

DOE/NETL-2000/1125

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**SNOX<sup>TM</sup> Flue Gas Cleaning Demonstration  
Project: A DOE Assessment**

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**June 2000**

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## TABLE OF CONTENTS

<b>I.</b>	<b>Introduction</b> .....	8
<b>II.</b>	<b>Technical and Environmental Assessment</b> .....	10
	A. Promise of the Technology.....	10
	B. Process Description .....	13
	C. Project Objectives/Results .....	15
	D. Environmental Performance .....	16
	E. Post-Demonstration Achievements .....	17
<b>III.</b>	<b>Operating Capabilities Demonstrated</b> .....	18
	A. Size and Type of Unit Demonstrated .....	18
	B. Performance Level Demonstrated .....	19
	NO <sub>x</sub> -Emissions Reduction .....	21
	SO <sub>2</sub> -Emissions Reduction.....	21
	Particulates Emissions Reduction.....	21
	Other Emissions Reduction.....	22
	By-Products Quality and Quantities Produced.....	22
	Contributions to CCT Program.....	22
	C. Major Operating and Design Variables Studied.....	23
	Parametric Studies.....	23
	Design, Equipment and Operating Changes .....	25
	D. Boiler Impacts.....	26
	E. Commercialization of the Technology.....	28
	Current Status .....	28
	Future Work.....	30
<b>IV.</b>	<b>Market Analysis</b> .....	31
	A. Potential Markets .....	31
	B. Economic Assessment for Utility Boiler Applications.....	32
	SNOX <sup>TM</sup> Costs.....	32
	Comparison with Other Technologies .....	35
<b>V.</b>	<b>Conclusions</b> .....	36
<b>VI.</b>	<b>References</b> .....	38

## EXECUTIVE SUMMARY

This document is a U.S. Department of Energy (DOE) post-project assessment of a project funded in Round 2 of the Clean Coal Technology (CCT) program, the SNOX<sup>TM</sup> Flue Gas Cleaning Demonstration Project. In December 1989, Asea Brown Boveri Environmental Systems (ABBES) entered into an agreement with DOE to conduct this study and to jointly fund the project, with Ohio Edison as the host and cosponsor. Additional funding was provided by the Ohio Coal Development Office and Snamprogetti USA, Inc. Haldor Topsoe A/S is the owner of the applicable patents and provided the technology. DOE provided 50% of the total project funding. The demonstration was conducted over a 33-month period from March 1992 to December 1994. After the operations demonstration and testing were completed, an economic evaluation of a commercial-scale SNOX<sup>TM</sup> plant was performed.

One of the major thrusts of the CCT program is to develop and demonstrate a suite of technology options for reducing the emissions of acid rain precursors that result from utility and industrial combustion of coal. These options include several different processes for reducing sulfur dioxide (SO<sub>2</sub>) or nitrogen oxide (NO<sub>x</sub>) content of flue gas. The SNOX<sup>TM</sup> process is particularly well-suited to the maximum reduction of both SO<sub>2</sub> and NO<sub>x</sub> and, as a side benefit, further reduces particulate emissions.

The SNOX<sup>TM</sup> process involves catalytic reduction of NO<sub>x</sub> in the presence of ammonia (NH<sub>3</sub>), followed by catalytic oxidation of SO<sub>2</sub> to SO<sub>3</sub>. The exit gas from the SO<sub>3</sub> converter passes through a novel glass-tube condenser in which the SO<sub>3</sub> is hydrated to H<sub>2</sub>SO<sub>4</sub> vapor and then condensed to a concentrated liquid sulfuric acid (H<sub>2</sub>SO<sub>4</sub>). Before entering the SNOX<sup>TM</sup> system, most of the fly ash is removed from the flue gas, leaving the boiler in a high-efficiency, fabric filter baghouse to minimize the cleaning frequency of the catalysts in the two downstream conversion processes. The SNOX<sup>TM</sup> process removes virtually all of the remaining fine particulates by capture on the catalyst or in the condensation of H<sub>2</sub>SO<sub>4</sub>.

Haldor Topsoe developed and commercialized this process in Europe and Asia. That development included the patented technologies, catalysts, and Wet-Gas Sulfuric Acid (WSA) condenser tower, the technology base for this project. Several CCT projects have used selective catalytic reduction (SCR) to remove NO<sub>x</sub>, and Haldor Topsoe had developed catalysts for that process. However, these technologies had not been demonstrated in an integrated process, nor had they been applied to coal-fired utility operations in the United States with locally available coals. In this project, ABBES and Haldor Topsoe combined their SO<sub>2</sub>-removal experience with the NO<sub>x</sub>-removal capabilities of SCR to demonstrate the improved technical performance and cost efficiency resulting from the synergy of integrating these traditionally separate flue-gas-cleaning processes.

The performance objectives of this project were:

- To demonstrate SO<sub>2</sub>-removal efficiency greater than 95%.
- To demonstrate NO<sub>x</sub>-removal efficiency greater than 90%.
- To demonstrate the commercial quality of the by-product H<sub>2</sub>SO<sub>4</sub>.
- To satisfy all Environmental Monitoring Plan requirements.
- To perform a technical and economic characterization of the technology.

All of these goals were met or exceeded in the demonstration project, which was conducted at Ohio Edison's Niles Station Unit No. 2 located in Niles, Ohio. The SNOX<sup>TM</sup> demonstration unit used a slipstream equivalent to 35 MWe of electric power.

During the demonstration project, the boiler was fired with an Ohio bituminous coal having an average sulfur content of 2.9%. SO<sub>2</sub>-removal efficiencies greater than 95% were achieved, reducing SO<sub>2</sub> to about 0.25 lb/10<sup>6</sup> Btu, well below the Clean Air Act Amendments (CAAA) Phase II requirement of 1.2 lb/10<sup>6</sup> Btu. The concentration of H<sub>2</sub>SO<sub>4</sub> produced was consistently in excess of

the specification of 93.2%, typically 94.7%, and the product met or exceeded all government specifications for impurity limitations.

NO<sub>x</sub> removals >90% were realized over a broad range of catalyst temperatures. Stack gas NO<sub>x</sub> concentrations were <0.10 lb/10<sup>6</sup> Btu, considerably below the Phase II CAAA requirement of 0.86 lb/10<sup>6</sup> Btu for cyclone boilers. With NO<sub>x</sub> removal located upstream of the SO<sub>2</sub>-removal step, it was possible to operate with high levels of NH<sub>3</sub> injection to achieve high conversion of NO<sub>x</sub>, with excess NH<sub>3</sub> destroyed in the SO<sub>2</sub>-conversion step.

Using a baghouse to clean particulates from the flue gas before entering the SNOX<sup>TM</sup> catalyst system minimizes catalyst loading and plugging; the SNOX<sup>TM</sup> system removes the remaining particulates to a very low concentration without extensive catalyst screening and cleaning. Particulate emissions downstream of the baghouse were <0.02 lb/10<sup>6</sup> Btu, representing an average collection efficiency of 98.5%, and the remaining particulates were further reduced through the SNOX<sup>TM</sup> system to about 0.013 lb/10<sup>6</sup> Btu, or a total system particulate removal over 99%. The acid condenser and mist eliminators reduce the potential for acid emissions to nearly zero and the storage, transport, and handling issues with ammonia and sulfuric acid are addressed by practices that are no different than typically used by other users of these materials.

Economics have been developed for a retrofit SNOX<sup>TM</sup> unit with 95% reduction in SO<sub>2</sub> emissions and 90% reduction in NO<sub>x</sub> emissions. At a power plant capacity of 500 MWe using a 3.2% sulfur Ohio bituminous coal, the estimated capital cost is \$305/kW. For a 15-year project life, the levelized cost on a current dollar basis is 7.8 mills/kWh. This is equivalent to \$256/ton of SO<sub>2</sub> + NO<sub>x</sub> removed. On a constant dollar basis, the levelized cost is 6.1 mills/kWh, equivalent to \$198/ton removed. Credits for sale of acid and heat recovery are included in the operating costs.

The capability of the SNOX<sup>TM</sup> process to reduce the SO<sub>2</sub> and NO<sub>x</sub> content of the flue gas from coal-fired utility and industrial boilers to well below the levels required to meet both the current and projected standards for emissions controls represents a significant advantage where emissions constraints are very stringent and where credits can be taken for reductions beyond those required. Despite the technical success of the demonstration, the regulatory constraints on emissions of SO<sub>2</sub> and NO<sub>x</sub> combined are not as yet sufficiently compelling as to make necessary the commercial use of the SNOX<sup>TM</sup> process at the present time. Other means of meeting regulations are currently adequate. The superior emissions-reduction capability of the SNOX<sup>TM</sup> process will be available for future applications and requirements.

## I. INTRODUCTION

The goal of the U.S. Department of Energy (DOE) Clean Coal Technology (CCT) Program is to provide the energy marketplace with a suite of advanced, cost-effective, highly efficient, and environmentally responsible coal-utilization technologies through cooperatively implementing a series of demonstration projects with industry stakeholders. These projects seek to establish at scale the commercial viability of the most promising advanced coal technologies that have developed beyond the proof-of-concept stage.

This document serves as DOE's post-project assessment of a project selected in CCT Round 2, "SNOX™ Flue Gas Cleaning Demonstration Project," as described in a Report to Congress [1]. In December 1989, Asea Brown Boveri Environmental Systems (ABBES) entered into a cooperative agreement to conduct the study. Ohio Edison was the host and cosponsor, with additional cofunding provided by the Ohio Coal Development Office and Snamprogetti USA, Inc. DOE provided 50% of the total project funding of \$31.4 million. DOE's participation in this project through Cooperative Agreement No. DE-FC22-90PC89655 is consistent with Public Law 100-202 as amended by Public Law 100-446.

The demonstration was started in March 1992 and was completed in December 1994. The independent evaluation contained herein is based primarily on information from ABBES's Final Report, Volume II: Project Performance and Economics, dated July 1996 [9], as well as other references cited.

The SNOX™ process is a combination of catalytic processes that remove sulfur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>) and residual particulate matter (PM) from flue gas that has been pre-cleaned with particulate removal. The process generates salable sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) meeting an industry wide standard (U.S. Government Specification O-S-801E) from the SO<sub>2</sub> and converts the NO<sub>x</sub> to harmless nitrogen and water vapor. The integrated design of the process enables high-pollutant-removal efficiencies, no significant waste production (only very low quantities of flue gas ash and



catalyst degradation fines), and significant heat recovery potential that can be used in the commercial application of the technology to attain increased thermal efficiency of the system.

The host site chosen for this CCT demonstration project was Ohio Edison's Niles Station located along the Mahoning River in Niles, Ohio, just northwest of Youngstown. There are two cyclone coal-fired, steam electricity-generating units at the plant.

The performance objectives of this project were as follows:

- To demonstrate SO<sub>2</sub>-removal efficiency greater than 95%.
- To demonstrate NO<sub>x</sub>-removal efficiency greater than 90%.
- To demonstrate the commercial quality of the by-product H<sub>2</sub>SO<sub>4</sub>.
- To satisfy all Environmental Monitoring Plan requirements.
- To perform a technical and economic characterization of the technology.

## II. TECHNICAL AND ENVIRONMENTAL ASSESSMENT

### II.A Promise of the Technology

This project was undertaken to evaluate the technical and economic feasibility of using the SNOX<sup>TM</sup> process to concurrently reduce emissions of SO<sub>2</sub> and NO<sub>x</sub> from coal-fired boilers. Within the integrated SNOX<sup>TM</sup> process, the first step is NO<sub>x</sub> removal by selective catalytic reduction (SCR), using ammonia (NH<sub>3</sub>) as the reagent. This is followed by catalytic conversion of SO<sub>2</sub> in the flue gas to sulfur trioxide (SO<sub>3</sub>), hydration to sulfuric acid in the vapor phase, and condensation in a Wet-Gas Sulfuric Acid (WSA) tower to provide high-quality liquid H<sub>2</sub>SO<sub>4</sub>.

To reduce the dust loading on the two catalysts, particulates in the flue gas are removed by conventional processes prior to the SNOX<sup>TM</sup> process. Existing particulate-collection devices may be reused if suitable. In the SNOX<sup>TM</sup> demonstration unit, a new high-efficiency fabric-filter baghouse was installed. Residual fine particulates are removed in the catalyst beds and the condensation step.

There is a potentially important benefit of this residual fine particle collection. Not only is there more complete removal of particulate matter, which exceeds the requirements of the PM<sub>10</sub> standard (particles greater than 10 microns in diameter), but the condensation of acid on super-fine particles and removal of such with the liquid acid product will be a significant aid in meeting the more stringent PM<sub>2.5</sub> standards (particles greater than 2.5 microns diameter).

The sequential combination of these functions improves the overall pollutant-reduction efficiencies, and is one of the novel attributes of the SNOX<sup>TM</sup> process. Another innovative aspect is that the SO<sub>2</sub> is converted into salable H<sub>2</sub>SO<sub>4</sub>, so there is no waste discharge during normal operations. Periodic screening to remove deteriorated catalyst and fines trapped in the catalyst beds will be required during routine scheduled maintenance outages.

In other CCT projects, SCR has been demonstrated to be a highly effective technology for catalytic removal of  $\text{NO}_x$  from flue gas. Although there is no theoretical limit to the degree of  $\text{NO}_x$  removal that can be achieved in the SCR process, problems associated with precise control of the  $\text{NH}_3/\text{NO}_x$  ratio and the need to avoid downstream by-products of  $\text{NH}_3$  and  $\text{SO}_3$  typically constrain performance to about 90% removal. The excess  $\text{NH}_3$ , called ammonia slip, generally occurs at higher levels of  $\text{NH}_3$  injection and with insufficiently precise control of injection and/or mixing. However, in the  $\text{SNOX}^{\text{TM}}$  process, the excess  $\text{NH}_3$  and  $\text{SO}_3$  generated are consumed in the  $\text{SO}_2$  converter unit. As configured in the  $\text{SNOX}^{\text{TM}}$  process with the catalytic  $\text{SO}_2$  converter downstream, a higher  $\text{NH}_3/\text{NO}_x$  ratio (close to the stoichiometric molar ratio of one) can be used and  $\text{NO}_x$  removal in excess of 90% can be achieved, without the potential for adverse conditions downstream.

Similarly, the high degree of particulate removal before the flue gas enters the  $\text{SNOX}^{\text{TM}}$  unit avoids excessive plugging and contamination of the catalyst's surfaces, enabling this process to achieve and maintain  $\text{SO}_2$  removal at 95%. Therefore, the  $\text{SNOX}^{\text{TM}}$  process capitalizes on technology demonstrated in other projects of the CCT Program to improve the effectiveness of the individual steps in the process and achieve greater pollutant-removal levels. In doing so, the  $\text{SNOX}^{\text{TM}}$  project extends and expands pollutant-removal capabilities demonstrated in separate CCT projects.

The key technological advances used in this process have been developed and demonstrated in Japan, Europe, and other projects in the United States. Haldor Topsoe has developed the sulfur capture and conversion-to- $\text{H}_2\text{SO}_4$  technologies, including the WSA tower, and has developed catalysts for both the  $\text{SO}_2$  conversion and SCR processes. The SCR process has been used in a number of configurations in other CCT projects. With each of the process steps already demonstrated separately, this project enables a demonstration of the effectiveness of integrating these several technologies and applying the process to flue gas cleaning in U.S. utilities using U.S. coals.

The  $\text{SNOX}^{\text{TM}}$  process incorporates a novel configuration of  $\text{NO}_x$ - and  $\text{SO}_2$ -removal steps to avoid the downstream negative effects of excess  $\text{NH}_3$  and  $\text{SO}_3$  and to capture the synergy of these steps. Because these catalytic processes are highly effective in reducing  $\text{NO}_x$  and  $\text{SO}_2$ , the  $\text{SNOX}^{\text{TM}}$

technology is well-suited to meet more stringent pollutant-control levels for flue gas cleaning, such as the CAAA Title IV Phase II standards. A SNOX<sup>TM</sup> process installation consists largely of proved, commercially available equipment; thus, the process can be used commercially without incurring major risks. While safe storage and transport of ammonia and sulfuric acid are of general concern, handling these two materials for the SNOX<sup>TM</sup> process is no different than that followed by other users or producers of ammonia or sulfuric acid. Furthermore, careful plant design following usual chemical plant practices avoids equipment deterioration caused by excessive acid, and provides mist elimination. This was an important part of this demonstration project.

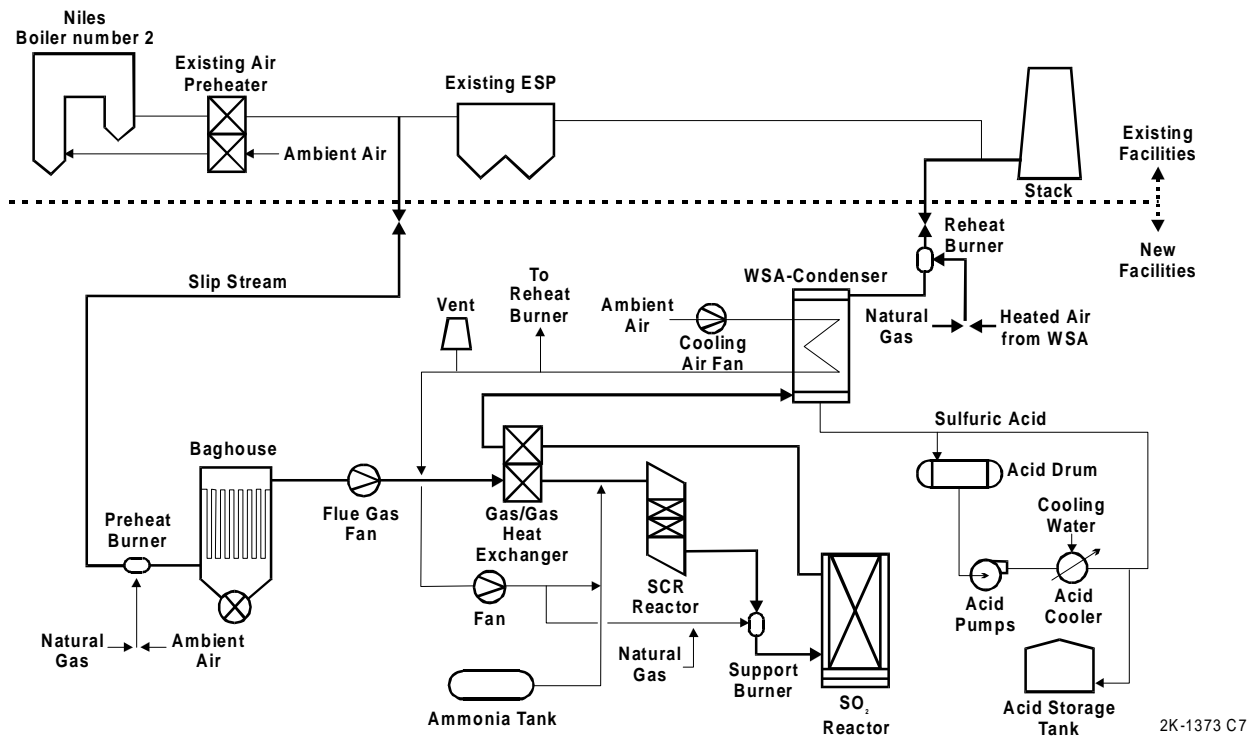
The SNOX<sup>TM</sup> process combines NO<sub>x</sub>, SO<sub>2</sub> and enhanced particulate-matter removal. The system has the potential for reducing these emissions while lowering fuel usage, improving station heat rate through heat recovery, and producing a marketable by-product, sulfuric acid. Since this process sees only the flue gas, the SNOX<sup>TM</sup> technology is applicable to all electric power plants and industrial and institutional boilers no matter what fuel is fired as long as NO<sub>x</sub> and SO<sub>2</sub> are to be removed. The only limitation is that more space is needed compared to a typical WFGD or SCR unit. Also, the space is needed near the boiler flue duct so that the flue gas can be economically transported to the SNOX<sup>TM</sup> unit, processed, and returned to the stack.

Continued development work and initial commercial applications by the technology developer, Haldor-Topsoe, at a number of locations around the world have brought the technology to a stage of readiness for use in coal-fired utility applications in the United States. The demonstration illustrated that the technology is ready when the market demand arises, and the regulatory environment requires this level of flue gas treatment.

## II.B Process Description

The SNOX<sup>TM</sup> process schematic for the demonstration project is shown in Figure 1. A flue gas slipstream equivalent to 35 MWe was taken from one of the two 108-MWe boilers at the Niles Station. The particulates were significantly reduced in a conventional pulse-jet baghouse fitted with high-efficiency bags. The flue gas was then sent to the SCR unit for NO<sub>x</sub> removal - the first step of the SNOX<sup>TM</sup> process. In the SCR unit, ammonia is injected into the flue gas to enable reaction with

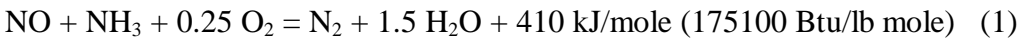
**Figure 1: SNOX<sup>TM</sup> Process Schematic**



NO<sub>x</sub> over a catalyst to produce nitrogen and water vapor. SO<sub>2</sub> removal is accomplished by catalytic oxidation to SO<sub>3</sub>, followed by hydration to H<sub>2</sub>SO<sub>4</sub> in the vapor state and then condensation to produce a high-quality, commercial-grade acid.

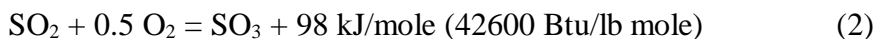
Prior to the SNOX<sup>TM</sup> unit in the demonstration plant, the flue gas is cleaned in a high efficiency fabric filter, removing most of the particulate matter. In commercial applications, it is possible to consider other particulate-removal technologies, such as an electrostatic precipitator (ESP) and consider the trade-off of cost versus the accumulation of dust in the SNOX<sup>TM</sup> system (catalyst beds and acid condensation).

The filtered flue gas is heated to the SCR reaction temperature (730°F) in a gas/gas heat exchanger. Then in the SCR reactor, nitrogen oxides are selectively reduced with ammonia to elemental nitrogen on a Haldor Topsoe DNX catalyst. This catalyst is a monolithic titanium dioxide-based catalyst with high tolerance to both thermal shock and dust. The reduction follows Equation 1.



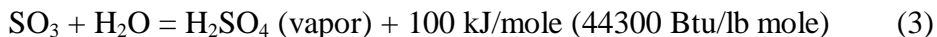
In this equation, NO is taken to represent NO<sub>x</sub>. The small amount of NO<sub>2</sub> present in the flue gas is similarly reduced.

The gas leaving the SCR reactor, containing residual ammonia and minimal residual fine particulates, is reheated with natural gas, oil, or steam to reach the optimum SO<sub>2</sub> converter inlet temperature (780°F). In the converter, filled with Haldor Topsoe VK-WSA catalyst, SO<sub>2</sub> is oxidized to SO<sub>3</sub>. Without any reagents or additives, over 95% of the entering SO<sub>2</sub> is oxidized via Equation 2.



In addition, unburned hydrocarbons in the flue gas and ammonia slip from the SCR reactor are completely oxidized. This allows high NO<sub>x</sub> removal with high SCR space velocities, without the risk of downstream ammonium salt scaling. The well-known Haldor Topsoe VK-series catalysts have been successfully used in more than 250 sulfuric acid plants worldwide over the past two decades.

Flue gas leaving the hot side of the gas/gas heat exchanger is further cooled to about 210°F in the WSA condenser. During cooling, SO<sub>3</sub> and water react exothermically to form H<sub>2</sub>SO<sub>4</sub>, which condenses and is collected as concentrated acid. The acid formation reaction is shown in Equation 3 and the condensation is described by Equation 4.



The proprietary WSA condenser is in principle an air-cooled multi-tube falling film heat exchanger. The tubes are made of borosilicate glass, and other acid-wetted parts are either constructed of or lined with acid-proof materials such as acid brick and fluoropolymers. Cooling air leaving the condenser can be integrated with the boiler as preheated combustion air to significantly offset flue gas cleaning system operating costs.

## II.C Project Objectives/Results

The goal of this project was to demonstrate SNOX<sup>TM</sup> retrofit technology for reducing SO<sub>2</sub>, NO<sub>x</sub>, and particulate emissions from coal-fired utility boilers. The project was designed to confirm pilot scale results and to develop scale-up procedures necessary for commercial application of the technology, as well as to resolve those technical issues that could not be adequately addressed in an engineering study or pilot-scale tests.

The 1970 Clean Air Act established New Source Performance Standards (NSPS) for emissions of SO<sub>2</sub>, NO<sub>x</sub>, and particulates, among other pollutants, from stationary coal-fired power plants. These regulations were made more stringent in the Clean Air Act Amendments (CAAA) of 1990.

A specific objective of the SNOX<sup>TM</sup> project was to demonstrate SO<sub>2</sub>, NO<sub>x</sub> and particulate removal during extended operation with fully-integrated, commercial-sized components to meet the following targets:

- Demonstrate SO<sub>2</sub>-removal efficiency greater than 95%.
- Demonstrate NO<sub>x</sub>-removal efficiency greater than 90%.
- Demonstrate the commercial quality of the by-product H<sub>2</sub>SO<sub>4</sub>.
- Satisfy all Environmental Monitoring Plan requirements.
- Perform a technical and economic characterization of the technology.

All of the performance targets were met or exceeded during the test program. SO<sub>2</sub>-removal efficiency was greater than 95%, NO<sub>x</sub> removal was about 93%, and particulate emissions were reduced to less than 0.015 lb/10<sup>6</sup> Btu. The process typically produced H<sub>2</sub>SO<sub>4</sub> at a concentration of 94.7% as compared with a specification value of 93.2%.

#### II.D Environmental Performance

The primary incentives for the CCT Program and for this demonstration project in particular are to reduce pollution and demonstrate technologies that enable coal to be used in an environmentally acceptable manner. Thus, the environmental performance is a primary measure of the accomplishments of the project. The SNOX<sup>TM</sup> demonstration project addressed the removal of NO<sub>x</sub>, SO<sub>2</sub>, and particulates from flue gas. The project targets for removal of pollutants were very ambitious, greater than 95% for SO<sub>2</sub> and greater than 90% for NO<sub>x</sub>, and were intended to provide a technology option with a high degree of simultaneous pollutant removal. The process was



conceived, integrated, and designed to achieve these targets with minimal creation of secondary waste streams. The demonstration achieved and exceeded all of those target objectives.

In the commercial application of this process, the hot air discharge from the WSA condenser can be used as preheated combustion air to the boiler. The recovered thermal energy increases the plant's efficiency, resulting in a reduced coal-feed rate or higher electricity production. In addition to the economic advantage of heat recovery, an increase in plant thermal efficiency results in decreased emissions per MW generated. This capability was not demonstrated in the SNOX<sup>TM</sup> project.

Emissions reductions are achieved without producing additional solid or slurry wastes. The spent catalyst and the small quantities of catalyst collected from the siftings in the cleaning of the catalyst beds will be returned to the manufacturer for recycling, or sent to a reclamation facility for metal recovery. Compared to other processes, the SNOX<sup>TM</sup> process has the advantage of not requiring additional land for settling ponds, solid-waste storage, or landfills. Furthermore, the storage tank area for the NH<sub>3</sub> reagent and for the product acid is less than the storage area needed for limestone or other solid reagents. The environmental impact on land quality is considered to be neutral.

The potential for emissions of acid mist is minimized by the design of the WSA tower condenser and the installation of individual acid-mist eliminators on each tube. Sulfuric acid mist is controlled to < 5 ppm.

## II.E Post-Demonstration Achievements

The major activity since completion of the demonstration project has been the development of a marketing strategy, as discussed in subsequent sections. A team including ABB and Snamprogetti USA has been selected to market the SNOX<sup>TM</sup> technology. An eight-state region consisting of Pennsylvania, West Virginia, Kentucky, Ohio, Tennessee, Missouri, Illinois, and Indiana represents approximately 128 GWe of existing coal-fired electric stations that are potentially suited for conversion to the SNOX<sup>TM</sup> technology. This area is the initial focus for commercialization.

### III. OPERATING CAPABILITIES DEMONSTRATED

#### III.A Size and Type of Unit Demonstrated

The demonstration project was conducted at Ohio Edison's Niles Station, using a slipstream of flue gas from Boiler No. 2, which is a 108-MWe cyclone-fired boiler. The boiler fires high-sulfur bituminous coal from Ohio and Pennsylvania. Properties of the coal used at the Niles Station during the demonstration are summarized in Table 1. While the feed coal to the plant was obtained from different sources over the course of the project, the composition did not vary significantly during the project.

Table 1

#### COAL ANALYSIS SUMMARY

	<b>HHV</b>	<b>Moisture</b>	<b>Ash</b>	<b>Sulfur</b>
	<b>Btu/lb</b>	<b>%</b>	<b>%</b>	<b>%</b>
<b>Monthly Averages</b>				
<b>High</b>	<b>12,201</b>	<b>9.36</b>	<b>12.48</b>	<b>3.07</b>
<b>Low</b>	<b>11,685</b>	<b>5.43</b>	<b>10.11</b>	<b>2.52</b>
<b>Annual Averages</b>				
<b>1991</b>	<b>11,862</b>	<b>6.80</b>	<b>11.79</b>	<b>2.82</b>
<b>1992</b>	<b>12,018</b>	<b>7.14</b>	<b>10.90</b>	<b>2.79</b>
<b>1993</b>	<b>11,933</b>	<b>7.36</b>	<b>11.27</b>	<b>2.66</b>
<b>1994</b>	<b>11,911</b>	<b>7.36</b>	<b>11.44</b>	<b>2.88</b>

In its usual operating configuration, flue gas from the two units at the Niles Station passes through the combustion air preheater, an existing ESP and exit via a two-flue, 393 ft tall stack. For the demonstration project, a slipstream was taken after the boiler's combustion air preheater and prior to the ESP as feed to the SNOX<sup>TM</sup> unit. The slipstream was equivalent to about 35 MWe of power generation. Although this is a relatively modest capacity, the fabric filters used in the baghouse, the catalyst beds, and the equipment used in all of the process operations were representative of full-scale commercial equipment. The chemical principles involved in NO<sub>x</sub> reduction, SO<sub>2</sub> conversion, and acid condensation are independent of plant size. Thus, the results of this demonstration project should be applicable to any member of the boiler population.

The project served to demonstrate the performance of the SNOX<sup>TM</sup> technology in the North American power-generation industry, i.e. with U.S. fuels and operating staff. Even though the technology had been fully characterized on pilot and prototype units prior to the contracting of the DOE project, the final scale-up to utility size required additional experience. Since all major components in earlier plants had been designed in a modular fashion utilizing full-scale components, scale-up would not be expected to result in any new process problems. However, achieving the correct distribution of gas through the various modules such as the SCR reactor, SO<sub>2</sub> converter, and WSA condenser remained to be demonstrated at full scale. This final scale-up experience was obtained through the DOE project. Thus, the size of this project was appropriate to the demonstration of capabilities for the U.S. utility industry.

### III.B Performance Level Demonstrated

The demonstration testing and operating activities of the SNOX<sup>TM</sup> unit occurred over a period of 33 months. The unit was continuously operated for periods of up to two months, while the typical run time was several weeks. The unit was operated for a total of 8000 hours in both full and partial load. The demonstration was primarily intended to provide operating experience. However, a series of parametric tests directed toward design improvements, risk reduction, and the technology's ability

to meet, or exceed, the target levels of emissions for NO<sub>x</sub>, SO<sub>2</sub>, and particulates over an extended period of time, was completed.

ABBES reported that the SNOX<sup>TM</sup> unit was able to consistently achieve NO<sub>x</sub> and SO<sub>2</sub> removals that met, or exceeded, target levels. SO<sub>2</sub> and NO<sub>x</sub> concentration data at the inlet and outlet locations were recorded and reported during the demonstration period. A review of the available reported data (primarily daily average data) indicates that:

- Daily average data on NO<sub>x</sub> and SO<sub>2</sub> removal were reported on 280 days out of the 33 month period from March 1992 through December 1994.
- The 95% SO<sub>2</sub>-removal target was achieved in 169 days.
- The 90% NO<sub>x</sub>-removal target was achieved in 195 days, with 93-94% removal achieved in 150 days.

On those days when performance data for the SNOX<sup>TM</sup> demonstration unit were not reported, either the host boiler unit was not operated, the SNOX<sup>TM</sup> unit was not operated, or the data recording system reported no results. Specific explanations were not provided. The data that were reported support the contention that the performance regularly met or exceeded the targets for removing NO<sub>x</sub> and SO<sub>2</sub>.

Several issues regarding the effectiveness, lifetime, and cleaning requirements of the two different catalysts were not discussed by ABBES and the data reported on the NO<sub>x</sub> and SO<sub>2</sub> removals were not sufficient to address those issues. ABBES expects that catalyst life will be about 8 to 10 years. Reported catalyst degradation data over the operating period were insufficient to confirm this. The frequency of catalyst cleaning, degradation rate, and effectiveness are important factors in determining the size of the reactor beds and the amount of catalyst needed, which in turn have a significant impact on the projected commercial economics.

## **NO<sub>x</sub> Emissions Reduction**

NO<sub>x</sub> emissions were typically reduced by 93 to 94%, exceeding the target value of 90%. The SCR unit maintained a high level of emissions reductions over an extended period. Installation of the SCR before the SO<sub>2</sub>-removal step permits the NO<sub>x</sub>-reduction system to be operated with excess NH<sub>3</sub>, which is not feasible when SCR is operated alone. Thus, the SNOX<sup>TM</sup> process can reduce NO<sub>x</sub> emissions more completely than other available post-combustion technology configurations. The currently established standard for NO<sub>x</sub> emissions for cyclone boilers under CAAA Phase II is 0.86 lb/10<sup>6</sup> Btu. The typical emissions rate for this project was about 0.11 lb/10<sup>6</sup> Btu, which is approximately 1/8 of the standard.

## **SO<sub>2</sub> Emissions Reduction**

As indicated previously, the reduction of SO<sub>2</sub> emissions in the SNOX<sup>TM</sup> technology is accomplished in two basic steps: (1) catalytic oxidation of SO<sub>2</sub> to SO<sub>3</sub>, and (2) hydration of SO<sub>3</sub> to H<sub>2</sub>SO<sub>4</sub>, which is condensed to produce a concentrated liquid acid. During the demonstration project, the catalytic oxidation efficiency in conversion of SO<sub>2</sub> to SO<sub>3</sub> was consistently >95%, leaving the gas phase SO<sub>2</sub> emissions at <0.3 lb/10<sup>6</sup> Btu. This is substantially less than the 1.2 lb/10<sup>6</sup> Btu standard. In the second step, the SO<sub>3</sub> hydration and condensation efficiency was typically >99.5%.

## **Particulate Emissions Reduction**

The SNOX<sup>TM</sup> technology can be operated in a normal ash loading flue gas environment. However, removing the fly ash prior to the two catalytic processes minimizes blinding or clogging. In addition, the frequency of catalyst cleaning and screening can be reduced, and result in cost savings. Thus, a high-efficiency fabric-filter baghouse was installed upstream of the SNOX<sup>TM</sup> process and was demonstrated to remove particulates with an efficiency of 98.6%. A large percentage of the residual particulates that pass through the baghouse are collected on the catalyst beds. The small amount of

remaining particulate matter serves as condensation nuclei in the WSA condensation tower. The resulting overall system efficiency for removal of particulates averaged 99.1%.

### **Other Emissions Reduction**

Particulate removal during this demonstration effectively reduced the discharge of trace impurities and air toxics. Emissions of air toxics and fine particles were reduced to <1% of the original flue gas content. Under separate funding, Battelle performed independent tests, which showed the removal efficiencies for this project to be >99%. [Ref. 10 as quoted in Ref. 9]

### **By-Products Quality and Quantities Produced**

The sale of the H<sub>2</sub>SO<sub>4</sub> by-product returns revenue to the project, keeping the cost of the SNOX<sup>TM</sup> technology competitive. To meet market requirements, the H<sub>2</sub>SO<sub>4</sub> must meet U.S. Specification O-S-801E. The by-product H<sub>2</sub>SO<sub>4</sub> from this project had a concentration of 94.7% as compared to the specification of 93.2%. While it was noted above that some residual particles and trace impurities were captured in the acid condensation, the acid still met, or exceeded, specifications. Although, the collection rate varied with operating conditions, about 95% of the sulfur in the flue gas was collected as H<sub>2</sub>SO<sub>4</sub> product. A total of 5600 tons of acid were produced over the demonstration period of operation of about 8000 hours.

### **Contributions to CCT Program**

To demonstrate project requirements that reduce NO<sub>x</sub> and SO<sub>2</sub>, the SNOX<sup>TM</sup> technology built upon the experience of existing SO<sub>2</sub>-capture units and the evolving SCR technology. SCR has been demonstrated to be an effective means of NO<sub>x</sub> control, but has been limited to <90% removal to avoid unacceptable levels of NH<sub>3</sub> slip and SO<sub>3</sub> formation, which can produce undesirable by-products: ammonium sulfate, (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, and ammonium bisulfate, NH<sub>4</sub>HSO<sub>4</sub>. In the SNOX<sup>TM</sup> configuration, the SO<sub>2</sub>-capture process downstream of the SCR unit effectively reacts the NH<sub>3</sub> slip into nitrogen and

water and converts the  $\text{SO}_3$  into sulfuric acid. This enables the SCR technology to be operated at the maximum  $\text{NO}_x$ -removal level. SCR's capability to achieve greater  $\text{NO}_x$ -removal percentages (>95%) was demonstrated during baseline operations. In this project, the  $\text{NH}_3/\text{NO}_x$  ratio was varied from 0.90 to 1.10, showing that essentially complete  $\text{NO}_x$  removal can be attained. This supplements the design data obtained from other CCT projects and international commercial facilities, and constitutes an important contribution to the CCT Program.

### III.C Major Operating and Design Variables Studied

#### **Parametric Studies**

- **Effect of  $\text{NH}_3/\text{NO}_x$  Ratio:** The  $\text{NH}_3/\text{NO}_x$  molar ratio at the SCR inlet was varied between 0.90 and 1.10 during each of three separate groupings of tests; all of these were performed at 100% unit load and an SCR inlet temperature of 715°F. The relationship of this ratio to  $\text{NO}_x$  reduction and residual  $\text{NH}_3$  is important to fine tune the process to achieve high levels of  $\text{NO}_x$  reduction, while avoiding potential downstream problems resulting from excess  $\text{NH}_3$ .

The data generally conformed to the expected range of removal levels of 92 to 96%, with the  $\text{NO}_x$  outlet concentration tending to decrease as the  $\text{NH}_3/\text{NO}_x$  ratio increased. Removal levels approaching the stoichiometric value were generally attained at ratios of 0.9 to 1.0. The test data clearly demonstrated the effectiveness of the process to readily exceed the target of 90%  $\text{NO}_x$  removal and to achieve nearly complete removal at higher  $\text{NH}_3/\text{NO}_x$  ratios. Although the trends are evident, the data and analysis presented by ABBES did not establish a well-defined relationship; e.g., during one of the data-collection periods, the concentration of  $\text{NO}_x$  measured at the SCR outlet was lower than stoichiometrically complete reactions could attain.

- **$\text{SO}_2$  Oxidation Across the SCR Unit:** Tests were conducted at three successive time periods to determine the amount of  $\text{SO}_2$  that is converted into  $\text{SO}_3$  in the SCR reactor. In conventional SCR applications, the amount of  $\text{SO}_2$  conversion in the SCR unit is intentionally

limited to less than 1% so as to reduce the potential for downstream formation of sulfates with attendant problems of clogging and blinding the catalyst.

In the SNOX<sup>TM</sup> configuration, higher SO<sub>2</sub> conversions in the SCR reactor are acceptable and actually contribute to the reduction of duty requirements for the SO<sub>2</sub> converter. SO<sub>2</sub> conversion in the SCR was 2.7%, 2.9%, and 3.8% in the three periods, indicating the possibility of increased SO<sub>2</sub> conversion over time. This demonstrated that even though SO<sub>2</sub> conversions were substantially higher than the conventional SCR design criterion of 1%, there were no apparent adverse effects that might be the consequence of excess SO<sub>3</sub> production in the SCR.

- **Effect of Gas Flow on Ammonia Emissions:** Tests were made at three different system loads (110%, 100%, and 75% of design) to determine the effect of flow rate on performance. At 75% and 100% flow, the measured NH<sub>3</sub> content in the system outlet was reported to be zero, while the 110% flow case showed a small amount of residual NH<sub>3</sub> content, averaging 0.8 ppmv in the tests. This indicates that, despite the reduced residence time in the SO<sub>2</sub> converter catalyst bed at the higher load flow rate, nearly complete destruction of residual NH<sub>3</sub> was achieved, with typically less than 1 ppmv of NH<sub>3</sub> escaping through the SNOX<sup>TM</sup> system.
- **Variation of SO<sub>2</sub> Converter Outlet Flow:** Flow measurements at the four outlet nozzles from the converter showed velocity variations to be within 6% of the average.
- **Variation of Gas Temperature at Inlet to SO<sub>2</sub> Converter:** The most effective use of the SO<sub>2</sub> oxidation catalyst is achieved with uniform temperature across the cross-section of the catalyst bed. Measured temperatures at each of the five inlet nozzles or ducts distributed across the flow cross-section were quite uniform, varying from 798°F to 844°F with an average of 811°F.



- **Effect of Catalyst Bed Temperature on SO<sub>2</sub> Oxidation Efficiency:** In this test sequence, the catalyst bed temperature was varied over the range of 715°F to 800°F at three different system loads (80%, 100%, and 110% of design). The results are consistent with expected trends of higher SO<sub>2</sub>-removal efficiency at higher bed temperature and lower gas flow (or lower space velocity).

### **Design, Equipment and Operating Changes**

Although the primary focus of this demonstration project was to meet the objectives of high levels of NO<sub>x</sub> and SO<sub>2</sub> removal, it is also important to use the commercial scale experience and operation over a significant time period to determine the adequacy of design features and equipment selections. Some equipment and material failures occurred that necessitated repairs and/or replacement of the following items:

- **Ammonia pump replaced:** Original diaphragm pump had loss of prime and flashing. Replaced by geared rotary pump.
- **Burners replaced:** Problems with tripping and failure to reach operating temperature led to several attempts at design fixes and finally to a redesign and replacement of the preheat and reheat burners and control system.
- **Fabric filter (PTFE) bag replaced:** Inadequate particle retention was attributed to improper operating temperatures (preheat burner problem) and the resulting acid-rich particulate caking on the bag surfaces during project start-up, leading to bag deterioration. Once the temperatures and flows were corrected, the filter bags were replaced in total and performed well during the remainder of the demonstration period.
- **Flue gas outlet duct and expansion joints replaced:** Excessive deterioration from concentrated acid droplets was corrected by relining the duct with a vinyl ester coating and replacing expansion joints with a seal air type.
- **WSA tower inlet nozzle repaired:** Flue gas leakage at the joints between acid brick and metal flanges was corrected by new materials selections.

- **Flue gas booster fan repaired:** Bearing failure was corrected by the installation of a forced oil system plus new bearings.
- **Acid-holding tank lining replaced:** Improved lining material was selected and solved an excessive-deterioration problem.
- **Electrical modifications:** Changes in electrical systems and test sensors were made as needed in the project.

The costs incurred in modifications and replacements listed above increased the installed plant cost by 4.3%. This amount would be less in subsequent installations because the changes would be incorporated from the beginning.

#### III.D Boiler Impacts

The SNOX<sup>TM</sup> demonstration project did not have a direct effect on performance of the host boiler, since it involved only post-combustion treatment of a flue gas slipstream. However, in commercial applications of SNOX<sup>TM</sup> technology, it is anticipated that significant heat recovery would be available to the boiler, which would generate additional power.

Heat addition, transfer, and recovery are of significant importance in the SNOX<sup>TM</sup> process as they influence the operating cost. The process generates recoverable heat in several ways. The reactions that take place with respect to NO<sub>x</sub> and SO<sub>2</sub> removal are exothermic and increase the temperature of the flue gas. This includes the NO<sub>x</sub>/NH<sub>3</sub> reactions, SO<sub>2</sub> oxidation, SO<sub>3</sub> + water to form gaseous sulfuric acid, and condensation of the sulfuric acid. This heat, plus supplemental heat added upstream of the SCR, is recovered in the WSA condenser cooling air discharge for use in the furnace as combustion air. Because the WSA condenser lowers the temperature of the flue gas to about 210°F (99°C) compared to the 300°F range for a typical utility plant, additional thermal energy is recovered.

The total heat available is substantial and is equivalent to about 4.1% of the boiler's total heat input without including support heat, which is added before the SCR and SO<sub>2</sub> converter. With this heat

included, the total heat available for recovery from the SNOX<sup>TM</sup> process to the boiler is about 5.9% of plant input. As a part of the economic study of this project, the amount of potentially recoverable heat generated by SNOX<sup>TM</sup> has been calculated based on a reference 500-MWe power plant. It is equivalent to 20.6 MWe of power without support heat and 29.5 MWe of power with fuel-fired support heat (using a plant net heat rate of 9478 Btu/kWh and valuing all heat sources equally independent of their temperatures). By contrast, the amount of auxiliary power required by the SNOX<sup>TM</sup> process is about 12.5 MWe for this size plant and operating parameters. For a retrofit application, the thermal energy recovered by SNOX<sup>TM</sup> can be used to reduce the coal feed rate or to produce more electricity if modifications to the boiler and generating equipment can be made easily and economically.

Heat losses in both the flue gas and hot air ducts will decrease the amount of heat that can actually be recovered. In addition, not all of the air produced by the WSA condenser can be used under all operating conditions of the boiler and SNOX<sup>TM</sup> system. Given these reductions, it is estimated that 70 to 80% of the heat generated by SNOX<sup>TM</sup> can be transferred back to the boiler. This transferred heat is available in two forms. About 40% enters the furnace as higher temperature combustion air. The other 60% enters the cycle via the SNOX<sup>TM</sup> trim cooler where boiler feed water is used as the cooling medium.

For a specific application, the actual amount of heat recovery would have to be determined based on the heat exchanger and ductwork design, and the impact on boiler operations. This heat recovery can compensate for the auxiliary power required to operate the SNOX<sup>TM</sup> unit and alleviate a potential loss of net power production. To develop a generalized estimate, ABBES assumed 70% capture of the potentially recoverable heat (5 to 10% of plant input). For the 500-MWe example power plant, the heat recovery is more than the supplemental power needed for the SNOX<sup>TM</sup> plant and, thus, provides a potential net gain that is equivalent to 8 MWe (70% of 29.5 MWe less 12.5 MWe).

### III.E Commercialization of the Technology

#### **Current Status**

No commercial installations of SNOX<sup>TM</sup> have been made to date in the United States. A number of pilot-scale test facilities and modest-scale industrial applications have successfully operated in several European and Asian countries, and a 305-MWe power plant retrofit installation in Denmark has been operating commercially for several years. Thus, commercialization has been initiated in international projects. There are several installed facilities in which removal of sulfur compounds in flue gas is accomplished with catalytic oxidation and acid-condensation components of the SNOX<sup>TM</sup> process. In addition, there are applications using the full process including the NO<sub>x</sub>-removal step, but these projects are not adequate demonstrations in the U.S. utility environment for U.S. coals that contain ash and toxics. This project provides an experience base upon which U.S. applications can be built.

Since the project's inception, technical and cost information has been requested by a number of electric utility operators. Although no sales have been made for application to major coal-fired utility power plants in the United States, utility perception of the viability of the technology has been positive and has not been a deterrent to selling the process. Visitors to the SNOX<sup>TM</sup> Demonstration Plant in Niles, Ohio, have been impressed with the system's simplicity, cleanliness, reliability, and overall particulate/NO<sub>x</sub>-/SO<sub>2</sub>-removal performance. Many interested parties have also visited the Danish 305-MWe plant and were likewise impressed with its appearance and operation. Therefore, while potential utility users have not selected the SNOX<sup>TM</sup> process at this time, it is likely that this option will rank high when the market/regulatory environment demands its use.

ABBES intends to use a team approach with ABB, working in conjunction with Snamprogetti and Halder Topsoe to market the technology in the United States. These two team members are among the most substantial companies in the world selling power systems and the only companies that have experience with this technology. For NO<sub>x</sub>-emissions reduction alone, SCR, with or without low-NO<sub>x</sub> burners, is achieving recognition as the technology of choice.

Part of the reason for lack of sales to date is related to the size of the actual market that developed in compliance with Phase I of the CAAA. This market was much smaller than predicted and, therefore, did not offer a large pool of potential flue-gas-cleaning sites. Also, because of the limited degree of NO<sub>x</sub> regulation under Phase I, utilities were not forced to select NO<sub>x</sub>-control processes with reduction capabilities exceeding those of combustion modifications, such as low-NO<sub>x</sub> burners.

There is an evolving market niche today that uses low-cost, high-sulfur, hydrocarbon emulsion fuels, such as Orimulsion, in oil-fired plants. Even with the addition of pollution-control equipment, the fuels are priced to produce competitive power rates. Typically, these are Eastern U.S. plants that have port access and are in major cities. Because of their location many are in non-attainment areas with respect to ozone (and one of its precursors, NO<sub>x</sub>). In this market segment, the process advantages (high removal of both SO<sub>2</sub> and NO<sub>x</sub>; low-land requirements; supplemental very fine particulate removal) will enhance the competitive position of SNOX<sup>TM</sup>. Market opportunities are being actively pursued for this application.

In summary, the more stringent U.S.-wide NO<sub>x</sub> regulations forthcoming under Phase II will provide an impetus for the affected utilities to examine combined NO<sub>x</sub>-/SO<sub>2</sub>-control technologies such as the SNOX<sup>TM</sup> process. Air-toxics control (along with PM<sub>10</sub> and PM<sub>2.5</sub>) is likely to be important in the near future, and the performance of the SNOX<sup>TM</sup> process in these areas will be a major selling point. The SNOX<sup>TM</sup> process is specifically designed to combine the highest levels of removal of both SO<sub>2</sub> and NO<sub>x</sub> in conjunction with conventional particulate removal. The resulting nearly complete particulate removal (especially fine particulates) adds a peripheral, but important, advantage to the very effective reductions of SO<sub>2</sub> and NO<sub>x</sub> in the flue gas, particularly as PM<sub>2.5</sub> standards are implemented.

### **Future Work**

Although commercial-scale development of SNOX<sup>TM</sup> has been completed, additional work would be required to evaluate its benefits in specific applications. The SNOX<sup>TM</sup> process is expected to reduce the net plant heat rate by recovering additional energy from the hot, clean flue gas following the baghouse. This was discussed briefly in the section on Boiler Impacts.

Heat recovery is an important component of the overall low operating cost of the system. This feature was not fully demonstrated in the Niles Station project. A gas/gas-heat exchanger was incorporated in the demonstration installation and was an important component of the operations part of the demonstration. However, it is not practical to make the necessary boiler plant modifications to enable the full integration of the heat-recovery system, particularly the use of preheated air from the SNOX<sup>TM</sup> plant as combustion air in the boiler. While integrating recovered heat into the boiler cycle has been accomplished efficiently in the Danish 305-MWe unit, other methods or concepts may need to be employed for boiler-specific applications in the United States. In addition to development in this area, capital cost reduction is always of importance and will be examined as the SNOX<sup>TM</sup> process is considered for various applications.

Utilization of the process in a "hot scheme," wherein particulate removal is accomplished at SCR and SO<sub>2</sub> reactor temperatures, is also an area requiring further development, primarily with respect to the

high-temperature particulate filtration. In this scheme, the flue gas temperature would not be lowered until the end of the SNOX<sup>TM</sup> process, and the reheat loop and associated heat exchanger would be eliminated. If successful, a decrease in capital and operating cost would be realized.

## **IV. MARKET ANALYSIS**

### IV.A Potential Markets

The SNOX<sup>TM</sup> process is potentially applicable to flue gas cleaning for all types of conventional coal-fired units including stoker, cyclone, and pulverized coal-fired boilers. Of the available options to reduce emissions, the SNOX<sup>TM</sup> process offers the greatest reduction levels for all three of the major pollutants of concern: NO<sub>x</sub>, SO<sub>2</sub>, and particulates. Therefore, its strongest market opportunities would be expected in situations where the tightest controls on emissions exist and there are nearby markets for the H<sub>2</sub>SO<sub>4</sub> by-product. Candidates might likely be found in those urban areas where the Phase I limits are already being exceeded and the greatest premium is placed on emissions reductions.

In the United States relatively few of the plants regulated under Phase I of the 1990 CAAA have installed scrubbers for SO<sub>2</sub> control. A large proportion of these plants have achieved compliance by fuel switching or by purchasing SO<sub>2</sub>-emission credits. Based on the current market price and availability for SO<sub>2</sub> allowances, scrubbing to meet Phase II emissions limits could be a viable option.

Currently, many small industrial boilers rely on the use of natural gas, thus avoiding the need for pollution-control systems. If gas becomes less available and/or more expensive, the economics would change and coal could become the fuel of choice, providing new opportunities for SNOX<sup>TM</sup>. There are currently 2400 MWe of small, industrial gas-fired boilers installed annually in the United States.

If 10% of these new sales were to switch to coal, the potential market for SNOX<sup>TM</sup> would be about 240 MWe. However, this would not likely be a market for SNOX<sup>TM</sup>. A large international power market is also developing, representing additional opportunities for SNOX<sup>TM</sup>.

The SNOX<sup>TM</sup> process is a demonstrated option for control of the two major pollutants associated with acid rain. Accordingly, this technology has the potential to significantly penetrate the large pre-NSPS boiler market for all types of boilers (cyclone, stoker and pulverized coal-fired).

Existing cyclone boilers are particularly well-matched with the SNOX<sup>TM</sup> process for early applications. Other available methods to control NO<sub>x</sub> and SO<sub>2</sub> are not as effective for use in cyclone fired boilers. Cyclone boilers produce relatively low fly ash loadings and, therefore, are not very suitable for sorbent injection. Wet scrubbing of SO<sub>2</sub> is viable, but these systems can have large space requirements, reduce power plant availability, reduce power plant electrical output, and increase spent material production. Further, low-NO<sub>x</sub> burners and overfire or concentric air additions are not compatible with the operating characteristics of the cyclone chamber. Consequently, there is a need for an alternative new technology that is efficient, economical and reliable, and that can be used in cyclone and other retrofit applications.

#### IV.B Economic Assessment of Utility Boiler Applications

##### **SNOX<sup>TM</sup> Costs**

The ABBES Final Report [9] includes an economic estimate prepared for a SNOX<sup>TM</sup> technology facility added to an existing 525-MWe (gross) power plant, having a net output of 500 MWe before the SNOX<sup>TM</sup> unit was added. The projected process incorporates improvements based on experience gained from the 35-MWe demonstration and other commercial installations already in operation in Europe. For an assumed 95% reduction in SO<sub>2</sub> emissions and 90% reduction in NO<sub>x</sub> emissions, the estimated capital cost is \$305/kW. In preparing operating cost estimates, credits were taken for sale of the H<sub>2</sub>SO<sub>4</sub> produced (@ \$25/ton) and for heat recovery from the SNOX<sup>TM</sup> process for use in the boiler system (@ \$2.00/10<sup>6</sup> Btu and with a transfer efficiency of 75%).

For a 15-year project life, the levelized cost on a current dollar basis is 7.8 mills/kWh. This is equivalent to \$256/ton of SO<sub>2</sub> + NO<sub>x</sub> removed. On a constant dollar basis, the levelized cost is 6.1 mills/kWh, equivalent to \$198/ton of SO<sub>2</sub> + NO<sub>x</sub> removed. The weight-basis ratio of SO<sub>2</sub> removed



to NO<sub>x</sub> removed is about 9:1. Using 1999 as a point of reference, SO<sub>2</sub> emissions credits are now commercially available at about \$190/ton and the NO<sub>x</sub>-emission credit program has only begun to start trading. However, the cost of the SNOX<sup>TM</sup> process is higher than current SO<sub>x</sub> options on a per-ton-removed basis. The cost of SO<sub>x</sub> and NO<sub>x</sub> credits and the necessity to meet a new level of stringent emissions regulations will require economic justification. Sales of the byproduct also have a large influence on the final cost projections. The economics are given in more detail in Table 2.

Table 2  
**Summary of Performance and Cost Data**  
 1996 Dollars

<b>Coal Properties</b>	<b>Units</b>	<b>Value</b>	
Higher Heating Value (HHV)	Btu/lb	11,900	
<b>Power Plant Attributes with Controls</b>			
Plant capacity, net	MWe	487	
Power produced, net	10 <sup>9</sup> kWh/yr	3.84	
Capacity factor	%	90.4	
Coal fed	10 <sup>6</sup> tons/yr	1.72	
<b>SO<sub>2</sub>-Emissions Control Data</b>			
Removal efficiency	%	95	
Emissions without controls	lb/10 <sup>6</sup> Btu	5.76	
Emissions with controls	lb/10 <sup>6</sup> Btu	0.29	
Amount removed	tons/yr	105,962	
<b>NO<sub>x</sub>-Emissions Control Data</b>			
Removal efficiency	%	90	
Emissions without controls	lb/10 <sup>6</sup> Btu	0.69	
Emissions with controls	lb/10 <sup>6</sup> Btu	0.07	
Amount removed	tons/yr	11,666	
<b>Total Capital Requirement</b>	<b>\$/kW</b>	<b>305</b>	
	<b>Levelization Factor<sup>a</sup></b>	<b>mills/kWh</b>	<b>\$/ton SO<sub>2</sub>+NO<sub>x</sub> removed</b>
<b>Levelized Cost, Current \$</b>			
Capital charge	0.160	6.36	208
Fixed O&M	1.314	1.08	35
Variable O&M (including credits)	1.314	0.39	13
Total		7.83	256
<b>Levelized Cost, Constant \$</b>			
Capital charge	0.124	4.93	161
Fixed O&M	1.000	0.82	27
Variable O&M (including credits)	1.000	0.30	10
Total		6.05	198

The above SNOX<sup>TM</sup> system costs were developed based on a standard set of design premises and DOE Guidelines [4]. A typical SNOX<sup>TM</sup> plant includes facilities for the following:

- selective catalytic reduction of NO<sub>x</sub>
- catalytic oxidation of SO<sub>2</sub> to SO<sub>3</sub>
- production of H<sub>2</sub>SO<sub>4</sub> in the WSA condenser
- sulfuric acid storage and loading
- ammonia storage
- SO<sub>2</sub>-catalyst screening
- balance of plant and auxiliaries

Particulate collection has not been included in the cost assessment of the SNOX<sup>TM</sup> plant because of the variability in different retrofit situations. To maintain the desired particulate content in the flue gas inlet to the SNOX<sup>TM</sup> process, the existing power plant particulate-collection system may be adequate. In some cases, it may be necessary to upgrade the existing equipment or add new units to produce a satisfactory particulate inlet for the SNOX<sup>TM</sup> plant.

For the case evaluated, it is assumed that flue gas from the boiler is taken downstream of the air preheater, treated in the SNOX<sup>TM</sup> plant, and directed to the stack. The cooling air for the WSA condenser is taken from the atmosphere by means of blowers and discharged to the boiler air preheater for combustion air. Ammonia, used to reduce NO<sub>x</sub>, is received at an ammonia off-loading station and stored in tanks. The sulfuric acid by-product is held in storage tanks until transferred to transport vessels through the acid-loading station.

The economics assume a 10-year, single-bed life for the SCR catalyst. Two beds are initially installed and a third is added after 5 years. Subsequently, one bed is removed and replaced every 5 years. Therefore, each bed is actually in service for 10 years. Yearly cost for the SO<sub>2</sub> catalyst is based on a life expectancy of 10 years and a cleaning frequency of one time per year, with a loss of 2.5% of catalyst per cleaning. These assumptions are consistent with data from extensive non-coal applications, and may be reasonable but are not supported by data from the SNOX<sup>TM</sup> demonstration project. However, they are supported by the full-scale European SNOX installations.

### **Comparison with Other Technologies**

ABBES compared SNOX<sup>TM</sup> economics with those for a combination of conventional technologies designed to achieve comparable emissions control [9]. For this comparison study, the reference technologies selected by ABBES are a typical limestone, forced oxidation wet flue gas desulfurization (WFGD) system to control SO<sub>2</sub> with SCR for the control of NO<sub>x</sub>. SNOX<sup>TM</sup> has lower capital requirements (13% less) and significantly lower operating and maintenance costs (less than 50% of the WFGD/SCR costs) for a 385-MWe plant burning 2.9% sulfur coal.

## V. CONCLUSIONS

The SNOX<sup>TM</sup> test program effectively demonstrated the high-efficiency, simultaneous removal of SO<sub>2</sub> and NO<sub>x</sub> from the flue gas of a high-sulfur coal-fired boiler, along with additional removal of particulates, potential for heat-rate improvement, and production of a high-quality, commercial-grade sulfuric acid by-product. The degree of emissions removal for SO<sub>2</sub> and NO<sub>x</sub> exceeded project goals.

As a commercially proven technology, the SNOX<sup>TM</sup> process provides a technically superior system for the simultaneous control and maximum removal of NO<sub>x</sub>, SO<sub>2</sub>, and particulates. The capital costs are competitive for high-removal, multi-pollutant control options. The modest operating cost is counter-balanced by the revenues generated from a marketable H<sub>2</sub>SO<sub>4</sub> by-product and by savings on heat recovery, making the SNOX<sup>TM</sup> technology attractive for new and retrofit applications.

In summary, the SNOX<sup>TM</sup> technology offers the following commercial advantages:

- Simultaneous removal of 95+% SO<sub>2</sub>, 90+% NO<sub>x</sub>, and 99+% particulate matter, at costs comparable with those of other technologies.
- SO<sub>2</sub> emissions rates typically less than 0.3 lb/10<sup>6</sup> Btu when firing 3-4% sulfur coal. This level of emissions readily complies with both the 1990 CAAA Phase I limit of 2.5 lb/10<sup>6</sup> Btu and the Phase II limit of 1.2 lb/10<sup>6</sup> Btu.
- NO<sub>x</sub> emissions averaging about 0.1 lb/10<sup>6</sup> Btu, which is far lower than the lowest Phase I limit of 0.45 lb/10<sup>6</sup> Btu for Group 1 boilers (tangentially fired) and the Phase II limit for cyclone boilers of 0.86 lb/10<sup>6</sup> Btu.
- Particulate emissions of 0.012 lb/10<sup>6</sup> Btu, which is significantly lower than the NSPS value of 0.03 lb/10<sup>6</sup> Btu.

- Lower overall station heat rate from integrating the SNOX<sup>TM</sup> unit with the combustion air preheat system. This occurs because recovery of the heat released in the SO<sub>2</sub>/NO<sub>x</sub> reactions and the greater thermal efficiency result from lower flue gas stack temperatures when leaving the SNOX<sup>TM</sup> process.
- No increase in solid plant wastes because SNOX<sup>TM</sup> is a non-sorbent process.
- Production of marketable sulfuric acid.

Since the SNOX<sup>TM</sup> technology sees only the flue gas, it is applicable to all electric power plants and industrial/institutional boilers no matter what fuel is fired, as long as NO<sub>x</sub> and SO<sub>2</sub> are to be removed. The only limitation is that a moderate amount of space is needed near the boiler flue duct so that the flue gas can be economically transported to the SNOX<sup>TM</sup> unit, processed, and returned to the stack.

The technology is ready for commercial application, but its use will be limited at the present time because of other lower cost means of meeting SO<sub>2</sub> regulations. The market for a combined SO<sub>2</sub>/NO<sub>x</sub> control technology like SNOX<sup>TM</sup> should develop with the more stringent NO<sub>x</sub> emissions limits required by OTAG and other state and federal organizations.

This project used design features that were built upon other CCT projects in such a way as to extend the existing body of demonstrated technologies. For example, SCR used as a stand-alone post-combustion environmental control add-on was shown in the SCR demonstration project to regularly achieve 80% removal of NO<sub>x</sub>, but removal above about 90% required a degree of control of NH<sub>3</sub>/NO<sub>x</sub> ratio not easily achieved. When integrated with the sulfur-capture technology in SNOX<sup>TM</sup>, which provides the capacity to oxidize the excess NH<sub>3</sub>, SCR can achieve essentially complete removal of NO<sub>x</sub>. The high level of particulate control may have significant application for yet-to-be-promulgated regulations of several titles of the CAAA.

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