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**SOUTHERN COMPANY SERVICES PROJECT JOINT VENTURE**

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**DEMONSTRATION OF SELECTIVE CATALYTIC  
REDUCTION FOR THE CONTROL OF NO<sub>x</sub> EMISSIONS  
FROM HIGH-SULFUR, COAL-FIRED BOILERS**



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

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**NOVEMBER 2002**

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**ENVIRONMENTAL CONTROL DEVICES**

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# SOUTHERN COMPANY SERVICES

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**Southern Company Services, Inc., provided a major impetus for adoption of SCR technology in the United States by addressing utility concerns quantitatively and in a manner directly relatable to commercial applications.**

## OVERVIEW

This project is part of the U.S. Department of Energy's (DOE) Clean Coal Technology Demonstration Program (CCTDP) established to address energy and environmental concerns related to coal use. DOE sought cost-shared partnerships with industry through five nationally competed solicitations to accelerate commercialization of the most promising advanced coal-based power generation and pollution control technologies. The CCTDP, valued at over five billion dollars, has significantly leveraged federal funding by forging effective partnerships founded on sound principles. For every federal dollar invested, CCTDP participants have invested two dollars. These participants include utilities, technology developers, state governments, and research organizations. This project is one of 16 selected from 55 proposals submitted in response to the CCTDP's second solicitation.

Southern Company Services, Inc. (Southern), a subsidiary of Southern Company, conducted the Demonstration of Selective Catalytic Reduction for the Control of  $\text{NO}_x$  Emissions from High-Sulfur, Coal-Fired Boilers project. Gulf Power Company's Plant Crist provided the host site and the Electric Power Research Institute (EPRI) and Ontario Hydro co-funded the project and provided technical input. The project began in June 1990 and operational testing occurred between July 1993 and July 1995. In simplistic terms, the selective catalytic reduction (SCR) process consists of injecting ammonia ( $\text{NH}_3$ ) into boiler flue gas and passing the flue gas through a catalyst bed where the oxides of nitrogen ( $\text{NO}_x$ ) and  $\text{NH}_3$  react to form water vapor and nitrogen (an element that comprises 78 percent of air).

While SCR had demonstrated high capture efficiency for  $\text{NO}_x$  in Japan and Europe, utilities in the United States had major concerns about the effectiveness of applying SCR to U.S. coals containing high sulfur and trace metals capable of poisoning the SCR catalysts. Evaluation of SCR for U.S. applications was deemed important because of pressure to further reduce  $\text{NO}_x$  emissions, a precursor to ozone formation.

To address these concerns, Southern structured a project that successfully demonstrated a range of SCR catalyst compositions, geometries, and manufacturing methods at conditions typical of U.S. high-sulfur, coal-fired utility operations. The eight catalysts ultimately tested met design specifications, providing 80 percent  $\text{NO}_x$  removal within acceptable performance parameters relative to downstream equipment. The project was instrumental in subsequent adoption of SCR by a significant percentage of the utility industry. By 2004, it is estimated that 30 percent of coal-fired boilers will be equipped with SCR.

# THE PROJECT

At the time of project inception, the Clean Air Act Amendments of 1990 were being forged. A phased introduction of source emission requirements for coal-fired boilers suggested that low-NO<sub>x</sub> burner and selective non-catalytic reduction (SNCR) technology may not be adequate for year 2000 regulations. Moreover, potential National Ambient Air Quality Standards (NAAQS) ramifications for NO<sub>x</sub> reinforced the need for deeper control capability. SCR represented the potential for providing that capability, but concerns existed about SCR catalyst longevity, cost effectiveness, and the potential for downstream equipment damage, particularly for high-sulfur coals. Another concern was that U.S. coals contain trace elements, such as arsenic, that can poison SCR catalysts. Also, SCR use results in NH<sub>3</sub> slip and sulfur dioxide (SO<sub>2</sub>) oxidation to sulfur trioxide (SO<sub>3</sub>). When combined in the presence of water, the NH<sub>3</sub> and SO<sub>3</sub> form ammonium sulfate ((NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>) and ammonium bisulfate (NH<sub>4</sub>HSO<sub>4</sub>), which adheres to and corrodes and plugs equipment like the air preheater (APH).

Although SCR found its roots in the United States, development and commercialization occurred overseas. U.S. utilities had a paucity of experience with the evolved SCR technology and needed answers to the concerns posed above. Southern structured a project that accommodated simultaneous evaluation of up to nine separate catalysts by constructing parallel test units. Three 2.5-MWe equivalent reactors and six 0.20-MWe equivalent reactors were installed in a slip stream pulling flue gas from the boiler. The test units were of a size that enabled direct translation of results to commercial units.

Six catalyst suppliers (two each from the United States, Europe, and Japan) provided eight different catalysts. The tests were conducted on flue gas derived primarily from burning Illinois No. 6 coal, a typical midwestern high-sulfur coal (2.3 percent sulfur). The objectives for the demonstration were to evaluate:

- Performance of variety of SCR catalyst compositions, geometries, and manufacturing methods at typical U.S. high-sulfur, coal-fired utility operating conditions.
- Catalyst resistance to poisoning by trace metal species present in U.S. coals but not present, or present at much lower concentrations, in fuels from other countries.
- Effects on the balance-of-plant equipment from sulfur compounds formed by reactions between SO<sub>2</sub>, SO<sub>3</sub>, and NH<sub>3</sub>.

## Project Sponsor

Southern Company Services, Inc.

## Additional Team Members

Electric Power Research Institute—cofunder

Ontario Hydro—cofunder

Gulf Power Company—host

## Location

Pensacola, Escambia County, FL (Gulf Power Company's Plant Crist, Unit No. 5)

## Technology

Selective catalytic reduction (SCR)

## Plant Capacity/Production

8.7-MWe equivalent (three 2.5-MWe and six 0.2-MWe equivalent SCR reactor plants)

## Coal

Illinois bituminous, 2.3% sulfur

## Demonstration Duration

July 1993–July 1995

Five sets of parametric testing

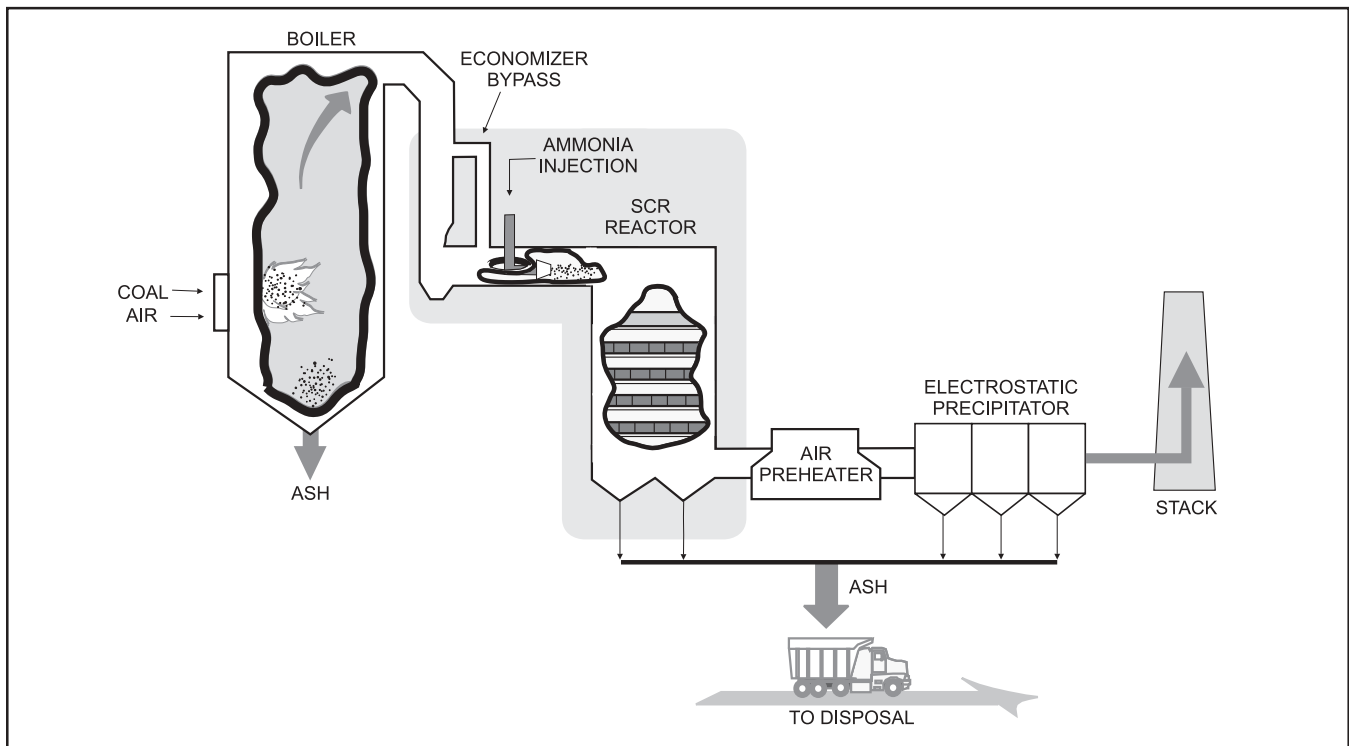
## Project Funding

Total project cost	\$23,220,729	100%
DOE	9,406,673	40%
Participant	13,823,056	60%



**SCR test facility installed at Gulf Power's Plant Crist, Unit No. 5, a 75-MWe tangentially fired, dry bottom boiler**

# THE TECHNOLOGY



## BACKGROUND

In 1957, the U.S.-based Englehard Corporation patented selective catalytic reduction of  $\text{NO}_x$  using  $\text{NH}_3$  as the reducing gas. The original platinum, or platinum group metal, catalysts proved to be unsatisfactory because of the need to operate in a temperature range in which explosive ammonium nitrate forms. Other base metal catalysts were found to have low activity. Research conducted in Japan to address the need for major  $\text{NO}_x$  emission reductions led to the development of vanadium/titanium catalysts. This combination forms the basis of current SCR catalyst technology, which has undergone significant development and application in Japan and Europe. Titanium oxide provides the structure, or is the substrate, for the active components — oxides of vanadium and, in some cases, tungsten. For SCR applications, this ceramic mixture is usually configured as a honeycomb or flat plate. The honeycomb form is usually extruded with the catalyst either incorporated throughout the structure (homogeneous) or coated on a substrate. In the plate geometry, the support material is generally coated with catalyst.

SCR systems can be installed at any of three locations in a power plant: (1) upstream of the APH and electrostatic precipitator (ESP) (hot-side, high-dust), as shown above; (2) upstream of the APH and downstream of the ESP (hot-side, low-dust); and (3) downstream of the APH and ESP (cold-side, low-dust). In commercial practice, most SCRs are hot-side, high-dust installations. This location is preferred because it obviates the need to reheat the flue gas to reaction temperature, thereby minimizing loss of thermal efficiency. Most installations use an economizer bypass to provide flue gas to the reactors at the desired temperature during periods when flue gas temperatures are low, such as low load operation.

When processing flue gas containing dust, the reactors are typically arranged vertically, with downflow of flue gas. For optimum catalyst utilization, the catalyst is typically arranged in a series of three or four beds, or layers, with provisions for an additional layer that is not initially installed. As the catalyst activity declines, the additional catalyst is installed. As deactivation continues, catalyst beds are replaced on a rotating basis, one layer at a time, starting with the top. This strategy results in maximum catalyst utilization. The catalyst is subjected to periodic soot-blowing to remove deposits, using steam as the cleaning agent.

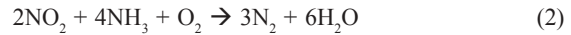
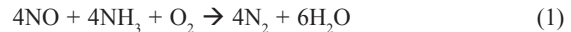
## SCR PROCESS

In the SCR process,  $\text{NH}_3$  is injected into boiler flue gas prior to its entering an SCR reactor comprised of a series of catalyst beds. The SCR catalyst aids the reaction of  $\text{NH}_3$ , excess oxygen ( $\text{O}_2$ ), and  $\text{NO}_x$  to form nitrogen ( $\text{N}_2$ ) and water ( $\text{H}_2\text{O}$ ) (see equations 1 and 2 in box). The SCR catalyst also oxidizes a small fraction of the  $\text{SO}_2$  produced in the boiler by oxidation of sulfur in the coal to  $\text{SO}_3$ . Some of the injected  $\text{NH}_3$  remains unreacted and passes through the catalyst bed. This phenomenon is referred to as  $\text{NH}_3$  slip. It is essential to hold  $\text{NH}_3$  slip to below 5 ppm, preferably 2–3 ppm, and to limit  $\text{SO}_2$  oxidation to  $\text{SO}_3$  (see equation 3 in box). As mentioned previously, the  $\text{NH}_3$  and  $\text{SO}_3$  combine to form the sticky and corrosive  $(\text{NH}_4)_2\text{SO}_4$  and  $\text{NH}_4\text{HSO}_4$  (see equations 4 and 5 in box). This problem is exacerbated with high-sulfur coals because of the potential for high  $\text{SO}_3$  levels, both from  $\text{SO}_3$  formation in the boiler and oxidation of  $\text{SO}_2$  in the SCR reactor.

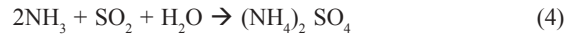
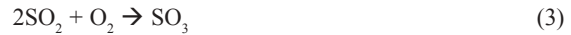
$\text{NO}_x$  reduction is controlled for the most part by the  $\text{NH}_3/\text{NO}_x$  ratio. Therefore, with excess catalyst in the reactor,  $\text{NO}_x$  reduction remains essentially constant over the life of the catalyst. Ammonia slip increases somewhat over time until it reaches the design limit, at which point fresh catalyst is added.

The titanium/vanadium oxide catalysts beds are maintained in a temperature range of 650–750 °F. This temperature range provides sufficient heat for catalyst activity, while minimizing the rate of oxidation of  $\text{SO}_2$  to

### Chemistry of the SCR Process



### Side Reactions



$\text{SO}_3$ , which is more temperature sensitive than the catalyst reaction. The specific optimum operating temperature chosen is a function of the catalyst. It is essential to operate at as high a temperature for maximum catalyst activity, which allows for maximum space velocity (volumetric flue gas flow rate divided by the catalyst volume) and, thus, minimize catalyst volume to keep catalyst costs down. Catalyst cost constitutes 15–20 percent of the capital cost of an SCR unit.

## APPARATUS

For the demonstration project, three 2.5-MWe equivalent reactors and six 0.20-MWe equivalent reactors were installed in a slip stream pulling flue gas from Plant Crist's Unit No. 5 as shown in Figure 1. Each reactor contained a different catalyst for side-by-side performance comparisons. Eight of the nine reactors were designed for hot-side, high-dust operation. The other was designed for hot-side,

low-dust operation to evaluate the effect of particulate loading on performance.

Each reactor train was equipped with an electric duct heater to independently control flue gas temperatures and a venturi meter to measure the flue gas rate. An economizer bypass line maintained a minimum flue gas temperature of 620 °F to the high dust reactors. Anhydrous  $\text{NH}_3$  was independently metered to a stream of heated dilution air and was injected via nozzles into the flue gas upstream of each SCR reactor. The flue gas, containing  $\text{NH}_3$ , passed through the reactors, each of which had the capacity to contain up to four catalyst layers.

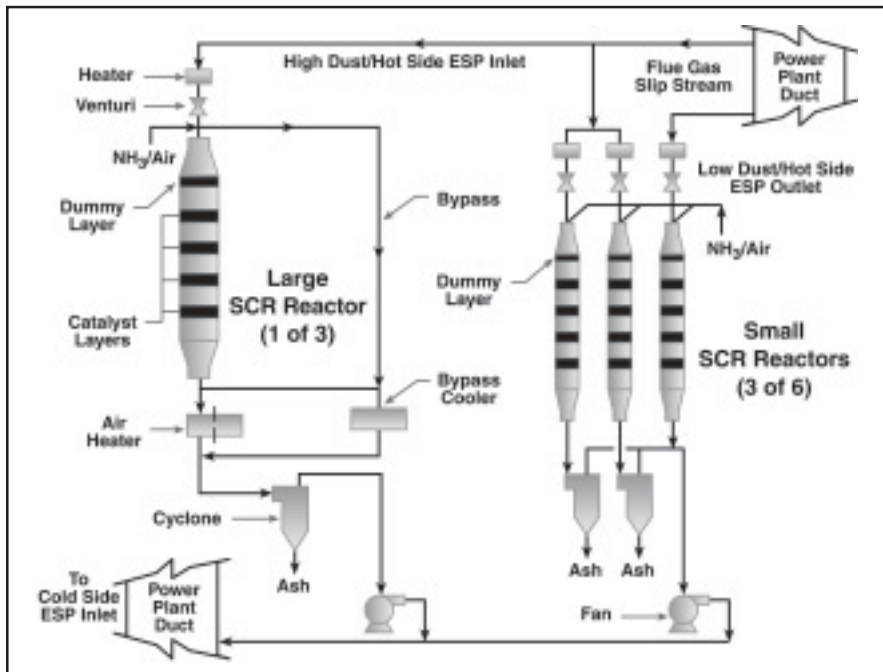
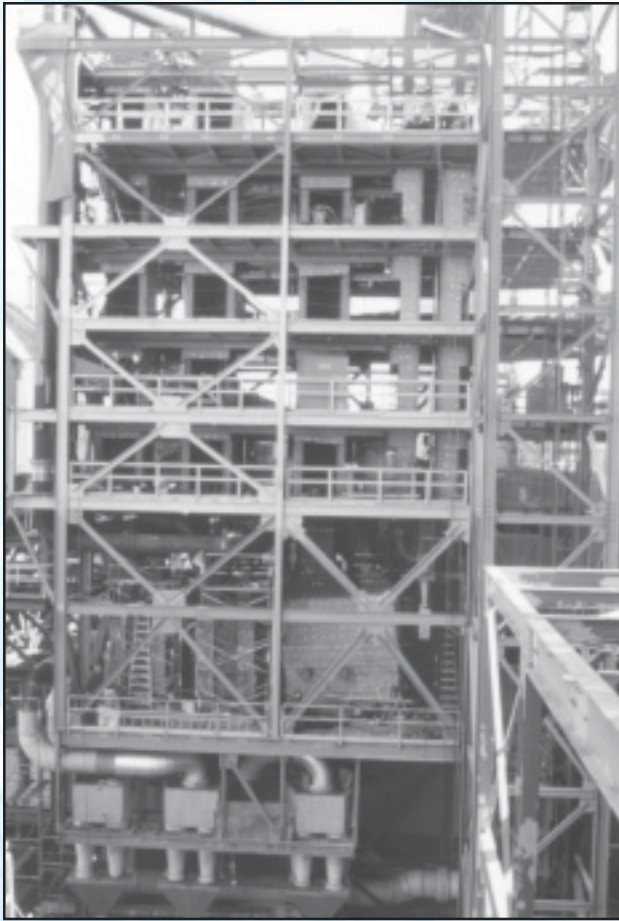


FIGURE 1. SCR TEST APPARATUS



**SCR Test Facility**

For each of the three larger reactor trains, the flue gas exiting the reactor entered a specially modified pilot-scale APH, each of different design. The modified APHs were used to better simulate full-scale APHs for improved extrapolation of results to commercial scale. The APHs were incorporated in the project to evaluate the effects of SCR on APH deposit formation and the effects of the deposits on APH performance and operation.

All reactor trains except the low-dust train had a cyclone downstream of the SCR reactor to protect the induced draft fans from particulate matter. The exhausts from all of the SCR reactors were combined into a single manifold and re-injected into the host boiler's fuel gas stream ahead of the cold-side ESP. The preheated air streams for the APHs on the larger reactors were also combined into a single manifold and also returned to the host boiler draft system.

The test facility examined the performance of eight SCR catalysts (one reactor was idled due to the withdrawal of a project participant) differing in chemical makeup and physical form. Each catalyst supplier was given great latitude in designing its catalyst offering provided it met the following requirements:

- Catalyst baskets that match predetermined reactor dimensions.
- A maximum of four catalyst layers.
- A minimum 80 percent  $\text{NO}_x$  reduction at baseline conditions.
- A maximum baseline  $\text{NH}_3$  slip of 5 ppm.
- A maximum baseline  $\text{SO}_2$  oxidation rate of 0.75 percent.
- A two-year life while meeting the above performance criteria.

In general, the performance of fixed-bed catalytic reactors can readily be scaled up. Consequently, the SCR test apparatus was not commercial scale, but deemed directly scalable to commercial applications. The catalyst modules used in the larger reactors were full-scale versions of the catalysts used commercially in Europe and Japan. The test units were designed to ensure that the flue gas slip streams were fully represented in terms of gaseous and solid species and that the catalyst modules were exposed to flue gas conditions identical to those experienced in full-scale installations.



# DEMONSTRATION RESULTS

## ENVIRONMENTAL

- $\text{NO}_x$  reductions of over 80 percent were achieved at an ammonia slip well under the 5 ppm deemed acceptable for commercial operation.
- For most catalysts, flow rates could be increased to 150 percent of design without exceeding the ammonia slip design level of 5 ppm at 80 percent  $\text{NO}_x$  reduction.
- While catalyst performance increased above 700 °F, the benefit did not outweigh the heat rate penalties.
- Increases in ammonia slip, a sign of catalyst deactivation, went from less than 1 ppm to approximately 3 ppm over the nearly 12,000 hours of operation, thus demonstrating that deactivation in coal-fired units was in line with worldwide experience.
- Long-term testing showed that  $\text{SO}_2$  oxidation was within or below the design limits necessary to protect downstream equipment.

## OPERATIONAL

- Fouling of catalysts was controlled by adequate soot-blowing procedures.
- Long-term testing showed that catalyst erosion was not a problem once soot blowing procedures were adopted.
- Air preheater performance was degraded because of ammonia slip and subsequent by-product formation; however, solutions were identified.
- The SCR process did not significantly affect the results of Toxicity Characteristic Leaching Procedure (TCLP) analysis of the fly ash.

## ECONOMIC

- Levelized costs on a 30-year basis for a 250-MWe unit, with a SCR inlet  $\text{NO}_x$  concentration of 0.35 lb/10<sup>6</sup> Btu, were 2.39, 2.57, and 2.79 mills/kWh (constant 1996\$) for 40, 60, and 80 percent removal efficiency, respectively, which equates to 3,502; 2,500; and 2,036 \$/ton (constant 1996\$), respectively.



**Plant Crist cyclones for SCR reactors.**

## OPERATIONAL PERFORMANCE

Over the two-year test period, operating experience with individual catalysts ranged from 4,000 to 13,000 hours. Parametric testing was conducted every 4 to 6 months. Catalysts were provided initially by three U.S. suppliers (Englehard, Grace, and Cormetech), two European suppliers (Haldor Topsoe and Siemens), and two Japanese suppliers (Hitachi Zosen and Nippon Shokubai). Englehard subsequently withdrew from the project, and its low-dust catalyst was replaced by one of Cormetech's low-dust catalysts. Table 1 shows the catalysts tested at Plant Crist. Table 2 shows the properties of the Illinois No. 6 bituminous design coal.

All of the catalysts performed well in both parametric and long-term testing, achieving at least 80 percent NO<sub>x</sub> removal with a maximum NH<sub>3</sub> slip of 5 ppm. Although the catalysts varied somewhat in operating characteristics, such as activity and pressure drop, no

one catalyst demonstrated superior performance compared to the others. Catalyst deactivation was consistent with the deactivation experienced in Europe and Japan. Extrapolating the test data to 16,000 hours, reflective of two years of operation, suggests an average decrease in catalyst activity of about 20 percent, which is acceptable. In practice, this decrease could range from 10 to 30 percent.

Tests showed no evidence of unusual deactivation effects attributable to the use of high-sulfur U.S. coals. Testing did not detect detrimental effects due to trace metals, such as arsenic. Laboratory tests, however, clearly revealed accumulation of trace metals on the surface of the catalyst.

Both plate and honeycomb catalysts performed satisfactorily. A major difference between these catalyst configurations is pressure drop, which must be taken into account in designing commercial SCR installations. Plate catalysts typically offer lower pressure drops. Performance comparisons between high-dust and low-dust reactor configurations were inconclusive because of problems associated with the design of the low-dust reactor.

Some catalyst bed erosion occurred during testing, but catalyst erosion was not considered to be a significant problem because most of the erosion was attributed to aggressive soot-blowing. Over time, the soot-blowing procedures adopted in the test program proved to be

**TABLE 1. SCR CATALYSTS TESTED AT PLANT CRIST**

Reactor	Catalyst Supplier	Reactor Size	Dust Level	Catalyst Composition	Configuration
A	W.R. Grace (Noxeram)	Large	High	V-W/Ti	Honeycomb
B	Nippon Shokubai K.K.	Large	High	V-W/Ti-Si	Honeycomb
C	Siemens AG	Large	High	V/Ti	Plate
D	W.R. Grace (Synox)	Small	High	V/Ti-Si	Honeycomb
E	Cormetech	Small	High	V-W/Ti	Honeycomb
F	Haldor Topsoe	Small	High	V/Ti	Plate
G	Hitachi Zosen	Small	High	V/Ti	Plate
J	Cormetech	Small	Low	V-W/Ti	Honeycomb
V – vanadium oxide		W – tungsten oxide	Ti – titanium oxide	Si – silicon oxide	

**TABLE 2. PROPERTIES OF COAL USED IN PLANT CRIST TESTS COAL SOURCE: ILLINOIS No. 6 BITUMINOUS**

<b>Proximate Analysis, wt% (as received)</b>	
Fixed Carbon	47.65
Volatile Matter	34.16
Moisture	9.80
Ash	8.39
Total	100.00
HHV, Btu/lb	12,500
<b>Ultimate Analysis, wt% (as received)</b>	
Carbon	67.48
Hydrogen	4.51
Nitrogen	1.43
Sulfur	2.33
Chlorine	0.14
Oxygen	5.92
Ash	8.39
Water	9.80
Total	100.00

satisfactory, as evidenced by the overall stability of the pressure drop across the catalyst beds for the test period.

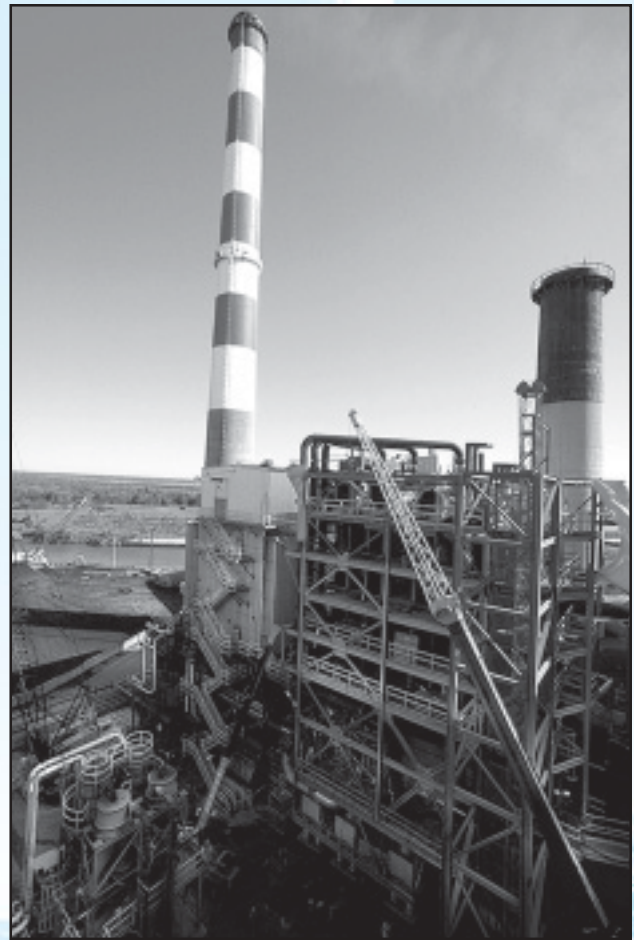
There was significant variation in the rate of oxidation of  $\text{SO}_2$  to  $\text{SO}_3$  among the catalysts tested. The amounts of  $(\text{NH}_4)_2\text{SO}_4$  and  $\text{NH}_4\text{HSO}_4$  formed were sufficient to result in corrosion and plugging of the APHs downstream of the large SCR reactors. Periodic washing was required to maintain APH performance. The need to choose appropriate materials of construction for APHs for commercial SCR installations was evident. Regenerator-type air heaters outperformed recuperators in SCR applications in terms of both thermal performance and fouling.

### **LONG-TERM TESTS**

The long-term test results are expressed by the decrease in activity over time, as measured by the rate constant  $k$ . The precise kinetic relationship determining  $k$  is of little concern. What is of importance is the ratio  $k/k_0$ , where  $k$  is the rate constant at a given time in the deactivation cycle and  $k_0$  is the initial rate constant with fresh catalyst. In this project, the catalyst activity  $k/k_0$  was determined by dividing fractional  $\text{NO}_x$  conversion at a given time by the  $\text{NO}_x$  conversion with fresh catalyst (following first order kinetic principles). For the SCR test program, the relative activity began at 1.0 and gradually decreased to an average of about 0.8 at 12,000 hours.

### **BOILER IMPACTS**

In commercial practice, an SCR impacts boiler operation only from the standpoint of avoiding temperature spikes in adjusting the boiler to varying loads. Careful temperature control must be maintained at all times to ensure effective SCR operation.



**Plant Crist SCR under construction**

## PARAMETRIC STUDIES

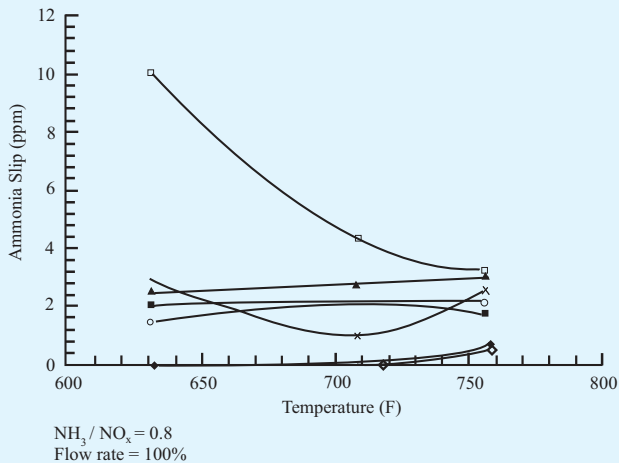
The parametric studies investigated the effects of reactor operating temperature,  $\text{NH}_3/\text{NO}_x$  molar ratio, and space velocity on catalyst performance. Five sets of parametric data were obtained.

**Effect of Temperature on  $\text{NH}_3$  Slip.** As shown in Figure 2,  $\text{NH}_3$  slip remained fairly constant at less than 5 ppm over the range of 620–750 °F for most of the catalysts, while maintaining a constant 0.8  $\text{NH}_3/\text{NO}_x$  molar ratio. The exception was the Grace Synox catalyst, which experienced a 10 ppm  $\text{NH}_3$  slip at the lowest temperature and decreased to the same levels as the other catalysts at the higher temperatures.

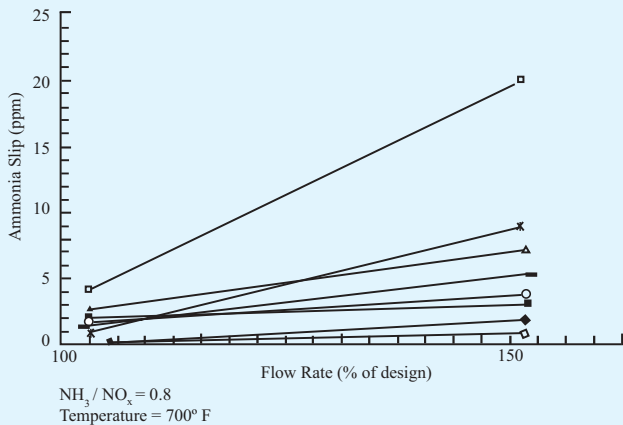
**Effect of  $\text{NH}_3/\text{NO}_x$  Molar Ratio on  $\text{NH}_3$  Slip.** Except for one catalyst,  $\text{NH}_3$  slip remained constant at approximately 2 ppm for  $\text{NH}_3/\text{NO}_x$  molar ratios of 0.6 up to those approaching 0.9, after which the  $\text{NH}_3$  slip increased dramatically. This observed phenomenon very likely resulted from the difficulty in precision measuring and controlling  $\text{NH}_3$  flow, as well as poor mixing of  $\text{NH}_3$  and  $\text{NO}_x$ . Both issues become critical when operating at  $\text{NH}_3/\text{NO}_x$  ratios that approach 1.0.

**Effect of Space Velocity on  $\text{NH}_3$  Slip.** As shown in Figure 3,  $\text{NH}_3$  slip remained fairly constant at less than 5 ppm for five of the catalysts for flow rates/space velocities over the range of 100 to 150 percent of the design.  $\text{NH}_3$  slip increased significantly above 5 ppm for the other three catalysts studied in this part of the test program.

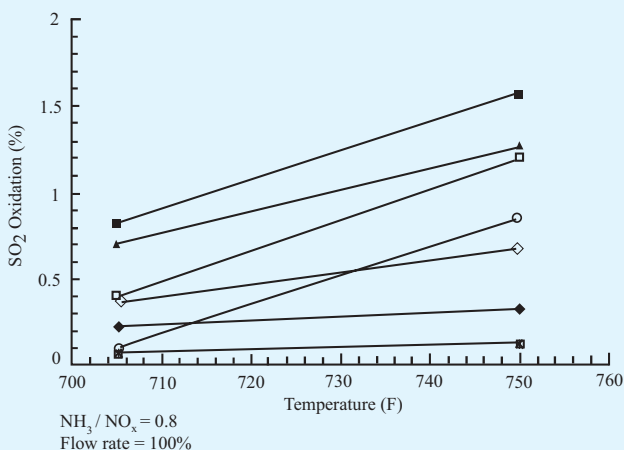
**Effect of Temperature on  $\text{SO}_2$  Oxidation.** As shown in Figure 4, the rate of  $\text{SO}_2$  oxidation remained fairly constant at less than 0.2 percent for two of the catalysts and increased to varying degrees for the other catalysts as the temperature was increased. The tests showed that  $\text{SO}_2$  oxidation is much more temperature sensitive than  $\text{NO}_x$  reduction and is a function of catalyst formulation. The optimum temperature will vary from catalyst to catalyst.



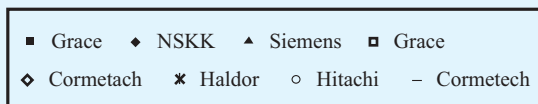
**FIGURE 2. EFFECT OF TEMPERATURE ON  $\text{NH}_3$  SLIP**



**FIGURE 3. EFFECT OF SPACE VELOCITY ON  $\text{NH}_3$  SLIP**



**FIGURE 4. EFFECT OF TEMPERATURE ON  $\text{SO}_2$  OXIDATION**



## ENVIRONMENTAL PERFORMANCE

As discussed, the  $\text{NH}_3/\text{NO}_x$  ratio controlled  $\text{NO}_x$  reduction and the  $\text{NH}_3$  slip was the ultimate controlling factor in the degree of  $\text{NO}_x$  reduction achieved and the extent of operation possible on a catalyst bed. The demonstration showed that 80 percent  $\text{NO}_x$  reduction at less than 5 ppm  $\text{NH}_3$  slip was readily achievable for a two-year catalyst life. Indications are that a 60 percent  $\text{NO}_x$  reduction set point would extend the catalyst life, as evidenced by  $\text{NH}_3$  slip at or near the detection limit of 1 ppm at this level of control. At  $\text{NO}_x$  reduction levels approaching 90 percent and beyond,  $\text{NH}_3$  slip increased dramatically, pointing out the difficulty of achieving the precise metering control and effective mixing needed as the  $\text{NH}_3/\text{NO}_x$  ratio approached 1.0.

Evaluation of environmental impacts as a result of applying SCR technology included TCLP analysis and resistivity analysis for the fly ash. TCLP and resistivity analysis indicated that SCR technology caused no appreciable change in fly ash parameters.

Ammonia volatilized from the SCR fly ash when a significant amount of water was absorbed in the fly ash, but ammonia did not easily evolve from dry fly ash. The study also showed that aqueous solution pH affected ammonia extraction, implying that wet handling of ash may be affected by the solution pH. The ammonia on the ash increased the potential for release of barium from the ash, but no notable changes in other metal "extractabilities" were found. The results of these studies indicate that precautions may be necessary in the handling of fly ash due to the potential for ammonia evolution.

## ECONOMIC PERFORMANCE

Southern prepared a cost estimate for a 250-MWe greenfield unit, using a projected process design for the  $n^{\text{th}}$  plant, which incorporates improvements based on experience gained from the demonstration project. The estimate assumes application to either a wall-fired or tangentially fired unit equipped with low  $\text{NO}_x$  burners. The coal feed contains 2.5 percent sulfur by weight. The SCR design calls for reducing and inlet  $\text{NO}_x$  concentration of 0.35 lb/10<sup>6</sup> Btu to 0.14 lb/10<sup>6</sup> Btu, or 60 percent. The assumed catalyst deactivation is 20 percent at 16,000 hours, or a  $k/k_0$  ratio of 0.8 at that time. The catalyst price is \$400 per cubic foot.

Table 3 summarizes the key cost and performance data. The estimated capital cost for the 250 MWe unit is \$54/kW (1996 dollars). For a 30-year project life, the levelized cost on a current dollar basis is 2.57 mills/kWh, or \$2,500/ton of  $\text{NO}_x$  removed. On a constant dollar basis, the levelized cost is 1.85 mills/kWh, or \$1,802/ton of  $\text{NO}_x$  removed.

**TABLE 3. ECONOMICS OF THE SCR PROCESS IN A GREENFIELD INSTALLATION**

<b>Coal Properties</b>	<b>Units</b>	<b>Value</b>	
Higher heating value (HHV)	Btu/lb	12,500	
<b>Power Plant Attributes With Controls</b>			
Plant capacity, net	MWe	250	
Power produced, net	10 <sup>9</sup> kWh/yr	1.34	
Capacity factor	%	65	
Coal fed	10 <sup>6</sup> tons/yr	0.54	
<b>NO<sub>x</sub> Emissions Control Data</b>			
Removal efficiency	%	60	
Emissions without SCR	lb/10 <sup>6</sup> Btu	0.35	
Emissions with SCR	lb/10 <sup>6</sup> Btu	0.14	
NO <sub>x</sub> removed	tons/yr	1,374	
<b>Total Capital Required<sup>a</sup></b>	<b>\$kW</b>	<b>54</b>	
	<b>Levelization Factor</b>	<b>mills/kWh</b>	<b>\$/ton NO<sub>x</sub> removed</b>
<b>Levelized Cost<sup>b</sup>, Current \$</b>			
Capital charge <sup>a</sup>	0.150	1.50	1,464
Fixed O&M <sup>a</sup>	1.362	0.32	310
Variable O&M <sup>a</sup>	1.362	0.75	726
Total		2.57	2,500

<sup>a</sup>All costs in 1996 dollars.

<sup>b</sup>Levelization based on 30-year project life, 38% tax rate, 3% inflation, and the following capital structure: 50% debt @ 8.5% return, 15% preferred stock @ 7.0% return, and 35% common stock @ 7.5% return, giving a weighted cost of capital of 9.15% (including inflation).

For the same unit at 40 percent removal efficiency, the NO<sub>x</sub> removal cost equates to \$3,502/ton (constant 1996 dollars). Increasing the removal efficiency to 80 percent results in a NO<sub>x</sub> removal cost of \$2,036/ton (constant 1996 dollars). Varying the inlet NO<sub>x</sub> concentration also affects SCR economics. Again for the same unit, increasing the NO<sub>x</sub> inlet concentration to 0.45 lb/10<sup>6</sup> Btu, the NO<sub>x</sub> removal costs drop from \$2,500/ton to \$1,977/ton (constant 1996 dollars). Lowering the inlet NO<sub>x</sub> concentration to 0.25 lb/10<sup>6</sup> Btu results in a NO<sub>x</sub> removal cost of \$3,446/ton (constant 1996 dollars).

In summary, at a given plant capacity, levelized costs and NO<sub>x</sub> removal costs (\$/ton of NO<sub>x</sub> removed) decrease with an increasing NO<sub>x</sub> removal rate and increasing initial NO<sub>x</sub> concentration. This situation equates to an application where the boiler has high uncontrolled NO<sub>x</sub> levels and no combustion modification, such as low-NO<sub>x</sub> burners. Longer catalyst life, reduced catalyst prices, or both, reduce costs. Retrofit costs can be significantly greater, especially in cases involving difficult reactor siting and duct arrangements, new fans, and balanced draft conversions. In one case studied, the estimated cost was \$130/kW, representing \$65/kW for the SCR unit and \$65/kW for conversion to balanced draft operation.

Operating costs consist primarily of NH<sub>3</sub> reagent expense and catalyst replacement. Additional labor or maintenance costs due to the SCR units are minimal.

## COMMERCIAL APPLICATIONS

With the completion of the SCR test program at Plant Crist, the experimental facility was dismantled. But the demonstration provided the impetus for adopting SCR in the United States.

Soon after the SCR demonstration, six SCR installations ensued. One of these units, Birchwood, is an independent power producer jointly owned by Southern Energy, Inc. (SEI) and Cogentrix. SEI is a non-regulated subsidiary of Southern Company. The Birchwood SCR design considered data and operational lessons learned from the test program at Plant Crist as valuable input for specifying the process equipment. All of the SCR equipped boilers operate on low- to medium-sulfur coals; five of the SCR units are associated with new plants, and one is a retrofit. All of the units are hot-side, high-dust installations.

The U.S. SCR units are achieving NO<sub>x</sub> reductions up to 90 percent, depending on the uncontrolled NO<sub>x</sub> concentration and the desired level of NO<sub>x</sub> in the stack gas. There have been few problems in meeting NH<sub>3</sub> slip requirement, and catalyst deactivation has proceeded as predicted from the Plant Crist test data. In general, the plant staff and management at each facility are pleased with the SCR operation, although at least some periodic washing of APHs has been necessary.

As of 2002, approximately 25 percent of U.S. coal-fired capacity has been equipped with SCR, and that figure is projected to reach 30 percent by 2004. The SCR process is generally applicable to all boiler types comprising the more than 300 gigawatts of U.S. coal-fired capacity.

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