to be SO_2 diffusion controlled through the sulfated product layer. Because Na_2SO_4 is a larger molecule than Na_2SO_3, diffusion of SO_2 through an Na_2SO_4 layer is expected to be slower.

Research on dry $NaHCO_3$ injection and reaction kinetics suggests that high utilizations can be obtained at temperatures less than 450°F, with a minimum recommended temperature of 250°F.[16] Injection temperatures less than 300°F may result in reduced utilization because thermal decomposition is slow and incomplete. Baghouse operating temperatures lower than 450°F could not be not evaluated due to limitations of the SNRB™ demonstration heat transfer equipment.

Side Effects of $NaHCO_3$ Injection

When using sodium bicarbonate as a sorbent, modest levels of NO_x reduction were obtained without the use of ammonia injection. NO_x reduction with sodium injection is discussed in Section 4.6.13. This may become especially attractive in applications where only moderate levels of NO_x reduction are required or where acceptable overall NO_x reduction can be achieved with a combination of the SNRB™ system and combustion modifications, such as the installation of low-NO_x burners. Because high SO_2 removal is possible at relatively lower baghouse operating temperature with $NaHCO_3$ injection, the baghouse can be located downstream of the economizer in a retrofit situation so economizer modifications are not necessary.

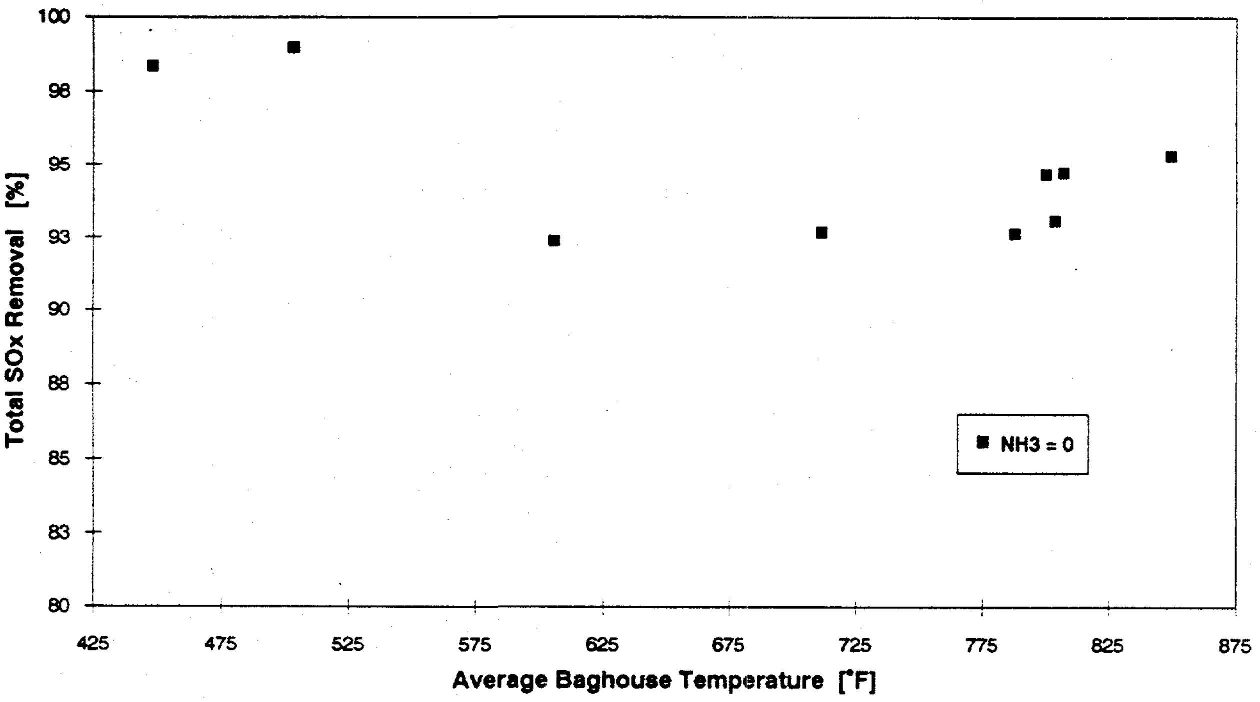


FIGURE 4-25 EFFECT OF TEMPERATURE ON SO_2 REMOVAL WITH Na_2/S OF 2.0

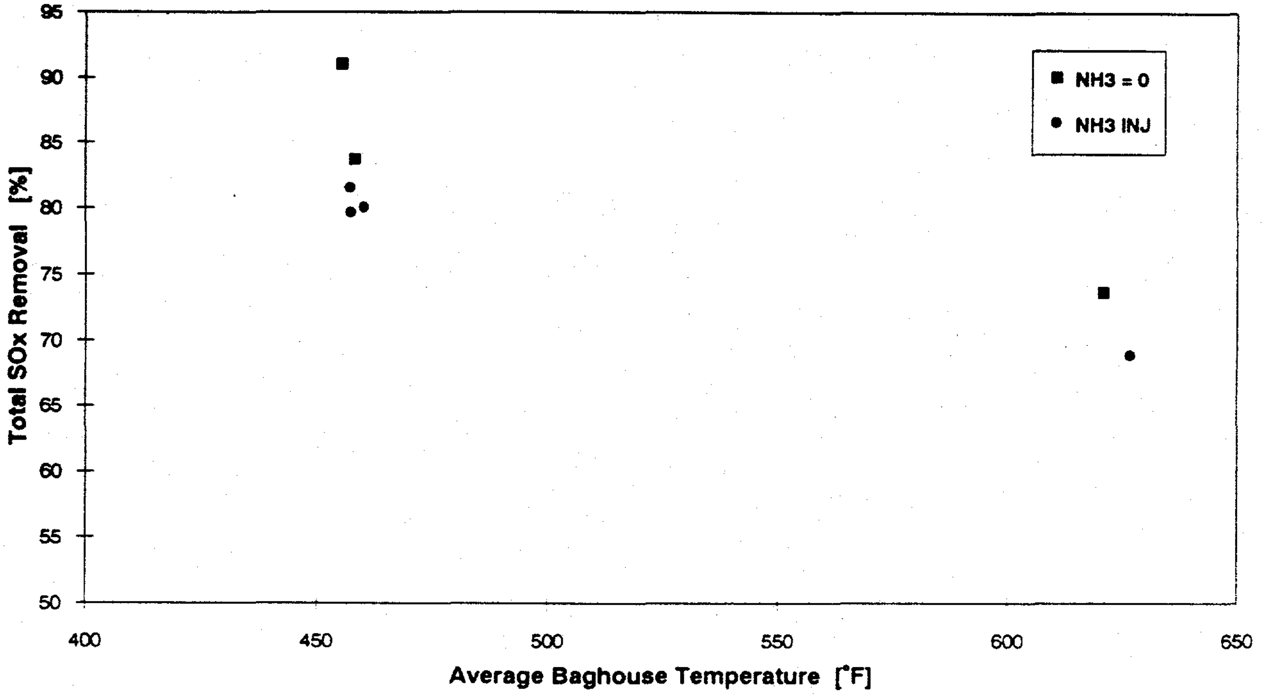


FIGURE 4-26 EFFECT OF TEMPERATURE ON SO_2 REMOVAL WITH Na_2/S OF 1.0

The possible formation of nitrous oxide (NO_2) is a concern in commercial SNRB™ applications using $NaHCO_3$ as the sorbent. NO_2 formation was observed in proof of concept sorbent injection studies conducted by KVB and at the first full-scale dry sodium injection system evaluated by the Public Service Company of Colorado.[17,26] One of the reaction products, sodium nitrate can react with SO_2 to produce NO_2, which can cause a brown stack plume at high concentrations. NO_2 formation can be detected with a chemiluminescent analyzer or by monitoring the opacity. NO_2 production can be suppressed through injection of urea or NH_3.[27]

The question of NO_2 generation was addressed at the SNRB™ demonstration during the $NaHCO_3$ sorbent tests. The ability of NH_3 injection to reduce NO_2 formation was evaluated. The NO_2 concentration at the baghouse inlet and baghouse outlet was measured with chemiluminescent analyzers that were switched from the NO_x to the NO channel. The difference in the steady state readings determined the NO_2 concentration. The tests were conducted over a baghouse temperature range of 450 to 625 °F and an NH_3/NO_x stoichiometry range of 0 to 0.90 mol/mol. The moderate suppression of NO_2 formation by ammonia injection is characterized in Figure 4-27. The difference in NO_2 concentrations measured at the baghouse inlet and baghouse outlet was reduced from approximately 18 ppm without NH_3 injection to 9 ppm with NH_3 injection. No significant increase in the opacity measured downstream of the baghouse could be correlated to the level of NO_2 formation as illustrated in Figure 4-28.

Benefits of a Sodium Bicarbonate System

- No economizer modifications would be required to incorporate a sodium based SNRB™ system into the existing boiler plant cycle.
- Lower temperature baghouse operation over a range of 300 - 550 °F would eliminate the need for high-temperature filter bags improving both capital and operating costs.
- $NaHCO_3$ provides an order of magnitude higher removal efficiency for HCl than for SO_2 and has been successfully used for acid gas (HCl and HF) removal at waste-to-energy plants. The upstream removal of HCl may limit downstream formation of dioxins and furans at lower temperatures in this application.
- The solid byproduct resulting from SNRB™ operation with $NaHCO_3$ has a lower pH than byproduct generated with hydrated lime injection.

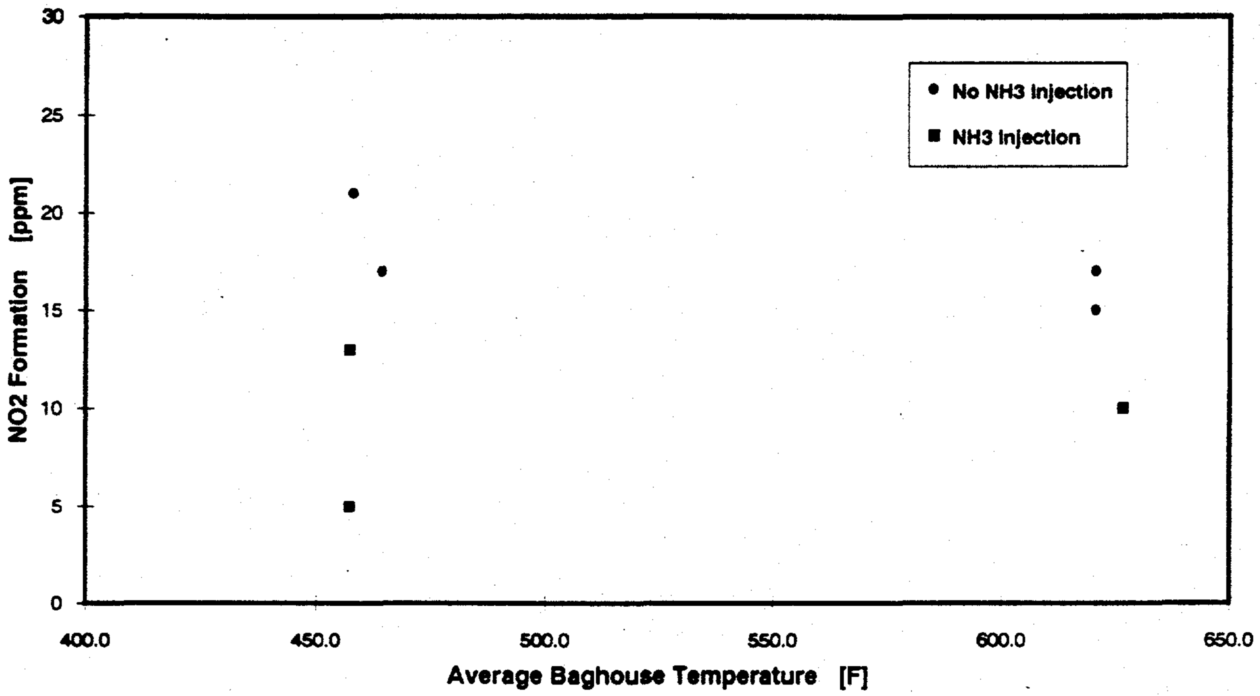


FIGURE 4-27 EFFECT OF NH_3 INJECTION ON NO_2

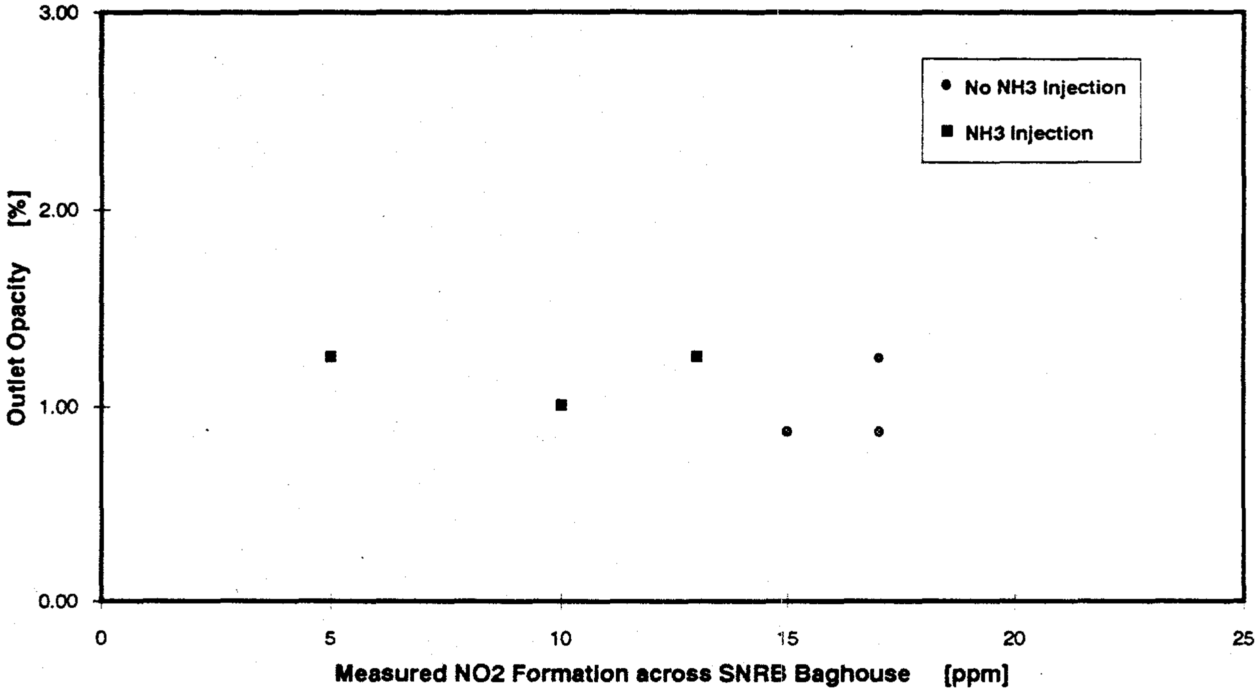


FIGURE 4-28 EFFECT OF NH_3 INJECTION ON OPACITY

- The coarser $NaHCO_3$ PSD provided for baghouse operation at a reduced pressure drop compared to operation with hydrated lime with a similar cleaning cycle. This could also be viewed as a lower rate of pressure drop increase across the baghouse with $NaHCO_3$ resulting in less frequent bag cleaning to maintain the same pressure drop. Operation at reduced pressure drop provides an operating cost savings whereas less frequent cleaning may extend bag life.

- A sodium bicarbonate SNRB^{TM} may also provide for higher air toxics capture over a hydrated lime based system. Operation of the fabric filter at lower temperature should aid the capture of condensible substances.

The disadvantages of the use of sodium bicarbonate include the relatively higher sorbent unit cost, lower NO_x reduction and potentially higher solid byproduct disposal costs.

4.5.12 Secondary Effects on SO_x Removal

Effect of Air-to-Cloth Ratio

To examine the possible effect of the air-to-cloth ratio on SO_2 removal, data sets with the same sorbent, Ca/S stoichiometry, baghouse temperature and sorbent injection location were compared. The data sets that met this criteria permitted evaluation over an air-to-cloth range of 3.0 - 4.5 ft/min. Over this range of operation, no direct link between the air-to-cloth ratio and total SO_2 removal could be established. The data is presented in Figure 4-29.

Effect of SO_2 Concentration

The rationale behind promoting SO_2 removal through reduction of the sorbent particle size and thereby increasing surface area is that the CaO/SO_2 reaction is diffusion-limited. Therefore, the initial SO_2 concentration would be expected to have a direct effect on the reaction rate. However, over the range of SO_2 concentrations evaluated (2100 - 2700 ppm) no effect was observed. Apparently, the range of concentrations generated in operation of the host boiler was too narrow to demonstrate the effects of inlet SO_2 concentration. The SNRB^{TM} system operators had no control over the inlet SO_2 concentration. A comparison of performance with injection of the commercial hydrate at the baghouse inlet is presented in Figure 4-30. A similar observation was made for SO_2 removal with the modified hydrates.

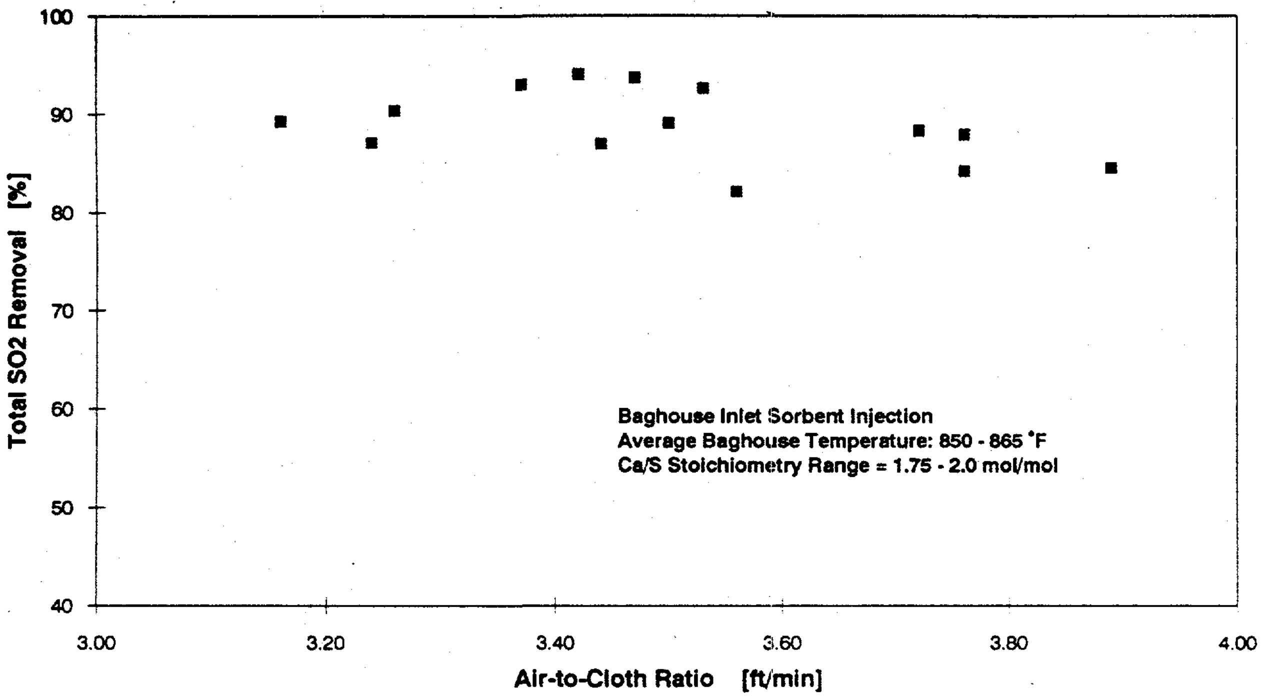


FIGURE 4-29 EFFECT OF AIR-TO-CLOTH RATIO ON TOTAL SO_2 REMOVAL

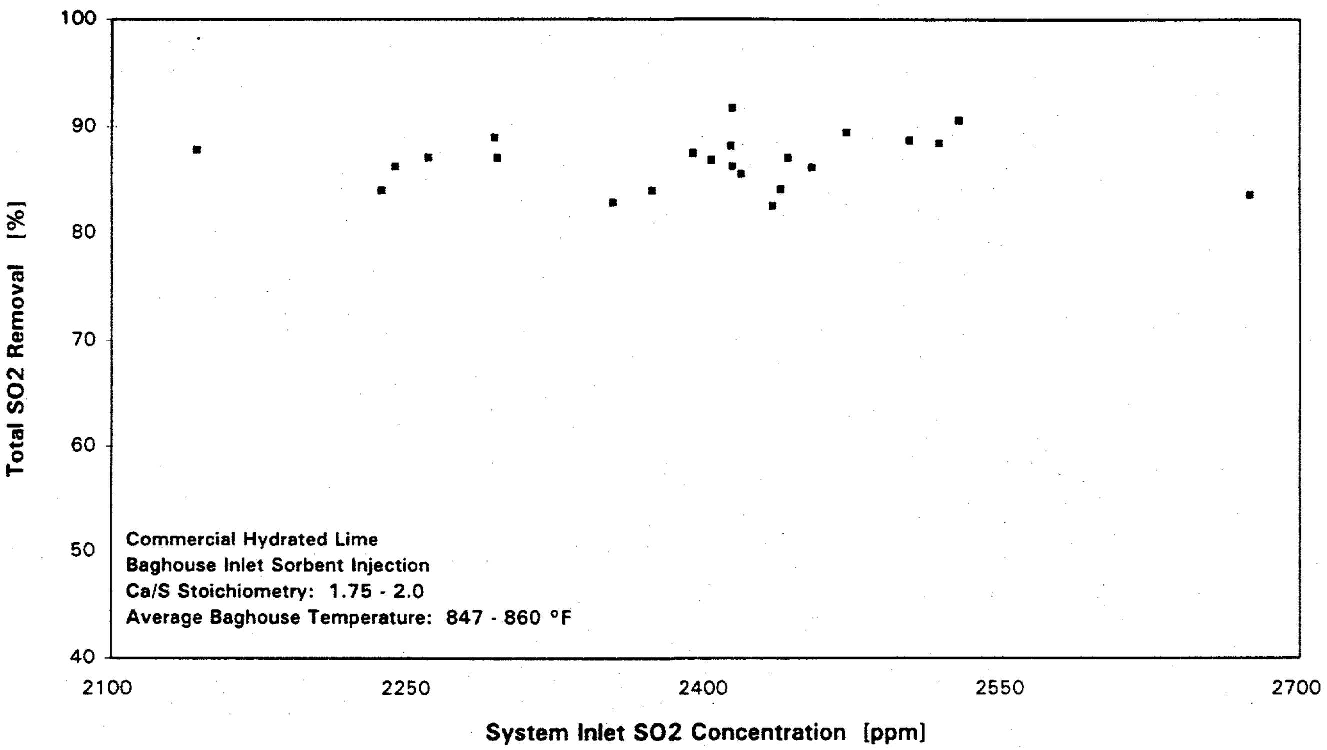


FIGURE 4-30 EFFECT OF INLET SO_2 ON TOTAL SO_2 REMOVAL

Effect of Injector Diameter

A noticeable improvement in lime utilization was observed in the laboratory pilot tests as the sorbent injection velocity was increased from 15 ft/sec to over 250 ft/sec. The higher sorbent injection velocities dispersed agglomerates and enhanced flue gas entrainment due to turbulent mixing. Two different field demonstration injectors were designed to generate injection velocities in the range of 200 to 250 ft/sec for good dispersion of the solids. Midway through the test period, the original 2 1/2 inch diameter injector nozzle was replaced with a 2 inch diameter nozzle increasing the injection velocity from approximately 200 ft/sec to 250 ft/sec for the same transport air flow rate. No significant change in SO_2 removal performance was observed.

Effect of Cleaning Cycle

Since SO_2 removal begins in the flue work and continues in the baghouse, pulsing the filter cake from the bags will influence SO_2 removal. As the quantity of the filter cake on the bags increases, the amount of unreacted sorbent available for reaction increases. The SO_2 removal efficiency increases with time until the bags are cleaned, at which point the SO_2 removal decreases due to the removal of solids from the surface of the bags. This phenomena results in a periodic variation of SO_2 removal as exhibited in Figure 4-31. In the slipstream demonstration, the SO_2 removal decreased by up to 5% with each compartment cleaning, but the effect was temporary and removal quickly returned to its former level. Pulsing a baghouse compartment also temporarily reduced the compartment temperature by approximately 5°F which should have negligible effect on SO_2 removal.

The SNRB^{TM} demonstration baghouse was operated with 5 of the 6 available compartments on-line. Cleaning one compartment affected about 20% of the sorbent available for reaction in the baghouse. For larger commercial applications where more compartments may be required, a smaller percentage of the filter cake will be affected during cleaning and the effect of cleaning on SO_2 removal will be dampened.

Effect of Cleaning Pressure

The bag cleaning pressure was maintained at 30 - 40 psig for the entire test program. The primary intention of varying the bag cleaning pressure was to study the resulting uniformity of cleaning along the 20 foot bag length. An increase in effective cleaning pressure leads to higher operating cost. As 30 - 40 psig was sufficient for complete and thorough cleaning, there was no incentive to evaluate higher pressures that may lead to increased costs and accelerated bag wear.

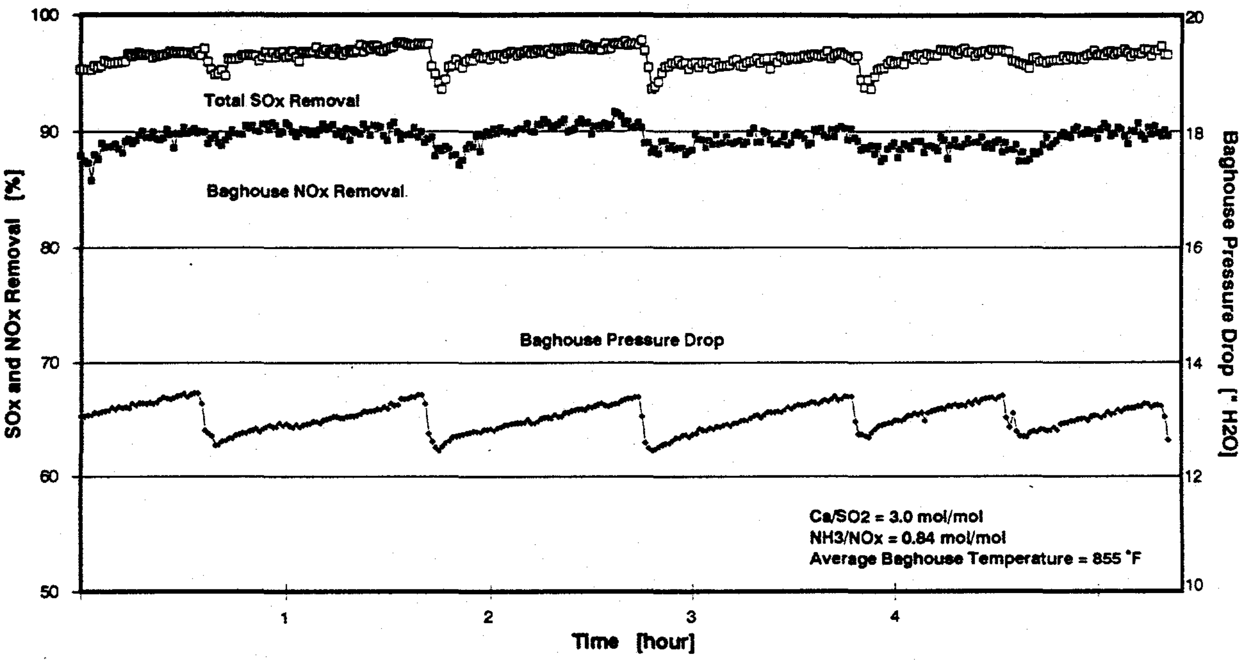


FIGURE 4-31 IMPACT OF BAG CLEANING ON SO_2 AND NO_X REMOVAL

Effect of NH_3 Injection

The possible interference of NH_3 injection on SO_2 removal performance was investigated by two methods. First, the level of steady state SO_2 reduction before and after NH_3 was introduced into the system were compared. There was no obvious change in SO_2 removal that could be differentiated from normal deviations in the continuous data. The second method was by comparing the SO_2 removal averaged over sufficient test periods during which ammonia had and had not been injected. No direct link could be established between NH_3 injection and SO_2 removal with hydrated lime injection. The observed effect of NH_3 injection upon SO_2 removal with $NaHCO_3$ injection was discussed in Section 4.5.11.

4.5.13 Effect of Boiler Fluctuations

To determine suitable control responses to boiler load changes in a commercial SNRB^{TM} application, the effects of actual load changes on the demonstration facility were studied. According to the test plan, the load changes were to be simulated by reduction of the flue gas flow. However, as Ohio Edison frequently dropped load on the host boiler, the effects of actual fluctuations were evaluated. Boiler No.8 typically experienced a load drop at night during warmer months when electricity demand was down. Accompanying a drop in load from 155 MWe to 80 MWe, the temperature of the flue gas entering the SNRB^{TM} facility dropped by approximately 40 °F and the flue gas flow through the facility dropped by approximately 4%. For temporary, cyclic boiler load operation, the baghouse/catalyst temperature decrease may not be significant enough to seriously impact performance. In the demonstration, the incoming flue gas temperature dropped rapidly whereas the baghouse/catalyst temperature dropped more slowly. Based on this 40 °F baghouse temperature drop alone, total SO_2 removal in the baghouse would not be greatly affected as described in Section 4.5.7. However, the impact on SO_2 removal would be significant if a minimum baghouse operating temperature of 800 °F could not be maintained. A 4% drop in flue gas flow resulted in an ATC ratio drop of approximately 4%. As discussed in Section 4.5.12, the ATC ratio had little effect of total SO_2 removal.

Figure 4-32 illustrates the observed change in SO_2 concentration by approximately 340 ppm or 14% typical with an increase in boiler load. Load fluctuations did not appear to affect SO_2 removal when the Ca/S stoichiometry was maintained through automatic control at a pre-selected setpoint. The hydrated lime injection system did not have any difficulty trending the changes in SO_2 concentration and as a consequence there was no long-term effect on SO_2 removal. Figure 4-33 exhibits both the short term change in SO_2 removal accompanying a load increase and the recovery to previous removal levels.

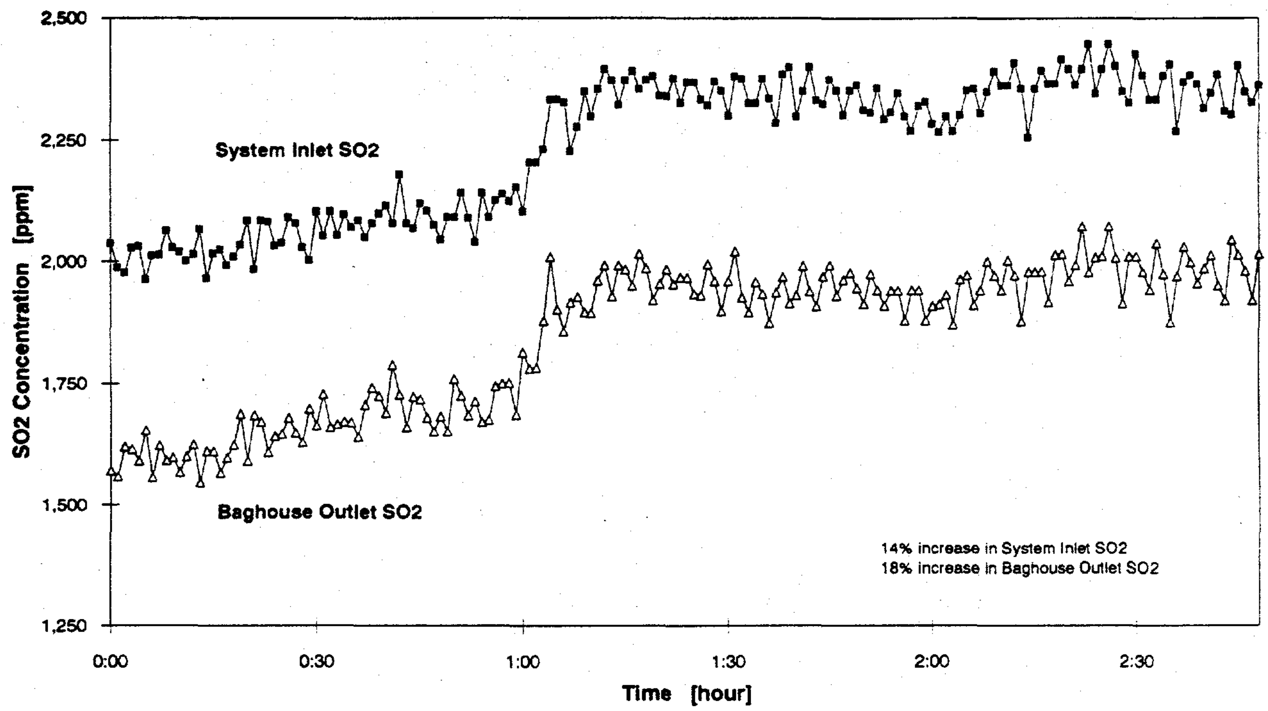


FIGURE 4-32 EFFECT OF LOAD CHANGE ON INLET SO_2

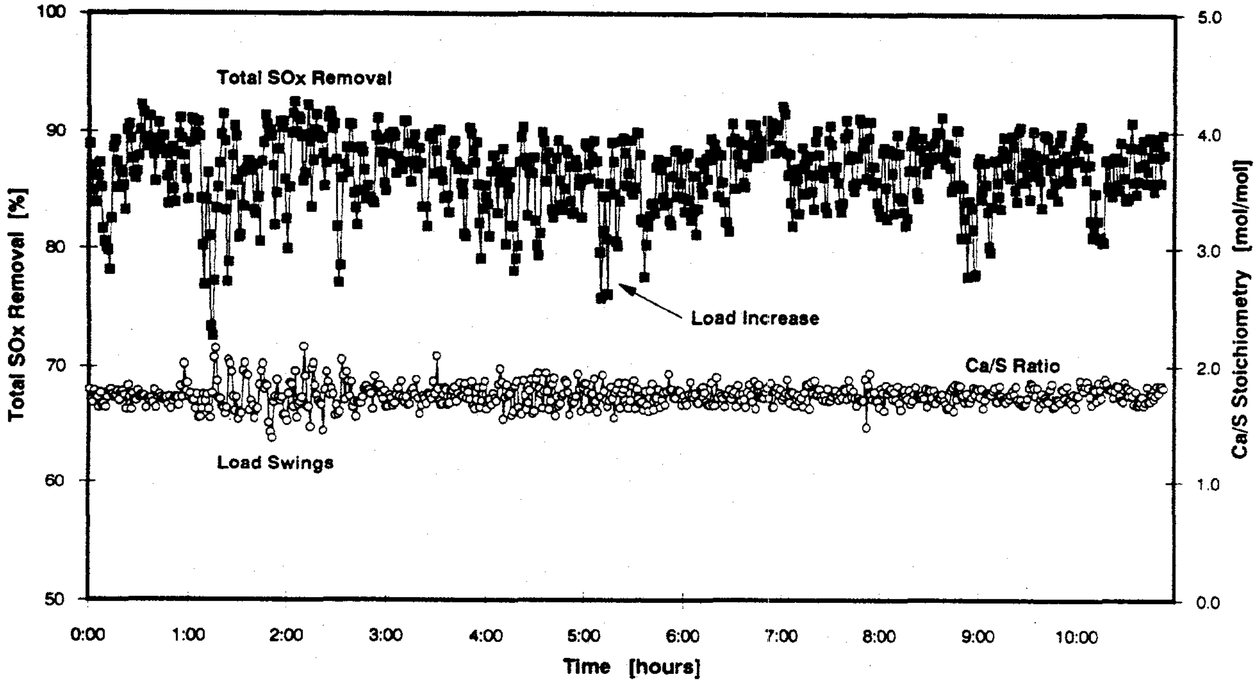


FIGURE 4-33 IMPACT OF LOAD CHANGES ON SO_2 REMOVAL

4.5.14 Success of Lab Pilot Design Improvements

The major recommendations for the 5-MWe demonstration from the design verification pilot test program with respect to SO_2 removal included:

- Further study on the effect of sorbent residence time and injection temperature
- High sorbent injection velocity to promote flue gas/sorbent mixing and obtain a finer sorbent PSD
- Evaluation of alternate sorbents to improve SO_2 removal efficiency and cost-effectiveness

The maximum SO_2 removal achieved in the laboratory pilot tests with hydrated lime at a Ca/S stoichiometry of 2.0 was approximately 75%. Comparison between the SO_2 removal achieved in the lab and the large scale field test demonstrates the effectiveness of the suggested design improvements. Continued investigation of the effect of sorbent residence time and injection temperature encouraged the discovery of improved performance with sorbent injection at lower temperatures just ahead of the baghouse. The selected sorbent injection velocity proved sufficient to disperse the sorbent and prevent build-up in the flue work. The alternative hydrated lime sorbents and sodium bicarbonate all provided increased SO_2 removal.

4.5.15 Corrosivity Evaluation

Acid Deposition Probe

To evaluate the potential for the SNRB™ process to potentially improve boiler cycle efficiency, an air-cooled acid deposition probe (ADP) was exposed to flue gas downstream of the simulated air heater at approximately 200 °F - 300 °F. Removal of SO_3 through sorbent injection could reduce the acid dew point allowing the air heater flue gas exit temperature to be reduced, yielding higher boiler efficiency. Briefly, the ADP was operated to maintain a set temperature profile across the length of the probe which spanned the flue work diameter. The probe was custom-designed and manufactured at the Alliance Research Center by the Materials Performance Section. Probe construction and operation details are presented in Appendix I.

Analysis of the probe after exposure to flue gas for approximately 300 hours suggests that the air preheater downstream of a commercial SNRB™ application may be operated at a flue gas exit stream temperature of 250°F with minimum acid dew point corrosion. B&W currently recommends limiting minimum metal temperatures to 180°F in a pulverized coal burner or cyclone furnace burning coal with a sulfur content of 4.0%. The suggested minimum exit gas temperature of 250 °F roughly corresponds to the design limit used for extended surface tubular air heaters on units burning 0.4% sulfur coal. Combustion of a theoretical 0.4%

sulfur coal with a heating value of 12,000 Btu/lb would generate approximately 0.67 lb $SO_2/10^6$ Btu. Operation of the SNRB™ facility resulted in emissions of 0.14 to 2.3 lb $SO_2/10^6$ Btu over the corrosion probe study period with an average of 1.13 lb $SO_2/10^6$ Btu. When the baghouse operated at 85 - 90% removal, outlet SO_2 emissions averaged 0.55 lb $SO_2/10^6$ Btu with a standard deviation of 0.8. The suggested minimum operating temperature based on the air heater design criteria appears to be consistent with the observed conditions downstream of the SNRB™ baghouse.

Measured corrosion rates for the Corten (A588) and carbon steel (A36) materials as a function of temperature are illustrated in Figure 4-34. Higher corrosion rates were observed for the samples cooled to temperatures below 250°F. It is apparent from Figure 4-34 that the Corten material had a corrosion rate approximately 50% of the carbon steel.

Operation at the recommended minimum temperature of 250°F for an air heater downstream of SNRB™ would not result in a significant improvement in plant efficiency. Longer term corrosion testing is needed to further assess the impact of reduced operating temperatures on heat recovery equipment performance.

SO_3 Measurements

Sulfur Trioxide (SO_3) measurements were conducted by two independent testing companies at the SNRB™ demonstration. The time-averaged B&W SO_2 removal data concurrent with the independent company SO_3 measurements are presented in Appendix J.

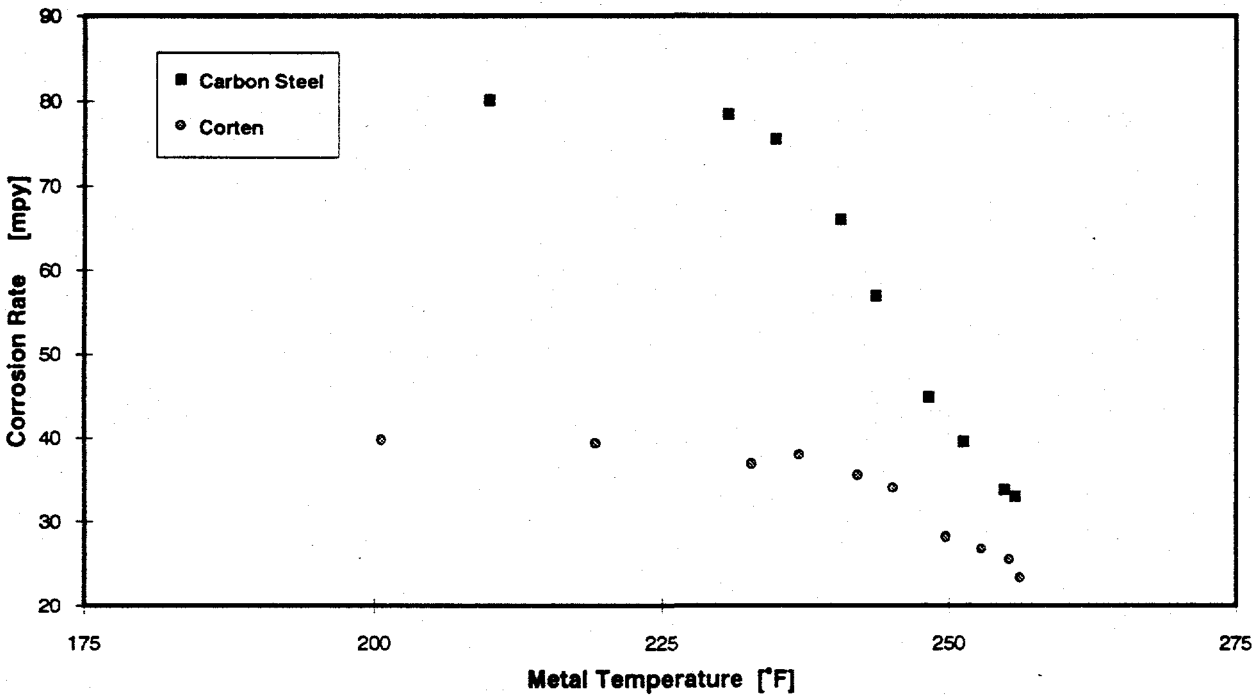


FIGURE 4-34 EFFECT OF METAL TEMPERATURE ON CORROSION RATE

Initial tests were carried out by Total Source Analysis (TSA) over the period of October 27 -November 5, 1992. TSA sampling was conducted at three locations: the system inlet, baghouse outlet and after the outlet flue gas cooler (simulated air preheater). Commercial hydrated lime was injected directly upstream of the SNRB™ baghouse. These sampling locations were chosen to characterize the SO_3 entering the facility, evaluate SO_3 removal across the baghouse and determine the impact of air preheater operation on SO_3 concentration in the flue gas.

The miniature acid-condensation system (MACS) was used to sample SO_3 in the flue gas. Each measurement was conducted over a period of 20 minutes. Sampling was performed in triplicate at each location. Figure 4-35 presents the TSA SO_3 data for the three sampling locations over the testing period. The SO_3 concentration measured at the baghouse outlet were essentially the same as that at the system inlet considering the wide degree of variation from 2 to 10 ppm at both locations. SO_3 measured after the simulated air preheater (at 300 °F) was consistently less than the other two locations suggesting there may have been some condensation in the gas cooler. Based on the general rule of thumb for SCR catalyst that predicts SO_3 formation at 1% of the SO_2 concentration, the SO_3 levels measured are low. The average SO_3 concentrations measured by TSA at the system inlet, baghouse outlet and the gas cooler were 4.8 ppm, 5.5 ppm and 1.3 ppm respectively. The measurements were examined for correlation with baghouse outlet temperature, coal sulfur content, coal moisture content, Ca/S stoichiometry, and SO_2 concentration in the flue gas. No correlations were observed.

To asses the impact of lime injection on the SO_3 emissions, the accuracy of the sampling method and SO_2 oxidation to SO_3 by the SCR catalyst must be taken into account. If operated properly, the MACS train provides reliable and reproducible SO_3 values with little interference from SO_2.[28] TSA reports an overall average SO_3 recovery of 95% with a coefficient of variance of ± 6.7%. Norton Company, the SCR catalyst manufacturer, claims an SO_2 oxidation rate of less than 05% at typical SNRB™ operating conditions. The oxidation rate should be based on the SO_2 measured at the SNRB™ baghouse outlet as the SCR catalyst is located downstream of SO_2 and particulate control. For 80 - 85% SO_2 removal with system inlet SO_2 concentrations of 2,000 - 2,500 ppm, approximately 1.5 - 2.5 ppm SO_3 may be formed by SO_2 oxidation across the catalyst.

Reduced SO_3 concentrations after the simulated air preheater suggests possible SO_3 deposition as ammonium bisulfate or more likely, on fly ash and reaction products deposited in the air heater gas channels. Ammonia slip measured by TSA directly downstream of the SNRB™ baghouse was consistently less than 4.0 ppm during the air preheater SO_3 measurements. In addition, there were no visible deposits of whitish ammonium bisulfate salts observed during air preheater inspections.

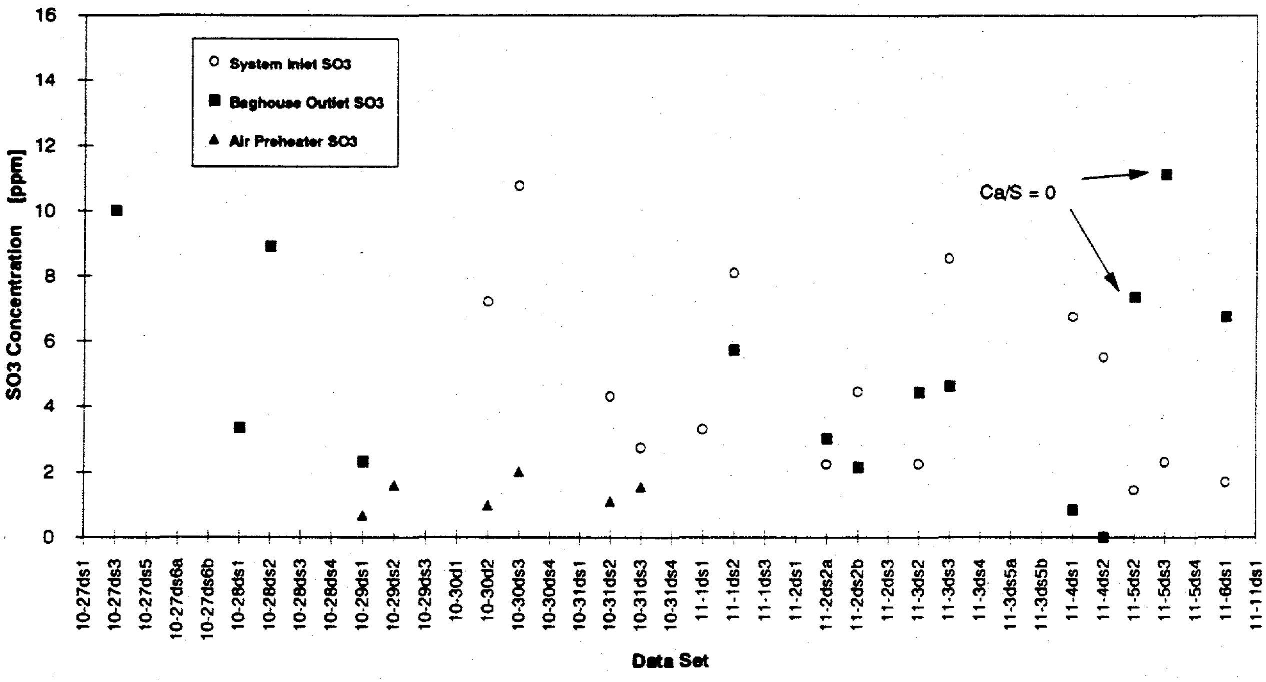


FIGURE 4-35 SO_3 MEASUREMENTS AT KEY PROCESS LOCATIONS

Continuous SO_3 measurements were conducted across the SNRB™ facility by Environmental Energy Services, Inc. (EES) from December 14 - 17, 1992. During these tests, an alternate sorbent, sugar hydrated lime, was injected directly upstream of the SNRB™ baghouse. A description of the continuous SO_3 measurement technique is provided in Appendix J. EES used two different analyzers to monitor SO_3 simultaneously at the system inlet and baghouse outlet.

Figure 4-36 provides an example of the SO_3 measurements over a seven hour period with the corresponding SO_2 concentrations measured by B&W. This plot has shows periodic SO_3 spiking at both the system inlet and baghouse outlet to 20 ppm. The SO_3 variations could not be correlated SNRB™ system inlet or baghouse operating conditions or EES analyzer operation. EES reported that they had never observed this behavior and suggested that additional SO_3 measurements upstream of the SNRB™ facility could have determined whether the spiking was related to boiler operation. The SNRB™ operating conditions were similar to those in the earlier TSA sampling program. Overall, the average SO_3 concentrations measured by EES were very similar to the TSA results. The SO_3 concentration averaged 8.2 ppm at the system inlet and 9.1 ppm.

The continuous SO_3 monitor was reported to have a system accuracy of approximately ± 5% of the reading dependent on the range, temperature and sampling condition. EES has verbally suggested an accuracy of ± 3% for the SNRB™ sampling.

Based on the low SO_3 concentrations measured, the sampling method accuracies and possibility of SO_2 oxidation generating SO_3, it cannot be concluded that calcium-based sorbent injection upstream of the SNRB™ baghouse at 850 to 900 °F effectively reduced SO_3 emissions from the boiler.

The SO_3 measurements did not support the potential of the SNRB™ process to improve plant efficiency through removal of SO_3 to allow the air heater to operate at lower temperatures without concern over acid corrosion. The SO_3 concentration measurements conducted by two independent companies indicated low levels of SO_3 formation across the baghouse that could easily be accounted for by sampling error. The low SO_3 levels measured at the system inlet were not representative of a typical power plant.

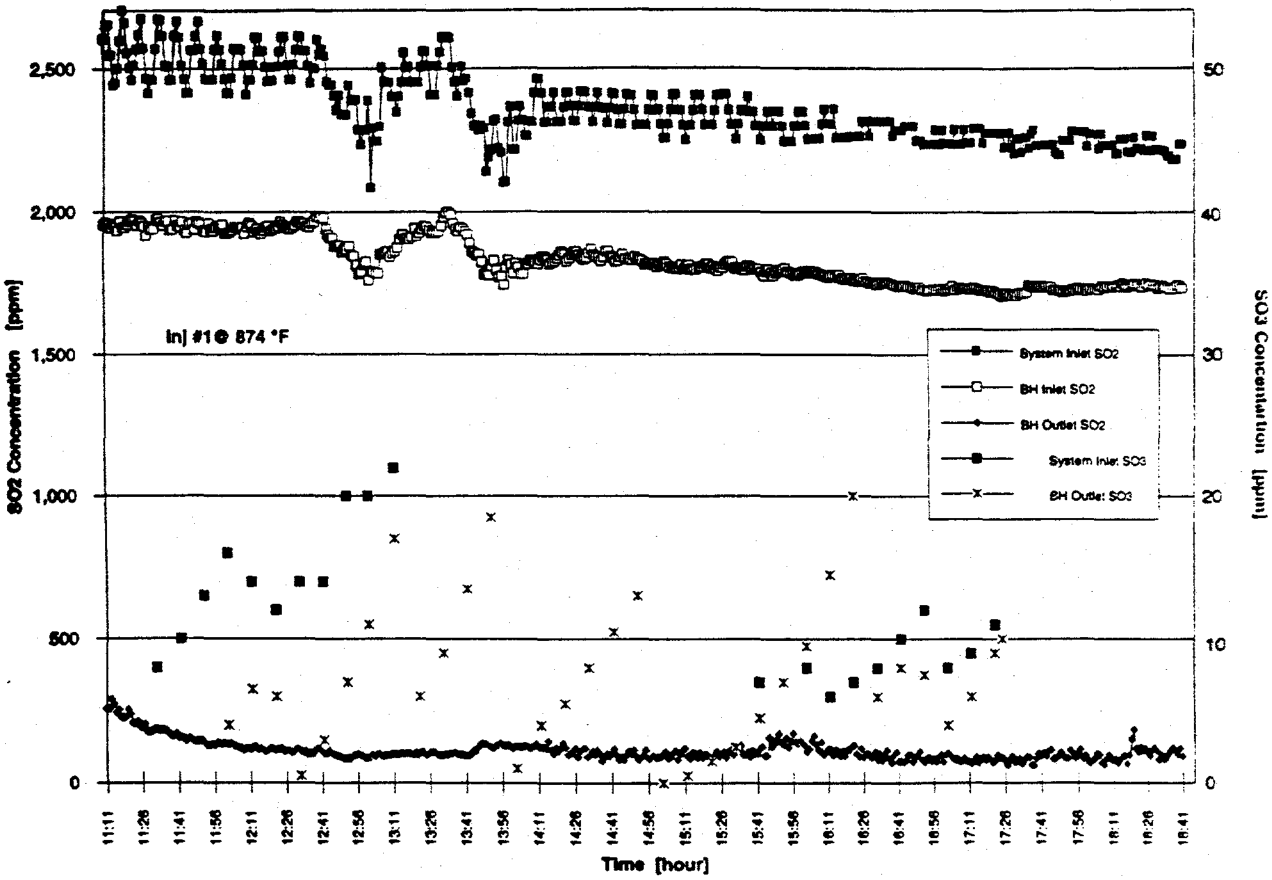


FIGURE 4-36 CONTINUOUS SO_2 AND SO_3 MEASUREMENT PROFILE

4.5.16 SNRB™ Byproduct Disposal

Operation of the demonstration facility generated a total of approximately 830 tons of fly ash and byproduct solids. The pH or corrosivity of the baghouse solids was routinely measured prior to landfill disposal and was consistently less than 12.5 which is the delimiter for classification between a solid and hazardous waste. The byproduct solids pH measurements for the various sorbents is summarized in Appendix K. An independent measurement at Ohio State University found the byproduct pH to be 12.2.

The Toxicity Characteristic Leaching Procedure (TCLP) was conducted quarterly on SNRB™ byproduct solids. The TCLP test procedure is designed to determine the mobility of both organic and inorganic contaminants present in liquid, solid and multiphase wastes. The TCLP test was developed to simulate the leaching potential of a waste when it is disposed in a landfill designed for municipal waste. Such landfills are known to generate organic acids from decomposition of organic matter. The TCLP test does not actually simulate real-world conditions but does create a worst case environment for leaching.[29]

Table 4-9 provides a comparison of the average SNRB™ byproduct TCLP analysis with the regulatory limits. The data in the table confirms the non-toxic nature of the SNRB™ byproduct. The toxicity characteristics were independently verified through the "Land Application Uses For Dry FGD By-Products" project sponsored by OCDO and DOE. In that project, leachate analysis was performed at the Ohio State University.[30] The complete TCLP analytical results are summarized in Appendix L.

TABLE 4-9 SNRB™ BYPRODUCT TOXICITY CHARACTERISTIC ANALYSIS

EPA HAZARDOUS WASTE NUMBER	CONTAMINANT	RESULT [mg/l]	OSU RESULT [mg/l]	REGULATORY LEVEL [mg/l}
D004	Arsenic, Total	<1	<0.08	5.0
D005	Barium, Total	<10	.19	100
D006	Cadmium, Total	<0.1	0.003	1.0
D007	Chromium, Total	<1	<0.004	5.0
D008	Lead, Total	<1	<0.04	5.0
D009	Mercury, Total	<0.04	<0.04	0.2
D010	Selenium, Total	0.27	<0.27	1.0
D011	Silver, Total	<1	<0.024	5.0

An approximate comparison was made of the byproduct generation rate for a SNRB™ system and an ESP/wet scrubber combination based on the following assumptions:

- Boiler firing 3.5% sulfur coal
- 90% SO_2 removal for the SNRB™ system operating at a Ca/S stoichiometry of 2.0 mol/mol
- Wet scrubber operating at a stoichiometry of 1.03.

Under these conditions, SNRB™ would generate about the same mass rate of solids as the wet scrubber with a 75% oxidized by-product combined with the fly ash collected in the ESP. A SNRB™ system would generate approximately 15% more solids than an ESP and forced oxidation limestone wet scrubber with an end product filter cake of 90% solids. [11]

There have been reports of high NH_3 content in fly ash at coal-fired SCR applications preventing resale and complicating disposal of the fly ash. Adsorption of NH_3 on the SNRB™ byproduct would not be favored at typical SNRB™ operating temperatures above 700°F. Ammonia will adsorb on fly ash only at temperatures below 450°F.[31] To test the worst case scenario for NH_3 adsorption, byproduct solids from $NaHCO_3$ injection into the baghouse at approximately 450°F were analyzed with X-Ray Diffraction (XRD) for ammonia and compounds that may have resulted from reaction with NH_3. The XRD patterns generated for baghouse samples collected during tests with and without NH_3 injection are compared in Figure 4-37. The four patterns are very similar indicating no obvious difference in the ashes resulting from tests with and without ammonia injection. Thorough examination of the patterns involving ammonia injection did not reveal the presence of ammonia or even ammonium bisulfate salts. If ammonia were present on the baghouse solids, it would have been detected by operators during the baghouse solid sampling and solid transport from the storage silo to the disposal truck. The threshold odor limit for ammonia is 5 ppm. The odor of ammonia did not emanate from the byproduct solids at any point in the test program, even during tests with deliberately high NH_3/NO_x stoichiometry designed to yield high NH_3 slip.

Although the solid byproduct was landfilled in the demonstration project, beneficial uses for the byproduct exist. Representative baghouse samples were sent to a major cement manufacturer to evaluate the material for use as an addition to their portland cement products. Testing revealed some pozzolanic activity, however addition of the product did not improve the existing strength properties of the portland cement. The cement manufacturer suggested that SNRB™ solids may be of use to local ready-mix cement producers. Other potential applications for the SNRB™ solids include use as an agricultural lime substitute, soil amendment in coal surface mine reclamation, and a highway embankment construction material. A comprehensive study conducted at the Department of Agronomy at the Ohio State University on the chemical, physical, mineralogical and engineering properties of numerous dry FGD by-products concluded that they are highly

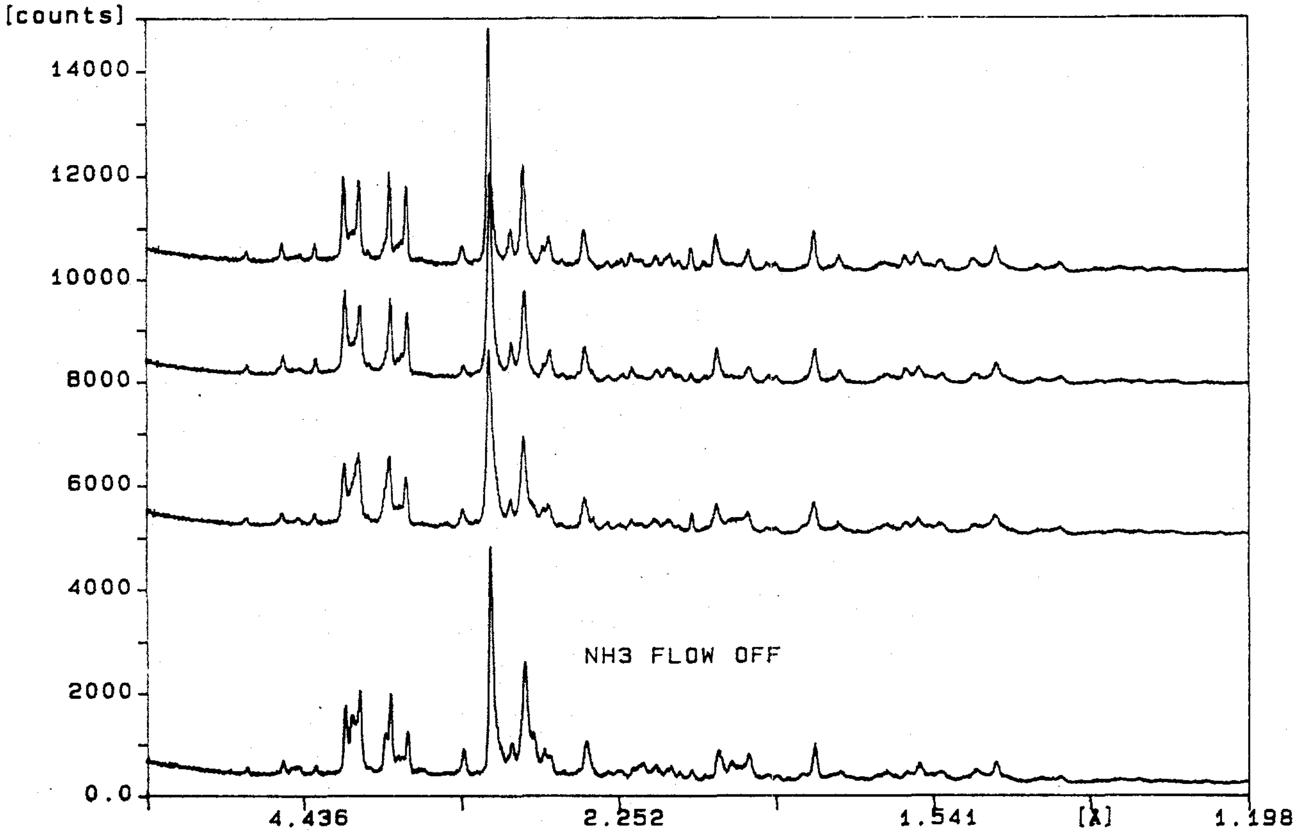


FIGURE 4-37 SNRB™ SOLIDS X-RAY DIFFRACTION PATTERNS

effective as alkaline amendments for acid soil.[32] Various dry FGD byproducts including the SNRB™ solids were evaluated for engineering properties. Compacted SNRB™ material was found to have higher strength and greater stiffness than natural soils typically used in the construction of highway embankments. The compacted density was also lower than typical compacted soil densities and good compaction was achieved over a fairly broad range of moisture contents. The data suggested that FGD by-product materials, used in the construction of highway embankments, would be lighter and require less right of way due to the potential for constructing steeper slopes.[30]

4.5.17 SO_x Removal Conclusions

Higher SO_2 removal efficiencies were consistently achieved with relatively lower temperature (825 to 900 °F) sorbent injection at the baghouse inlet location in comparison to injection at higher temperatures (1100 to 1200 °F) in the flue work further upstream of the baghouse. At this location, the injection temperature was approximately 25 °F greater than the baghouse operating temperature. The lower sorbent injection temperature simplifies integration of the process with the boiler since the need for penetration of the high temperature region of the furnace is eliminated. The high baghouse operating temperature for a calcium system however, will require some modification of the economizer heat transfer surface.

The following key points summarize SNRB™ system SO_2 removal performance in the demonstration test program:

- With the baghouse operating above 830°F, injection of a commercial hydrated lime sorbent injected at Ca/S ratios of 1.8 and above resulted in SO_2 removals over 80%.

- SO_2 removals of 85 to 90% were obtained with Ca utilizations of 40 to 45%. This is significantly higher than the 60% removal, 30% utilization typical of other dry $Ca(OH)_2$ injection processes.

- The use of $NaHCO_3$ as the SO_2 sorbent permitted high removal efficiencies at significantly reduced baghouse operating temperatures.

- SO_2 emissions were reduced to less than the CAAA Phase II compliance limit of 1.2 lb/10^6 Btu with a 3 to 4% sulfur coal using Ca/S ratios as low as 1.5 or Na_2/S ratios less than 1.

4.6 NO$_x$ REMOVAL

4.6.1 Introduction

The feasibility criteria for SCR catalyst applications include: minimal NH_3 slip and SO_2 oxidation, the use and disposition of a potentially hazardous material, handling and storage of ammonia, influence of process byproducts and environment, and NO$_x$ removal performance. Factors that can affect catalyst performance in coal-fired SCR applications include the catalyst composition, operating temperature, molar ratio of NH_3 to NO$_x$, and the catalyst space velocity. The catalyst space velocity (CSV) is defined as the ratio of the volumetric gas flow through the catalyst to the total volume of catalyst. The CSV is expressed in units of reciprocal time and is inversely proportional to the flue gas residence time in the catalytic reactor.

The design of the SNRB^{TM} system provides a unique environment for application of SCR NO$_x$ control to coal-fired boilers. Removal of SO_2 and fly ash before the catalyst and operation above 800 °F provide optimum conditions for high efficiency NO$_x$ reduction.

4.6.2 Ammonia Injection Process

Only the ammonia injection port located approximately 25 feet upstream of the baghouse was used in the demonstration program. A second port located in the high temperature flue gas region was not used. A complete packaged anhydrous ammonia storage and injection system pictured in Figure 4-38 supplied ammonia to the injection point. The ammonia vapor was piped off the headspace of the 1000 gallon storage tank. The system included a back-up ammonia vaporizer which was not used. The ammonia was mixed with air in the transport line in approximately a 1:20 ratio before transport to the ammonia injection grid inside the flue work. The injection grid was designed to provide a uniform distribution of ammonia in the flue gas. The injection grid location was far enough upstream the baghouse to ensure proper mixing of the ammonia with the flue gas.

The ammonia flow, controlled by a signal from the Net-90, was measured with an in-line turbine flowmeter. The flow setpoint was calculated based on the baghouse inlet flue gas flowrate, the baghouse inlet NO$_x$ concentration and the NH_3/NO$_x$ stoichiometry setpoint. The design details of the ammonia injection system are summarized in Table 4-10.

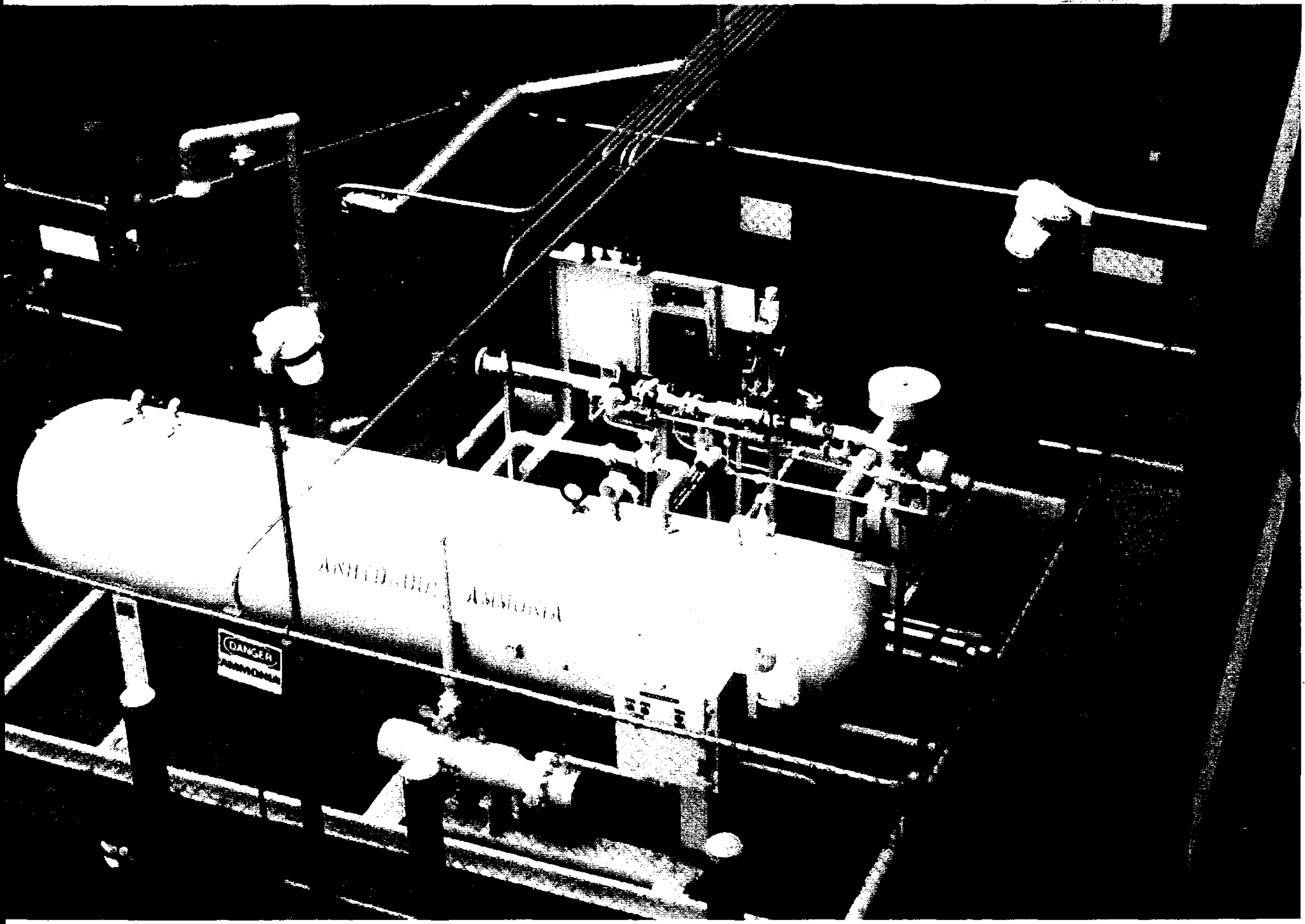


FIGURE 4-38 AMMONIA STORAGE AND INJECTION SYSTEM

TABLE 4-10 AMMONIA INJECTION SYSTEM
1000 Gallon Storage Tank
3-30 lb/hr Ammonia Feed
1-1/4" Transport Line
Variable Speed Dilution Air Blower
1125 lb/hr Maximum Injection Air Flow

4.6.3 Operations Summary

The commercial, non-toxic zeolite NC-300™ catalyst from Norton Chemical Process Products Company was used as the SCR catalyst. The catalyst geometry, formulation or volume were not modified over the 2,300 operating hours of the demonstration. The catalyst assemblies consisted of cylindrical monoliths with a density of 25 cells/inch^2 (cspi). The monoliths were delivered pre-assembled into catalyst holders which were suspended from the baghouse tubesheet inside the filter bags.

The different operating scenarios evaluated at the demonstration included:

- Baseline NO_x removal without the SCR catalyst and without ammonia injection,
- Baseline NO_x removal with the SCR catalyst but without ammonia injection,
- Baseline NO_x removal without the SCR catalyst but with ammonia injection,
- NO_x removal with and without calcium-based sorbent injection,
- NO_x removal with sodium bicarbonate injection.

Most of the operation was performed with hydrated lime injection. The typical operating range of conditions for tests involving NH_3 injection for the reduction of NO_x are summarized in Table 4-11.

The NO_x removal data reported in this section represents NO_x removal across the baghouse and is based on the NO_x concentrations measured at the baghouse inlet and baghouse outlet. The baghouse outlet location was directly downstream of the baghouse. The baghouse inlet gas sampling location was approximately 25 ft upstream of the ammonia injection grid and 50 ft upstream of the inlet to the baghouse.

TABLE 4-11 TYPICAL OPERATING CONDITIONS

Baghouse inlet NO_x concentration	350 - 490 ppm
Baghouse inlet O_2 concentration	4.0 - 6.2 %
NH_3/NO_x stoichiometry	0.62 - 0.91 mol/mol
NH_3 Flow rate	5.7 - 9.2 lb/hour
NH_3 Injection Temperature	810 - 885 °F
Catalyst Temperature	785 - 865 °F
Catalyst Space Velocity	2770 - 3250 1/hour

The reported NO_x removals represent the average performance achieved with steady state operation over 3 to 7 hours. Figure 4-4 presents a typical NO_x removal data set. All of the reduced SNRB^{TM} demonstration NO_x removal data are compiled in Appendix G. The term "average catalyst temperature" used throughout this report is an average of the five temperatures measured within each of the baghouse compartments on-line during a data set. The average catalyst temperature is also reported as the average baghouse temperature. Appendix B contains a schematic showing the 12 foot long catalyst thermocouple locations. The accuracy associated with each temperature measurement was ±4 °F.

4.6.4 NO_x Removal Performance Summary

The SNRB^{TM} project objective was to achieve 90% NO_x emission reduction at a cost-effective NH_3/NO_x stoichiometry while limiting ammonia slip to less than 5 ppm. The NO_x removal capabilities of the SNRB^{TM} system were also investigated over a range of operating conditions to meet the commercial needs for facilities requiring from 50 to 95% NO_x emission reduction. The primary factors affecting NO_x reduction were the NH_3/NO_x stoichiometry and the catalyst temperature. NO_x removals greater than 90%, with ammonia slips generally less than 5 ppm, were consistently achieved in the demonstration. NH_3 slip measurements were made using a modified EPA Method 5 sample train. Results showed that NO_x removal increased with increasing NH_3/NO_x stoichiometry as expected. NO_x removal also increased with catalyst temperature, with optimum removal achieved in the range of 800 to 900 °F. The Norton NC-300^{TM} catalyst was designed for optimal performance between 700 and 900 °F. This overlaps the optimum temperature range for SO_2 removal (800 to 850 °F) with a hydrated lime sorbent. The catalyst space velocity was found to have a minimal effect on NO_x removal over the range of flue gas flow rates evaluated.

4.6.5 Baseline NO_x Removal

Three different types of tests were performed to characterize the degree of NO_x reduction from mechanisms other than the reaction with ammonia in the presence of the SCR catalyst. These additional mechanisms represent baseline NO_x reduction in the SNRB™ system.

The first category of tests were performed without NH_3 injection or sorbent injection with the catalyst installed. Operation in this mode resulted in baseline NO_x emission reduction of 2 to 10% depending on the catalyst temperature as presented in Figure 4-39. This test category represents true baseline removal because in a commercial SNRB™ application, NH_3 injection could be easily turned off but the SCR catalyst would most likely be installed initially with the filter bags. Reaction of NO_x with the steel surfaces of the catalyst holders and perforated filter bag retainers may be partially responsible for the observed NO_x reduction. The demonstration experience corresponds well with the baseline NO_x removal of 6 to 11% observed in the earlier lab pilot tests when the catalyst was not present. In the pilot tests, ammonia was injected far upstream of the baghouse and passed through a small diameter duct which provided a relatively high ratio of steel surface area to flue gas volume.

A second series of tests were performed without NH_3 or sorbent injection as well as without the SCR catalyst in place. These tests yielded negligible levels of NO_x removal.

The third series of tests were conducted at various ammonia injection rates without the SCR catalyst installed. This mode of operation generated the highest levels of baseline NO_x removal across the baghouse. NO_x emission reduction of 10 to 25% was observed with increasing NH_3/NO_x stoichiometry as shown in Figure 4-40.

Fly ash was present in the baghouse in all three baseline test series. However, the second test series revealed that fly ash alone was not reactive with NO_x over the operating temperature range. Comparison of the results from the second and third test series indicate that the high NO_x reduction in the third series may be explained by reaction with NH_3 in the presence of fly ash. The reactive components in the fly ash may be the iron oxides or the unburned carbon. Additional research suggests that the reaction of carbon and NO_x is minimal.[33]

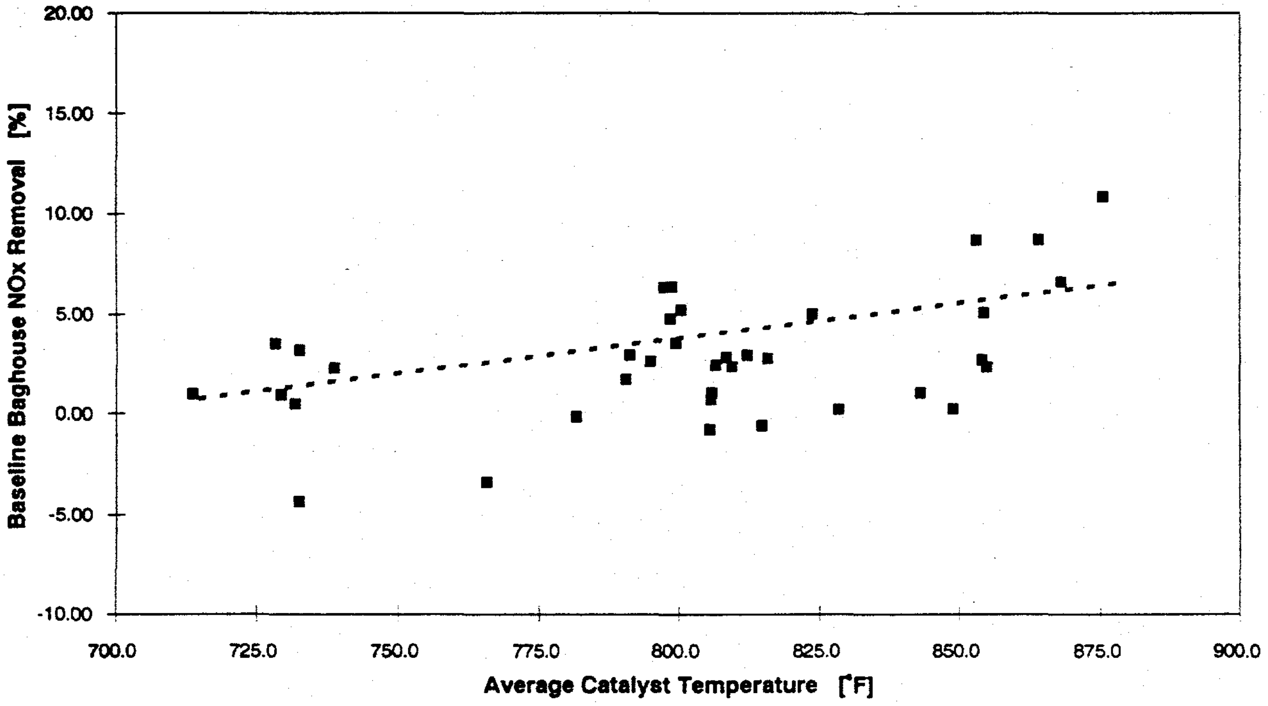


FIGURE 4-39 EFFECT OF CATALYST TEMPERATURE ON BASELINE NO_x REMOVAL

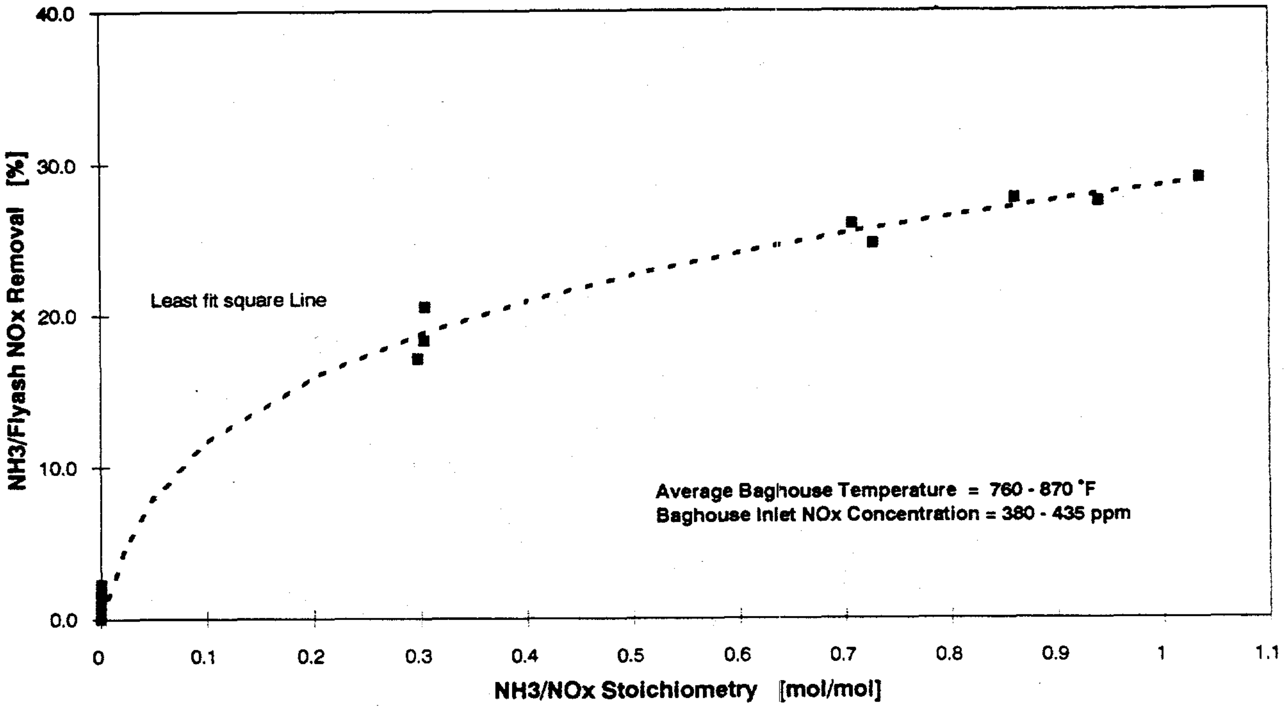


FIGURE 4-40 EFFECT OF NH_3/NO_X RATIO ON FLY ASH NO_X REMOVAL

4.6.6 Ammonia Oxidation

Fly ash in flue gas may act as a catalyst for the oxidation of ammonia and the reduction of NO_x by ammonia. Janssen et. al. studied the reduction of NO_x by ammonia on fly ash in a laboratory reactor.[31] Considerable conversion of ammonia and NO_x was found at temperatures greater than 400 °C (752 °F). Ammonia oxidation products may include nitrogen (N_2), nitrous oxide (N_2O), NO_x and water according to the following reactions:

$$4\ NH_3\ (g) + 3\ O_2\ (g) > 2\ N_2\ (g) + 6\ H_2O\ (g) \quad (1)$$

$$2\ NH_3\ (g) + 2\ O_2\ (g) > N_2O\ (g) + 3\ H_2O\ (g) \quad (2)$$

$$4\ NH_3\ (g) + 5\ O_2\ (g) > 4\ NO\ (g) + 6\ H_2O\ (g) \quad (3)$$

The tests conducted by Janssen revealed that above 700 °F the oxidation of ammonia becomes important and that N_2 and N_2O were produced in equal amounts. No NO_x was detected in the oxidation experiments, eliminating reaction (3) as a predominate reaction.

In the SNRB™ system, ammonia is injected into the flue gas containing a high level of SO_2. The NH_3/SO_2 reaction is favored at temperatures below 450 °F, significantly lower than the ammonia injection temperature range of 700 to 900 °F. Furthermore, in the demonstration program the ammonia injection grid was regularly examined and found to be free of ammonium bisulfate deposits. These observations suggest that reaction with SO_2 is not a likely source of ammonia consumption.

In contrast to the findings of Janssen, N_2O measurements across the SNRB™ laboratory pilot baghouse with ammonia injection revealed no N_2O generation. [1] The absence of N_2O formation in the baghouse is supported by the theoretical mechanism developed by Norton for SCR of NO_x with NH_3 over the NC-300™ zeolitic catalyst. Norton postulated that any N_2O formed by the oxidation of NH_3 may decompose as the gases pass through the zeolite catalyst.[34] The degree of ammonia oxidation was characterized by three different methods at the field demonstration.

NH_3 Oxidation Check - Method 1

Ammonia measurements were made in conjunction with an EPA Method 5 sample train directly upstream of the baghouse to determine if any ammonia had reacted since the point of injection. The baghouse inlet NO_x concentration which served as the basis for the NH_3/NO_x stoichiometry was measured approximately

25 feet upstream of the ammonia injection point and 50 feet upstream of the baghouse inlet. At a CSV of 3,200 1/hr, the ammonia would mix with the NO_x, lime and fly ash in the flue work for approximately 0.5 seconds before reaching the baghouse entrance. The measured NH_3/NO_x stoichiometries at the baghouse inlet were on average only 65% of the injection NH_3/NO_x stoichiometry, indicating that some ammonia destruction occurred in the flue work between the NH_3 injection grid and the baghouse inlet. The NH_3/NO_x verification measurements were repeated by the independent sampling company. The NH_3/NO_x stoichiometries calculated from the NH_3 measurements at the baghouse inlet are compared to the NH_3/NO_x stoichiometry set points in Figure 4-41. The possibility of NH_3 oxidation was further substantiated as the measured NH_3/NO_x stoichiometries were on average 86% of the injection stoichiometry. The dashed line in Figure 4-41 represents perfect agreement between the estimated and measured NH_3/NO_x stoichiometries.

NH_3 Oxidation Check - Method 2

Norton conducted bench-scale ammonia oxidation tests over the SNRB™ byproduct solids in a glass reactor. The tests were conducted with no NO_x or SO_x in the feed gas at a space velocity of 150,000 1/hr. Testing over a temperature range of 660 to 855 °F indicated the degree of ammonia destruction increased with temperature as illustrated in Figure 4-42. Over the optimum SNRB™ baghouse operating temperature range of 800 to 850 °F, approximately 11% of the NH_3 was converted. Low levels of NO_x formation (less than 12 ppm) were measured.

NH_3 Oxidation Check - Method 3

A recommendation from the design verification pilot tests was to evaluate the effect of baghouse operating temperature on NH_3 oxidation by measurement of N_2O downstream of the baghouse. Attempts were made to measure N_2O at the baghouse inlet 0.5 seconds downstream of the NH_3 injection point and at the baghouse outlet with a continuous Anarad N_2O analyzer. Unfortunately, the analyzer experienced numerous electronic problems and the measurements could not be completed.

Both Method 1 and Method 2 for evaluating the degree of ammonia oxidation indicate that some ammonia destruction was occurring from contact with the fly ash/lime/SO_2 reaction products in the SNRB™ system resulting in low levels of NO_x generation. In light of the apparent ammonia oxidation, which reduced the amount of NH_3 available for reaction, and the less than theoretical stoichiometric NH_3/NO_x requirement for NO_x reduction observed in the test program, the fly ash catalyzed reaction may have been a significant contributor to overall NO_x emissions reduction.

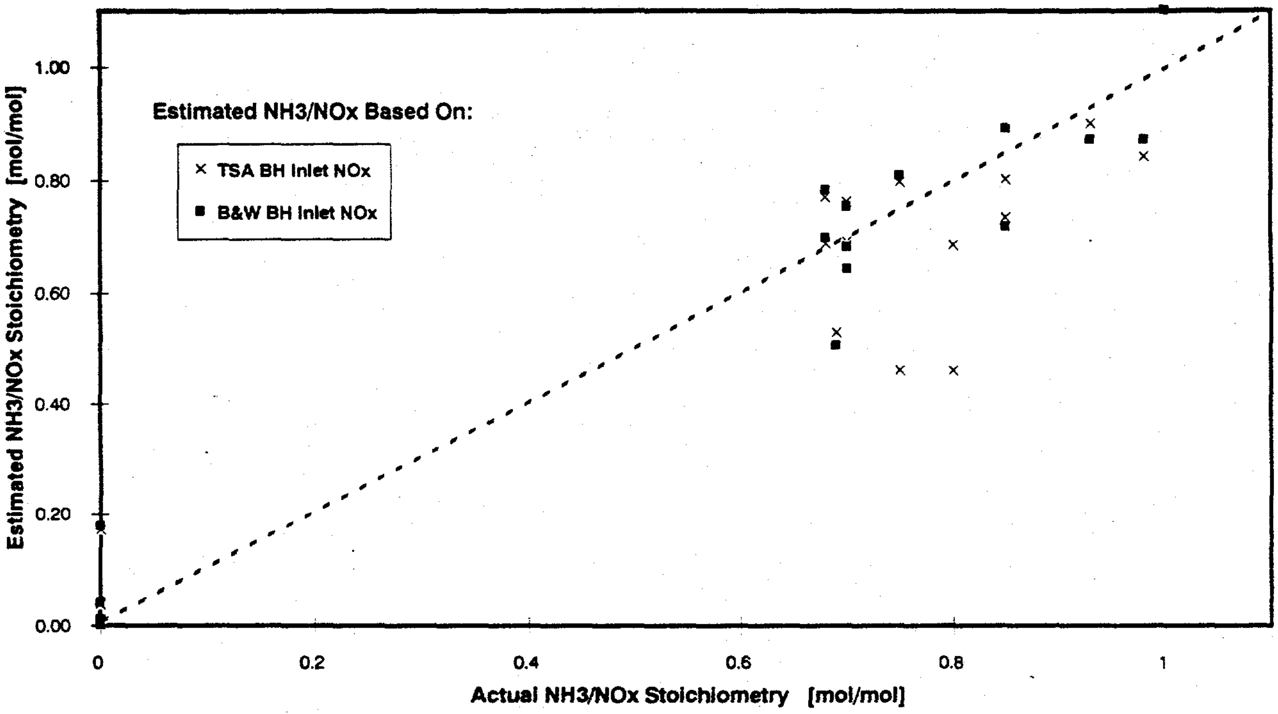


FIGURE 4-41 COMPARISON OF ESTIMATED AND ACTUAL NH_3/NO_x RATIOS

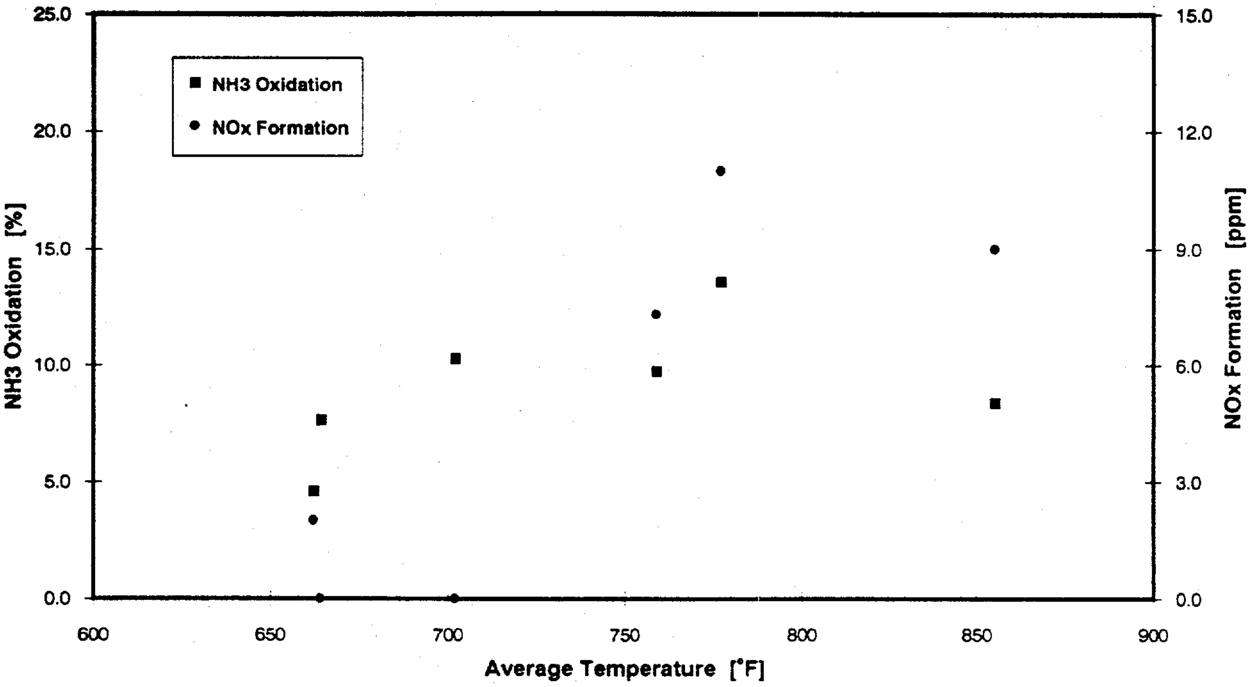


FIGURE 4-42 BENCH SCALE NH_3 OXIDATION TESTS

4.6.7 Catalytic Activity of Fly Ash

In addition to destruction of ammonia, fly ash may catalyze NO_x reduction by ammonia as reported by Janssen and Bobman.[30,34] Above 480 °F the overall reactions are reported to occur are:

$$4\ NO\ (g) + 4\ NH_3\ (g) + O_2\ (g) > 4\ N_2\ (g) + 6\ H_2O\ (g) \qquad (4)$$

$$4\ NO\ (g) + 4\ NH_3\ (g) + 3\ O_2\ (g) > 4\ N_2O\ (g) + 6\ H_2O\ (g) \qquad (5)$$

Norton performed bench-scale tests to evaluate NO_x reduction reactivity of the SNRB™ byproduct solids. Solids samples representative of operation at Ca/S stoichiometries of 1.5 and 2.0 mol/mol were evaluated. A slight degree of activity (6.2% NO_x reduction) was observed with the solids from operation at a Ca/S stoichiometry of 2.0. This result does not compare well with the 10 to 25% NO_x removal observed in the demonstration tests without the SCR catalyst installed. The bench-scale tests were conducted in a glass reactor without SO_2 or H_2O, which are normally present in operation of the SNRB™ system. Other differences from actual SNRB™ operating conditions included low NO_x concentrations (100 ppm) and high space velocity (150,000 1/hour).

Bobman and Weber evaluated various "throwaway" substances including fly ash for catalytic reduction of NO_x with ammonia in both bench-scale and pilot-scale equipment.[35] The testing demonstrated relationships between the level of NO_x reduction and the temperature of the reaction, fly ash composition, and the crystalline phases present as identified by x-ray diffraction. The quantity and form of iron in the ash was shown to dramatically influence fly ash catalytic activity.

The bench-scale tests performed by Bobman and Weber revealed a proportional relationship between NO_x removal and temperature. The best catalyzing agent was a lignite fly ash which achieved 25% NO_x removal at 880 °F. This is similar to the SNRB™ demonstration tests in which the solids included bituminous coal ash and a variety of calcium compounds. The lignite fly ash contained 9.1% Fe_2O_3. The Fe_2O_3 content in SNRB™ byproduct averaged 5.6 - 12.3%. The pilot unit tested was very similar to the SNRB™ pilot baghouse. Fly ash and ammonia were injected upstream of a pulse-jet baghouse containing Nextel™ fabric bags. Again, the lignite fly ash had the highest catalytic activity with a maximum NO_x reduction of 29% at 817°F. Bobman and Weber selected iron-bearing materials to evaluate based on earlier literature reports in which iron oxides were observed to promote the reduction of NO_x.[35]

In tests at the SNRB™ demonstration without the catalyst installed, the NH_3/NO_x stoichiometry appeared to control the rate of reaction as shown in Figures 4-43 and 4-44. The fly ash-catalyzed NO_x removal immediately responded to changes in the NH_3/NO_x stoichiometry. As indicated in Figure 4-43, a consistent 15% NO_x reduction was observed at an NH_3/NO_x ratio of 0.5 to 0.6. No correlation was found between the catalytic activity of the fly ash and temperature over the evaluated range of 760 to 860 °F.

4.6.8 Effect of Catalyst Temperature

The zeolite catalyst was designed to provide uniform performance over a wide temperature range. This design characteristic improves the flexibility of the zeolite catalyst in coal-fired applications characterized by changes in flue gas temperature accompanying boiler load fluctuations. The temperature insensitivity of the NC-300™ catalyst was examined in the demonstration over a range of 700 to 900 °F. Figure 4-45 illustrates that over a temperature window of 780 to 865 °F the zeolite catalyst provided a consistent level of emission control for each of several NH_3/NO_x stoichiometries. NO_x emissions reduction at 700 to 750 °F was approximately 3% lower than observed at the higher temperatures.

Norton has improved the zeolite catalyst formulation evaluated in the SNRB™ demonstration program to exhibit even greater temperature insensitivity. The stable framework of the zeolite provides for application of SCR over a wide temperature range, including temperatures greater than 1000 °F. Norton reports that the ion-exchange capability of the improved zeolite facilitates the optimization of SCR catalysts over a wider temperature range than V_2O_5/TiO_2 promoted and metal oxide catalysts as shown in Figure 4-46. For the new zeolite catalyst, greater than 90% NO_x removal is predicted for a temperature range of 600 to 1050 °F. [7]

In alternate SO_2 sorbent tests with sodium bicarbonate, the catalyst was exposed to temperatures as low as 450 °F. To avoid ammonium bisulfate salt formation and deposition on the catalyst, the majority of the $NaHCO_3$ tests were performed without NH_3 injection. Operation with NH_3 injection confirmed that the NH_3/NO_x reaction is not favored at the lower temperatures and that the reaction between $NaHCO_3$ and NO_x predominates at the lower temperatures. NO_x removal observed with $NaHCO_3$ injection is discussed further in Section 4.6.14.

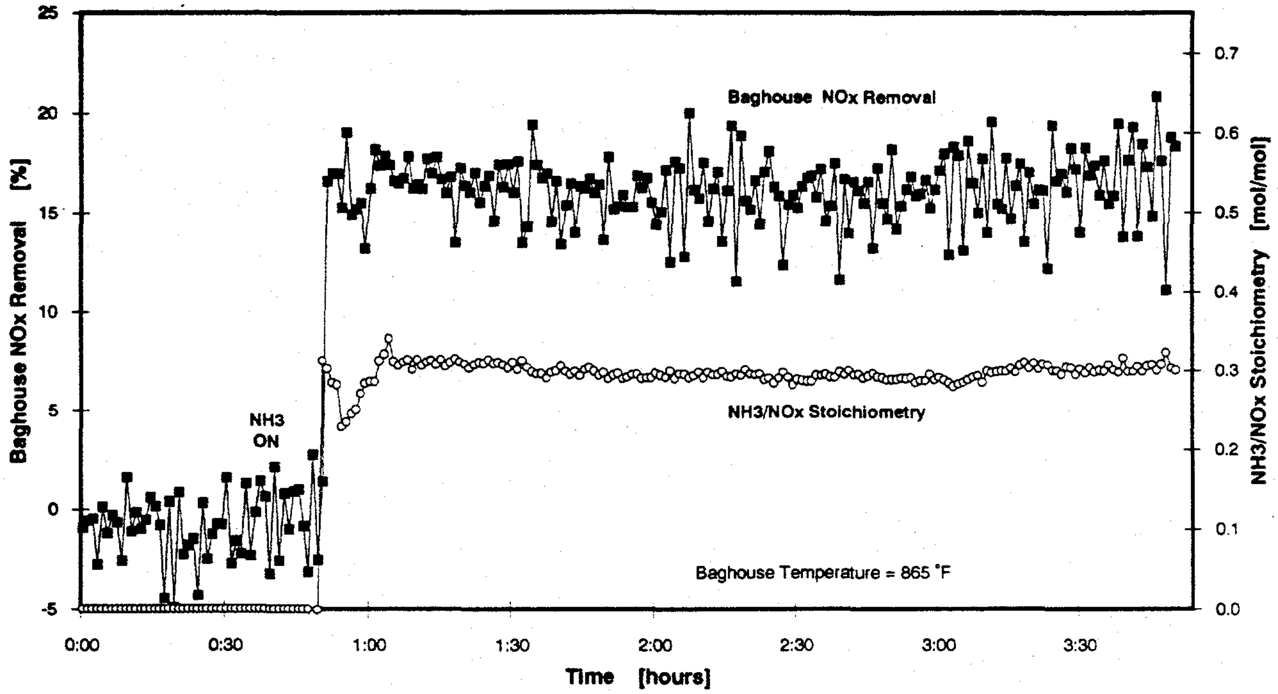


FIGURE 4-43 EFFECT OF NH_3/NO_x RATIO WITHOUT CATALYST - 1

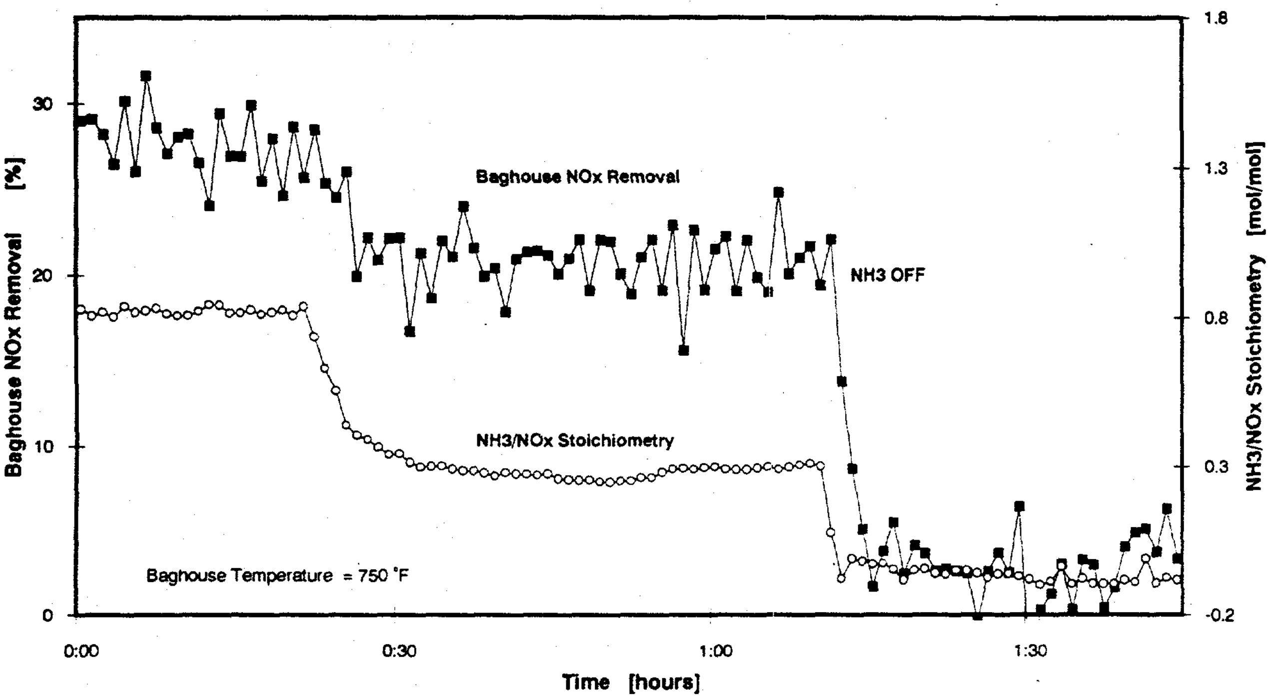


FIGURE 4-44 EFFECT OF NH_3/NO_x RATIO WITHOUT CATALYST - 2

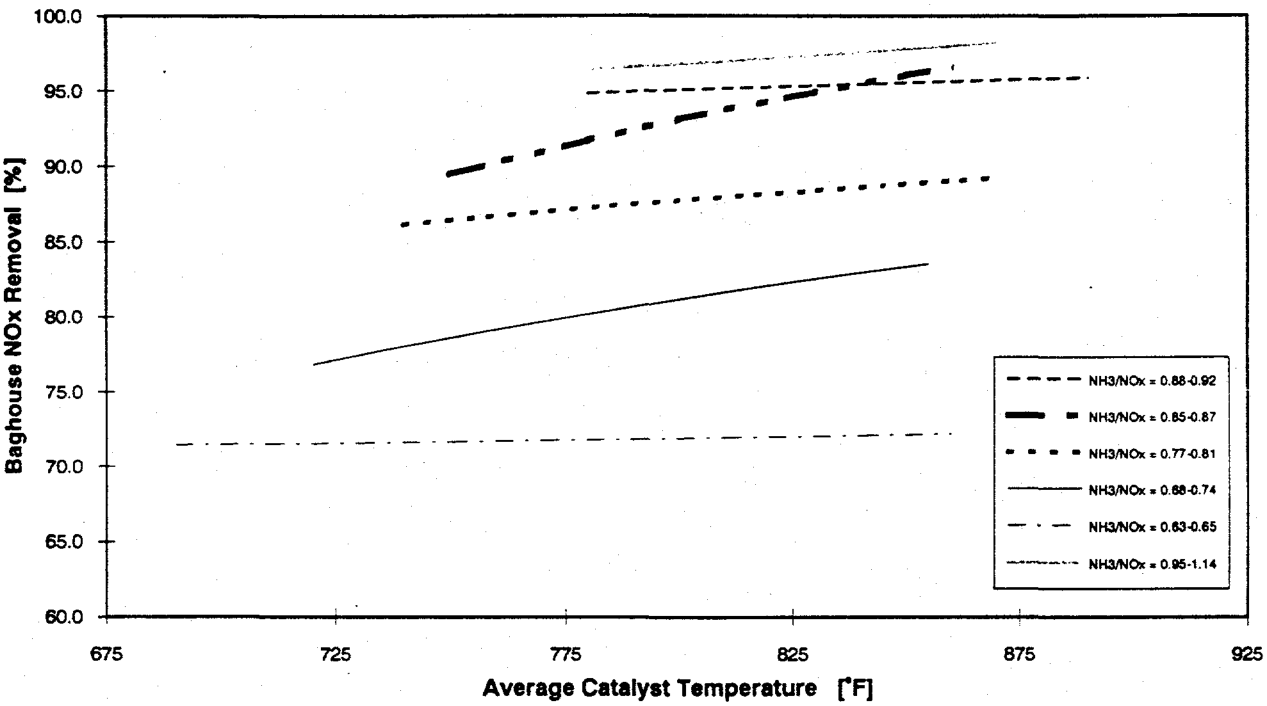


FIGURE 4-45 EFFECT OF CATALYST TEMPERATURE ON NO_x REMOVAL

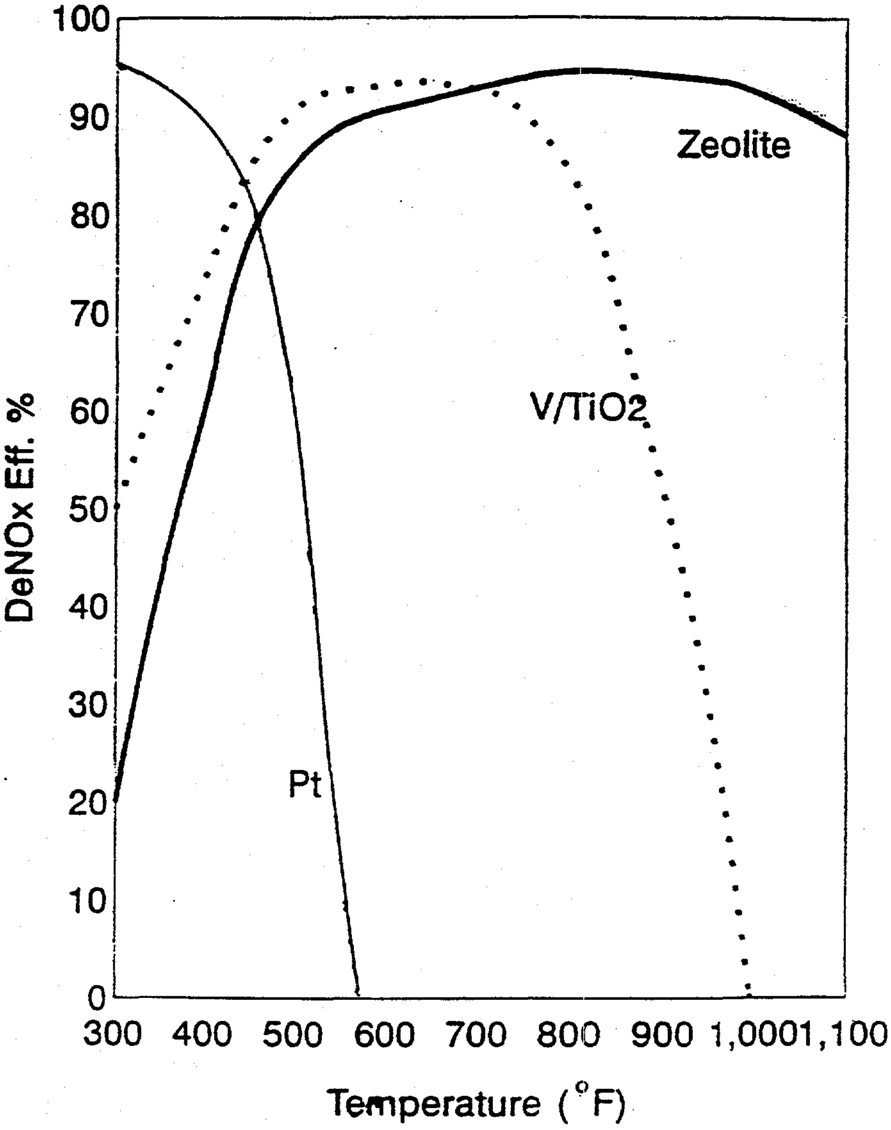


FIGURE 4-46 RELATIVE SCR CATALYST PERFORMANCE

4.6.9 Effect of Catalyst Space Velocity

The catalyst space velocity (CSV) effectively controls the time the flue gas is in contact with the catalyst. For the demonstration program, the design catalyst space velocity was 3,300 1/hour corresponding to a baghouse air-to-cloth (ATC) ratio of 4.0 ft/min and operating temperature of 800 °F. In the SNRB™ system, the operating CSV is determined by the ATC ratio. An early perceived benefit of pulse-jet baghouse was operation at exceptionally high ATC ratios of 5 to 7 acfm/ft^2. However, in commercial practice a trend towards operation at lower ATC was recognized by Belba et. al. to ensure reasonable pressure drops, less frequent cleaning and thus longer bag life and lower outlet particulate emissions.[10] In response to this trend, the decision was made to limit operation to a maximum ATC ratio to 5.0 acfm/ft^2 which in turn affected the CSV evaluated. As a result, a CSV range of 2,100 to 3,400 1/hr was evaluated for impact on NO_x removal efficiency.

The effect of CSV on NO_x removal is presented Figures 4-47 and 4-48 which represent operation over narrow NH_3/NO_x stoichiometry ranges of 0.68 to 0.74 and 0.85 to 0.92. The data was additionally sorted for operating temperatures of 800 °F and 850 °F to limit the influence of catalyst temperature variation on NO_x reduction. For the given NH_3/NO_x stoichiometries, the CSV had no influence on the observed NO_x removal. These findings are supported by bench-scale tests conducted by Norton. [1] In the bench-scale tests, the CSV had a significant impact on NO_x removal at catalyst temperatures less than 750 °F, with improved removal at reduced CSV. As the catalyst temperature was increased, the influence of the CSV was diminished, especially over the SNRB™ baghouse temperature range of 800 to 850 °F.

4.6.10 Effect of NH_3/NO_x Stoichiometry

The relationship between NO_x removal and the NH_3/NO_x stoichiometry has been extensively examined for different types of SCR catalysts and has been routinely found to be linear. In most studies, optimum conversion has typically been found to occur at a molar ratio of NH_3 to NO_x approximately equal to 1.0. However the SNRB™ catalyst location differs from typical high-dust or low-dust SCR configurations in that the primary reactants initially pass through a continually self-renewing layer of solids on the filter bag surfaces. The reactions that occur across the filter cake in the SNRB™ baghouse appear to also include NO_x reduction. The actual NH_3/NO_x ratio contacting the catalyst may be greater than the set point due to NO_x reduction upstream of the catalyst. This phenomena would generate test results that suggest less than the theoretical stoichiometry of NH_3 to NO_x is required for the observed NO_x reduction. The reported NO_x reduction has been adjusted for baseline NO_x reduction observed with the catalyst installed but without ammonia injection.

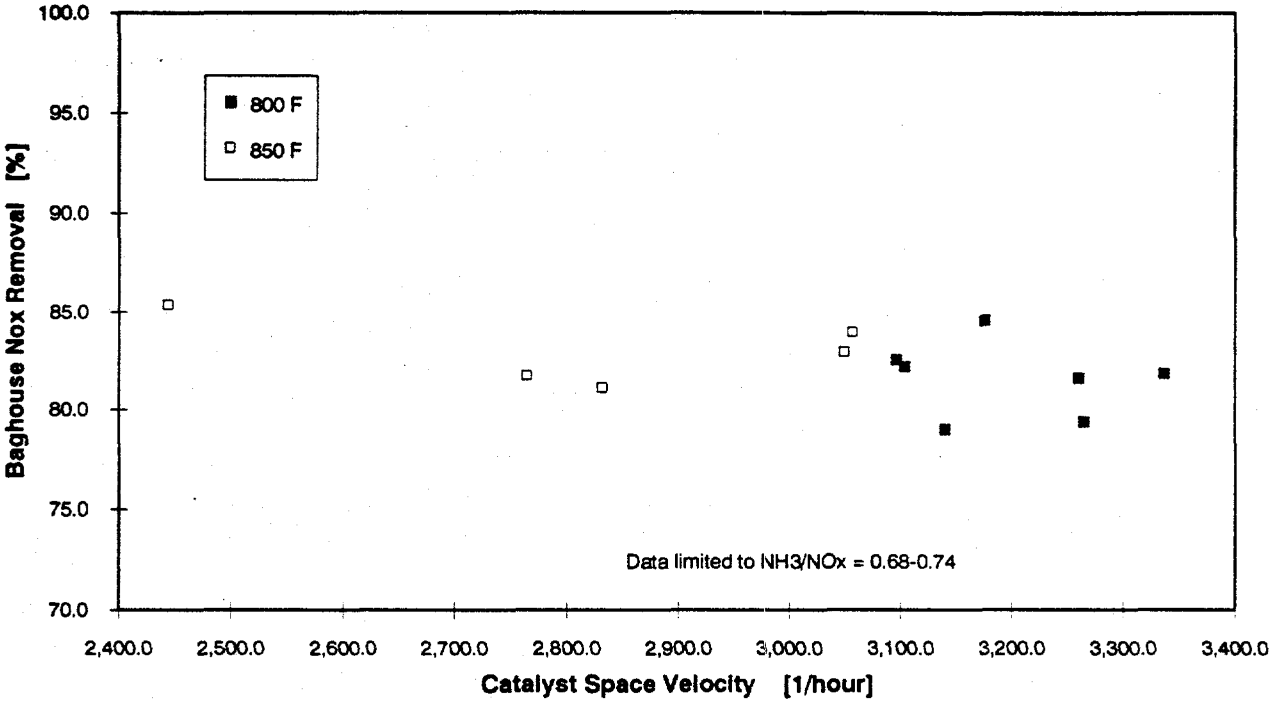


FIGURE 4-47 EFFECT OF SPACE VELOCITY ON NO_x REMOVAL -1

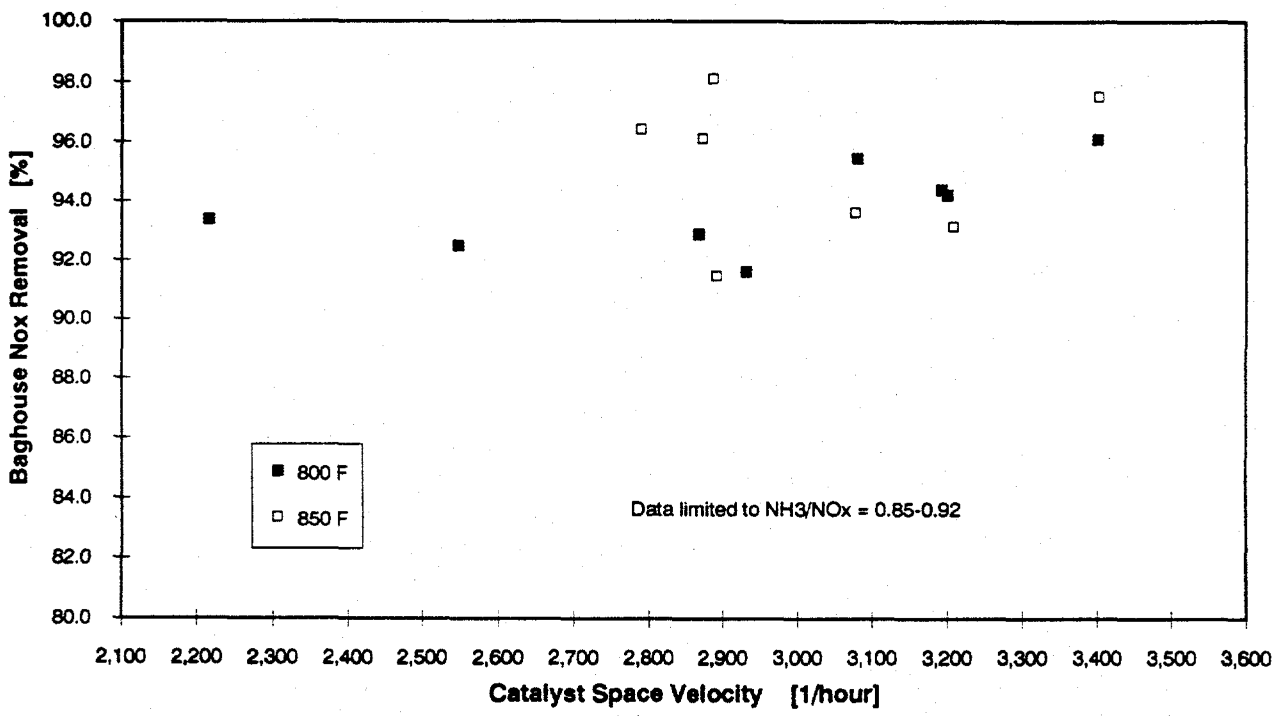


FIGURE 4-48 EFFECT OF SPACE VELOCITY ON NO_X REMOVAL - 2

The NH_3/NO_x stoichiometry was the operating parameter which had the strongest impact on NO_x removal. The degree to which NO_x reduction was a function of the NH_3/NO_x stoichiometry over the catalyst temperature range of 790 to 865 °F is shown in Figure 4-49. The project goal of 90% NO_x emissions reduction was achieved with operation above an NH_3/NO_x stoichiometry of 0.85 with the baghouse operating at 790 to 865 °F. The concentration of NO_x in the flue gas did not appear to significantly influence the rate of NO_x conversion. The average inlet NO_x concentration was approximately 0.63 ± 0.09 lb/10^6 Btu.

NO_x emissions were reduced to less than 0.05 lb/10^6 Btu with operation at NH_3/NO_x stoichiometries of 0.85 - 0.92 mol/mol and catalyst temperatures of 790 to 870 °F. This level of emissions is well below the CAAA Phase I compliance limit of 0.45 lb/10^6 Btu. The baghouse outlet NO_x emissions are presented as a function of the NH_3/NO_x stoichiometry in Figure 4-50.

4.6.11 Ammonia Slip

Ammonia slip is defined as the amount of unreacted ammonia downstream of the SCR catalyst. As the catalyst loses activity through aging and deactivation, the ammonia slip increases. Ammonia slip is used in many SCR applications as an indicator of the need for catalyst addition or replacement.

Experience at Japanese SCR installations suggests safe operation corresponds to 5 ppm ammonia slip at the lowest level of catalyst activity. This limit has been recommended extensively as a design criteria in Europe and Japan. Two operating problems arising from high ammonia slip are unacceptable ammonia levels in the fly ash and the formation of ammonium bisulfate salts. Fly ash already contains a minute amount of ammonia, about 10 mg NH_3/kg fly ash on average, which originates from combustion.[36] If the NH_3 slip is maintained at less than 5 ppm, the amount of ammonia in the ash will not prevent disposal or sale of the fly ash.[37] Maintaining ammonia slip below 5 ppm and SNRB™ operating temperatures above 450°F would effectively eliminate ammonia contaminated fly ash generation in a commercial application.

Less than 5 ppm ammonia slip also prevents ammonium sulfate salt (NH_4HSO_4 and $(NH_4)_2SO_4$) formation from the reaction of excess NH_3 and SO_3. Ammonium bisulfate (NH_4HSO_4) causes corrosion of downstream steel surfaces. Another benefit of limiting ammonium sulfate salt formation and ammonia slip is that both NH_4HSO_4 and $(NH_4)_2SO_4$ in addition to NH_3 contribute to increased PM-10 emissions.

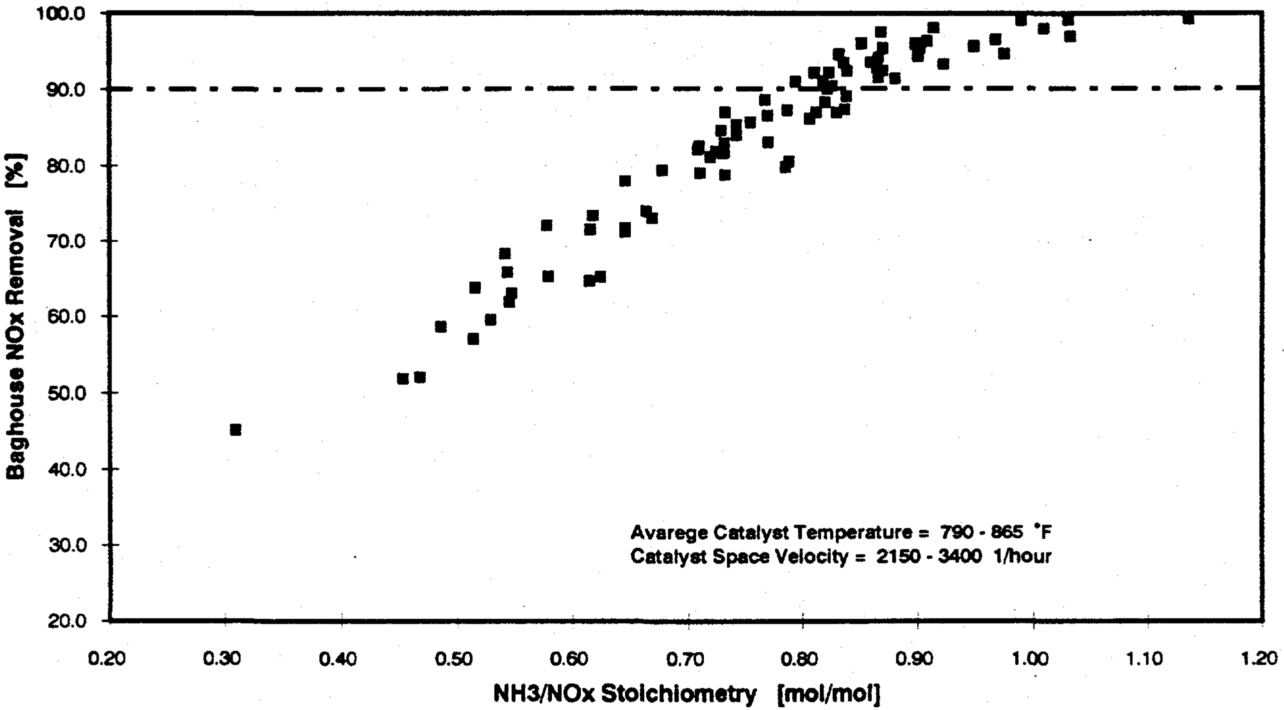


FIGURE 4-49 EFFECT OF NH_3/NO_X RATIO ON NO_X REMOVAL

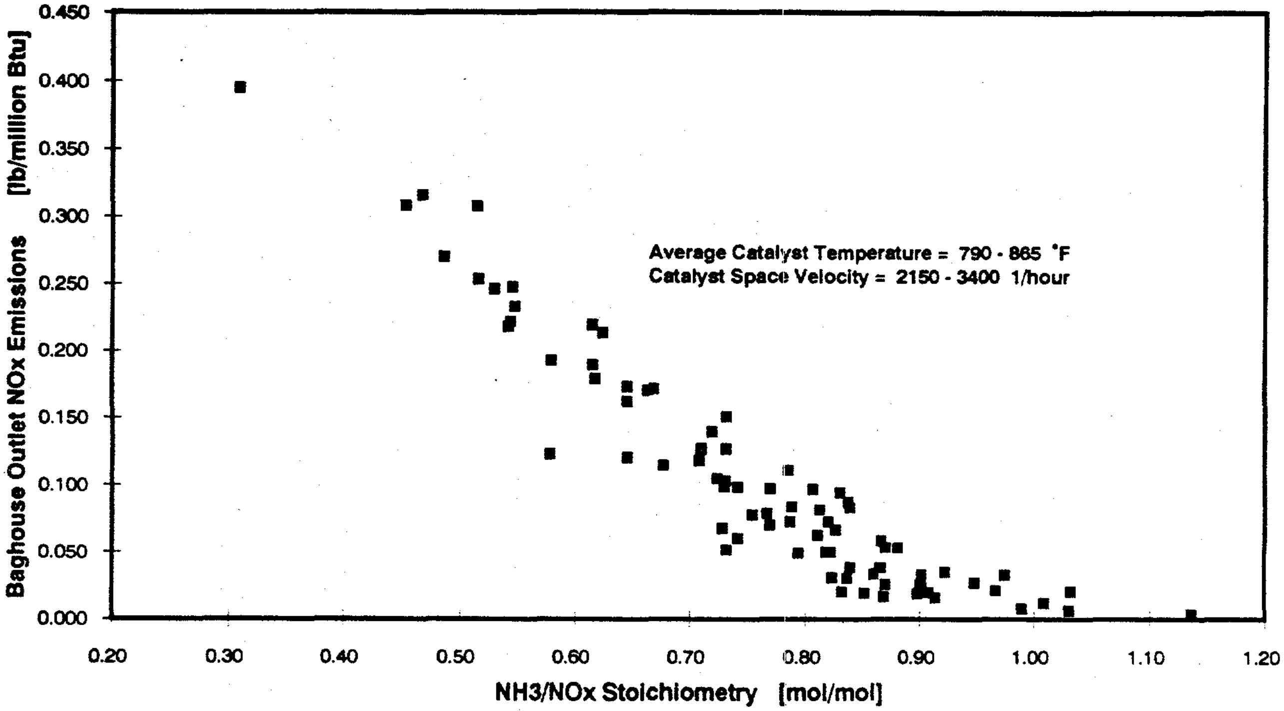


FIGURE 4-50 EFFECT OF NH_3/NO_x RATIO ON NO_x EMISSIONS

Ammonia slip is a function of the ammonia feed rate and the NO_x reduction efficiency. The effect of ammonia feed rate as reflected by the NH_3/NO_x stoichiometry was examined over the range of 0.50 to 1.15 mol/mol. Ammonia slip measurements conducted by B&W and Norton and the corresponding NO_x removal performance are plotted as a function of NH_3/NO_x stoichiometry in Figure 4-51. Flue gas sampling for the ammonia slip measurements was performed directly downstream of the baghouse with an EPA Method 5 sample train. The NH_3 solutions collected in the train were split for duplicate analysis by B&W and Norton. Two different analysis methods were employed. Norton used an automatic titrator while B&W used an NH_3 selective electrode. Less than 5 ppm on average was measured downstream of the baghouse when the NH_3/NO_x stoichiometry was below 0.92 mol/mol. The performance goal of maintaining less than 5 ppm NH_3 slip while operating at 90% NO_x removal was achieved over a temperature range of 780 to 870 °F and NH_3/NO_x ratios of 0.85 - 0.92 mol/mol. According to Figure 4-51, operation at NH_3/NO_x stoichiometries above 1.0 resulted in high ammonia slip. Operation at high NH_3/NO_x stoichiometries was limited to avoid the adverse consequences of high NH_3 slip.

Ammonia slip measurements conducted by the independent sampling company, TSA, and the corresponding NO_x performance are plotted as a function of NH_3/NO_x stoichiometry in Figure 4-52. Ammonia slip averaged 1.5 ± 1.0 ppm over the NH_3/NO_x stoichiometry range of 0.70 - 1.0 mol/mol. Unlike the measurements conducted by B&W, the TSA results do not show an increase in slip at an NH_3/NO_x stoichiometry of 1.0. These low slip measurements at the high NH_3/NO_x stoichiometry are suspect.

The NH_3 slip data was examined over two narrow NH_3/NO_x stoichiometry ranges to determine if the measured slip could be correlated to variation in catalyst temperature or space velocity. No direct link between the measured NH_3 slip and catalyst temperature or CSV could be established.

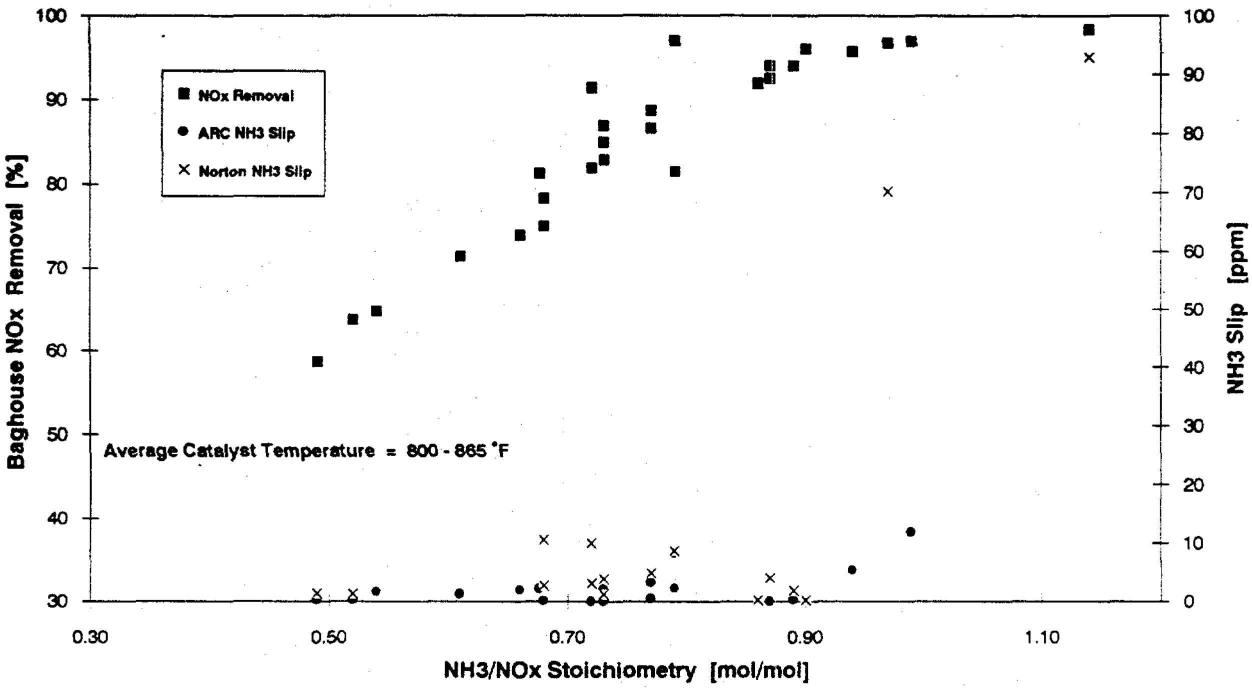


FIGURE 4-51 AMMONIA SLIP MEASUREMENTS

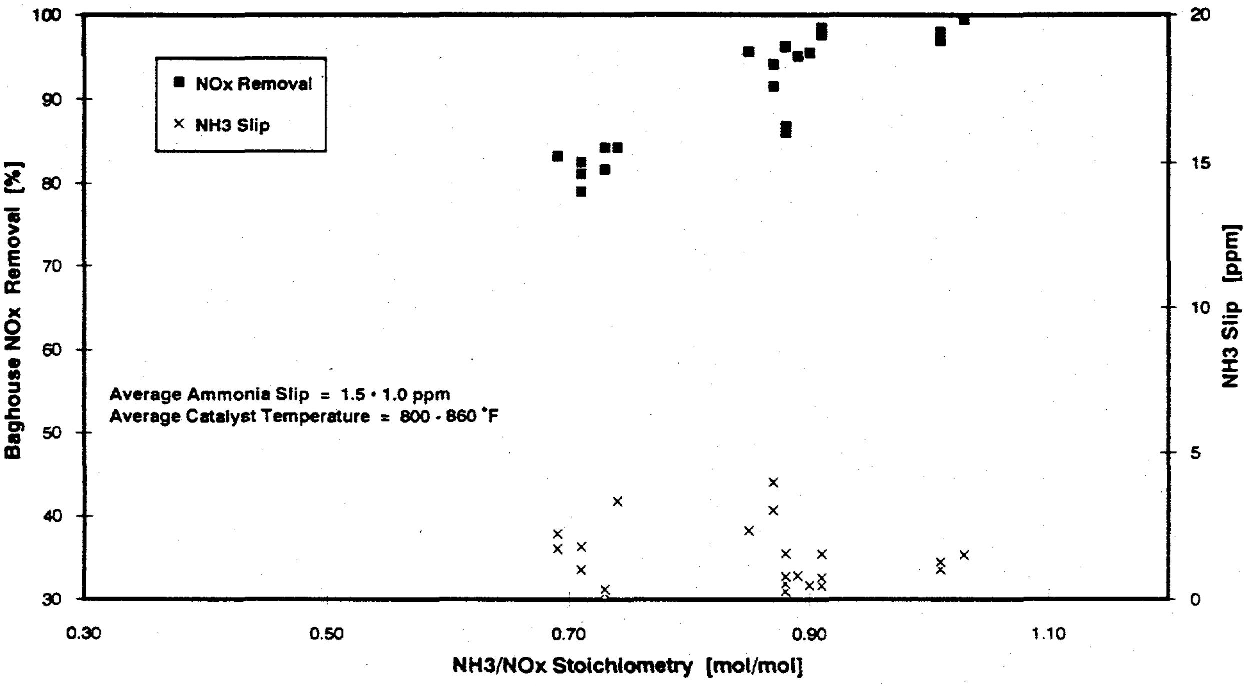


FIGURE 4-52 SUBCONTRACTOR AMMONIA SLIP MEASUREMENTS

4.6.12 Effect of Boiler Fluctuations

A slight increase in NO_x removal was observed with reduction in boiler load. The increase in baghouse NO_x removal resulting from the change in boiler load did not appear to be a result of the drop in CSV or the decrease in catalyst temperature which were characteristic of the load change as previously discussed. The relatively slow response of the NH_3/NO_x ratio control to a rapid change in inlet NO_x concentration is believed to be responsible for the observed increase in NO_x removal. The ammonia flow controller could not respond to the rapid 18% drop in baghouse inlet NO_x concentration quickly enough to permit over-ramping the desired NH_3/NO_x ratio. The highly porous zeolite catalyst may also serve as an ammonia reservoir. The impact of a quick drop in boiler load is illustrated in Figure 4-53. Note the increase in opacity downstream of the baghouse following the NH_3/NO_x ratio spike. When the SNRB™ system operators had warning of a decrease in boiler load, the controller was temporarily placed in manual operation and the NH_3 input was reduced until the NO_x concentration stabilized to avoid overloading the SCR catalyst with NH_3 and producing high levels of ammonia slip.

The impact of a sudden increase in boiler load is illustrated in Figure 4-54. The rapid increase in the system inlet NO_x resulted in an increase in NO_x emissions until the NO_x concentration and NH_3/NO_x ratio steadied out. The impact of a sudden load increase and corresponding drop in NH_3/NO_x ratio on NO_x reduction is shown in Figure 4-55. Note the variation in NH_3/NO_x ratio resulting from unsteady boiler operation in the period initially following the load increase. The effect of extreme boiler load variation on NO_x concentrations at the baghouse inlet and outlet is shown in Figure 4-56 which illustrates the difficulties observed with the ammonia feed system tracking the rapid fluctuation in inlet NO_x concentration.

The ammonia flow controller was not tied in to a boiler load signal in the slipstream demonstration. In a commercial system, control of the NH_3/NO_x ratio would be directly linked to operation of the boiler to allow for anticipation of load changes to maintain consistent NO_x emissions. The boiler operator could switch to manual control of the ammonia flow on first indication of instability or in anticipation of changes in operation that could increase or decrease NO_x output. For load drops, reducing the NH_3 flow by approximately 15% and placing the system in manual control should be sufficient to avoid catalyst saturation. For load increases, the NH_3 flow can be increased by approximately 15%. The ammonia injection controller can be returned to automatic operation when the NO_x concentration is steady.

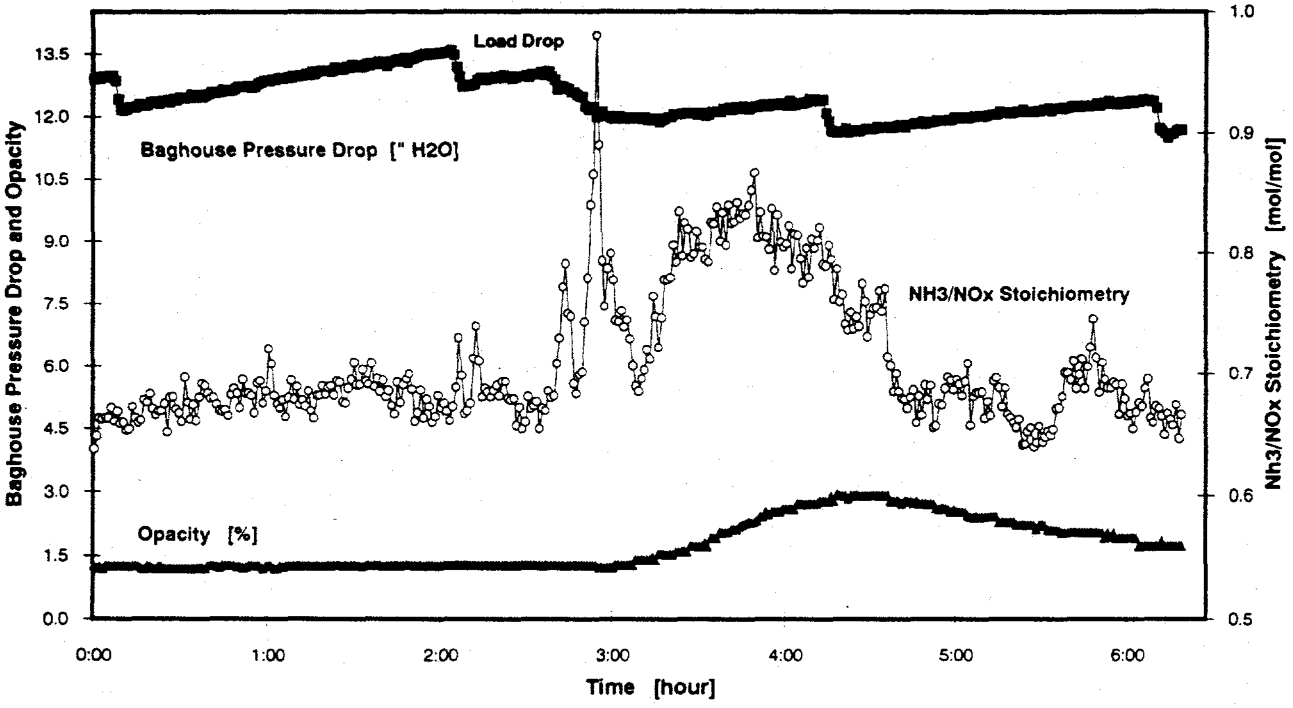


FIGURE 4-53 EFFECT OF HIGH NH_3/NO_X ON OPACITY

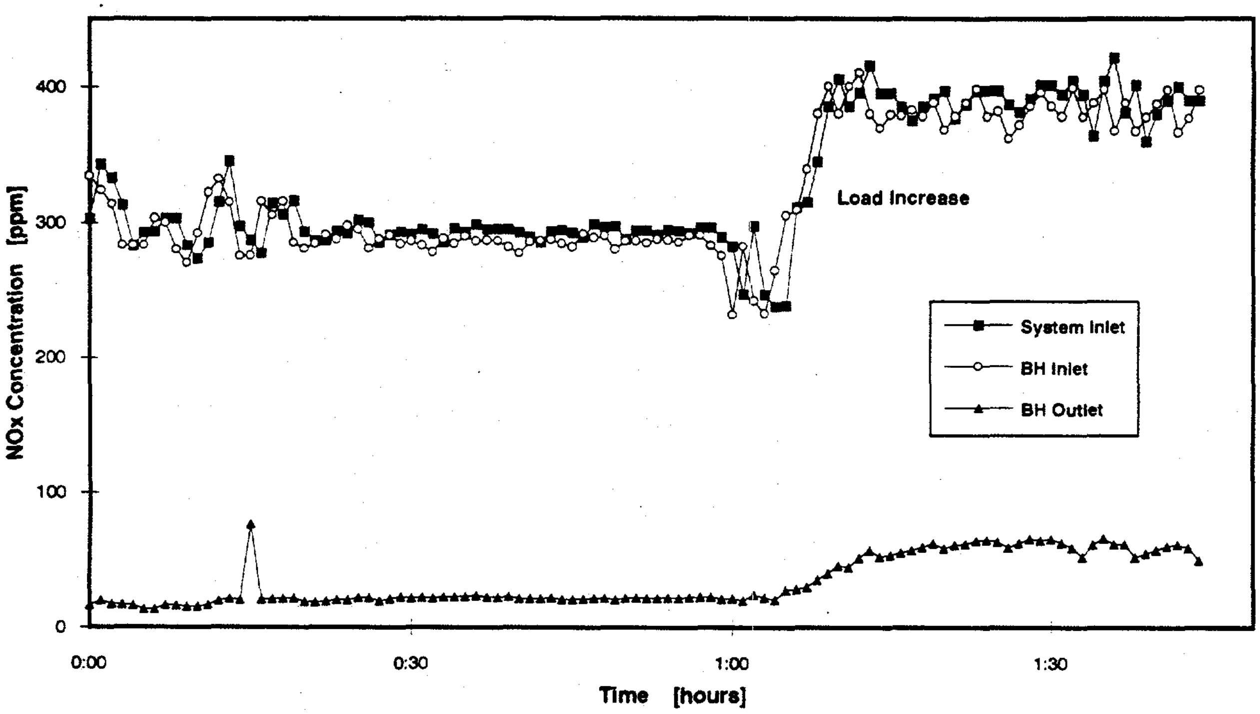


FIGURE 4-54 EFFECT OF SUDDEN BOILER LOAD INCREASE ON NO_x CONCENTRATIONS

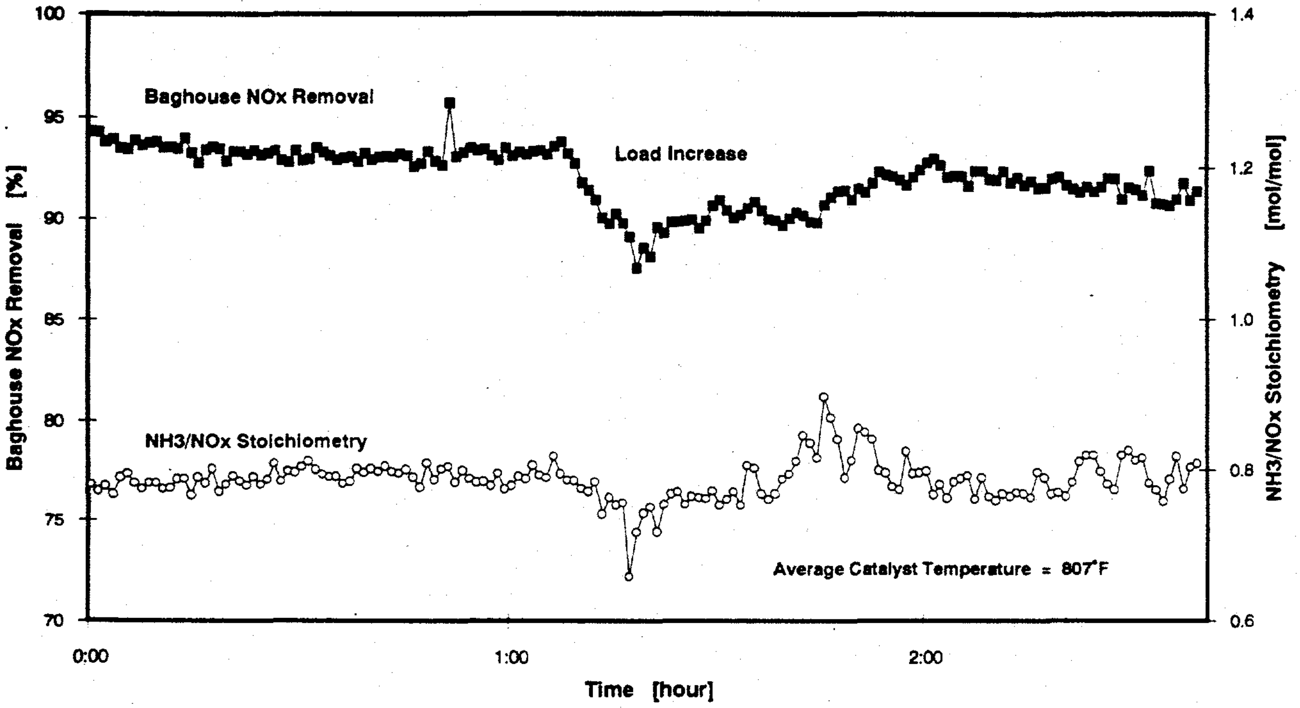


FIGURE 4-55 EFFECT OF SUDDEN BOILER LOAD INCREASE ON NO_x REDUCTION

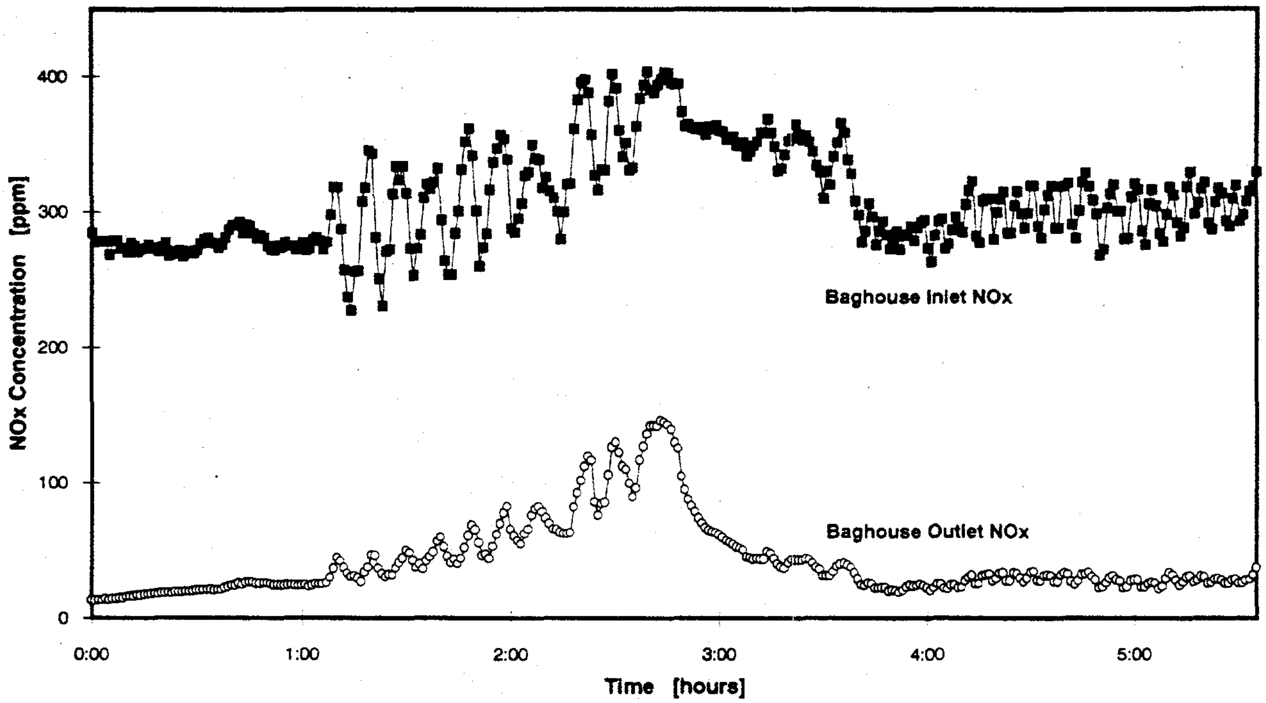


FIGURE 4-56 EFFECT OF EXTREME BOILER LOAD SWINGS ON NO_x CONCENTRATIONS

4.6.13 Catalyst Deactivation Studies

SCR catalyst deactivation is caused mainly by fine particulates that deposit on the surface and plug the micropores of the zeolite and sulfur poisoning of the reactive sites. Sections of the catalyst monoliths were periodically removed from the SNRB™ baghouse and sent to the manufacturer, Norton Chemical Process Products Company, for SCR deactivation studies. Total operating time on the SCR catalyst in the SNRB™ demonstration program was 2,315 hours. This included periods with and without SO_2 sorbent injection. During periods of operation without sorbent injection, the SCR catalyst was exposed to a harsher environment that predicted for a commercial application due to the high concentration of SO_2. For approximately 32% of the total operating time (740 hours), the SCR catalyst was subjected to SO_2 levels of 2,000 - 3,000 ppm. The operating history for each of the catalyst sampling periods is summarized in Appendix M.

The first catalyst assembly was removed after exposure to high temperature operation for approximately 360 operating hours. This period of operation was referred to as the "screening tests" where testing was conducted over a range of operating parameters. During the screening tests, commercial hydrated lime was injected for the majority of the 360 hours. The catalyst temperature averaged 800 °F and NH_3/NO_x stoichiometry averaged 0.85 mol/mol.

The second catalyst sample was removed after approximately 1,720 hours of operation. Operating conditions varied widely, however the catalyst temperature averaged 800 °F and the NH_3/NO_x stoichiometry averaged 0.85 mol/mol. In addition to commercial hydrated lime, several alternate sorbents were injected for SO_2 control; calcium lignosulfonated lime injection for 212 hours, sugar hydrated lime injection for 267 hours and approximately 72 hours of operation with sodium bicarbonate ($NaHCO_3$) injection. SCR catalyst deactivation due to $NaHCO_3$ injection is a concern for other applications. However, the SNRB™ arrangement with particulate removal upstream of the SCR catalyst results in very low levels of $NaHCO_3$, if any, directly contacting the catalyst. Baghouse outlet particulate emissions (fly ash, reaction products and sorbent) averaged 0.018 $lb/10^6$ Btu, corresponding to an average collection efficiency of 99.89%. Emission testing with the catalyst removed showed no apparent difference in particulate collection efficiency, indicating that fine particulates were not being trapped in the catalyst.

The third catalyst sample was removed from the SNRB™ baghouse after approximately 2,300 hours at the conclusion of the test program. The catalyst had additional exposure to $NaHCO_3$ injection for 45 hours and was installed for the approximate 270 hours of air toxics emissions testing which concluded the test program.

Periodic tests were performed at similar operating conditions to evaluate catalyst and bag degradation with time by comparing emissions control performance. The periodic test results do not indicate catalyst deactivation characterized by either decreased NO_x reduction or increased NH_3 slip at similar NH_3/NO_x stoichiometries, inlet NO_x concentration, catalyst space velocities and operating temperatures. The periodic test results are presented in Figure 4-57.

Physical Condition of the Catalyst

Some properties of the catalyst were altered over the course of the demonstration without adversely affecting NO_x removal performance. Powder catalyst samples were analyzed with X-Ray diffraction (XRD) to examine possible deformation of the zeolite framework. Compared to a fresh sample, the crystallinity index was found to drop to approximately 60% of the original index after the initial test period of 360 hours. The crystallinity index reflects the total area of the peaks measured by XRD, where one peak represents a single phase of the zeolite. The lack of substantial deactivation indicates that some of the zeolite phases were not essential to the catalytic activity.

The BET surface area of the catalyst samples was reduced by 30 to 40% in operation of the SNRB^{TM} demonstration. However, no appreciable loss in pore volume was noted. A loss in pore volume would result from exposure to high dust concentrations which caused pluggage. The highest reduction in surface area occurred during the initial test period and then stabilized. The results suggest that the existing NC-300^{TM} pore structure appears to be stable under SNRB^{TM} operating conditions and exposure to ash downstream of the baghouse.

Table 4-12 summarizes the catalyst characteristics of fresh and the aged samples. The crystallinity index, BET surface area and pore volume are reported as % of the original property.

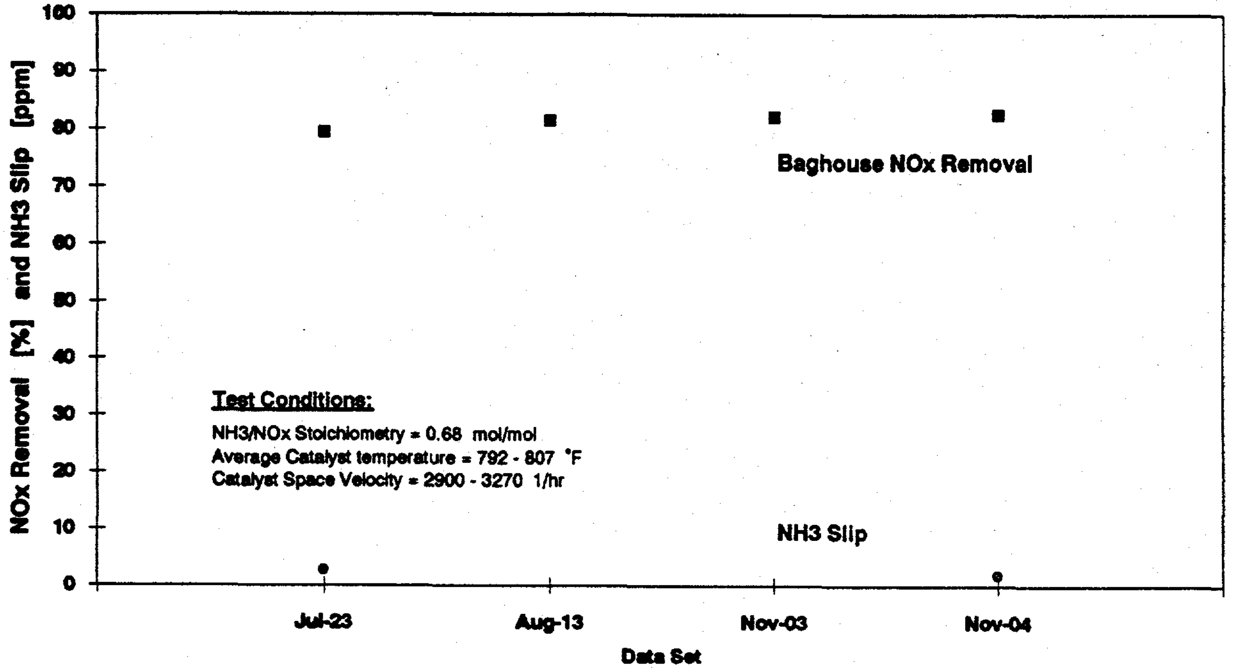


FIGURE 4-57 PERIODIC NO_X REMOVAL PERFORMANCE TESTS

TABLE 4-12 PHYSICAL PROPERTIES OF THE AGED SNRB™ NC-300 CATALYST					
On-Stream Hours	Fresh	360	360	1720	2315
Crystallinity Index [%]	100	64	62	NA	NA
Bulk Density [lb/ft^3]	33.8	33.6	NA	27.8	33.6
BET Surface Area [%]	100	62.5	71.9	60.6	76.9
Hg Pore Volume [%]	100	89.6	96.4	97.1	98.7

Bench-Scale Activity Tests

The aged catalyst samples were tested for NO_x removal efficiency by Norton using standard bench-scale activity test conditions. These tests were performed at higher catalyst space velocities than typical of SNRB™ operation to provide for greater sensitivity to changes in activity. The results shown in Figure 4-58 corroborate the periodic tests conducted at the field demonstration site and indicate no apparent catalyst deactivation over the 2,300 hours of high temperature operation.

SO_2 Oxidation

Zeolite catalysts have inherently lower SO_2 oxidation activity and resistance to fouling than promoted SCR catalysts.[38] Svachula et. al. performed bench-scale tests to address the oxidation of SO_2 to SO_3 for vanadia (V_2O_5) promoted SCR catalysts. The effects of operating conditions, (contact time and temperature), gas composition (O_2, SO_2, NO_x etc.), and catalyst design parameters (wall thickness and V_2O_5 content) were studied.[39] One major conclusion was that the rate of SO_2 oxidation increased markedly with increasing V_2O_5 content at a reaction temperature of 680 °F as illustrated in Table 4-13.

TABLE 4-13 EFFECT OF V_2O_5 LOADING ON SO_2 OXIDATION

CATALYST	V_2O_5 LOADING	CONVERSION [%]
D	Low	0.2
A	Medium	1.4
E	High	6.3

Norton reports low SO_2 oxidation rates for the NC-300™ series catalyst. Generally, the SO_2 to SO_3 oxidation must be kept below 1% to avoid operating and maintenance problems.[39] During bench-scale tests which emulated SNRB™ operating conditions, consistently less than 0.5% SO_2 oxidation was measured. The SO_3 concentrations measured across the SNRB™ baghouse by two independent sampling companies employing two different sampling methods showed the same trends. The SO_3 concentration at the baghouse outlet with sorbent injection was approximately 0.8 ppm higher than at the baghouse inlet. If the injected sorbent was not removing SO_3, (which is feasible with the SO_3 concentration < 10 ppm and the sorbent being removed from the gas prior to the catalyst) this corresponded to an average SO_2 oxidation rate of 0.32% based on 250 ppm SO_2 contacting the catalyst. This low level of SO_2 oxidation agrees with the Norton bench-scale oxidation rate measurements.

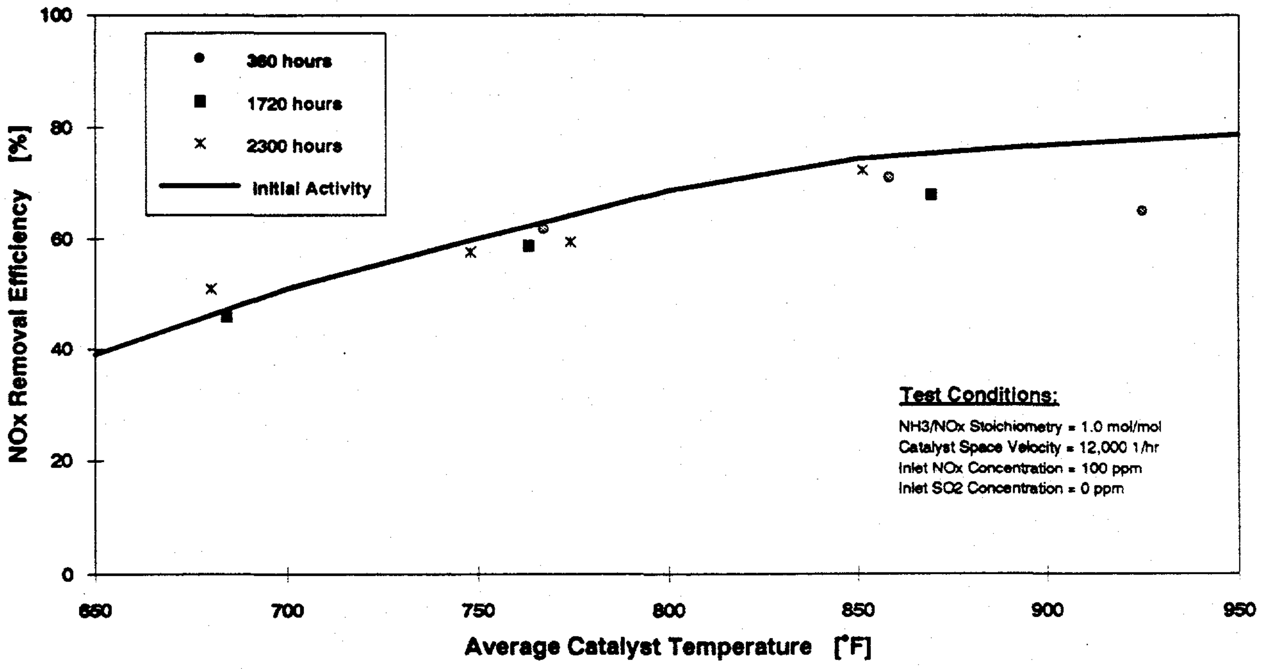


FIGURE 4-58 ZEOLITE CATALYST ACTIVITY TESTS

Catalyst Pluggage

Evidence of catalyst pluggage was not observed by B&W or Norton on removal of the catalyst from the baghouse. In some high-dust, high-sulfur SCR applications the degree of channel pluggage can increase substantially after several shut-down/start-up cycles, resulting in drastic changes in catalyst activity. It is speculated that moisture introduced into the SCR reactor after shut-down enhances the plugging process by reacting with SO_3 to produce sulfuric acid which immediately reacted with the alkaline salts in the fly ash, forming a sticky mixture of sulfated salt, fly ash and sulfuric acid.[7] Channel pluggage can cause increased pressure drop, uneven flow distribution and loss of performance. These effects were not observed in the SNRB™ demonstration. Periodic baghouse inspections after the numerous facility shutdowns (approximately 27) revealed low levels of this type of sticky material on the exposed steel surfaces, but visual inspection did not reveal any catalyst contamination. This was most likely due to the protected catalyst location.

Norton analyzed catalyst samples using Scanning Electron Microscopy with Energy Dispersive X-Ray Spectroscopy (SEM/EDX) to identify types of catalyst contamination in SNRB™ operation. SEM/EDX is a surface specific technique, penetrating perhaps 250 Å into the catalyst surface. The major deposits on the catalyst surface were identified as sulfur, potassium, and iron. Low levels of calcium were also detected on the catalyst surface. The relative intensity of the elements detected on the surface with respect to a fresh catalyst sample are plotted as a function of operating time in Figure 4-59. Ash analysis of SNRB™ baghouse solids by Inductively Coupled Plasma (ICP) was somewhat in agreement with the SEM/EDX analysis having identified calcium, sulfur and iron compounds to be the major constituents whereas potassium (K) was repeatedly measured at less than 1% by weight. The low potassium levels in the coal ash do not justify potassium as an expected major constituent of deposits on the catalyst surface. Overall, the SEM/EDX results indicate that the low levels of SNRB™ product that did contact the catalyst resulted in little catalyst contamination.

Sulfur and potassium are known to poison V_2O_5 promoted catalysts. High sulfur concentrations can lead to an increase in SO_3 emissions via SO_2 oxidation. However, this does not appear to be the case with the zeolite NC-300™ catalyst. The bench-scale SO_2 oxidation measured for the catalyst samples removed from the baghouse was consistently less than 0.5% and did not increase with operating time. The effect of potassium on the zeolite catalyst is not currently known, however the surface levels detected did not appear to influence the catalyst performance.

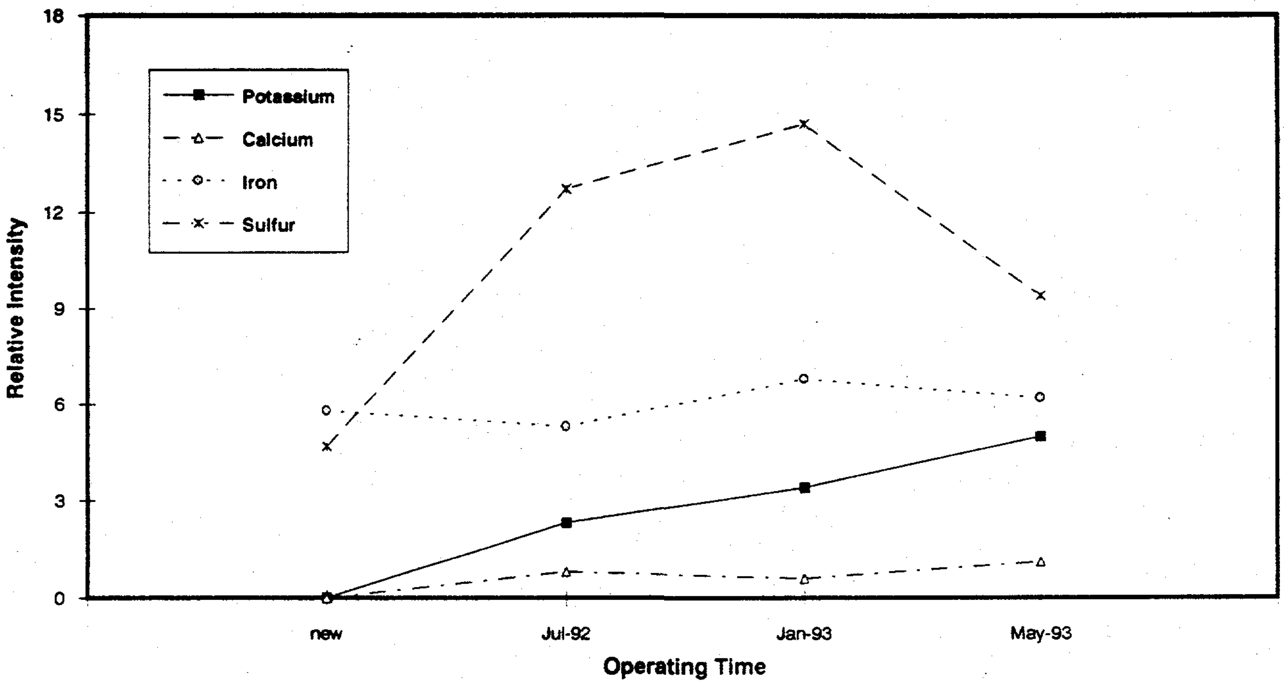


FIGURE 4-59 CATALYST SURFACE ANALYSIS

Atomic Adsorption Spectroscopy (AAS) was applied to analyze the bulk contamination of powdered samples of the catalyst. AAS confirmed the finding of the SEM/EDX work that no significant contamination resulted from over 2,300 hours of SNRB™ operation. The AAS tests detected no appreciable levels of sodium compounds, which are reported to deteriorate acidic sites effective for NH_3 adsorption. The contamination analysis results confirm Norton's commercial experiences with NC-300™ which has excellent resistance to contamination for a variety of SCR applications.

Catalyst Erosion

Catalyst pluggage and erosion plague high-dust, high-SO_2 SCR applications. Since the SNRB™ catalyst is downstream of particulate and SO_2 removal, low catalyst erosion rates were anticipated. This eliminates the need to add "dummy" catalyst sections to protect the actual catalyst from erosion. As expected, upon removal of the catalyst at the end of the demonstration after 2,315 hours of operation and approximately 475 bag cleanings per compartment little erosion was visually observed. As a whole, no deformation of the monolith structures was visible, indicating excellent physical integrity under SNRB™ operating conditions. A small area in the center of the top layer of the catalyst was slightly eroded. The erosion probably resulted from the 30 to 40 psig compressed air used for bag cleaning and affected only the top 1/2 inch of the catalyst directly under the blow pipe.

Catalyst Life Expectancy

Throughout the demonstration program, no catalyst deactivation was evident nor was any deactivation observed in the Norton bench-scale tests conducted on catalyst samples retrieved from the demonstration. The catalyst was not appreciably physically altered by the operation of the SNRB™ system. The demonstration program was not designed to determine catalyst life. Life testing would have several years of steady operation at optimal SNRB™ conditions until reduced NO_x removal performance or increased ammonia slip signified catalyst deactivation. The SCR catalyst was exposed to atypical SNRB™ conditions known to influence catalyst life including high SO_2 concentrations and frequent passage through the acid and water dewpoints during facility start-up and shut-down. Outage frequency has been identified as an important factor affecting catalyst activity and performance.[40]

Norton typically provides a minimum three year commercial performance guarantee for the NC-300™ SCR catalyst independent of the SNRB™ process. SNRB™ catalyst life expectation based on the field testing, Norton deactivation studies and recent SCR catalyst application surveys is much higher. SCR systems have operated without catalyst additions or replacement for 4-5 years for coal-fired boilers, 7-10 years for oil-fired boilers and more than 10 years for gas-fired boilers.[40] Of the three industrial applications, SNRB™ operating conditions most resemble the low dust, low sulfur environment produced by a gas-fired boiler. A five year catalyst life has been assumed for SNRB™ system economic projections. A longer catalyst life significantly reduces levelized operating costs.

4.6.14 Secondary Effects on NO_x Removal

Effects of O_2 Level

The influence of the level of oxygen present on NO_x removal performance was evaluated in the demonstration. Previous Norton studies conducted with the NC-300™ catalyst have shown that no reduction of NO_x occurs in the absence of oxygen. As the concentration of O_2 was increased from 0 to 4%, the NO_x conversion increased and then leveled off with only slight additional improvement from 4 to 10% O_2. In the SNRB™ demonstration, the O_2 levels in the flue gas ranged from 3 to 7%. Figure 4-60 shows no effect of the O_2 concentration over the evaluated range of 4 - 7% on NO_x removal. The operating data was sorted to eliminate the affects of other parameters, especially the NH_3/NO_x stoichiometry and catalyst temperature. The result was comparable to Norton's bench-scale test findings.

Effects of SO_2 Level

The effect of the SO_2 concentration contacting the SCR catalyst on NO_x removal performance was also investigated. The data was carefully sorted to eliminate the effects of parameters known to influence NO_x reduction performance including NH_3/NO_x ratio and operating temperature. The narrow NH_3/NO_x ratio range of 0.68 to 0.74 was selected because of the wide range of SO_2 concentrations available at these operating conditions. Sufficient data was not available to characterize the impact of SO_2 concentration at other NH_3/NO_x ratios. A slight decrease (7%) in NO_x removal which coincided with an increase in the SO_2 concentration from 300 to 850 ppm is shown in Figure 4-61. This effect would have little bearing on commercial applications where SO_2 removal is relatively constant. Unless affected by load conditions, the SO_2 concentration contacting the catalyst is highly dependent on the Ca/S stoichiometry. The Ca/S stoichiometry was found to be relatively easy to hold constant even under severe load swings.

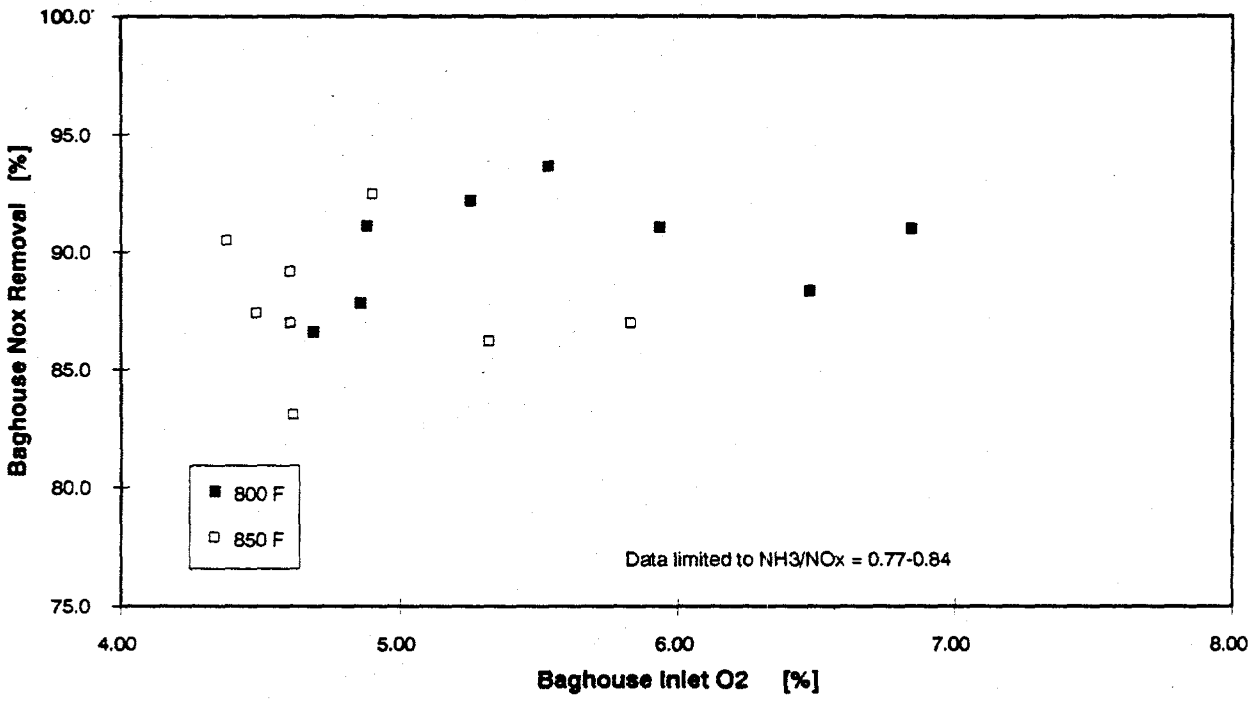


FIGURE 4-60 EFFECT OF 0_2 CONCENTRATION ON NO_x REMOVAL

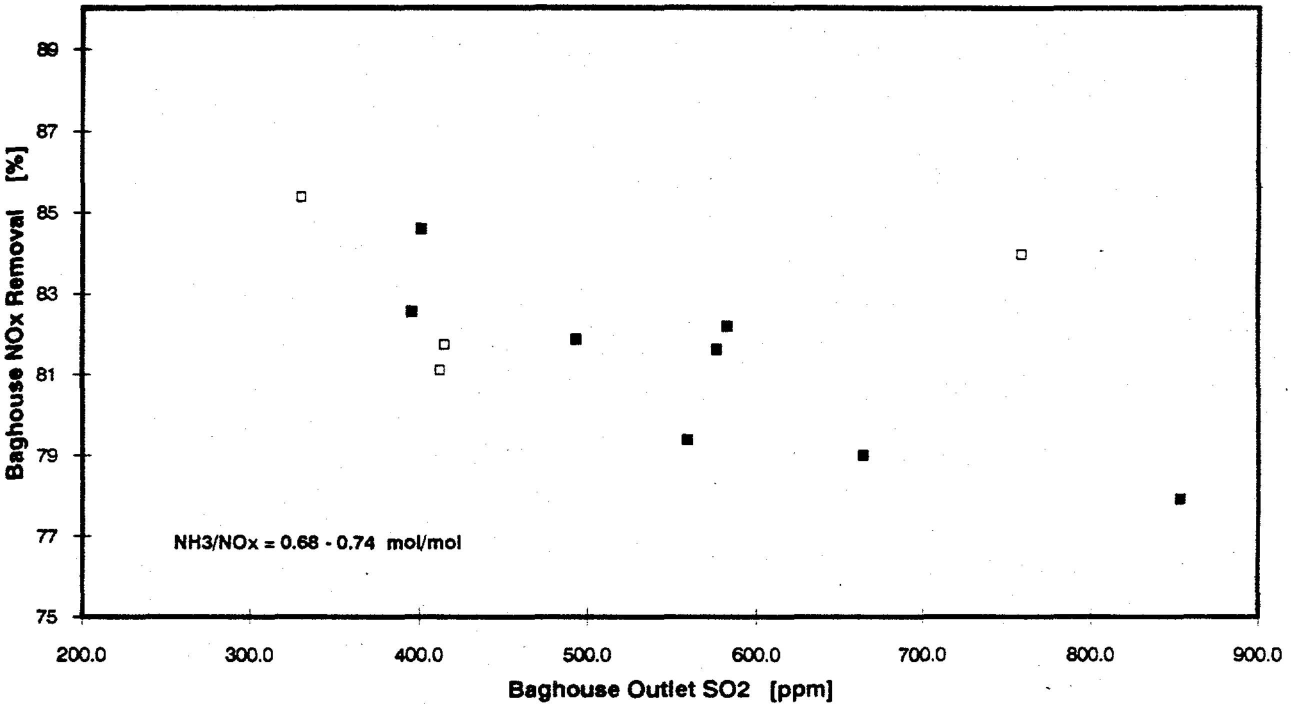


FIGURE 4-61 EFFECT OF SO_2 CONCENTRATION ON NO_X REMOVAL

NO_x Removal by $NaHCO_3$

Sodium bicarbonate injection for SO_2 emission control also resulted in modest levels of NO_x reduction without the use of ammonia injection. This may be especially attractive for SNRB™ applications where only moderate NO_x reduction is required or where acceptable overall NO_x reduction can be achieved with a combination of the SNRB™ system and combustion modifications, such as the installation of low-NO_x burners.

In the SNRB™ demonstration, NO_x removal was measured during operation with $NaHCO_3$ injection and in operation with both $NaHCO_3$ and NH_3 injection. The impacts of Na_2/S and NH_3/NO_x stoichiometries on NO_x reduction at a constant baghouse temperature of 460 °F are summarized in Table 4-14. NO_x reduction appeared to improve as the Na_2/S ratio was increased without ammonia injection. At 460 °F, NO_x removal improved form 19% to 32% when the Na_2/S stoichiometry was increased form 0.5 to 2.0. Table 4-14 reveals that NO_x reduction improved significantly with increased NH_3/NO_x stoichiometry at a constant rate of Na_2/S injection. The continuously monitored data in Figure 4-62 demonstrates the NO_x removal improvement with NH_3 injection. Note the simultaneous drop in the baghouse outlet opacity upon NH_3 injection. The $NaHCO_3$ system trip indicated in Figure 4-62 indicates the impact of the sodium sorbent.

TABLE 4-14 EFFECT OF Na_2/S AND NH_3/NO_x STOICHIOMETRY ON NO_x REMOVAL

Na_2/S	NH_3/NO_x	% NO_x REDUCTION
0.5	0.0	19.3
	0.8	42.1
1.0	0.0	19.6
	0.5	43.2
	0.8	50.0
	0.9	51.6
2.0	0.0	31.7

The effect of baghouse temperature on NO_x reduction with $NaHCO_3$ injection was studied over a range of 425 to 800 °F. Figure 4-63 illustrates that NO_x reduction dropped off significantly as the baghouse temperature was increased from 450 to 800 °F when the Na_2/S ratio was maintained at a constant value. Based on the results of other sodium injection studies, NO_x removal is not expected to drop off significantly at baghouse operating temperatures of 300 to 450 °F.

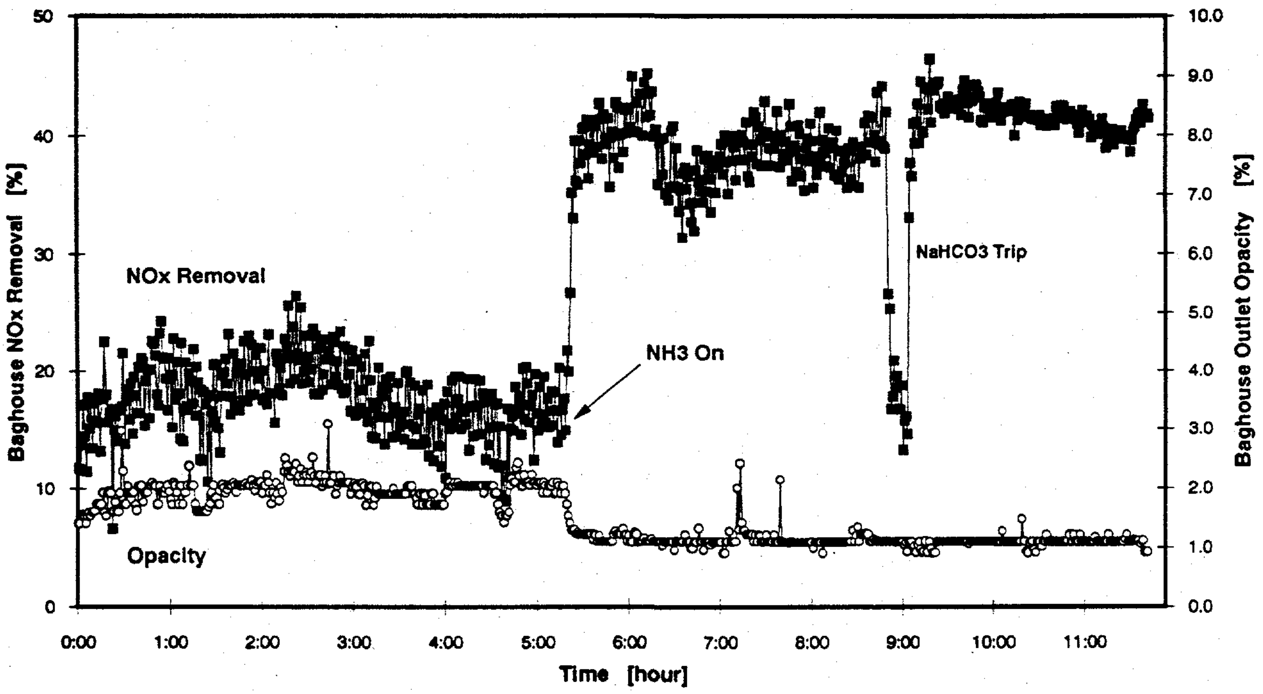


FIGURE 4-62 EFFECT OF NH_3 INJECTION ON NO_X REDUCTION AND OPACITY

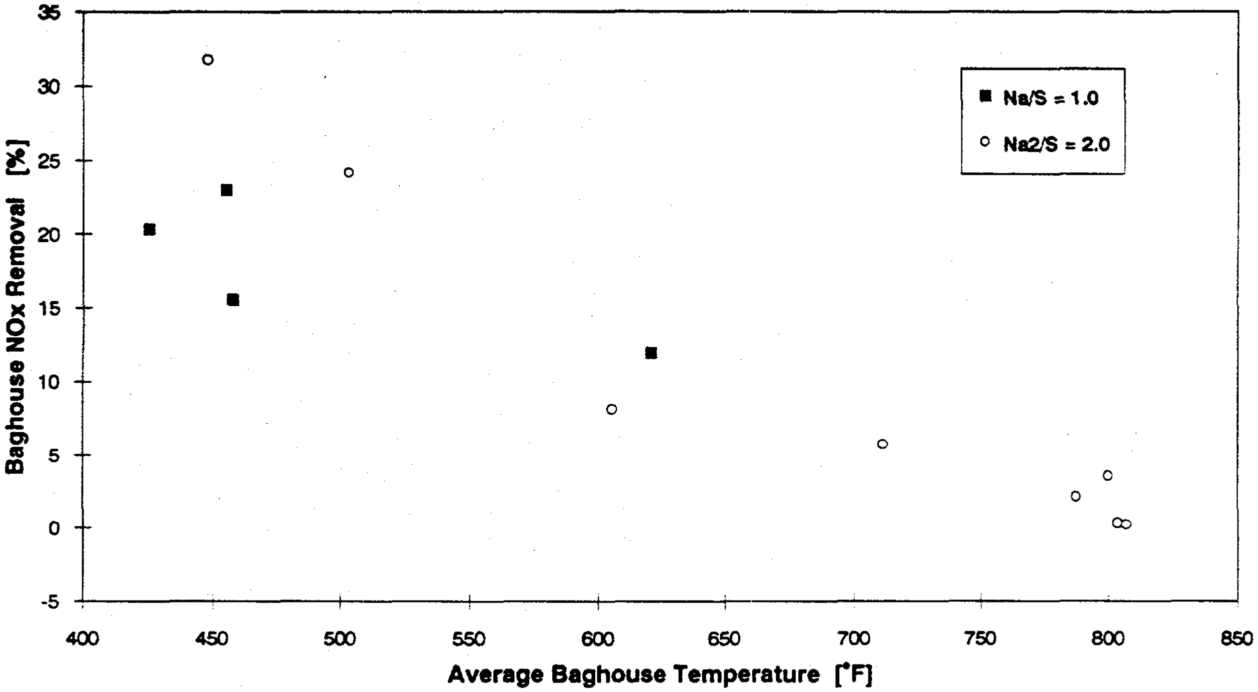


FIGURE 4-63 EFFECT OF TEMPERATURE ON NO_x REMOVAL WITH $NaHCO_3$

Effect of Cleaning Cycle

The effect of the bag cleaning cycle on NO_x removal is illustrated in Figure 4-4. NO_x removal dropped slightly with each module cleaning. Removal of the filter cake reduces the resistance to flow in the module that is cleaned, resulting in a temporary increase in gas flow through the bags. The short-term decline in NO_x removal be attributed to either increase in the CSV or removal of reactive fly ash from the surface of the filter bags. The cleaning air pulse also reduced the average catalyst temperature by approximately 5 °F which may contribute to the temporary dip in NO_x removal. Similar to the effect of compartment cleaning on SO_x removal, the effect on NO_x reduction will most likely be dampened at a larger scale since individual compartment cleaning will involve a much lower percentage of the total flue gas flow and reactive solids.

4.6.15 Design Improvements from Lab Pilot

Design improvements identified in the SNRB™ verification test program were proven beneficial to the larger field demonstration. The major recommendations regarding NO_x reduction included the use of the cylindrical monolith catalyst and the application of gasketting material around the catalyst. Selection of the monolith over pellet catalyst dramatically reduced catalyst installation time and the time required to replace filter bags during start-up of the facility. The combination of the gasketting material and circular extrusion of the monolith reduced flue gas bypass, ammonia slip and vibrational damage.

4.6.16 Catalyst Replacement and Disposal

The catalyst represents a majority of the SCR system cost (50 to 70 percent).[41] Therefore the catalyst life and associated addition or replacement schedules significantly impact the economics of the SCR system. Catalyst life expectancies for high dust applications range from 3 to 11 years. A realistic catalyst life guarantee for a high dust coal-fired application is 2 to 3 years. However catalyst life for low dust, low SO_2 operating conditions should be significantly longer.[40] There were no indications of catalytic deactivation such as a gradual drop in removal efficiency or increased ammonia slip over 2,300 hours of SNRB™ operation or in surface studies conducted by Norton. Norton has applied the NC-300™ catalyst in a low dust environment without finding any deactivation in six years.

Toxicity Characteristic Leaching Procedure (TCLP) analysis was performed on a representative sample of the exposed NC-300™ catalyst prior to disposal of the catalyst. Comparison of the analytical results with the regulatory limits verifies that after 2,300 hours of operation the catalyst remained non-hazardous as shown in Table 4-15. The negligible metal levels detected also support the deactivation study findings.

TABLE 4-15 SNRB™ CATALYST TOXICITY CHARACTERISTIC ANALYSIS			
EPA HAZARDOUS WASTE NUMBER	CONTAMINANT	RESULT [mg/l]	REGULATORY LEVEL [mg/l]
D004	Arsenic, Total	< 1	5.0
D005	Barium, Total	< 10	100
D006	Cadmium, Total	< 0.1	1.0
D007	Chromium, Total	< 1	5.0
D008	Lead, Total	< 1	5.0
D009	Mercury, Total	< 0.04	0.2
D010	Selenium, Total	< 0.1	1.0
D011	Silver, Total	< 1	5.0

Long-term SCR catalyst operations experience degradation with time and catalyst replacement or addition are required to restore activity. For plate or stacked catalyst configurations, catalyst replacement schedules typically involve the addition rather than the full replacement of catalyst to completely utilize remaining catalyst activity. The addition of fresh catalyst to the catalyst assemblies in the SNRB™ system may be more time consuming than replacement of the entire assembly.

Access to the SCR catalyst in the SNRB™ system is unimpeded and will not disrupt the high-temperature filter bags. To conserve catalyst activity without addition, the catalyst can be replaced by compartment. Table 4-16 outlines a 10 year proposed catalyst replacement schedule. The assumptions made for the schedule are that the baghouse is divided into six individual compartments with typical operation requiring five compartments on-line, and equal flow distribution of flue gas and ammonia into the baghouse compartments. A very conservative estimate of a 15% yearly drop in catalyst activity was applied.

The first compartment replacement can be scheduled when the overall activity reaches 70%. Allowing the overall activity to drop below 70% may encourage high ammonia slip. During the first two years compartment 6 remains off-line as a spare module and is used only as needed for maintenance on the other compartments. The only period of downtime is scheduled at the beginning of year 3 to allow catalyst replacement of compartment 1. At some point during year 3 the catalyst in compartment 5 can be leisurely replaced since it is off-line. Catalyst activity will be maintained on average at approximately 80% for the first

5 years and maintained at 70% for the duration of the installation without downtime. The key to the elimination of downtime after year 2 is maintaining one compartment off-line. Individual compartment catalyst replacement would occur on a yearly basis after year 2.

TABLE 4-16 PROPOSED CATALYST REPLACEMENT SCHEDULE

ACTIVITY %						TIME	OVERALL*
MOD 1	MOD 2	MOD 3	MOD 4	MOD 5	MOD 6	YEAR	ACTIVITY
100	100	100	100	100	100**	0	100%
70	70	70	70	70	100**	2	70%
100	70	70	70	**downtime	100	2	82%
85	55	55	**	100	85	3	76%
70	40	**	100	85	70	4	73%
55	**	100	85	70	55	5	70%
**	100	85	70	55	40	6	70%
100	85	70	55	40	**	7	70%
85	70	55	40	**	100	8	70%
70	55	40	**	100	85	9	70%

*No unit downtime after the 2nd Year
**Compartment OFFLINE

Several catalyst manufacturers have recently introduced recycling programs for SCR catalysts. However, catalyst recycling is far more practical for promoted catalysts than the zeolitic catalyst for two reasons. First, the active surface of a promoted catalyst can be removed and economically recovered. Second, the promoted catalyst is considered hazardous for disposal purposes whereas the zeolitic catalyst can be safely disposed in a solid waste landfill. In the case of the zeolite catalyst, recycling is currently not a cost effective option.

4.6.17 Ammonia Storage and Handling

The ammonia supply system includes equipment for storage, vaporization, air mixing, and injection of ammonia. The ammonia can be supplied to the SCR system either as anhydrous grade or aqueous NH_3. The use of ammonia in the SCR process presents several potential problems. Ammonia is on the EPA list of extremely hazardous substances under Title III, Section 302 of the Superfund Amendment Reauthorization Act (SARA). Releases of ammonia to the atmosphere can result from slip or bypass of the SCR reaction or accidental releases during transport, transfer or storage. Ammonia slip is not a considered to be a regulatory problem because it is emitted at the stack level. Of greater concern is the accidental release of ammonia from the storage and handling equipment. Limiting the stored ammonia concentration to less than 40% greatly reduces the volatilization rate. In many countries there are strict safety regulations for the transportation and handling of ammonia. Anhydrous grade ammonia boils at -28 °F and is primarily stored in pressurized tanks or in cooled tanks.

When ammonia is diluted with water at 28%, the strict rules applicable to handling and storage of anhydrous NH_3 can be avoided. An aqueous ammonia storage facility would be much larger and more costly than an anhydrous ammonia facility. Extra equipment, such as a staged stripping process may be required to separate the NH_3 from the water because salts present in the water can deactivate the catalyst. Use of deionized water as the diluent can eliminate the need for the costly separation equipment. Transportation of aqueous ammonia is also more expensive.

Anhydrous ammonia was selected for use in the SNRB™ demonstration and is believed to be the preferred reagent for commercial applications as less is required for on-site storage at a lower cost. The energy and equipment requirements for vaporization of anhydrous NH_3 are less than aqueous ammonia. Safe and reliable ammonia supply systems can be manufactured that meet the stringent safety requirements as evidenced by the majority of SCR installations in Germany utilizing anhydrous NH_3. In some areas such as California, the customer cannot select the reagent more appropriate to the application and is required by law to use aqueous ammonia.

Ammonia is mixed with dilution air and injected under pressure upstream of the baghouse and catalyst. Other SCR operations have reported significant ammonium sulfate deposition on the ammonia injection grid due to low ammonia/air mixture temperatures at the nozzle and high levels of SO_3 in the flue gas.[40] Periodic inspection of the SNRB™ ammonia injection nozzles throughout the demonstration did not reveal pluggage or accumulation of ammonium salts. This can be attributed to the combination of the higher injection temperatures and low SO_3 concentrations entering the high-temperature baghouse. Ammonia and SO_3 begin to form salts at temperatures below 450°F and would not be likely to form upstream of a commercial SNRB™ baghouse including the lower temperature sodium bicarbonate application.

4.6.18 NO_x Removal Conclusions

Key SNRB™ NO_x reduction observations from the demonstration program may be summarized as follows:

- 90% NO_x emission reduction was readily achieved with ammonia slip limited to less than 5 ppm. This performance reduced NO_x emissions to less than 0.10 lb/10^6 Btu.
- NO_x reduction was insensitive to temperature over the catalyst design temperature range of 700 to 900 °F.
- Catalyst space velocity (volumetric gas flow/catalyst volume) had a minimal effect on NO_x removal over the range evaluated.
- Turndown capability for tailoring the degree of NO_x reduction by varying the rate of ammonia injection was demonstrated for a range of 50 to 95% NO_x reduction.
- No appreciable physical degradation or change in catalyst activity was observed over the duration of the test program.
- The degree of oxidation of SO_2 to SO_3 over the zeolite catalyst appeared to be less than 0.5%. SO_2 oxidation is a concern for SCR catalysts containing vanadia to promote the NO_x reduction reaction.
- TCLP analysis of the catalyst on completion of the field tests confirmed that metal concentrations were well below regulatory limits and the catalyst remained non-hazardous for disposal.

4.7 BAGHOUSE PERFORMANCE

The particulate emission control performance of the Nextel™ and S2-Glass filter bags was evaluated over a variety of baghouse operating conditions including different sorbents, air-to-cloth (ATC) ratios, particulate loadings and cleaning cycles. The baghouse effectively controlled particulate emissions to NSPS compliance levels throughout the test program. The results of particulate sampling at the baghouse inlet and outlet are summarized in Appendix G.

4.7.1 SNRB™ Baghouse Description

The demonstration baghouse shown in Figure 4-64 was designed for operation at flue gas temperatures up to 900 °F. Table 4-17 summarizes the key baghouse design specifications. The baghouse consisted of six compartments arranged in a three-by-two array. Hot flue gas entering the baghouse was uniformly distributed to each of the six compartments through a tapered inlet manifold. Manually operated butterfly dampers located at the inlet of each compartment were used for compartment isolation. The flue gas entered at the bottom and exited at the top of each compartment. Pneumatically operated poppet valves at the outlet of each compartment could be used to isolate the compartment from the outlet gas manifold. The baghouse could be bypassed during start-up, shutdown, or a system upset with a pneumatically operated poppet valve connecting the inlet and outlet manifolds.

Commercial scale bag assemblies were evaluated in the demonstration. Twenty foot long bags were selected to minimize plan area requirements for commercial retrofit applications. The enclosed penthouse above the baghouse facilitated bag installation and removal and provided protection for the pulse-jet cleaning equipment located on the top of each compartment. A pulley was used to hoist bags and retainers from the tubesheet.

The pulse-jet cleaning system was designed to permit either on-line or off-line cleaning with either manual or automatic control. Cleaning could be automatically initiated based on pressure differential, time, or a combined pressure/time basis. Bag cleaning pressure ranged from 30 to 40 psig, although the system was designed for cleaning pressures up to 100 psig. Holes drilled in the undersides of 2.5 inch diameter pulse pipes directed the cleaning air into the bags. There were six pulse pipes per compartment, each cleaning seven bags simultaneously. A venturi was located above each bag to direct the cleaning air along the length of the bag.

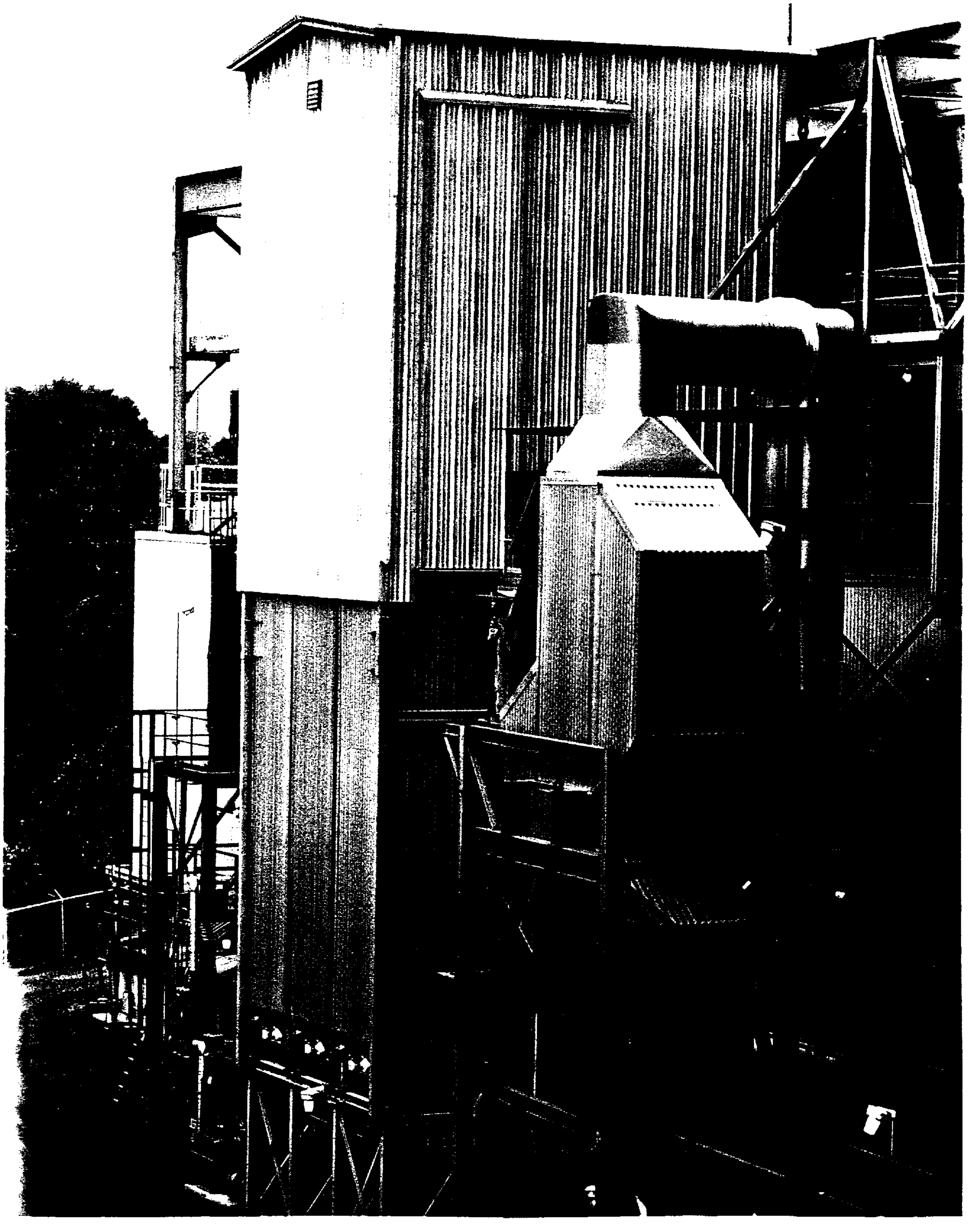


FIGURE 4-64 SNRB™ DEMONSTRATION BAGHOUSE

TABLE 4-17 BAGHOUSE SPECIFICATIONS	
Design Criteria	
Gas Volume	30,000 acfm @ 800 °F
Number of Compartments	6
Compartment Arrangement	3 x 2
Number of Bags/Compartment	42
Bag Size	6-1/4" Diameter x 20' Length
Filtration Area/Bag	31.25 ft^2
Air-to-Cloth Ratio	4.0 ft/min
Pulse-Jet Cleaning	
Type	On-line or Off-line
Cycle Control	Time, differential pressure, or manual
Pulse Air Pressure	30 - 40 psig
Pulse Duration	80 - 100 milliseconds

Two types of high-temperature fabrics, Nextel™ and S-2 glass, were evaluated in the 5 MWe field demonstration facility. Nextel™ is a woven ceramic fabric developed and manufactured by 3M. The bags were selected for the field demonstration because of the chemical and temperature resistance exhibited by the ceramic material during high-temperature tests previously conducted at B&W and the University of North Dakota.[19,21] Although Nextel™ woven fabrics have proven durable without the application of conventional finishes, the ceramic fibers can be damaged when bent around a sharp radius. For this reason, the Nextel™ bags were supported on perforated retainers and not on conventional wire cages. The Nextel™ bags were held to the retainer by constant torque clamps at the top and bottom.

S2-Glass, manufactured by Owens-Corning Fiberglas, is a formulation of fiberglass with better strength properties at high temperatures than conventional fiberglass fabrics. A proprietary abrasion-resistant coating was applied to the bags to protect the fibers. The coating lubricates or protects the glass fibers from abrading themselves, helps promote dust release and protects the fibers from chemical attack. The S2-Glass bags were supported on standard wire cages and were attached to the tubesheet with conventional snap rings. The S2-Glass fabric had been evaluated in previous short-term SNRB™ pilot tests conducted by B&W for Owens-Corning. The properties of the Nextel and S2-Glass fabrics are compared in Table 4-18.

TABLE 4-18 FILTER FABRIC CHARACTERISTICS					
FABRIC	MATERIAL	COMPOSITION	FINISH	WEIGHT	MAX TEMP
Nextel™	Ceramic	SiO_2, Al_2O_3, B_2O_3	None	16.4 oz/yd^2	2200°F
S2-Glass	Fiberglass	SiO_2, Al_2O_3, MgO	Proprietary	22.0 oz/yd^2	>900°F

4.7.2 Baghouse Operation

Preparation of the high-temperature baghouse for initial operation was discussed in Section 3.2.3, Shakedown Testing. To aid performance and protect the bags on initial start-up, the bags were pre-coated with Neutralite to establish a base layer of material on the bags before passing flue gsa to the baghouse. Precautions used in routine start-ups throughout the demonstration program included:

- Blow out all pressure transmitters lines.
- Inspection of baghouse components and verification of operating mode.
- Verification of the integrity of the hopper door seals.
- Bypass flue gas around baghouse until flue gas temperature exceeded 450 °F.
- Introduction of flue gas at 50% of design flow to the baghouse.
- Incremental increase of flue gas flow to the baghouse.

The following procedure was used when the baghouse was removed from service:

- Sorbent injection system shut down.
- Bags cleaned on-line as flue gas temperature was slowly reduced.
- Cleaned compartment isolated from flue gas and flue gas flow rate reduced to remaining on-line compartments.
- Baghouse bypass damper opened after all modules cleaned.
- Inspect hoppers for particulate accumulation and signs of corrosion.
- Check alignment and condition of bags from the bottom of the compartments.
- Replace gasketting on hopper doors as necessary.
- Verify compartment isolation damper operation.

More extensive baghouse inspections were performed during boiler outages and extended facility shutdowns. The activity included:

- Inspection of baghouse flues and manifold for accumulation of solids and corrosion.
- Check compartment tubesheets for solids accumulation from leaking gaskets or bag damage.
- Replacement of tubesheet gasketting or filter bags as necessary.
- Check bag cleaning equipment for proper alignment.
- Perform preventative maintenance on ash handling system slide gates and seals.
- Visually confirm operation of all dampers.
- Verify compressed air system operation.

About half way through the test program, the Nextel^{TM} bags in compartment 3 were replaced with S2-Glass bags. The S2-Glass bags were installed to further evaluate their applicability in integrated, high-temperature SNRB^{TM} operation. The Alternative Bag Test program is discussed in Section 6.0.

Particulate collection efficiency was examined over a variety of SNRB^{TM} operating conditions including a range of air-to-cloth ratios, baghouse pressure drops, sorbent feed rates, bag cleaning frequencies, and boiler loads. In addition, particulate removal was briefly evaluated with the SCR catalyst removed. Boiler load variation can affect baghouse operation through changes in the fly ash loading and particle size distribution. Infrequent measurement of particulate emissions during reduced boiler load operation were conducted since Ohio Edison seldom reduced boiler load for extended periods sufficient for sampling.

Over the course of the demonstration program, the baghouse was operated at high temperature for 2,315 hours. During typical operation, five of the six available compartments were in service. The coal fired came from several sources and generally contained 4.3 to 8.0% moisture, 10 to 13% ash, 3.0 to 4.0% sulfur, and had an average heating value of 12,000 Btu/lb. The flue gas entering the baghouse contained 1350 to 2250 ppm SO_2, 300 to 450 ppm NO_x, 4.0 to 6.0% O_2 and 3 to 4 grains/scf particulates. Injection of sorbent into the baghouse nominally tripled the particulate loading in the gas stream. The difference in the flue gas composition between the system inlet and baghouse inlet reflects the propane-fired burner combustion gases and the transport air used for sorbent and ammonia injection. Typical baghouse operating conditions are summarized in Table 4-19.

The initial test plan specified baghouse operation over an air-to-cloth ratio range of 3.0 to 6.0 acfm/ft^2. The current industry trend toward more conservative air-to-cloth ratios in commercial pulse-jet baghouses influenced the decision to limit the range to 3.0 to 5.0 acfm/ft^2. Operation at lower air-to-cloth ratios results in lower baghouse pressure drop, less frequent cleaning and extends bag life.

TABLE 4-19 TYPICAL RANGE OF BAGHOUSE OPERATING CONDITIONS	
Compartments On-Line	5
Flue Gas Flow	39,000 - 44,000 lb/hr
Air-to-Cloth Ratio	3.1 - 3.85 acfm/ft^2
Sorbent Injection Rate	300 - 515 lb/hr
Total Inlet Particulate Loading	12.0 - 22.0 lb/10^6 Btu 7.0 - 12.5 grains/scf
Baghouse Temperature	800 - 875 °F
Cleaning Cycle	45 - 90 minutes
Maximum Pressure Drop	11.5 - 14 "H_2O
Minimum Pressure Drop	10.0 - 12.5 "H_2O

In the demonstration program, both the Nextel™ and S2-Glass bags were frequently exposed to environments harsher than anticipated at commercial applications. Total high-temperature operating time for the Nextel™ bags was 2,315 hours. For approximately 32% of the total operating time, the Nextel™ bags were exposed to high levels of SO_2 and HCl when the facility was operated without sorbent injection. The S2-Glass bags were exposed to high SO_2 and HCl levels for approximately 360 hours or 24% of the total 1,490 hours of operation with the compartment of S2-Glass bags in service.

The pulse-jet cleaning conditions were relatively steady throughout the field demonstration. Cleaning was normally initiated by the baghouse pressure differential with one compartment cleaned on-line each time the upper control point was reached. Cleaning air pressure was maintained at 30 to 40 psig. This range was sufficient for complete and thorough cleaning along the 20-foot bag length. There was no incentive to evaluate higher pulse pressures that could lead to accelerated bag wear in a commercial application. The pulse duration was 80 to 100 milliseconds and the time between cleaning each row of bags in a compartment was approximately 30 seconds. Approximately , three minutes were required to clean a single compartment.

Off-line cleaning was not evaluated in the field demonstration. Off-line cleaning is typically used for difficult-to-remove filtercakes or for reduction in particulate emissions, neither of which were a concern in operation of the SNRB™ system demonstration. One disadvantage of off-line cleaning with regard to the SNRB™ process is a possible reduction of SO_x and NO_x emission control performance. Off-line cleaning may require that a cool, isolated compartment be placed in service to maintain the air-to-cloth ratio when a module is isolated for cleaning. Alternatively, the air-to-cloth ratio in the active compartments may be allowed to increase temporarily when one compartment is isolated for cleaning.

4.7.3 Baghouse Performance

The uniformity of SNRB™ baghouse operation is illustrated in Figure 4-65. During this period of operation, five compartments were on-line and particulate emissions were well below the NSPS compliance limit. Key parameters which describe baghouse operation, namely baghouse pressure drop, air-to-cloth (ATC) ratio, and opacity are plotted over an eight-hour period. The bags in each of the compartments were cleaned to essentially the same degree in each cleaning cycle as indicated by the minimum pressure drop reached during cleaning. In this period of operation, bag cleaning was initiated by pressure differential approximately every 45 minutes. Another indication of the uniformity of the baghouse operation was that under steady state conditions cleaning by pressure differential occurred on a regular time cycle as well.

Bag cleaning had a small effect on gas flow. Upon removal of the filter cake resistance to flow, the ATC ratio temporarily increased by approximately 5%. A continuing increase in tubesheet pressure drop indicative of bag blinding was not observed over the course of the demonstration project. As expected, small spikes in opacity measured downstream of the baghouse corresponded to the periods of bag cleaning.

Throughout the demonstration, the bag cleaning cycle and ATC ratio were adjusted to evaluate the effect on baghouse pressure drop. System pressure drop is an important design parameter since higher pressure drop increases auxiliary power consumption and operating costs. Table 4-20 provides examples of pressure drop performance. The average system pressure drop is similar to the total pressure drop for a combination of a baghouse, an SO_2 scrubber and an SCR unit.

TABLE 4-20 SNRB™ BAGHOUSE PRESSURE DROP TESTS

Air-to Cloth [acfm/ft^2]	Sorbent Injection	Cleaning Cycle [minutes]	Max Pressure Drop ["H_2O]	Min Pressure Drop ["H_2O]	Avg Pressure Drop ["H_2O]
3.4	yes	70	13.3	12.2	12.8
3.5	yes	45	11.4	10.8	11.1
3.7	yes	45	12.25	11.5	11.9
3.95	yes	66	13.6	12.7	13.1

Table 4-20 identifies several baghouse operating trends and tradeoffs. Frequent bag cleaning, characterized by a short cleaning cycle, reduces the average baghouse pressure drop at a given ATC ratio. Increased ATC ratio at a constant cleaning cycle will increase the pressure drop. The operational tradeoff is between higher pressure drop (infrequent cleaning) resulting in higher energy use and lower pressure drop through more frequent cleaning possibly resulting in reduced bag life.

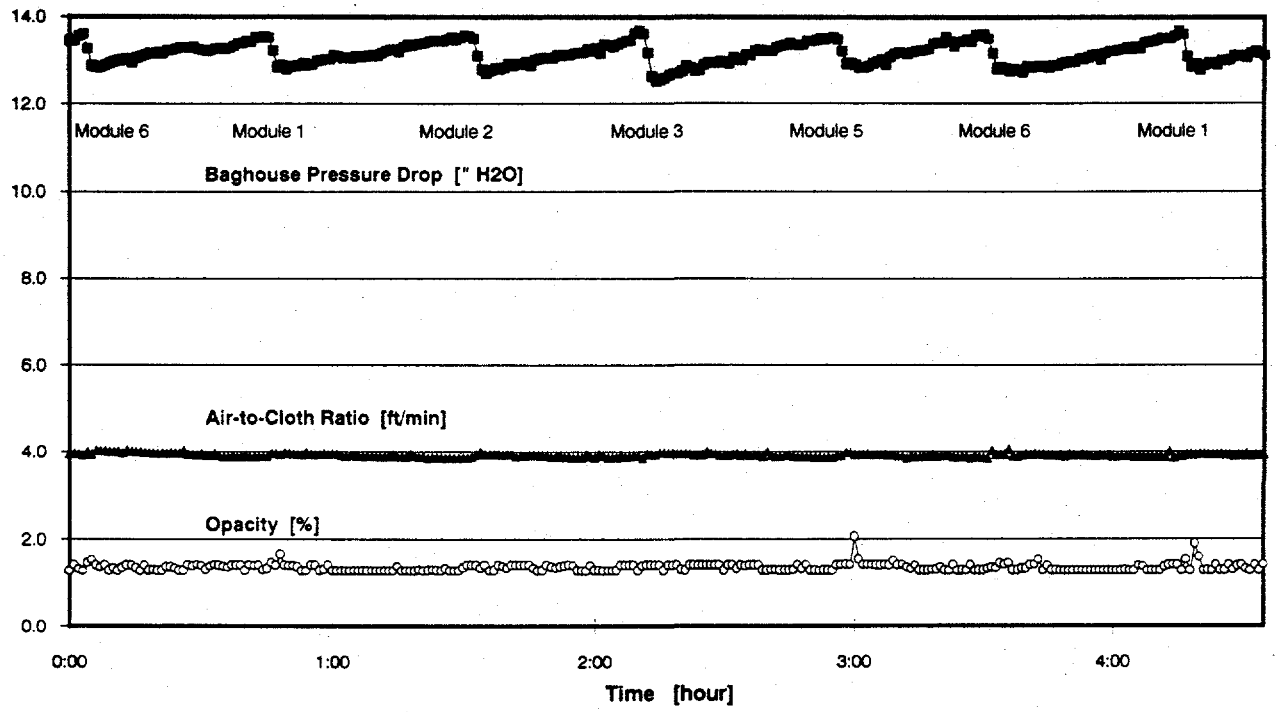


FIGURE 4-65 BAGHOUSE OPERATION UNIFORMITY

Overall, baghouse operation at an ATC ratio of 3.5 acfm/ft^2 and an average cleaning cycle of 65 minutes produced an average pressure drop of 12.5" H_2O. Operation at an ATC ratio of 4.0 acfm/ft^2 with a similar cleaning frequency produced an average pressure drop of about 13.0" H_2O. An industry survey sponsored by EPRI found that full-scale pulse-jet baghouses (without SCR catalyst and sorbent injection) were operating at or below an average tubesheet pressure drop of 6.0" H_2O at an ATC ratio of 4.0 acfm/ft^2.[45]

To evaluate baghouse performance, particulate loadings at the baghouse inlet and baghouse particulate emissions were measured over a wide range of operating conditions. The SNRB™ baghouse performance was found to be relatively insensitive to both Ohio Edison boiler operation and SNRB™ system sorbent injection.

Baghouse Inlet Loadings

The dust loading at the SNRB™ baghouse inlet may have been affected by several parameters including Ohio Edison boiler load, sorbent injection rate and the coal characteristics. Baghouse inlet loadings were measured by three parties, B&W and two independent test contractors. The contractors were present during the independent sampling and the air toxics emissions test programs. All inlet particulate loadings were measured using EPA Method 5 sample trains and the sampling time averaged one hour. The average baghouse inlet loadings are summarized in Table 4-21. Baseline ash loading without sorbent injection was fairly uniform as the ash content of the coal did not significantly vary over the test period. Changes in the sorbent injection rate contributed largely to the range of particulate loadings at the baghouse inlet. Sorbent injection essentially tripled the amount of particulate entering the baghouse from the baseline levels. The baghouse inlet loading measurements in lb/million Btu are labelled with the corresponding sorbent injection rates in Figure 4-66. The inlet loadings are reported in grains/scf in Figure 4-67.

TABLE 4-21 SNRB™ BAGHOUSE INLET LOADINGS

	BASELINE		SORBENT INJECTION	
	[lb/million Btu]	[grains/scf]	[lb/million Btu]	[grains/scf]
B&W	5.62	3.80	10.75*	6.92
Independent Testing	5.81	3.89	19.59	11.13
Air Toxics Testing	N/A	N/A	16.75	9.27
Average	5.66	3.33	16.94	9.64

* Two of the four measurements were conducted during low boiler load operation.

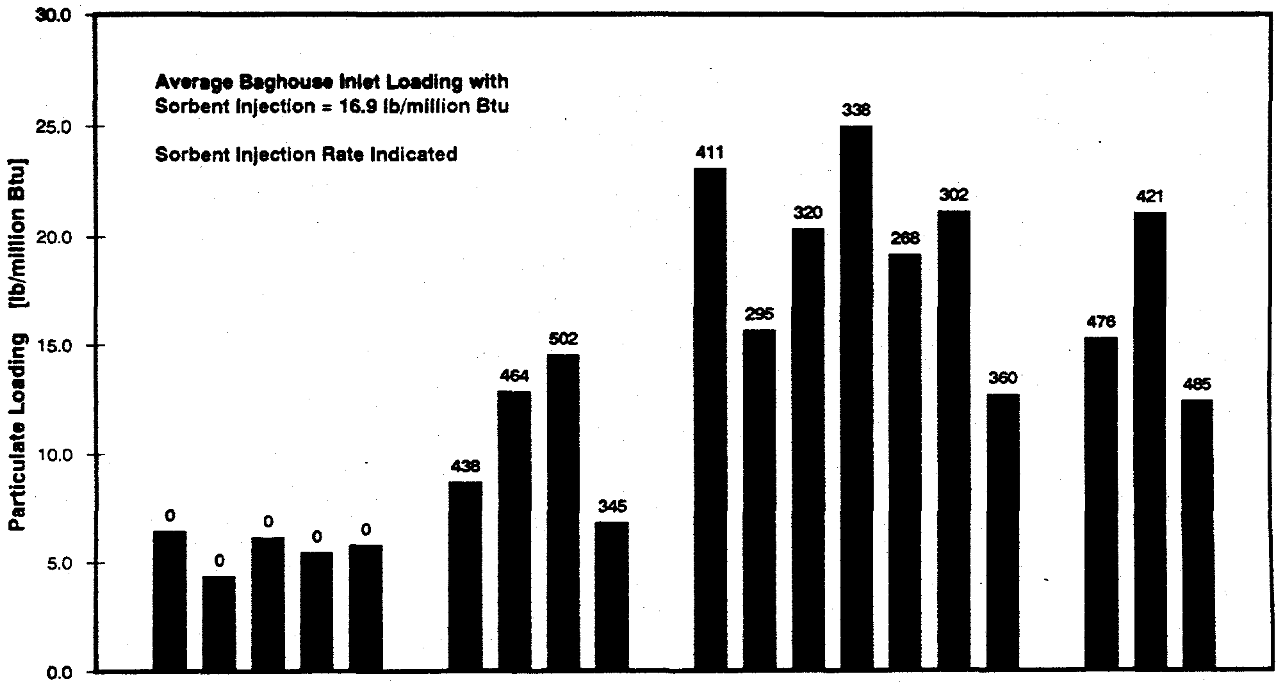


FIGURE 4-66 BAGHOUSE INLET PARTICULATE LOADING (LB/MILLION BTU)

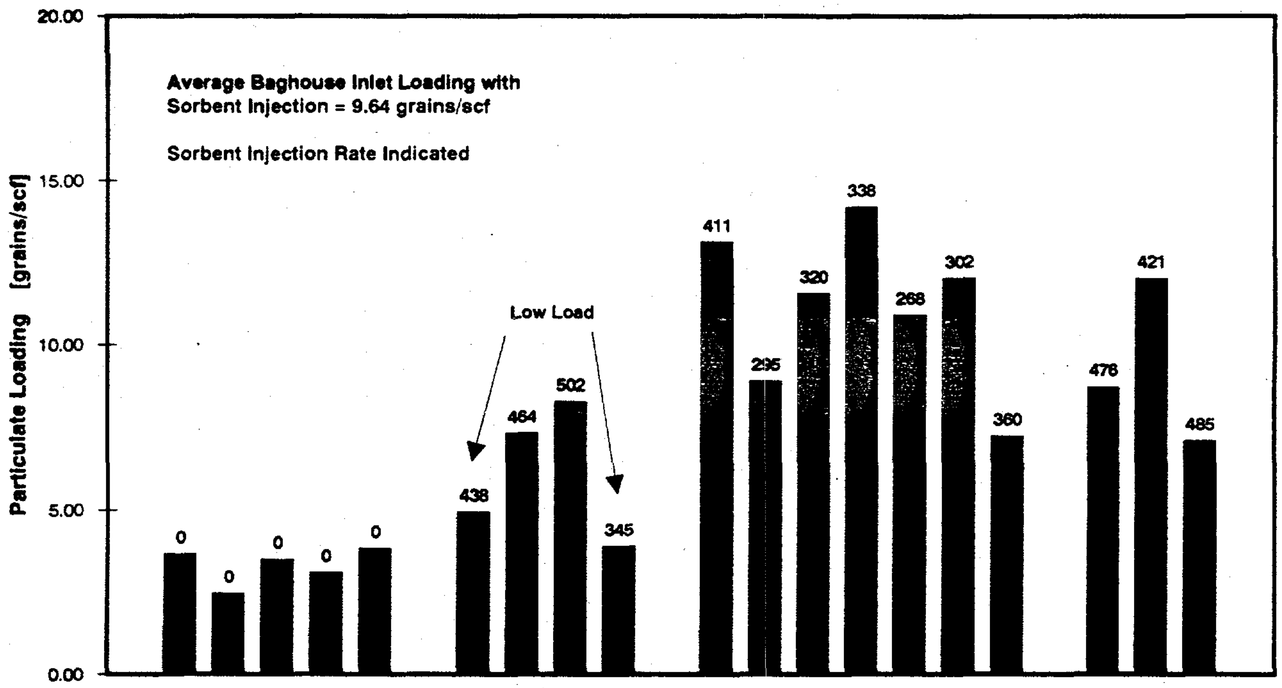


FIGURE 4-67 BAGHOUSE INLET PARTICULATE LOADING (GRAINS/SCF)

Baghouse Outlet Emissions

Most of the SNRB™ baghouse outlet emissions measurements were performed with an EPA Method 5 sampling train. In the Air Toxics Emissions Test Program, the baghouse outlet particulates were collected with an EPA Method 26A sample train. The EPA Method 26A train was selected to simultaneously collect acid gases (HCl and HF) and radionuclides. The major difference between the EPA Method 26A sample train and the EPA method 5 train is the use of different impinger solutions which had no bearing on particulate collection. A recommendation from the pilot design verification tests was the use of an EPA Method 17 sample train for particulate emission measurements. Method 17 utilizes a smaller filter than Method 5 and is believed to be better suited for low dust concentration measurements. However, the baghouse outlet temperature at the sampling location exceeded the maximum allowable for the M17 train.

Baghouse outlet particulate sampling time averaged two hours and included periods of bag cleaning. Particle emissions have been shown to increase during bag cleaning due to dust penetration through the fabric as the weave is opened up by the cleaning air pulse. Figure 4-68 confirms that the combination of baghouse design, operating conditions, and high-temperature fabric bags demonstrated collection efficiencies in compliance with the NSPS limit of 0.03 lb/10^6 Btu. Baghouse particulate emissions during operation with sorbent injection averaged 0.019 lb/10^6 Btu or 0.010 grains/scf yielding an overall particulate emissions control efficiency of 99.89%.

As indicated in Figure 4-68, compliance was maintained during injection of several different sorbents including hydrated lime, calcium lignosulfonated lime, and sodium bicarbonate. The figure represents measurements by both B&W and the independent testing contractors which were generally in good agreement. Operation of the SNRB™ system varied significantly in the operating periods during which the emissions data in Figure 4-68 was collected. The operating conditions included:

- SO_2 sorbent injection of 270 to 600 lb/hr
- Flue gas flow variation resulting in ATC ratio range of 2.95 to 4.85 acfm/ft^2
- Baghouse pressure differential of 11.2 to 15.0 inches H_2O
- Cleaning cycle frequency of 30 to 120 minutes (75 minute average)

A relative measure of the particulate emissions was provided by a continuous opacity monitor located downstream of the baghouse. The opacity monitor recorded transient events such as the increased emissions accompanying bag cleaning. The opacity monitor was used to study the real-time changes in baghouse performance during boiler load fluctuations and when the sorbent injection system was started up.

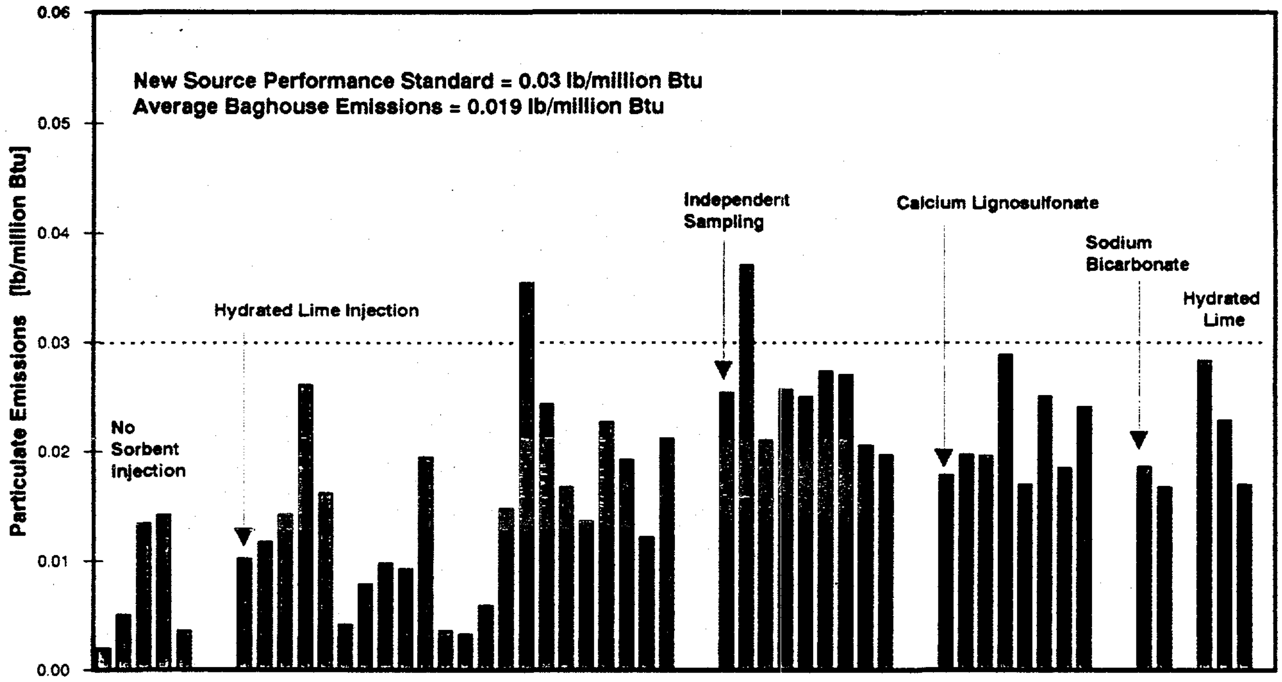


FIGURE 4-68 SNRB™ BAGHOUSE PARTICULATE EMISSIONS

4.7.4 Effect of Baghouse Operation on Emissions

Under normal SNRB™ operation, the particulate emissions did not significantly vary with changes in baghouse operation. Variations in overall baghouse outlet particulate emissions or opacity could not be correlated to ATC ratio, baghouse pressure drop, bag cleaning frequency, or the combination of modules in service.

Figure 4-69 summarizes opacity measurements over a range of SO_2 sorbent injection rates. The observed opacity was independent of the SO_2 sorbent injection rate. The measurements reflect two distinct operating periods in the demonstration program. Note that both opacity measurements early in the test program and those more than 1,000 hours of operation later are generally less than 2%. No increase in opacity over time at similar operating conditions was observed. The steady long term data in Figure 4-69 is representative of expected SNRB™ system performance.

Increased filtration velocities through the fabric have been shown to contribute to higher particle penetration.[46] Examination of baghouse opacity without sorbent injection revealed a trend toward higher opacity as the ATC ratio was increased as shown in Figure 4-70. While the absolute opacity values may have been influenced by the misalignment of the opacity monitor, the trend measured over a relatively operating time is clear. Misalignment of the opacity monitor due to vibration of the flue work was compensated for using frequent calibration and alignment checks.

Particulate emissions measured during periods of known baghouse operating problems are not reported as they do not represent the expected emissions from the baghouse under normal conditions. Five such emission measurements were obtained. Abnormal baghouse operation included hopper bridging and automatic baghouse bypass which occurred in response to a power supply surge. An overfilled hopper increased particulate re-entrainment onto the filter bags. A curious phenomena which periodically accompanied hopper bridging was the high temperatures (>1000 °F) reached by the ash accumulated in the hopper. Chemical analysis of the bridged ash revealed higher than normal (>6%) carbon content which was indicative of incomplete combustion in the boiler. Since the baghouse was operated at temperatures less than 900 °F, combustion of the carbon in the fly ash was suspected to have continued in the hopper. Continued combustion caused the solids to agglomerate and the subsequent agglomeration prevented simple removal of the solids from the hopper. Insertion of a thermocouple in the center of the hopper alerted the facility operator to solids accumulation and reduced the frequency of hopper bridging.

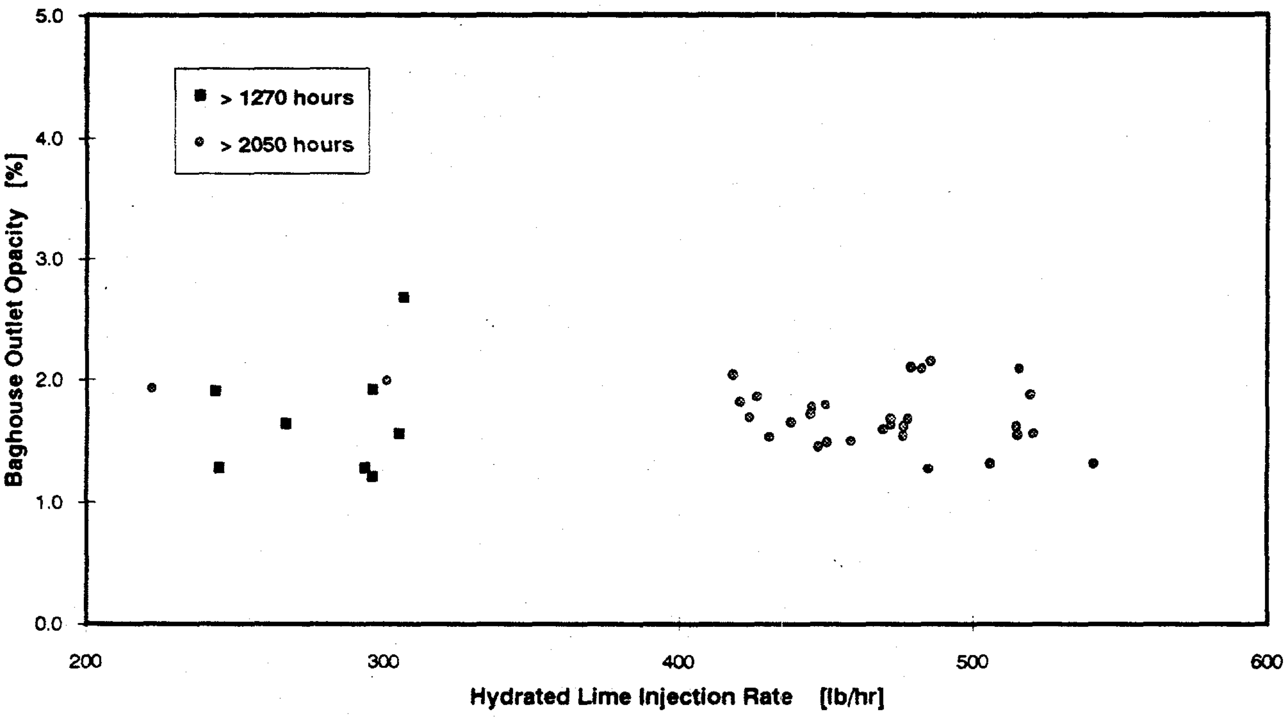


FIGURE 4-69 EFFECT OF OPERATING TIME ON OPACITY

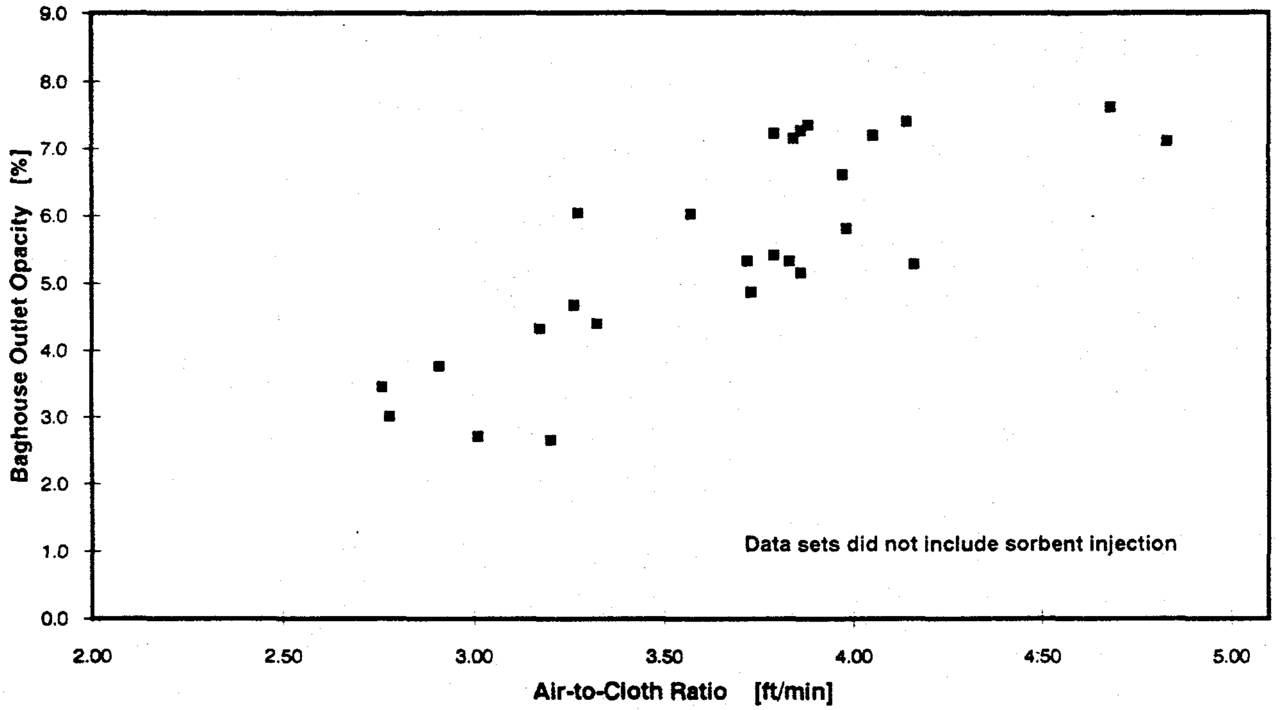


FIGURE 4-70 EFFECT OF AIR-TO-CLOTH RATIO ON OPACITY

4.7.5 Effect of SO_2 Removal Process on Baghouse Operation

SO_2 sorbent characteristics and the sorbent injection rate were examined for influence on particulate emissions or baghouse outlet opacity. Average particulate emissions obtained during periods of hydrated lime, calcium lignosulfonated lime (CLS) and $NaHCO_3$ injection are summarized in Table 4-22. Baghouse particulate emissions were not measured during the sugar hydrated lime (SHL) injection tests.

TABLE 4-22 EFFECT OF SORBENT TYPE ON BAGHOUSE EMISSIONS

	PARTICULATE EMISSIONS	
	[lb/10^6 Btu]	[grains/scf]
No Sorbent Injection	0.008	0.004
Hydrated Lime	0.018	0.009
CLS	0.021	0.012
$NaHCO_3$	0.017	0.010

A primary sorbent characteristic that may affect penetration of the filter bag fabric is the particle size distribution. As reported in Section 4.5, the particle size distribution and mean particle size were different for the calcium and sodium sorbents. The average particulate emissions listed in Table 4-22 suggest that baghouse performance was insensitive to the particle size distribution and sorbent type. Figure 4-71 presents a summary of opacity measurements for each of the SO_2 sorbents evaluated over a wide range of sorbent injection rates. Figure 4-71 confirms that low baghouse outlet opacity was maintained independent of the sorbent type and injection rate.

The transient data presented in Figure 4-72 reveals no change in the baghouse outlet opacity despite two step increases in the Ca/S stoichiometry or sorbent loading. The increase in Ca/S stoichiometry over the three periods illustrated resulted in a four-fold increase in the baghouse inlet particulate loading.

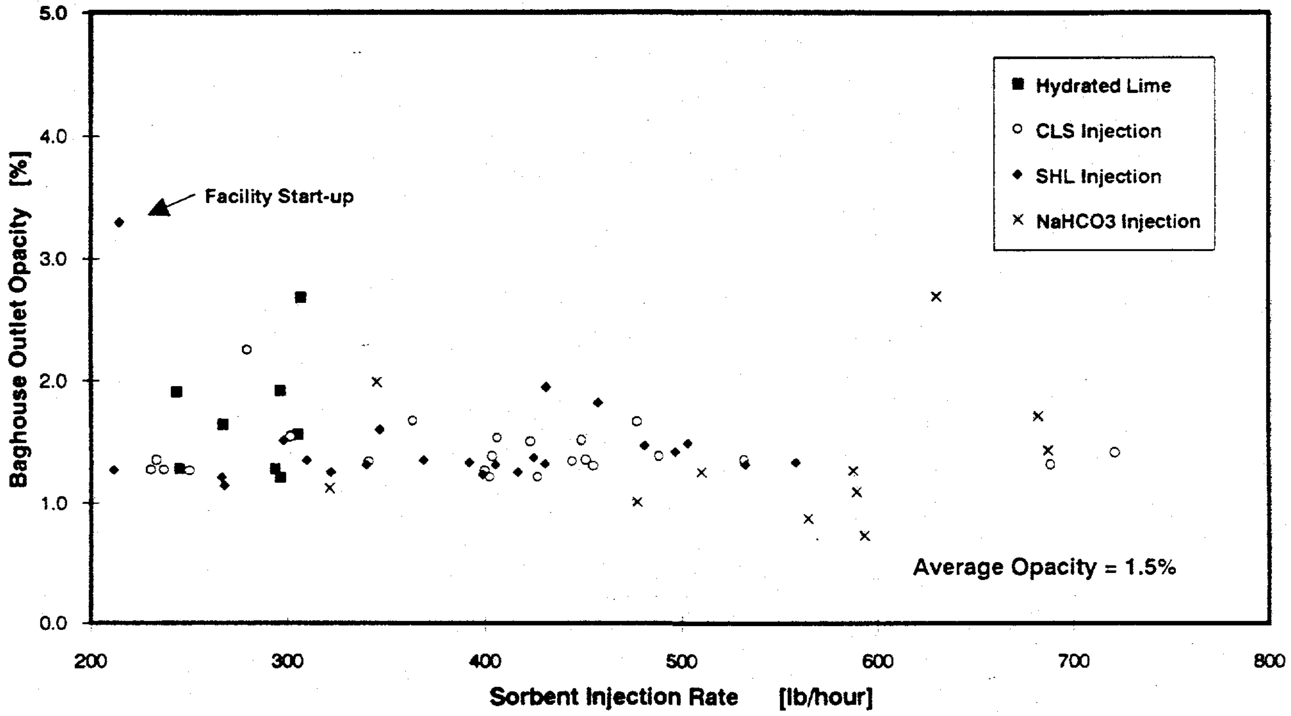


FIGURE 4-71 EFFECT OF SORBENT TYPE ON BAGHOUSE OUTLET OPACITY

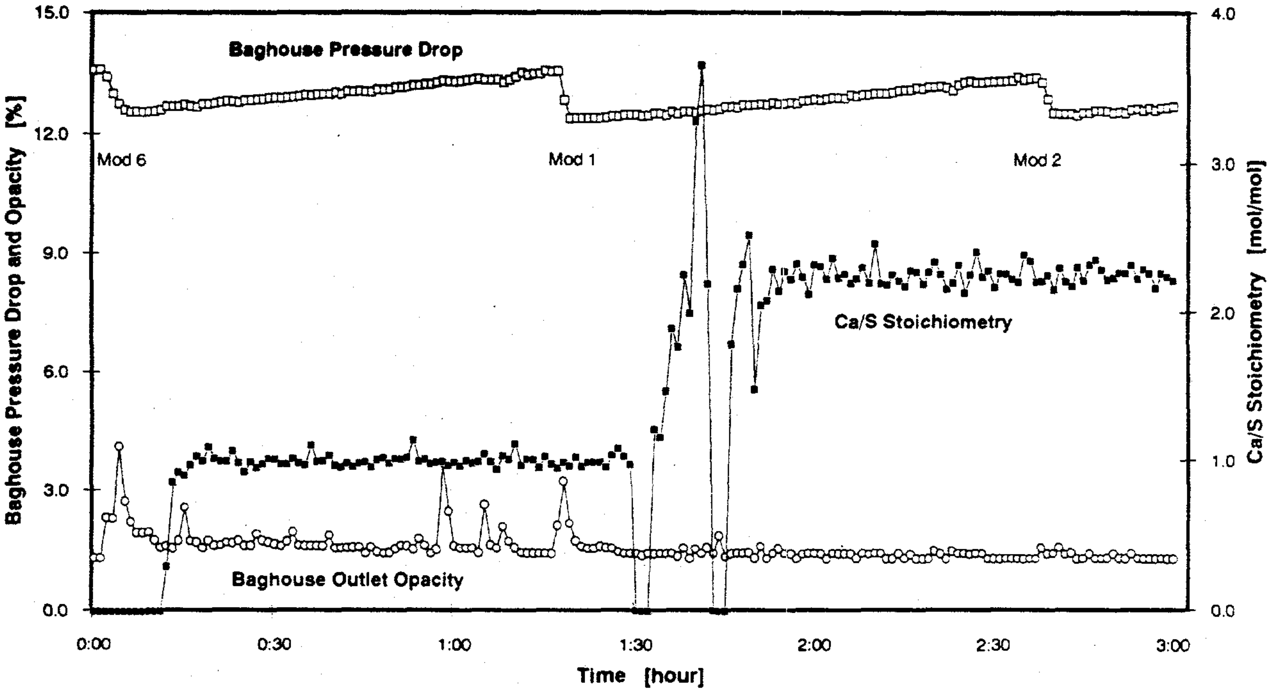


FIGURE 4-72 EFFECT OF Ca/S RATIO ON BAGHOUSE OPERATION

A reduction in baghouse pressure drop was observed during operation with $NaHCO_3$ relative to hydrated lime injection for otherwise constant baghouse operating conditions. The average $NaHCO_3$ sorbent particle is much larger than the average fly ash and lime hydrate particles. Packing of larger particles on the bag surface leads to a higher porosity filtercake. The greater volume of open space in the filtercake reduces the resistance to flue gas flow through the cake and produces a lower baghouse pressure drop when compared to operation with hydrated lime at a similar ATC ratio. On average, the maximum and minimum pressure drops observed with hydrated lime injection with the baghouse operating at an ATC ratio of 3.4 acfm/ft^2 and cleaning cycle of 70 minutes were 13.4 and 12.2" H_2O. At similar $NaHCO_3$ loading and baghouse operation, the maximum and minimum pressure drops were reduced to 11.7 and 11.0" H_2O. An example of the reduction in pressure drop is provided in Figure 4-73. No sorbent was injected into the baghouse prior to the test period featured in Figure 4-73. Upon the introduction of the $NaHCO_3$ sorbent, the baghouse differential pressure continually dropped when the cleaning cycle was maintained at a 95 minute interval. The benefit of reduced pressure drop can be evaluated by two different approaches relative to operation with hydrated lime. Maintaining the same cleaning cycle time will result in lower baghouse pressure drop and reduced fan power costs. Alternatively, the cleaning cycle can be lengthened to maintain the pressure drop and potentially improve bag life through less frequent cleaning.

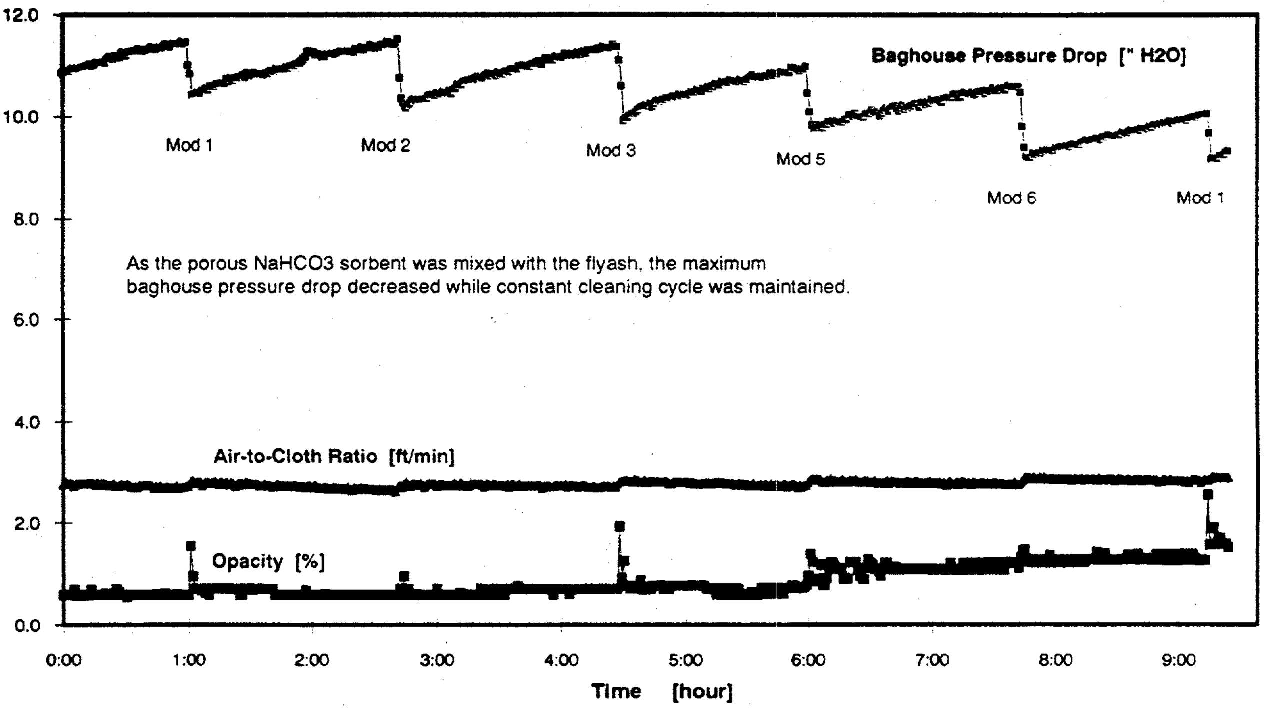


FIGURE 4-73 EFFECT OF $NaHCO_3$ INJECTION ON BAG CLEANING

4.7.6 Effect of NO_x Removal Process on Baghouse Operation

The NO_x removal process can potentially affect baghouse operation and performance as a result of NH_3 injection. Ammonia injection can increase particulate emissions through the formation of ammonium sulfate salts at high concentrations of NH_3 and SO_3 and low temperature. In general, SNRB™ operation at optimized conditions consistently demonstrated ammonia slip less than 5 ppm and low concentrations of SO_3 (< 10 ppm) downstream of the baghouse. Low temperature (< 450 °F) operation may be conducive to ammonium sulfate salt formation on the NH_3 injection grid upstream of the baghouse. Periodic inspections of the NH_3 injection grid throughout high-temperature demonstration of the SNRB™ technology did not reveal the presence of ammonium sulfate salts. However, after low temperature operation at 450 °F with $NaHCO_3$ and NH_3 injection, some solids suspected to be ammonium sulfate salts were present on the grid.

Both NH_3 and ammonium sulfate salts may contribute to fine particulate emissions. When the catalyst was saturated with NH_3 (typically following a steep boiler load drop) the baghouse opacity was observed to increase and remain at a higher level as the excess NH_3 desorbed from the catalyst. Increased opacity resulting from high ammonia slip is shown in Figure 4-74. Prior to NH_3 injection the opacity was approximately 1%. Immediately after overshooting the NH_3/NO_x stoichiometry setpoint, the baghouse NO_x removal quickly exceeded 90% and the opacity increased to 4% even though the ammonia feed rate was decreased.. The ability of the zeolite to serve as a reservoir for ammonia slows the desorption of the ammonia from the catalyst. Approximately four hours after catalyst saturation, the SCR system recovered. Recovery from the catalyst saturation would have been faster if the NH_3 had been turned off completely.

The effect of the catalyst on baghouse performance and particulate emissions was studied during two replicate series of tests performed with and without the SCR catalyst installed. The baghouse outlet opacities measured during the tests conducted with the catalyst installed were similar to the opacities measured without the catalyst. Additional confirmation that the catalyst did not serve as a particulate collection device is supported by the EPA Method 5 measurements conducted when the catalyst was removed. The baghouse outlet emissions without the catalyst averaged 0.024 $lb/10^6$ Btu (0.016 grains/scf) on the basis of two measurements. Emissions without the catalyst fall within the range of 0.004 - 0.037 $lb/10^6$ Btu measured with the catalyst installed. The emissions measurements conducted with the catalyst in place averaged 0.019 $lb/10^6$ Btu (0.010 grains/scf).

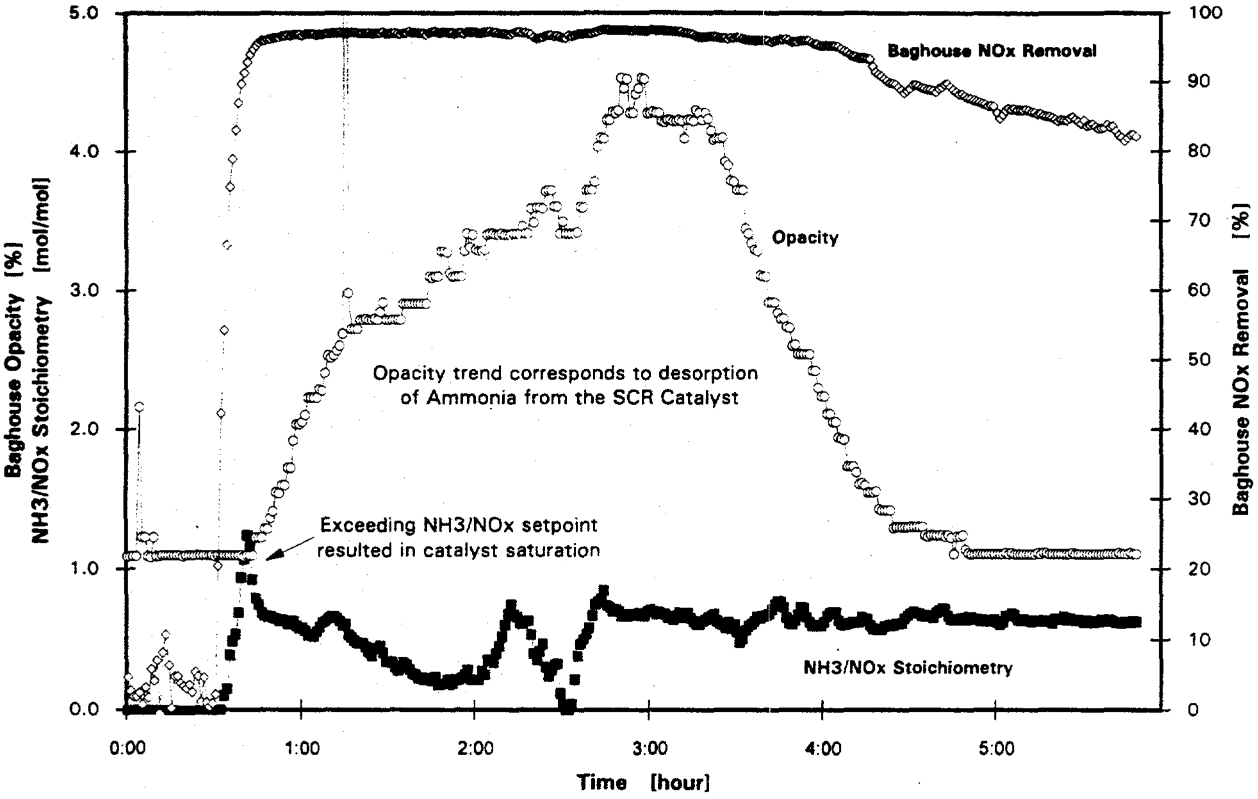


FIGURE 4-74 EFFECT OF CATALYST SATURATION ON OPACITY

The replicate tests also enabled the evaluation of the catalyst contribution to the overall baghouse pressure drop. To evaluate the catalyst contribution, a constant baghouse cleaning cycle was maintained during which every on-line compartment was cleaned to remove the filtercake from the bags. To determine the amount of pressure drop attributable to the catalyst, the differences in "clean" pressure drop with and without the catalyst were compared. The "clean" pressure drops were measured immediately after all five of the in-service compartments were cleaned. The "clean" pressure drop is not the same as the average pressure drop. Addition of the catalyst increased the system pressure drop by approximately 5.5" H_2O during typical baghouse operation at an ATC ratio of 4.0 acfm/ft^2. The pressure drop test data is presented in Figure 4-75.

4.7.7 Effect of Boiler Operation

Figures 4-76 and 4-77 illustrate the effect of boiler operation on fabric filter operation and performance. The drop in boiler load as shown in Figure 4-76 at approximately 2 hours and 45 minutes generally led to a reduction in the flue gas flow as indicated by the decrease in ATC ratio and inlet particulate loading. Particulate concentration measurements at the baghouse inlet confirmed that the average inlet loading was reduced as a result of a boiler load drop. Baghouse inlet particulate loading decreased from 16.9 to 7.8 lb/10^6 Btu (9.6 to 5.1 grains/scf) as boiler load was reduced from 150 to 75 MWe. The low boiler load inlet loading measurements are highlighted in Figure 4-67.

Adjustments in the baghouse cleaning cycle accompanying a boiler load increase are illustrated in Figure 4-77. During a boiler load increase the ATC ratio and inlet SO_2 concentration rise and increase the sorbent injection requirements. Since the rate of pressure drop increase is a function of the solids collection rate and flue gas flow, the frequency of bag cleaning increased with the boiler load increase. A slight escalation in the baghouse opacity accompanied the boiler load increase.

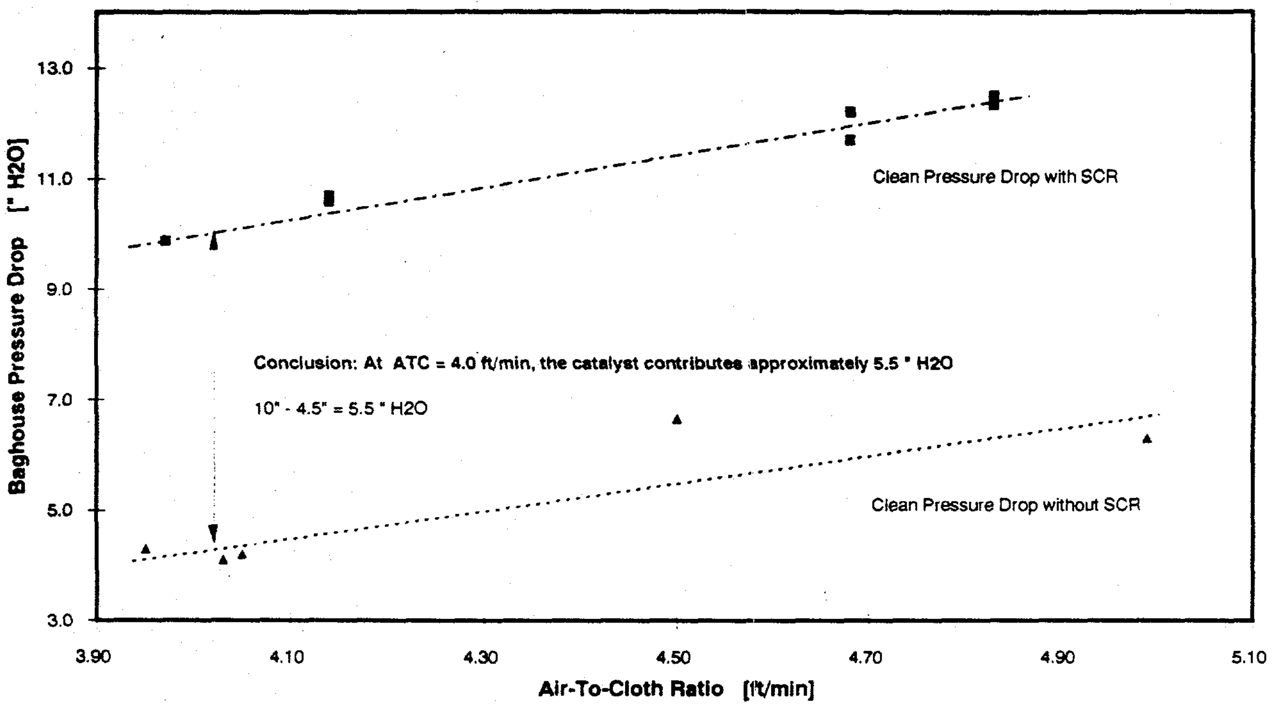


FIGURE 4-75 CATALYST CONTRIBUTION TO BAGHOUSE PRESSURE DROP

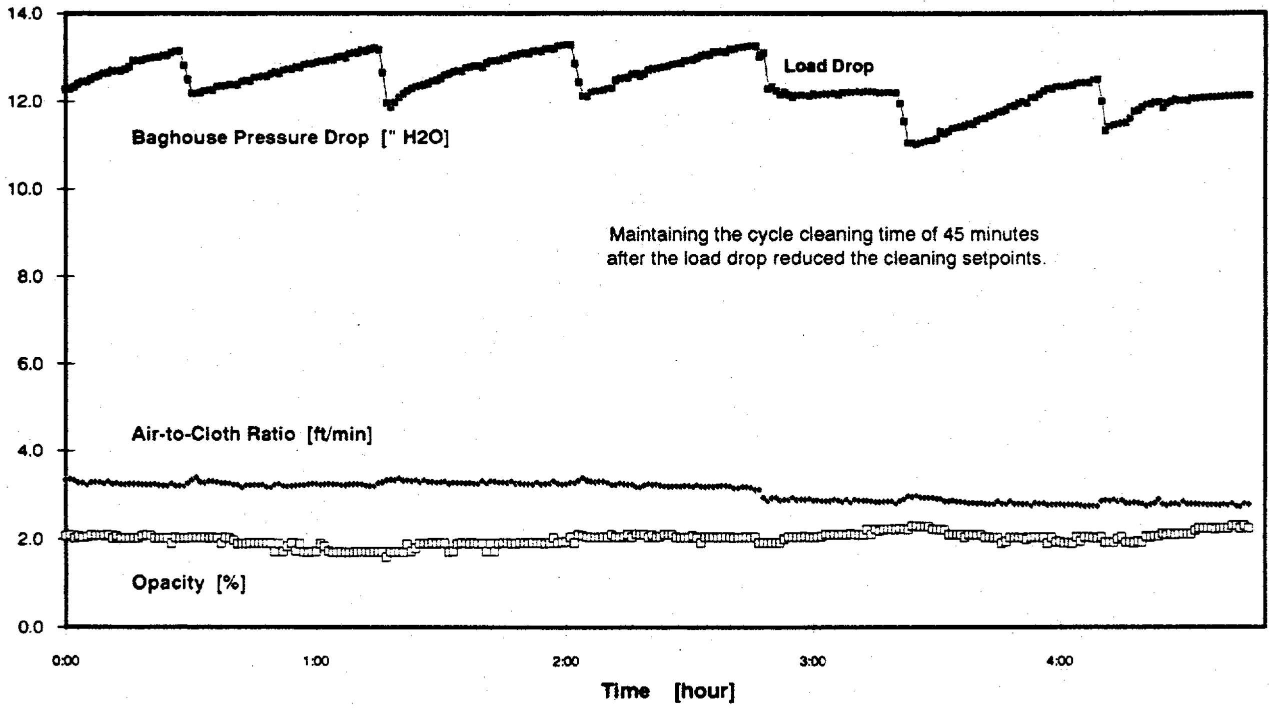


FIGURE 4-76 EFFECT OF LOAD DROP ON BAGHOUSE OPERATION

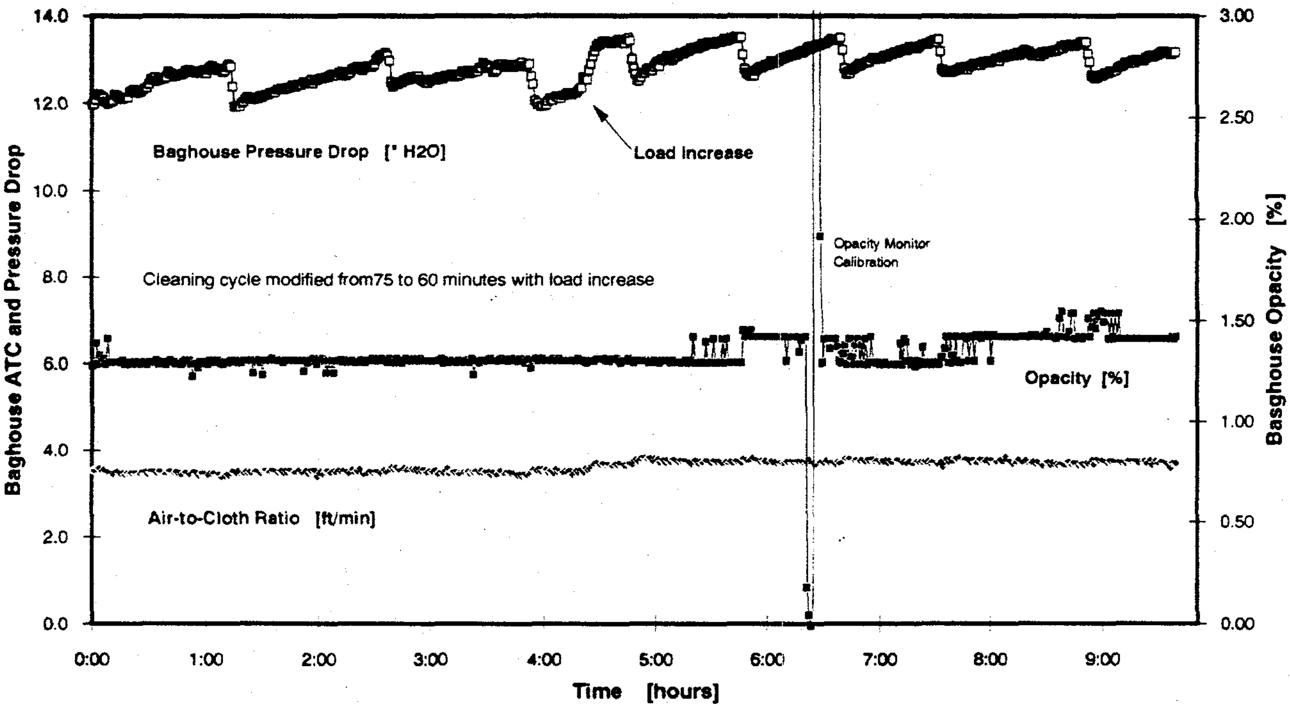


FIGURE 4-77 EFFECT OF LOAD INCREASE ON BAGHOUSE OPERATION

4.7.8 Performance Tests

A 225 hour performance test in which the SNRB™ system was operated at optimal conditions was conducted as the final operating period of the demonstration program. The operating conditions are outlined in Section 4.5.9. The baghouse cleaning cycle frequency throughout the performance test was maintained at 45 minutes. Since Ohio Edison made every effort to hold operation at full boiler load (150 MWe) and the sorbent feed rate was fairly constant for the duration of the test, the 45 minute cleaning interval resulted in a fairly uniform baghouse pressure drop as illustrated in Figure 4-78. Cleaning every 45 minutes and operation at an ATC ratio of 3.7 acfm/ft^2 generated an average baghouse pressure drop of 11.9 ± 0.35" H_2O.

Particulate emissions were measured by an independent contractor during the performance test. The baghouse inlet loading and outlet emissions averaged 16.7 lb/10^6 Btu (9.3 grains/scf) and 0.023 lb/10^6 Btu (0.013 grains/scf) corresponding to a collection efficiency of 99.86%. The baghouse inlet and baghouse outlet measurements are represented by the three columns on the far right in Figures 4-66 and 4-68.

In spite of efforts to maintain steady test conditions, the ATC ratio dropped briefly to 3.75 from 3.4 acfm/ft^2 during the performance test. Since the cleaning cycle was held to 45 minutes, the performance test provided the opportunity to monitor the effect of ATC ratio on baghouse pressure drop. The maximum and minimum baghouse pressure drops are plotted as a function of the ATC ratio in Figure 4-79. The ATC ratio is shown to have a direct impact on the baghouse pressure drop.

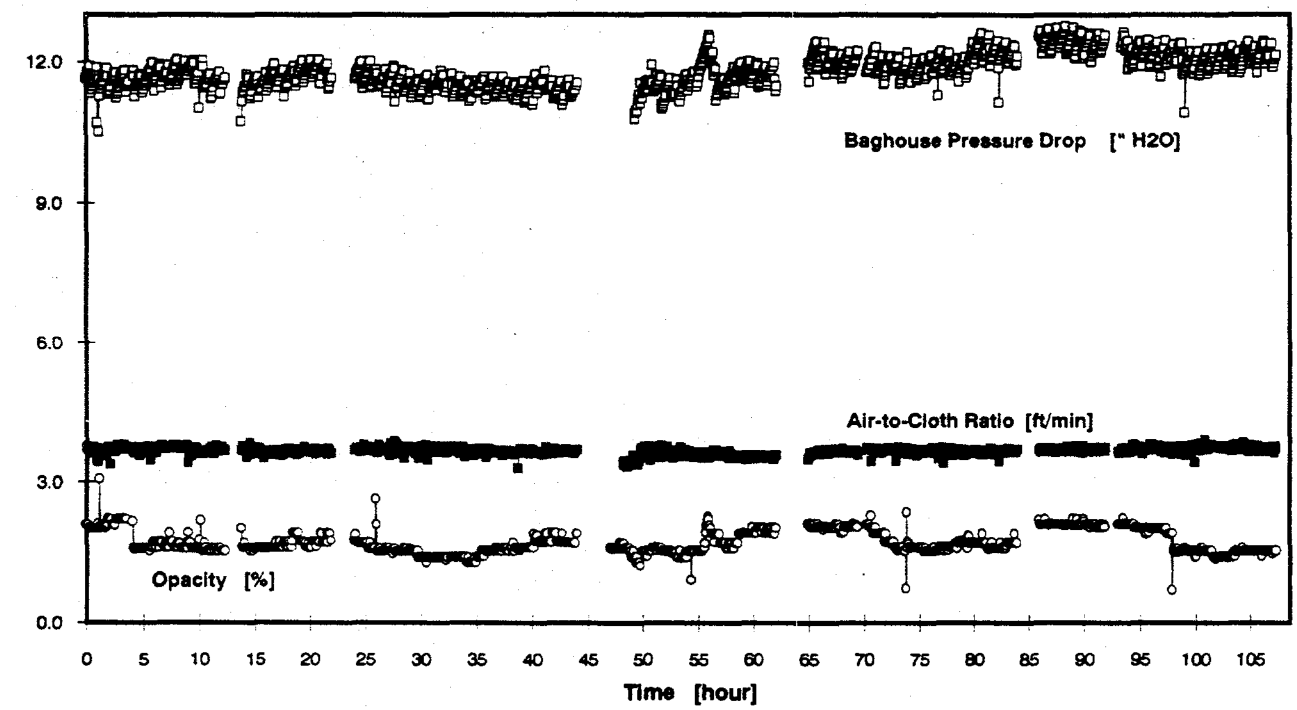


FIGURE 4-78 PERFORMANCE TEST BAGHOUSE OPERATION

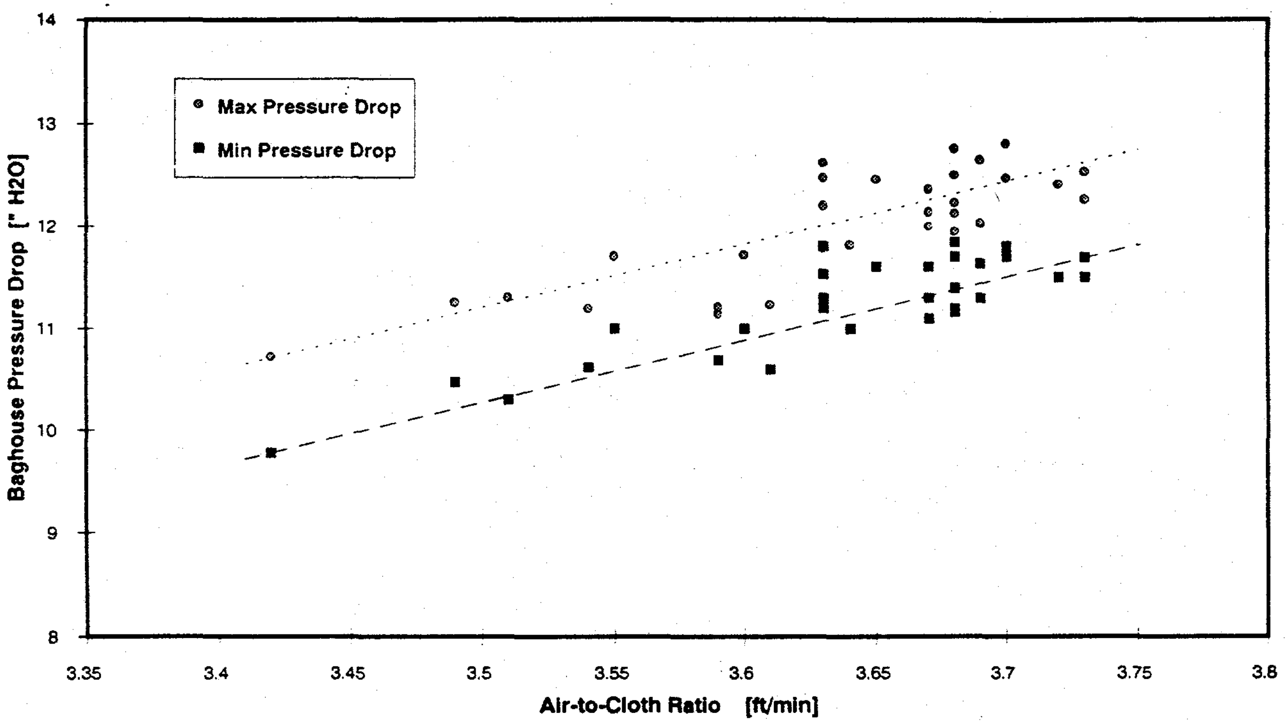


FIGURE 4-79 EFFECT OF AIR-TO-CLOTH RATIO ON BAGHOUSE PRESSURE DROP

4.7.9 Fine Particulate Measurements

The penetration of fine particulate through the SNRB™ baghouse was evaluated during the performance and independent verification phases of the demonstration program. Fine particulate emissions are suspected to cause adverse health effects and provide sites for condensing trace elements. Particle size distribution (PSD) measurements were measured at the baghouse inlet and outlet simultaneously with Anderson cascade impactors by an independent contractor. The sampling technique detected particulate in the range of 0.25 - 8.0 microns. For the PSD sampling, the SNRB™ baghouse was operated at an ATC ratio of 3.5 to 4.0 acfm/ft^2 with hydrated lime injection rates of 270 to 420 lb/hr and a baghouse operating temperature of 800 to 850 °F. Six sets of impactor measurements were performed with hydrated lime injection and one set was conducted without sorbent injection. The results of the seven sets of PSD measurements are summarized in Appendix N.

Figure 4-80 compares the PSD at the baghouse inlet and outlet when operating with and without sorbent injection. The obvious characteristic of Figure 4-80 is the increased coarseness of the solids entering the baghouse when hydrated lime was injected. In the absence of sorbent injection, approximately 83% of the incoming fly ash was less than 7 microns. The addition of hydrated lime reduced the percentage of solids at the baghouse inlet with diameters less than 7 microns to 45%. Particulate less than one micron generally accounted for less than 1% of the inlet loading to the SNRB™ baghouse with sorbent injection and 6% of the total without sorbent injection. The PSD of the baghouse outlet solids were consistent with and without lime injection. Despite the large increase in the sorbent loading from 0 to 420 lb/hr, the baghouse retained high particulate collection efficiency. About 80% of the particulate penetrating the baghouse was less than 7 microns in size.

The results of the PSD measurements conducted during the performance tests are compared to independent measurements by a second contractor in Figure 4-81. The baghouse was operated at similar conditions in the two sampling periods. During the performance tests, the baghouse was maintained at an ATC ratio of 3.7 acfm/ft^2 with a hydrated lime injection rate of about 460 lb/hour and a baghouse temperature of 855°F. The SNRB™ facility was operated at optimal conditions and the Ohio Edison boiler was maintained at full boiler load, therefore most of the factors that could contribute to variations in PSD were held constant. The baghouse inlet PSD during the performance tests was measured with a Mark V five-stage series cyclone which allowed greater sampling time than a cascade impactor. For this reason the PSD measured during the performance tests are probably more representative than those measured with the lower capacity cascade impactor. Baghouse outlet PSDs were measured with a cascade impactor. The PSDs at the baghouse inlet and outlet were measured simultaneously.

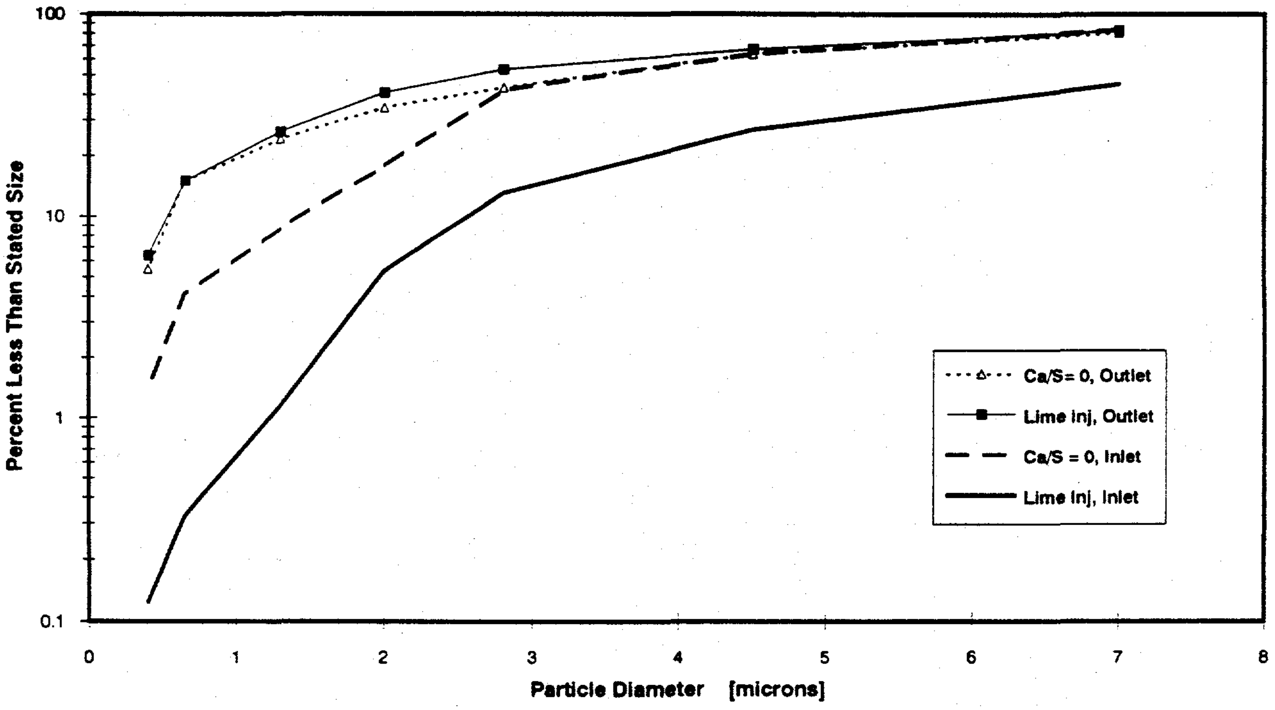


FIGURE 4-80 BAGHOUSE INLET AND OUTLET PARTICLE SIZE DISTRIBUTION

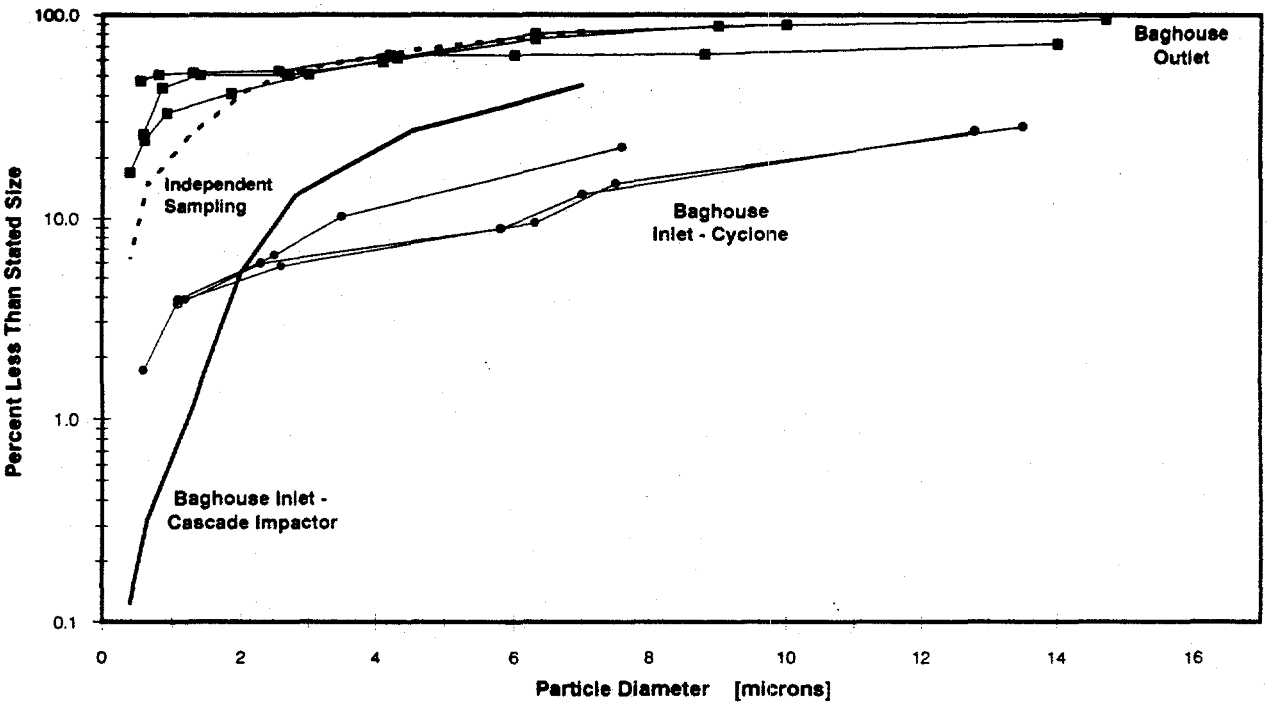


FIGURE 4-81 PARTICLE SIZE DISTRIBUTION COMPARISON

The cyclone measured a coarser PSD for solids entering the baghouse compared to the cascade impactor. The percentage of particulate at the baghouse inlet less than 7 microns was determined to be approximately 10%. Particulate less than one micron generally accounted for less than 3% of the inlet loading to the SNRB™ baghouse. The results of the performance test measurements at the baghouse outlet were very similar to the independent contractor results and indicated about 70% of the particulate penetrating the baghouse were finer than 7 microns. Table 4-23 compares the results of the fine particulate measurements.

TABLE 4-23 FINE PARTICULATE MEASUREMENTS

	Independent Sampling	Performance Tests
Baghouse Inlet	Cascade Impactor	Cyclone
% Less than 7 micron	45	10
% Less than 1 micron	1	3
Baghouse Outlet	Cascade Impactor	Cascade Impactor
% Less than 7 micron	83	70
% Less than 1 micron	20	40

4.7.10 Bag Characterization for Disposal

Toxicity Characteristic Leaching Procedure (TCLP) analyses were performed on representative samples of the Nextel™ and S2-Glass filter bag fabrics removed from the baghouse at the conclusion of the demonstration program. The results are summarized in Table 4-24. The TCLP analysis replaced the extractive procedure (EP) leaching method used to determine whether a waste exhibits toxic characteristics. Care was taken not to completely disturb or remove the filtercake from the bags prior to analysis. Comparison of the analytical results to the applicable regulatory limits for the constituents confirm the non-hazardous nature of the used Nextel™ and S2-Glass bags.

TABLE 4-24 SNRB™ FILTER BAG TCLP ANALYSIS

EPA Hazardous Waste Number	Contaminant	Nextel™ [mg/l]	S2-Glass [mg/l]	Regulatory Limit [mg/l]
D004	Arsenic, Total	<1	<1	5.0
D005	Barium, Total	<10	<10	100
D006	Cadmium, Total	<0.1	<0.1	1.0
D007	Chromium, Total	<1	<1	5.0
D008	Lead, Total	<1	<1	5.0
D009	Mercury, Total	<0.04	<0.04	0.2
D010	Selenium, Total	<0.1	<0.1	1.0
D011	Silver, Total	<1	<1	5.0

4.7.11 Baghouse Performance Conclusions

Control of particulate emissions below the NSPS level of 0.03 lb/10^6 Btu was demonstrated over a wide range of baghouse operating conditions and verified by an independent sampling company. Overall baghouse particulate collection efficiency averaged 99.89%. Variation in baghouse outlet particulate emissions could not be correlated with air-to-cloth ratio, SO_2 sorbent injection rate, baghouse pressure drop, bag cleaning frequency, or the combination of compartments in service.

A summary of key observations related to particulate collection and SNRB™ baghouse operation follows.

- Hydrated lime injection increased the baghouse inlet particulate loading from an average of 5.6 to 16.5 lb/10^6 Btu (3.2 to 9.3 grains/SCF).
- Emission testing with and without the SCR catalyst installed revealed no apparent difference in collection efficiency.
- On-line cleaning with a pulse air pressure of 30 to 40 psi was sufficient for cleaning the bag/catalyst assemblies.
- Typically, one of the five baghouse modules in service was cleaned every 45 to 90 minutes to maintain operation within the differential pressure setpoint range.

- Baghouse opacity was generally less than 2% at an ATC ratio of 3.5 to 4.0 acfm/ft^2.

- Filter fabric performance was relatively insensitive to boiler operation and SNRB™ sorbent injection.

- The SCR catalyst contribution to the baghouse pressure drop was approximately 5.5 inches H_2O at an ATC ratio of 4.0 acfm/ft^2. The catalyst contribution may be higher or lower for specific NO_x reduction requirements.

- Baghouse operation at an ATC ratio of 3.5 acfm/ft^2 and cleaning frequency of 65 minutes produced an average baghouse pressure drop of 12.5 inches H_2O. Similar operation at an ATC of 4.0 acfm/ft^2 increased the average pressure drop to 13.0 inches H_2O.

4.8 INDEPENDENT TESTING OF THE SNRB™ PROCESS

Evaluation of the SNRB™ process by a third-party emissions testing sub-contractor was completed in October and November 1992 over a period of 240 hours of operation. The evaluation primarily consisted of EPA-approved continuous emissions monitoring of key process streams and grab sampling of the solid byproduct. The independent testing verified the accuracy and reliability of the sampling methods employed by B&W throughout the demonstration and provided a comparison of the SNRB™ emissions control performance measurements. A summary the gaseous streams sampled and the sampling methods used for verification of SNRB™ performance follows. Independent verification of particulate collection measurements were discussed in Section 4.7.

The SO_3 concentration in the flue gas at the system inlet, baghouse outlet and downstream of the outlet flue gas cooler was measured using miniature acid-condensation system (MACS).[28] The sampling locations were chosen to characterize the SO_3 entering the facility and evaluate SO_3 removal across the baghouse. These SO_3 measurements were previously discussed in Section 4.5.15.

4.8.1 SO_2 Measurements

The accuracy of the B&W SO_2 sampling method was verified by Total Source Analysis (TSA), an independent sampling agency. TSA used UV-based SO_2 monitors to verify SNRB™ system SO_2 removal performance. Continuous SO_2 measurements were conducted simultaneously at the system inlet and baghouse outlet for comparison of total SO_2 removal. The O_2 levels at the system inlet and baghouse outlet were measured concurrently in accordance with EPA Method 19 for normalization of the SO_2 concentrations to 3% O_2.

The continuous SO_2 monitors were able to detect transient changes in SO_2 concentration with time. An example of the fluctuations in the SO_2 concentrations simultaneously measured at the system inlet and outlet by TSA and B&W is presented in Figure 4-82. Figure 4-83 provides an example of how well the continuous total SO_2 removal based on the TSA measurements and B&W measurements compared. The total SO_2 removals based on the TSA measurements were generally within 4.6% of the removals based on the B&W measurements. Table 4-25 summarizes the average deviations between the SO_2 measurements by B&W and TSA.

TABLE 4-25 DEVIATION IN TSA AND B&W SO_2 MEASUREMENTS

	% DEVIATION	UNIT DEVIATION
System Inlet SO_2	3.3%	64 ppm SO_2
System Inlet O_2	5.9%	0.33% O_2
Baghouse Outlet SO_2	11.4%	48 ppm SO_2
Baghouse Outlet O_2	4.6%	0.32% O_2
Total SO_x Removal	4.6%	3.1%

An example of how well the simultaneous system inlet and baghouse outlet SO_2 concentration measurements by TSA and B&W compared over a 3-hour period is presented in Figure 4-84. Similar comparisons of the averaged system inlet and baghouse outlet SO_2 concentrations are provided in Appendix O.

The total SO_2 removals calculated for each data set based on the TSA and B&W measurements are presented in Figure 4-85. The Ca/S stoichiometry was varied during the independent tests to confirm the trend of increased removal efficiency with increased stoichiometry.

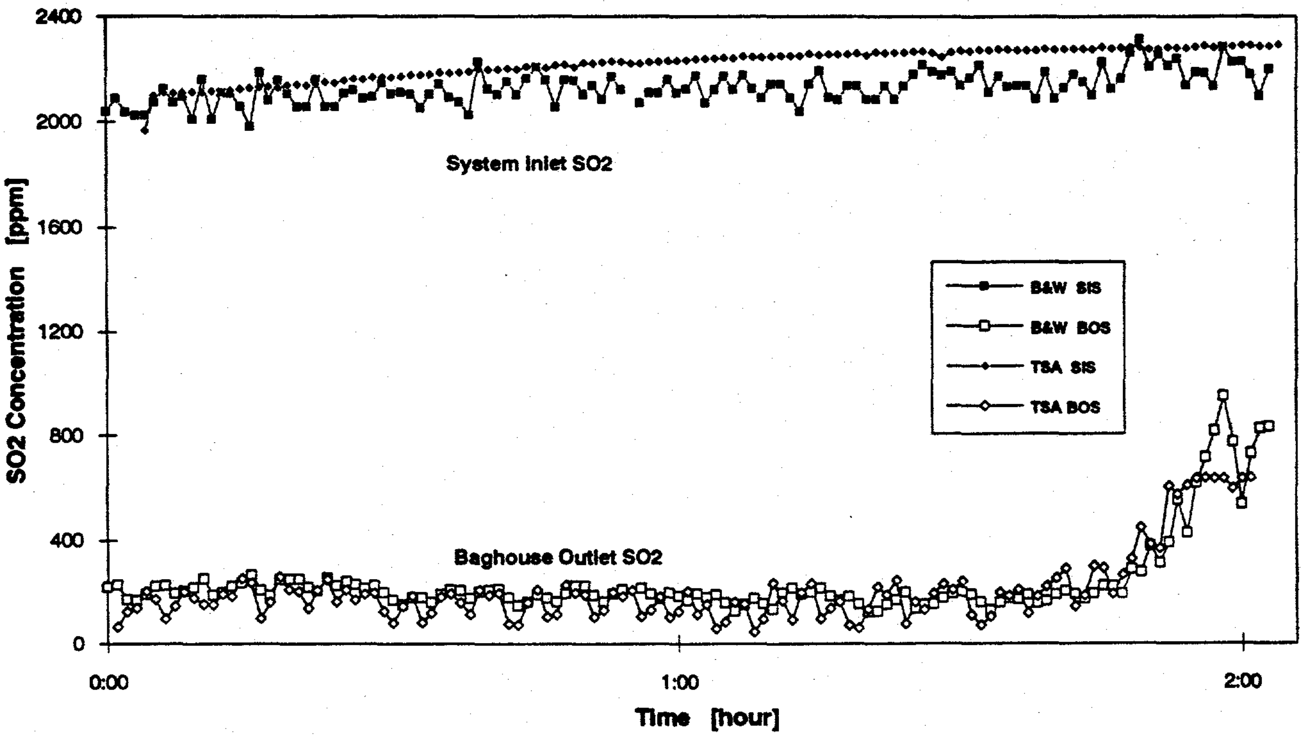


FIGURE 4-82 VERIFICATION OF INLET AND OUTLET SO_2 FLUCTUATIONS

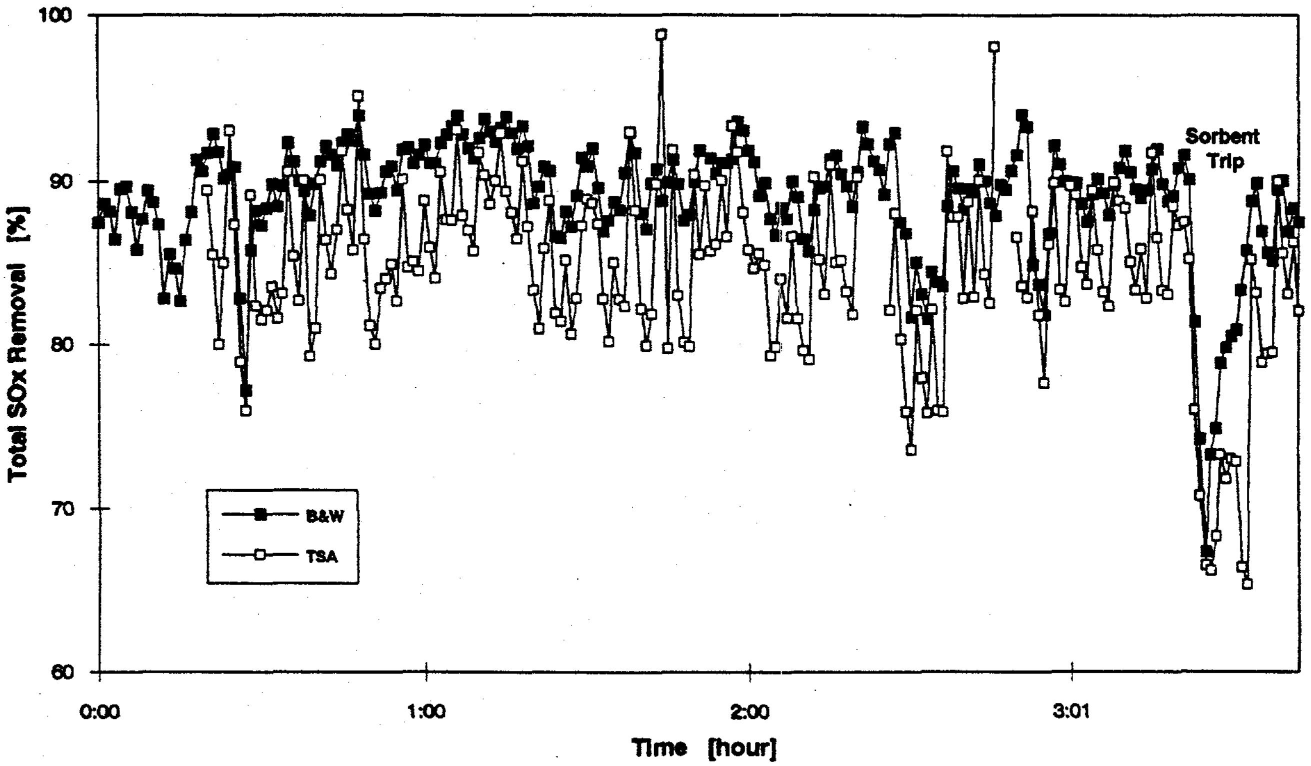


FIGURE 4-83 VERIFICATION OF SO_2 REMOVAL

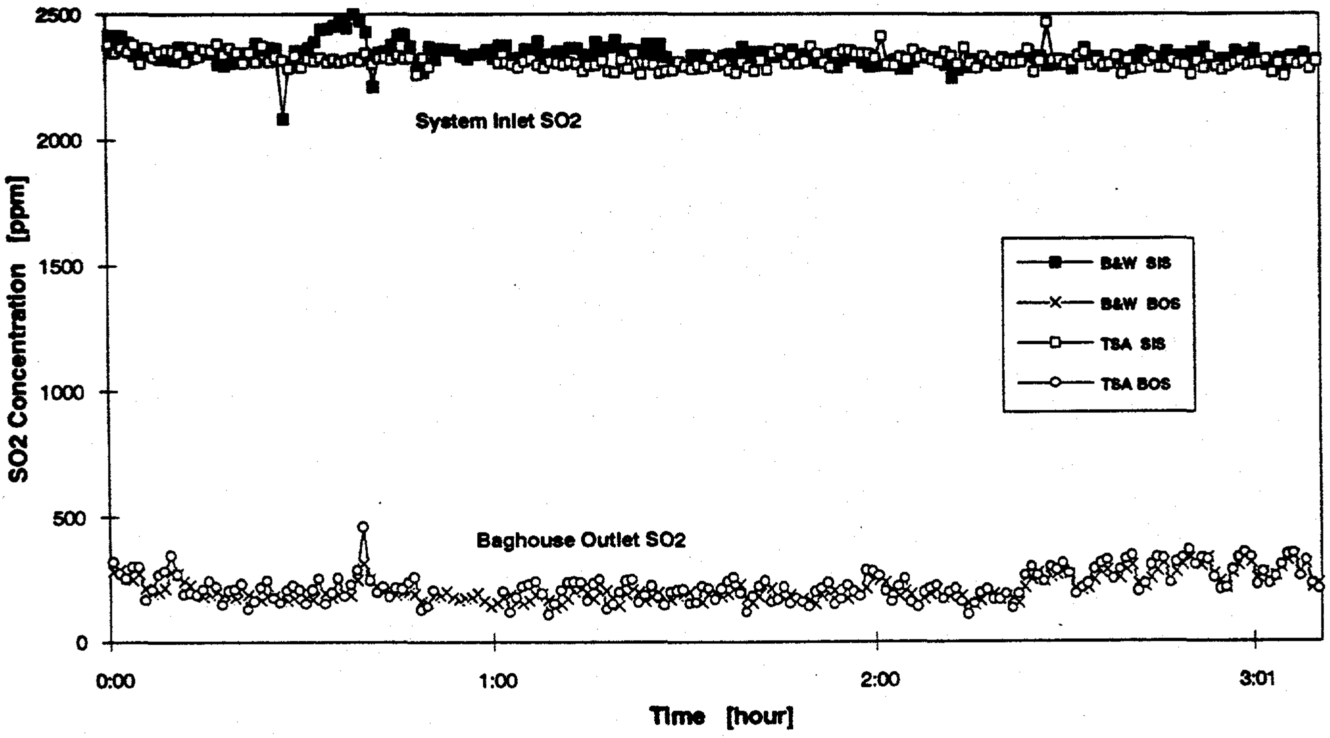
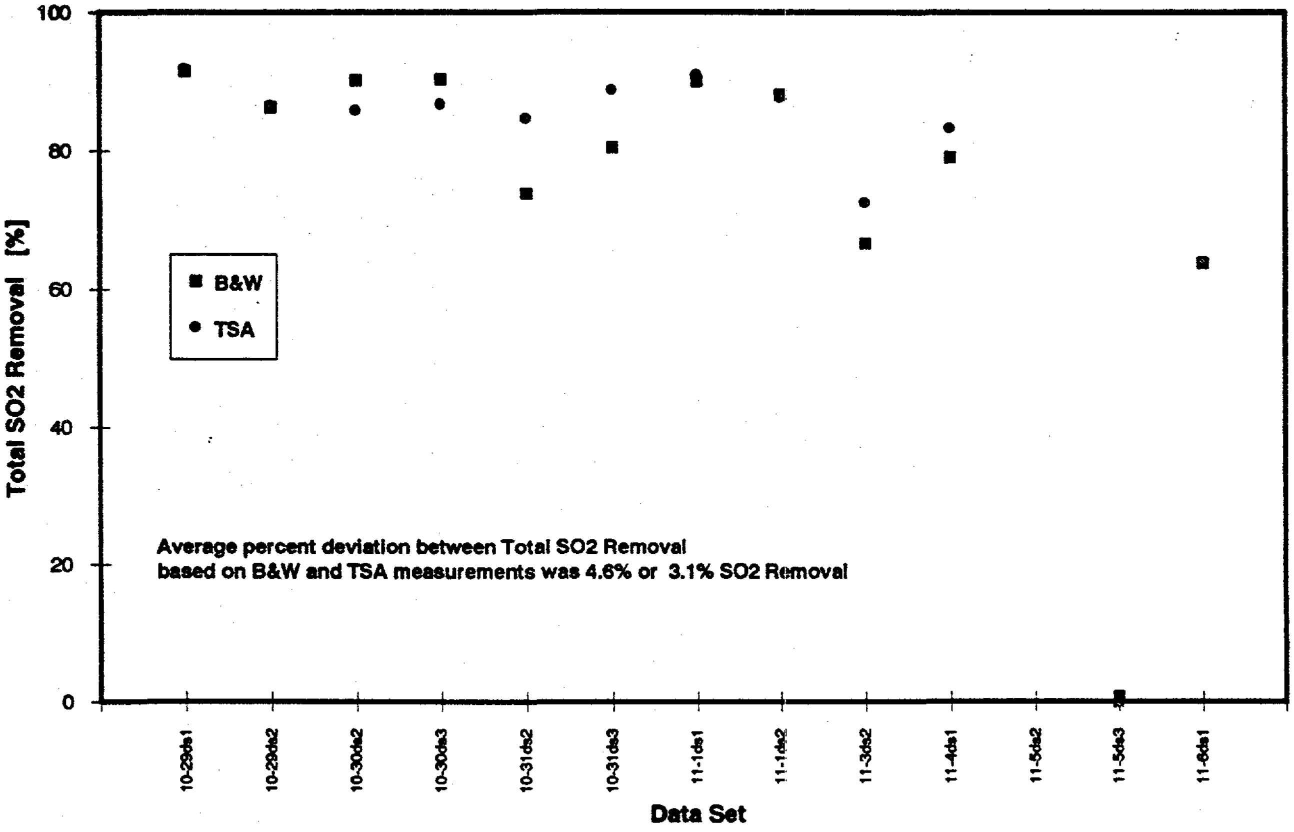


FIGURE 4-84 VERIFICATION OF MEASURED SO_2 CONCENTRATIONS



Average percent deviation between Total SO2 Removal
based on B&W and TSA measurements was 4.6% or 3.1% SO2 Removal

FIGURE 4-85 VERIFICATION OF AVERAGE SO_2 REMOVALS

4.8.2 NO$_x$ Measurements

TSA used chemiluminescence NO$_x$ monitors and Method 5 sample trains to verify the SNRB™ system NO$_x$ reduction performance and the corresponding ammonia slip. Continuous NO$_x$ measurements were conducted simultaneously at the baghouse inlet and baghouse outlet for comparison of baghouse NO$_x$ reduction. The O$_2$ levels at the baghouse inlet and outlet were measured concurrently in accordance with EPA Method 19 for normalization of the NO$_x$ concentrations to 3% O$_2$. Independent verification of the ammonia slip downstream of the baghouse was discussed in Section 4.6.11. The NH$_3$/NO$_x$ stoichiometry was varied during the independent tests to confirm the trend of increased removal efficiency and NH$_3$ slip with increased stoichiometry.

The continuous NO$_x$ monitors were able to detect transient changes in NO$_x$ concentration with time. An example of the continuous fluctuations in the NO$_x$ concentrations simultaneously measured at the baghouse inlet and outlet by TSA and B&W is presented in Figure 4-86. On average, the NO$_x$ reduction measured by TSA was within 1.8% of the value determined by B&W. Table 4-26 summarizes the observed average deviations between the simultaneous B&W and TSA measurements.

TABLE 4-26 DEVIATION IN TSA AND B&W NO$_x$ MEASUREMENTS

	% DEVIATION	UNIT DEVIATION
Baghouse Inlet NO$_x$	6.9%	35 ppm NO$_x$
Baghouse Inlet O$_2$	6.9%	0.34% O$_2$
Baghouse Outlet NO$_x$	10.0%	13 ppm NO$_x$
Baghouse Outlet O$_2$	4.6%	0.32% O$_2$
NO$_x$ Reduction	11.5%	1.8%

The continuous baghouse inlet and outlet NO$_x$ concentrations measured by TSA and B&W during one data set are compared in Figure 4-87. In Figure 4-88, the calculated NO$_x$ removals based on the TSA measurements and B&W measurements are compared. In the period of operation covered in Figure 4-88, the TSA and B&W analyzers were responding to a reduction in the NH$_3$/NO$_x$ stoichiometry.

The average baghouse NO$_x$ removals based on the TSA and B&W measurements are plotted for all of the data sets from the verification tests in Figure 4-89. Similar comparisons of the averaged baghouse inlet and baghouse outlet NO$_x$ concentrations are provided in Appendix O.

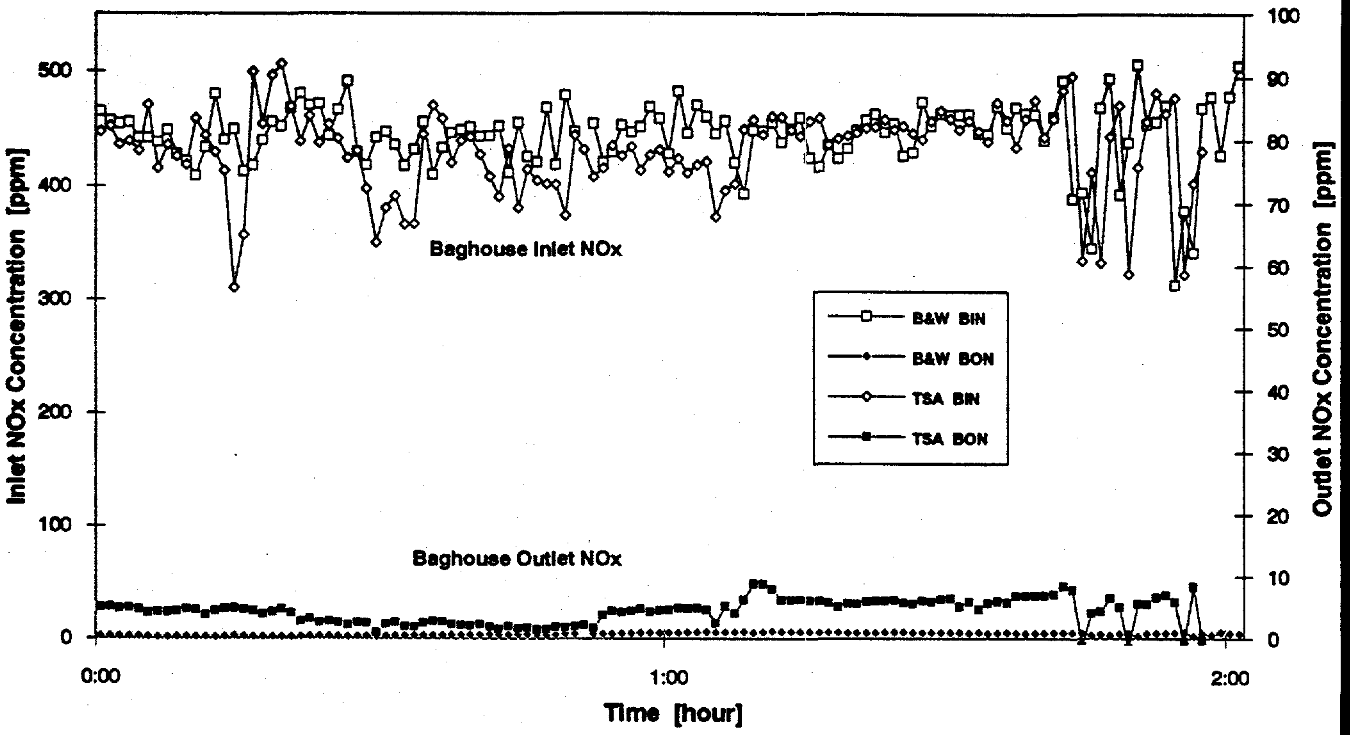


FIGURE 4-86 VERIFICATION OF NO_x CONCENTRATIONS FLUCTUATIONS

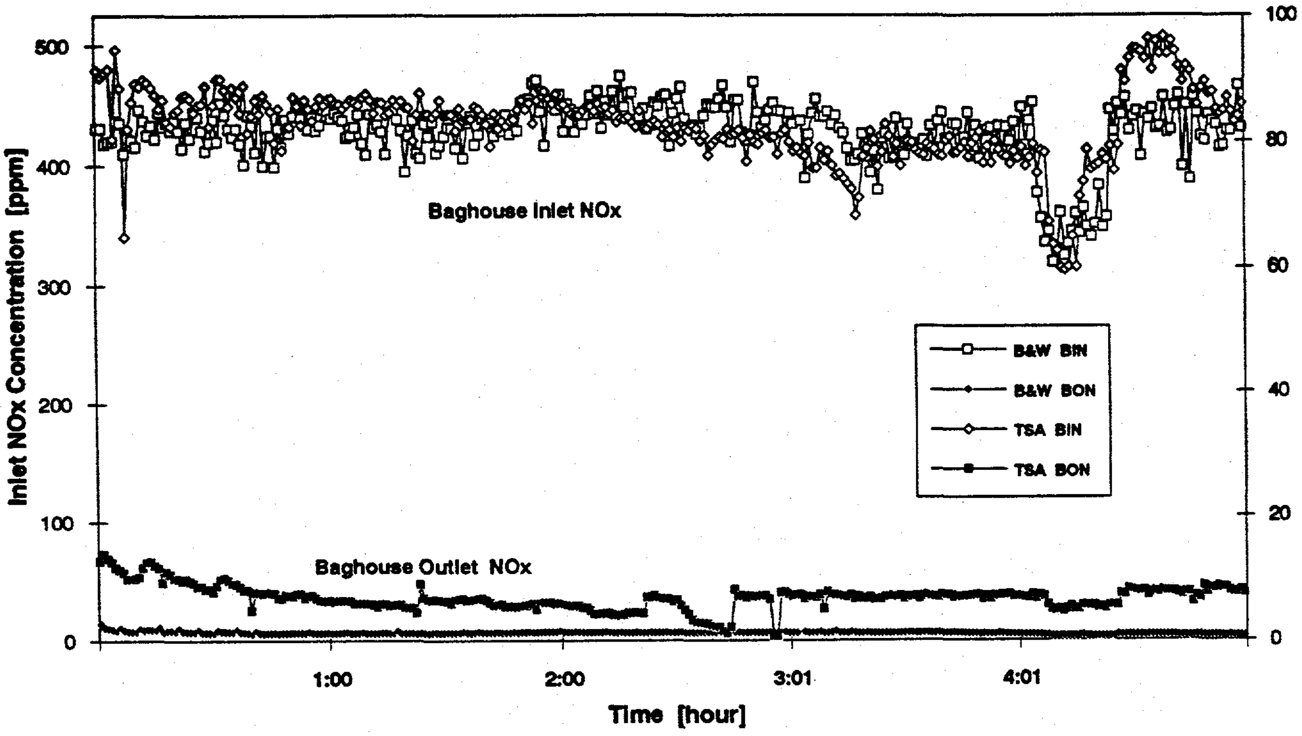


FIGURE 4-87 VERIFICATION OF NO_x CONCENTRATION MEASUREMENTS

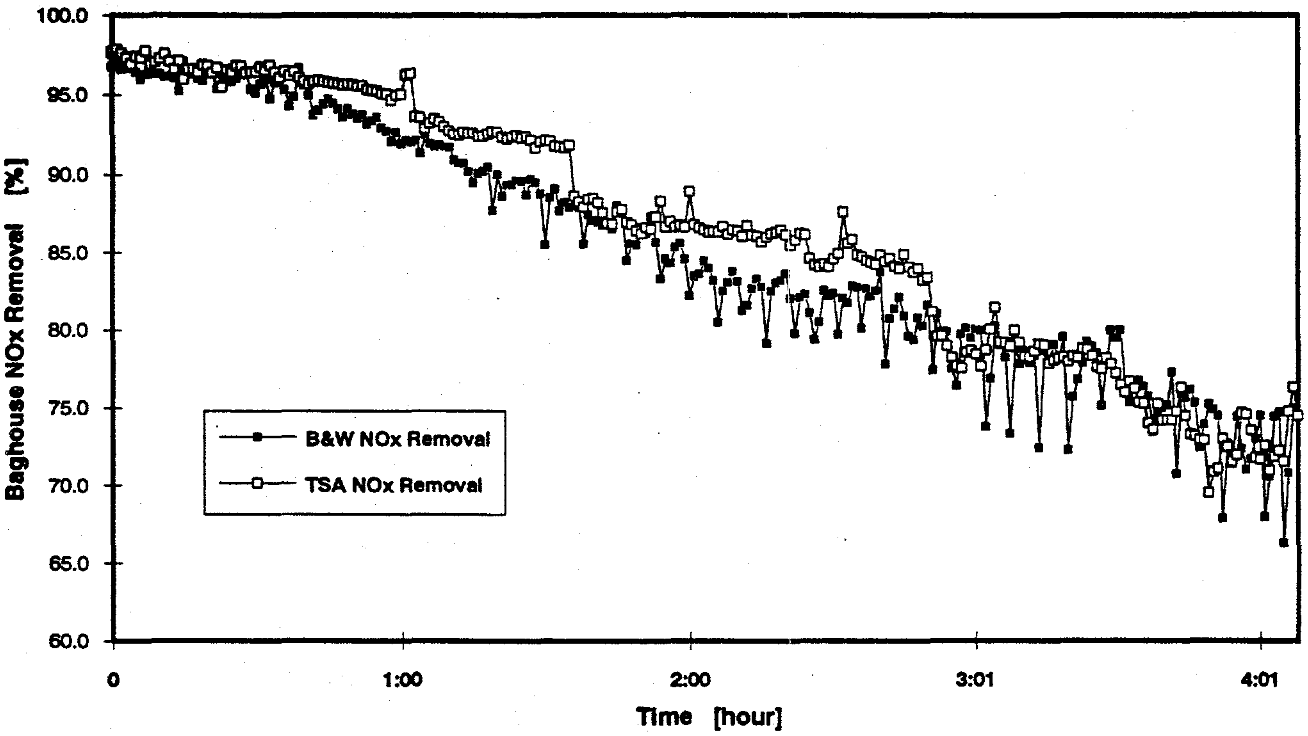


FIGURE 4-88 VERIFICATION OF NO_x REMOVAL

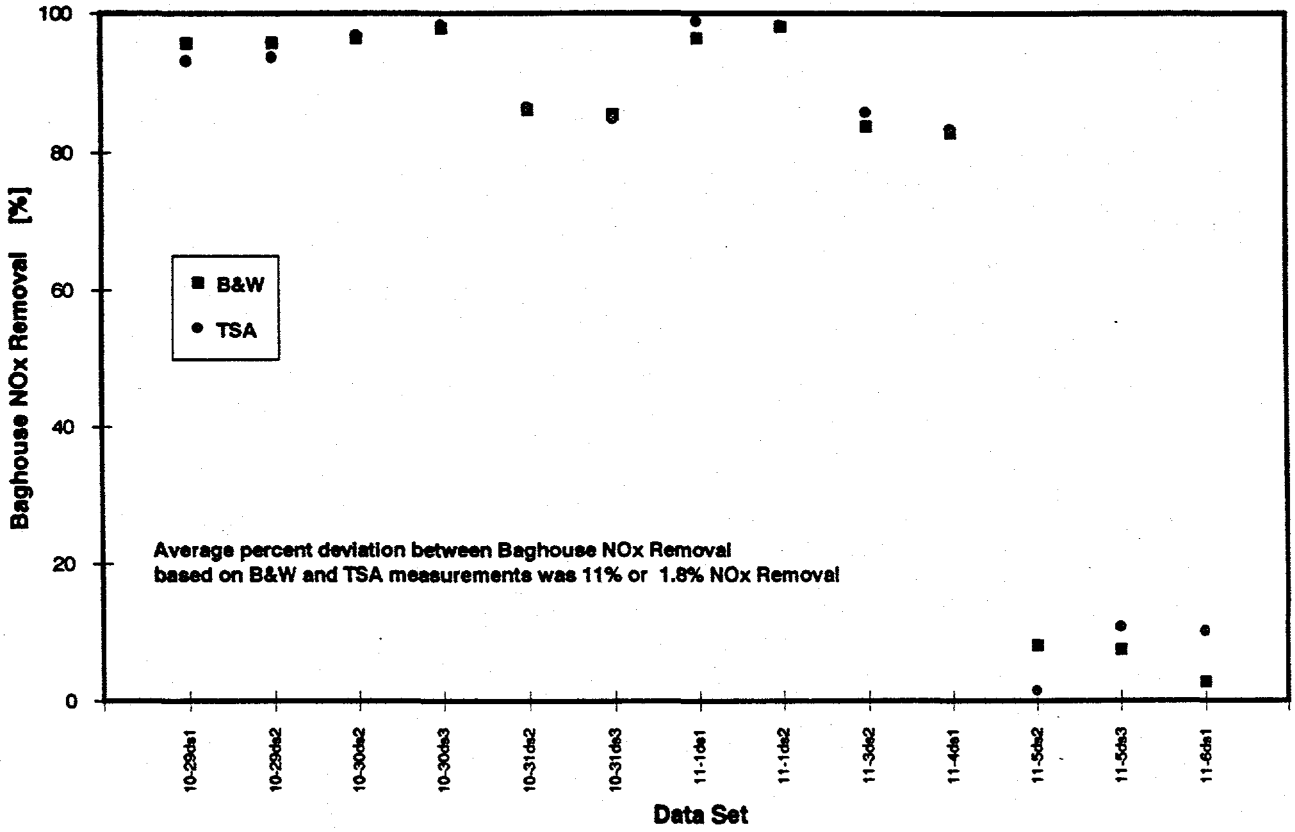


FIGURE 4-89 VERIFICATION OF NO_X REDUCTION AVERAGES

4.9 ENVIRONMENTAL PERFORMANCE

The slipstream SNRB™ demonstration project had a negligible impact on the environment. The high efficiency SO_2, NO_x and particulate emissions reduction impacted only a small fraction (about 1%) of the flue gas from the Ohio Edison R.E. Burger Plant. The flue gas treated in the SNRB™ facility was returned to the inlet of the plant ESP and eventually exited the single stack at the plant with the remainder of the untreated flue gas. Approximately 830 tons of solid byproduct were transported to a solid waste landfill for disposal. Corrosivity and TCLP analyses of the solids confirmed the non-hazardous characteristics of the material. No accidental emissions of ammonia, propane, hydrated lime or solid byproduct occurred over the life of the demonstration project. A summary of the operating conditions, byproduct solids characterization, propane and ammonia usage for each operating quarter is presented in Appendix P.

Following completion of operations at the demonstration facility, the SCR catalyst and filter bags were evaluated and found to have TCLP characteristics suitable for disposal as a solid waste. The catalyst was subsequently placed in a solid waste landfill for disposal. The used filter bags were stored for possible future use.

The potentially significant reduction in SO_2, NO_x and particulate emissions of a commercial application of the technology will have a direct beneficial impact on the environment. The demonstration performance results discussed in detail in this section are strong evidence of the degree of emissions control expected in commercial operations. Accidental emissions from the auxiliary ammonia and SO_2 sorbent storage and injection systems are controlled with well established commercial technologies. Beneficial use of the byproduct solids will further reduce the impact on the environment.

5.0 FILTER FABRIC ASSESSMENT TESTS

In a commercial SNRB™ application, the initial and replacement costs of the filter bags would be a significant part of the overall capital and operating costs. The purpose of this field pilot testing was to evaluate alternative bag fabrics over an extended period of time for fabric strength degradation and overall performance.

5.1 FACILITY DESCRIPTION

The effect of long-term operation at elevated SNRB™ temperatures was evaluated through installation of three types of filter fabrics in the baghouse which was previously used in SNRB™ laboratory pilot tests at B&W's Alliance Research Center. The baghouse was relocated to the City of Colorado Springs' Martin Drake plant. A photograph of the overall facility is shown in Figure 5-1. Flue gas was drawn from the power plant's economizer outlet flue work to the slipstream baghouse. The test facility consisted of a flue tie-in to the boiler economizer outlet flue work, the high-temperature baghouse, a compressed air system, an ID fan, and pneumatic ash return system.

The pulse-jet baghouse contained 12 full-size bag/catalyst assemblies, arranged in a three by four array. On-line bag cleaning with dry, compressed air was initiated by a baghouse pressure differential setpoint of approximately 14 inches of water. A cleaning air pressure of 50 psig with a pulse duration of 200 milliseconds was used. The bags were approximately 6-1/4 inches in diameter by 20 feet in length, yielding a total collection area of 375 ft^2. Table 5-1 summarizes the types of filter bags and bag supports installed in the baghouse.

TABLE 5-1 FILTER BAGS EVALUATED DURING TEST PROGRAM

Fabric	Manufacturer	Number of Bags	Bag Support
Nextel™ (30x38)	3M	4	Perforated Retainers
Nextel™ (38x30)	3M	1	Perforated Retainers
S2-Glass	Owens-Corning	3	Wire Cages
S2-Glass	Owens-Corning	3	Perforated Retainers
Silontex	Acurex	1*	Perforated Retainer

*Originally 3 Silontex bags were installed; two were removed due to cleaning problems.

FIGURE 5-1 FILTER FABRIC PILOT FACILITY

Nextel^{TM} is a high-temperature woven ceramic fabric manufactured by 3M. Two different weaves, 30x38 and 38x30, were evaluated during this test program. These numbers represent the number of yarns per inch in the warp (vertical) and fill (horizontal) directions in the weaving process. The ceramic Nextel^{TM} fabric has a weight of 16.4 oz/yd^2. The Nextel^{TM} bags were supported on perforated retainers rather than conventional wire cages because of concern over potential fiber breakage at the support wire contact points. Constant torque clamps at the top and bottom of the retainer were used to hold the bag on the retainer. Since this test program, 3M has demonstrated the use of a modified wire cage support for Nextel^{TM} fabric bags.

S2-Glass is manufactured by Owens-Corning Fiberglas and is a formulation of fiberglass with better strength properties at high temperatures than E-glass, which is used in conventional fiberglass fabric filter applications. An abrasion-resistant coating is applied to the bags to protect the fibers. A previous generation S-glass bags were evaluated at SNRB^{TM} operating conditions during a short-term test program conducted by B&W.[47] The woven S2-Glass fabric has a weight of 22 oz/yd^2. The S2-Glass bags were supported on both wire cages and perforated retainers. A conventional snap ring design was used in conjunction with the wire cages.

Silontex is a calcium silicate material traditionally used for high-temperature fabric insulation. A prototype weave design was developed by Acurex for manufacturing the bags for this test program. The fabric weight was 73 oz/yd^2, significantly heavier than both the Nextel^{TM} and S2-Glass. These bags are not yet produced commercially. The Silontex fabric was characterized by a significantly coarser weave than the other fabrics and consisted of fewer and larger yarns.

In order to evaluate the bags objectively, the bags were installed in a random order to minimize gas flow, temperature, or particulate loading bias. The filter bag locations are illustrated in Figure 5-2.

In addition to evaluation of the high-temperature bag durability, an alternative monolith catalyst design was tested for its influence on baghouse operation and bag cleanability. The new monolith had a higher cell density than the design tested at the 5-MWe field demonstration. Compared to the original design, a smaller volume of the higher cell density catalyst would be required to provide the same level of NO_x reduction. The alternative design had the potential to reduce overall baghouse pressure drop. The effect of the catalyst on baghouse operation and bag cleanability was investigated at various times during the test program.

The test facility did not include sorbent or ammonia injection for SO_2 and NO_x removal. Since a low sulfur western coal was fired, the SO_2 concentration contacting the bags was comparable to that in flue gas from an eastern coal application with 80 - 90% SO_2 reduction. The low SO_2 concentration minimized acid attack during baghouse start-up and shutdown.

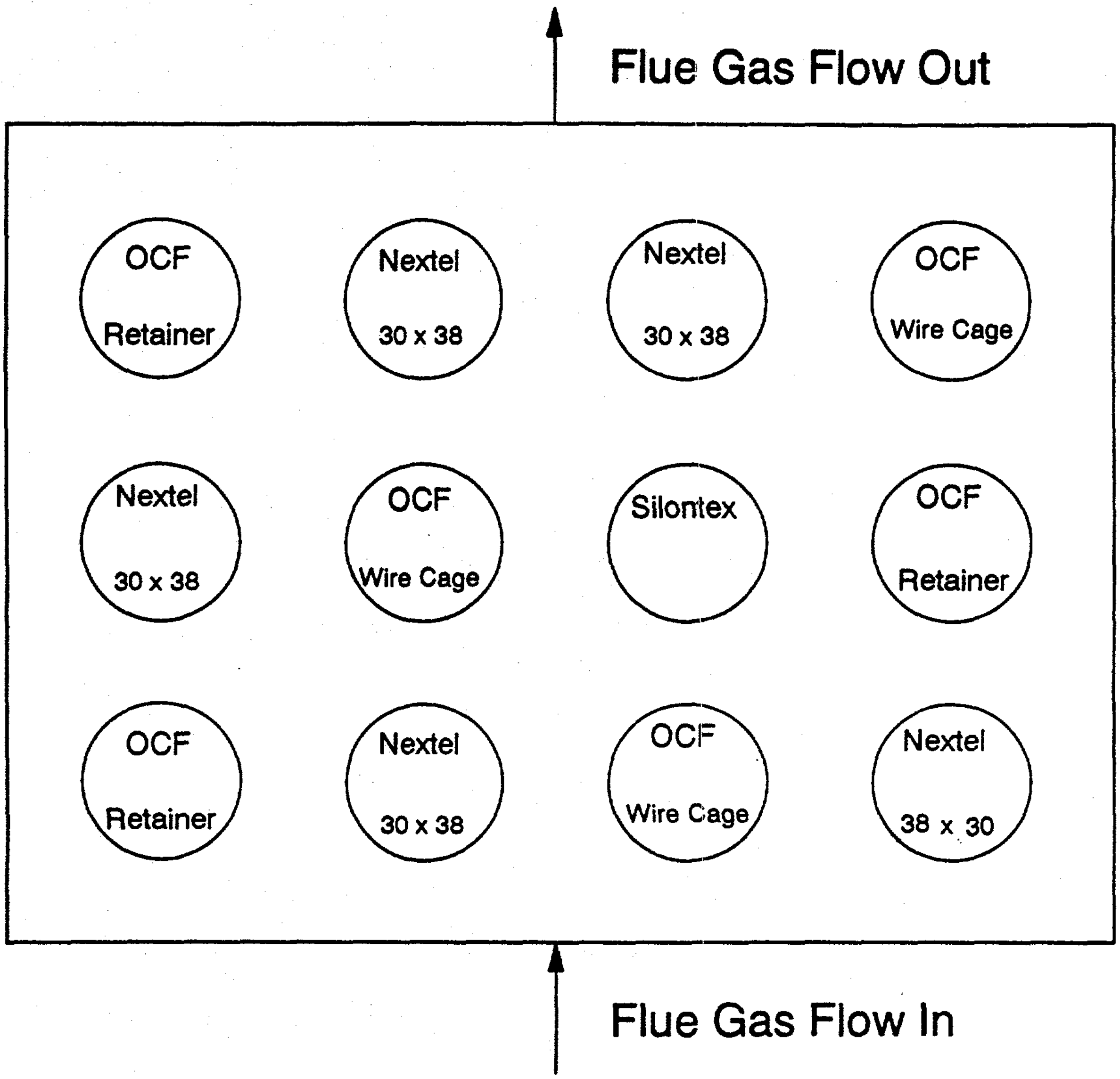


FIGURE 5-2 FILTER BAG CONFIGURATION

Baghouse inlet particulate loading and emissions were not quantified in the Filter Fabric Assessment Program. Had the emissions been sampled, an emissions source could not be distinguished between the various bag types. Particulate penetration was qualitatively surmised by inspecting the tubesheet for signs of gasket leaks, particulate accumulation and impingement on the surface of the clean gas plenum. The tubesheet was consistently clean during each inspection.

5.2 BAGHOUSE OPERATION

Over a 12-month test period, the baghouse was operated for approximately 3,700 hours. A summary of the operating conditions is presented in Table 5-2.

TABLE 5-2 SUMMARY OF BAGHOUSE OPERATING CONDITIONS

Operating Time	3,700 hours
Cleaning Pulses	11,200 / bag
Baghouse Inlet Temperature	600° to 720°F
Baghouse Differential Pressure	11 to 14 inches H_2O
Gas Volume	1,300 acfm @ 650°F
Air-to-Cloth Ratio	3.0 to 4.2 ft/min
Bag Cleaning Cycle	30 to 40 minutes
Inlet Dust Loading (approx.)	2.0 grains/scf

Data from the baghouse were recorded on a continuous chart recorder and included:

- Orifice static and differential pressure
- Baghouse differential pressure
- Baghouse inlet and catalyst (bag) temperatures
- Triboelectric probe for particulate emissions

An example of the chart recorder data is shown in Figure 5-3. This figure shows a typical period of steady-state operation. As expected, the baghouse differential pressure followed a saw-tooth pattern. As fly ash began to accumulate on the bag surface the baghouse differential pressure increased. Each sharp decrease in baghouse differential pressure represents a bag cleaning cycle.

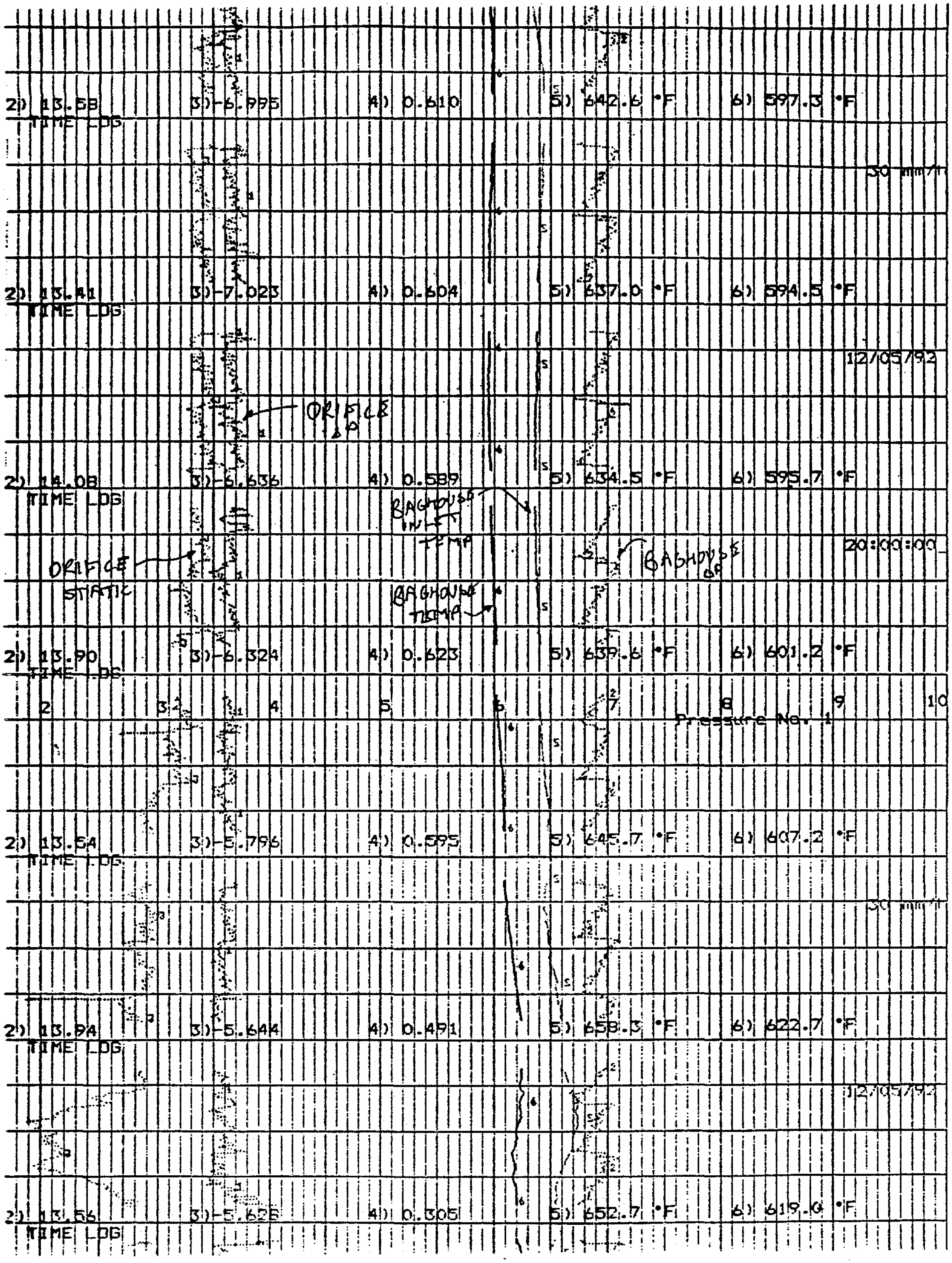


FIGURE 5-3 CHART RECORDER OUTPUT OF TYPICAL OPERATION

The baghouse operating parameters, air-to-cloth ratio (ATC) and differential pressure, were established to ensure steady operation with minimal over sight. Martin Drake plant personnel checked the baghouse once per shift. Baghouse operation at high ATC could have prevented the baghouse differential pressure from dropping below the lower bag cleaning set point. As a result, the bags would be continuously pulsed, which would not be representative of typical pulse-jet baghouse operation. Similarly, setting the lower bag cleaning set point at too low a differential pressure would result in continuous pulsing of the bags. At a given ATC ratio, the baghouse reached a minimum equilibrium differential pressure, corresponding to the point at which all of the bags had been pulsed. By setting the lower bag cleaning set point above this minimum differential pressure, continuous pulsing of the bags was avoided.

In Figure 5-4, baghouse differential pressure and ATC ratio are shown as functions of elapsed operating days. All of the data shown correspond to steady-state baghouse operation. The baghouse differential pressure shown in the figure is the "clean" pressure drop, that is, after the bag cleaning had been reset. Thus, this pressure drop approximates the minimum equilibrium differential pressure. Likewise, the ATC ratio shown in the figure can be considered the equilibrium ATC ratio: any increase in the ATC ratio would increase the clean baghouse differential pressure above its equilibrium value and result in continuous pulsing. The trend of increasing differential pressure with decreasing ATC ratio was observed suggesting that bag blinding may have been occurring. This blinding could have been caused by several factors:

- Non-ideal operation. Over the duration of the test program, the baghouse experienced numerous start-ups and shutdowns due to problems with the I.D. fan and as a result of boiler outages.

- Continuous pulsing. Extended periods of continuous pulsing occurred at various times during the test program. After pulsing, fine particulates tend to redeposit on the bag surface whereas the coarser material drops into the hopper. Frequent bag pulsing may have resulted in a high concentration of fines on the bags which resulted in higher pressure drop due to reduced filter cake porosity.

- Tightly packed filter cake. The lack of SO_2 sorbent injection may have resulted in a less porous, higher pressure drop filter cake. In addition, hydrated lime typically aids the removal of the fly ash upon cleaning and minimizes the amount of fines redeposited on the bag surface.

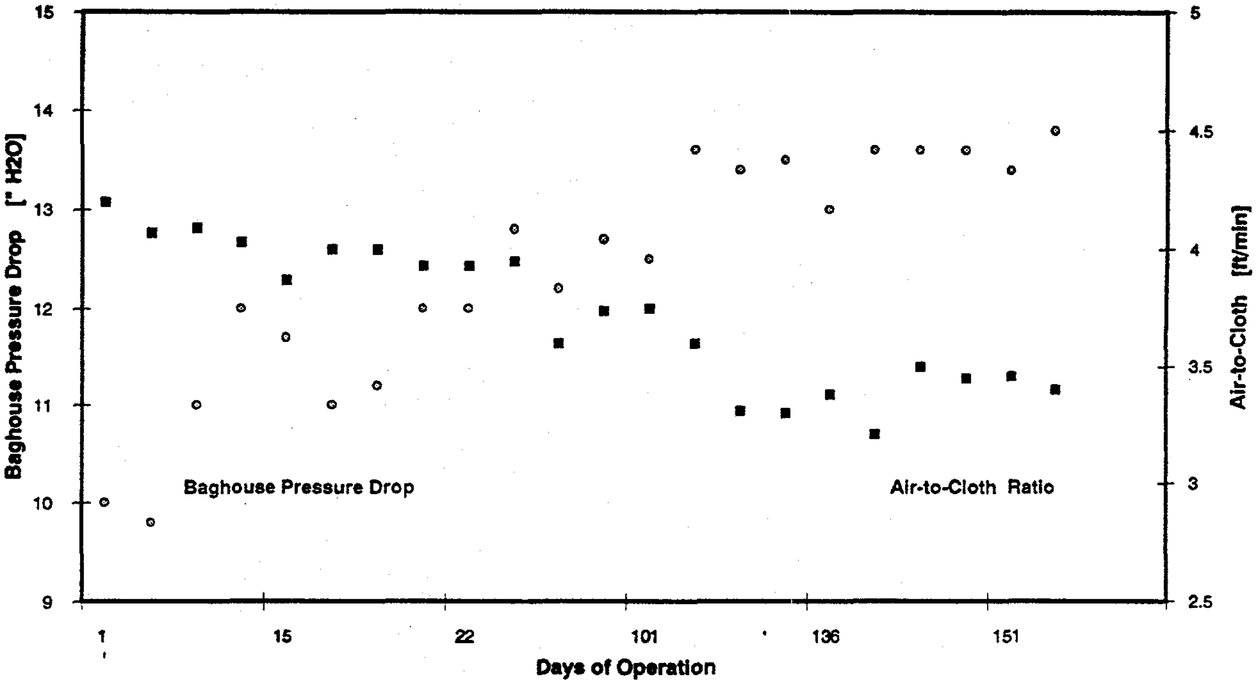


FIGURE 5-4 FILTER FABRIC PILOT OPERATION

5.3 VISUAL INSPECTION OF THE BAGS

After 3,700 hours of operation and 11,200 pulse-jet cleanings per bag, the bags were removed from the baghouse at the end of the field tests. In spite of the non-ideal test conditions and numerous transitions through the acid dewpoint, no significant damage to the Nextel™, S2-Glass, or Silontex bags was noted during visual inspection. A summary of the observations for each bag/support combination follows.

Bag 1: S2-Glass - Wire Cage:

No damage visible due to operation. Top and bottom of bag were damaged during removal of the cage from the bag. A rusty pattern resembling the wire cage was visible on the inside surface of the bag.

Bag 2: Nextel™- 30x38:

Several areas in the middle and top of the bag were damaged (slits and broken vertical yarns). The damaged areas did not look like snags which result from installation or removal. Ash penetration was more prevalent at the creases.

Bag 3: S2-Glass - Retainer:

No damage was observed. The perforated retainer pattern was visible on the inside surface of the bag.

Bag 4: Silontex:

The ash layer on the bag surface was heavier at the bottom. No damage was observed.

Bag 5: Nextel™ - 38x30:

Three small holes were present in the bottom one-third of bag. The ash pattern was similar to bag #2

Bag 6: S2-Glass - Wire Cage:

No damage was observed. The snap ring was cut in order to remove bag from the wire cage.

Bag 7: S2-Glass - Retainer:

No damage was observed. Less ash was present on bag surface compared to the other S2-Glass bags. The perforated retainer pattern was visible on the inside of the bag.

Bag 8: Nextel™ - 30x38:

One hole was found in the bottom clamp area and one cut was observed on the top clamp area. This damage may have resulted from over tightening the clamps. The bag also had small horizontal slits in three areas.

Bag 9: Nextel™ - 30x38:

The bag was cut along the top edge of bottom clamp and abrasive wear was evident underneath the top clamp. Again, this damage may have resulted from over tightening the clamps. One vertical fiber was broken and was pulled out in the middle third of the bag.

Bag 10: S2-Glass - Wire Cage:

There were several holes in the bottom of the bag which were most caused from forcing the wire cage into the bag or attempts to pull the wire cage out of the bag. The bottom of the bag was filled with fly ash and the entire inside surface of the bag was coated with ash. The ash in the bottom of the bag was a different color than that on the outer bag surface.

Bag 11: S2-Glass - Retainer:

No damage was observed. The clamp area at the top of the bag could not be distinguished from the filtration area due to fly ash on the bag surface.

Bag 12: Nextel™ - 30x38:

The bag was cut at the top edge of the bottom clamp and a punch-type hole was present at the bottom edge of the top clamp. Three areas in the middle third of the bag showed signs of horizontal weave separation. The Nextel™ tape placed under the clamp to cover the top weld on the perforated retainer showed signs of cutting and abrasive wear.

Based on visual inspection of the bags at the end of the field tests, the Nextel™ and S2-Glass fabrics both appear suitable for SNRB™ high-temperature, pulse-jet operation. In general, the S2-Glass bags tended to retain a greater amount of fly ash upon cleaning than the Nextel™ bags. The exposed S2-Glass also seemed to be less flexible than the new fabric, while the Nextel™ fabric retained its original flexibility. The S2-Glass bags, on the other hand, were more durable than the Nextel™ bags, experiencing little damage related to installation or operational wear. The absence of damage from abrasion of the S2-Glass on the wire cages after a multitude of pulse-jet cleanings was significant. Abrasion is a major cause of failure for conventional fiberglass fabrics. Several of the Nextel™ bags had horizontal slits at the top and bottom locations where the bags were clamped to the perforated retainers. The bags are clamped to the retainers in non-filtration areas.

5.4 FABRIC PRESSURE DROP ANALYSIS

To compare the contributions of the fabric and filter cake to the overall pressure drop for the various fabrics and verify the cleaning difficulties associated with the heavy Silontex fabric, a series of bench-scale fabric pressure drop tests was conducted. Samples from each of the twelve bags were evaluated for "as-received" and "cleaned" pressure drop performance. Each fabric sample was placed in a flanged assembly and tested over a range of ATC ratios. Each sample was then shaken to remove the loose fly ash and tested again. A schematic of the testing apparatus is shown in Figure 5-5.

In Figures 5-6a to 5-6d, the "as-received" and "cleaned" pressure drops are shown as a function of ATC ratio for each of the four bag fabric/support combinations used in the test program. The "as-received" pressure drop for both S2-Glass support arrangements, especially that used with the perforated retainers, was significantly higher than the pressure drop for the Nextel™ fabric. The "cleaned" pressure drops were also higher than those for Nextel™. Assuming that each of the bags received similar handling during removal, this suggests that the S2-Glass fabric retained a greater amount of fly ash, even after cleaning. This point is illustrated in Figure 5-7. In Figure 5-7, S2-Glass-W refers to the S2-Glass fabric supported on a wire cage and S2-Glass-P refers to the perforated retainer. The pressure drop for the exposed S2-Glass was two to three times higher than the exposed Nextel™, even though the new fabric pressure drops were comparable as shown in Figure 5-8.

The data shown in the above figures also illustrate the following observations:

- Sensitivity of pressure drop to filter cake thickness. The filter cake present on the S2-Glass samples from the perforated retainers was less than 1/16" thick but yielded relatively high pressure drops. The filter cake was tightly compacted and was comprised of small fly ash particles. This information indicates that relatively thin filter cakes comprised only of fly ash can create significant pressure drops. This can result in shortened bag cleaning cycles which may accelerate wear failure of the fabric.

- Bag cleanability by bag type. The Nextel™ bags were the most easily cleaned. A majority of the fly ash appeared to come off during removal of the bags from the baghouse removal, indicating low adherence of the fly ash to the fabric. This is also evident in the comparatively low "as-received" pressure drops. A visual observation of off-line cleaning during the test program supports the laboratory tests. The Silontex bags were the most difficult to clean. Two of the three original bags were removed from the pilot baghouse due to their low cleanability, which was most likely due to the high unit weight of the fabric. Visual inspection and the fabric pressure drop tests indicate this particular Silontex weave could not be use for a pulse-jet application.

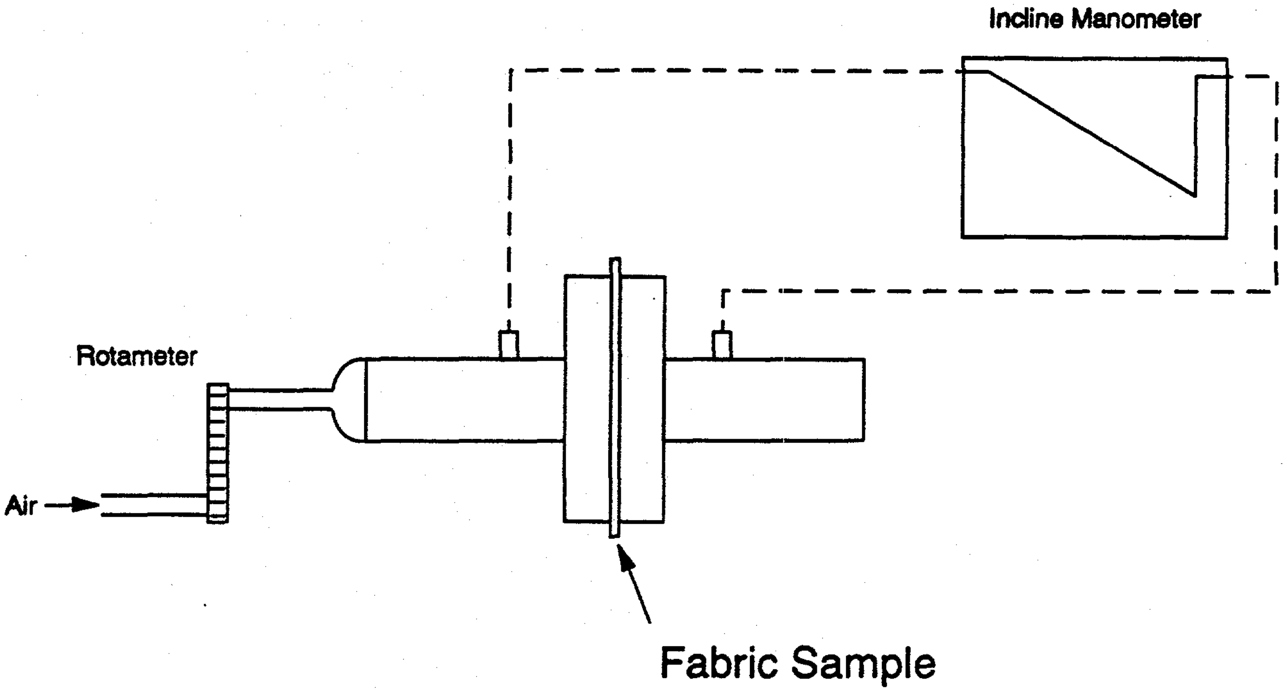


FIGURE 5-5 SCHEMATIC OF FLOW VS PRESSURE DROP APPARATUS

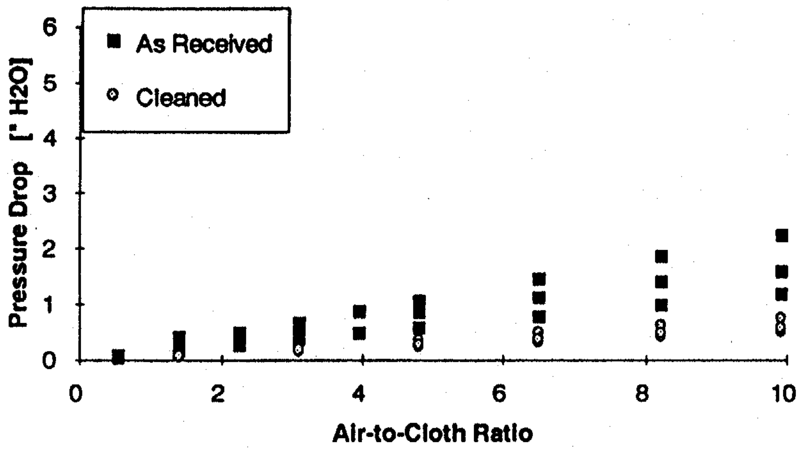


Figure 5.6a ATC Ratio vs. Fabric Pressure Drop: S2-Glass on a Wire Cage

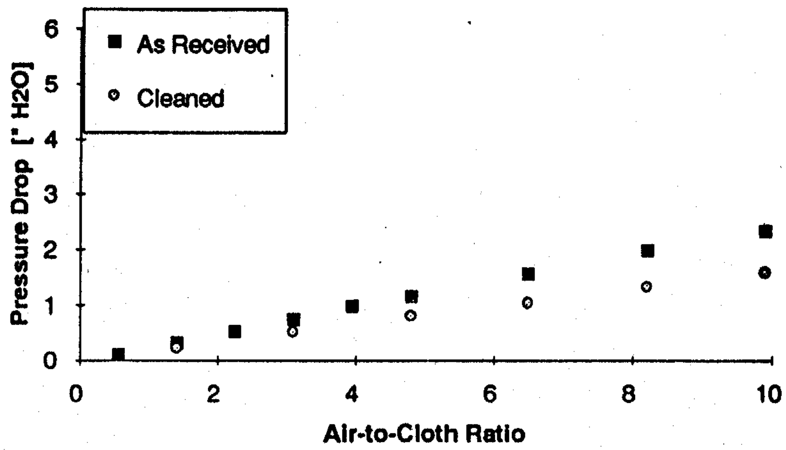


Figure 5.6b ATC Ratio vs. Fabric Pressure Drop: Silontex

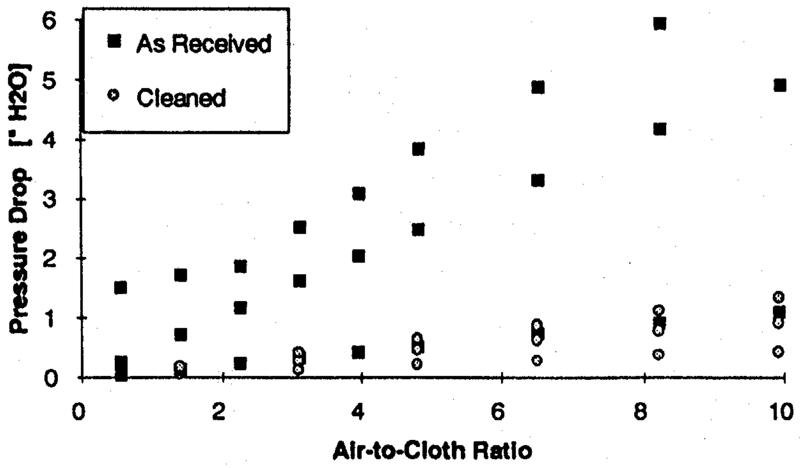


Figure 5.6c ATC Ratio vs. Fabric Pressure Drop: S2-Glass on a Retainer

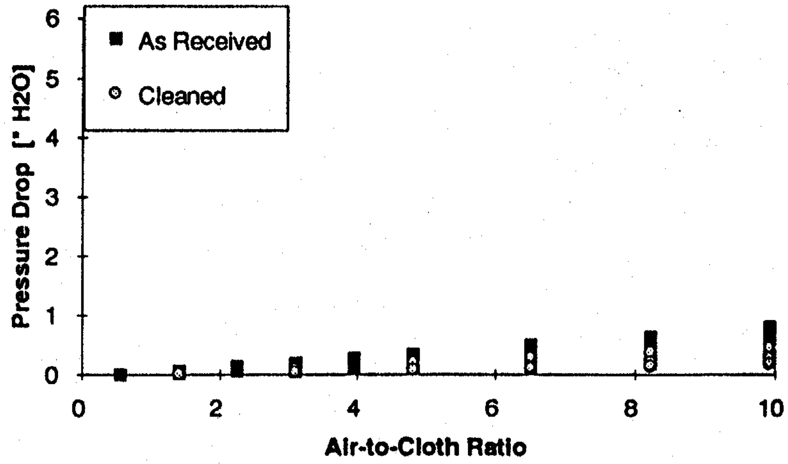


Figure 5d. ATC Ratio vs. Fabric pressure Drop: Nextel

FIGURE 5-6 AIR-TO-CLOTH RATIO VS FABRIC PRESSURE DROP

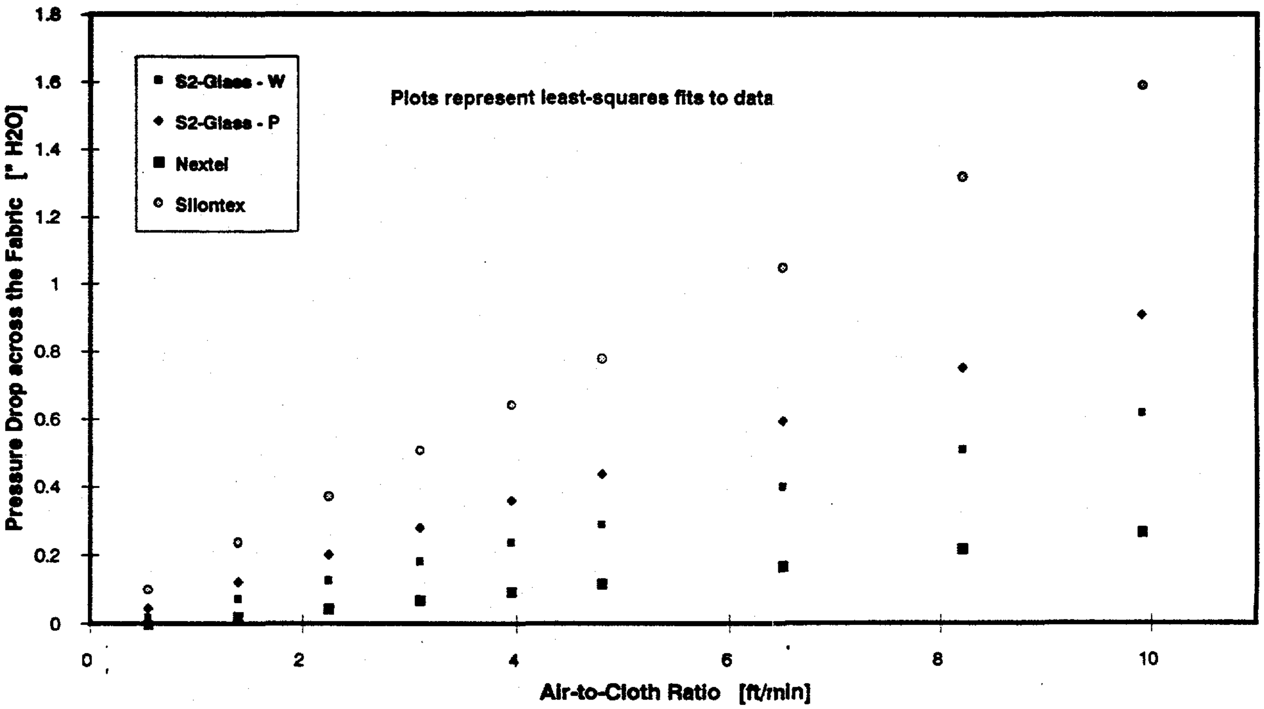


FIGURE 5-7 BENCH-SCALE PRESSURE DROP ANALYSIS - CLEANED FABRIC

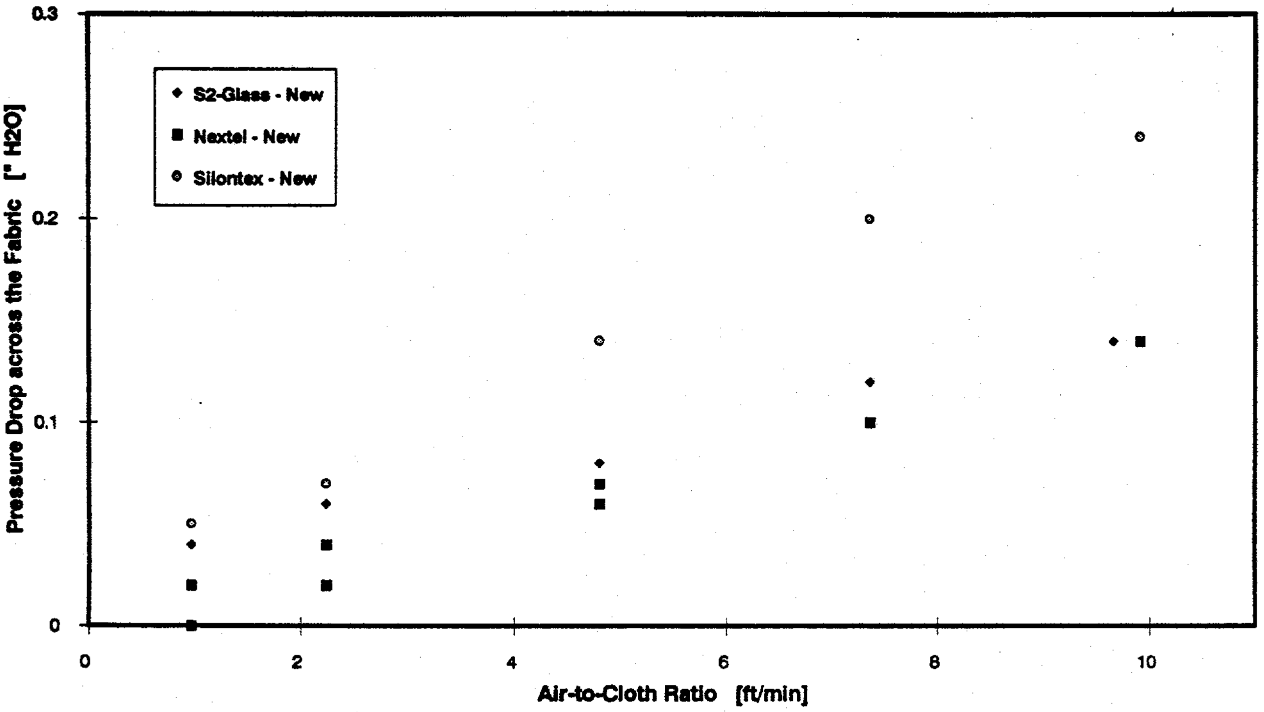


FIGURE 5-8 BENCH-SCALE PRESSURE DROP ANALYSIS - NEW FABRIC

5.5 STRENGTH TEST RESULTS

At the midpoint and at the end of the test program, Mullen burst strength tests were performed on fabric samples to test for fabric strength degradation. The Mullen burst strength test determines the pressure necessary to rupture a secured specimen of fabric and was designed to show the relative total strength of the fabric to withstand pulsing and pressure. Table 5-3 summarizes the strength test results in terms of percent retained strength relative to a new bag after 2,000 and 3,700 hours of flue gas exposure and operation of the pilot baghouse.

TABLE 5-3 MULLEN BURST STRENGTH TEST RESULTS

		% RETAINED STRENGTH	
Fabric	New	2,000 hours	3,700 hours
Nextel™	100%	70%	80%
S2-Glass	100%	66%*	55%*
Silontex	100%	N/A	96%

*Original strength exceeded the capacity of the Mullen burst strength test apparatus, approximate value used to calculate % retention.

The original strength of the S2-Glass fabric was greater than the 1,400 psig cut-off on the Mullen burst strength apparatus. Although the S2-Glass had a higher rate of strength decrease, the absolute strength of the S2-Glass was more than twice the strength of the Nextel™ fabric at the end of the test program.

The effect of the type of bag support, wire cage or retainer, on the S2-Glass fabric was evaluated. The mullen burst strength and MIT flex of the S2-Glass fabric which had operated on a standard wire cage exceeded the strength and flex of the fabric on the perforated retainer. The MIT flex endurance test determines the number of cycles a filter media specimen can be rapidly flexed in an arc under a specified load until the fabric ruptures. The MIT flex measures the ability of the fabric to withstand self-abrasion from flexing and is primarily used to evaluate the rate of bag deterioration.

5.6 HIGH-DENSITY SCR CATALYST

The higher cell density catalyst did not appear to impact cleaning of the commercial size filter bags. The tests did not conclusively show a reduction in baghouse pressure drop due to reduced catalyst volume relative to the lower density monolith. The durability test pressure drop data could not be compared to the field demonstration pressure drop data because of disparities in baghouse operation. The filter cake properties and bag cleaning pressure differed between the two programs. Hydrated lime was not injected upstream of the baghouse. Baghouse studies have suggested that a filter cake comprised of fly ash yields a higher pressure drop than a combined fly ash/lime filter cake.[52] It has been postulated that the plate-like lime particles results in a more porous filter cake. Hence, the higher bag cleaning pressure required to uniformly and completely clean the bags may be attributed to either the higher catalyst cell density or the less porous filter cake.

5.7 SUMMARY

Visual observations and fabric strength testing in the filter fabric assessment test program led to the selection of the S2-Glass and Nextel™ filter fabrics for the larger 5-MWe demonstration baghouse. Both fabrics appear suitable for commercial SNRB™ high-temperature, pulse-jet operation. The tendency of the S2-Glass bags to retain a greater amount of fly ash upon cleaning than the Nextel™ bags was supported by the pressure drop analysis tests, the air permeability tests and bag inspection. In addition, the exposed S2-Glass appeared less flexible than the new fabric, while the Nextel™ maintained comparable flexibility. The S2-Glass bags, on the other hand, were more durable than the Nextel™ bags, experiencing no visible damage related to operational wear or fatigue. The prevalent damage observed on several of the Nextel™ bags was concentrated in non-filtration areas.

The particular Silontex weave tested was determined to not be acceptable as a high-temperature, pulse-jet fabric due to the inability to sufficiently clean the bag as determined by both visual inspection and laboratory fabric pressure drop tests.

The mullen burst strength of the S2-Glass fabric after 3,700 hours of exposure was twice that of the Nextel™ fabric. However, the Nextel™ fabric did retain a significantly higher percentage of the original fabric strength.

Permeability evaluation of the Nextel™ and S2-Glass fabrics confirmed that the Nextel™ fabric had better filter cake release characteristics which was supported by the bench-scale pressure drop analysis tests.

Although long-term bag life predictions should not be made on the basis of only 3,700 hours of testing, the fabric assessment tests demonstrated that two fabrics certainly have potential for achieving economically acceptable bag life. Exposure to over 11,000 cleaning pulses is equivalent to over a year of normal operation. S2-Glass bags supported on wire cages were selected for further evaluation at the 5-MWe demonstration facility based on the fabric assessment tests.

6.0 ALTERNATIVE BAG DEMONSTRATION

A major emphasis of the SNRB™ project was the demonstration of alternative, high-temperature filter fabrics to broaden the supply base for this key component of the technology. The 3M Nextel™ bags were selected as the base bag for the demonstration based on excellent performance in earlier pilot test programs. Based on the good performance exhibited in the Filter Fabric Assessment Program, the Owens-Corning S2-Glass bags were selected for installation in one compartment midway through the demonstration. The Alternative Bag Demonstration, refers to the period of baghouse operation with both the S2-Glass and Nextel™ filter fabrics.

The Nextel™ and S2-Glass fabrics were selected on the basis of temperature and corrosion resistivity, structural stability, cleanability, and cost. Corrosion resistivity was a chief concern. Fiberglass is typically resistant to acids with the exception of hydrofluoric acid (HF), concentrated sulfuric acid and hot phosphoric acid. The Nextel™ fabric is also subject to chemical attack by HF. For efficient cleaning, both fabrics met the criteria of being flexible, lightweight and inelastic to obtain maximum acceleration for dust removal when pulsed.[46] The fabrics also had sufficient weight to maintain a good surface area for filtration. The characteristics of the two fabrics are compared in Table 6-1.

TABLE 6-1 FABRIC CHARACTERISTICS

			RESISTANCE TO:				
Fiber	Max Temp [°F]	Weight [oz/yd^2]	Alkalies	Organic Acids	Oxidizing		Organic Solvent
					Acids	Agents	
S2-Glass	>900	22	Fair	Very Good	Very Good	Excellent	Very Good
Nextel™	2,200	16	Good	Very Good	Very Good	Excellent	Excellent

6.1 FIBERGLASS BAGS

The most commonly used fabric in baghouses in the US has been felted or woven glass. S2-Glass, manufactured by Owens-Corning Fiberglas, is a formulation of fiberglass with better strength properties at high temperatures than conventional fiberglass fabrics. An abrasion-resistant coating is applied to the bags to protect the fibers. The 22 oz/yd^2 weight fabric was selected over the conventional 16 oz/yd^2 weight fabric since the heavier fabric tends to exhibit lower particulate penetration. The drawback was that a heavier fabric contributes more to the overall baghouse pressure drop. Conventional 20 wire cages were used for support. The carbon steel cages were not protected against corrosion.

An exhaustive study to characterize the performance and operating experiences with pulse-jet fabric filters (PJFF) applied to coal-fired boilers has been conducted by the Electric Power Research Institute (EPRI). Since the SNRB™ Alternative Bag Demonstration was among the first to examine the applicability of the S2-Glass fabric to coal-fired boilers, the EPRI study did not address the S2-Glass fabric. However, on the subject of conventional fiberglass fabrics the study provided the following comments. Woven fiberglass bags provide reasonable bag lives and pressure drops while still maintaining very low outlet emissions comparable to those achieved by felts. However, fiberglass is less forgiving than felts and care must be taken to assure proper bag/cage fit (pinch) and caution used when installing the bags. Also, fiberglass is more susceptible to abrasion and related design and construction problems that may exacerbate abrasion such as pulse pipe misalignment, flue gas maldistribution, and hopper dust removal problems. Off-line cleaning, in which the compartments are isolated from the flue gas stream for cleaning, was developed in part to accommodate the more fragile woven fiberglass bag.[10]

6.2 FABRIC SELECTION PROCESS

Concurrent to the pilot scale SNRB™ verification test program, a series of bench-scale exposure tests were conducted on a variety of baghouse filter fabrics to predict performance in the high-temperature SNRB™ baghouse. The fabrics were exposed to different combinations of heat, moisture and sodium bicarbonate solution to determine the impacts on fabric strength. The exposed fabric Mullen Burst strength data were more pertinent in evaluation of high-temperature fabrics than fresh strength data. The Mullen Burst strength test determines the pressure necessary to rupture a secured specimen of fabric and is designed to characterize the relative total strength of the fabric to withstand pulsing and pressure. The percent change in the Mullen Burst strength for the various fabrics and exposure conditions are plotted in Figure 6-1. The exposure condition "Na/300°F/850°F" refers to first soaking the fabric in a 7% weight solution of $NaHCO_3$ for ten minutes followed by heating the fabric to 300°F for 4 hours and 850°F for 16 hours. All exposure times at 850°F were 16 hours.

The Nextel™ fabric retained a much higher percentage of its strength than did the other fabrics after exposure to the test conditions. Exposure to $NaHCO_3$ at temperatures of 850° and 650°F actually increased the Mullen Burst strength of the Nextel™ fabric. The S-Glass fabric was an experimental weave with a construction identical to a commonly used E-glass fabric suited for a reverse-gas baghouse rather than a pulse-jet baghouse. This base S-Glass fabric was modified resulting in the improved S2-Glass fabric evaluated in the demonstration baghouse. The strength of the glass fabrics were reduced significantly by all three $NaHCO_3$/heat exposure combinations, but less so at 650°F than at 850°F. Figure 6-1 reveals $NaHCO_3$ and high temperature exposure as decisive factors in the strength retention characteristics of the S-Glass fabric, whereas moisture had little effect. The Owens-Corning S-Glass exhibited approximately 42% more initial strength than the Nextel™

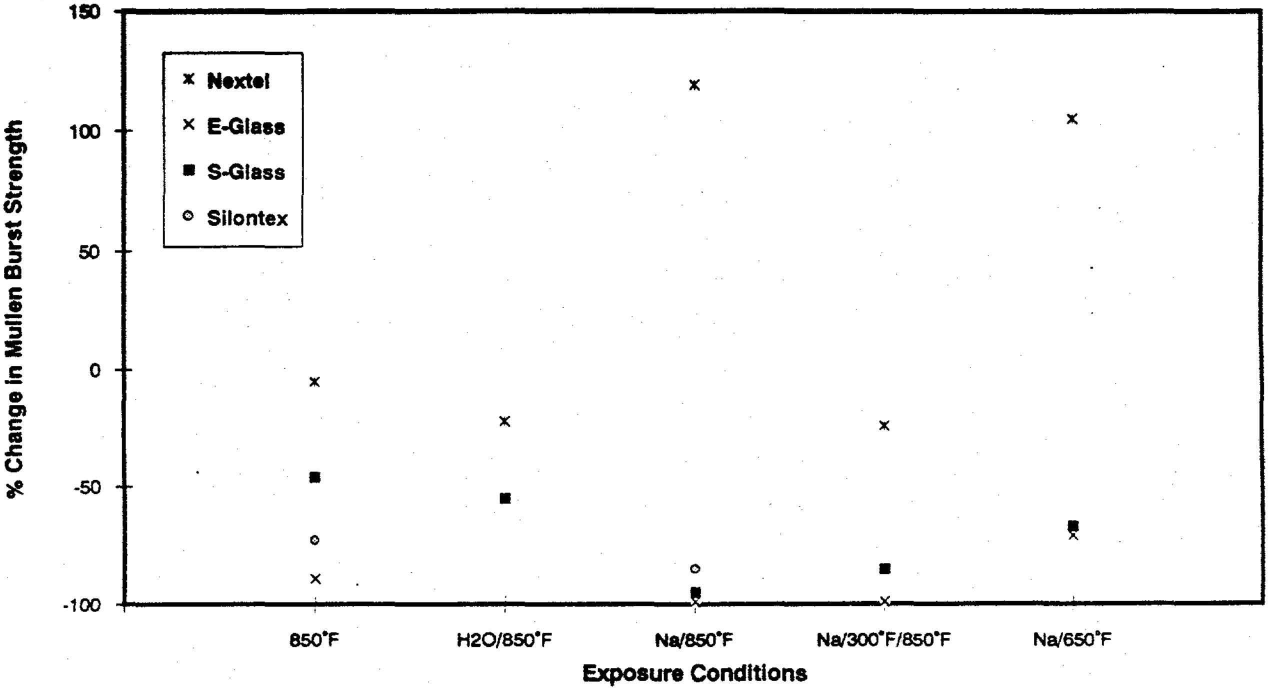


FIGURE 6-1 HIGH TEMPERATURE FILTER FABRIC EXPOSURE TESTS

fabric, therefore the exposed strengths of the two fabrics were comparable in the cases where the fabrics were not exposed to $NaHCO_3$. However, on the basis of strength retention, the Nextel™ fabric appeared to be the most promising of the fabrics evaluated.

The Filter Fabric Assessment Program detailed in Section 5 was the final basis for fabric selection for the Alternative Bag Demonstration. At the completion of the Filter Fabric Assessment Program , Mullen Burst Strength, MIT Flex and air permeability tests were performed according to ASTM standards (provided in Appendix C) on select fabric filter bag samples to test for degradation in fabric characteristics. The MIT Flex Endurance Test determines the number of cycles a filter media specimen can be rapidly flexed in an arc under a specified load until the fabric ruptures. The MIT Flex test measures the ability of the fabric to withstand self-abrasion from flexing and is primarily used to characterize the rate of bag deterioration. The air permeability test characterizes resistance to air flow through a fabric sample.[53]

The Mullen Burst strength of the S2-glass fabric after 3,700 hours of flue gas exposure in the pilot baghouse was twice that of the Nextel™ fabric. To compare the percent decline in Mullen Burst strength between the two fabrics, an approximate value was used for the original or clean strength of the S2-Glass fabric since it exceeded the capacity of the test apparatus. The Nextel™ and S2-Glass fabrics retained 80% and 55% of the original burst strength after 3,700 operating hours in the pilot, high-temperature baghouse. Permeability evaluation of the Nextel™ and S2-Glass fabrics suggested the Nextel™ fabric had better filtercake release which may result from the smoother surface of the Nextel™ relative to the S-2 Glass fabric.

In addition to a comparison between fabric type, the effect of the type of bag support on the S2-Glass was evaluated. The Mullen Burst strength and MIT Flex of the S2-Glass fabric which had operated on a standard wire cage exceeded the strength and flex measurements of the fabric on the perforated retainer. The wire cages were selected for S2-Glass in the Alternate Bag Demonstration on the basis of commercial operating experience, lower unit cost and the better strength and flex retention properties of the fabric.

The Nextel™ bags, which served as the base fabric, were installed in all six baghouse compartments at the beginning of the demonstration program. Three S2-Glass fabric bags in good condition after short-term service in pilot baghouse tests at the Alliance Research Center were placed in compartment #3 along with the Nextel™ bags. The three "long-term" S2-Glass bags were clamped on perforated retainers. The Nextel™ bags in compartment #3 were replaced with S2-Glass bags midway through the demonstration.

6.3 BAG INSTALLATION

Installation and removal of the S2-Glass bags was simpler and less time consuming than for the Nextel™ bags. The S2-Glass bags require different support and mounting equipment than the Nextel™ bags. The ability to sew the S2-Glass fabric eliminates the need for constant torque clamps to hold the bag to the retainer and permits mounting from the tubesheet using conventional snap rings. Of the three different cage mounting systems evaluated in the EPRI pulse-jet survey, the snap band or ring was found to provide the best bag to tubesheet seal and was the easiest to install.[44]

Installation of the S2-Glass bags involved fewer steps than installation of the Nextel™ bags. The bags were suspended from the tubesheet by the snap ring and the wire cages were slid inside. Sample bag/cage assemblies were lifted from the tubesheet to check the fit between the bag and cage (pinch). Too much pinch can lead to premature bag failure whereas a tight pinch can inhibit bag cleaning. Installation of the Nextel™ bags at the beginning of the demonstration program required the following steps. First, the bag was pulled carefully onto the perforated retainer. The upper and lower clamp areas were wrapped with two layers of Nextel™ tape and the clamps were secured to the retainer with a torque wrench. The assembly was then carefully suspended from the tubesheet using caution to avoid damaging adjacent bags already hanging from the tubesheet. The retaining clamps presented a potential hazard for snagging adjacent bags as the assembly was lowered into place. Average Nextel™ installation time was 1.8 manhours per bag. S2-Glass installation time averaged less than 1.0 manhour per bag. Installation time included adding the catalyst and gasketting material, securing the bags to the tubesheet, closing up the baghouse compartment and some leak checking activity.

The supporting tubesheet gasket arrangement for the S2-Glass bags was less complicated than the gasketting used for the Nextel™ bags. However, the tubesheet was originally designed to suspend Nextel™ bags and some modifications were necessary to accommodate the S2-Glass bags. The modifications involved covering the existing tubesheet with Kaowool insulation to serve as a gasket between the old tubesheet and the new tubesheet which had smaller openings for the bags. The clamps used with the Nextel™ bag arrangement require that the holes in the tubesheet be larger than the filter bag diameter. With the snap ring support, the hole is much closer to the actual diameter of the filter bag. In a commercial application, the S2-Glass tubesheet design would be simpler than for the Nextel™ bags since only one gasket between the catalyst holder and the wire bag support cage would be required to seal the bag/catalyst assembly. Mounting of the Nextel™ bags requires two gaskets; one between the tubesheet and the bag retainer and one for the catalyst holder. The use of fewer gaskets may improve particulate collection since misaligned tubesheet gaskets for Nextel™ bags were found to be a source of particulate emissions. In fact, the majority of the facility baghouse maintenance during the demonstration involved gasket realignment or replacement.

6.4 BAGHOUSE OPERATION

To accumulate as much operating time on the S2-Glass bags as possible, the facility was operated with compartment #3 consistently on-line after the S2-Glass bags were installed. Established baghouse operating procedures were not modified after the S2-Glass installation. The S2-Glass bags were not subjected to special care and the same cleaning pressure and cleaning cycle used in the other modules were applied to compartment #3. Although recommended for conventional woven glass bags to minimize abrasion, off-line cleaning was not used in the field demonstration.

Total high-temperature operating time for the compartment of S2-Glass fabric bags was 1,490 hours. The S2-Glass bags were exposed to high SO_2 and HCl concentrations during baseline tests for approximately 360 hours or 24% of the total operating time. The S2-Glass bags were frequently exposed to environments harsher than anticipated in commercial operation. Based on 1,500 hours of operation and an average cleaning cycle of 66 minutes, each of the S2-Glass bags were cleaned approximately 270 times during the Alternative Bag Demonstration.

Operating time on the Nextel™ bags in the remaining five compartments exceeded 2,300 hours. The Nextel™ bags were exposed to untreated flue gas containing high SO_2 and HCl concentrations for 740 hours or 32% of the total operating time. The bag cleaning cycle averaged 66 minutes for a total of 420 pulses per Nextel™ bag.

When the baghouse was not in service, the lower portions of the bags were visually inspected from the bottom of the hoppers. These periodic inspections revealed a gradual warping or twisting of some of the perforated retainers as discussed in Section 3.2.3. Most of the baghouse maintenance performed to maintain low particulate emissions consisted of simple gasket replacement. Over the entire demonstration period, only 5 of the Nextel™ bags were replaced representing a replacement rate of 2%. None of the 42 S2-Glass bags required replacement in the shorter alternative bag demonstration operating span. A total of 19 tubesheet gaskets required replacement. Typical baghouse/filter fabric guarantees include an allowance for a bag failure rate of 5 - 10% per year for either a compartment or for the entire baghouse.[53]

6.5 BAGHOUSE PERFORMANCE

NSPS particulate emissions compliance with the Nextel™ fabric was demonstrated by EPA Method 5 measurements before installation of the S2-Glass bags in one of the baghouse compartments. Particulate collection efficiency of the isolated module containing the S2-Glass bags was not separately measured in the test program. This would have required baghouse operation only with the S2-Glass bags. To provide some insight into the relative particulate collection efficiency of the S2-Glass bags, the emissions measured before and after the S2-Glass bag installation can be compared. As indicated in Figure 6-2, no significant change in emissions was observed following installation of the S2-Glass bags. Baghouse emissions measurements (16 tests) with five compartments of Nextel™ bags on-line ranged from 0.002 to 0.020 grains/scf with an average of 0.009 grains/scf. Baghouse emission measurements (30 samples) with four compartments of Nextel™ and one compartment of S2-Glass ranged from 0.007 to 0.021 grains/scf with an average of 0.013 grains/scf. A higher percentage of the Nextel™ only emission test results were less than 0.01 grains/scf than observed with the mixture of bags.

Pilot testing of the S2-Glass bags in a pulse-jet baghouse at Energy & Environmental Research Center at the University of North Dakota and at the B&W Alliance Research Center demonstrated particulate emissions well below 0.03 lb/million Btu.[50,54]

6.6 BAG REMOVAL

Prior to removal of the S2-Glass and Nextel™ bags at the completion of the demonstration, the compartment tubesheets were inspected for evidence of particulate penetration in the form of gasket leaks, particulate accumulation on the tubesheet or particulate impingement elsewhere in the compartments. Minimal particulate deposits were observed on the tubesheets.

Bag removal at the end of the demonstration was efficient and was not constrained by the bag length. A pulley was used to hoist the bags from the tubesheet. The major concern during bag removal was to avoid angling the bags as they were raised from the tubesheet to avoid damaging other bags still suspended from the tubesheet. The potential for abrasion of the bag in the process of removal was minimized by wrapping the circumference of the sharp tubesheet opening with nalgene tubing. The removed bags were carefully examined, folded, documented and stored.

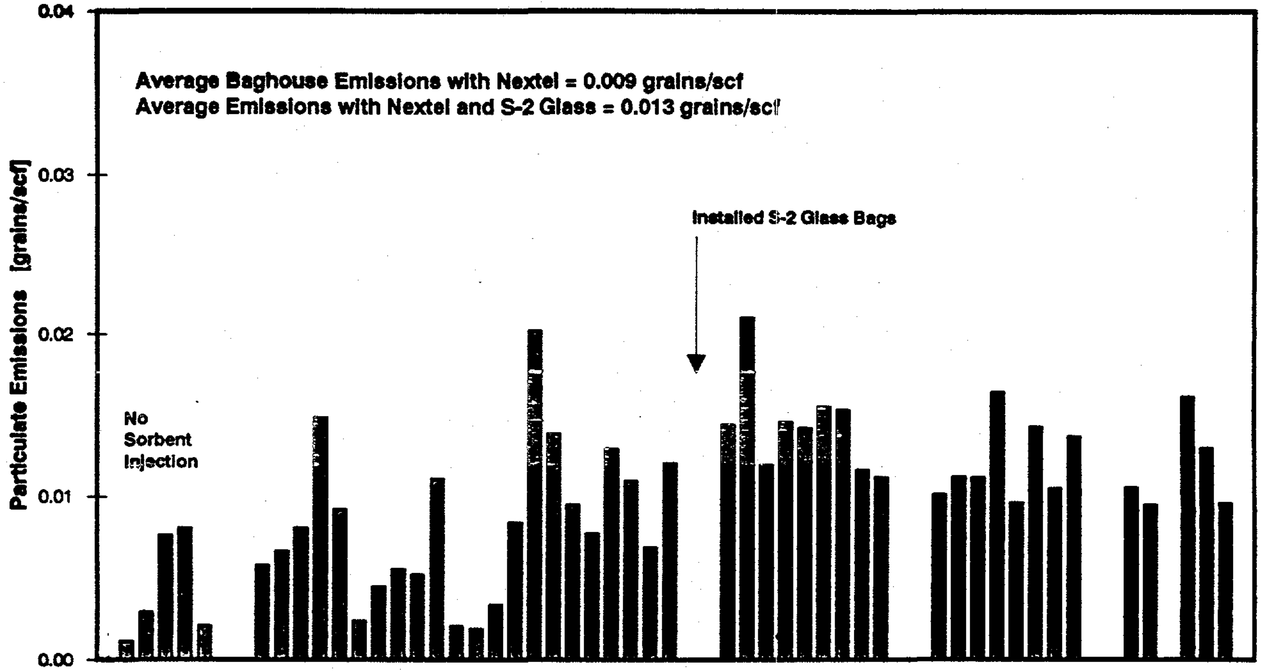


FIGURE 6-2 PARTICULATE EMISSION TEST SUMMARY

6.7 PHYSICAL CONDITION OF FILTER FABRICS

Nextel™

A representative selection of Nextel™ bags were removed from compartments #1 and #6 at the end of the demonstration following 2,315 hours of operation. The removal procedure was attended by representatives of 3M and B&W. The 24 bags were examined for signs of damage and/or failure. Observations by 3M and B&W included:

OBSERVATION	PROBABLE CAUSE
• Rust patterns especially at the top of the bag	Acid attack of retainers
• Solid filtercake on the top of the bags	Frequent outages
• Bag damage in the clamp area	Excessive clamping pressure
• Self-sealing mechanism on damaged areas	Solids buildup on retainer
• No particulate seepage noticeable on retainer in areas corresponding to bag edge folds	Handling improvements

Unreacted sorbent in the filtercake on the bags generally protects them from acid attack. However, the bags were susceptible to acid attack for more than 25% of the operating time when sorbent was not injected into the flue gas. Residual filter cake on the bags wold offer some protection. The inspection indicated that the bags were not directly attacked, but the adjacent steel surfaces of the bag retainers and the baghouse were subject to corrosion. Uniform rust stains along the inside length of the bags appeared to correspond to the perforated design of the bag retainer and the spiral lock seam. The carbon steel retainers were not treated with a protective coating prior to installation.

Irregular rust patterns observed at the top of the bags were likely caused from acid condensation during outages, start-ups and shutdowns. Periodic inspection of the baghouse tubesheets during shutdown periods revealed acid attack of the tubesheet and clean gas plenum walls. Patterns of discoloration on the walls of the baghouse indicated that enough moisture condensed that some drippage onto the fabric occurred. The patterns suggest that the top of the bags were susceptible to dampness during shutdown. These stained areas were examined during the strength tests performed by 3M. The red color of the patterns indicated that the steel surfaces and not the fabric were attacked, otherwise the discolorations would be distinctly yellow.[55]

The Nextel™ bags were clamped to the retainers at the top and bottom. A double strip of Nextel™ tape was placed under the clamps to protect the bag fabric. Some damage was observed on at least half of the examined Nextel™ bags in both the top and bottom clamped areas. Slits were observed directly underneath the clamp in a non-filtration area of the bag. The slits did not present a path for particulate leakage through the bags. The slits were likely caused by the end of the clamp. The effect would be exaggerated by over torquing the clamp during installation. The slits were not along the length of the clamp in a filtration area which would reflect excessive flexing against the clamp during bag cleaning.

Small holes underneath the clamp were also observed in the pilot design verification tests. Increasing the width and thickness of the Nextel™ protection strip between the bag and clamp for the demonstration tests was suggested to alleviate this problem in the demonstration. The purpose of the Nextel™ strip was to protect the bag from the clamp end and flexing against the clamp during cleaning. However, it was evident during removal of the bags that double Nextel™ tape strips were not consistently placed under the clamps during installation of all of the bags.

The filter cake was uniform along the entire length of the Nextel™ bags, however, minor amounts of hardened particulate were found on the top section of some of the Nextel bags. Although the bags were routinely cleaned prior to shutdown, the maximum cleaning pulse energy was introduced below the top of the bags at the bottom of the catalyst assembly. As a result, the lower sections of the bags may have been cleaned better than the top portion and some residual filtercake may have been left on the top. Passage though numerous start-up and shutdown cycles exposed the bags to acid and water dewpoints. The solids probably adsorbed water during the shutdown period and this created the hardened substance observed on the top surfaces of some of the bags.

Particulate seepage through the creased edge fold of the Nextel™ bag was a concern in the pilot design verification tests. Fabric handling and storage improvements were made by 3M to decrease the stress imposed and damage to the crease area (weave turnaround area). The new handling and storage procedures did reduce fiber breakage along the crease and minimal accumulation of particulate on the retainers corresponding to the crease location was evidence of decreased penetration.

On removal from the baghouse, minor damage was noted on 3 bags of the 24 bags. Of the three bags, one was from compartment #1 and the remaining two were located in compartment #6. The damage consisted of small holes from 1 mm to 3 mm in diameter. Initially the fabric appeared to possess a "self-healing" quality since the holes were partially or completely plugged. On closer inspection, it was evident that particulate had accumulated on the retainer surface and hardened in the holes effectively sealing the leaks. Whether or not the holes were sealed over by the filtercake, a 3 mm hole representing only 0.00024% of the filtration area of a single bag (not the entire baghouse) would not substantially contribute to particulate emissions.

The sample bags were sent to 3M for visual inspection and strength testing. The main objectives of the tests were to determine the change in fabric strength as a function of:

a) duration of exposure to hot flue gas in the baghouse
b) the location of the bag within the baghouse and within the compartments
c) the location of the fabric sample with respect to the cage support and cleaning pulse.

3M reported that the interior of most of the bags had a rust-like discoloration from the retainers. The degree of discoloration varied but did not correlate to the strength test results. The presence of rust on the bags does not affect the properties of the Nextel™ fabric at SNRB™ operating temperatures. Iron oxide may react with the Nextel™ fabric at temperatures greater than 1000 °F.

Close inspection of the bags by 3M revealed additional signs of wear and possibly installation damage. Four bags had small cuts which appeared to be related to bag installation. Six of the bags had minor wear such as frayed fiber edges or pinholes at the crease in the fabric. Of the damaged areas observed, only one hole was judged by 3M to be significant with respect to particulate emissions. The other wear spots were either too small or had been sealed with hardened filtercake.

Nextel™ bags were selected for strength analysis from all positions in the baghouse including those closest to the compartment walls. Initial fabric strength measurements were performed at three different locations (top, center & bottom) on four select bags to determine the best location for comparison. The center fabric samples were selected as the best location for comparison. Tensile strength tests were then performed on samples from the center sections of the remaining 20 filter bags to test for fabric degradation. Each strength measurement was performed three times. The tensile strength test differs from the Mullen Burst Strength test, therefore the results cannot be directly compared. The tensile test provides stretch, elongation and tear data for fabrics and can be used to measure the relative strengths of warp and fill yarns.[51] Table 6-2 summarizes the strength test results along the length and orientation of the bag in terms of percent retained strength after 2,300 hours of operation compared to a new bag. The fresh or "control" bag was from the same production batch as those originally installed in the SNRB™ baghouse.

TABLE 6-2 NEXTEL^{TM} TENSILE STRENGTH TEST RESULTS

	% RETAINED STRENGTH	
	Compartment #1	Compartment #6
Top	79.3	76.7
Middle	77.2	68.4
Bottom	77.2	70.5
Average	77.7	72.0
Warp	106	102
Fill	83.2	75.7
Turn/Crease	58.9	57.8

On the basis of tensile strength tests performed on one inch wide specimens with six inch span lengths, the following conclusions were made by 3M:

1) Tensile strength in the warp direction was essentially unaffected by baghouse operation. The slight increase indicated by the warp strength numbers was within the measurement error. Warp refers to the fibers running lengthwise in a woven fabric.

2) Tensile strength in the fill direction (bag circumference) decreased about 21% compared to control samples. The tensile strength measured in the fill direction is representative of overall bag strength. This is consistent with the Mullen Burst test data.

3) Strength loss in the turn or crease area was greater than that in other areas of the fabric. 3M does not view the turn as a potential failure area since the retained tensile strength was measured at greater than 100 lb.

4) Average bag strength in compartment #6 (closest to the inlet gas flow) was approximately 9% lower than compartment #1 (downstream).

5) Bag position within a baghouse compartment did not have a significant effect on tensile strength.

6) The strength of the bag cleaning pulse may have had a slight effect on fabric strength. The samples taken from the middle and bottom of the bags had strengths about 6% lower than those taken from the top. The center and bottom portions of the bags were subject to a higher pulse cleaning pressure than at the top since the pulse first contacts the bag below the catalyst holder.

7) There was no correlation between the observed rust discoloration of the Nextel™ fabric and tensile strength. There were no indications of chemical degradation.

Comparison of the field demonstration Nextel™ tensile strengths with the strengths of Nextel™ bags used in the earlier laboratory verification and filter fabric assessment tests shows a general increase in bag strength as a result of improved manufacturing procedures and baghouse operation. The comparison is provided in Figure 6-3.

A disadvantage associated with the Nextel™ bags was the tendency of the spiral seam welded perforated retainers to curve. In previous laboratory testing with straight seam welded retainers, no curving or unwinding of the seam in the retainer was observed. Extensive twisting may result in contact of adjacent bags and potentially lead to premature bag failure. The spiral seam retainer design was a lower cost alternative to the straight seam design. Straight seam welded retainers are recommended for baghouse operation with the Nextel™ filter fabric bags.

S2-Glass Fabric

The S2-Glass bags were visually inspected for damage and signs of degradation at the end of the Alternate Bag Demonstration. The bags were in good shape after 1,500 hours of operation. Essentially no damage was observed and the only indication that the bags had been in service was a light occurrence of rust stains. The bags remained flexible and the bag shape and structure appeared unaffected by the high-temperature operation. Unlike the Nextel™ bags, patches of filtercake had not hardened at the bottoms of the bags which may reflect the fewer number of start-up cycles the S2-Glass bags endured. One small hole (approximately ¼" diameter) was located at the bottom of one bag.

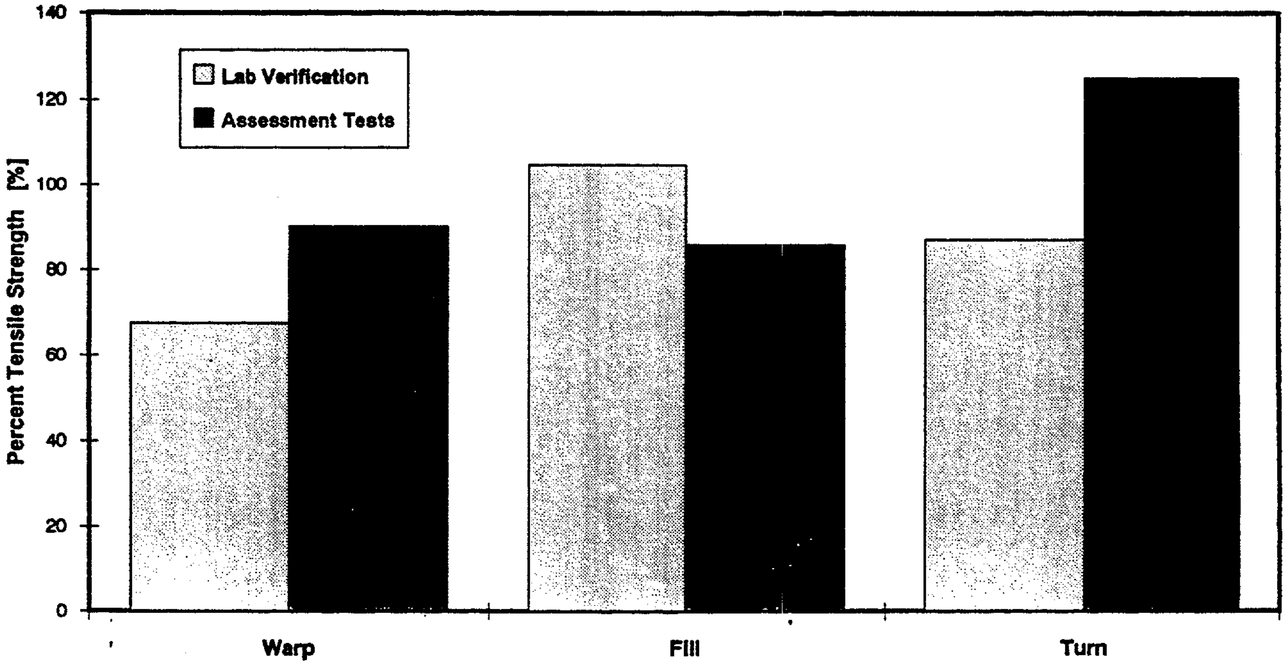


FIGURE 6-3 COMPARISON OF BAG STRENGTH RETENTION

Faint rust markings on the outside of the bags along the length of the bags did not have a regular pattern and are believed to have resulted from physical handling. Prior to installation of the S2-Glass bags, the Nextel™ bags and rusty bag retainers were removed from compartment #3. Light rust lines on the inside of the S2-Glass bags corresponded with the cage support wires which had corroded slightly in service. The carbon steel wire cages were not pre-treated with a protective coating prior to service. The snap rings located at the top of the bag which supported the weight of the bag and filtercake were in very good condition.

Two representative S2-Glass bags were selected for Mullen Burst and MIT Flex Endurance testing to be performed by Grubb Filtration. One of the bags was from the original three "long term" bags installed in compartment #3 at the beginning of the program. The bag was supported on a retainer and was subject to high temperature operation for 2,300 hours. The second bag was exposed for 1,500 hours with a wire cage support. Samples from the top, middle and bottom sections of the bags were evaluated to determine average properties and to detect uneven wear.

Table 6-3 summarizes the strength test results in terms of percentage retained strength after 1,500 and 2,300 hours of operation in comparison to a new bag. The MIT Flex Endurance Test determines the number of cycles a filter media specimen can be rapidly flexed in an arc under a specified load until the fabric fibers break. Table 6-4 compares the number of cycles required to rupture the S2-Glass after 1,500 and 2,300 hours of service. Vertical creases were observed in each of the bag section samples approximately 90° on either side of the seam. Although no significant fiber breakage was evident at these creases, distinct filling yarn distortion was observed. Strength testing was performed on the creased area as well as in typical non-creased areas to assess the potential for premature failure at the fabric creases.

TABLE 6-3 S2-GLASS RETAINED MULLEN BURST STRENGTH

	% RETAINED STRENGTH	
BAG SAMPLE SECTION	1,500 hours Wire Cage	2,300 hours Retainer
Top	42.0	38.0
Middle	40.1	37.8
Bottom	37.1	37.1
Average	39.8	37.6
Creases	37.8	27.1

TABLE 6-4 S2-GLASS MIT FLEX		
	CYCLES TO FAILURE	
FABRIC WEAVE CHARACTERISTIC	1,500 hours	2,300 hours
Warp	118	108
Fill	111	139
Crease	119	119

The comparable Mullen Burst strength and MIT flex test data for the S2-Glass bags supported on the retainer and on the wire cage agrees with the earlier pilot-scale tests. The retainer did not appear to impact the strength retention properties of the S2-Glass fabric. At the completion of the fabric assessment test program, the Mullen Burst strength and MIT flex data for the bag installed on the wire cage were slightly higher than the strength and flex of the bag on the perforated retainer.

Comparison of the percentage retained Mullen Burst strength after 1,500 and 2,300 hours of operation suggests that the fabric strength had stabilized in 1,500 hours of SNRB™ operation. The pilot test data reported in Section 5 indicated a higher percentage of fabric strength retention following a longer period of operation. The average retained strength of approximately 40% after 1,500 hours of SNRB™ operation was lower than the 55% retained by the S2-Glass bags after the 3,700 hour pilot durability test in Colorado Springs. Operating differences at the two facilities may have contributed to the lower strength retention including: hydrated lime and sodium bicarbonate sorbent injection, higher baghouse operating temperature (850 °F vs. 650 °F) and ammonia injection at the 5 MWe demonstration. It has been suggested that the temperature difference was the primary contributing factor.[56]

The lower burst strength on the center and bottom portions of the S2-Glass bags relative to the top section was also observed with the Nextel™ bags. The catalyst assembly inside the bags caused the cleaning air pulse to first contact the fabric near the midpoint of the bag length. The use of relatively low pressure cleaning air may have minimized fabric strength loss along the lower portions of the bags. Even with a 62% reduction in fabric strength, at the end of the program the S2-Glass bags possessed nearly twice the Mullen Burst strength of a used Nextel™ bag. The lowest Mullen Burst strength measured on the crease area of the S2-Glass bag after 2,300 hours of operation is comparable to the Mullen Burst strength of a new Nextel™ fabric sample.

The results of the MIT Flex tests on samples of the bag crease area from the demonstration baghouse were much better than earlier tests with samples from the pilot baghouse. Only 1 to 5 cycles were required to rupture fibers in the crease area of fabric samples from the pilot program, compared to 119 cycles for bag samples from the demonstration baghouse. It is believed that periods of continuous pulsing and a loose bag/cage fit may have contributed to the low MIT Flex data. The 1/2" to 3/8" pinch on the S2-Glass bags in the pilot baghouse exceeded the recommended 1/4" pinch. The good fit of the bags in the 5 MWe demonstration resulted in more uniform flex quality and reduced the potential of bag failure in service.

Grubb Filtration Testing Services performed a careful inspection of the S2-Glass bags. Both the long term and shorter term bags were free of internal dust. The inside surfaces of the fabric at the top of the bags were rust-stained and there were a few spots of rust staining the external surfaces of the bags. Wire cage impressions were not pronounced on the external bag surface. The internal cage impressions were lightly and sporadically rust colored, to a greater extent at the top. Unlike conventional fiberglass which abrades against wire cages, cage ring impressions were essentially non-existent, except for one impression 1 1/2" from the bottom of the cage. No visual fabric damage was evident on either the internal or external surfaces of the bag sections, even at the cage wire impressions. Thorough inspection of the pilot durability test bags also revealed no abrasion resulting from contact with the wire cages.

6.8 SUMMARY

The Alternative Bag Test Program demonstrated the application of both the Nextel™ and S2-Glass fabrics under actual high-temperature SNRB™ process operation. Both fabrics exhibited acceptable filtration efficiency, standard strength and flex characteristics and resistance to chemical attack. Both 3M and Owens Corning had expressed concern for potential fiber damage from exposure to the acid halides (HF and HCl) present in the flue gas. Hydrated lime injection for SO_2 removal also resulted in significant reductions in levels of HF and HCl in the flue gas contacting the filter bags.

Although the demonstration program did not provide for operation over the anticipated filter bag life of three years, both the Nextel™ and S2-Glass fabrics appear to have the potential for acceptable long-term performance in a SNRB™ system baghouse. In 2,300 hours of high-temperature operation, problems were encountered with only 2% of the Nextel™ filter bags most of these could be attributed to installation problems. No problems were encountered with the S2-Glass fabric bags over this period. A typical pulse-jet baghouse/filter fabric vendor guarantee includes a maximum bag failure rate of 5 to 10% per year for either a compartment or for the entire baghouse.[53] The 2,300 hours of operation represents 40% of the expected operating period for one year in a retrofit application of the technology. The 3,700 hours of operation attained in the pilot durability test of the fabrics represents 65% of the expected one year operating time of a retrofit application operating at a 65% capacity factor. Analysis of fabric samples suggests that service lives comparable to filter bags for conventional pulse-jet baghouse applications can be achieved.

3M has continued to improve the design and weave of the Nextel™ fabric since completion of the demonstration program. Additional pulse-jet baghouse operating experience has shown that a modified wire cage bag support may be suitable for the improved Nextel™ filter bag. The SNRB™ demonstration experience led to the following conclusions concerning use of the Nextel™ fabric:

- Caution must be used in clamping the bags to the retainers to avoid fiber damage on installation.
- The fabric appears to clean very well with minimal blinding and clean pressure drop build-up.
- The fabric retains a high percentage of the original strength after extended flue gas exposure.
- No indication of chemical attack was observed despite numerous start-up/shutdown cycles.

Owens Corning Fiberglas has continued development and demonstration testing of the S2-Glass fabric since completion of the SNRB™ demonstration. Much of this on-going work includes evaluation of a catalytic coating to the fabric for NO_x reduction. The following conclusions summarize experience with the S2-Glass fabric:

- The fabric has very good handling and installation durability characteristics.
- Fabric strength appeared to stabilize after an initial period of operation and remained high.
- No evidence of abrasion damage was observed due to contact with the wire cage supports.
- Good fit to the supporting cage is essential to minimize the potential for flex failure of the fabric.

7.0 AIR TOXICS EMISSIONS TESTING

A comprehensive test to quantify air toxics emissions and flow rates was performed at Ohio Edison's R.E. Burger Plant near Shadyside, Ohio. The test involved monitoring emissions from the pulverized-coal-fired boiler, the electrostatic precipitator (ESP), and B&W's SOx-NOx-Rox Box^{TM} (SNRB^{TM}) Flue Gas Clean-Up Demonstration. Funding for the program was provided by the U.S. Department of Energy (DOE), the Electric Power Research Institute (EPRI), Ohio Edison, and the Ohio Coal Development Office (OCDO). The project provided critical, timely input for consideration in the formulation of pending air toxics emission regulations. Field activities were completed in May 1993. This section addresses target analytes, sampling methodology/locations, field coordination, field sampling lessons learned, and the measurement results.

7.1 INTRODUCTION

Utility Air Toxics Program

The U.S. Department of Energy (DOE) is collaborating with the Electric Power Research Institute (EPRI), the U.S. Environmental Protection Agency (EPA), and the Utility Air Regulatory Group (UARG) to develop a comprehensive data base for the emissions of hazardous air pollutants (HAPs or air toxics) from utility boilers. The Clean Air Act Amendments of 1990 identified 189 such substances, and charged the EPA with determining the need for emissions control regulations for each substance. The quantification of emissions from existing plants is a necessary first step in this process. The air toxics data base will be used by the EPA, in conjunction with the results of studies of the impacts of these emissions on public health, to determine if air toxics emissions control regulations are required. Development work on the data base is being supported by DOE's Pittsburgh Energy Technology Center, Office of Project Management, and by EPRI under its Power Plant Integrated Systems: Chemical Emissions Study (PISCES) project.

Objectives of SNRB^{TM}/ESP Air Toxics Monitoring

The objectives of the SNRB^{TM}/ESP Air Toxics Monitoring Project were to characterize emissions from a coal-fired boiler and SNRB^{TM} process and compare the air toxics emissions control performance of the SNRB^{TM} hot catalytic baghouse technology with an ESP. The project included the collection of representative samples of all major input and output streams of the boiler and SNRB^{TM} demonstration unit, and the subsequent laboratory analysis of these samples to determine the partitioning of the hazardous substances among the various process streams. The substances of interest included trace metal, volatile and semi-volatile organic, aldehyde, halides, and radionuclide species. For comparison purposes, the air toxics emissions performance of the host utility unit was considered the emissions baseline. Material balances for the selected air toxics were subsequently calculated around the SNRB™ and host boiler systems, including the removal efficiencies across the ESP and the SNRB™ baghouse. This presented a unique opportunity to provide a direct comparison of an advanced emissions control technology with a common conventional control technology.

Project Team

Ohio Edison, OCDO, EPRI, and DOE provided financial support, technical guidance, and review for the comprehensive air toxics test. Ohio Edison provided access to the R. E. Burger Plant, monitored and maintained boiler operating conditions, held coal supply constant during the field study, and assisted in process sampling. B&W operated the SNRB™ process and provided overall project management. Battelle (Columbus, Ohio) provided the quality assurance project plan (QAPP) and implementation, sampling and analysis, and project management, and were assisted in stack sampling by Energy and Environmental Research Corporation (EERC) of Irvine, California. Frontier Geosciences (Seattle, Washington), assisted in the field by B&W, provided sampling and analysis for mercury speciation.

7.2 TECHNICAL APPROACH FOR AIR TOXICS SAMPLING PROGRAM

Ohio Edison's Boiler # 8 and Electrostatic Precipitator

A blend of medium sulfur, bituminous Ohio coals from a single supplier was fired in the 156-MWe (gross generating capacity) Boiler #8 at Ohio Edison's R. E. Burger Plant. Boiler #8 is a pre-NSPS, pulverized coal, wall-fired boiler. This type of boiler is representative of approximately 63% of the 24,000 MWe of coal-fired generating capacity in the state of Ohio. The boiler components were inspected, cleaned, and adjusted during a scheduled annual maintenance outage approximately 6 months prior to the test program. The unit had been out-of-service for 3 of the 4 months preceding the test.

The boiler was operated at a constant load of 151-MWe for the two days preceding the air toxics test program and for the duration of the seven day test period. The project team set allowable ranges for operating conditions to assure constant combustion conditions. The allowable ranges for boiler operation included 3.0 to 5.0% oxygen, steam temperature at the superheater exit of 1000° - 1060°F and at the reheater exit of 950° - 1010°F, steam pressure of 2000 - 2075 psi, and steam generation rate of 0.95 - 1.2 x 10^6 lb/hr.

The Buell ESP was installed in 1982. Design conditions include flow of 638,000 acfm at 290°F, specific collection area of 409 $ft^2/1000\ ft^3$ gas, gas velocity of 3.9 ft/sec, and bulk gas residence time of 12.3 seconds.

SNRB™ Demonstration Operation

For the air toxics test program, commercial hydrated lime was injected just upstream of the baghouse at 850° to 900°F and a Ca/S ratio of approximately 2. Ammonia, injected into the flue ahead of the baghouse, reacted with NO_x on the surface of the zeolite catalyst incorporated into the 3M Nextel™ filter bag assemblies. Ammonia injection was controlled at an NH_3/NO_x ratio setpoint of 0.85 and the baghouse temperature averaged 855°F. Operation of the baghouse at this elevated temperature was required for optimal SO_2 and NO_x emission control. Five of the six pulse-jet baghouse modules were in service resulting in an air-to-cloth ratio of 3.6 to 3.75 ft/min. The average SNRB™ operating conditions are summarized in Table 7-1.

The SNRB™ process availability was greater than 99% during the 225 hours of operation in support of the air toxics emissions test program. A summary of the SNRB™ system SO_2 and NO_x emissions control performance is included in Appendix G.

Sampling Locations

The primary objective of the air toxics monitoring project was to characterize the major input and output streams of the boiler and 5-MWe SNRB™ unit during normal, full-load operation. The process streams identified in Figure 7-1 were selected for characterization during the project. Several of the Burger Plant's Boiler #8 streams were sampled to provide information on the baseline emissions of the host utility unit. The boiler flue gas stream was sampled at Locations 10 and 12 to characterize the removal of toxic substances across the existing ESP, and the composition of the resulting flue gas stream at the stack. The fly ash

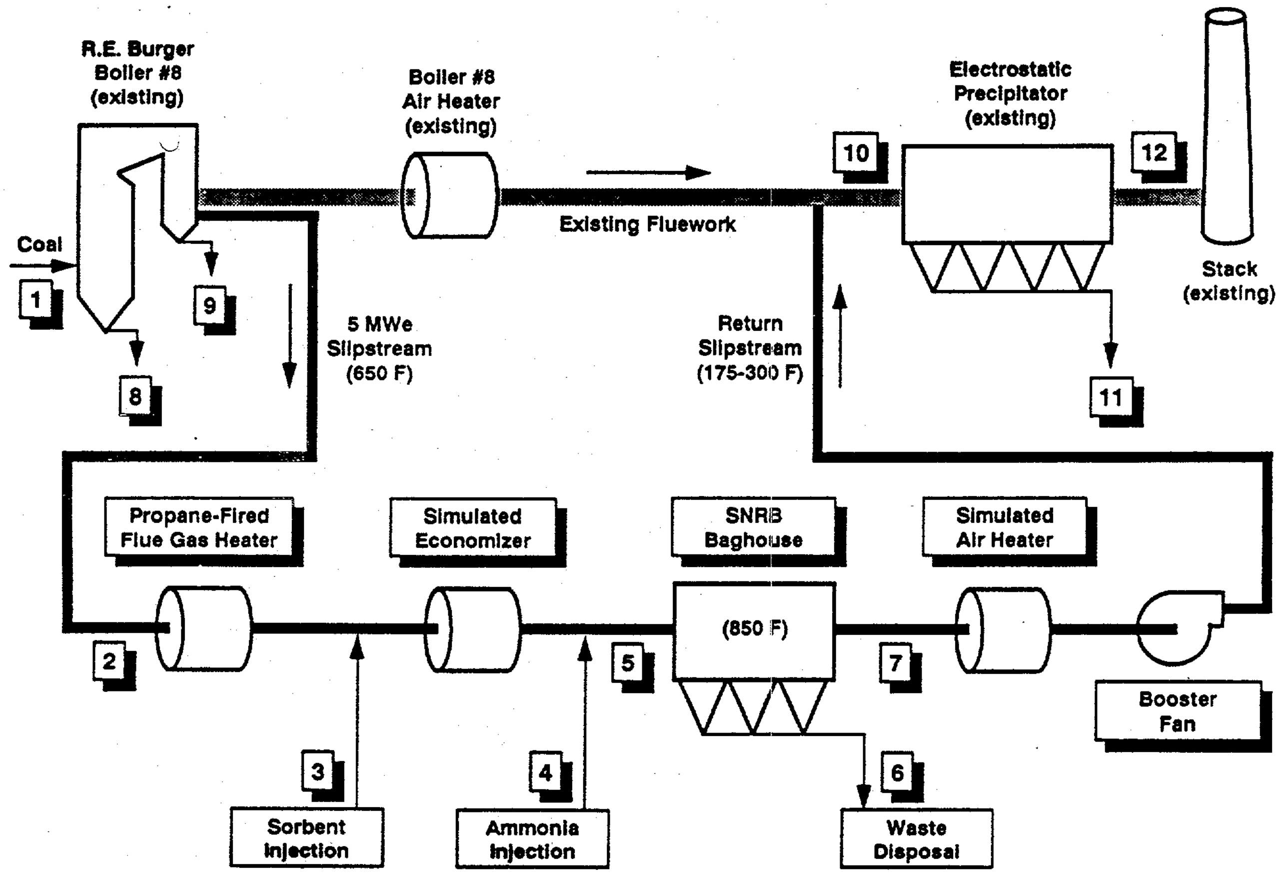


FIGURE 7-1 PROCESS STREAM SAMPLING

TABLE 7-1 AVERAGE SNRB™ OPERATING CONDITIONS			
		Range	Average
Bag/Catalyst Temperature	°F	845 - 860	855
Air-to-Cloth Ratio	ft/min	3.6 - 3.75	3.7
NH_3/NO_x Stoichiometry	mol/mol	0.80 - 0.98	0.88
Ca/S Stoichiometry	mol/mol	1.8 - 2.1	2.0
Sorbent Feed Rate	lb/hr	433 - 472	453
System Inlet SO_2	ppm	2290 - 2400	2350
Baghouse Inlet NO_x	ppm	390 - 410	400
Baghouse Outlet SO_2	ppm	170 - 260	210
Baghouse Outlet NO_x	ppm	35 - 42	38
Cleaning Cycle	minutes	43 - 49	46
Baghouse Pressure Drop	"H_2O	11.5 - 12.2	11.8

collected by the ESP (Location 11) was sampled, as was the Boiler #8 bottom ash (Location 8), and economizer ash (Location 9). Fly ash, collected from the ESP hoppers in four rows corresponding to the eight ESP fields, was later combined into a weighted row composite sample. No ash was collected from the last row even with very long accumulation times because of the high particulate collection efficiency of the first six fields. Finally, the feed coal and pulverized coal (Location 1) to the host boiler were characterized to permit comparison of the measured flue gas composition at the SNRB™ system inlet with the composition expected based on the coal analyses. The results of the extensive coal analyses are provided in Appendix Q. Pulverizer reject samples were collected and reject flow rates were determined to obtain the quantities of trace metals and halides leaving the boiler system in the pulverizer rejects stream. Characterization of these samples was used to calculate material balances around the ESP and Boiler #8.

In Figure 7-1, Locations 5 and 7 represent the key inlet and outlet flue gas streams for the SNRB™ high-temperature baghouse. The temperature of the flue gas stream at location 5 (baghouse inlet) averaged 865 °F and the temperature at location 7 (baghouse outlet) was about 790°F. Location 7 defined the outlet conditions of the SNRB™ process.

Flue gas was also sampled at Location 2 to:

- define the flue gas at the slipstream SNRB™ system inlet
- characterize the flue gas stream entering the Boiler #8 air heater
- allow sorting out the effects of the propane heater, lime and ammonia injection on the overall SNRB™ process

Although an integral component of the slipstream demonstration, the propane heater would not be part of a commercial SNRB™ system. The propane heater could have been a source of volatile organic compounds (VOCs). The hydrated lime may be a significant source of heavy metals.[57] The flue gas temperature at Location 2 was about 640°F. The applicability of the proposed sampling protocols to flue gas streams at these elevated temperatures was given careful consideration. Locations 3 and 4 represent the other major input streams for the SNRB™ process: the SO_2 sorbent and SCR reagents, respectively. Location 6, the SNRB™ solid by-product collected by the fabric filter, represents the other major output stream from the process. Each of these streams, except the ammonia stream, was sampled during the study. Chemical analyses of the hydrated lime and by-product solids are included in Appendix Q.

Differences in measured air toxics levels between Locations 2 and 10 may indicate the effect of the air heater on the fate of air toxics in the boiler operating system.

Air Toxics Targeted for Study

Table 7-2 summarizes the compounds monitored during this project and the sampling streams for each analyte. This list was selected to provide data compatible with other studies being conducted by the DOE, EPA, and EPRI. The analytes of interest are a subset of the 189 substances identified in the 1990 Clean Air Act Amendments, and include trace metals, VOCs, semi-volatile organics (polycyclic aromatics and dioxins/dibenzofurans), aldehydes (carbonyls), halides (chloride and fluoride), and radionuclide species. The targeted analytes expanded the conventional DOE/EPRI/EPA/UARG list by adding these less-studied compounds: dioxins and dibenzofurans; in addition to benzene and toluene, the US EPA Method TO14 list of 41 VOCs; in addition to formaldehyde, carbonyls up to C_6; and mercury speciation (after the method developed by Nicholas Bloom[58]). Mercury speciation is important because of the different mercury species measured in power plant stack emissions (Hg^0, Hg^{2+}, methyl mercury) may show wide variations in environmental fate and toxicity[59]. It was also of interest to determine whether the SNRB™ process affected the conversion or removal of the mercury species compared with the host boiler and ESP.

TABLE 7-2 SNRB/ESP SAMPLING AND ANALYSIS MATRIX

SAMPLING LOCATION	1	2	3	4	5	6	7	8	9	10	11	12
Mass flow rate	X	X	X	X	X	X	X	X	X	X	X	X
High heat value	X											
Proximate analysis	X											
Ultimate analysis	X											
Unburned carbon						X		X	X		X	
Trace elements:												
Total	X	X	X		X	X	X	X	X	X	X	X
Vapor phase		X			X		X			X		X
Solid phase		X			X		X			X		X
Hg Speciation							X					X
Particulate loading		X			X		X			X		X
Particulate sizing					X		X			X		X
Volatile organics		X			X		X			X		X
Semivolatile organics		X			X		X			X		X
Dioxins/furans					X		X			X		X
Aldehydes		X			X		X			X		X
Cl, F	X	X	X		X	X	X	X	X	X	X	X
Radionuclides	X				X		X			X		X
Loss on ignition						X		X	X		X	

ace elements include As, Ba, Be, Cd, Co, Cr, Hg, Mn, Ni, Pb, Sb, Se, V

ass balance calculations include As, Ba, Be, Cd, Cl, Co, Cr, F, Hg, Mn, Ni, Pb, Sb, Se, V

Particle size distribution measurements were added to characterize the heavy loading of fine lime particles in the SNRB™ process and compare emissions control as a function of particle size for the ESP and SNRB™ baghouse. Any differences found in metals emissions for the two control technologies may have been related to the inlet particle size distribution. Mass balances were performed for trace metals and halides.

Sampling Schedule

Sampling of the process streams was conducted during a nine-day period. This included two days of boiler and SNRB™ "conditioning" at full-load followed by a seven-day sampling period of nominal 12-hour days completed on May 2, 1993. Three identical test runs were conducted during the week. Triplicate samples were collected for each run. Stack sampling personnel arrived up to seven days in advance for site preparation and a project team pre-test walk-through. The sampling schedule called for a two-day period to complete a single test. Day 1 included semi-volatile organics, a combined chloride/fluoride/radionuclide train, and aldehydes. Day 2 included metals, mercury speciation, particle size distribution, and volatile organics. The schedule was constructed in such a manner as to conduct simultaneous sampling for particular analytes at all locations and was revised in the field to ensure that sampling was conducted in the most cost-effective manner consistent with the objectives of the project.

Throughout all of the air toxics testing, comprehensive operating data from the boiler, ESP, and SNRB™ system were recorded by Ohio Edison personnel and B&W's data acquisition system. This operating data was used by Battelle for the calculation of mass balances.

Sampling Methods

The sampling protocols, sampling times, and targeted detection limits for the flue gas streams are given in Table 7-3. Sampling periods at the ESP/SNRB™ exit locations were increased as necessary to achieve the required detection limits (longer sampling time results in a larger sample volume and thus more analyte collected for analysis). Actual detection limits were sample-specific because they depended on the actual sampling volume, the presence of interferences, and the instrument performance at the time of sample analysis.

TABLE 7-3 SAMPLING METHODS, SAMPLING TIMES, AND TARGETED DETECTION LIMITS

ANALYTE	US EPA METHOD NO.	SAMPLING TIME (hr)	DETECTION LIMIT
Combined Semivolatiles Polycyclic Aromatics (PA) Dioxins (D)	23	4	PA: 0.15-0.3 ng/dscm D : ng to pg/dscm
Combined Cl / F / Radionuclides/Particulate Matter	26A	2	Cl: 0.5 ug/dscm F : 0.1 ug/dscm
Aldehydes	0011	2	1.4 ug/dscm
Metals	29	1.4[a] 8[b]	0.3-5 ug/dscm[a] 0.05-0.9 ug/dscm[b]
Mercury Speciation	Frontier Geosciences Method	2	Total Hg: 0.05 ug/m^3 Methyl Hg: 0.05 ng/m^3 Ionic Hg: 0.02 ug/m^3
Particle Size	Cyclones Cascade Impactors	0.3 $\leq$ 2	NA NA
Volatile Organics	18 (Tedlar bags)	1	0.1 ppb

[a] at inlet locations (Locations 2, 5 and 10)
[b] at exit locations (Locations 7 and 12)

7.3 ANALYTICAL METHODS

Battelle's selection of appropriate methods for the preparation and analysis of samples was based on the desire to compare data with other DOE and EPRI studies, the specific analytes of interest, the sample matrix, and the required detection limits. Techniques used to lower the detection limits included combination of metals train fractions for a single Hg determination and the use of selected ion monitoring mass spectrometry for polycyclic aromatic hydrocarbon (PAH) determinations. Several sampling and analytical modifications incorporated in this project must be given consideration when interpreting the data. Few validated methods for several of the analytes specifically for power plant emissions were available when the program was conducted.

7.4 FIELD STUDY LESSONS LEARNED

This project was significantly more complicated than most previous stack sampling studies. One complication was the requirement for simultaneous sampling of inlets and outlets of two processes at "non-standard" temperatures, pressures, acid gas concentrations, and particulate loading conditions. Sampling twelve separate streams required a significant amount of personnel coordination. Some lessons learned in the field in this particular study are offered for consideration in planning future air toxics testing programs:

Pre-Test Planning

- Establish the data quality objectives, the sampling and analysis procedures to be used, and the procedures to assess the data quality in a Quality Assurance Project Plan (QAPP).
- Develop a list of acceptable process operating conditions and ranges to simplify real-time sampling decisions.
- Determine the effort, time and compromises necessary to obtain representative solid samples.
- Evaluate the applicability of stack methods, usually developed for MSW or other combustors rather than coal-fired power plants, to the sampling circumstance. The SNRB™ testing presented stack sampling temperatures, SO_x and NO_x concentrations, particulate loadings, and stack dimensions that required modifications of existing methods.
- Identify and anticipate sources of test interruptions such as power failures or process operation out of predetermined acceptable ranges. Develop operating procedures and a chain-of-command for these situations.

Field Sampling

- Determine sampling priorities with the project team and compare priorities daily against the progress made in the field. Focus continually on the highest priority objectives.
- Maintain direct and constant communication between all members of the project team to coordinate stack sampling at various locations.
- Identify sampling difficulties early in the program by trying all planned alternative sampling methods upfront.

- Anticipate at least one contingency day in the field sampling plan. For this project, the one contingency day resulted in 95% sampling completeness (97 collected samples compared with 102 planned samples) rather than 80% completeness for the original period. Given the difficulties of field studies, most would regard the 95% completeness as a success.

7.5 AIR TOXICS EMISSION RESULTS

7.5.1 Material Balances

Material balances were performed to account for the air toxics of interest across the boiler, the boiler/ESP combination and the SNRB™ facility[60]. Boiler emissions were measured at locations 2 and 10 representing the SNRB™ inlet and the ESP inlet. Much consideration was given to which location should provide the basis of the air toxics removal efficiencies across the SNRB™ system. The ESP inlet sampling location was downstream of the SNRB™ outlet and therefore was slightly diluted by the treated flue gas exiting the SNRB™ system. The SNRB™ inlet levels of metals were comparable to the metals content measured in the ESP ash and the boiler economizer ash, as it should be, whereas the ESP inlet metals levels were consistently lower. Table 7-4 compares the ash and metals concentrations measured at the ESP and SNRB™ inlet locations. Since the slipstream to the SNRB™ facility was split from the flue gas leading to the Ohio Edison ESP, the two streams should contain similar concentrations of air toxics. For all but 2 metals listed in Table 7-4, the concentrations measured at the SNRB™ inlet were considerably higher than at the ESP inlet. Furthermore, the material balances performed around the boiler were consistently low (more measured going in than going out). The material balances around the ESP were consistently high (less coming in than going out). If the measured fly ash concentration entering the ESP were biased low, both the boiler and ESP material balances would be resolved. Similarly, the consistent lack of closure of the material balances across SNRB™ also suggests that the sampling collection efficiency at the SNRB™ baghouse inlet was low.

TABLE 7-4 COMPARISON OF METALS CONTENT MEASUREMENTS IN SNRB™ AND ESP INLET FLUE GAS STREAMS

SUBSTANCE	SNRB™ INLET	ESP INLET	ESP/SNRB™ RATIO	ANALYTICAL METHOD [(a)]
Ash	8.5	9.0	1.06	Gravimetric
Hg	9.88	10.3	1.04	CV-AAS
Cr	784	397	0.51	ICP-AES
Cd	7.23	3.32	0.46	ICP-AES
Ni	376	182	0.48	ICP-AES
Ba	1,550	692	0.45	ICP-AES
Co	158	67	0.42	ICP-AES
Mn	788	398	0.51	ICP-AES
V	1,120	625	0.56	ICP-AES
Be	45.1	22	0.49	ICP-AES
As	460	335	0.73	GF-AAS
Pb	186	135	0.73	GF-AAS
Sb	8.39	11.3	1.35	GF-AAS
Se	148	124	0.84	GF-AAS

(a) Units for ash are in g/dscm. Units for metals are μg/dscm.

Sampling conditions and experience also identified the ESP inlet measurements as the least representative of the boiler emissions. Sampling at the ESP inlet has historically been very difficult due to the high dust concentration and stratification.[60] In addition, Battelle reported that all of the ports at the ESP inlet were not sampled. To eliminate the uncertainty associated with the measurements at the ESP inlet, the reported SNRB™ removal efficiencies in this section were based on the measurements conducted at the SNRB™ inlet and baghouse outlet (locations 2 and 7). The exception is particulate removal efficiency which is based on the particulate loading measured at the SNRB™ baghouse inlet (location 5) to reflect the rate of hydrated lime injection.

Many of the heavy metals material balance closures were within the EPRI PISCES recommended range of +/- 30% of the inlet stream values (70 - 130%).[61] Cadmium, barium, antimony and selenium closures were outside this range for both the boiler and the SNRB™ system. The heavy metal material balance closures for the boiler and SNRB™ systems are presented in Table 7-5. The reported closures are based on the data screened for extreme values outside one standard deviation.

TABLE 7-5 MATERIAL BALANCE CLOSURE FOR THE BOILER AND THE SNRB™ SYSTEM

ELEMENT	MATERIAL BALANCE CLOSURE (PERCENT)	
	BOILER	SNRB™
Hg	73	155
Cr	84	101
Cd	NC[(a)]	34
Ni	73	84
Ba	48	19
Co	102	106
Mn	71	104
V	78	121
Be	94	73
As	115	556
Pb	39	77
Sb	NC[(a)]	66
Se	61	138

(a) NC - Not calculated, element not found in pulverized coal samples

Metals present in the hydrated lime solids stream accounted for less than 10% of the input to the SNRB™ system for most of elements. The amounts of barium, cobalt and antimony in the lime feed were significant enough to represent greater than 10% of the total for each metal in the combined flue gas, fly ash and lime stream at the SNRB™ baghouse inlet. No mercury, cadmium, nickel, beryllium, lead, or selenium were detected in the feed lime.

The metals mercury and cadmium were not detected in the SNRB^{TM} baghouse solids and thus the baghouse flue gas outlet represented 100% of the emissions of these two metals. Intermediate levels of partitioning of the inlet metals to the SNRB^{TM} solids were observed for barium (15%) and beryllium (46%). The other metals (chromium, nickel, cobalt, manganese, vanadium, arsenic, lead, antimony, and selenium) all showed greater than 100% of the inlet flow partitioned to the SNRB^{TM} solids, with some also showing trace flue gas emissions on the order of 0.0001 lb/hr or less.

No partitioning of mercury to the SNRB^{TM} solids was detected. This differed from the ESP ash which represented on average 24% of the mercury in the ESP exit streams. The difference may be explained by the unusually high unburned carbon content of the ESP ash (7.3% by weight). Carbon is believed to be a possible adsorbent for mercury. In contrast, at 0.35% by weight, the SNRB^{TM} ash was low in unburned carbon. Dilution of the SNRB^{TM} product by sorbent injection cannot account for the differences in unburned carbon. Sorbent injection typically tripled the particulate loading to the SNRB^{TM} baghouse from baseline levels without sorbent injection.

7.5.2 Particulate Matter

Removal efficiencies for particulate matter and trace substances were calculated using the measured concentrations of substances corrected for field blanks. Baghouse outlet particulate emissions averaged 0.023 lb/10^6 Btu corresponding to an average collection efficiency of 99.86%. Inlet loading to the SNRB^{TM} baghouse averaged 16.75 lb/10^6 Btu. Baseline loadings without sorbent injection measured at the ESP inlet averaged 6.19 lb/10^6 Btu. A lower concentration of fly ash, 5.12 lb/10^6 Btu, was measured at the SNRB^{TM} system inlet. This lower value may reflect particulate stratification at the ESP inlet sampling location or unequal fly ash partitioning at the slipstream take-off. The baghouse inlet and outlet particulate loading measurements were in close agreement with those conducted by B&W and an independent contractor in earlier phases of the test program.

The results of the cyclone and cascade impactor measurements performed at the SNRB^{TM} baghouse inlet and outlet were discussed in Section 4.7.8. A comparison of the particle size distribution (PSD) of the baghouse inlet and outlet streams generated the following conclusions:

- Under typical SNRB^{TM} operating conditions, less than 3% of the solids entering the baghouse were finer than one micron. Approximately 10% of the solids were smaller than 7 microns.
- The PSD of the outlet stream was finer than at the inlet with 40% of the emissions having a particle size less than 1 micron. Approximately 70% of the solids were smaller than 7 microns.

The PSD of the SNRB™ inlet stream was significantly coarser than at the ESP inlet due to the addition of the hydrated lime.

7.5.3 Heavy Metals

Table 7-6 summarizes the SNRB™ system emissions and removal efficiencies for metals, particulate and acid halides. Data for three replicate measurements is included in Table 7-6 to demonstrate the deviation between the individual runs. The observed variation between individual runs, especially for cadmium and nickel, resulted a hesitancy to report average removal efficiencies for the individual species. Overall, of the 41 calculated removal efficiencies 35 were greater than 94% removal and 37 were greater than 90% removal. Mercury was the only species for which the measured emissions exceeded the SNRB™ inlet measurements.

For all metals except mercury, cadmium, nickel, and antimony there was a reduction in flue gas concentrations consistently in excess of 92% through the SNRB™ process. Some of these metals have been identified as "high risk" pollutants (arsenic, beryllium, cadmium, magnesium, mercury and nickel) by the EPA. The removal efficiency of the SNRB™ process was equal to or greater than that of the ESP for six of the metals including barium, manganese, vanadium, beryllium, arsenic, and selenium. Comparison of the individual removal efficiencies measured across the ESP and SNRB™ during each run reveals that the SNRB™ process provided equal or greater emission control for 32 of the 41 runs for which efficiencies could be calculated. Conventional wisdom regarding air toxic capture contends that lower temperature favors the condensation of metals on fine particulate and subsequent removal from the gas phase. If temperature were the only factor influencing air toxics capture, the air toxics removal performance of the SNRB™ baghouse would conflict with convention wisdom since the baghouse was operated at a much higher temperature (855°F) than the ESP (300 °F).

With the exception of mercury at the SNRB™ exit, all heavy metals measured were predominantly found in the particulate phase (i.e., on the filter of the EPA Method 29 train). The portion of several metals partitioned to the vapor phase increased at the SNRB™ exit compared to the SNRB™ inlet/baghouse inlet but this observation could not be explained. No mercury was detected in the lime feed or SNRB™ by-product solids.

TABLE 7-6 SNRB^{TM} SYSTEM AIR TOXIC EMISSIONS AND REMOVAL EFFICIENCIES

	SNRB^{TM} Inlet Loading (Location 2) [lb/10^{12} Btu]			SNRB^{TM} Outlet Emissions (Location 7) [lb/10^{12} Btu]			SNRB^{TM} Removal Efficiency [%]		
Sampling Run	1	2	3	1	2	3	1	2	3
Particulate [(a)]	15.33	21.07	12.43	0.031	0.022	0.015	99.80	99.89	99.88
Mercury	4.94	6.41	11.29	11.05	11.27	15.11	—	—	—
Chromium	545.11	212.72	1111.11	0	10.40	.05	100	95.11	99.99
Cadmium	5.87	1.18	10.20	0.33	1.11	0.18	94.38	5.83	98.24
Nickel	247.46	122.01	532.84	2.51	89.82	0	98.99	26.38	100
Barium	738.31	591.79	2363.40	0	0.30	0	100	99.95	100
Cobalt	100.96	36.16	241.77	0	2.73	0	100	92.45	100
Manganese	458.50	192.37	1186.77	0	1.28	0.24	100	99.33	99.98
Vanadium	732.62	490.25	1463.78	0	0	0	100	100	100
Beryllium	29.43	14.15	64.57	0	0	0	100	100	100
Arsenic	403.31	246.37	458.16	NS	2.18	0.27	—	99.12	99.95
Lead	172.57	83.48	176.49	NS	0.81	0	—	99.03	100
Antimony	6.03	7.41	6.60	NS	1.51	0	—	79.63	100
Selenium	118.49	72.46	160.88	NS	0	0	—	100	100
Fluoride	154.5	—	4534.9	72	< 1	39	53.4	100	99.14
Chlorine	7070.6	28821.4	52.6	601	807	2	91.5	97.2	96.2

NOTES:

[(a)]	Particulate matter measurements reported in lb/10^{6} Btu
NS	Indicates no sample data

A zero value indicates compound not detected in sample or not detected at a level greater than the field blank.

7.5.4 Acid Halides

In addition to effectively controlling SO_2 emissions, hydrated lime injection substantially reduced the acid halide (HF and HCl) concentration in the flue gas. Based on the concentrations measured at the SNRB™ system inlet, the calculated removal efficiencies averaged 84% for fluoride and 95% for chloride. The ESP did not reduce fluoride or chloride emissions. Removal of acid halides, especially HF, upstream of particulate removal and NO_x control is advantageous to extending the lives of both the filter bags and SCR catalyst. In general, the ceramic Nextel™ fabric has been shown to be resistant to acidic or alkali substances in the gas or solid phase. The exception is HF. Hydrofluoric acid can also harm the chemical structure of the S-2 Glass fabric. Sorbent injection protects the Nextel™ and S2-Glass fabrics from acid attack and accelerated degradation.

7.5.5 Mercury Speciation

Mercury species were measured at the SNRB™ outlet using the method of Bloom[55]. The method uses two sorbent traps to measure combined Hg^{2+}/methyl mercury (two forms of oxidized mercury) and a second set of two sorbent traps to collect elemental mercury (Hg^0). Unfortunately, the samples collected showed evidence of oxidized mercury breakthrough to the second set of traps in the sampler. Thus, the measured levels of oxidized forms of mercury should be considered suspect and regarded as minimum values. The percentage of the total mercury reported for each species was:

Ionic mercury (Hg^{2+})	Greater than or equal to 45%
Methyl mercury	Greater than or equal to 9%
Elemental mercury	Less than or equal to 47%

Sampling at the ESP outlet, which showed no breakthrough problems, measured much lower elemental mercury levels. The sampling problem encountered limits the conclusions that can be drawn regarding the effects of the SNRB™ system on the various mercury species present in the flue gas.

After the conclusion of the project, Bloom discovered the data reported as methyl mercury in this and other coal flue gas sampling projects was a laboratory artifact. The methyl mercury data was likely to be predominantly Hg^{2+}. Thus methyl mercury is likely to be much less than 9% of the total. This is an important finding because methyl mercury is considered to be the species with the highest health risk factor.

The total mercury emissions measured by the Bloom method, which were not affected by the sorbent breakthrough or laboratory artifact, averaged 8.2 +/- 1.2 ug/dscm at the SNRB™ system outlet. This can be compared to the total mercury measured by Method 29 which averaged 12.8 ug/dscm. The total mercury emissions calculated from the mercury speciation measurements showed a higher variation than found with the Method 29 measurements.

7.5.6 Polynuclear Aromatic Hydrocarbons

Emissions factors for polycyclic aromatic hydrocarbons (PAH) exiting SNRB™ are presented in Table 7-7. Note that the PAH results are given in units of pounds per 10^{15} Btu. The field blank levels of PAH showed 25-50 percent of the levels (reported as ng/dscm) of the actual emissions measured. Therefore the emissions factors in Table 7-7 are likely to be biased high.

7.5.7 Volatile Organic Compounds (VOCs)

The average concentration of VOCs measured at the SNRB™ baghouse outlet are summarized in Table 7-8. Note that the emissions factors are reported in lb/10^{12} Btu. Approximately 81% of the 78 total measurements on these flue gas samples indicated non-detectable levels of the analyte in the sample.

The average benzene and toluene levels at the SNRB™ baghouse outlet were 4.9 and 4.0 parts per billion, respectively. The field blank levels were close to these levels measured in the flue gas samples. The benzene and toluene emission levels were within the emission range of 0.5 - 10 micrograms/m^3 determined in the EPRI PISCES program.

7.5.8 Polychlorinated Dioxins and Dibenzofurans

The emission factors for dioxins and furans are presented in Table 7-9. Note that the emissions are reported in lb/10^{18} Btu.

The polychlorinated dioxin and dibenzofuran results appear problematic. The results for three samples at a given location varied by 2 to 3 orders of magnitude. Very low internal standards recoveries for several samples (less than 50% recovery and sometime less than 1% recovery) suggest the SNRB™ system inlet data are suspect. The data for run 2 in Table 7-9 is very unusual. The levels reported are higher than conventional wisdom would suggest for coal-fired boiler emissions. These data should be compared to results at other power plants to determine if the emission factors determined are representative.

TABLE 7-7 AVERAGE PAH EMISSIONS FACTORS AT SNRB™ OUTLET		
PAH	OUTLET EMISSIONS [lb/10^{15} Btu]	STANDARD DEVIATION [lb/10^{15} Btu]
Naphthalene	201.6	177.0
2-Methylnaphthalene	14.7	17.4
1-Methylnaphthalene	8.0	9.7
Biphenyl	10.4	5.5
Acenapthylene	2.4	1.0
Acenaphthene	8.1	13.0
Fluorene	59.5	41.5
Phenathrene	117.1	134.4
Anthracene	7.8	4.7
Fluoranthene	59.3	69.9
Pyrene	22.0	29.2
Benzo[a]anthracene	4.7	2.8
Chysene	11.9	1.9
Benzofluoranthenes	16.3	5.9
Benzo[e]pyrene	6.7	4.7
Benzo[a]pyrene	8.0	3.3
Indeno[1,2,3-c,d]pyrene	8.7	5.2
Dibenzo[a,h]anthracene	6.5	8.9
Benzo[g,h,i]perylene	10.1	6.6

TABLE 7-8 EMISSIONS FACTORS FOR VOC EXITING SNRB™

VOC	OUTLET EMISSIONS [lb/10^{12} Btu]	STANDARD DEVIATION [lb/10^{12} Btu]
Trichlororfluoromethane	ND < 1.5	0.08
1,1-Dichloroethene	ND < 1.1	0.06
Dichloromethane	444.22 *	767.90
3-Chloropropene	8.87 *	12.20
1,1-Dichloroethane	1.16 *	0.42
1,1,2-trichloror-1,2,2-trifluoroethane cis-1,2-Dichloroethene	ND<2.1 ND < 1.1	0.11 0.06
Trichlorormethane	ND <1.3	0.07
1,2-dichloroethane	ND < 1.1	0.06
1,1,1-Trichlororethane	2.54 *	2.04
Benzene	7.19	2.88
Toluene	0.71 *	0.40
Carbon tetrachloride	ND < 1.7	0.09
Trichloroethene	ND < 1.3	0.08
cis-1,3-dichloropropene	1.99 *	1.48
trans-1,3-Dichlororpropene	1.22 *	0.07
1,1,2-trichloroethane	ND < 1.5	0.08
1,2-Dibromoethane	1.87 *	0.28
Tetrachloroethene	ND < 1.9	0.10
Chlororbenzene	ND < 1.3	0.07
m + p-Xylene	8.25 *	12.31
4-Ethyl toluene	ND < 1.4	0.07
1,3,5-Trimethylbenzene	ND < 1.4	0.07
1,2,4-Trimethylbenzene	ND < 1.4	0.07
p-Dichlororbenzene	26.66 *	43.44

* Average of these measurements includes one or more non-detect values

TABLE 7-9 EMISSIONS FACTORS FOR FURANS AND DIOXINS EXITING SNRB™

	OUTLET EMISSIONS [lb/10^{18} Btu]			AVERAGE OUTLET EMISSIONS [lb/10^{18} Btu]	STANDARD DEVIATION [lb/10^{18} Btu]
COMPOUND	RUN 1	RUN 2	RUN 3		
2378-TCDD	ND <0.56	3.86	ND <0.87	1.76	1.82
12378-PeCDD	ND <1.07	47.75	ND <1.13	16.65	26.94
123478-HxCDD	ND <0.76	114.50	ND <1.33	38.86	65.50
123678-HxCDD	ND <1.27	122.99	ND <1.18	41.81	70.30
123789-HxCDD	1.81	250.71	ND <1.74	84.76	143.72
1234678-HpCDD	ND <7.21	1487.09	8.75	501.01	853.96
OCDD	ND <12.00	3961.98	ND <12.00	1328.66	2280.52
2378-TCDF	3.04	111.56	2.67	39.09	62.76
12378-PeCDF	ND <2.49	91.24	ND <1.23	31.66	51.61
23478-PeCDF	1.93	122.47	1.40	58.60	98.61
123478-HxCDF	9.85	2899.78	3.44	3.44	NC
123678-HxCDF	ND <3.86	443.24	1.16	1.16	NC
123789-HxCDF	3.41	621.00	2.40	208.93	356.86
234678-HxCDF	ND <0.61	38.75	ND <0.92	13.43	21.93
1234678-HpCDF	ND <30.97	3225.68	ND <41.51	1116.06	1870.30
1234789-HpCDF	ND <1.88	442.88	1.71	148.82	254.66
OCDF	5.10	1974.98	4.98	661.69	1137.34
Total TCDD	ND <0.56	28.51	ND <0.87	9.98	16.05
Total PeCDD	ND <1.07	177.67	ND <1.13	59.96	101.94
Total HxCDD	1.81	923.36	ND <1.33	308.84	532.20
Total HpCDD	ND <7.21	2616.40	14.44	879.35	1504.33
Total TCDF	9.27	232.33	8.30	83.30	129.06
Total PeCDF	1.93	796.44	2.76	267.04	458.47
Total HxCDF	13.25	6616.14	7.00	2212.13	3813.99
Total HpCDF	ND <30.97	4506.02	4.32	1513.77	2591.40

ND: Value below detection limit.

NC: Not Calculated.

Field spikes, a part of Method 23, were not employed and the Method 23 extraction solvent, toluene, was not used. It is not known if these modifications affected the results. The reason for the modifications of the Method 23 procedure was to allow the simultaneous PAH measurements. For the same sampling locations, the PAH results varied by an order of magnitude. The dioxins and dibenzofurans measurements varied by 3 to 4 orders of magnitude.

7.5.9 Carbonyls

No formaldehyde or carbonyls were detected at detection limits of 0.03 to 0.3 micrograms per dry standard cubic meter.

7.5.10 Radionuclides

Radionuclide analysis was performed on the coal samples and the solids collected in the filters of the EPA Method 26A sampling trains at the SNRB™ baghouse outlet (location 7) and on the filter solids collected during EPA method 5 sampling at the SNRB™ baghouse inlet (location 5). The results are summarized in Table 7-10. The results were not corrected for filter reagent or Method 26A train blanks.

For these analysis, Pb^{210} and U^{238} were detected in the samples at similar levels detected in the filter reagent blank and the Method 26A train blanks. Battelle judged that the flue gas emission measurements were suspect. The results were generally two orders of magnitude higher than emissions expected based on analysis of the coal samples.

TABLE 7-10 RADIONUCLIDES DETECTED IN SNRB™ GAS AND SOLID SAMPLES

Analyte	Coal Feed			SNRB™ Inlet			SNRB™ Outlet		
Sample	1	2	3	1	2	3	1	2	3
Pb^{210}	0.437	<0.43	<0.50	<213.76	<264.62	<241.80	79.15	74.44	111.17
Ra^{226}	0.226	0.28	0.292	<19.09	21.75	<31.87	<5.96	<6.28	<5.83
Ra^{228}	0. 226	0.225	0.249	<48.10	<45.48	<61.55	<13.27	<11.21	<13.11
Th^{230}	<4.0	<3.9	<4.0	<1068.80	<1075.04	<1428.83	<265.40	<287.00	<296.12
U^{234}	<13	<13	<13	<4046.18	<4630.94	<5715.30	<1232.23	<1121.05	<1165.05
U^{235}	<0.15	<0.14	<0.18	<41.23	<42.17	<52.76	<11.37	<12.11	<11.65
U^{238}	0.493	<0.57	0.377	342.78	310.93	496.79	104.27	95.96	85.44

Coal feed results in pCi/gm, other samples are in pCi/dscm.

7.6 HAP EMISSIONS CONTROL SUMMARY

The SNRB™ air toxics emissions test program was a very comprehensive attempt to measure the emissions control potential of several categories of hazardous air pollutants. Simultaneous inlet/outlet measurements for two control devices and non-standard temperature and particulate loading conditions further complicated the test program. Some difficulties were encountered in obtaining consistent samples of the trace emissions of selected compounds.

Key conclusions from the air toxics emissions test program include:

- Capture efficiencies for all metals except mercury generally averaged over 95%: Metal emission factors were within the range of values reported in the literature for coal-fired power plants.

- The SNRB™ system did not reduce mercury emissions.

- Injection of the hydrated lime sorbent for SO_2 emission control also resulted in high efficiency chloride emissions reduction (91- 97%) and significant reduction in fluoride emissions (53 - 100%).

- The emission rates for volatile organic compounds and polycyclic aromatic hydrocarbons were very low for both the ESP and SNRB™.

- Measurements of radionuclide and dioxin/dibenzofuran emissions generated inconsistent results. The radionuclide measurements are not consistent with the coal analysis. These trace emission measurements were generally close to the method measurement detection limits.