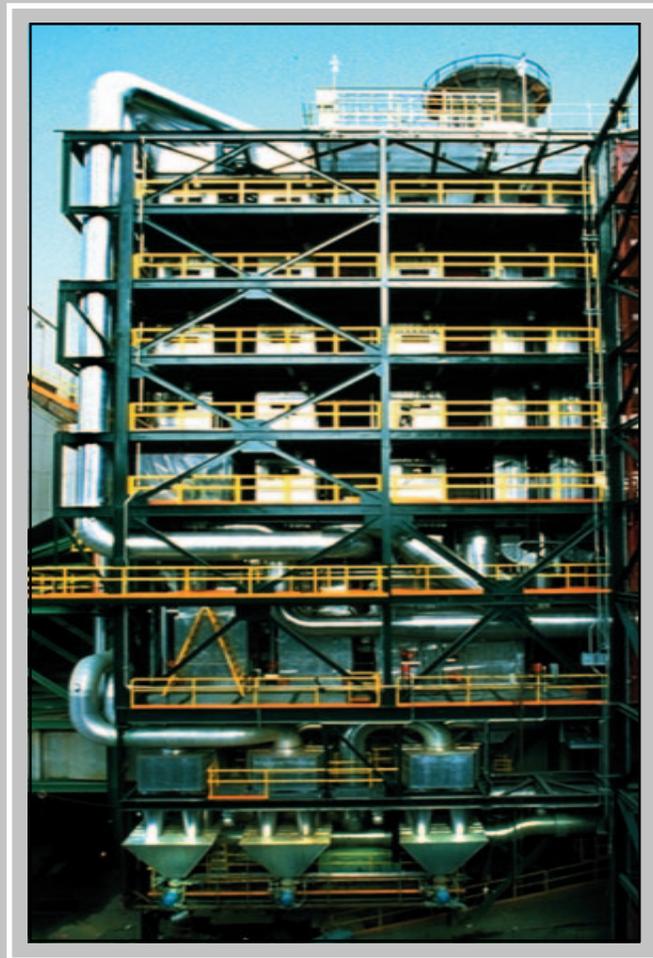


# CLEAN COAL TECHNOLOGY



Control of Nitrogen Oxide Emissions:  
Selective Catalytic Reduction (SCR)

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

The U.S. Department of Energy and Southern Company Services, Inc.



Cover image: Photo of SCR Project at Plant Crist.

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

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**CLEAN  
COAL  
TECHNOLOGY**

## Control of Nitrogen Oxide Emissions: Selective Catalytic Reduction (SCR)

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# Introduction and Executive Summary

The Clean Coal Technology (CCT) Demonstration Program is a government and industry co-funded effort to demonstrate a new generation of innovative coal utilization processes in a series of “showcase” facilities built across the country. These projects are on a scale sufficiently large to demonstrate commercial worthiness and to generate data for design, construction, operation, and technical/economic evaluation of full-scale commercial applications.

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

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

Part of this program is the demonstration of technologies designed to reduce emissions of oxides of nitrogen ( $\text{NO}_x$ ) from existing coal-fired utility boilers.  $\text{NO}_x$  is an acid rain precursor and a contributor to atmospheric ozone formation, which is a health hazard and is also related to smog formation.  $\text{NO}_x$  emissions are regulated under the

provisions of the Clean Air Act and particularly the Clean Air Act Amendments (CAAA) of 1990.

This report discusses a CCT project which demonstrated selective catalytic reduction (SCR) technology for the control of  $\text{NO}_x$  emissions from high-sulfur, coal-fired boilers. The project was conducted by Southern Company Services, which served as a cofunder and as the host at Gulf Power Company’s Plant Crist near Pensacola, Florida. Other participants and cofunders were the Electric Power Research Institute (EPRI) and Ontario Hydro. DOE provided 40% of the total project cost of \$23 million. The project was administered for DOE by its Federal Energy Technology Center (FETC).

The SCR process consists of injecting ammonia ( $\text{NH}_3$ ) into boiler flue gas and passing the flue gas through a catalyst bed where the  $\text{NO}_x$  and  $\text{NH}_3$  react to form nitrogen and water vapor. The objectives of the demonstration project were to investigate:

- Performance of a wide 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 that may not be present in fuels from other countries.
- Effects on the balance-of-plant equipment from sulfur compounds formed by reactions between sulfur dioxide ( $\text{SO}_2$ ), sulfur trioxide ( $\text{SO}_3$ ), and  $\text{NH}_3$ , such as plugging and corrosion of downstream equipment.

The catalysts were tested over a two-year period, during which they were exposed to flue gas from a coal-fired

boiler at Plant Crist, under conditions identical to those experienced in commercial installations. Catalyst suppliers (two U.S., two European, and two Japanese) provided eight different catalysts. All catalysts performed well, giving  $\text{NO}_x$  removal rates of 80% or better with acceptable  $\text{NH}_3$  slip. The results demonstrated the applicability of SCR under both high dust and low dust conditions.

Economics were estimated for an SCR unit installed in a new 250 MWe power plant, using a projected process design that incorporates improvements based on experience gained from the SCR demonstration project. The boiler is assumed to be either a wall-fired or a tangentially fired unit, equipped with low- $\text{NO}_x$  burners and burning 2.5 wt% sulfur coal. Design  $\text{NO}_x$  concentration at the reactor inlet is 0.35 lb/10<sup>6</sup> Btu.  $\text{NO}_x$  reduction is assumed to be 60%, giving an outlet concentration of 0.14 lb/10<sup>6</sup> Btu, with a design  $\text{NH}_3$  slip of 5 ppm. The capital cost is \$54/kW. For a 30-year project life, the levelized cost on a current dollar basis is 2.6 mills/kWh. This is equivalent to \$2500/ton of  $\text{NO}_x$  removed. At the same plant capacity and 90% removal, the capital cost increases to \$66/kW but the levelized cost decreases to \$1260/ton.

The demonstration project at Plant Crist contributed significantly to the body of knowledge regarding the application of SCR on U.S. coals. Currently, six commercial SCR units have been installed and are operating on low- and medium-sulfur U.S. coals. Because SCR is applicable to almost any kind of boiler, a significant market for SCR exists in the United States, especially in light of increasingly stringent limitations on  $\text{NO}_x$  emissions.

# Control of Nitrogen Oxide Emissions: Selective Catalytic Reduction (SCR)

## Background

The Clean Coal Technology (CCT) Demonstration Program, which is sponsored by the U.S. Department of Energy (DOE), is a government and industry co-funded technology development effort conducted since 1985 to demonstrate a new generation of innovative coal utilization processes. At the same time, the U.S. Environmental Protection Agency (EPA) is in the process of promulgating new regulations, authorized by the 1990 Clean Air Act Amendments (CAAA), concerning emissions from a variety of stationary sources, including coal-burning power plants.

The CCT Program involves a series of “showcase” projects, conducted on a scale sufficiently large to demonstrate commercial worthiness and generate data for design, construction, operation, and

technical/economic evaluation of full-scale commercial applications. The goal of the CCT Program is to furnish the U.S. energy marketplace with advanced, more efficient, and environmentally responsible coal-utilizing technologies. These technologies will mitigate some of the economic and environmental impediments that inhibit utilization of coal as an energy source.

The CCT Program also has opened a channel to policy-making bodies by providing data from cutting-edge technologies to aid in formulating regulatory decisions. DOE and participants in several CCT projects have provided the EPA with data to help establish NO<sub>x</sub> emissions targets for coal-fired power plants subject to compliance under the CAAA.

A major issue of concern is emissions of nitrogen oxides (NO and NO<sub>2</sub>, collectively referred to as NO<sub>x</sub>). Under the CCT Program, a project was undertaken to evaluate the performance and economics of the selective catalytic reduction (SCR)



Plant Crist, Pensacola FL

process for removing  $\text{NO}_x$  from the flue gas of boilers fired with U.S. high-sulfur coals. A major advantage of SCR is that the reaction products, nitrogen and water, are innocuous compounds already present in the air.

The SCR process was initially discovered in the United States. Although it is widely used in Japan and Europe, including numerous installations on coal-burning power plants, there were technical uncertainties associated with applying SCR to plants burning U.S. high-sulfur coals, primarily involving the danger of forming excessive amounts of ammonia-sulfur compounds with attendant plugging and corrosion of downstream equipment. There was also concern over the presence of trace metals such as arsenic, which can lead to catalyst deactivation.

The SCR demonstration project, conducted at Gulf Power Company's Plant Crist near Pensacola, Florida, was designed to evaluate the performance and

cost of SCR technology under typical boiler conditions in the United States. Its successful completion would demonstrate a process capable of meeting increasingly stringent  $\text{NO}_x$  emission regulations.

## $\text{NO}_x$ Emissions Standards

### *History*

The Clean Air Act was originally passed in 1967. It was amended in 1970, 1977, and most recently in 1990. The CAAA authorized the EPA to establish standards for a number of atmospheric pollutants, including sulfur dioxide ( $\text{SO}_2$ ) and  $\text{NO}_x$ . The regulations establish New Source Performance Standards (NSPS) for these flue gas components. Updating the emissions standards every five years is mandated.

## The Clean Coal Technology Program

The Clean Coal Technology (CCT) Program is a unique partnership between the federal government and industry that has as its primary goal the successful introduction of new clean coal utilization technologies into the energy marketplace. With its roots in the acid rain debate of the 1980s, the program is on the verge of meeting its early objective of broadening the range of technological solutions available to eliminate acid rain concerns associated with coal use. Moreover, the program has evolved and has been expanded to address the need for new, high-efficiency power-generating technologies that will allow coal to continue to be a fuel option well into the 21st century.

Begun in 1985 and expanded in 1987 consistent with the recommendation of the U.S. and Canadian Special Envoys on Acid Rain, the program has been implemented through a series of five nationwide competitive solicitations. Each solicitation has been associated with specific government funding and program objectives. After five solicitations, the CCT Program comprises a total of 40 projects located in 18 states with a capital investment value of nearly \$6.0 billion. DOE's share of the total project costs is about \$2.0 billion, or approximately 34 percent of the total. The projects' industrial participants (i.e., the non-DOE participants) are providing the remainder—nearly \$4.0 billion.

Clean coal technologies being demonstrated under the CCT Program are establishing a technology base that will enable the nation to meet more stringent energy and environmental goals. Most of the demonstrations are being conducted at commercial scale, in actual user environments, and under circumstances typical of commercial operations. These features allow the potential of the technologies to be evaluated in their intended commercial applications. Each application addresses one of the following four market sectors:

- Advanced electric power generation
- Environmental control devices
- Coal processing for clean fuels
- Industrial applications

Given its programmatic success, the CCT Program serves as a model for other cooperative government/industry programs aimed at introducing new technologies into the commercial marketplace.

Two major portions of the CAAA relevant to NO<sub>x</sub> control are Title I and Title IV. Title I establishes National Ambient Air Quality Standards (NAAQS) for six criteria pollutants, including ozone, while Title IV addresses controls for specific types of boilers, including stationary coal-fired power plants. Title IV is often referred to as the Acid Rain Program.

Title IV uses a two-phase NO<sub>x</sub> control strategy. Effective January 1, 1996, Phase I established regulations for 256 Group 1 boilers, namely dry-bottom, wall-fired boilers and tangentially fired (T-fired) boilers. In Phase II, which begins in 2000, lower emission limits are set for Group 1 boilers, and initial limits are set for 145 Group 2 boilers, which include cell-burners; cyclones; wet-bottom, wall-fired boilers; and other types of coal-fired boilers. In addition to the 256 Phase I, Group 1 boilers, there are another 607 wall-fired and T-fired boilers that must meet the applicable limits in Phase II.

### *Ozone Formation*

When NO<sub>x</sub> and volatile organic compounds (VOCs) enter the atmosphere, they react in the presence of sunlight to form ground-level ozone, which is a major ingredient of smog. The current NAAQS for ozone is 0.12 ppm (1 hour average). At this level many large- and medium-sized urban areas are classified as nonattainment, and many power plants are within these nonattainment areas. Furthermore, the Northeast Ozone Transport Region (NOTR), consisting of 12 states and the District of Columbia, is considered nonattainment with respect to sources in that region.

A number of studies have indicated that the current ambient standard for ozone is inadequate to protect either human health or the environment. For this reason the EPA has proposed a more

## NO<sub>x</sub> Regulations under the Clean Air Act Amendments of 1990

NO<sub>x</sub> emissions are generated primarily from transportation, utility, and other industrial sources. They are reported to contribute to a variety of environmental problems, including acid rain and acidification of aquatic systems, ground level ozone (smog), and visibility degradation. For these reasons, NO<sub>x</sub> emissions are regulated in many ways by different levels of government throughout the country.

### Ozone Non-Attainment

Title I of the CAAA requires the states to apply the same limits to major stationary sources of NO<sub>x</sub> as are applied to major stationary sources of volatile organic compounds. In general, these new NO<sub>x</sub> provisions require (1) existing major stationary sources to apply reasonably available control technologies (RACT), (2) new or modified major stationary sources to offset their new emissions and install controls representing the lowest achievable emission rate, and (3) each state with an ozone nonattainment region in it to develop a State Implementation Plan (SIP) that, in most cases, will include reductions in stationary source NO<sub>x</sub> emissions beyond those required by the RACT provisions of Title I. These requirements apply in certain ozone nonattainment areas and ozone transport regions.

### Mobile Sources

Title II of the CAAA calls for reductions in motor vehicle emissions. Emission limits for new vehicles constitute the majority of reductions from vehicles. Emission limits for various classes of vehicles will be implemented throughout this decade.

### Acid Rain

Title IV of the CAAA focuses on a particular set of NO<sub>x</sub> emitting sources—coal-fired electric utility plants—and uses a two-part strategy to reduce emissions. The first stage of the program is projected to reduce NO<sub>x</sub> emissions in the United States by over 400,000 tons/yr between 1996 and 1999 (Phase I). These reductions are achieved by the installation of low-NO<sub>x</sub> burner (LNB) technology on dry-bottom wall-fired boilers and tangentially fired (T-fired) boilers (Group 1). In Phase II, which begins in 2000, EPA may establish more stringent standards for Group 1 boilers and establish regulations for Group 2 boilers (boilers applying cell-burner

### Coal-Fired Boiler NO<sub>x</sub> Emissions Limits, lb/10<sup>6</sup> Btu (Title IV)

	Phase I	Phase II
Implementation Date	1996	2000+
Status of Regulations	<i>Promulgated</i>	<i>Proposed*</i>
<b>Group 1 Boilers</b>		
Dry-Bottom Wall-Fired	0.50	0.46
Tangentially Fired	0.45	0.40
<b>Group 2 Boilers</b>		
Wet-Bottom Wall-Fired	NA	0.84
>65 MWe		
Cyclone-Fired	NA	0.86
>155 MWe		
Vertically Fired	NA	0.80
Cell Burner	NA	0.68
Fluidized Bed	NA	Exempt
Stoker	NA	Exempt

NA = Not applicable

\*Final ruling is anticipated by December 1997

technology, cyclone boilers, wet-bottom boilers, and other types of coal-fired boilers). Currently EPA has proposed a rule that would set lower Phase II, Group 1 emission limits and establish limits for Group 2, resulting in an additional projected reduction of 820,000 tons/yr.

### Implementation

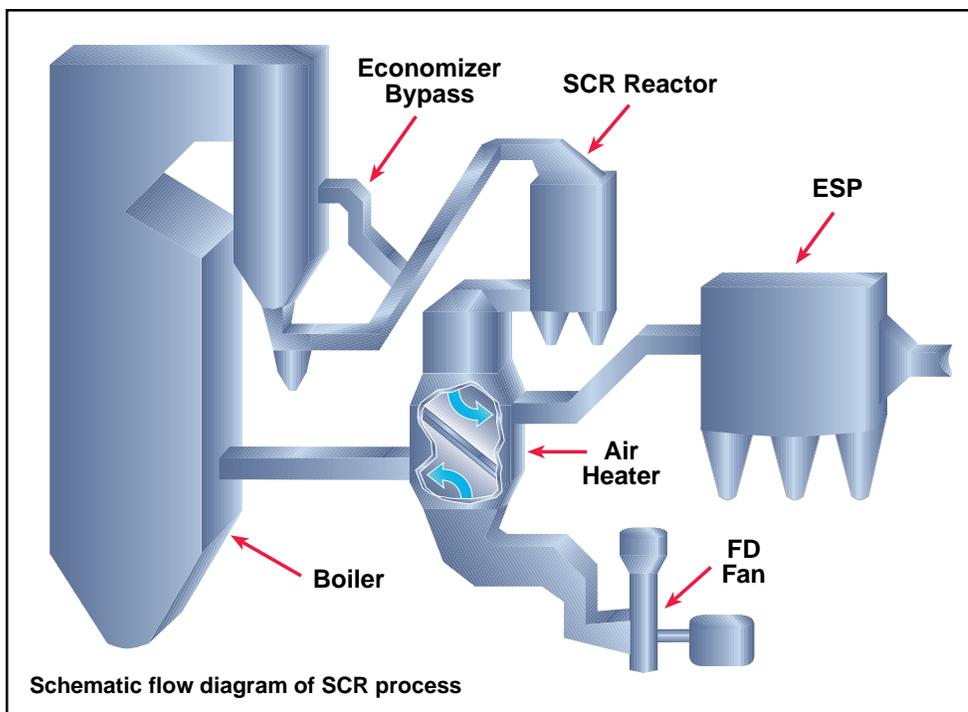
The emission limitations proposed by EPA under Title IV for Phase II, Group 1 boilers are more stringent than the Phase I standards. The statute requires that emission control costs for Group 2 boilers be comparable to those for Group 1 boilers.

EPA has the authority to set Title IV NO<sub>x</sub> limitations at higher levels if a utility can demonstrate that a boiler could not meet the standard by using LNB technology. The regulations also allow for emissions averaging in which the emissions levels established by EPA are applied to an entire group of boilers owned or operated by a single company. Averaging is not limited geographically.

stringent NAAQS for ozone: 0.08 ppm (8 hour average). An area would be considered nonattainment when the third highest daily maximum 8-hour concentration, averaged over three years, is above 0.08 ppm. EPA is also seeking comment on a standard of 0.07 ppm.

## NO<sub>x</sub> Control Technologies

The primary technology currently used in utility boilers for NO<sub>x</sub> reduction is combustion modification using low-NO<sub>x</sub> burners (LNBs), frequently combined with overfire air (OFA). This technology has generally proven adequate to meet Title IV emissions requirements. In fact, field experience with combustion modification technologies demonstrated in the CCT Program substantiated the validity of the current regulations. Utilities subject to the most stringent requirements may be forced to use post-combustion technologies such as SCR, either alone or in combination with LNBs.



## The SCR Process

### History

Selective catalytic reduction of NO<sub>x</sub> using ammonia (NH<sub>3</sub>) as the reducing gas was patented in the U.S. by Englehard Corporation in 1957. The original catalysts, employing platinum or platinum group metals, were 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 done in Japan in response to severe environmental regulations in that country led to the development of vanadium/titanium catalysts which have proved successful. This combination forms the basis of current SCR catalyst technology.

In addition to Japan, several countries in Western Europe have enacted stringent NO<sub>x</sub> emission regulations which essentially mandate the installation of SCR, and extensive catalyst development work has been done, especially in Germany. As a result, SCR has been applied on numerous boilers in Europe. Encouraged in part by the initial success of the SCR test program at Plant Crist, there are now six commercial installations of SCR on coal-burning power plants in the U.S.

### Process Description

NO<sub>x</sub>, which consists primarily of NO with lesser amounts of NO<sub>2</sub>, is converted to nitrogen by reaction with NH<sub>3</sub> over a catalyst in the presence of oxygen. A small fraction of the SO<sub>2</sub>, produced in the boiler by oxidation of sulfur in the coal, is oxidized to sulfur trioxide (SO<sub>3</sub>) over the SCR catalyst. In addition, side reactions may 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>. There are complex relationships governing the formation of

these by-products, but they can be minimized by appropriate control of process conditions.

### Ammonia Slip

Unreacted NH<sub>3</sub> in the flue gas downstream of the SCR reactor is referred to as NH<sub>3</sub> slip. It is essential to hold NH<sub>3</sub> slip to below 5 ppm, preferably 2-3 ppm, to minimize formation of (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> and NH<sub>4</sub>HSO<sub>4</sub>, which can cause plugging and corrosion of downstream equipment. This is a greater problem with high-sulfur coals, caused by higher SO<sub>3</sub> levels resulting from both higher initial SO<sub>3</sub> levels due to fuel sulfur content and oxidation of SO<sub>2</sub> in the SCR reactor.

### Operating Temperature

Catalyst cost constitutes 15-20% of the capital cost of an SCR unit; therefore it is essential to operate at as high a temperature as possible to maximize space velocity and thus minimize catalyst volume. At the same time, it is necessary to minimize the rate of oxidation of SO<sub>2</sub> to SO<sub>3</sub>, which is more temperature sensitive than the SCR reaction. The optimum operating temperature for the SCR process using titanium and vanadium oxide catalysts is about 650-750°F. 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.

### Reactor Placement

SCR systems can be installed at any of three locations in a power plant:

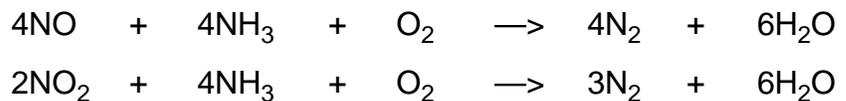
- (1) upstream of the air preheater (APH) and electrostatic precipitator (ESP) [referred to as hot side, high dust]
- (2) upstream of the APH and downstream of the ESP [hot side, low dust]
- (3) downstream of the APH and ESP [cold side, low dust].

## How NO<sub>x</sub> Is Formed in a Boiler

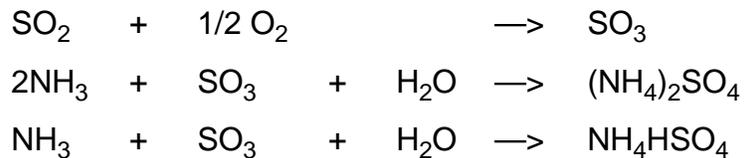
Most of the NO<sub>x</sub> formed during the combustion process is the result of two oxidation mechanisms: (1) reaction of nitrogen in the combustion air with excess oxygen at elevated temperatures, referred to as thermal NO<sub>x</sub>; and (2) oxidation of nitrogen that is chemically bound in the coal, referred to as fuel NO<sub>x</sub>. For coal-fired units, thermal NO<sub>x</sub> generally represents about 25% and fuel NO<sub>x</sub> about 75% of the total NO<sub>x</sub> formed. In addition, minor amounts of NO<sub>x</sub> are formed through complex interaction of molecular nitrogen with hydrocarbons in an early phase of the flame front; this is referred to as prompt NO<sub>x</sub>.

The quantity of NO<sub>x</sub> formed depends primarily on the "three t's": temperature, time, and turbulence. In other words, flame temperature and the residence time of the fuel/air mixture, along with the nitrogen content of the coal and the quantity of excess air used for combustion, determine NO<sub>x</sub> levels in the flue gas. Combustion modifications delay the mixing of fuel and air, thereby reducing temperature and initial turbulence, which minimizes NO<sub>x</sub> formation.

## Chemistry of the SCR Process

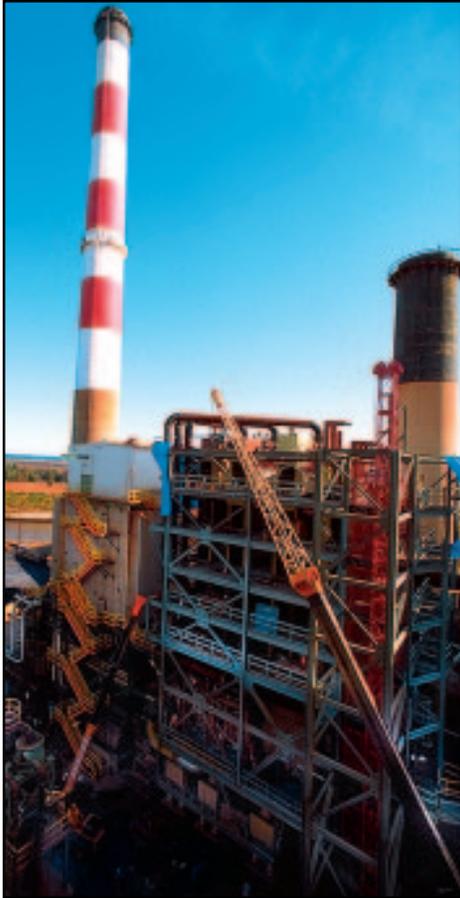


### Side Reactions



In the Plant Crist tests, which operated on a slip stream from the power plant flue gas, each reactor was located upstream of the APH; thus these were hot side installations. Seven of the eight reactors were also high dust installations.

In commercial practice, most SCR reactors are hot side installations. This location is preferred because it obviates the need to reheat the flue gas to reaction temperature, thereby minimizing loss of thermal efficiency.



Plant Crist SCR unit under construction

## Catalysts

SCR catalysts are made of a ceramic material that is a mixture of carrier (titanium oxide) and active components (oxides of vanadium and, in some cases, tungsten). The two leading shapes of SCR catalyst used today are honeycomb and plate. The honeycomb form usually is an extruded ceramic with the catalyst either incorporated throughout the structure (homogeneous) or coated on the substrate. In the plate geometry, the support material is generally coated with catalyst. When processing flue gas containing dust, the reactors are typically vertical, with downflow of flue gas. The catalyst is typically arranged in a series of two to four beds, or layers. For better catalyst utilization, it is common to use three or four layers, with provisions for an additional layer which is not initially installed.

As the catalyst activity declines, additional catalyst is installed in the available spaces in the reactor. As deactivation

continues, the catalyst is 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 sootblowing to remove deposits, using steam as the cleaning agent.

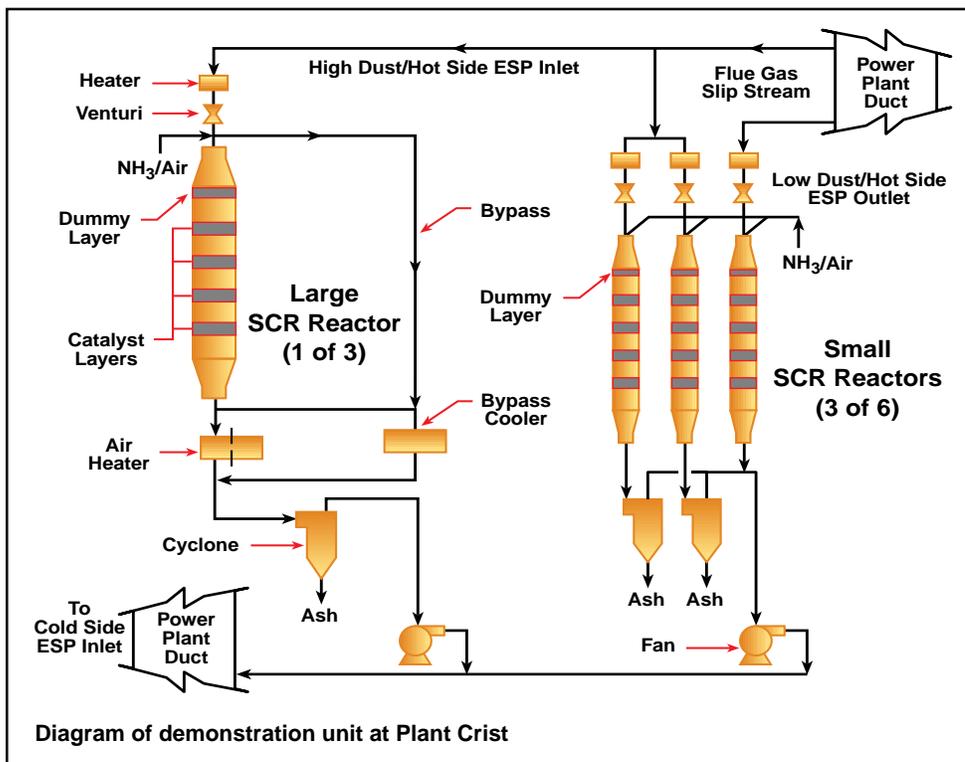
## Clean Coal Technology SCR Demonstration Project

### Goals and Objectives

The goal of the demonstration project at Plant Crist was to evaluate SCR retrofit technology for reducing  $\text{NO}_x$  emissions from utility boilers burning high-sulfur U.S. coals. The project was designed to confirm pilot plant 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.

The objectives of this project were to investigate:

- Performance of a wide variety of SCR catalyst compositions, geometries, and manufacturing methods at typical U.S. utility operating conditions.
- Catalyst resistance to poisoning by trace metal species present in high-sulfur 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  $\text{SO}_2$ ,  $\text{SO}_3$ , and  $\text{NH}_3$  (e.g., plugging and corrosion of downstream equipment).



### Project Description

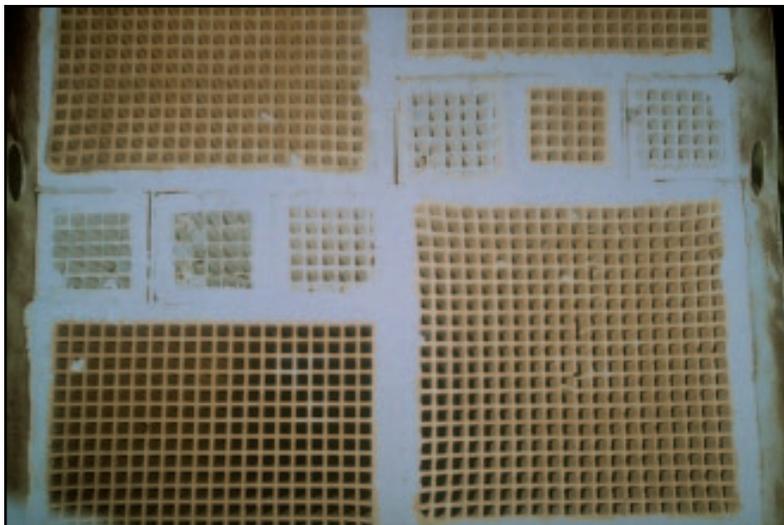
The demonstration project was conducted at Gulf Power's Plant Crist, located near Pensacola, Florida. Plant Crist consists

of seven fossil-fuel burning generating units. Units 1, 2, and 3 are small gas- and oil-fired boilers, while Units 4 through 7 are coal-fired. The SCR test facility was built in and around the ductwork on Unit 5. This unit is a tangentially fired, dry-bottom boiler, rated at 75 MWe (gross), built by Combustion Engineering and placed into operation in 1961. The unit is equipped with hot side and cold side ESPs for particulate control.

The individual SCR reactors operated on a slip stream taken from the flue gas of Unit 5. There were three 2.5-MWe equivalent reactors and six 0.20 MWe equivalent reactors, each containing a different catalyst for side-by-side performance comparisons. Eight of the nine reactors were designed to treat flue gas containing the full particulate loading (high dust), extracted from the inlet duct of the hot side ESP, while one small reactor was designed to treat flue gas extracted from the hot side ESP outlet (low dust). Because of design problems, it was not possible to fully evaluate the differences in performance between the single low dust reactor and the high dust units.

Each reactor train was equipped with an electric duct heater to independently control flue gas temperature and a venturi meter to measure the flue gas flow 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.

For each of the 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



Clean catalyst installed in one of the SCR reactors



Plugging that may occur during normal operations of an SCR facility



Damage caused by erosion in the catalyst bed

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.

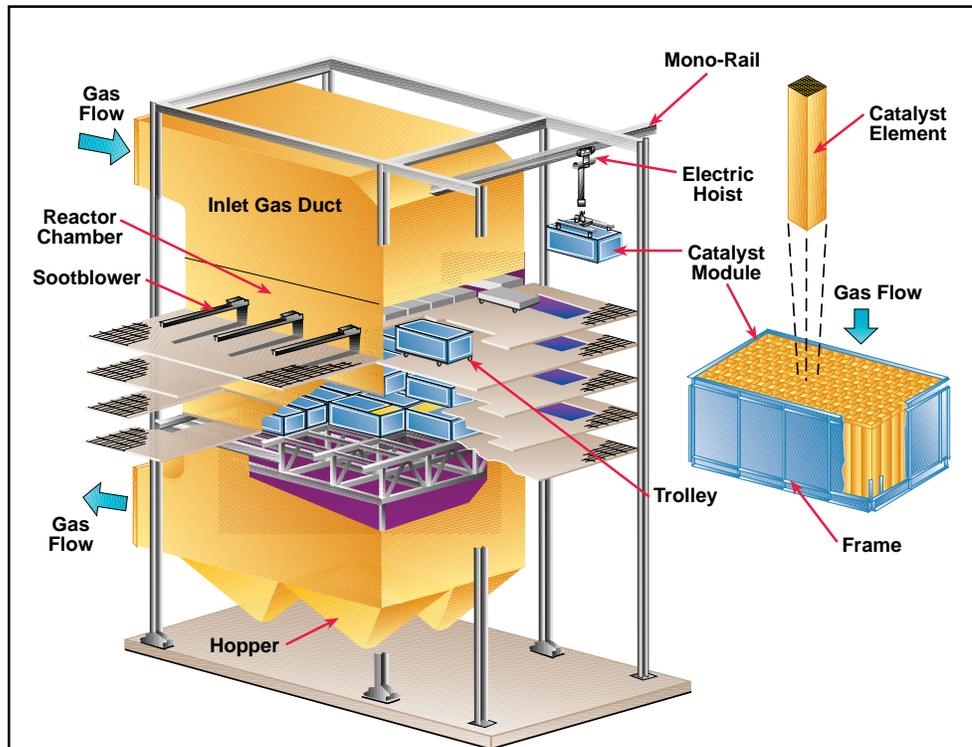
All reactor trains except the low dust train had a cyclone downstream of the SCR reactor to protect the induced draft fans from particulates. The exhausts from all of the SCR reactors were combined into a single manifold and reinjected into the host boiler's flue gas stream ahead of the cold side ESP. The preheated air streams from the APHs on the larger reactors were also combined into a single manifold and returned to the host boiler draft system at the existing host APH outlet. All particulate matter removed from the test facility was combined with ash from the host unit's ESP and sent to ash disposal.

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% NO<sub>x</sub> reduction at baseline conditions
- A maximum baseline NH<sub>3</sub> slip of 5 ppm
- A maximum baseline SO<sub>2</sub> oxidation rate of 0.75%
- A 2-yr life while meeting the above performance criteria

It was determined that full-scale demonstration of SCR technology was not required. The major issues to be addressed were questions of chemistry which could be adequately investigated using a slip stream facility and, in general, the performance of fixed-bed catalytic reactors can readily be scaled up. A full-scale facility would have been unnecessarily expensive while providing little additional in the way of technical information. However, 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 representative 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.

The tests were conducted on flue gas derived primarily from burning Illinois No. 6 coal, a typical midwestern high-sulfur (2.3% sulfur) coal widely used for power generation.



Vertical-flow fixed-bed type reactor chamber

source: Southern Company 1995

## Performance

The catalysts were tested over a two-year period (16,000 hours), including parametric testing every four to six months. Catalysts were provided 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). After Englehard withdrew from the project, its low dust catalyst was replaced by one of Cormetech's low dust catalysts.

All of the catalysts performed well in both parametric (short tests varying operating conditions) and long term (baseline) testing, achieving at least 80% NO<sub>x</sub> removal with 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 was found superior.

Catalyst deactivation proceeded as expected based on European and Japanese experience, with an average decrease in activity of 20% over the two-year period. No unusual deactivation effects could be attributed to the use of high-sulfur U.S. coals, and no detrimental effects of trace metals such as arsenic were detected.

## Properties of Coal Used in Plant Crist Tests Coal Source: Illinois No. 6 Bituminous

### Proximate Analysis, wt% (as received)

Fixed Carbon	47.65
Volatile Matter	34.16
Moisture	9.80
Ash	8.39
Total	100.00
HHV, Btu/lb	12,500

### Ultimate Analysis, wt% (as received)

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

## SCR Catalysts Tested at Plant Crist

Reactor	Catalyst Supplier	Reactor Size	Dust Level	Composition	Catalyst 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

## Kinetics of the SCR Reaction

In some of the earlier literature on the kinetics of the SCR process, the rate constant is defined in the following equations, which assume that the reaction is first order with respect to  $\text{NO}_x$  or  $\text{NH}_3$ :

$$k/SV = -\ln(1-x/r)$$

$$s = (r-x)N_o \quad \text{or} \quad r = x + s/N_o,$$

where  $k$  = rate constant  
 $SV$  = space velocity  
 $x$  = fractional conversion of  $\text{NO}_x$   
 $r$  = molar ratio of  $\text{NH}_3$  to  $\text{NO}_x$  at reactor inlet  
 $s$  =  $\text{NH}_3$  slip  
 $N_o$  =  $\text{NO}_x$  concentration at reactor inlet.

More recent work has shown that the process can be better represented by a modified Langmuir-Hinshelwood relationship, as follows:

$$k/SV = -\ln(1-x/r) + \ln[(1-x)/(1-x/r)]/KN_o(1-r),$$

where  $K$  = adsorption coefficient of  $\text{NO}_x$  on the catalyst.

The latter relationship more accurately predicts space velocity (and hence catalyst volume) required to both remove  $\text{NO}_x$  and minimize  $\text{NH}_3$  slip, especially at higher conversion levels.

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. Other differences include geometric surface area, resistance to poisoning, and conversion of  $\text{SO}_2$  to  $\text{SO}_3$ .

No serious plugging of the catalysts was experienced, indicating that the sootblowing procedures used in the test program were satisfactory. Performance comparisons between high dust and low dust reactor configurations were inconclusive because of problems associated with the design of the test facility.

There was significant variation in the rate of oxidation of  $\text{SO}_2$  to  $\text{SO}_3$  among the catalysts tested, but the amounts of  $(\text{NH}_4)_2\text{SO}_4$  and  $\text{NH}_4\text{HSO}_4$  were minor. However, there was some corrosion of the APHs downstream of the SCR reactors. Appropriate materials of construction for APHs need to be chosen for commercial SCR installations.

The environmental impacts of the technology studied in the test program are significant. SCR has been shown to provide high levels of  $\text{NO}_x$  removal with minimal  $\text{NH}_3$  slip. Widespread use is anticipated in the future, providing a major reduction in  $\text{NO}_x$  emissions from coal-fired power plants in the United States.

## SCR Process Conditions

	Design Basis for 80% Conversion	Parametric Tests
Temperature, °F	700	620-750
Flow, SCFM	5000 (large reactors) 400 (small reactors)	60% to 150% of Design
$\text{NH}_3/\text{NO}_x$ Molar Ratio	~0.81	0.6 to 1.0

## Long Term Testing of Catalyst Deactivation

The results of the long term catalyst tests are expressed in terms of the decrease in activity over time, as measured by the rate constant,  $k$ . From a practical standpoint, the precise kinetic relationship is of little concern. What is important is the ratio  $k/k_o$ , where  $k$  is the rate constant at a given time in the deactivation cycle and  $k_o$

is the initial rate constant with fresh catalyst. For this project this ratio, and thus catalytic activity, was determined by dividing the fractional  $\text{NO}_x$  conversion at a given time by the conversion at time zero, based on assuming first order kinetics. For the SCR test program at Plant Crist, the relative activity began at 1.0 at time zero and decreased to an average of about 0.8 at 12,000 hours.

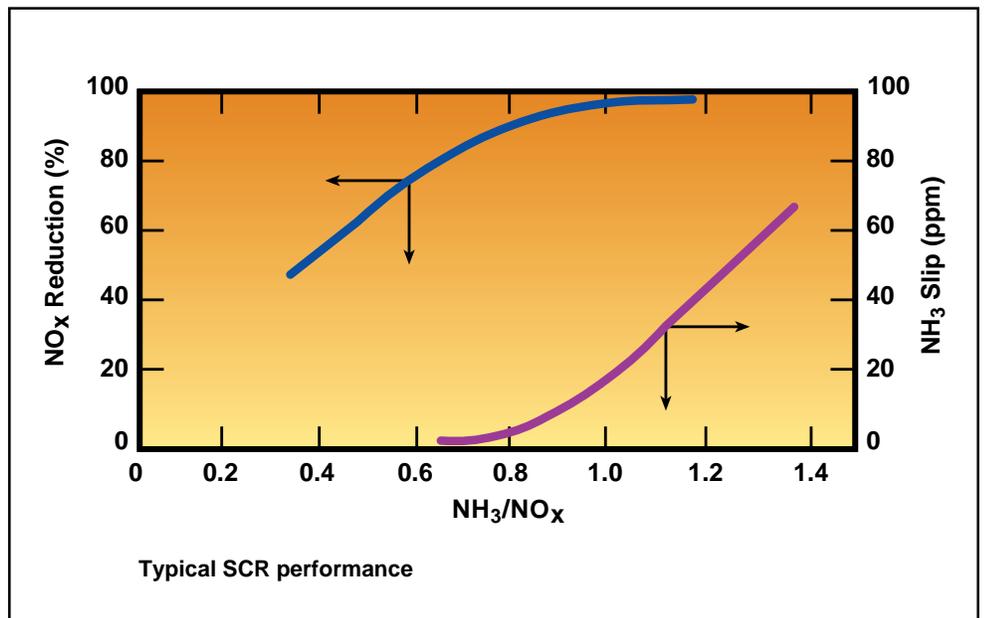
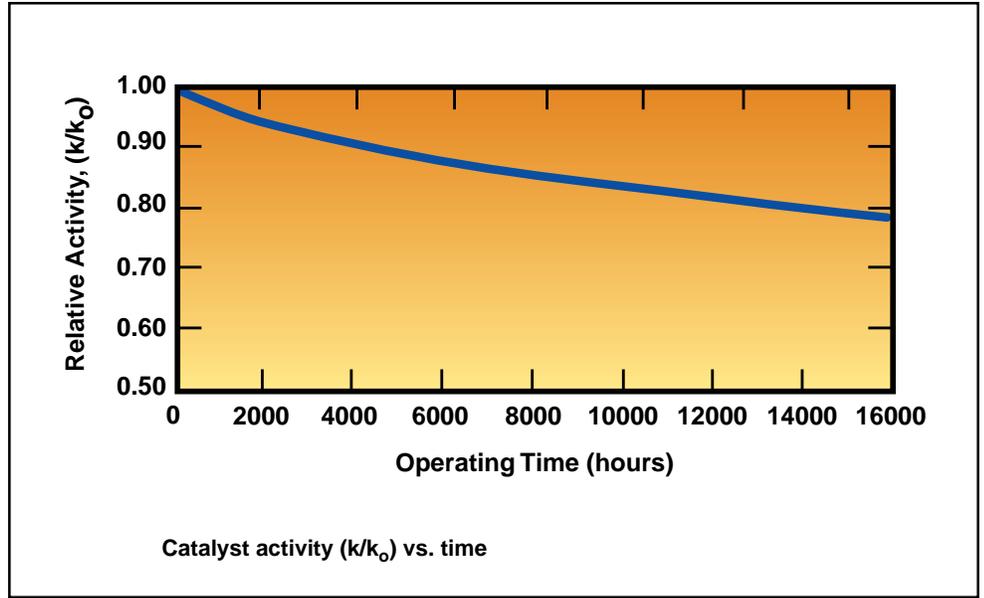
## Parametric Studies

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

The tests covered the range of  $620^\circ\text{F}$  to  $750^\circ\text{F}$ , with the design operating temperature being  $700^\circ\text{F}$ . As temperature was increased while maintaining a constant 0.8  $\text{NH}_3/\text{NO}_x$  ratio,  $\text{NH}_3$  slip remained fairly constant at less than 5 ppm. The parametric tests covered the range of 0.6 to 1.0, with the design  $\text{NH}_3/\text{NO}_x$  molar ratio being 0.8.  $\text{NH}_3$  slip generally remained constant at about 2 ppm at low levels of  $\text{NH}_3/\text{NO}_x$  ratio, increasing significantly above a ratio of about 0.9.

At an operating temperature of  $700^\circ\text{F}$  and an  $\text{NH}_3/\text{NO}_x$  ratio of 0.8, increasing the gas flow rate (and hence the space velocity) from 100% to 150% of the design value resulted in a fairly constant  $\text{NH}_3$  slip of less than 5 ppm for three of the catalysts.  $\text{NH}_3$  slip increased to significantly greater than 5 ppm for the other three catalysts studied in this part of the test program.

As the temperature was increased, the rate of  $\text{SO}_2$  oxidation was fairly constant at less than 0.2% for two of the catalysts, while increasing to varying degrees for the other catalysts.



## Significance of Test Results

The test data show that the SCR process can achieve high (up to 90%) NO<sub>x</sub> reduction while meeting acceptable NH<sub>3</sub> slip levels over an extended period of operation (at least two years). In practice, SCR reactors are designed not just to meet specified NO<sub>x</sub> levels at startup, but sufficient catalyst volume is provided to allow for catalyst deactivation.

NO<sub>x</sub> reduction is controlled for the most part by the NH<sub>3</sub>/NO<sub>x</sub> ratio. Therefore, even with excess catalyst in the reactor, NO<sub>x</sub> 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. Although relatively high NH<sub>3</sub> slip was observed in this study at high levels of NO<sub>x</sub> reduction, this effect probably resulted from the difficulty in maintaining precise measurement and control of NH<sub>3</sub> flow while operating at NH<sub>3</sub>/NO<sub>x</sub> ratios approaching 1.0. This effect could be

### Commercial SCR Installations on Coal-Fired Utility Boilers in the U.S.

Plant	Birchwood	Stanton (Unit 2)	Carneys Point (2 Units)	Logan	Indiantown	Merrimack 2
Owner/ Operator	SEI <sup>a</sup> / Cogentrix	Orlando Utilities Commission	USGen <sup>b</sup>	USGen <sup>b</sup>	USGen <sup>b</sup>	Public Service of NH
Location	King George County, VA	Orlando, FL	Carneys Point, NJ	Swedesboro, NJ	Indiantown, FL	Concord, NH
Capacity, MWe (net)	220	425	260	225	330	330
Coal Sulfur, wt%	1.0	1.1-1.2	<2.0	<1.5	0.8	1.5
Boiler Type	T-fired	Wall-fired	Wall-fired	Wall-fired	Wall-fired	Wet-bottom
Burner Type <sup>c</sup>	LNB/OFA	LNB/OFA	LNB/OFA	LNB/OFA	LNB/OFA	Cyclone
Catalyst Supplier	Siemens	Siemens	IHI <sup>d</sup>	Siemens	Siemens	Siemens
Inlet NO <sub>x</sub> , lb/10 <sup>6</sup> Btu	0.17	0.32	0.32	0.35	0.25	2.66
Outlet NO <sub>x</sub> , lb/10 <sup>6</sup> Btu	0.075	0.17	0.13	0.14	0.15	0.77
NO <sub>x</sub> Reduction, %	56	47	59	60	40	71
NH <sub>3</sub> Slip, ppm	<5	2	<5	<5	<5	<2
Date SCR Commercial SCR Installation	11/96 New	6/96 New	3/94 New	9/94 New	12/95 New	5/95 Retrofit

<sup>a</sup> Southern Energy, Inc.

<sup>b</sup> U.S. Generating Company, a Pacific Gas and Electric Company/Bechtel partnership

<sup>c</sup> LNB = Low-NO<sub>x</sub> burners; OFA = overfire air

<sup>d</sup> Ishikawajima-Harima Heavy Industries

encountered in commercial units in cases where the owner/operator attempts to “stretch” the performance of the catalyst.

## Commercial Applications of SCR Technology

With the completion of the SCR test program at Plant Crist, the experimental facility was dismantled. Supported in part by the successful demonstration of SCR technology at Plant Crist, several U.S. companies have decided to use SCR on coal-fired utility boilers.

At present, there are six such installations. 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 was based on data from the test program at Plant Crist. Since all of the U.S. installations are relatively new, there has not been sufficient time to evaluate long-term performance, particularly with respect to catalyst deactivation. All of the SCR units are hot side, high dust installations. Five of the SCR units are associated with new plants and one is a retrofit. The feed coals range in sulfur content from about 0.8 to 2.0 wt%.

All of the U.S. SCR units are operating successfully, with NO<sub>x</sub> reductions ranging from 40 to 71% depending on the uncontrolled NO<sub>x</sub> concentration and the desired level of NO<sub>x</sub> in the stack gas. With the exception of one unit which appears to have initially contained insufficient catalyst because of higher uncontrolled NO<sub>x</sub> than the catalyst was designed for, there have been no problems in meeting NH<sub>3</sub> slip requirements or with deposition of solids, and catalyst deactivation has proceeded as predicted from the Plant Crist test data.

The poorly performing unit initially experienced frequent plugging of the air preheater surfaces downstream of the SCR reactor. This problem was remedied by installation of additional catalyst, bringing performance to the desired level. In general, the plant staff and management at each facility are pleased with the SCR operation.

## Future Work

The demonstration project and the subsequent commercial applications on coal-fired boilers in the United States have shown that SCR can achieve high levels of NO<sub>x</sub> reduction at an acceptable cost. This has been a major contributing factor in EPA’s recent actions in proposing more stringent control of NO<sub>x</sub> emissions from coal-burning power plants. It is expected that design improvements will be made as operating experience is gained.

The degree to which SCR will be incorporated in new or future retrofit applications will depend on the severity of NO<sub>x</sub> control standards yet to be promulgated.



SCR reactor cyclones at Plant Crist

## Boiler Population in the OTAG Region

Boiler Type	Number of Units	Generating Capacity, MWe
Wall-fired	315	94,327
Tangentially fired	315	112,000
Cyclone	77	22,329
Cell-fired	33	24,143
Wet-bottom	23	4,712
Roof-fired	29	3,111
<b>Total</b>	<b>792</b>	<b>260,622</b>

**Economics of SCR Process**  
**1996 Dollars**  
**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 Requirement</b>	<b>\$/kW</b>	<b>54</b>

	<b>Levelization Factor [a]</b>	<b>mills/ kWh</b>	<b>\$/ton NO<sub>x</sub> removed</b>
<b>Levelized Cost, Current \$</b>			
Capital charge	0.154	1.50	1464
Fixed O&M	1.362	0.32	310
Variable O&M	1.362	0.75	726
Total		<u>2.57</u>	<u>2500</u>

<sup>a</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 9.150% (including inflation).

In fact, the success of the experimental work at Plant Crist and the experience gained in the subsequent commercial applications in the U.S. have contributed significantly to consideration of more stringent NO<sub>x</sub> emissions criteria.

## Market Analysis

The SCR process is applicable to all types of boilers including stoker, cyclone, wall-fired and tangentially fired boilers. A potential market for SCR is in the Ozone Transport Assessment Group (OTAG) region.

OTAG, which was created under the auspices of the EPA for the purpose of developing recommendations for ozone reduction, comprises the 37 contiguous states except the 11 westernmost states. All boilers in the OTAG region are potential candidates for SCR, although regulations are still being formulated and many of these boilers may not be subject to NO<sub>x</sub> emissions limits so stringent as to require the use of SCR. In any given case the economic viability of SCR will be highly dependent upon retrofit difficulty and other site specific factors.

The need for SCR will be dictated by the power plant NO<sub>x</sub> emissions limits now being considered, since LNBs (with or without OFA) will not be able to meet the lower NO<sub>x</sub> target levels. Utilities subject to the most stringent requirements may be forced to use SCR, either alone or in conjunction with LNBs.

## Economics

### SCR Costs – Southern Company Estimates

The Southern Company has prepared economic estimates for the SCR process. The base case is 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 boiler is either a wall-fired or T-fired unit, equipped with LNBS. The coal feed is assumed to contain 2.5 wt% sulfur. Design  $\text{NO}_x$  concentration at the reactor inlet is 0.35 lb/10<sup>6</sup> Btu.  $\text{NO}_x$  reduction is assumed to be 60%, giving an outlet concentration of 0.14 lb/10<sup>6</sup> Btu. Catalyst deactivation is assumed to be 20% at 16,000 hr; that is, the  $k/k_0$  ratio is 0.8 at that time.

The estimated capital cost is \$54/kW. For a 30-year project life, the levelized cost on a current dollar basis is 2.57 mills/kWh. This is equivalent to \$2500/ton of  $\text{NO}_x$  removed.

The economics are highly dependent on a number of variables including plant capacity, degree of  $\text{NO}_x$  removal, and inlet  $\text{NO}_x$  concentration. At a given plant capacity, levelized costs on a \$/ton of  $\text{NO}_x$  removed basis decrease with increasing  $\text{NO}_x$  removal rate and increasing initial  $\text{NO}_x$  concentration, such as would occur in situations where SCR is used on boilers with the highest uncontrolled  $\text{NO}_x$  levels and without combustion modification. Longer catalyst life and/or reduced catalyst prices also reduce costs.

### Effect of $\text{NO}_x$ Removal Rate on SCR Economics 1996 Dollars Greenfield Installation

$\text{NO}_x$ Removal, %	50	60	70	80	90
Outlet $\text{NO}_x$ , lb/10 <sup>6</sup> Btu	0.39	0.31	0.23	0.15	0.08
Capital, \$/kW	55	57	59	62	66
\$/ton $\text{NO}_x$ removed (current dollar basis)	1750	1540	1390	1290	1260

### Sensitivity Analysis of SCR Economics 1996 Dollars Greenfield Installation

#### Effect of Capacity

Capacity, MWe	125	250	700
$\text{NO}_x$ Removal, %	60	60	60
Inlet $\text{NO}_x$ , lb/10 <sup>6</sup> Btu	0.35	0.35	0.35
Capital, \$/kW	61	54	45
\$/ton $\text{NO}_x$ removed (current dollar basis)	2811	2500	2165

#### Effect of Inlet $\text{NO}_x$

Capacity, MWe	250	250	250
$\text{NO}_x$ Removal, %	60	60	60
Inlet $\text{NO}_x$ , lb/10 <sup>6</sup> Btu	0.45	0.35	0.25
Capital, \$/kW	61	54	45
\$/ton $\text{NO}_x$ removed (current dollar basis)	1977	2500	3446

### SCR Costs – Other Estimates

The above cost estimates, prepared by Southern, assume the use of combustion modification to reduce NO<sub>x</sub> in the flue gas to 0.35 lb/10<sup>6</sup> Btu at the SCR reactor inlet, with only 60% additional reduction in the SCR unit required to achieve the target NO<sub>x</sub> emissions level of 0.14 lb/10<sup>6</sup> Btu. Alternatively, it is useful to consider situations where all of the NO<sub>x</sub> reduction is achieved via SCR. The effects of inlet NO<sub>x</sub> concentration, unit capacity, and NO<sub>x</sub> removal rate on SCR economics were investigated in a DOE study. The base case is assumed to have an inlet NO<sub>x</sub> concentration of 500 ppm, or about 0.77 lb/10<sup>6</sup> Btu, representing a typical T-fired boiler. Boiler capacity is 250 MWe, as in the Southern study. Ammonia slip is 5 ppm and catalyst life is 4 years.

It should be noted that as the NO<sub>x</sub> removal efficiency increases, the capital cost increases but the levelized cost decreases because of the larger number of tons/yr of NO<sub>x</sub> removed.

The above costs are consistent with figures obtained recently from a major supplier of SCR catalyst, incorporating

detailed engineering estimates for six retrofit units ranging from 190 MWe to 570 MWe, with 85% NO<sub>x</sub> removal. Capital costs were \$55 to \$84/kW, and levelized costs were \$950 to \$1400/ton of NO<sub>x</sub> removed.

An alternative approach to SCR commercialization involves the Build, Own, Operate, and Maintain (BOOM) concept, in which a third party provides the capital for the SCR unit, eliminating the need for a major expenditure on the part of the utility. The third party also operates and maintains the SCR unit, charging the utility an agreed upon price for providing SCR services. Preliminary proposals using this concept show favorable economics compared with conventional funding approaches.

### Comparison with Other Technologies

The only other commercially available technology capable of achieving NO<sub>x</sub> removal levels comparable to that of LNBs is selective noncatalytic reduction (SNCR). Since SNCR does not require use of a catalyst, it may be considerably less expensive than SCR. However, typical NO<sub>x</sub> removals for SNCR are 25-45%, whereas U.S. commercial SCR installations are achieving up to about 70% NO<sub>x</sub> removal. In addition, some experience has shown that SNCR applications are limited to smaller boilers because of difficulties in achieving uniform distribution of reagent in the flue gas stream, and numerous control problems have arisen especially where loads fluctuate. Therefore, SCR may be preferred over SNCR in some situations. Hybrid processes, using SNCR followed by SCR, have the potential for operating flexibility at lower overall cost. Such configurations need to be evaluated on a case-by-case basis.

### Worldwide Installations of SCR on Coal-Fired Utility Boilers 1996 Data

Country/Region	Capacity, MWe
Austria	1,200
Germany	33,000
Japan	7,700
Netherlands	1,000
Scandinavia	1,100
United States	2,000
Total	46,000

## Conclusions

The SCR demonstration project was successful. All of the catalysts in the test program met design specifications, providing at least 80% NO<sub>x</sub> removal at an NH<sub>3</sub> slip of 5 ppm or less. Although the catalysts varied somewhat in operating characteristics such as activity and pressure drop, no one catalyst was found superior. Catalyst deactivation proceeded as expected based on European and Japanese experience,

with an average decrease in activity of 20% over a two-year period. No unusual deactivation effects could be attributed to the use of high-sulfur U.S. coals containing typical concentrations of metals such as arsenic. Both plate and honeycomb catalysts performed satisfactorily.

There was significant variation in the rate of oxidation of SO<sub>2</sub> to SO<sub>3</sub> among the catalysts tested, but the amount of oxidation was minimal, and excessive formation of (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> and NH<sub>4</sub>HSO<sub>4</sub> was avoided. Some corrosion of the air preheaters was experienced, indicating

the need to specify appropriate materials of construction in this service. No serious plugging of the catalysts was found, indicating that the sootblowing procedures used in the test program were satisfactory.

A commercial-scale SCR unit can be installed for about \$50-60/kW in a new plant. Retrofit costs could be significantly higher. Six commercial SCR units are operating successfully on low- and medium-sulfur coals in the United States. A significant market for SCR potentially exists, especially in light of increasingly stringent limitations on NO<sub>x</sub> emissions.



SCR demonstration facility at Plant Crist

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Plant Crist is only 5 miles from this pristine beach



SCR unit at Birchwood Power Plant

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SCR unit at Merrimack Power Plant Unit 2

## List of Acronyms and Abbreviations

Btu .....	British thermal unit
CAAA .....	Clean Air Act Amendments of 1990
CCT .....	Clean Coal Technology
DOE .....	U.S. Department of Energy
EPA .....	U.S. Environmental Protection Agency
EPRI .....	Electric Power Research Institute
ESP .....	electrostatic precipitator
FETC .....	Federal Energy Technology Center
kW .....	kilowatt
kWh .....	kilowatt hour
LNB .....	low-NO <sub>x</sub> burners
MWe .....	megawatts of electric power
NAAQS .....	National Ambient Air Quality Standards
NO <sub>x</sub> .....	nitrogen oxides
NOTR .....	Northeast Ozone Transfer Region
NSPS .....	New Source Performance Standards
OFA .....	overfire air
OTAG .....	Ozone Transport Assessment Group
RACT .....	Reasonably Available Control Technology
SCR .....	selective catalytic reduction
SNCR .....	selective noncatalytic reduction
VOCs .....	volatile organic compounds