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March 14, 2006

Mr. Terry O'Clair
Division of Air Quality
North Dakota Department of Health
918 East Divide Avenue, 2nd Floor
Bismarck, ND 58501-1947

MAR 2006
Received
Air Quality

Subject: BART Analysis
Technical Infeasibility of SCR

Dear Mr. O'Clair:

During the meeting between Basin Electric Power Cooperative, Minnkota Power Cooperative, and the Department, on February 21, 2006 concerning the above subject, the Department requested the reference materials used for Steve Benson's report. Enclosed are copies of the requested reference materials.

Sincerely,

John T. Graves, P.E.
Environmental Manager

C: Cris Miller, BEPC w/enc.

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SCR catalyst performance in flue gases derived from subbituminous and lignite coals

Steven A. Benson*, Jason D. Laumb, Charlene R. Crocker, John H. Pavlish

Energy and Environmental Research Center, University of North Dakota, PO Box 9018, Grand Forks, ND 58202-9018, United Sates

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Abstract

Lignite and subbituminous coals from the United States of America have characteristics that impact the performance of catalysts used in selective catalytic reduction (SCR) for nitrogen oxide removal and mercury oxidation. Typically, these coals contain ash-forming components that consist of inorganic elements (sodium, magnesium, calcium, and potassium) associated with the organic matrix and mineral grains (quartz, clays, carbonates, sulfates, and sulfides). Upon combustion, the inorganic components undergo chemical and physical transformations that produce intermediate inorganic species in the form of inorganic gases, liquids, and solids. The alkali and alkaline-earth elements are partitioned between reactions with minerals and reactions to form alkali and alkaline-earth-rich oxides during combustion. The particles resulting from the reaction with minerals produce low-melting-point phases that cause a wide range of fireside deposition problems. The alkali and alkaline-earth-rich oxides consist mainly of very small particles (<5 μm) that are carried into the backpasses of the combustion system and react with flue gas to form sulfates, and possibly carbonates. These particles cause low-temperature deposition, blinding, and plugging problems in SCR systems. These coals also contain the very low levels of chlorine that are necessary for mercury oxidation. Slipstream testing was conducted at two selected subbituminous-fired power plants and one lignite-fired power plant to determine the impacts of ash on SCR plugging, blinding, and mercury oxidation. The results indicated a high potential for

* Corresponding author. Tel.: +1 701 777 5177; fax: +1 701 777 5181.
E-mail address: sbenson@undeerc.org (S.A. Benson).

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blinding and plugging due to the formation of sulfate-bonded deposits and no evidence for mercury oxidation.
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Keywords: Coal; Selective catalytic reduction (SCR); Blinding; NO_x; Mercury; Oxidation

1. Introduction

Selective catalytic reduction (SCR) for NO_x control and mercury oxidation was investigated using a slipstream reactor at power plants firing subbituminous and lignite coals to determine the potential for ash plugging, catalyst blinding, and mercury oxidation. SCR units lower NO_x emissions by reducing NO_x to N_2 and H_2O. Ammonia (NH_3) is the most common reducing agent used for the SCR of NO_x. The SCR process involves the use of a metal oxide catalyst such as titanium dioxide-supported vanadium pentoxide catalyst (V_2O_5). These units are operated at about 340–370 °C (650–700 °F). Subbituminous and lignitic coals are known for their ability to produce alkali and alkaline-earth sulfate-bonded deposits at low temperature (<1000 °C) in utility boilers. The mechanisms of the formation of low-temperature sulfates have been extensively examined and modeled by the Energy and Environmental Research Center (EERC) in work termed Project Sodium and Project Calcium in the early 1990s [1,2]. Deposit buildup of this type blinds or masks the catalyst, diminishing its reactivity for converting NO_x to N_2 and water and potentially creating increased ammonia slip [3]. Elemental mercury oxidation has been observed in laboratory-, pilot-, and full-scale testing using SCR catalysts [4–6]. In these studies, the metal oxides, V_2O_5 and TiO_2, have been shown to promote the conversion of elemental mercury to oxidized and/or particulate-bound mercury. Full-scale tests in Europe [7] and the United States [8] have indicated that the V_2O_5 and TiO_2 catalyst may promote the formation of oxidized mercury. The ability to oxidize mercury is largely dependent on the composition of the coal [8].

Lignite and subbituminous coals produce ash that plug and blind catalysts [9–12]. The problems currently being experienced on SCR catalysts include the formation of sulfate- and phosphate-based blinding materials on the surface of catalysts and the carrying of deposit fragments, or popcorn ash, from other parts of the boiler and depositing them on top of the SCR catalysts [3]. The most significant problem that limits the successful application of SCR catalysts to lignite coal is the formation of low-temperature sodium–calcium–magnesium sulfates, phosphates, and possibly carbonates that will form on the surfaces of catalysts and the carryover of deposits that will plug the catalyst openings, resulting in increased pressure drop and decreased efficiency [3,11–14]. The degree of the ash-related impacts on SCR catalyst performance depends upon the composition of the coal, the type of firing systems, flue gas temperature, and catalyst design [11–15].

Cichanowicz and Broske [13] conducted tests on a South African and a German Ruhr Valley coal and found that the German Ruhr Valley coal significantly increased the pressure drop across the catalyst because of the accumulation of ash. They found that the German coal produced a highly adhesive ash consisting of alkali (K and Na) sulfates. In addition, they reported that the alkali elements are in a water-soluble form and highly

Table 1
Description of power plants tested

	Baldwin	Columbia	Coyote
Unit #	1	2	1
Utility	Dynegy	Alliant	Otter Tail
Boiler type	Cyclone	T-Fired	Cyclone
Fuel type	Antelope—subbituminous	Caballo—subbituminous	Beulah—Zap lignite
Load	Base	Base	Base
Location	Baldwin, IL	Portage, WI	Beulah, ND
MW	600	520	425

mobile and will migrate throughout the catalyst material, reducing active sites. The water-soluble form is typical of organically associated alkali elements in coals. The German Ruhr Valley coal has about 9.5% ash and 0.9% S on an as-received basis, and the ash consists mainly of Si (38.9%), Al (23.2%), Fe (11.6%), and Ca (9.7%), with lower levels of K (1.85%) and Na (0.85%) [13]. Cichanowicz and Muzio [14] summarized the experience in Japan and Germany and indicated that the alkali elements (K and Na) reduced the acidity of the catalyst sites for total alkali content (K+Na+Ca+Mg) of 8–15% of the ash in European power plants. Licata et al. also found that alkaline-earth elements such as calcium react with SO_3 on the catalyst, resulting in plugging of pores and a decrease in the ability of NH_3 to bond to catalyst sites. The levels of calcium in the coals that caused blinding ranged from 3% to 5% of the ash. Studies conducted on the impact of alkali elements associated with biomass found that, when biomass is fired, poisoning and blinding of SCR catalysts occurred [16,17].

The slipstream reactors were installed at three power plants. Two of the plants were cyclone fired: one with lignite and one with subbituminous coal. The third plant was a pulverized-coal, tangentially fired unit with subbituminous coal. The slipstream reactors were designed to expose SCR catalysts to flue gas and particulate matter under conditions that simulate gas velocities, temperatures, and ammonia injection of a full-scale plant. The control system maintains catalyst temperature, pulse air to remove accumulated deposits, constant gas flow across the catalyst, and records pressure drops and temperatures. The reactor was operated in an automated mode and can be controlled via modem connection. Testing at each power plant was conducted over a 6-month period. The reactor was inspected and cleaned at 2-month intervals, and a catalyst section was removed for analysis. The

Table 2
Key selection criteria

Field test 1—Columbia Station
Tangentially fired boiler to show differences in ash partitioning as compared to cyclone-fired systems. High-potential-blinding coal in Caballo, which can be burned nearly 100% for the entire test.
Field test 2—Baldwin Station
Plant is cyclone fired. Units are already equipped to do slipstream testing. Plant currently fires a blend of Antelope and tires; plant is willing to fire 100% Antelope. High potential blinding coal in Antelope.
Field test 3—Coyote Station
Cyclone-fired with lignite. High potential blinding with high alkali and alkaline-earth elements. Coal can have very high sodium contents and is known to cause significant low-temperature deposition.

Table 3
Ultimate analysis results (dry basis)

	Antelope	Caballo	Beulah
Ash content	7.28	6.59	11.62
Total sulfur	0.33	0.51	1.49
Carbon	69.97	67.88	61.50
Hydrogen	4.77	4.83	3.96
Nitrogen	1.05	1.24	1.08
Oxygen (by difference)	16.61	18.96	20.35

catalysts and associated ash deposits were analyzed to determine the characteristics of the ash on the surface and in the pores. In addition, the mercury speciation in the flue gas upstream and downstream of the catalyst was conducted at 2-month intervals during the testing at the lignite-fired plant. The ability of the SCR catalyst materials to catalyze gaseous elemental mercury (Hg^0[g]) to a more soluble and chemically reactive $Hg^{2+}X$(g) forms was evaluated, along with the potential increase in particle-associated mercury, Hg(p). Increasing the oxidized and particulate fractions of mercury has the potential to increase the capture efficiency of mercury by conventional control devices such as wet flue gas desulfurization (FGD) scrubbers and electrostatic precipitators (ESPs).

This paper summarizes pressure drop, formation of deposits that blind the surface of the catalyst, and the ability of SCR catalysts to oxidize mercury.

2. Experimental

2.1. Overview of test program and fuel characteristics

A portable SCR slipstream reactor system was designed and constructed to conduct full-scale evaluation of the SCR catalyst ash plugging and blinding and mercury oxidation. A particle-laden flue gas slipstream was isokinetically extracted from the flue gas duct ahead of the air heater at full-scale utilities using an induced-draft fan. Two systems were constructed

Table 4
Ash composition (wt.% equivalent oxide)

Oxide	Antelope	Caballo	Beulah
SiO_2	24.82	26.70	16.50
Al_2O_3	13.55	16.60	13.30
TiO_2	1.39	1.10	0.80
Fe_2O_3	7.52	5.10	16.60
CaO	26.68	25.10	19.50
MgO	7.14	8.00	7.40
K_2O	0.17	0.30	0.20
Na_2O	1.47	1.00	5.20
P_2O_5	0.90	1.70	0.00
SO_3	16.33	14.40	19.80

so that data may be collected simultaneously from two full-scale sites. Testing was conducted at three boilers, including tests on a cyclone boiler firing Powder River Basin (PRB) coal, a lignite-fired cyclone boiler, and a pulverized coal boiler burning PRB. SCR catalysts were exposed to flue gases and combustion-derived fly ash particles for 6-month time periods to study the blinding effect of fly ash and ash deposits on catalyst performance.

The electric utility units selected for testing are shown in Table 1. The plants where the SCR slipstream system was installed included Alliant Energy's Columbia Station, Dynegy's Baldwin Station, and Otter Tail Power Company's Coyote Station. Table 1 describes the plants, and Table 2 summarizes the characteristics and selection criteria.

The units tested were selected based on the fuels fired, boiler type, and availability of the unit for sampling. The average composition of the coals fired during the testing is

Table 5
CCSEM analysis results for Beulah, Antelope, and Caballo (values are wt.% on a mineral basis)

	Caballo	Antelope	Beulah
Total mineral wt.% on a coal basis	2.8	3.2	8.4
Quartz	40.4	31.5	11.0
Iron oxide	0.0	2.4	4.4
Periclase	0.0	0.0	0.0
Rutile	2.4	0.3	0.0
Alumina	0.0	0.0	1.1
Calcite	0.0	0.4	0.1
Dolomite	0.0	0.5	0.0
Ankerite	0.0	0.0	0.2
Kaolinite	23.7	17.1	4.9
Montmorillonite	0.4	6.5	6.6
K Al-silicate	0.0	1.6	7.2
Fe Al-silicate	0.0	0.8	9.0
Ca Al-silicate	0.1	1.0	2.6
Na Al-silicate	0.0	0.0	0.1
Aluminosilicate	0.7	3.3	3.2
Mixed Al-silicate	0.0	1.0	5.5
Fe silicate	0.0	0.0	0.0
Ca silicate	0.0	0.4	0.0
Ca aluminate	0.0	0.0	0.0
Pyrite	16.2	0.0	0.8
Pyrrhotite	0.0	4.8	18.4
Oxidized pyrrhotite	0.0	0.5	0.5
Gypsum	0.4	0.0	0.5
Barite	0.8	0.5	3.0
Apatite	0.0	0.2	0.0
Ca Al-P	8.5	13.5	0.1
KCl	0.0	0.0	0.0
Gypsum/barite	0.0	0.1	0.0
Gypsum/Al-silicate	0.1	0.9	4.0
Si-rich	0.3	3.7	4.9
Ca-rich	0.0	0.0	0.0
Ca–Si-rich	0.0	0.1	0.0
Unclassified	3.2	8.7	11.9
Total	100.0	100.0	100.0

listed in Tables 3 and 4. The subbituminous coals were typically low ash, nominally 4.5% to 5.5% with very high levels of calcium in the ash. In comparison, the lignite contains higher levels of ash and lower calcium but higher levels of sodium. The alkali and alkaline-earth elements are primarily associated with the organic matrix of the coal as salts of carboxylic acid groups [18]. The portion of the ash-forming components that are associated with the organic matrix of the coal for subbituminous coal ranges from 30% to 60% [18]; for the lignite coal, the portion is about 20% to 40%. The remaining ash-forming components consist of mineral grains. For these coals, the percent organically associated is 29% for the Antelope, 36% for Caballo, and 19% for Beulah. The minerals present in the coals determined by computer-controlled scanning electron microscopy (CCSEM) analyses are listed in Table 5. The primary minerals present in the subbituminous coals include quartz and various clay minerals with some pyrite and a mineral that is rich in Ca, Al, and P. This mineral has been identified in some coals as crandalite. The primary minerals found in the Beulah coal include clay minerals (kaolinite), pyrite, and quartz.

2.2. SCR slipstream system

The SCR slipstream system consists of two primary components: the control room and the SCR reactor. The reactor section consists of a catalyst section, an ammonia injection system, and sampling ports for NO_x at the inlet and exit of the catalyst section. The control

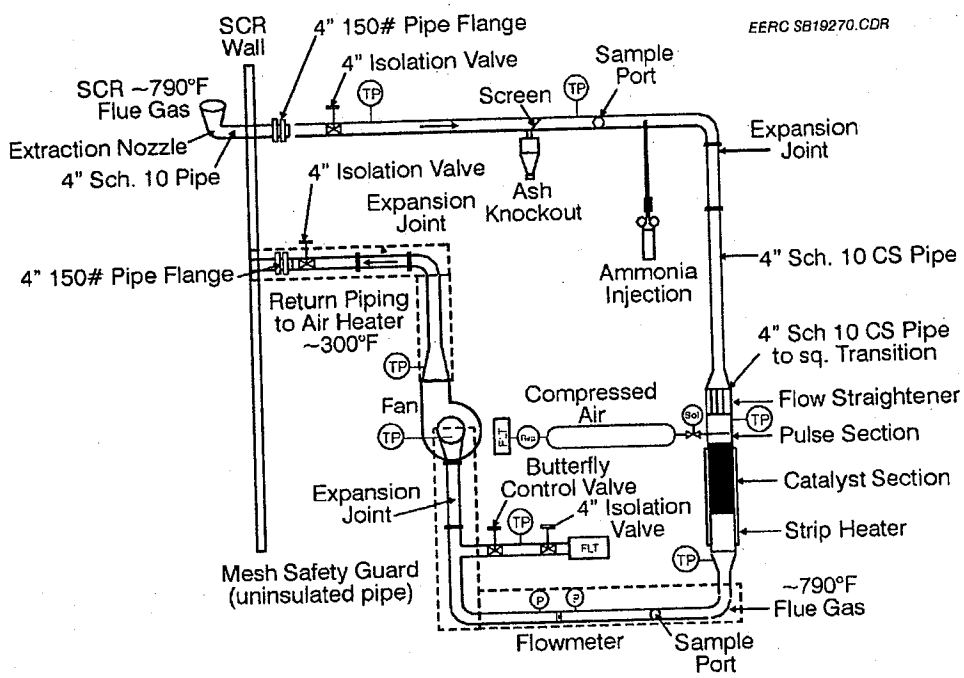

Fig. 1. Schematic diagram of SCR slipstream system.

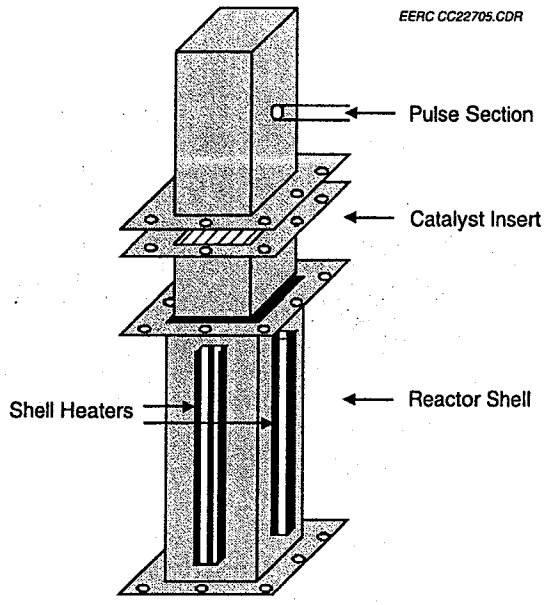

Fig. 2. Diagram of reactor section SCR slipstream system.

room houses a computer system that logs data and controls the gas flow rates, temperatures, pressure drop across the catalyst, and sootblowing cycles. The computer was programmed to maintain constant temperature of the catalyst, gas flow rates, sootblowing cycles, and ammonia injection. The computer is equipped with a modem that

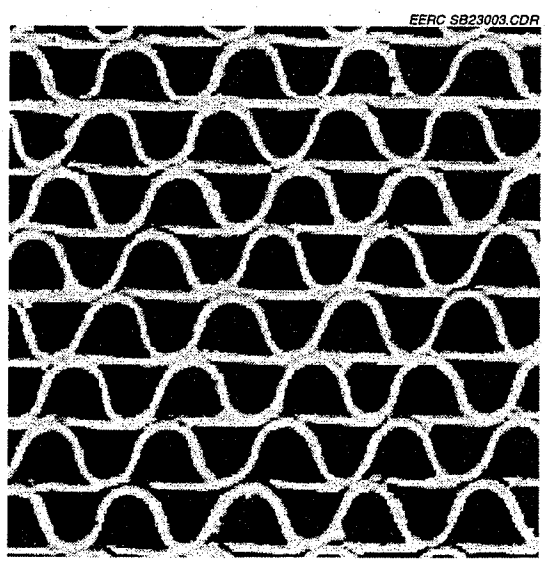

Fig. 3. Haldor Topsoe SCR catalyst showing the gas flow passages.

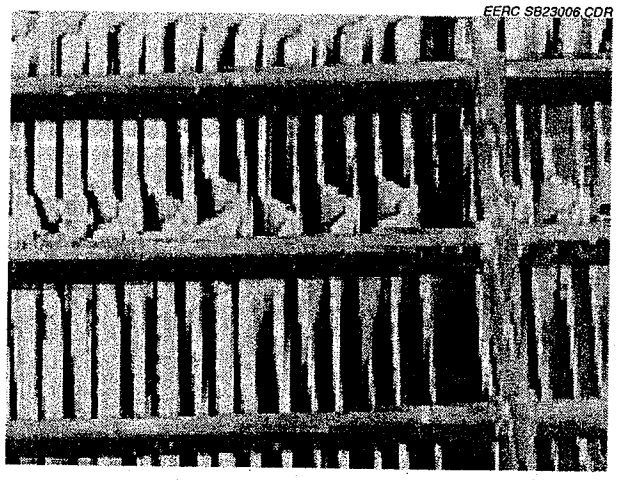

Fig. 4. Babcock Hitachi SCR catalyst showing the gas flow passages.

allowed for downloading of data and modification of the operation of the reactor from a remote computer located at the EERC.

A schematic diagram of the SCR slipstream system is shown in Fig. 1. Flue gas is isokinetically extracted from the convective pass of the boiler upstream of the air heater. The temperature is typically about 790 °F. The flue gases pass through a 4-in. pipe equipped with sampling, thermocouple, and pressure ports. Ammonia is injected into the piping upstream of the reactor section. The reactor consists of a steel housing that is approximately 8.5 in. square and 8 ft long. The reactor section illustrated in Fig. 2 has three components, including a flow straightener, a pulse section or sootblower, and a catalyst test section. A metal honeycomb is used as a flow straightener upstream of the catalyst section and is about 6 in. long. A purge section was installed ahead of the catalyst test section to remove accumulated dust and deposits. The catalyst test section is located downstream of the purge section. The entire catalyst section is insulated and equipped with strip heaters for temperature control. The catalyst test section is 3.28 ft (1 m) in length and houses three catalyst sections. Thermocouple and pressure taps are located in the purge sections for measurements before and after each section.

The induced-draft fan is used to extract approximately 400 acfm (200 scfm) of flue gas from the convective pass of the utility boiler to achieve an approach velocity of 5.2 m/s

Table 6
Selected operating conditions of the SCR catalysts

Plant name	Average SCR inlet temperature (°F)	Average SCR outlet temperature (°F)	Air pulse frequency	Flue gas flow rate (acfm)
Baldwin	645	549	Once per day and on demand	393
Columbia	672	662	Once per day and on demand	385
Coyote	675	667	Once per day and on demand	385

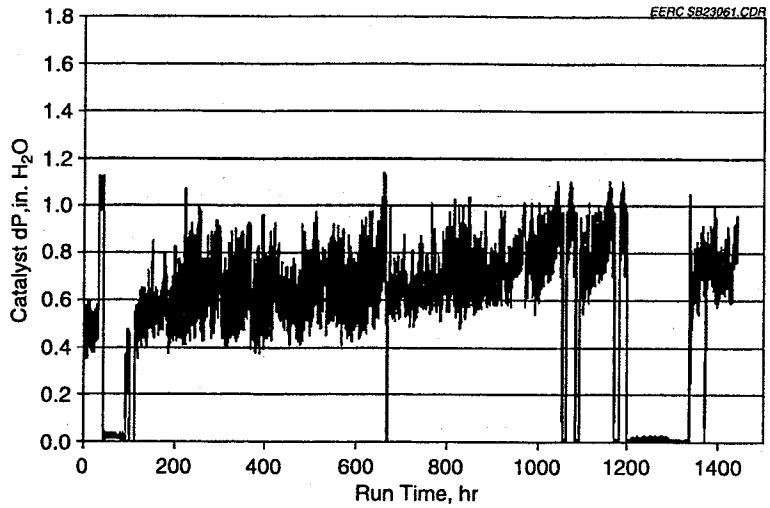

Fig. 5. Catalyst pressure drop at Baldwin Station at 0 to 2 months of operation.

(17.0 ft/s). The total gas flow through the reactor represents a thermal load of approximately 300 kW.

The range of operating conditions for the reactor is listed below:

- Gas temperature: ~700–800 °F
- Gas flow rate: 400–500 acfm
- Approach velocity range: 5.0–5.5 m/s
- Ammonia injection rate: 0.5:1 with NO_x level
- Tempering air for fan: ~50–200 scfm

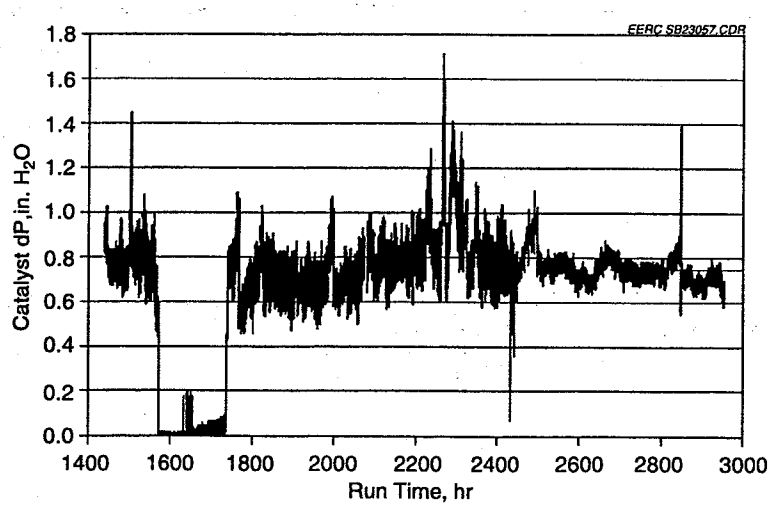

Fig. 6. Catalyst pressure drop at Baldwin Station at 2 to 4 months of operation.

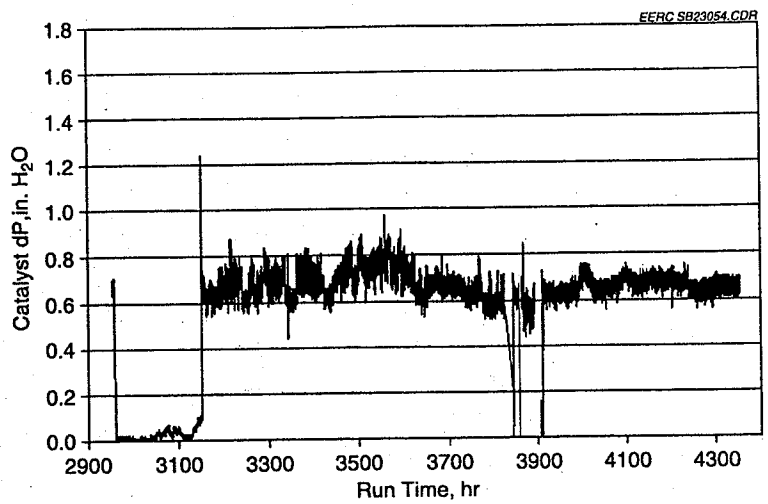

Fig. 7. Catalyst pressure drop at Baldwin Station at 4 to 6 months of operation.

- Catalyst dP: 0.5–1.0 in. water column
- Fan sized for up to 30 in. water column.

2.2.1. SCR catalyst

The catalyst installed at the Baldwin and Coyote Stations was the Haldor Topsoe catalyst. Topsoe's DNX-series of catalysts comprises SCR DENOX catalysts tailored to suit a comprehensive range of process requirements. DNX-series catalysts are based on a corrugated, fiber-reinforced titanium dioxide (TiO_2) carrier impregnated with the active components vanadium pentoxide (V_2O_5) and tungsten trioxide (WO_3). The catalyst is shaped to a monolithic structure with a large number of parallel channels. The unique catalyst design provides a highly porous structure with a large surface area and an ensuing

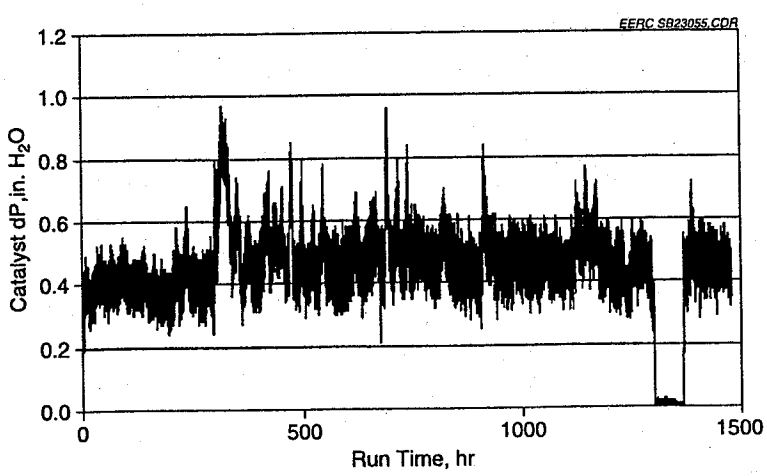

Fig. 8. Catalyst pressure drop at Columbia Station at 0 to 2 months of operation.

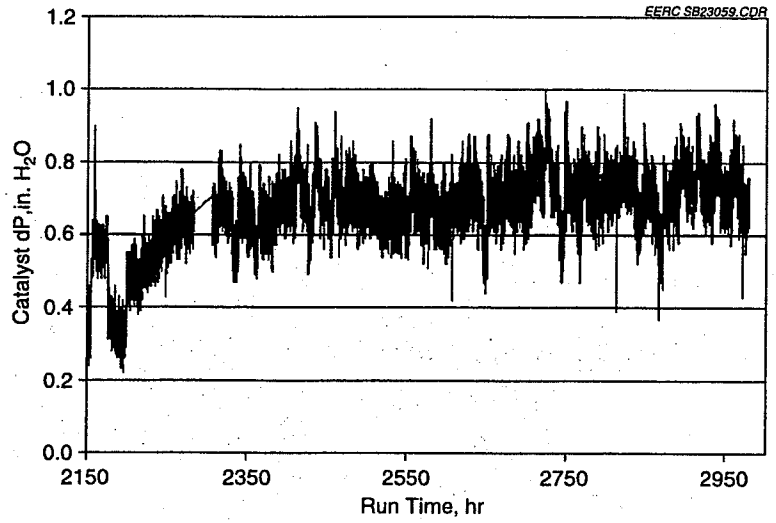

Fig. 9. Catalyst pressure drop at Columbia Station at 2 to 4 months of operation.

large number of active sites. Fig. 3 is an image of the Haldor Topsoe SCR catalyst. The pitch of the catalyst was approximately 6 mm.

The catalyst installed at the Columbia Station was a Babcock Hitachi plate-type catalyst. This catalyst is a TiO_2-based plate catalyst, developed and manufactured by Hitachi. Fig. 4 shows the design of the catalyst. The pitch of the catalyst was approximately 10 mm.

2.2.2. System performance measurement

Upon installation at each utility boiler unit, flue gas temperature, composition, and velocity measurements were obtained using portable equipment. Shakedown testing of the

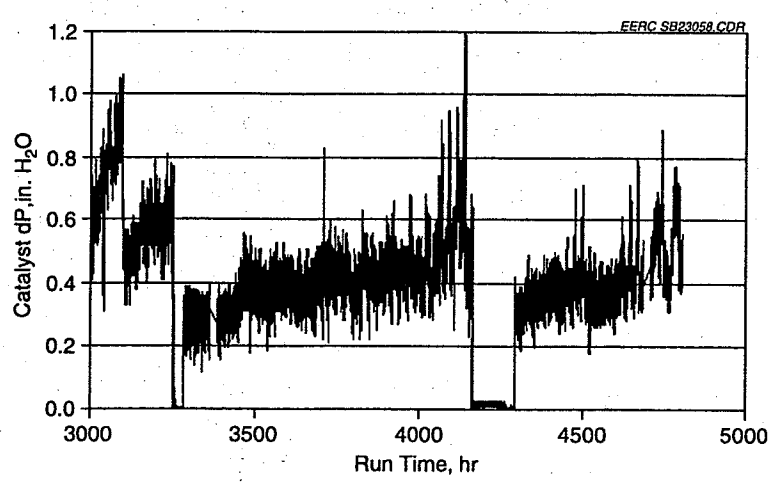

Fig. 10. Catalyst pressure drop at Columbia Station at 4 to 6 months of operation.

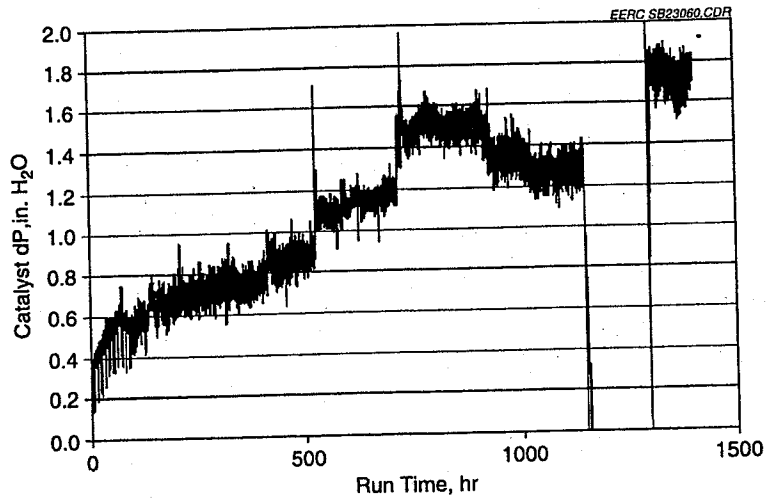

Fig. 11. Catalyst pressure drop at Coyote Station at 0 to 2 months of operation.

unit was conducted to ensure that all components were operating properly and that data were being logged and could be retrieved. After installation and shakedown were completed, the reactor was operated in a computer-controlled, automated mode and monitored on a daily basis to ensure proper operation and data quality. During operation of the SCR slipstream system, catalyst temperature, sootblowing frequency, and pressure drop across the catalyst were monitored and logged. Samples of the exposed SCR catalyst and associated deposits were obtained after exposure to flue gas and particulate for 2, 4, and 6 months. The samples of the catalyst were analyzed to determine the components that were bonding and filling pores, resulting in decreased reactivity.

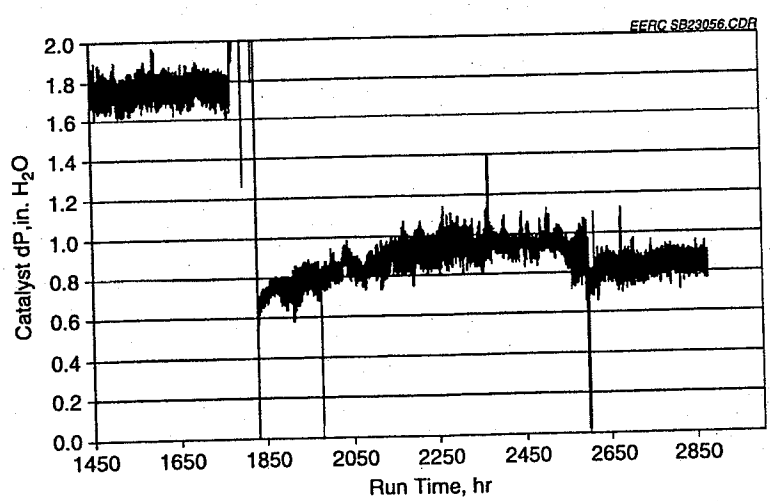

Fig. 12. Catalyst pressure drop at Coyote Station 2 to 4 months of operation.

The characteristics of ash that accumulated on the catalyst were examined using SEM–X-ray microanalysis and X-ray diffraction (XRD) [18]. Correlations between the physical and chemical characteristics of any ash deposits on the SCR test section and entrained-ash sample collected at the chamber inlet and the coal inorganic composition will be made to

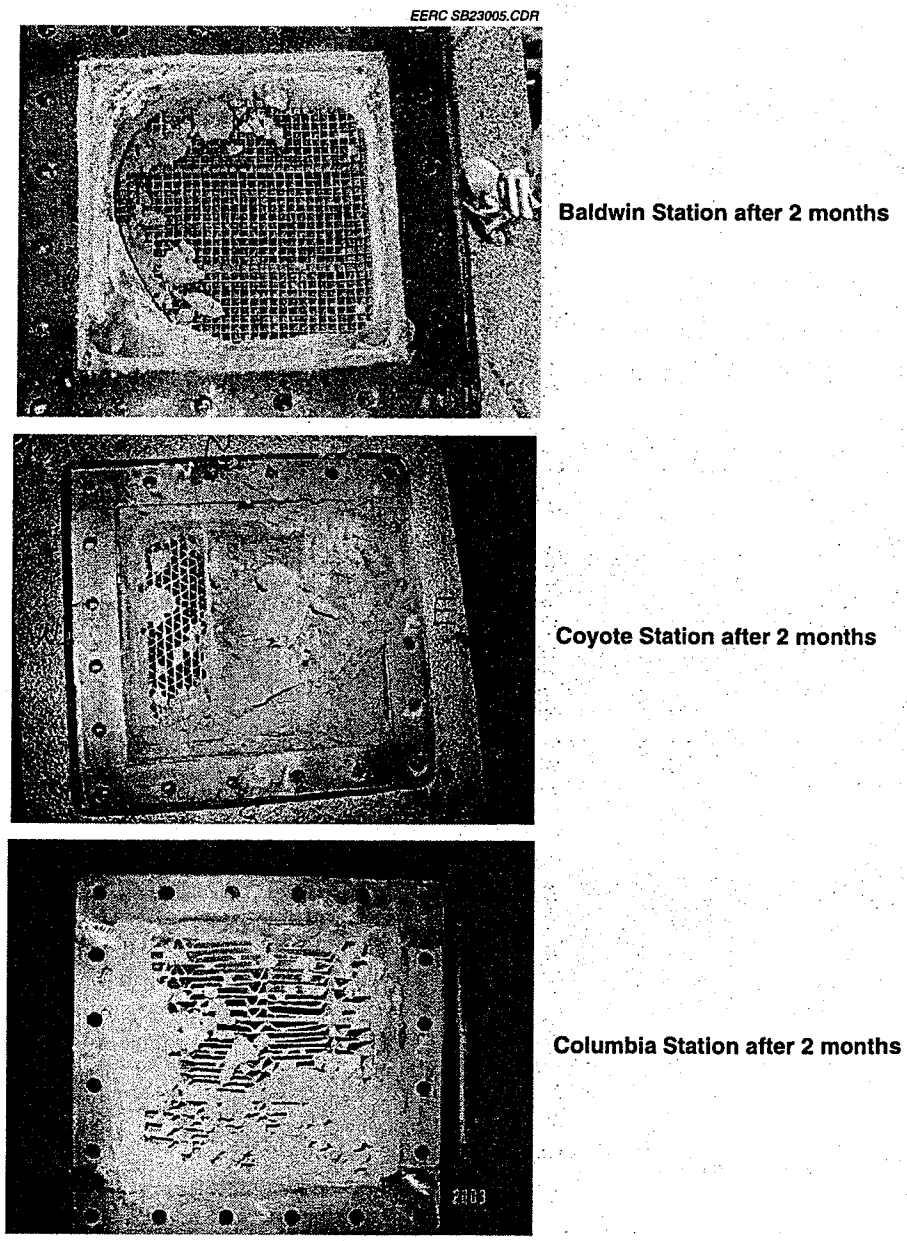

Fig. 13. Pictures of catalyst inlet after about 2 months of testing at each plant.

discern mechanisms of SCR blinding. Entrained ash was collected at Columbia Station only and characterized to composition and size.

2.3. Analysis of flue gas constituents across the catalyst—Ontario Hydro method for mercury speciation

At the Coyote Station, the Ontario Hydro (OH) mercury speciation sampling train was used to determine mercury forms across the SCR test section. The OH extractive mercury speciation sampling technique was used to measure potential mercury conversion across the SCR system over a period of several hours after fresh installation of the SCR test chamber and again just prior to removal of SCR catalyst sections.

The procedure used to conduct the mercury speciation sampling was American Society for Testing and Materials (ASTM) Method 06784-02 entitled "Standard Test Method for Elemental, Oxidized, Particle-Bound and Total Mercury in Flue Gas Generated from Coal-Fired Stationary Sources (Ontario Hydro Method)" [19].

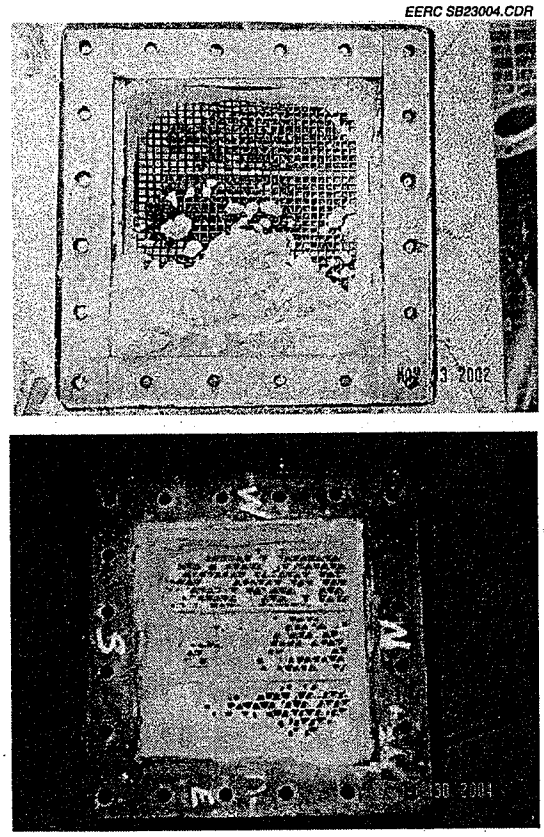

Fig. 14. Pictures of catalyst inlet after about 4 months of exposure to flue gas and particulate.

The OH method follows standard EPA methods for isokinetic flue gas sampling (EPA Methods 1–3 and EPA Method 5/17). A sample is withdrawn from the flue gas stream isokinetically through the filtration system, which is followed by a series of impingers in

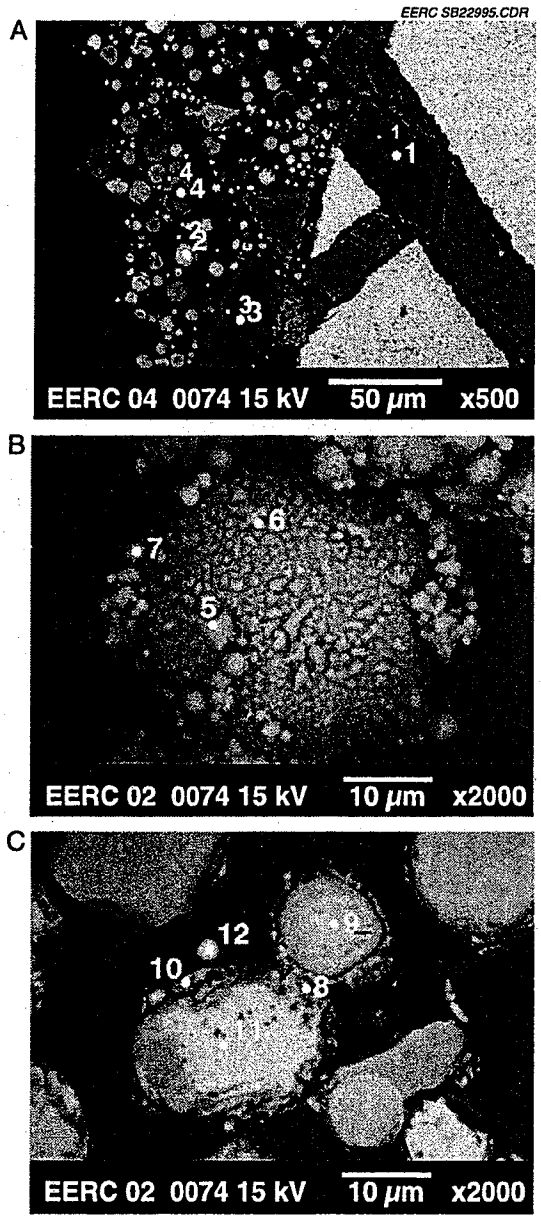

Fig. 15. SEM images of ash collected on catalyst surface at the Baldwin Station after 2 months of exposure. (A) Low-magnification image of ash deposit on catalyst surface, (B) high-magnification image of coated ash particle, and (C) high-magnification image of polished cross section showing coatings on particles.

an ice bath. Particulate-bound mercury is collected on the filter; Hg^{2+} is collected in impingers containing 1 N potassium chloride solution; and elemental mercury is collected in one impinger containing a 5% nitric acid and 10% peroxide solution and in three impingers containing a solution of 10% sulfuric acid and 4% potassium permanganate. An impinger containing silica gel collects any remaining moisture. The filter media is quartz fiber filters. The filter holder is glass or Teflon-coated. An approximate 2-h sampling time was used, with a target sample volume of 1 standard cubic meter.

3. Results and discussion

3.1. Pressure drop

3.1.1. Testing at the Baldwin Station

The reactor was installed at the Baldwin Station and operated for a 6-month time period on the Haldor Topsoe catalyst. The information obtained from testing included pressure drop, sootblowing cycles, and reactor temperatures. Table 6 summarizes the operating conditions of the reactors during the testing periods at all plants. Figs. 5–7 show the pressure drop across the catalyst test periods from 0 to 2 months, 2 to 4 months, and 4 to 6 months, respectively. During the first 2 months of operation, the pressure shown in Fig. 6 was about 0.5 in. of water; at the end of 2 months, the pressure drop was about 0.8 in. of water, indicating plugging had occurred. The air was pulsed a minimum of every 8 h in an attempt to maintain cleanliness. The reactor was monitored on a daily basis, and adjustments in pulsing cycles were made in order to minimize deposit accumulation. However, for the first 2 months, the pressure drop steadily increased. There are several periods where the unit was taken off-line; during those times, the temperature of the catalyst was maintained. At 2-month intervals, a section of catalyst was removed and replaced with a new one.

Table 7
Chemical composition of selected points and areas in Fig. 15

Element (wt.%)												
Oxide	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9	Point 10	Point 11	Point 12
Na_2O	0.2	0.0	0.2	2.3	2.5	3.0	3.6	0.7	0.6	1.6	0.4	0.9
MgO	0.0	6.3	0.0	3.1	3.0	1.3	1.6	2.5	4.5	3.0	3.6	3.5
Al_2O_3	3.6	17.9	6.9	29.6	8.4	5.5	4.4	5.4	22.7	12.2	21.2	14.2
SiO_2	92.1	5.9	86.5	39.9	3.4	53.2	15.7	3.4	16.1	1.0	8.1	2.3
P_2O_5	0.1	0.4	0.0	0.0	1.8	0.0	1.5	0.3	0.5	2.3	0.0	4.6
SO_3	3.3	0.4	5.2	0.1	51.8	18.1	52.4	53.0	0.0	46.4	0.0	19.7
K_2O	0.0	0.0	0.0	0.6	0.4	0.5	0.7	0.2	0.0	0.1	0.0	0.0
CaO	0.0	49.4	0.1	18.6	16.4	14.6	13.0	28.8	41.5	27.1	51.1	39.2
TiO_2	0.7	4.5	0.4	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fe_2O_3	0.0	14.6	0.7	3.6	12.3	3.8	7.1	5.7	14.2	6.5	15.6	15.6
BaO	0.0	0.6	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	100	100	100	100	100	100	100	100	100	100	100	100

For Months 2 through 4, the pressure drop was highly variable initially but was about 0.8 in. of water. From Months 4 through 6, the pressure drop was maintained between 0.6 and 0.8 in. of water. This is due to the installation of a fresh catalyst section and leaving two thirds of the catalysts in place that partially plugged. The gas velocity in the single section of new, clean catalyst was high because of channeling, and the result of the high gas flow was less deposition and accumulation. Gas velocity has a significant impact on the potential for deposits to form. However, at high gas velocity, low NO_x conversion is likely.

3.1.2. Testing at Columbia

The reactor was installed at the Columbia Station and operated for a 6-month period of time for the Babcock Hitachi catalyst. The information obtained from the testing included pressure drop information, sootblowing cycles, and reactor temperature. Table 6 shows the reactor temperature, air-pulsing cycles, and airflow rates. Figs. 8–10 show the test periods from 0 to 2 months, 2 to 4 months, and 4 to 6 months, respectively. The pressure drop across the SCR upon installation was about 0.4 in. of water and increased to an average of

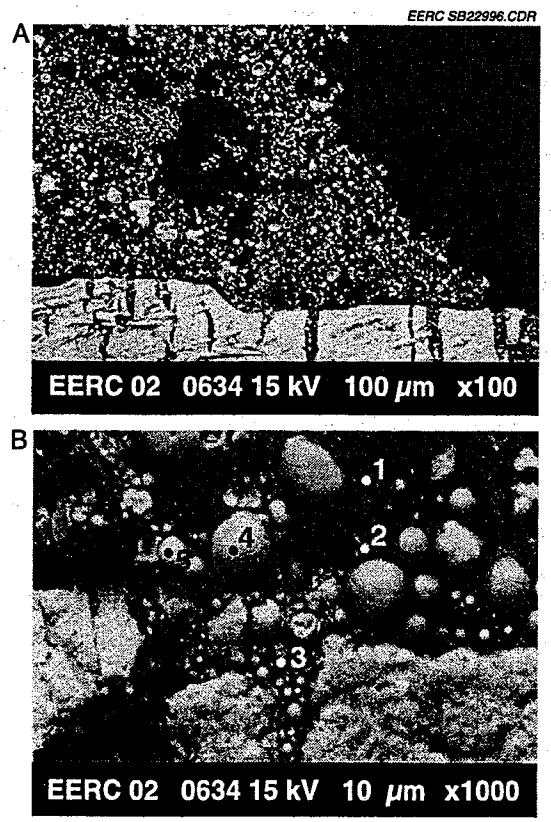

Fig. 16. SEM images of ash collected on catalyst surface at the Baldwin Station after 4 months of exposure. (A) Low-magnification image of ash deposit on catalyst surface, and (B) high-magnification image of polished cross section showing particles in a matrix of calcium- and sulfur-rich materials.

about 0.5 in. of water, but ranged from less than 0.4 to greater than 0.8 in. of water. Fig. 9 shows the pressure drop for Months 2 to 4. The pressure drop increased from about 0.5 to 0.7 in. of water because of accumulation of ash. Fig. 10 shows a rapid increase in pressure drop across the catalyst at about 3000 h of operation, and aggressive pulsing brought it down to 0.4 in. of water until the catalyst section was changed out at about 3200 h. After cleaning the reactor and replacing one catalyst section, the pressure drop was about 0.3 but increased to over 0.6 in. of water up to about 4100 h. There was an outage at the plant, and aggressive pulsing of the reactor was conducted; the pressure drop was brought back down to 0.3 but rapidly increased to over 0.5 in. of water within 500 h.

3.1.3. Testing at Coyote

The same reactor that was installed at the Baldwin Station was moved and installed at the Coyote Station. In addition, the same Haldor Topsoe catalyst was used in the reactor. The cleaning cycles, temperatures, and gas flow rates are listed in Table 6. The reactor was operated for a 6-month period of time. Figs. 11 and 12 show the test periods from 0 to 2 months and 2 to 4 months. As this paper is being prepared, the reactor is still operating on-site. The pressure drop across the catalyst upon installation was about 0.4 in. of water. After only 750 h, the pressure drop was 1.5 in. of water, indicating significant plugging. Very aggressive air pulsing was conducted, with little success in removing the deposits. The pressure drop for the catalyst was over two times greater than the pressure drop observed for the Baldwin Station utilizing the same reactor and same catalyst. At about 1700 h, the reactor was cleaned, and a section of catalyst was removed for characterization. The pressure drop after cleaning was about 0.8 to 1.0 in. of water. The pressure drop did not increase as rapidly because of the higher velocities through the clean section of the catalyst.

3.1.4. Visual observations of deposit characteristics

The tops of the catalysts were photographed during inspection and sampling of the catalyst sections. Fig. 13 shows the ash materials that accumulated on the catalyst inlet after 2 months of operation. The most significant accumulation was noted for the Coyote

Table 8
Chemical composition of selected points and areas in Fig. 16

Element (wt.%)					
Oxide	Point 1	Point 2	Point 3	Point 4	Point 5
Na_2O	1.7	2.3	0.0	0.3	1.0
MgO	5.9	3.0	1.2	1.8	3.8
Al_2O_3	3.7	2.5	3.3	5.7	6.3
SiO_2	9.7	31.5	13.3	70.0	18.5
P_2O_5	3.1	2.7	0.8	0.0	2.6
SO_3	48.1	31.0	35.8	0.0	32.1
K_2O	0.5	0.7	0.0	1.5	0.0
CaO	22.0	8.8	38.0	13.9	14.7
TiO_2	1.8	10.8	4.1	1.6	15.1
Fe_2O_3	2.1	6.6	3.4	4.2	5.9
BaO	1.4	0.0	0.0	0.9	0.0
Total	100	100	100	100	100

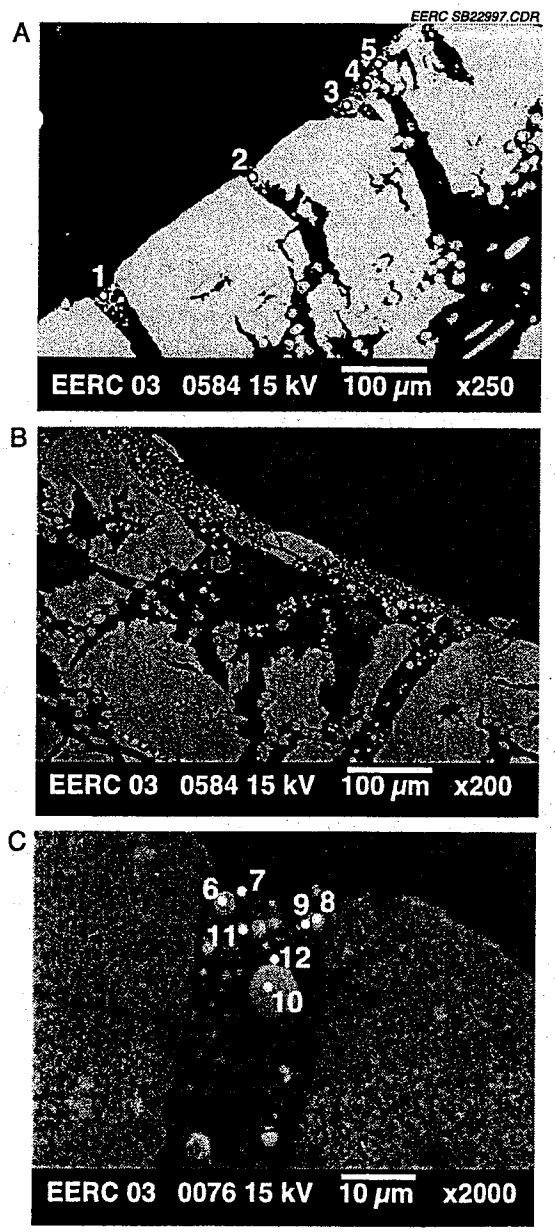

Fig. 17. SEM images of ash collected on catalyst surface at the Baldwin Station after 6 months of exposure. (A and B) Low-magnification images of ash deposit on catalyst surface and (C) high-magnification image of polished cross section showing particles in a matrix of calcium- and sulfur-rich materials.

Station, followed by Columbia and Baldwin. The Coyote Station had some larger pieces of ash deposit material on the surface as well as plugging of the catalyst passages. The Baldwin Station showed some obvious deposition along the walls of the reactor and some accumulation on the inlet sections. The Columbia Station showed more significant accumulation and plugging than the Baldwin Station.

After 4 months, the tops of the catalysts were photographed during inspection and sampling of the catalyst sections, as shown in Fig. 14. The most significant accumulation was noted for the Coyote Station and some accumulation for the Baldwin Station.

3.2. Deposit characteristics

The characteristics of the ash materials that collected on the catalyst surfaces and pores were characterized by SEM and X-ray microanalysis and, in selected cases, XRD was used to determine the crystalline phases present. The catalysts were sampled after 2, 4, and 6 months. The sections were sampled, and approximately 2.5-cm squares were mounted for SEM analysis on double-stick tape and in epoxy resin. The double-stick tape samples allowed for characterization of the external morphology of the particles and catalyst surface. The samples mounted in resin were cross-sectioned and polished, which allowed for more detailed and quantitative analysis of the bonding materials and materials that accumulated in the pores of the catalyst.

3.2.1. Plugging deposit characteristics

3.2.1.1. Baldwin Station deposits. Samples of catalyst were removed from the Baldwin Station after exposure to flue gases and particulate after 2, 4, and 6 months. Fig. 15 shows the characteristics of the ash deposit material on the SCR catalyst after 2 months of exposure. This is a polished cross section of a deposit on the surface of the catalyst. Fig. 15A shows particles on the surface of the catalyst that range in size from <1 to 15 μm. The larger particles range from oxides of solely silicon and iron to complex mixtures rich in

Table 9
Chemical composition of selected points and areas in Fig. 17

Element (wt.%)												
Oxide	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9	Point 10	Point 11	Point 12
Na_2O	0.6	1.0	2.1	0.3	0.5	2.7	1.7	0.4	0.5	2.2	1.3	1.7
MgO	4.3	2.5	6.3	0.7	1.6	7.6	4.5	6.4	5.9	5.0	3.4	6.4
Al_2O_3	14.8	16.0	15.6	15.5	14.7	0.9	5.0	2.4	3.0	19.2	10.8	3.8
SiO_2	3.3	7.8	18.8	57.7	7.7	47.3	8.4	18.4	18.5	31.0	17.9	16.7
P_2O_5	2.3	2.1	0.5	0.6	1.8	0.0	1.8	0.9	1.0	0.0	1.7	1.2
SO_3	30.7	20.4	17.7	0.0	29.0	0.8	37.9	1.7	5.3	0.0	22.5	13.9
K_2O	0.7	0.0	1.0	0.4	0.9	0.9	0.4	0.0	0.0	0.9	0.8	0.0
CaO	28.8	28.7	28.1	22.5	34.9	28.4	31.4	52.6	49.0	28.9	30.6	45.4
TiO_2	2.0	7.2	2.2	0.3	1.3	1.1	1.9	6.9	7.4	2.4	2.0	1.1
Fe_2O_3	11.4	12.9	6.2	0.0	7.6	7.9	7.1	5.7	6.0	6.3	6.1	6.5
BaO	1.1	1.4	1.4	2.0	0.0	2.5	0.0	4.6	3.5	4.2	2.9	3.3
Total	100	100	100	100	100	100	100	100	100	100	100	100

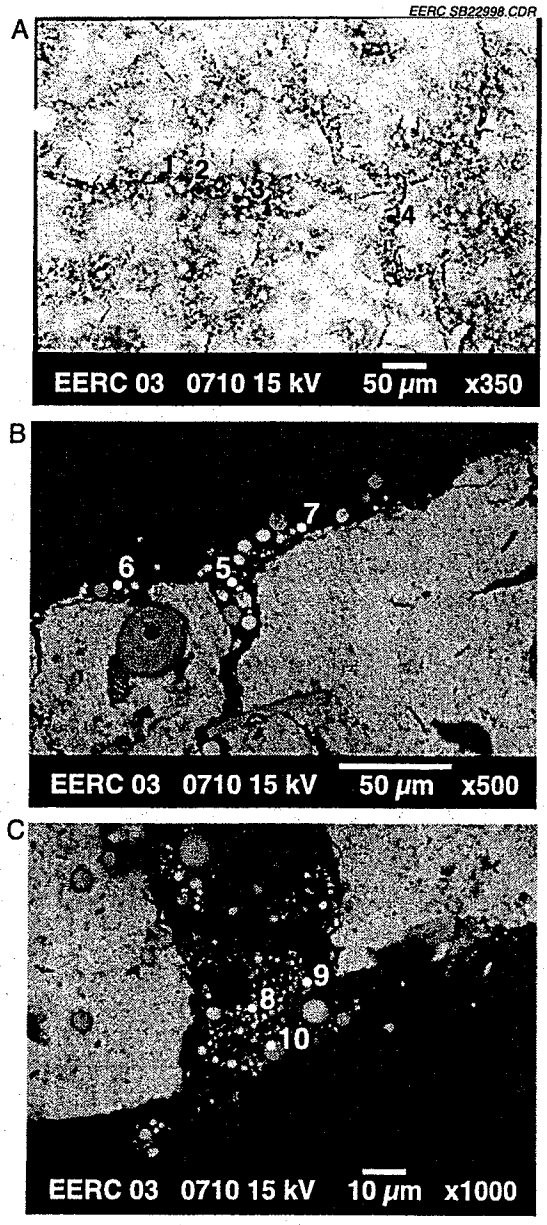

Fig. 18. SEM images of ash collected on catalyst surface at the Columbia Station after 2 months of exposure. (A) Low-magnification image of ash deposit on catalyst surface, (B) low-magnification image of polished cross section showing particles in a matrix of calcium- and sulfur-rich materials, (C) higher magnification image of bonding.

aluminum and calcium; aluminum, silicon, and calcium; aluminum, calcium, and iron; and sodium, calcium, aluminum, and silicon. Chemical analysis of selected particles is summarized in Table 7. The samples of ash mounted on double-stick tape allow for the

characterization of the external surfaces of the particles. The surface of a typical particle that is accumulating on the surface of the catalyst is shown in Fig. 15B. The blebs on the surface are composed of calcium and sulfur, with some iron and minor amounts of sodium and potassium. Fig. 15C shows a cross section of the deposited particles showing calcium- and aluminum-rich particles bonded together with a calcium- and sulfur-rich phase. This phase is in the form of calcium sulfate based on XRD analysis conducted on the deposited ash samples.

The 4-month sample from the Baldwin Station showed more extensive sulfation of the alkaline-earth elements present in the deposits. Fig. 16 shows the images of a polished cross section of an ash deposit on the surface of the catalyst. The deposit formed both on the surface of the catalyst and within the catalyst pores as shown in Fig. 16A. Fig. 16B shows a higher magnification view of the deposit on the catalyst surface. The deposit consists of particles of fly ash bonded together by a matrix of calcium- and sulfur-rich material, likely in the form of calcium sulfate. The chemical composition of selected points shown in Table 8 shows high levels of calcium and sulfur. There is much more extensive bonding of the materials with the sulfate matrix as compared to the 2-month sample.

The 6-month sample from the Baldwin Station showed extensive sulfation of the alkaline-earth elements present in the deposits. Fig. 17A and B shows regions of the catalyst where all the pores were blocked and a minimal amount of deposit on the surface of the catalyst. Fig. 17C shows a higher magnification view of the deposit that is filling the catalyst pore. The deposit consists of particles of fly ash bonded together by a matrix of calcium- and sulfur-rich material, likely in the form of calcium sulfate. The chemical compositions of selected points that indicate the presence of high levels of calcium and sulfur are listed in Table 9. There is much more extensive bonding of the materials with the sulfate matrix as compared to the 2-month sample. In addition, there are some regions of high levels of calcium, aluminum, and sulfur present. The calcium aluminum materials are likely derived from the calcium aluminum phosphate minerals found in the coal fired at this plant.

Table 10
Chemical composition of selected points and areas in Fig. 18

Element (wt.%)										
Oxide	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9	Point 10
Na_2O	0.0	0.9	1.3	0.1	0.3	0.0	0.6	1.0	0.5	1.8
MgO	0.7	1.5	3.2	3.9	0.9	0.0	1.5	2.9	1.4	0.7
Al_2O_3	12.2	17.6	20.9	12.2	5.9	5.5	12.4	13.6	9.0	20.7
SiO_2	10.8	4.1	23.3	7.3	6.3	9.4	6.1	15.4	7.9	61.8
P_2O_5	0.9	0.1	0.0	1.4	2.6	1.2	0.6	1.7	3.1	0.2
SO_3	15.2	17.6	16.8	17.1	32.3	33.3	22.0	19.5	30.7	0.0
K_2O	0.2	0.0	0.5	0.0	0.1	0.0	0.0	0.1	0.2	2.5
CaO	14.1	43.1	25.0	42.0	34.9	44.1	48.5	34.1	38.3	4.4
TiO_2	44.8	2.8	1.1	10.5	5.2	0.5	4.4	2.4	2.6	2.2
Fe_2O_3	1.1	12.3	3.9	5.5	11.5	3.1	2.3	6.0	6.3	4.4
BaO	0.0	0.0	4.2	0.0	0.0	2.8	1.6	3.3	0.0	1.3
Total	100	100	100	100	100	100	100	100	100	100

3.2.1.2. Columbia Station deposits. The 2-month sample from the Columbia Station showed particles adhering to the surface and filling pores in the catalyst, as shown in Fig. 18. Fig. 18A shows the external morphology of the catalyst surface showing

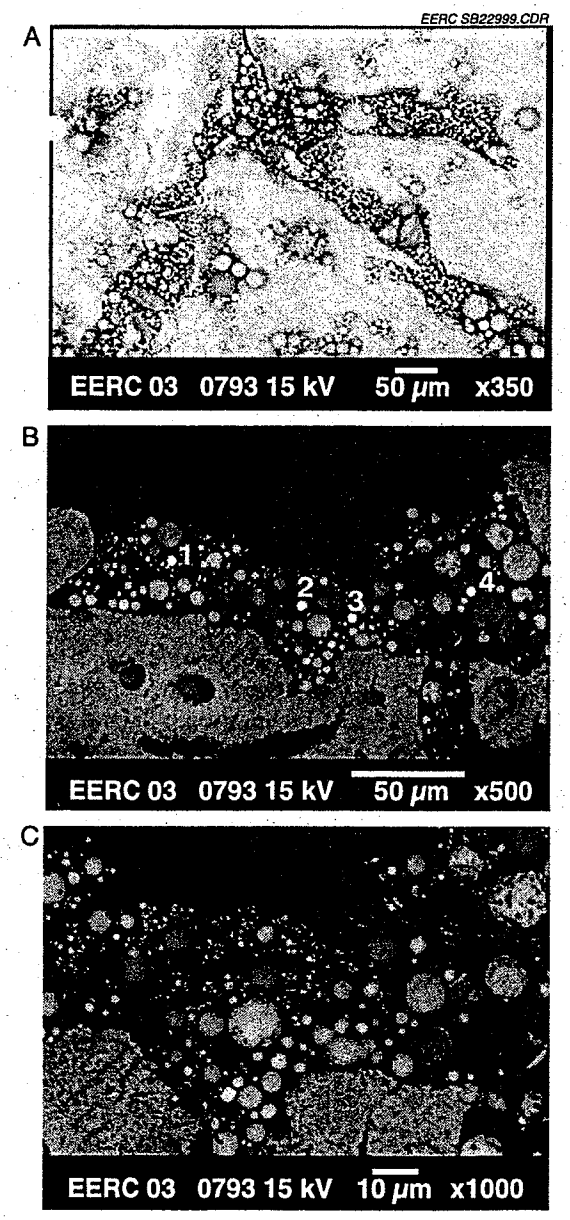

Fig. 19. SEM images of ash collected on catalyst surface at the Columbia Station after 4 months of exposure. (A) Low-magnification image of ash deposit on catalyst surface, (B) low-magnification image of polished cross section showing particles in a matrix of calcium- and sulfur-rich materials, (C) higher magnification image of bonding.

particles trapped in the pores of the catalysts. Chemical compositions of selected points are shown in Table 10. The 2-month sample shows significant evidence of sulfation after only 2 months of exposure. It appears to be more significant than that observed for the Baldwin 2-month sample. Fig. 18B and C shows a higher magnification view of the deposit that is filling the catalyst pore. The deposit consists of particles of fly ash bonded together by a matrix of calcium- and sulfur-rich material, likely in the form of calcium sulfate.

The 4-month sample from the Columbia Station showed particles adhering to the surface and filling pores in the catalyst, as shown in Fig. 19. Fig. 19A shows the external morphology of the catalyst surface showing particles trapped in the pores of the catalysts. Chemical compositions of selected points are shown in Table 11. It appears to be more significant than that observed for the Baldwin 2-month sample. Fig. 19B and C shows a higher magnification view of the deposit that is filling the catalyst pore. The deposit consists of particles of fly ash bonded together by a matrix of calcium- and sulfur-rich material, likely in the form of calcium sulfate.

The 6-month sample from the Columbia Station showed particles adhering to the surface and filling pores in the catalyst as shown in Fig. 20. Fig. 20A shows the external morphology of the catalyst surface showing particles trapped in the pores of the catalysts. Chemical compositions of selected points are shown in Table 12. Fig. 20B and C shows a higher magnification view of the deposit that is filling the catalyst pore. The deposit consists of particles of fly ash bonded together by a matrix of calcium- and sulfur-rich material, likely in the form of calcium sulfate. The 6-month samples show the most extensive degree of sulfation of the Columbia Station samples.

3.2.1.3. Coyote Station deposits. The 2-month sample from the Coyote Station showed particles adhering to the surface and filling pores in the catalyst as shown in Fig. 21. Fig. 21A shows the external morphology of the catalyst surface showing particles trapped in the pores of the catalysts. Chemical compositions of selected points are shown in Table 13.

Table 11
Chemical composition of selected points and areas in Fig. 19

Element (wt.%)				
Oxide	Point 1	Point 2	Point 3	Point 4
Na_2O	0.5	0.0	0.6	0.3
MgO	3.3	1.9	3.2	2.4
Al_2O_3	13.1	10.2	13.0	6.3
SiO_2	12.4	8.4	8.4	3.6
P_2O_5	1.3	0.5	2.1	0.6
SO_3	27.7	29.9	32.2	47.4
K_2O	0.2	0.6	0.1	0.8
CaO	32.1	38.1	28.9	33.2
TiO_2	1.0	2.7	1.3	0.0
Fe_2O_3	6.3	6.3	7.6	2.6
BaO	2.0	1.4	2.5	2.6
Total	100	100	100	100

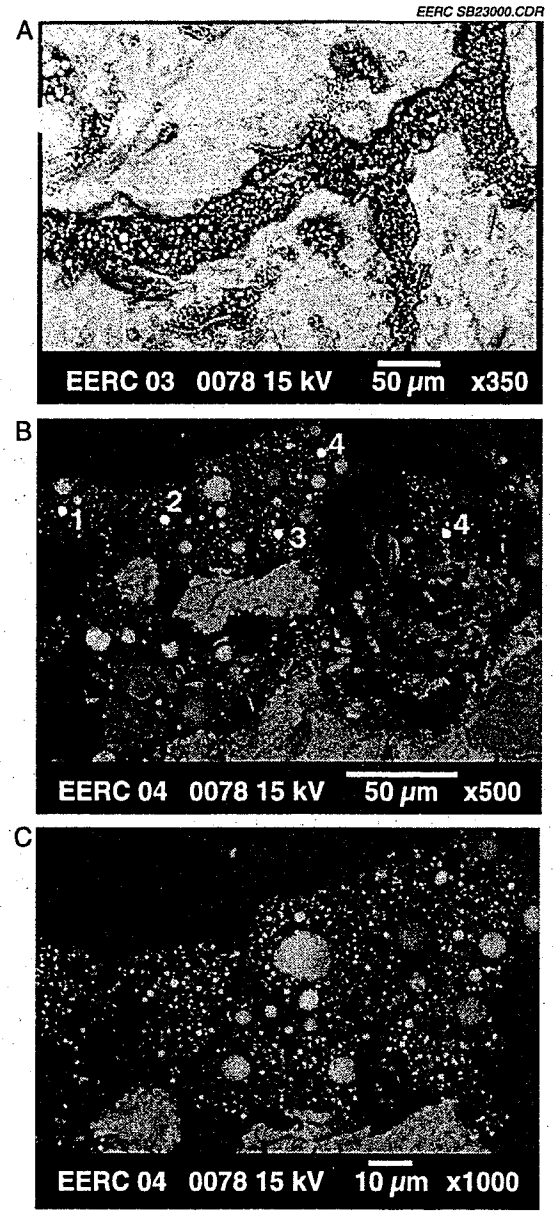

Fig. 20. SEM images of ash collected on catalyst surface at the Columbia Station after 6 months of exposure. (A) Low-magnification image of ash deposit on catalyst surface, (B) low-magnification image of polished cross section showing particles in a matrix of calcium- and sulfur-rich materials, (C) higher magnification image of bonding.

The 2-month sample shows significant evidence of sulfation after only 2 months of exposure and was much more pronounced than the 2-month samples for the Baldwin and Columbia Stations that are fired on PRB coals. Fig. 21B and C shows a higher

Table 12
Chemical composition of selected points and areas in Fig. 20

Element (wt.%)				
Oxide	Point 1	Point 2	Point 3	Point 4
Na_2O	0.1	0.0	0.3	0.6
MgO	1.8	0.7	1.7	2.2
Al_2O_3	10.9	9.6	6.2	11.3
SiO_2	13.1	11.3	12.4	19.5
P_2O_5	3.9	4.8	0.2	2.1
SO_3	27.6	34.0	35.5	30.0
K_2O	0.5	0.3	0.1	1.2
CaO	33.0	25.9	39.8	25.8
TiO_2	0.8	2.5	1.6	3.3
Fe_2O_3	6.1	9.7	1.9	2.9
BaO	2.1	1.2	0.0	1.1
Total	100.00	100.00	100.00	100.00

magnification view of the deposit that is filling the catalyst pore. The deposit consists of particles of fly ash bonded together by a matrix of calcium- and sulfur-rich material, likely in the form of calcium sulfate. The presence of sodium enhances the bonding and sulfation of the particles to form a strongly bonded matrix.

The 4-month sample from the Coyote Station showed particles adhering to the surface and completely filling and masking the pores in the catalyst as shown in Fig. 22. Fig. 22A shows the external morphology of the catalyst surface showing the masking of the catalyst surface. Chemical compositions of selected points are shown in Table 14. The 4-month sample shows more sulfation than the 2 months of exposure samples. Fig. 22B and C shows a higher magnification view of the deposit that is filling the catalyst pore. The deposit consists of particles of fly ash bonded together by a matrix of sodium-, calcium-, and sulfur-rich material, likely in the form of calcium sulfate. The presence of sodium and potassium enhances the bonding and sulfation of the particles to form a strongly bonded matrix. Significant sodium was found in the deposits, as shown in Table 14.

3.2.2. Deposit formation mechanisms

The mechanism for the formation of deposits that blind SCR catalysts involves the transport of very small particles rich in alkali and alkaline-earth elements, the surface of the catalyst, and reactions with SO_2/SO_3 to form sulfates. The formation of SO_3 from SO_2 is catalyzed by the SCR; this, in turn, increases the reaction rate of SO_3 to form sulfates. In some cases, the alkali and alkaline-earth elements will also react with CO_2 to form carbonates. XRD analysis shown in Fig. 23 identified $CaSO_4$ as a major phase and $Ca_3Mg(SiO_4)_2$ and $CaCO_3$ as minor phases.

Lignite and subbituminous coals contain high levels of organically associated alkali and alkaline-earth elements including sodium, magnesium, calcium, and potassium, in addition to mineral phases. The primary minerals present in these coals include quartz, clay minerals, carbonates, sulfates, sulfides, and phosphorus-containing minerals [18].

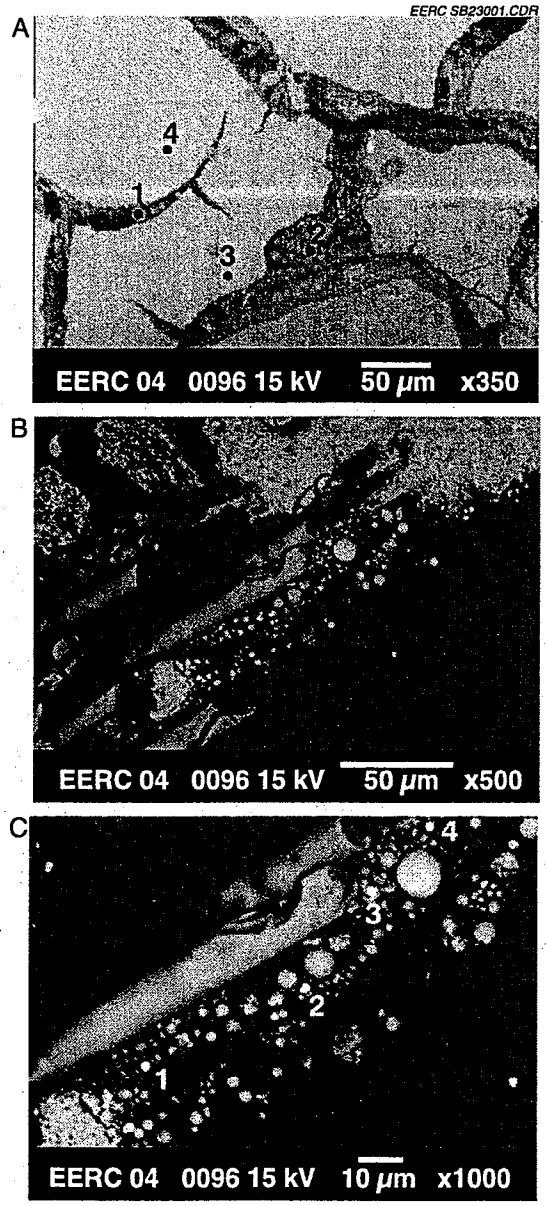

Fig. 21. SEM images of ash collected on catalyst surface at the Coyote Station after 2 months of exposure. (A) Low-magnification image of ash deposit on catalyst surface, (B) low-magnification image of polished cross section showing particles in a matrix of calcium- and sulfur-rich materials, (C) higher magnification image of bonding.

During combustion, the inorganic components in the coal are partitioned into various size fractions based on the type of inorganic component, their association in the coal, and combustion system design and operating conditions. There has been

Table 13
Chemical composition of selected points and areas in Fig. 21

Oxide	Point 1	Point 2	Point 3	Point 4
Na_2O	0.9	0.7	1.2	1.0
MgO	5.0	1.6	5.6	1.7
Al_2O_3	12.3	5.8	11.9	5.5
SiO_2	24.6	3.1	21.1	2.6
P_2O_5	0.7	0.0	0.5	0.0
SO_3	23.5	44.0	17.4	31.8
K_2O	0.5	0.3	0.8	0.4
CaO	14.9	36.4	19.6	46.9
TiO_2	7.2	1.9	8.0	2.1
Fe_2O_3	9.2	5.5	11.8	6.9
BaO	1.3	0.7	2.1	1.1
Total	100	100	100	100

significant research conducted on ash formation mechanisms and relationships to impacts on power plant performance [18–34]. Typically, during combustion the inorganic components associated with western subbituminous and lignite coal are distributed into various size fractions of ash, as shown in Fig. 24. The results shown in Fig. 24 were obtained from isokinetic sampling and aerodynamically size-fractionating ash particles from a full-scale pulverized-coal-fired boiler firing subbituminous coal and analyzing each size fraction. The results show that the smaller size fractions of ash are dominated by partially sulfated alkali and alkaline-earth elements. These ash particles are largely derived from the organically associated cations in the coal. The larger size fraction has higher levels of aluminum and silicon derived from the mineral fraction of the ash-forming component of the coal. Entrained ash was extracted from the Columbia Station at the point of the inlet to the SCR reactor and was aerodynamically classified and analyzed. The composition of the size fractions was compared to the chemical composition of the ash deposited on and in the catalyst, as shown in Fig. 25. The comparison shows that the composition of the particle captured in the SCR catalyst is very similar to the <5-μm size fraction. The deposited material shows significantly more sulfation than the entrained-ash size fraction, indicating that the sulfation process occurs after the particles are deposited in the catalyst.

The mechanism of SCR catalyst blinding when firing lignite or subbituminous coals is shown in Fig. 26 [35]. The requirements for the formation of deposits that blind SCR catalyst include firing a coal that produces significant levels of <5-μm-sized particles. The particles are transported into the pores of the catalyst and subsequently reacted with SO_3 to form sulfates. The sulfate forms a matrix that bonds other ash particles. The SCR catalyzes the formation of SO_3 and thereby increases the rate of sulfation [9,15]. The sulfation of CaO increases the molar volume, resulting in the filling of the pore. For coals that have high sodium contents, formation of low-melting-point phases such as pyrosulfates are possible [36]. Pyrosulfate materials can melt at temperatures as low as 535 °F in coal-fired power systems.

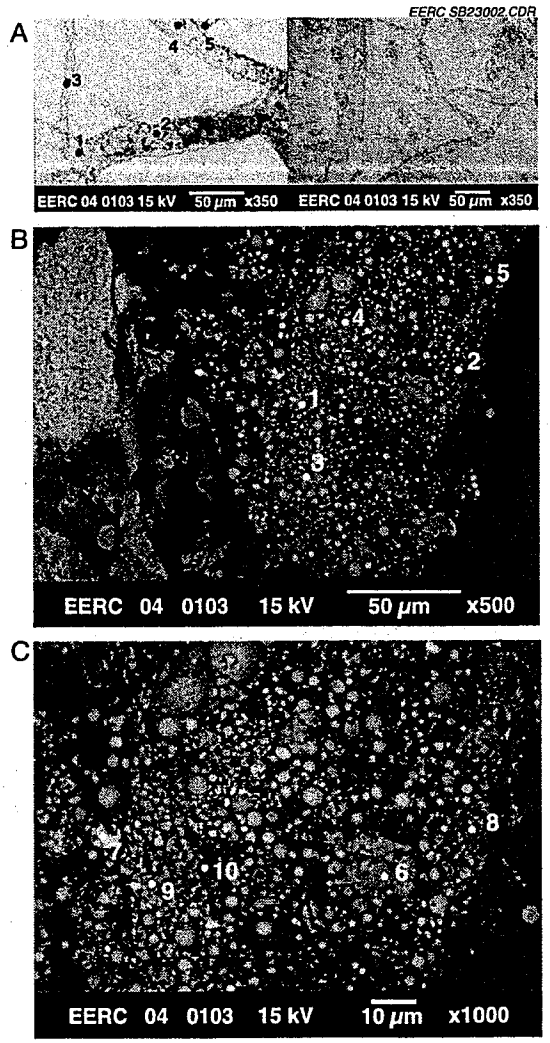

Fig. 22. SEM images of ash collected on catalyst surface at the Coyote Station after 4 months of exposure. (A) Low-magnification image of ash deposit on catalyst surface, (B) low-magnification image of polished cross section showing particles in a matrix of calcium- and sulfur-rich materials, (C) higher magnification image of bonding.

3.3. Flue gas measurements

3.3.1. Mercury transformations

The ability of mercury to be oxidized across the SCR catalyst was investigated at the Coyote Station. The Coyote Station is fired on North Dakota lignite, and the flue gases are dominated by elemental mercury. Measurement of mercury speciation was conducted using the OH method at the inlet and the outlet of the SCR catalyst. The measurements were made upon installation of the catalyst and after 2 and 4 months of operation. The

Table 14
Chemical composition of selected points and areas in Fig. 22

Element (wt.%)										
Oxide	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9	Point 10
Na_2O	6.7	1.9	7.1	6.2	3.1	9.5	2.6	10.4	8.9	4.4
MgO	1.1	1.7	1.1	2.6	3.2	1.2	1.9	1.3	3.0	3.7
Al_2O_3	2.6	8.8	4.0	4.8	10.5	2.6	8.6	4.2	4.9	10.6
SiO_2	7.0	21.1	11.3	5.6	32.2	6.3	18.2	10.5	5.0	28.9
P_2O_5	0.2	2.4	0.0	0.2	0.9	0.1	1.9	0.0	0.1	0.7
SO_3	54.7	38.5	56.4	57.5	30.4	41.8	28.4	44.9	44.5	23.4
K_2O	2.0	2.8	0.7	2.8	2.4	3.2	4.3	1.2	4.4	3.8
CaO	18.0	3.4	15.8	9.3	2.3	24.5	4.4	22.5	12.8	3.1
TiO_2	0.6	0.8	1.1	1.3	1.5	0.6	0.8	1.3	1.5	1.8
Fe_2O_3	5.8	5.1	2.1	6.5	9.8	7.7	6.6	2.9	8.9	13.2
BaO	1.4	13.5	0.5	3.4	3.6	2.4	22.3	0.9	5.9	6.3
Total	100	100	100	100	100	100	100	100	100	100

results of the mercury speciation measurement at the inlet and outlet of the SCR catalyst conducted upon installation are shown in Fig. 27. The inlet and outlet measurements were repeated three times and are shown in Fig. 27. The level of elemental mercury at the inlet was approximately 76% to 92%, with the remaining in the oxidized form ranging from 8% to 24%. Very little was in the form of particulate mercury at the inlet. Measurement of mercury speciation was conducted with the ammonia on and off. The results with the ammonia off showed an increase in the oxidized mercury to 43% of the total mercury occurring across the SCR catalyst. However, when the ammonia was introduced into the

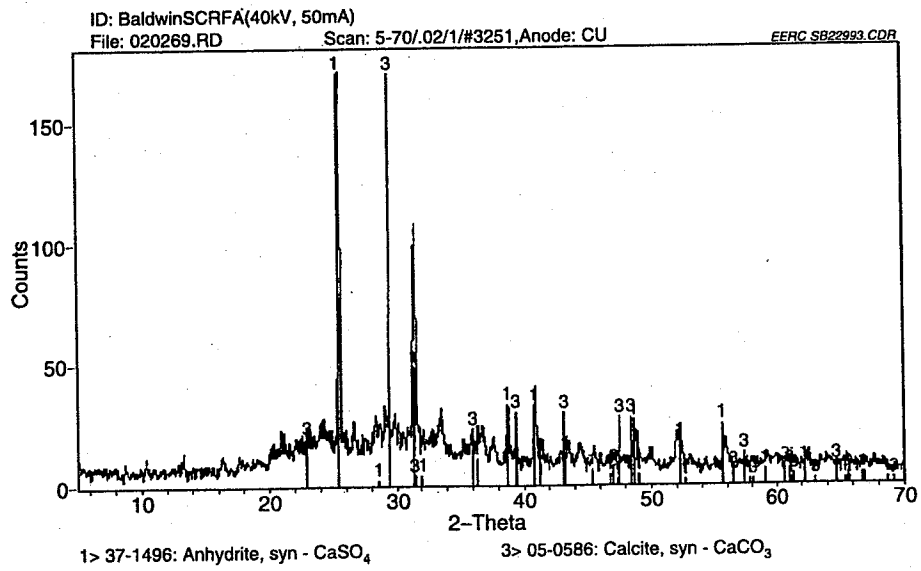

Fig. 23. X-ray diffraction of ash collected on SCR catalyst (1—$CaSO_4$, 2—$Ca_3Mg(SiO_4)_2$, and 3—$CaCO_3$).

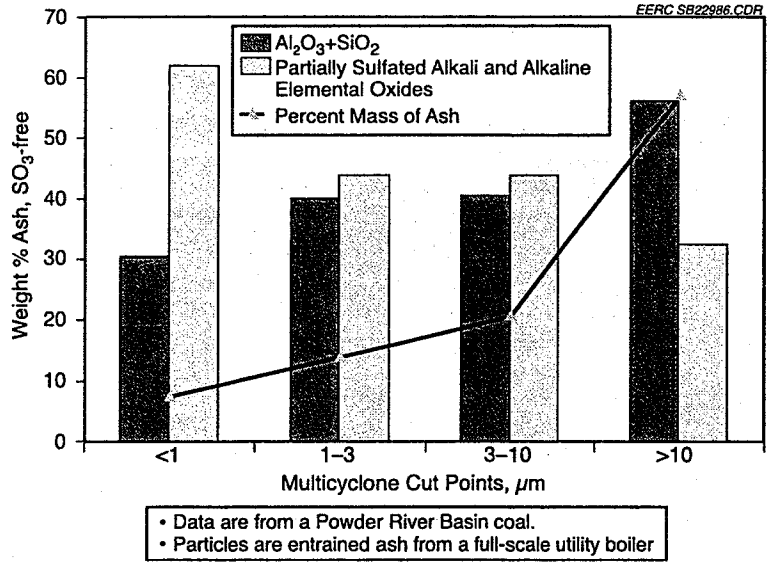

Fig. 24. Simplified illustration of ash partitioning in combustion systems [18].

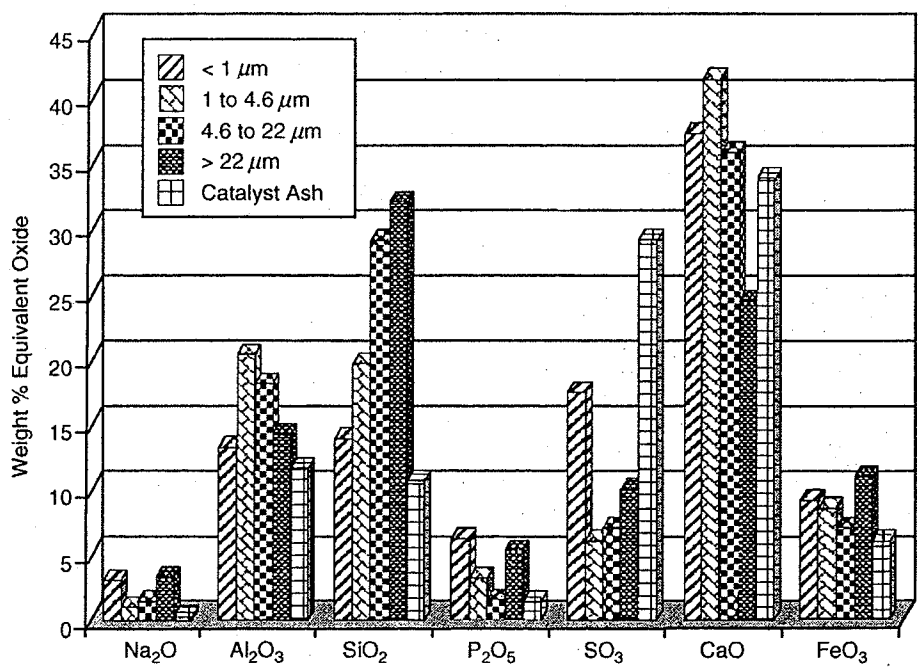

Fig. 25. Comparison of entrained ash and deposited ash on catalyst for Columbia Station.

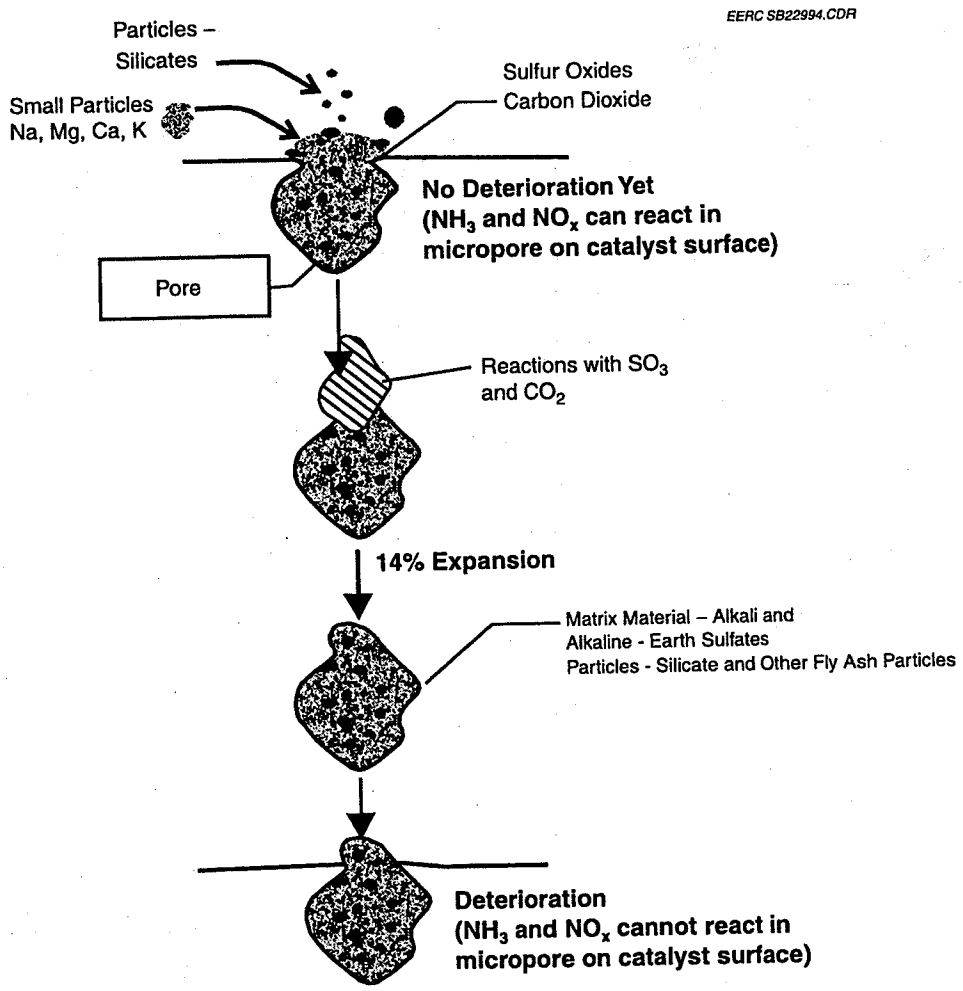

Fig. 26. Mechanism of SCR catalyst blinding via the formation of sulfates and carbonates (modified after Pritchard et al. [35]).

SCR catalyst, the amount of mercury oxidation decreased from 43% to 19%. There was an increase in the particulate mercury from 1.0% to 7.2%.

The mercury oxidation after the SCR catalyst was exposed to flue gas and particulate for 2 months is shown in Fig. 28. The level of oxidized mercury at the inlet ranges from 7.5% to 11.1% of the total mercury. The level of oxidized mercury at the outlet ranged from 7.6% to 14% of the total mercury. The level of particulate mercury increased from a negligible level to 3% of the total mercury at the outlet.

The results of mercury oxidation across the SCR catalyst after 4 months of exposure to flue gases and particulate are shown in Fig. 29. The results show a higher level of oxidized mercury at the inlet as compared to testing conducted at installation and after 2 months. The level of oxidized mercury at the inlet ranges from 32% to 38% of the total,

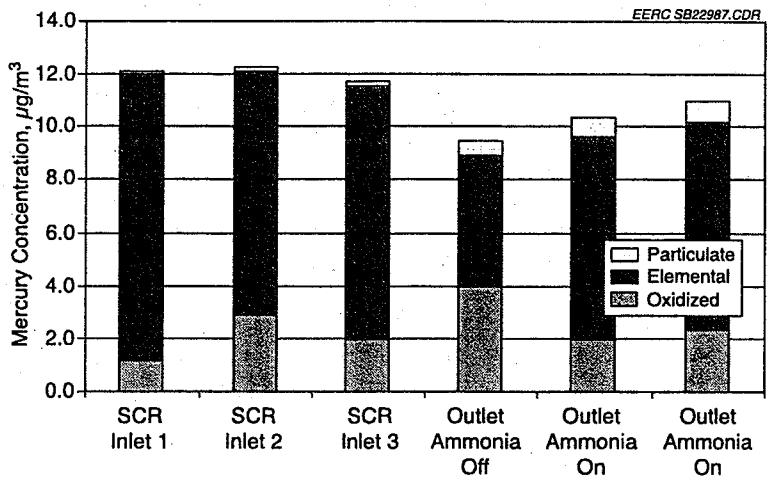

Fig. 27. Mercury speciation measurement at the inlet and outlet of the SCR catalyst upon installation of the catalyst.

with about 5% of the total in the particulate form. The outlet levels of oxidized mercury decrease after passing through the catalyst to about 20% of the total. The level of particulate mercury remained about the same across the catalyst.

4. Conclusions

A slipstream reactor is designed to expose SCR catalyst to coal combustion-derived flue gases and particulate. The system is computer-controlled and operates in an automated

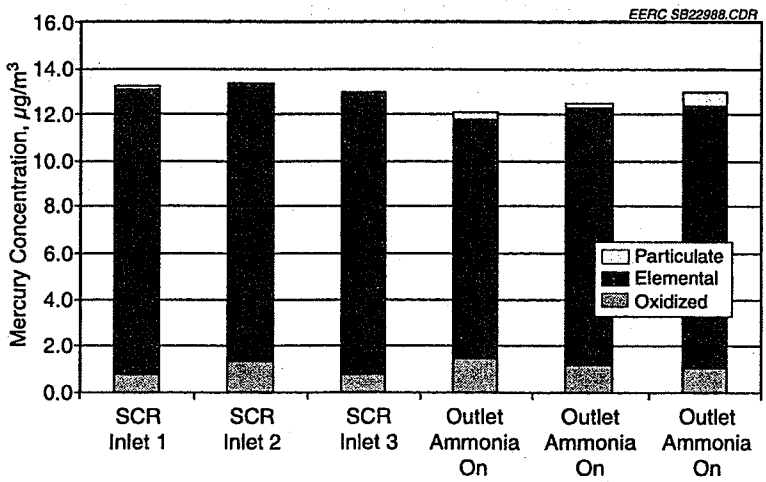

Fig. 28. Mercury speciation measurement at the inlet and outlet of the SCR catalyst after exposure to flue gases and particulate for 4 months.

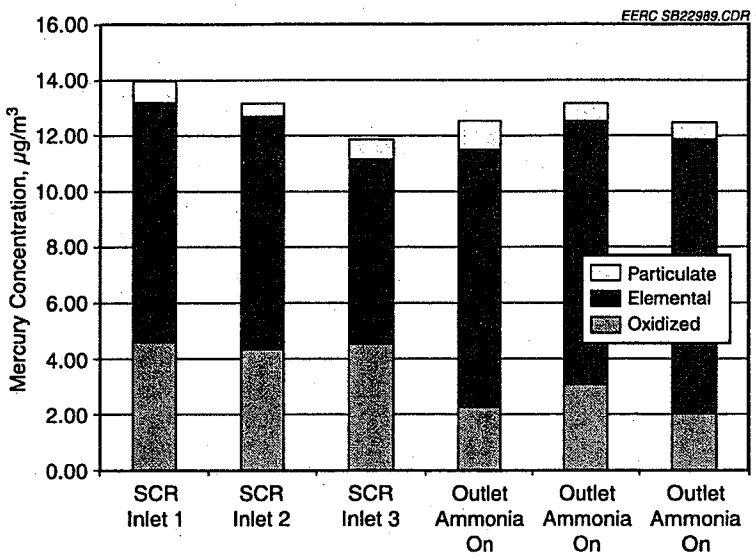

Fig. 29. Mercury speciation measurement at the inlet and outlet of the SCR catalyst after exposure to flue gases and particulate for 2 months.

mode. The system can be operated and monitored remotely through a modem connection. SCR catalyst testing was conducted at two subbituminous-fired plants and one lignite-fired plant. The boiler configurations for the subbituminous-fired plants included a cyclone- and a tangentially fired boiler. The boiler configuration for the lignite plant was a cyclone-fired system.

The pressure drop across the catalyst was found to be the most significant for the lignite-fired plant as compared to the subbituminous-fired plants. Both coals had significant accumulations of ash on the catalyst, on both macroscopic and microscopic levels. On a macroscopic level, there were significant observable accumulations that plugged the entrance as well as the exit of the catalyst sections. On a microscopic level, the ash materials filled pores in the catalyst and, in many cases, completely masked the pores within 4 months of operation.

The deposits on the surfaces and within the pores of the catalyst consisted of mainly alkali and alkaline-earth element-rich phases that have been sulfated. The mechanism for the formation of the sulfate materials involves the formation of very small particles rich in alkali and alkaline-earth elements, transport of the particles to the surface of the catalyst, and reactions with SO_2/SO_3 to form sulfates. XRD analysis identified $CaSO_4$ as a major phase and $Ca_3Mg(SiO_4)_2$ and $CaCO_3$ as minor phases.

Lignite and subbituminous coals contain high levels of organically associated alkali and alkaline-earth elements, including sodium, magnesium, calcium, and potassium in addition to mineral phases. During combustion, the inorganic components in the coal are partitioned into various size fractions based on the type of inorganic component and their association in the coal and combustion system design and operating conditions. The results of this testing found that the smaller size fractions of ash are dominated by partially

sulfated alkali and alkaline-earth elements. The composition of the size fractions was compared to the chemical composition of the ash deposited on and in the catalyst. The comparison shows that the composition of the particle captured in the SCR catalyst is very similar to the <5-μm size fraction.

The ability of mercury to be oxidized across the SCR catalyst was investigated at the Coyote Station. The Coyote Station is fired on North Dakota lignite, and the flue gases are dominated by elemental mercury. Measurement of mercury speciation was conducted using the OH method at the inlet and the outlet of the SCR catalyst. These results show limited oxidation of mercury across the SCR catalyst when firing lignite coals. The reasons for the lack of mercury oxidation include the following: no or low chlorine present in the coal and flue gas to catalytically enhance the oxidation of Hg^0, high levels of alkali and alkaline-earth elements acting as sorbents for any chlorine present in the flue gas, and low levels of acid gases present in the flue gas.

Acknowledgments

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Unresolved Technical Challenges to NOx Reduction for Coal-fired Power Generation

Kevin Davis, Michael Bockelie, Temi Linjewile, Hong-Shig Shim, Connie Senior, and Brad Adams
Reaction Engineering International

Kevin Whitty
The University of Utah

Robert Hurt
Brown University

Stan Harding
N.S. Harding and Associates

THE TRUE COST OF NOX CONTROL

In order to meet existing and impending restrictions on NOx emissions, the US utility industry has typically elected to use low-NOx firing systems (or combustion modifications) augmented where necessary with some form of post-combustion control. A number of specific technologies have been developed to satisfy this need including low-NOx burners, over-fire air systems, fuel switching, fuel staging or reburning, and selective catalytic/non-catalytic reduction. Although many regard these technologies as "plug and play," field experience has been to the contrary. This discussion involves a number of the more important unresolved side effects of NOx control technologies as well as potential tools and solution strategies for handling these difficulties. Lab-test, field-test and computational simulation results are presented regarding key issues including corrosion monitoring, soot formation, SCR catalyst deactivation, and flyash contamination by ammonia.

WATERWALL CORROSION

Combustion modifications to minimize NOx emissions typically result in the existence of reducing conditions in furnaces. As regulations demand further decreases in NOx emissions, it is possible (to a degree) to address these requirements with increased levels of air staging. However, in most practical situations, a number of adverse impacts prevent the application of deep staging. One of the more important limitations is the increased corrosion that can occur on wall tubes exposed to fuel rich combustion environments. In utility boilers, for example, the use of low-NOx burners and over-fire air has increased the frequency and severity of waterwall wastage, with local corrosion rates that can exceed 100 mils/yr. The susceptibility of such units has been attributed to the effects of several features including fuel selection, tube temperature, and firing system design. Formulating solutions to this problem can be complicated by the range of potential corrosion mechanisms, which can involve gas-phase sulfur and/or chlorine in addition to the direct deposition of unreacted solid fuel. The physics and chemistry controlling corrosion processes can be highly non-linear. Therefore, brief periods of exposure to atypical conditions can dominate the overall material loss between inspections. Consequently, control of high temperature corrosion requires a real-time indication of corrosion rates.

During the past two decades, efforts have been made to take real-time corrosion monitoring technologies, which have been successfully applied in low temperature environments, and develop/evaluate their usefulness in high-temperature combustion environments. Although this adaptation has had some success in certain industries [Kane and Cayard, 1998], tests in other areas, such as utility boilers, have generated a great deal of skepticism. Following a preliminary evaluation of available technologies, Reaction Engineering International (REI) identified electrochemical noise technology as a promising option for further development and evaluation [Davis et al., 2000]. The advantages of this technology include:

- High sensitivity
- Instantaneous response allowing real-time measurement
- Direct indication of corrosion
- Qualitatively and quantitatively useful
- Response can be related to type of corrosion (i.e., pitting vs. uniform)

Some of the challenges to using this technology include:

- Limited experience base for high temperature applications
- Sensitivity to service environment
- Large quantity of data to process and store

Although a sensor providing a real-time measurement of corrosion rates is a uniquely useful tool, the management of corrosion-related wastage in combustion systems can be made even more effective when complemented with additional tools. REI uses a multi-step approach as follows:

1. Fuel analysis and anecdotal information for the identification of potential corrosion mechanisms in a boiler or furnace
2. Identification of high risk locations using (1) CFD simulation and integrated correlations describing corrosion rates, as illustrated in Figure 1, and/or (2) plant observables such as ultrasonic testing and tube failures
3. Installation of a real-time monitoring system using single or multiple sensor locations
4. Comparison of sensor output and other plant data for the identification of key operating conditions
5. Validation of quantitative accuracy using precision metrology

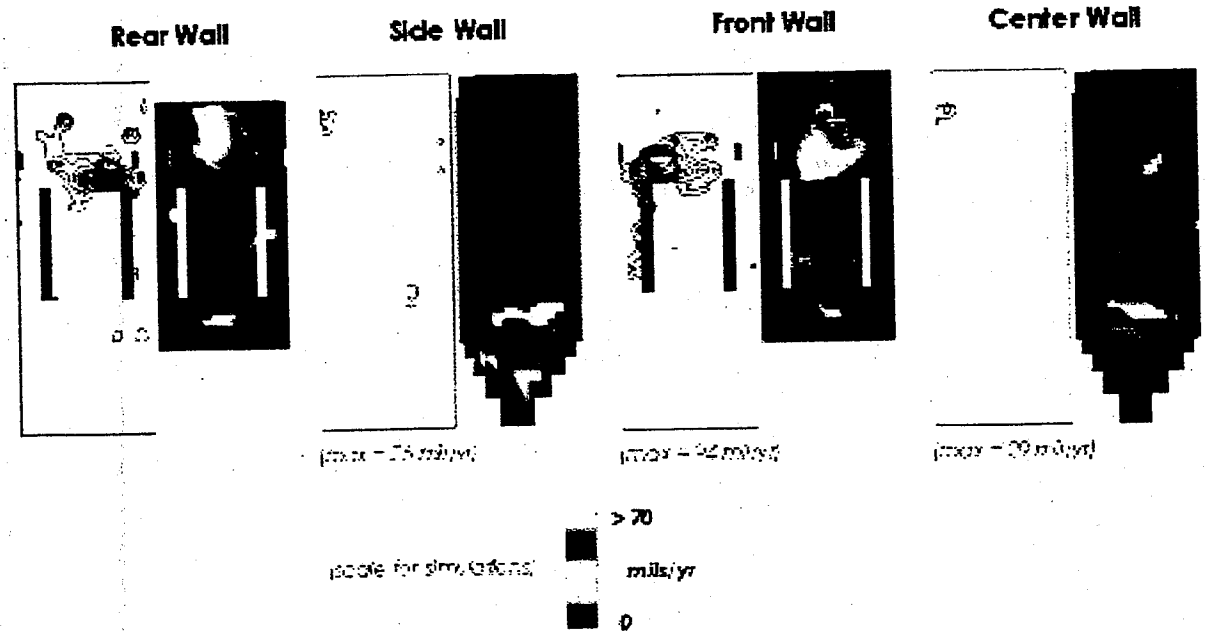

Figure 1. Predicted and Measured Tube Wastage Rates in Coal-fired Boiler.

Wall thickness measurements and maintenance history are used to determine the magnitude and general location of the problem. CFD modeling can then be used to identify the impact of operating conditions and fuel types and a

probe or number of probes can be installed to monitor potential trouble areas. In order to provide confidence in the quantitative accuracy of the sensors, a unique, high resolution, in-house approach to measuring sensor material loss is used as a comparative check on the integrated corrosion rate determined from the electrochemical signal [Davis et al., 2001].

As illustrated in Figure 2, field testing of the sensor has shown that the monitor is sensitive to extremely rapid and small changes in corrosion rate allowing identification of operating conditions or fuel properties that lead to corrosion and making it possible to correct the behavior before significant damage has been done.

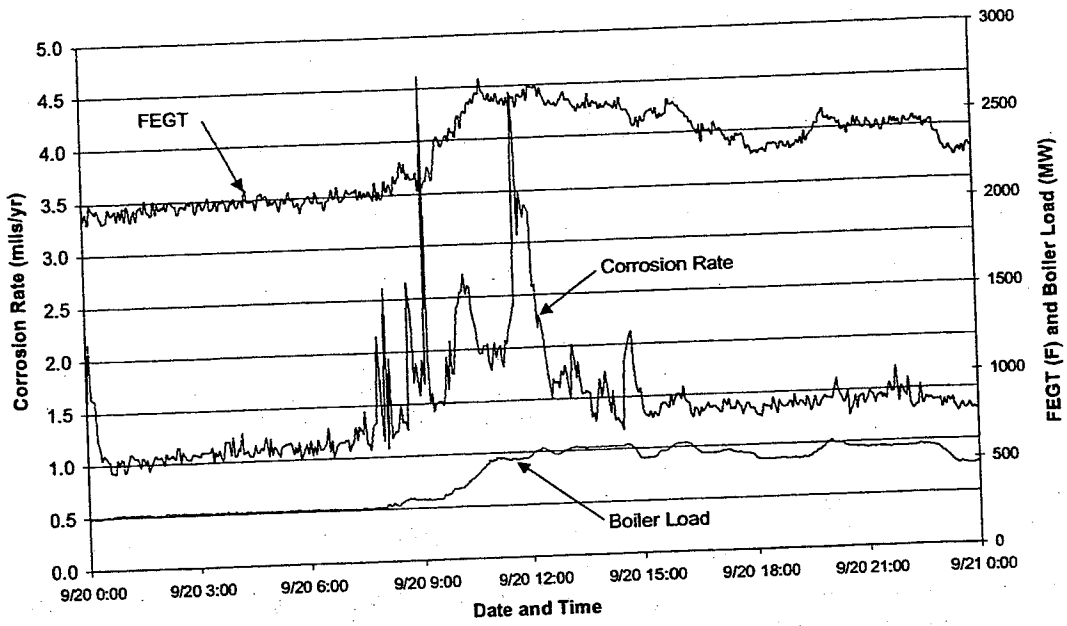

Figure 2. Measured Corrosion Rates in a 680MWe Coal-fired Boiler.

CARBONACEOUS SOOT

Increases in soot formation as a result of reducing environments created by low-NOx combustion modifications has been supported by field- and lab-scale observations [Veranth et al., 1998]. The potential impacts of soot include both furnace and downstream cleanup issues such as:

- Imbalances in boiler heat transfer due to enhanced lower furnace radiation
- Potential decreases in effectiveness of fuel-rich conditions for NOx reduction, particularly for low volatility fuels [Chen and Niksa, 1992]
- Increases in fine particulate emissions and opacity
- Negative impacts on ash salability

This study leverages experimental and modeling capabilities at REI and the University of Utah to improve understanding of the soot formation and destruction processes as well as their impact on the furnace and on clean-up equipment.

A semi-empirical soot model developed by Brown and co-workers [1998] was implemented into REI's two phase combustion CFD code, *GLACIER*. The model is comprised of three transport equations for tar mass fraction, soot

volume/mass fraction, and soot number density. Soot is assumed to form only from coal tars. Tar evolution is calculated from Lagrangian particle phase equations which use the Chemical Percolation Devolatilization (CPD) model to determine devolatilization rates and tar yields [Fletcher et al., 1992].

Computational simulation of the L1500 pilot scale test furnace at the University of Utah Combustion Research Laboratory has been performed with the purpose of better understanding the impact of the location of staged air injection on soot formation/destruction. The residence time from fuel injection to over-fire air (OFA) injection in a utility boiler depends upon a number of factors including the relative importance of NOx reduction vs. fuel conversion efficiency (as determined by CO emissions or carbon-in-flyash) and structural constraints (such as boiler size, the location of buckstays, and the location of division- or wing-walls). Two cases with different OFA locations, 3.25 (OFA 3) and 10.5 (OFA 9) meters from the burner exit (residence times of about 2 and 12 seconds, respectively) were simulated. Operating conditions and coal properties are shown in the Table 1. Backside furnace wall temperature and inlet temperature for coal/air were set to 350 K and 300 K, respectively.

Table 1. Pilot-scale Test Furnace Operating Conditions and Coal Properties

Burner Stoichiometric Ratio	0.85		As Received [%]
Overall Stoichiometric Ratio	1.15	C	65.99
Primary air flow rate [lb/hr]	473	H	3.97
Secondary air flow rate [lb/hr]	700	O	8.47
Tertiary air flow rate [lb/hr]	1392	N	1.29
Staging air flow rate [lb/hr]	929	S	3.49
Coal feeding rate [lb/hr]	345	Ash	9.87
Coal firing rate [MMBtu/hr]	4.01	Moisture	6.92

Simulation of the OFA 3 case results in tar and soot amounts as shown in Figure 3. As coal-off gases including tar evolve near the burner, soot begins to form and results in an increase in soot volume fraction and soot number density as shown. Oxidation reduces tar and soot concentrations and, as the air from the staging port mixes into the flow, there is nearly complete combustion of soot due to increased oxygen availability.

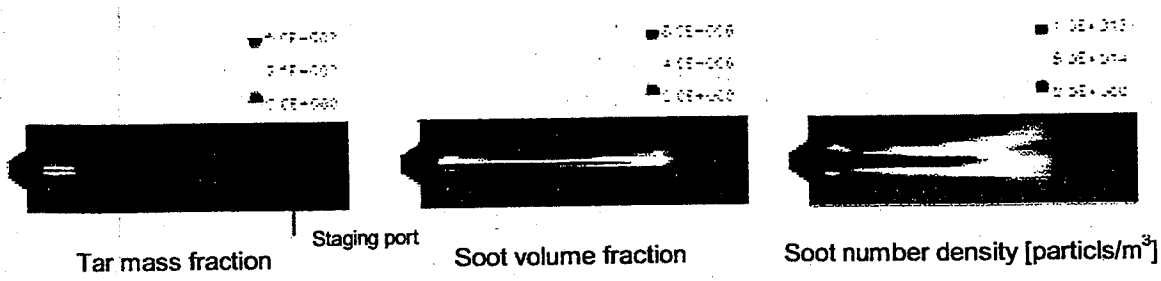

Figure 3. Calculated Tar Mass Fraction, Soot Volume Fraction, and Soot Number Density at Center Cross-Section of a Pilot-scale Furnace.

Figure 4 shows mass weighted soot volume fraction and oxygen concentration as a function of distance from burner exit. Maximum soot volume fraction occurs at about 1 m form the burner exit for both cases. After a peak, there is a rapid reduction of soot volume fraction. The rate of soot reduction slows down as oxygen level comes to zero at about 2 meters from the burner exit. OFA 3 case shows nearly complete soot burnout close to the staging port. OFA 9 case shows relatively high soot volume fraction at the upstream of the staging port, as there is no available oxygen to oxidize soot. In addition, soot volume fraction slowly increases and number density decreases (not shown in the figure) as agglomeration of soot particles occurs at the upstream of the staging port. Complete soot burnout does not occur in the OFA 9 case, possibly due to lower gas temperature and higher soot concentration to be removed. Further investigation should be performed to understand this feature.

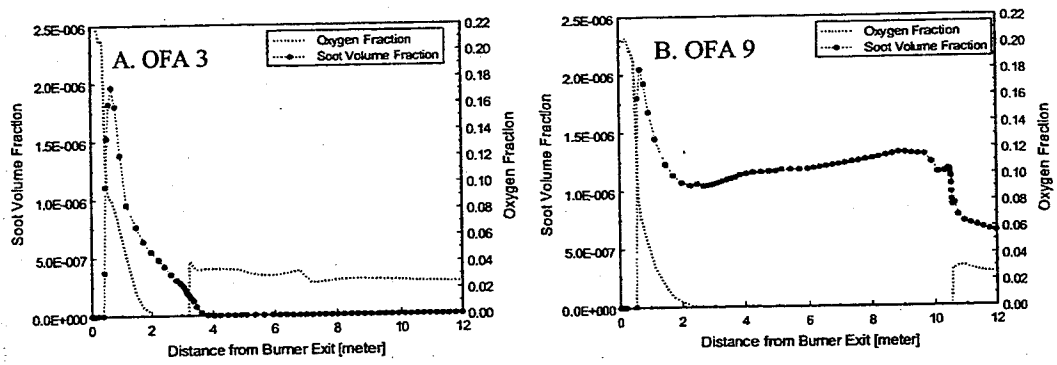

Figure 4. Mass-weighted average soot volume fraction and oxygen fraction as a function of distance from burner exit for two different ofa locations: a 3.25 meter, b 10.5 meter from the burner exit.

The competing nature of two processes, soot formation and destruction can be clearly seen in the above results. Near the burner, there is significant soot formation from the coal off-gas. After reaching a peak, the soot volume decreases due to oxidation (destruction) of the soot. However, as the available oxygen is consumed, the net destruction of soot slows. Eventually, there is no available oxygen and the net production of soot again increases. Downstream of the air staging port, the model predicts rapid oxidation of soot. The impact of staging port location seems to be significant in determining soot concentration in flue gas. The two cases studied in this paper employed a wide range of residence times, 2 ~ 12 seconds from fuel injection to over-fire air injection. As shown in Figure 4, increased residence time may cause inefficient soot burnout at the staging port and result in relatively high soot concentration in the flue gas.

Experimental validation of the soot model will be performed on a pilot-scale test furnace using a photoacoustic (PA) instrument [Moosmuller et al., 1998]. The schematic of the PA system is shown in Figure 5. The measured soot volume fraction will be compared with that of a simulation along the long axis of the furnace as a function of axial distance from the burner exit as well as radial distance from the centerline. The validated model will be applied to the pilot-scale test furnace again with various burner stoichiometries from 0.75 to 1.05.

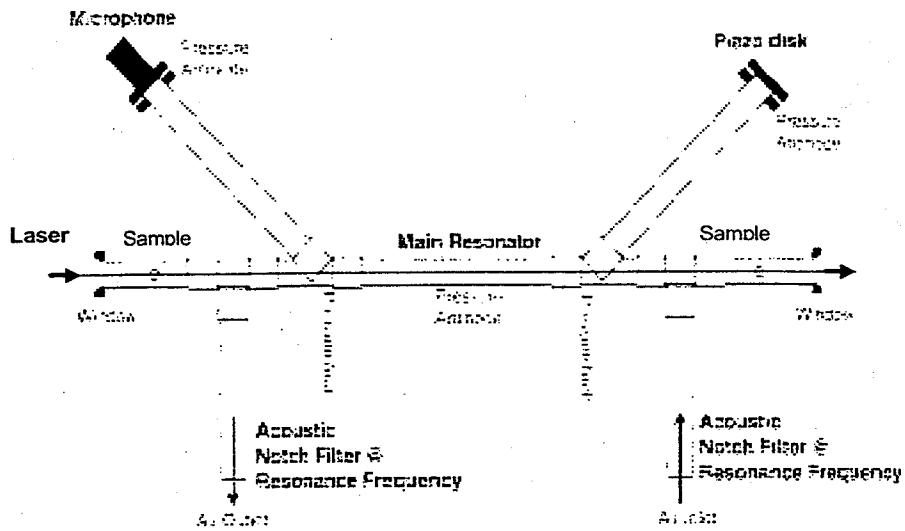

Figure 5. Photoacoustic (PA) instrument for the characterization of soot concentrations in pilot-scale testing.

SCR DEACTIVATION BY LOW RANK FUELS

The cost and effectiveness of NOx control strategies for coal-fired boilers has received considerable attention over the last two decades and a number of successful approaches have been applied. Utilities must weigh a number of issues when determining the best strategy for their specific units. Comparisons routinely include cost and the amount of NOx reduction, with selective catalytic reduction (SCR) often used as a standard for comparison. In order to make this comparison meaningful, the total cost of combustion modifications must be considered (carbon-in ash levels, waterwall wastage, etc.). However, the "real" cost of SCR for coal-fired boilers using low rank US coals and coal/biomass blends is very uncertain.

Loss of activity (or deactivation) of the catalyst with time has a significant impact on the amount of catalyst needed and on the frequency of catalyst replacement in SCRs. Both have a large effect on the operating costs of SCR units in coal-fired power plants. There are three mechanisms for deactivation of SCR catalyst in coal-fired power plants that have been identified:

1. Fouling (surface deposition)
2. Pore condensation (and/or pore blockage)
3. Poisoning

For a given situation one or more of these mechanisms may be occurring. We should not expect that a test on a single type of coal (e.g., PRB) would give us information on all of these mechanisms.

For PRB coals, there is a widely held belief that fouling by calcium sulfate deposits is the primary mechanism for catalyst deactivation [Siemens, 2000]. In some cases, sodium and potassium may be important. This may be due to poisoning (and perhaps pore-filling) when ash particles containing alkali sulfate come in contact with water if the catalyst drops below the dew point of the gas. This might be poisoning from the alkali or pore condensation. Either way, water washing should regenerate the active sites. (This is in contrast to arsenic poisoning, which is irreversible.)

The fouling phenomenon in SCR catalysts exposed to PRB coals is thought to occur via the following steps:

1. Deposition of ash particles containing CaO

2. Reaction of CaO in the ash with SO_3.

It has been noted that the deactivation and observed particle deposition occur in regions of higher turbulence at the inlet to the catalyst layer. The limiting step may be the deposition of submicron CaO particles on the catalyst surface. Free calcium in the ash, particularly in the finer (submicron) ash fractions will therefore be very important. The SO3 and water contents of the gas are also important, both for production of calcium sulfate and in determining the acid dew point. The latter is more likely to be important for the sodium/potassium routes to deactivation.

Limited information is available from Europe on the effect of biomass co-firing on SCR catalyst deactivation. But, in summary, deactivation of SCR-based catalysts can occur by chemical poisoning, fouling of catalyst by deposition of inorganic (or organic) material on its surface, or surface area decreases associated with plugging pores on the catalyst surface. All of these mechanisms are observed to some extent in commercial installations, but catalysts deployed in high-dust applications using high-rank coals have established commercial success for long lifetimes. Low-rank coals and biomass pose potentially greater deactivation threats because they contain relatively high amounts of alkali and alkaline earth materials that are more active in all of the above-cited deactivation mechanisms.

A series of experiments have been designed to delineate the mechanisms and rates of SCR catalyst deactivation. These experiments include two general types: flow-reactor investigations and in-situ analyses of reactions on pellet surfaces. The former are conducted in temperature-programmed test cells that operated as differential reactors exposed to controlled concentrations of reactants. The data from these experiments include NOx conversion, ammonia conversion, SO_2 and SO_3 conversion as a function of temperature, catalyst type and composition, and time. The latter include spectroscopic surface analyses of reacting and adsorbed species on surfaces during SCR reactions. The combination of experiments allows mechanisms and rates of NOx formation to be definitively determined under a variety of conditions. A simple SCR model has been developed. This model is based on the work of Dumesic and coworkers [1996] and involves a reaction scheme for adsorption of ammonia on Brønsted acid sites of vanadium oxide followed by activation of ammonia via redox sites (V=O). The activated ammonia is then assumed to react with gaseous or weakly adsorbed NO, producing N_2 and H_2O; this reaction also partially reduces the catalyst. The reduced sites react with O_2 in the gas stream and the catalytic cycle is complete. The reaction scheme has been shown to describe the kinetics of the SCR reaction under conditions that are relevant to field applications of SCR in the utility industry. The REI model is a one-dimensional model that uses the number of active sites per unit surface area as the chief parameter. The model has been shown to reproduce literature data well.

In addition to these more fundamental studies, a slipstream reactor will be deployed at two power plant sites. The objective of the power plant tests with the slipstream reactor is to evaluate commercial vanadium-based catalysts and to monitor their deactivation during exposure to a slipstream of flue gas. The slipstream reactor will operate. A conceptual drawing of the slipstream reactor is shown in the Figure 6. Four catalyst manufacturers have been contacted and have agreed to supply samples of both plate and honeycomb catalysts, for a total of five different catalysts. Due to proprietary considerations, a generic vanadia-based catalyst will also be used to allow for more detailed characterization. The reactor will be installed such that a sample of gas (approximately 250 scfm) can be withdrawn at the economizer outlet. The flue gas leaving the slipstream would be exhausted back into the main flue gas flow downstream of the air preheater. Inlet and outlet NOx will be monitored on-line at the slipstream reactor. Periodically, catalyst samples will be withdrawn and the activity will be tested under well-controlled conditions.

AMMONIA CONTAMINATION OF FLYASH

Ammonia vapor comes into contact with flyash in connection with selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), and/or electrostatic precipitator conditioning [Castle, 1980, Golden, 2001]. Typically some portion of the vapor phase ammonia adsorbs or deposits on flyash with the potential to cause problems in ash utilization, handling, and disposal [Larrimore, 2000]. Of particular concern for disposal is the possibility for high

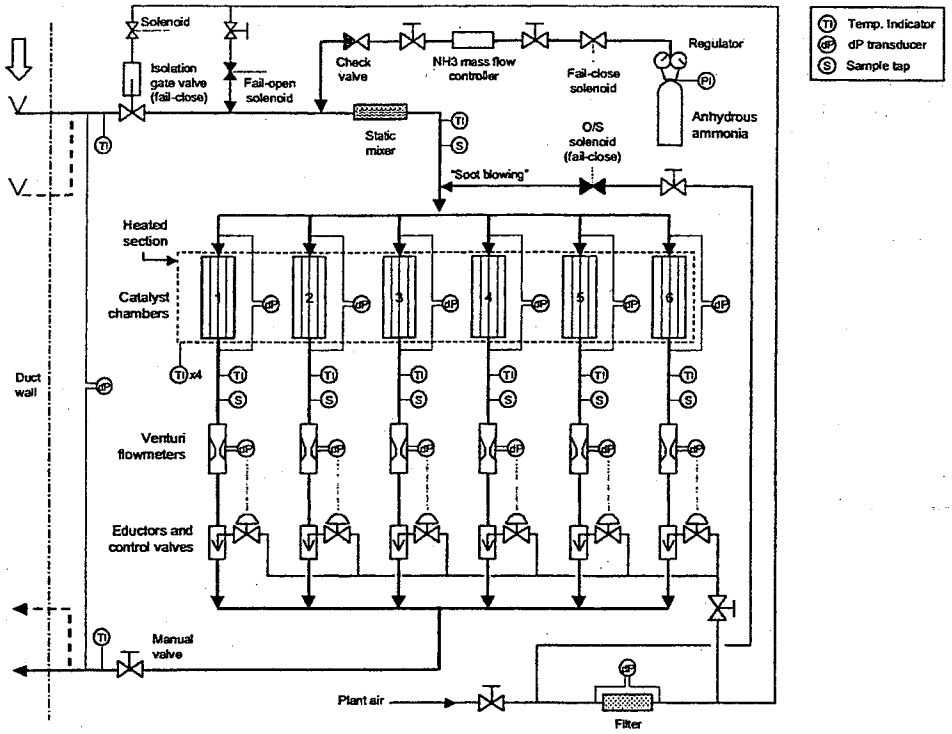

Figure 6. A slip-stream reactor for the simultaneous evaluation of six catalysts using ammonia injection, on-line NOx measurement, and periodic off-line catalyst reactivity monitoring.

ammonia contents in surface and groundwater near ash ponds [Golden, 2001] and at landfill sites in runoff, leachate and surrounding atmosphere [Lowe et al., 1989]. Problems in utilization arise not from degradation of concrete properties [Novak and Rych, 1989; Golden, 2001] but rather from worker exposure to odor, especially during enclosed concrete pours.

Ammonia associated with flyash can be in the form of ammonium sulfate or more commonly bisulfate particles [Golden, 2001], or ammonia species adsorbed on carbon sites [Rubel, 2001], likely on carbon surface oxides, or mineral surfaces. In the present study we have measured fundamental adsorption isotherms for ammonia on commercial ash samples and have explored methods of removing ammonia using controlled amounts of moisture – often referred to as semi-dry processing [Gasiorowski and Hrach, 2000].

Figure 7 shows adsorption data for the flyash before and after carbon removal by air oxidation. Above 10-4 relative pressure the adsorption of ammonia is significant and dominated by carbon rather than the mineral portions of the ash. Below 10-4 relative pressure the adsorbed amounts are small for all samples.

An important feature is the sharp uptake at around 10-4 relative pressure. A similar feature is not visible, at either the same relative pressure or at the same absolute pressure, in the results from nitrogen and carbon dioxide — it is unique to ammonia. Ozonation of the carbon surfaces enhances this feature, while the rest of the isotherm is not significantly altered, suggesting that this feature is related to ammonia chemisorption on carbon surface oxides. It appears that this monolayer coverage of the mineral grains occurs at very low vapor concentrations, while at higher ammonia concentrations carbon begins to dominant the adsorption process. The adsorbed amounts in Figure 7 are lower than those reported by Muzio et al [1995], and the difference suggests that one of the secondary flue gas

species, SO_2 or water vapor, are playing a cooperative role in ammonia adsorption. In general ammonia uptake onto flyash is now believed to be a combination of physical adsorption (primarily on the high surface-area carbon fraction), chemisorption (on acid sites on carbon and mineral phases), and, most importantly, the deposition of ammonium salts formed by reaction with SO_3.

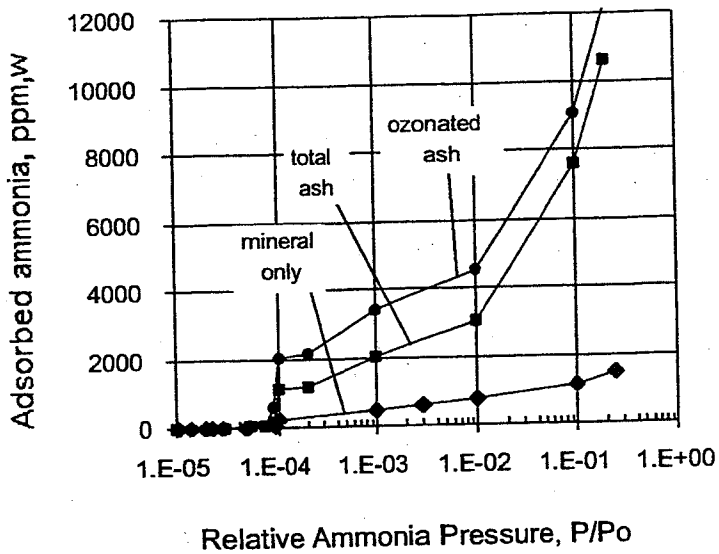

Figure 7. Full ammonia adsorption isotherms on bituminous coal flyash (6.2% LOI) at 273 K before and after carbon removal by air oxidation. Also shown is the ammonia isotherm on flyash subjected to ozonation.

Figure 8 illustrates the effect of contacting flyash with a flowing stream of humid air. This contacting method is effective at removing ammonia at moisture levels of less than 3 wt-%. It is believed that slight condensation in and around the individual ash/carbon particles causes the ammonia species to desorb, enter solution, and be converted to the highly volatile NH_3 form according to:

$$NH_3\,(aq) + H_2O\,(liq) \Longleftrightarrow NH_4^+\,(aq) + OH^-\,(aq) \qquad (1a)$$

$$NH_3\,(aq) \Longleftrightarrow NH_3\,(vap) \qquad (1b)$$

NH_3 is highly volatile so equilibrium 1b favors partitioning to the vapor phase, while equilibrium 1b is highly dependent on solution pH. At 20 ^oC pK_b = 4.767, which upon rearrangement gives

$$\log\{[NH_4^+]/[NH_3]\} = 9.23 - pH \qquad (2)$$

this combined reaction system therefore leads to NH3 as the predominate species and thus extensive ammonia volatilization whenever pH values are greater than about 10 in the condensed film. Water vapor is always below saturation in the Figure 8 experiments, so partial condensation occurs by adsorption on surfaces and capillary condensation in pores and fine intraparticle spaces and the amounts are low enough to maintain useful ash handling characteristics.

The rate of removal increases with increasing moisture content, but the total contact times are long. The process can be greatly accelerated by replacing the humid air with a flowing water aerosol (fog), which is capable of establishing 3 wt-% moisture or greater in the ash bed within several minutes. The ammonia liberation process is spontaneous for high-pH ashes, while for low-pH ashes it requires a basic additive, such as $Ca(OH)_2$ added as a dry powder to the ash or the use of a basic solution for fog generation [Gao, et al., 2002]. Controlled water addition together with intense mechanical agitation form the basis for a related process patented recently by Gasiorowski and Hrach [2000].

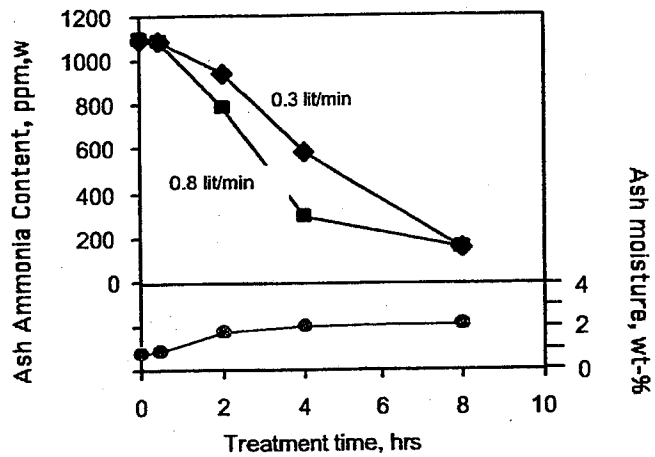

Figure 8. Results of ammonia removal experiments in flowing humid air (RH 93%) passed upward through 10 gm fixed beds of ash at one of two different flowrates. Sample: basic flyash, FA1.

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Principal Presenter & Co-authors

Name:	Kevin Davis
Title:	Manager, Engineering Development
Company:	Reaction Engineering International
Address:	77 West 200 South, Suite 210 Salt Lake City, UT, 84121, USA
Phone:	(801) 364-6925, ext. 23
FAX:	(801) 364-6977
E-mail:	davis@reaction-eng.com

Name:	Michael Bockelie
Title:	Executive Vice President
Company:	Reaction Engineering International
Address:	77 West 200 South, Suite 210 Salt Lake City, UT, 84121, USA
Phone:	(801) 364-6925
FAX:	(801) 364-6977
E-mail:	bockelie@reaction-eng.com

Name:	Temi Linjewile
Title:	Senior Engineer
Company:	Reaction Engineering International
Address:	77 West 200 South, Suite 210 Salt Lake City, UT, 84121, USA
Phone:	(801) 364-6925
FAX:	(801) 364-6977
E-mail:	linjewile@reaction-eng.com

Name:	Hong-Shig Shim
Title:	Senior Engineer
Company:	Reaction Engineering International
Address:	77 West 200 South, Suite 210 Salt Lake City, UT, 84121, USA
Phone:	(801) 364-6925
FAX:	(801) 364-6977
E-mail:	shim@reaction-eng.com

Name:	Connie Senior
Title:	Program Manager
Company:	Reaction Engineering International
Address:	77 West 200 South, Suite 210 Salt Lake City, UT, 84121, USA
Phone:	(801) 364-6925
FAX:	(801) 364-6977
E-mail:	senior@reaction-eng.com

Name:	Brad Adams
Title:	President
Company:	Reaction Engineering International
Address:	77 West 200 South, Suite 210 Salt Lake City, UT, 84121, USA
Phone:	(801) 364-6925
FAX:	(801) 364-6977
E-mail:	adams@reaction-eng.com

Name:	Kevin Whitty
Title:	Research Associate
Company:	University of Utah
Address:	1495 East 100 South 109 Kennecott Research Building Salt Lake City, Utah 84112-1114, USA
Phone:	(801) 585-9388
FAX:	(801) 585-5607
E-mail:	whitty@eng.utah.edu

Name:	Robert Hurt
Title:	Professor
Company:	Brown University
Address:	Division of Engineering, Box D 182 Hope St. Providence, RI 02912, USA
Phone:	(401) 863-2685
FAX:	(401) 863-1157
E-mail:	Robert_Hurt@brown.edu

Name:	Stan Harding
Title:	Principal
Company:	N.S. Harding & Associates
Address:	1019 Eaglewood Drive North Salt Lake, UT, 84054, USA
Phone:	(801) 294-5030
FAX:	(801) 294-5030
E-mail:	nsharding@attglobal.net

Twenty-Five Years of SCR Evolution: Implications For US Application And Operation

J. E. Cichanowicz
Consultant
236 N. Santa Cruz Avenue, Suite #202
Los Gatos, CA 95030

L. J. Muzio
Fossil Energy Research Corporation
23342-C South Pointe Drive
Laguna Hills, CA 92653

ABSTRACT

In the 25 years since the first commercial installations in Japan, SCR technology has evolved in response to changing application conditions. For example, present-day catalysts feature thinner walls, improved mass transfer and activity, and better poison resistance than earlier generation products. Additionally, catalyst management strategies frequently utilize catalysts from suppliers and with geometry different from the original specification, to improve operation and minimize cost. Catalyst regeneration rather than replacement is playing a role. Reactor design and layout has evolved to adopt, where necessary, static mixers to promote contacting of reagent and flue gas. These features improve performance and offer lower cost, but may increase the need for monitoring and diagnostic measurements.

INTRODUCTION

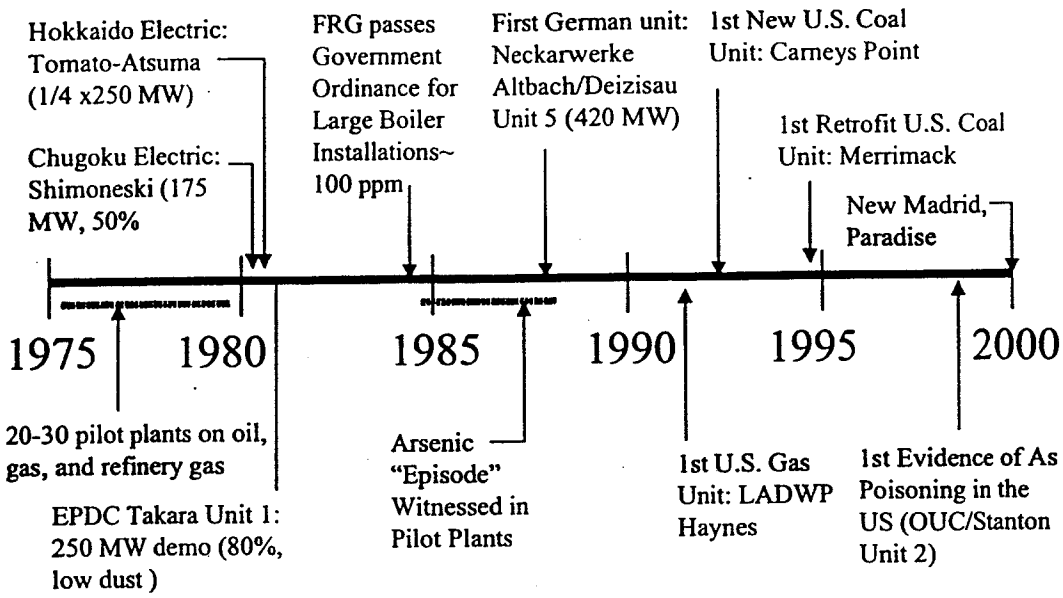
By the year 2004, in excess of 100 GW of coal-fired capacity in the US may be equipped with SCR NO_x control technology, to mitigate "seasonal" ozone production as mandated by Title I of the 1990 Clean Air Act Amendments [(1)]. The application of SCR in the US will have evolved from two prior generations of design: the first commercial applications in Japan in the late 1970s, and subsequent installations in Europe (predominantly Germany) in the mid-1980s. SCR process design basis and operating requirements have significantly evolved from these prior generations, both simplifying and, in some ways, complicating the pending operations in the U.S. This paper reviews the key design and operational evolutions, and projects how future US operation may be affected.

BACKGROUND AND HISTORY

Strict NO_x emission limits were implemented by the Japanese federal government as early as 1973. Local authorities mandated additional reductions, lead by Yokohoma City in 1980 [(2)]. Regarding new generating units, Japan's Electric Power Development Company (EPDC) was required to "cap' the NO_x emissions from the two-unit Takehara Station to allow construction of

a third, coal-fired unit. These requirements prompted early R&D and pilot investigations to evaluate SCR NO_x control to achieve at least 50-60% NO_x removal. Figure 1 presents a timeline of significant events regarding the development and commercialization of SCR technology.

Figure 1. Timeline Of Key SCR Events



Subsequent to the approximately 20-30 pilot plants operated in Japan in the late 1970s (mostly on fuel oil and natural gas), several demonstrations of coal-fired units were conducted. Among the first SCR demonstrations was the 175 MW Shimonoseki station of Chugoku Electric, treatment on 25% of flue gas from the Hokkaido Electric Tomato-Atsuma Station, and EPDC's Takehara Station, where for the latter parallel reactors compared catalyst from two suppliers. Both the Tomato-Atsuma and Takehara units employed hot-side ESPs, providing a low ash environment to the catalyst. NO_x removal from these units ranged from 50-80%, with a 5-10 ppm residual NH_3 limit. Thus, early coal-fired experience was divided between high dust and low dust applications.

Significant experience with high dust SCR continued with several early applications in Germany in the mid-1980s, in response to the Government Ordinance For Large Boilers, adopted by the-then Federal Republic of Germany [3]. Neckarwerke's Altbach/Deiszeiu Unit 5 was reportedly the first coal-fired commercial unit in Germany on a dry-bottom boiler, and Knepper C the first "slag-tap" boiler application. NO_x removal performance in the German and European applications increased to generally 80%, with selected high NO_x-emitting units such as Knepper C achieving 90%. Experience in Germany also identified arsenic poisoning of catalysts through both pilot plant tests and full-scale experience, and further demonstrated that control of residual NH_3 to 2-3 ppm (and not 5 ppm) was in most cases required to maintain ash utilization. In the US, the Haynes Station of the Los Angeles Department of Water And Power was the first utility SCR application, employing an in-duct design for natural gas firing. The first coal-fired applications for new plants (Carney's Point) and retrofit (Merrimack Unit 2) followed in the

early 1990s. Finally, arsenic poisoning was witnessed in the US at the Orlando Utilities Commission Stanton Unit 2 [4].

EARLY UNIT DESIGN CHARACTERISTICS

Table 1 summarizes the key design variables for several early SCR applications in Japan and Germany. NO_x reduction varied significantly, with removal efficiencies from 50% to approaching 90%, the latter applied to high NO_x emitting units. The low sulfur level of coals fired in Japan minimized concern for SO_2 conversion, at least for some units. Also, limited experience with high dust applications had not identified the true impact of residual NH_3; thus, control to 5 ppm (and at times 10 ppm) was allowed for coal-fired applications. Figure 2 illustrates the catalyst geometry employed at Tomato-Isaku and one Takehara reactor, which consisted of "pipes" with walls of 5 mm to avoid erosion. Conversion of SO_2 approached 2% for some of these designs, which was not problematic for the early low sulfur content coals.

Table 1. Early Commercial SCR Installations: Design Features

DESIGN VARIABLE	EPDC/ Takehara (1980)	Shimonoseki (1981)	Neckarwerke/ Altbach (1985)	Neckarwerke/ Walheim (1986)	EVS/ Heilbronn (1985)
High Dust/low Dust	LD	HD	HD	HD	HD
Inlet NO_x (ppm)	300	500	300	750	325
NO_x Reduction (%)	80	50	66	88	80
Residual $_{NH3}$ (ppm)	5	5	5	3	5
SO_2 Conv. (%)	1	1	<2	<2	<2
Space Velocity (1/h)	2300	3000	3340	1900	2850

Figure 2: Early Pipe-Shaped Catalyst Geometry

COMPARISON TO DESIGNS FOR US APPLICATION

There are numerous design features of SCR process equipment which distinguish the imminent US applications from predecessors. These include (a) catalyst technology, (b) process conditions applied, (c) reactor layout, (d) reagent injection equipment, (e) coal-fired experience base, (f) reagent type and handling systems, and (g) balance-of-plant activities. Items (a) through (e) will be addressed in some detail, with highlights noted for (f) and (g). Subsequent to this discussion, data describing long-term operation and evaluation of a catalyst management strategy employing regeneration is presented.

Catalyst

Possibly the most significant advances have been achieved in catalyst technology, resulting in increased performance and lower production cost. Improvements to both catalyst geometry and composition were realized.

Geometry

The limited strength of extruded material, or the ability to bond catalytically active ingredients onto a substrate, dictated catalyst geometry for early designs. Accordingly, relatively thick extruded walls or coatings were necessary to provide erosion resistance. Figure 2 depicted the pipe-shape geometry employed in several early applications, requiring a 5 mm thick wall to prevent erosion. Table 2 compares the geometrical characteristics of several early catalyst products, showing how the decrease in wall thickness improved available surface area for extruded material. Most notable in Table 2 is the increase in surface area-to-volume ratio, which for some specific products is significant. Of exception are the physical characteristics of plate-type catalysts, which offer among the highest open area (e.g., lowest flue gas pressure drop) and have remained relatively constant to exploit that important feature. Also of note is the introduction of ceramic fibers as substrate, offering significant surface area of reaction per unit weight.

Table 2. Evolution of Catalyst Physical Properties: 1979 – 2001

Physical Characteristic	Unit	Geometry	Pitch or Characteristic Dimension (mm)	Wall Thickness (mm)	Surface Area/Volume m2/m3	Open Area (%)
Japan 1979	various	pipe	30	5	~200	~60
Japan 1980	Shimonoseki	grid	9.8	1.8	333	67
Japan 1984, 1895	Sakata, Yokosuka	grid	7.4	1.4	438	66
Europe, 1985	Altbach-Deizshu	grid	7.2	1.4	448	64
Europe, 1986	Knepper	grid	7.4	1.1	460	73
Europe, 1989	Mehrum	plate	6	<1	330	82
US, 1995	OUC	plate	5.4	<1	368	84
US, 2000	New Madrid	grid	9.2	0.83	383	83
	various	grid	7.4	0.83	480	79
US, 2001	various	corrugated plate	10.6 (hyd dia)	1	390	78

For some SCR applications, the higher specific surface area, smaller pitch catalysts are purposely not utilized, and instead the larger pitch, lower specific surface area designs are used to avoid ash plugging and deposition. In fact, a "cascading" catalyst pitch (pitch size decreases with each catalyst layer in the direction of gas flow) is frequently used in many stations operating in Europe to manage ash deposition and plugging [5]. Although no SCR retrofit units in the US at present are using the cascading approach with initial catalyst inventory, some adjustment of pitch to operating characteristics is anticipated with experience.

Composition

Catalyst composition changes have increased activity while maintaining or reducing conversion of SO_2 to SO_3, and provided resistance to arsenic poisoning. Specifically, catalyst suppliers have employed additives as well as improved manufacturing and processing techniques that influence the available surface area for reaction. The common TiO_2-based catalysts also can employ molybdenum trioxide (MoO_3) and tungsten trioxide (WO_3), in addition to the key active ingredient, vanadium pentoxide (V_2O_5). Perhaps the most significant consequence of the improved manufacturing process has been the increased "porosity" of the catalyst – and the ability to offer high mass transfer and surface area for reaction – without compromise to erosion resistance.

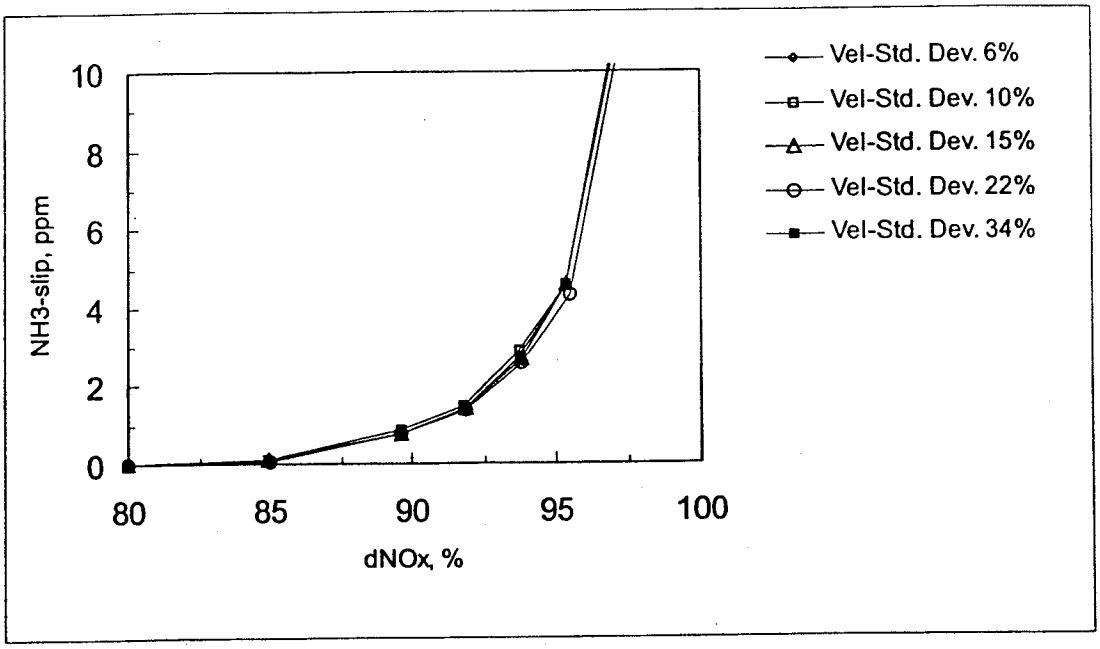
The combination of higher surface area per volume of catalyst and catalytic activity, coupled with catalyst management techniques, has probably reduced the initial volume of catalyst employed for a given application. Comparisons to early designs can be misleading as both NO_x removal targets and the initial catalyst guarantee period have evolved. However, Table 2 data when compared to present space velocities for 90% NO_x removal and 2 ppm residual NH_3 suggest lower volume is currently applied. This improvement leaves less margin for design or operating errors or anomalies compared to the more conservative European applications. Consequently, operators will benefit from detailed process monitoring to diagnose and detect performance trends as early as possible.

Process Conditions

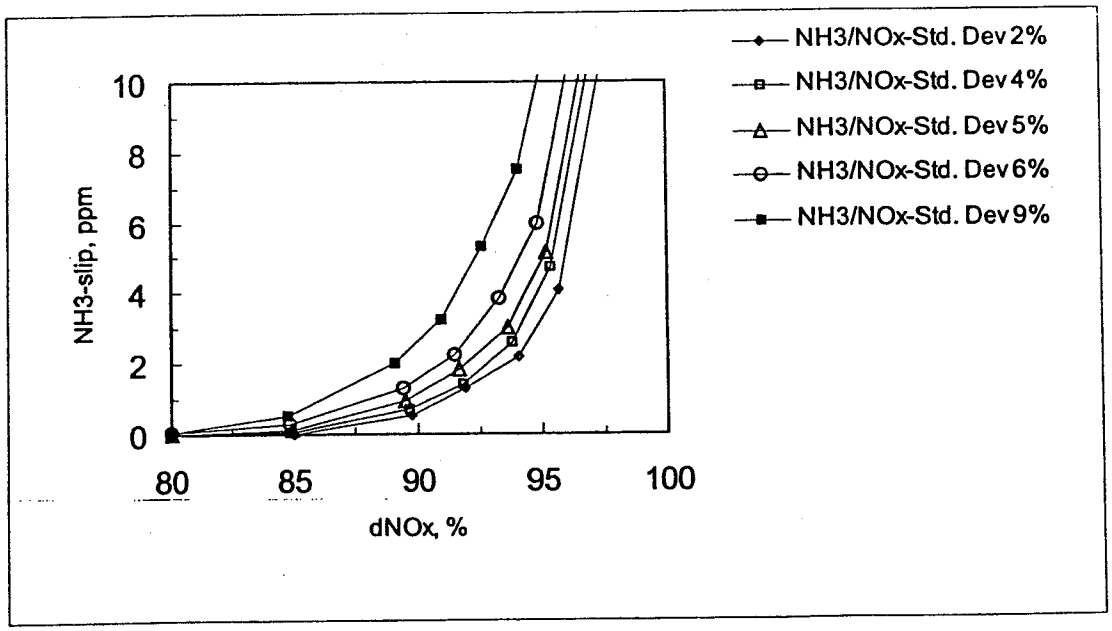
The selection of SCR "process conditions" – the distribution of flue gas velocity, NH_3/NO ratio, and the range of acceptable temperature that establish the operating environment for the catalyst - have evolved to support present performance targets. There are several methods of specifying the distribution of velocity and NH_3/NO ratio; this paper will utilize the standard deviation (SD) of the measurements.

Figure 3 illustrates the role of flue gas velocity and NH_3/NO ratio SD on NO_x removal performance and residual NH_3. These data represent a performance calculation for an inlet NO_x content of 0.30 lbs/MBtu, employing a catalyst with space velocity of 3200 1/h, and grid-type catalyst of 7.4 mm pitch. The process calculations employ a random distribution of initial velocity and NH_3/NO_x ratio across the surface of a catalyst, characterized by varying levels of non-uniformity. At each location on the catalyst, the local NO_x reduction and NH_3 slip were calculated and the results integrated over the surface. Uniform velocity enhances performance by providing uniform residence time across the catalyst, insuring no "cells" have inadequate

Figure 3: Role of Maldistributions in Velocity and NH_3/NO on SCR Performance



(a) Velocity Non-Uniformity Effects (NH_3/NO_x Non-Uniformity = 7%)



(b) NH_3/NO_x Non-Uniformity Effects (Velocity Non-Uniformity = 10%)

reaction time. Equally important, zones of erosion-inducing high velocity and deposit-inducing low velocity are minimized. Figure 3 shows that improved velocity distribution increases performance, but the payback for achieving extremely "flat" velocity profiles diminishes.

Figure 3 also shows the NH_3/NO_x uniformity is significantly more important than the velocity uniformity in providing for high NO_x removal. If any one "cell" of flue gas is deficient in either reactant (NH_3 or NO), then the reaction will not proceed to completion – regardless of the volume of catalyst that is utilized. Figure 3 also illustrates the criticality of NH_3/NO_x uniformity increases as NO_x reductions exceed 90%.

Most early generation designs in Japan and Europe are believed to feature distributions of velocity of a 15-20% SD, and of NH_3/NO ratio of 6% or greater SD. The evolution to high performance systems requiring 90% NO_x removal at 2 ppm slip has reduced the velocity distribution modestly to perhaps 10-15% SD, but significantly for NH_3/NO ratio. The specified SD for the latter is frequently less than 5%, and for some applications as low as 3%. As a consequence of these strict specifications, SCR process equipment and catalyst suppliers and owners have conducted aggressive modeling studies. Regarding physical "cold-flow" modeling, the scale of model, details of construction included in the simulation, and extent of measurements have significantly increased to support the high performance systems. The use of CFD has been integrated with physical flow models to augment the evaluation, particularly with the distribution of flue gas temperature.

One item that may become of concern is the ability to construct and install the arrangement of turning vanes, baffles, and flow rectifiers to the necessary accuracy as specified by the physical or CFD model. Construction tolerances of less than one inch may be problematic in actually achieving the flow distribution specified by the model. The challenge to operators of these systems may also be to insure the process conditions, once delivered by the process supplier, are maintained. Finally, as will be discussed subsequently, simply demonstrating that these strict process conditions are actually delivered by the process supplier may be a critical issue to SCR operators.

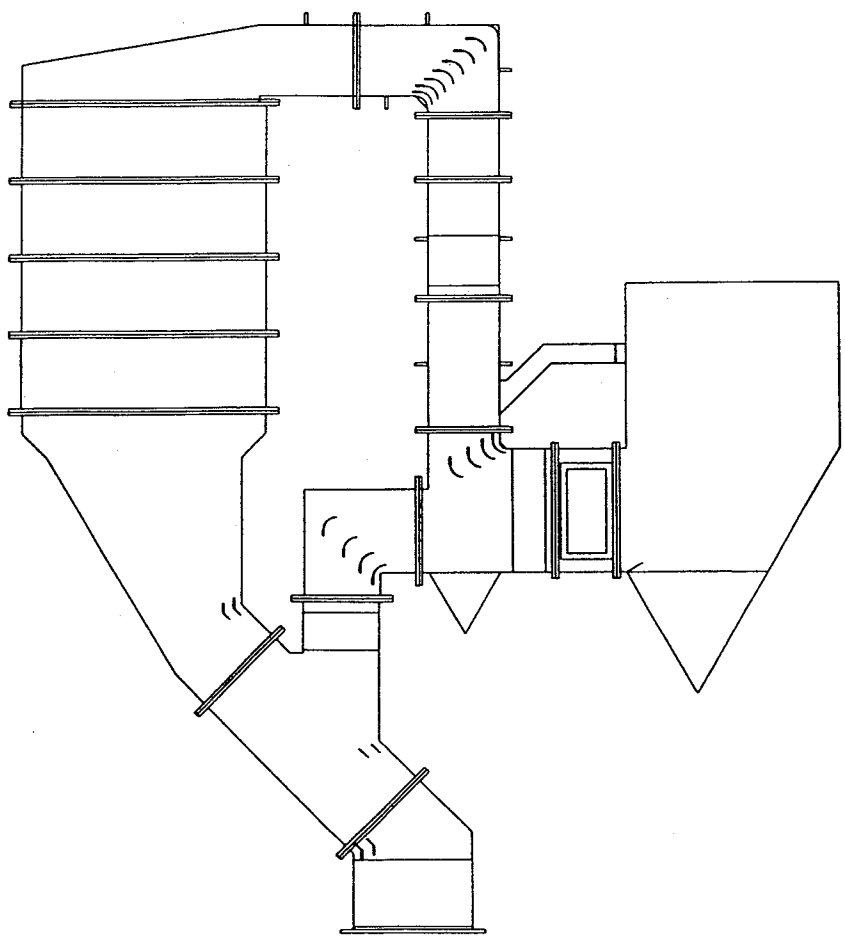
Reactor Layout

Reactor layout can vary widely, depending upon whether SCR is installed in a new plant, or retrofit to an existing unit.

Comparison of contemporary reactor designs to early applications in Japan and Europe is limited for several reasons. Many early SCR retrofits in Japan were "low dust" applications that inherently required smaller catalyst and reactor volume, without the complexity of handling high dust loading. Many boilers in Germany employ tower designs, allowing a more straightforward reactor (at least in terms of process conditions, if not structural steel) that was amenable to improved performance. The flue gas flow path for some tower boiler SCR retrofits could employ perhaps two "elbow" turns prior to the catalyst, which affords good flue gas handling practices. Certainly, not all European installations are represented by this concept, and numerous challenging retrofits were undertaken and successfully implemented.

Of note with US SCR applications is the potential for a larger fraction of flue gas to be bypassed around the economizer, to provide the operating temperature "floor", due to higher flue gas SO_3 content (from higher sulfur coals). The relatively large volume of flue gas to be bypassed around the economizer over a wide load range can complicate mixing patterns. Figure 4 depicts a specific reactor and ductwork layout in which a relatively large volume of flue gas exiting the economizer bypass was problematic in preventing the distribution of flue gas temperature and velocity to be simultaneously achieved. The diversion of flue gas around the economizer necessary to meet the temperature specification biased the flow field and significantly distorted the velocity profile. For example, at mid-load the bypass dampers are only 10-20% open and the system must mix the small, low velocity flow diverted around the economizer with the larger bulk flow. Conversely, at low load the bypass dampers are fully open, and the system must mix a large volume of large, high velocity flow diverted around the economizer with a small bulk flow. A combination of physical cold flow and CFD modeling was used to specify the details of ductwork layout and flue gas rectification devices. The specification was ultimately attained.

Figure 4: Reactor And Ductwork Arrangement for One US SCR Retrofits



Reagent Injection Equipment

Historically, the approach to achieving uniform mixing of reagent with NO_x is a high-density arrangement of individual injectors across a flue duct, with as many as 40-50 injectors per m2. The injectors can be individually adjusted to tune the delivery of reagent. In recent European applications, the use of a small number of large injectors (4-12) combined with static mixers has emerged as an alternative to a conventional ammonia injection grid (AIG). This concept is receiving increased attention due to the potential for reduced maintenance for individual injectors. The necessary hardware and design expertise both are offered "packaged" with SCR equipment or catalyst, and individually from suppliers of static mixers. Specifically, one catalyst supplier offers two versions of a static mixer for use in applications that employ their catalyst. Similarly, one SCR process supplier provides delta-wings as standard equipment in their system design. Several individual suppliers of static mixers (Sulzer, Koch, etc.) will provide static mixer technology as stand-alone offerings to be incorporated into the process design.

Recent US designs have employed up to five individual rows of static mixers to achieve a required distribution of velocity, temperature, and NH_3/NO ratio. For example, static mixers are deployed (1) at the flue gas economizer exit, to rectify imbalances in velocity, temperature, and composition, (2) downstream of the take–off duct for the process bypass, (3) prior to the reagent injectors, to rectify velocity maldistributions induced by a tight "elbow" turn required due to space constraints, (4) following the reagent injectors, to induce mixing, and (5) prior to the reactor entry plenum. The nominal gas pressure loss incurred by each row - less than 0.3-0.5 in w.g.– is the tradeoff for a correct distribution.

In summary, both the high density AIG and static-mixer concepts are employed in US applications. The need for extremely high performance may favor utilizing static mixers and fewer injectors over a conventional AIG. Experience with static mixers suggests that if installed correctly the units will be maintenance-free, and operators are predicating plans on this observation.

Coal Experience

Early SCR experience in Japan was dominated by low sulfur coals from Australia and S. Africa, the primary coal sources in the late 1970s. Despite the considerable understanding gained with these coals, generalization to European coals was greeted with the observation of arsenic poisoning at pilot scale. Although no episode similar to arsenic poisoning is anticipated for US applications, the uncertainty of broad deployment to a new set of coals merits that operators observe and document composition of coal fired to relate operations to catalyst activity.

Table 3 summarizes the key coal constituents that affect catalyst deactivation, identifying the most significant catalyst impact. Most notable is the role of alkali and alkaline earth elements that can induce alkali sulfate poisoning. Calcium sulfate was early recognized as a significant deactivating agent [(6)] the other more soluble alkali cited can penetrate catalyst pores when exposed to moisture (from tube leaks or condensation due startup). As described previously, arsenic is a well-documented poison that, although most acute for wet-bottom boilers that

employ ash recycle, is still problematic for dry bottom boilers with lower furnace gas exit temperatures.

Table 3: Key Coal Characteristics That Affect Catalyst Deactivation

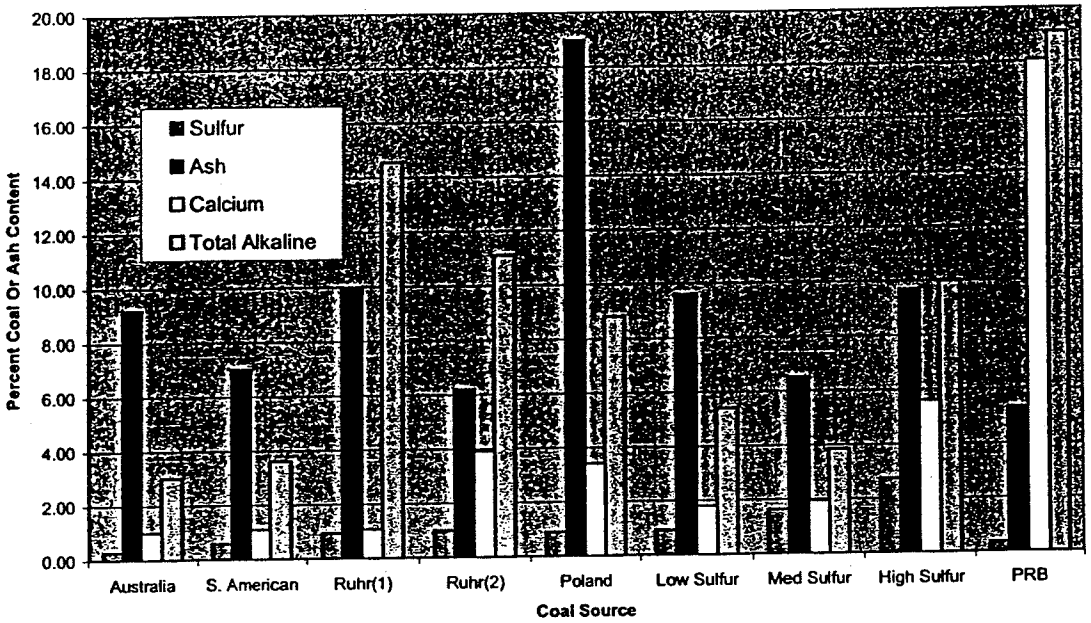
Coal Constituent	Process Or Catalyst Impact	Japanese Experience	European Experience	Anticipated US Conditions
Arsenic	Reacts with V, negating site activity and/or blocking micropores	Negligible coal As content did not identify phenomena	Identified through pilot and early commercial applications	Varies widely with As content in coal (2-40 ppm)
Alkaline material (K, Na, Mg)	Reduces "acidity" and effectiveness of catalyst acid sites	Total alkali <5% of ash (observed with oil firing)	Total alkali 8-15% of ash	5-12% of ash, up to 23% for PRB
Alkaline earth (primarily Ca)	Reacts with SO_3 formed at site to produce $CaSO_4$; plugging pores, ability of NH3 to bond at the site. Minimum Ca needed to mitigate arsenic poisoning	Generally 3-5% of coals fired (Australia, S. Africa)	3-5% of Ruhr, Saar Valley, and Polish coals	2-10% ash, up to 16% for PRB
Phosphorous	As phosphoric acid, can condense, react, and block pores.	Not recognized	Recognized in selected coals	Will depend on coal P content, and oxidizing/reducing conditions in furnace
Sulfur	Indirectly, sulfur provides a source of SO_3. which can react with Ca to form $CaSO_4$	<0.6%	<1.7%	0.4-3.5%

Regarding arsenic, it is known a minimum level of calcium in the coal is desired to mitigate arsenic poisoning. Thus, a minimum level of calcium in ash (~2%) is desired. Phosphorous can also deactivate catalyst, and sulfur – although not exerting a direct role – indirectly can contribute the alkali sulfate formation by production of SO_3.

Figure 5 compares coals utilized in the Japanese and European experience with those anticipated US applications. Figure 5 compares the content of (a) sulfur, (b) ash, (c) calcium in the fly ash, and (d) total alkalinity of fly ash constituents (calcium, potassium, magnesium, and sodium). Figure 5 shows experience in Japan was derived with relatively low sulfur (~0.4%), 2-3% calcium in ash, and negligible soluble alkali compounds. The coals used in Europe typically feature double the sulfur content, and increased calcium and total alkali in fly ash. The first US SCR installations were on low sulfur coals that (due to compatibility with dry scrubbing technology) resembled the coal used in Europe. The complete set of US coals that will see SCR duty in the US may present greater challenges than the first coals did, due to higher sulfur and in some case Fe content, which will increase SO_3 production by the catalyst. For some coals, low calcium content in fly ash may be inadequate to negate arsenic poisoning, and adding limestone or other alkali to the coal will be required. Finally, the case of Powder River Basin (PRB) coals may be of concern, depending on the application. Short-term exploratory tests suggested the extreme calcium content of PRB promotes alkali sulfate poisoning. However, not all catalyst

suppliers share this view, and the first commercial installation with PRB coal has not incurred any noticeable deactivation.

Figure 5: Comparison Of Coal Characteristics For Japanese, European, And Anticipated US Applications



In summary, some US coals are not described by the existing experience database, and despite the best efforts of catalyst suppliers, some risk to deactivation or balance-of-plant problems exists.

Reagent Type and Systems

In comparison to early SCR applications, which were limited to solely anhydrous ammonia as a reagent source, present applications can employ either anhydrous, or aqueous forms of ammonia (of 19.5 or 29% solution strength). In addition, depending on the progress of several early demonstration projects, urea may be applied. From strictly a cost standpoint, anhydrous reagent is usually preferred, as it requires the least delivered cost and capital equipment. However, concerns voiced by local communities have prompted adoption of aqueous reagent for many systems, and for urea on a limited basis.

In Europe, the first installations employed reagent receiving, storage, and handling standards that employed conservative measures such as underground tanks, double-wall tanks, and numerous fail-safe monitoring concepts. As SCR applications migrated from large, remotely located central stations to units in urban areas, interest in aqueous-ammonia reagent increased with local concerns for handling and storage. Anhydrous systems appear to dominate planned US

installations, although numerous aqueous systems will be utilized. Urea–based applications have received recent interest. In terms of impacting SCR operation, the use of aqueous and urea systems introduces additional complexity. Specifically, both approaches require a separate vaporization step, which entails additional process reactors, and managing and monitoring the reagent devolatilization or hydrolysis process. The manpower burden for such monitoring is not significant (with much of the duty remotely monitored), but the additional steps for evaporation of ammonia from the aqueous form, or devolatilization of HN fragments from urea introduces time delays that must be accounted for in process control system design or operation. With target performance of 90% standard and necessary for system compliance, these factors must be considered in control system design.

Balance-Of-Plant

A detailed treatment of balance-of-plant (BOP) factors is outside the scope of this paper; but several key items are identified.

Air Heater

Most European units were initially equipped with enameled-coated heat exchange baskets in the cold end of the air heater, and thus enjoyed superior protection from the additional, SCR-promoted SO_3. The use of enameled-coated heat exchange baskets is not commonplace in US applications; however Corten is frequently used for higher sulfur coals. An informal survey suggests that approximately 75% of the units retrofitting SCR in the US are believed to be upgrading air heaters to mitigate the impact of residual NH_3 and higher SO_3. These modifications include installing enameled surfaces, utilizing a more "open" geometry to retain the momentum of sootblowing media in the axial direction, or both [7]. The evolution of SCR process equipment has probably eased air heater concerns, as experience in Germany in the mid-1980s suggested residual NH_3 should be lowered from 5 to 2 ppm, for the purpose of ash utilization. The potential for air heater deposition has been reduced accordingly.

Flue Gas Handling

The need to retrofit additional flue gas flow capability to handle the higher resistance imposed by the reactor and process equipment varies significantly with specific units. Typically, the additional resistance ranges from 3 in. to7 in. w.g., depending on the application, with most installations probably incurring 4-5 in. w.g. It has been widely reported that most European installations did not require upgrade to flue gas handling equipment; however, the nationwide program to retrofit flue gas desulfurization processes completed in 1984 [3] required flue gas handling upgrade that in many cases was able to also accommodate SCR. An informal survey suggests that 50% of the units retrofit with SCR in the US require some improvement to flue gas handling, with upgraded motors or fans common.

Compared to previous experience, any reductions in flue gas resistance by improved catalyst design have probably been absorbed by static mixers and AIG components to provide a more effective NH_3/NO distribution— the price for which is paid in pressure drop. Thus, the evolution

of SCR application has probably not materially changed the additional flue gas handling requirements, or associated O&M.

Alkali Injection

Since arsenic poisoning was demonstrated a major contributor to catalyst deactivation, the need for a minimum quantity of available calcium in the fly ash has been recognized. Several European operators consistently inject or add limestone or lime to coals fired to augment the naturally available calcium in the ash, and claim a benefit in mitigating both arsenic poisoning and SO_3 outlet concentration [8]. Generally, anywhere from 0.5-2% of the coal mass consumption rate is augmented with lime, dolomotic limestone, or conventional limestone to provide alkalinity. Capital costs for such equipment are not excessive, but O&M procedures must accommodate servicing the alkali supply and equipment. The extent to which such systems will be applied in the US is uncertain. One major SCR process equipment supplier strongly advises deployment of such equipment, and most (but not all) catalyst suppliers agree that for certain applications the additional alkali is beneficial. However, Southern Company recently announced they would forgo alkali addition, and accept possibly higher catalyst deactivation in exchange for simplicity and reduced plant operating duties. In summary, the need to inject alkali to mitigate either arsenic poisoning or control SO_3 emissions may slightly increase O&M, but adoption of alkali injection/addition is not anticipated to be widespread.

LONG-TERM OPERATING CHARACTERISTICS

Operating data obtained for coal-fired SCR-equipped units shows that performance can vary over relatively short periods of time. Given that the NO_x tons cap for the SIP-Call is effectively a 5-month average, hourly or daily variances will not be of significance for many operators. However, in addition to the seasonal (or annual) tons cap, some states require some combination of a 30 day, 24 hour, or 8 hour rolling average to be observed. Specifically, several SCR-equipped units planned for operation in the Houston area must observe 24 hour daily averages of a magnitude that are not significantly above the annual cap. Also, new SCR-equipped units will in all likelihood be required to abide by a short-term average. Data from the Environmental Protection Agency's Electronic Data Reporting (EDR) site is used to explore the variability observed in the US to date.

Figure 6 presents typical scatter in SCR outlet data, obtained from a dry bottom boiler in the US with SCR operational for several years. The data presents NO_x emissions within 5% of full load. The details of operation and the intent of the operators are unknown; thus it is not possible to determine the source of variability. However, it is clear the optimal amount of reagent required by a particular set of process conditions is not consistently delivered to the reactor.

The variation can be quantified by applying statistical procedures to calculate the 30 day average, a 24 hour average, and an 8 hour rolling average. Figure 7 compares this data for four units. Two units are dry bottom boilers retrofit with SCR for high NO_x removal from approximately 0.45 lbs/MBtu (Units A and D); one cyclone boiler designed for 80-85% NO_x removal from 1.2-1.5 lbs/MBtu; (Unit C), and a new plant capable of 50-60% SCR NO_x removal from 0.5 lbs/MBtu (Unit E). The data in Figure 7 show that NO_x typified by short-term

averaging periods can be significantly greater than the calculated 30 day rolling average. These data can be used to establish an "operating margin" NO_x outlet rate that should be targeted if short-term compliance is required.

Figure 6: SCR Outlet Emissions Data Scatter For 90% Removal System

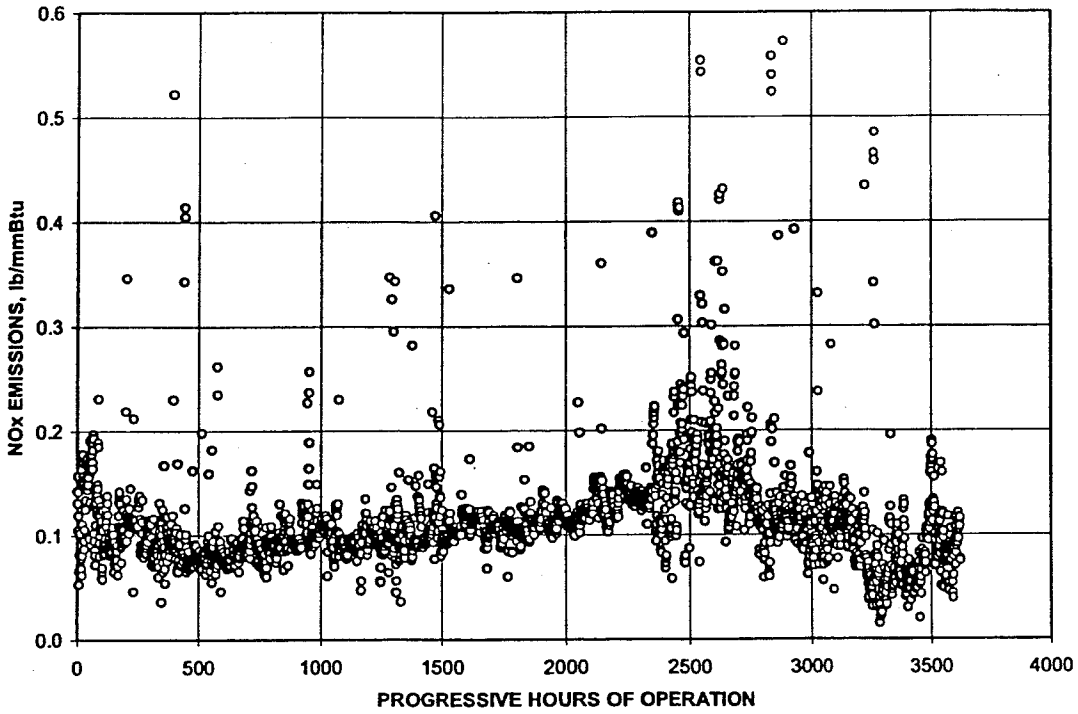


Figure 7: Comparison of 30 Day, 24 hour, and 8 Hour NO_x Outlet Data for Selected SCR-Equipped Units

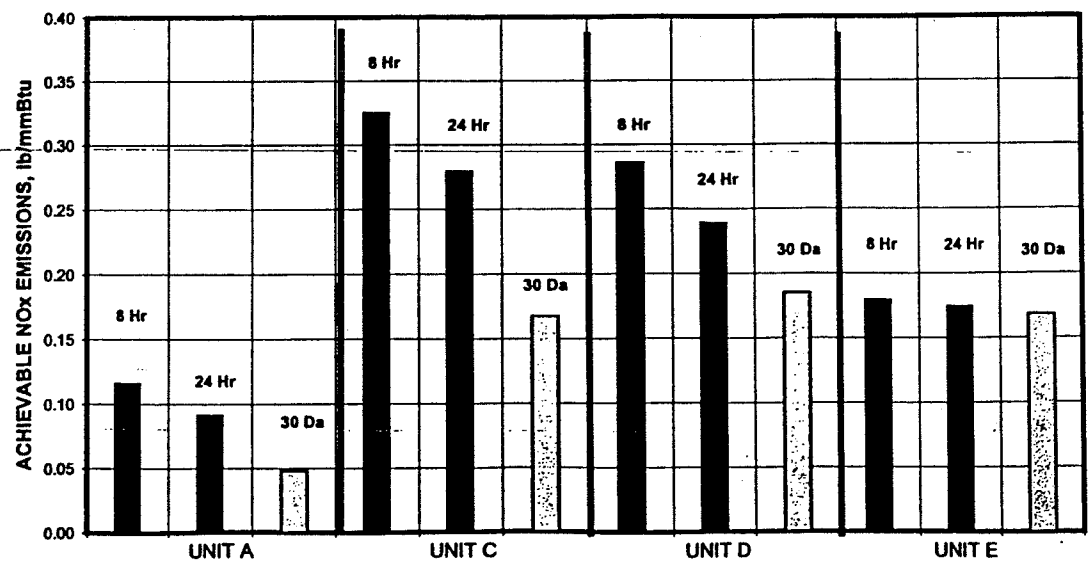
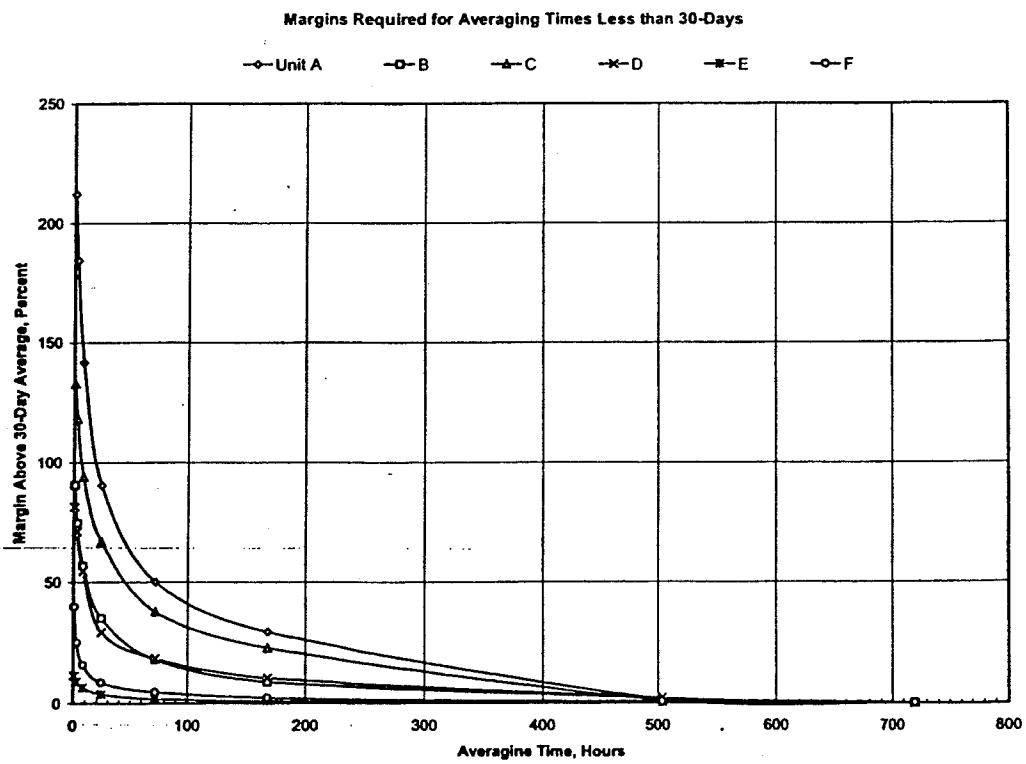


Figure 8 compares this "margin" for the four units cited, in addition to a second cyclone unit (Unit E) and a second new unit with 50% NO_x capability. This figure again depicts the wide variability in SCR outlet NO_x from Unit A; however, as the subject unit has operated with SCR for less than one year, the results should be considered preliminary. Data from most of the other units suggest operators may be required to consider additional monitoring activities to align shorter and longer term rolling averages.

Of note is that the least variability is exhibited by the unit that (a) features the longest operating history, and (b) requires the least NO_x reduction. It is not clear which, if any, of these factors is responsible for this observation.

One must be cautious with Figures 6-8, as operating time is limited for some units, and the intention of the operators is not clear (e.g., minimizing short-term variability may not be important). Regardless, the data illustrate that precise attention to operating duties and development of a learning curve are necessary for successful process operation. The results also suggest that any short-term monitoring requirements by local agencies consider practical limits to process operations.

Figure 8: Estimate of Operating Margin Required For Six SCR-Equipped Units



IMPLICATIONS FOR US O&M ACTIVITIES

Essentially all major utility systems are deploying SCR as the central element in their NO_x control strategy, and plan to "overcontrol" NO_x on the largest plants, allowing smaller, lower capacity factor units to adopt less stringent controls. The success of each NO_x compliance program is heavily dependent on successful operation of SCR at target levels.

Maximize NO_x Removal

NO_x Distribution Testing

The previous discussion shows regardless of whether a conventional AIG or static mixer system is utilized, achieving and maintaining extremely uniform contacting of reagent and NO is necessary. Testing on an annual basis will be necessary to determine the inlet and outlet NO_x distribution to infer the NH_3/NO ratio at the catalyst inlet. Many European utilities conduct these exercises on approximately an annual basis, which is recommended for US applications. With conventional high density AIG, considerable flexibility is available to bias reagent injection to different regions of the ductwork. Using static mixers and a limited number of injectors limits the flexibility, but does not eliminate the ability to bias the reagent. Process suppliers claim the mixing capabilities of static mixers eliminate any need for flexibility, but only experience will prove so. Regardless, the scale of influence of static mixers is limited, and compensating for large-scale variations (e.g., across the entire ductwork) may not be possible. Thus, even limited injectors with static mixers may require attention.

As discussed under I&C, the lowest SCR outlet NO_x may be attained with a boiler NO_x output optimization for distribution, not necessarily the least magnitude. Consistent testing of inlet/outlet NO_x profiles will identify optimal operating modes.

Catalyst Maintenance

The need to achieve high performance requires catalyst to retain activity as projected by the supplier. As both physical blocking by fly ash and a reduction in site activity (due to arsenic, alkali sulfate and other compounds) contribute to deactivation, inspection and cleaning are critical. The use of coupon tests conducted by the catalyst supplier (and possibly a third party) is essential to provide a snapshot of change in catalyst physical features and surface composition. The inspection and cleaning of catalyst during outages will be necessary to assure that the maximum surface area is clean-and-available to participate in NO_x reduction.

Data Historian

Operators will need to document the process operations and coal composition rigorously to validate that the conditions of guarantees have been observed. All units to some degree require this, but particularly those operators that have secured a catalyst supply contract separate from the process supply contract.

Many utilities have established a strategic alliance with a catalyst manufacturer for catalyst supply for an entire system. The selection of the particular supplier is based upon a firm cost estimate to provide adequate catalyst volume to achieve a projected performance target, presuming a fixed set of process conditions. A separate contract is arranged with a process supplier to provide the equipment to deliver those process conditions.

Under this scenario, it may not be straightforward to attribute responsibility for malperformance. For example, if performance targets are not satisfied, it is anticipated the catalyst supplier will first require demonstration that process conditions called for in the specification have been delivered– particularly if the catalyst supplier was not the responsible party for flow modeling. However, measuring velocity distribution in high temperature, particulate-laden flue gas to within the accuracy required may not be viable; thus, it may not be possible to validate process conditions.

Regarding coal composition, catalyst suppliers will require assurance that coals as specified are utilized; for example, it will be important to document that a minimum level of calcium is available to mitigate arsenic poisoning. A systematic and controlled methodology to sample and analyze coal, using agreed upon protocols, is necessary to construct an adequate arrangement.

System Wide Catalyst Management

The use of several SCR facilities across a generating system affords the opportunity to employ a systemwide approach to catalyst management. Even though a catalyst layer may have suffered deactivation necessitating replacement, that specific layer can still provide adequate NO_x removal – as long as the reactor has been designed to accommodate the lower initial activity. Also, catalyst regeneration techniques can increase activity for a cost below new catalyst.

Systemwide catalyst management has been deployed at several stations in Germany, and regeneration techniques have evolved in recent years. Several providers of catalyst recycling services have refined their offerings and are planning to offer such services for the U.S. market. Each regeneration technology is different, but appears to utilize a combination of (a) physical cleaning to remove ash adhered to catalyst, decreasing resistance to mass transfer, (b) washing with an aqueous or nonaqueous solvent to enhance removal of ash, or removal of soluble alkali sulfate compounds, and/or (c) introduction of additional vanadium on the catalyst service.

The potential benefits of a systemwide catalyst management strategy can be quantified by a simple example. Consider a three-unit system employing a large station (Unit A) equipped with a 3+1 reactor design. Units B and C are also equipped with a 3+1 reactor design, and each offer 50% of the generating capacity (and catalyst inventory and replacement requirements). All units fire a moderate-high arsenic content coal, install the fourth layer at 16,000 operating hours, and (when using new catalyst) replace existing layers at intervals of approximately 18,000 operating hours. "Spent" catalyst from all units is "pooled" for regeneration, eliminating the need for new catalyst after the 16,000 hour supplement and 34,000 hour replacement. Catalyst regeneration technology is assumed to restore activity (k/ko) to 0.85 for 65% of new catalyst cost.

Table 4 summarizes system catalyst management over a 15-year period, assuming seasonal operation for the initial four years and annual operation thereafter. The Baseline Case requires a total of 18 layers of new catalyst to be purchased for all units, at a NPV of $11.4 M. The Regeneration Case reduces total new catalyst purchased to 5 layers, with a total of 14 layers regenerated. The use of catalyst of lower activity requires one additional layer to be exchanged for Unit A, over the 15-year period. Total incurred cost is reduced by almost 20% to $9.5 M.

The scenario described in Table 4 is necessarily simplified; and selected to emphasize the benefits of catalyst regeneration. Specifically, the assumption of moderate-high arsenic content coal requires relatively frequent replacement. Also, the scenario assumes success in restoring activity for arsenic-poisoned catalyst; that catalyst layers can be regenerated more than once; and that catalyst deactivation rate after regeneration is the same as for new catalyst. An actual catalyst management strategy will require balancing of reactor potential required versus the generation of "spent" catalyst, and the cost and performance of regeneration technologies. Regardless, the potential benefits are notable, and merit an independent analysis of this alternative to purchase of new catalyst.

Table 4: Catalyst Management Strategy Including Regeneration for Hypothetical System

Catalyst Management Factor	Unit A	Unit B	Unit C	Total System
Reactor Design	3+1	3+1	3+1	
Initial Catalyst Inventory (c.m.)	500	250	250	
Catalyst Per Layer	250	125	125	
Baseline Strategy				
Catalyst Purchased (15 years)	6 layers	6 layers	6 layers	18 layers
NPV Of Catalyst Management ($M)	5.70	2.85	2.85	11.14
Regeneration Case (85/65)				
New Catalyst Purchased	1 layer	2 layers	2 layers	5 layers
Catalyst Regenerated (15 years)	6 layers	4 layers	4 layers	14 layers
NPV Of Catalyst Management ($M)	4.78	2.35	2.35	9.5

Improved I&C/Controls

One area that has not notably evolved, but with significant potential, is that of process controls. Current SCR processes employ a feedforward signal for reagent demand (based on boiler NO_x, or a surrogate such as load or steam flow) with a feedback signal, the latter based on measured outlet NO_x at the reactor exit or stack. Numerous operators have attempted to couple a continuous on-line ammonia monitor as an additional feedback signal, but until recently such instruments have not provided commercially acceptable service.

In practice, a residual NH_3 monitor may not provide significant value over inferring ammonia absorbed by fly ash. If the deposition of ammonium sulfates and bisulfates (ABS) is a phenomenon dependent on cumulative, long-term and "low level" exposure to residual NH_3 and SO_3, then monitoring ammonia absorbed on fly ash may be adequate. However, if process upsets and the "flooding" of residual NH_3 is a contributor, then a real-time monitor will be

useful. As ABS deposition depends on flue gas SO_3 concentration, it is likely that long-term exposure is dominant.

Perhaps more importantly, the need to maintain the uniformity of NH_3/NO ratio to standard deviations of below 5% may require control of the boiler NO_x emission distribution. Specifically, operators may find to achieve strict SCR outlet targets the boiler should be operated to produce the most uniform, and not necessarily the lowest, NO_x rate. For example, a boiler NO_x outlet of 0.35 lbs/MBtu characterized by a 3% SD may be preferable to 0.32 lbs/MBtu characterized by a 6% SD, if 90% removal is to be consistently achieved.

Finally, consistently delivering 90% NO_x removal may benefit from upgrade of the injection system (either conventional AIG or static mixer enhanced) from passive to active control. NO_x distribution profiles generated during operation with a fixed, permanent grid may be coupled to a series of control valves or other means to bias reagent across the grid. Although implementing this concept is not simple, the additional cost and O&M could significantly leverage the fixed investment in SCR.

OBSERVATIONS AND CONCLUSIONS

SCR technology has evolved considerably in the almost 25 years since the first commercial demonstrations in Japan. Equally significant, the scope of the applications and design requirements of the SCR installations for the SIP-Call has increased, with 90% removal and the need for NH_3/NO ratio as low as 3% SD. As a consequence, entire generating system NO_x compliance strategies depend on successful deployment of the SCR. And lacking a robust NO_x allowance market (at least in the early years), SCR system performance will directly impact the generation available from any one unit in a season. The following observations are offered regarding O&M activities to preserve the operation of these systems:

1. **Design Margin.** Both competitive market forces and the use of catalyst management strategies that minimize least first cost probably leave less design margin in catalyst sizing (compared to the Japanese and European experience), to "insure" against unforeseen events. Monitoring process parameters is essential to understand SCR operation, and detect any problems early.

2. **Proactive Diagnostic Measurements.** Efforts to determine the distribution of NH_3/NO ratio and other key process operating characteristics are essential to maintaining high performance. Although time-consuming and cumbersome, establishing the grid of inlet and/or outlet NO_x from which one can infer the NH_3/NO distribution will be useful. Also important will be inspection and evaluation of catalyst deactivation (possibly including a third party) during the annual outage.

3. **Short-Term SCR Outlet NO_x Variability.** Actual NO_x outlet data can vary widely over short periods of time, so that an 8-hour rolling average may be as much as 200% above the 30-day average. For units that must observe a strict short-term average in addition to a 5-month or annual NO_x "cap", a "target" should be determined to assure compliance.

4. **Data Historian.** A "data historian" activity will be beneficial to the owner/operator to track and document key operating parameters, including coal supply, and evaluation of trends between process operation and coal characteristics.

5. **Catalyst Management Options.** Catalyst management options are numerous, particularly across a utility operating system when catalyst can be interchanged between units. The ability to regenerate catalyst should be evaluated by the degree of activity restoration versus cost, and the net savings available within an entire system. Operators should consider an independent assessment of system wide catalyst management, including competing regeneration options, in addition to new catalyst purchase.

6. **I&C Improvements.** Various improvements to I&C systems should be considered, that are logical extensions to leverage the investment in SCR to extract additional NO_x tons. Such systems may not be optional but necessities, if additional complexity introduced by aqueous/urea reagent systems induce time lags into the I&C strategy.

These actions may not necessarily be expensive, but comprise additional duties in a competitive marketplace that are essential to preserve plant reliability.

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Utility Experience with SCR in Germany

Hans-Ulrich Hartenstein
KWH
c/o Licata Energy & Environmental Consultants, Inc.
2150 Central Park Avenue, Suite 207
Yonkers, N.Y. 10710-1843
E-mail: 113535.3501@compuserve.com
Tel.: 914-779-3451
Fax: 914-779-4234

Dr. Heinz Gutberlet
PreussenElektra Engineering GmbH
Headquarters Analytical Department
Bergmannsglückstraße 41-43
D-45896 Gelsenkirchen, Germany
E-mail: andrea.eickermann-schramm@peeng.preussenelektra.de
Tel.: 49-209-601-5042
Fax: 49-209-601-8090

Anthony Licata
Licata Energy & Environmental Consultants, Inc.
2150 Central Park Avenue, Suite 207
Yonkers, N.Y. 10710-1843
E-mail: licataener@aol.com
Tel.: 914-779-3451
Fax: 914-779-4234

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Abstract

The selective catalytic reduction (SCR) technology was primarily developed by Japanese industry for the reduction of NO_x concentrations from power plant flue gas emissions. The first commercial Japanese $DeNO_x$ plant began operation in 1980 while the first German high dust SCR plant started up in 1985 and the first German tail end SCR plant started up in 1986.

Two German environmental resolutions (GFAVO of June, 1983 and UMK of April, 1984) enhanced the adaptation of the SCR technique in German power plants. From the end of 1984 to 1987 most German utility owners ran pilot plant studies in order to become acquainted with this technology and to determine whether there are special deterioration mechanisms. The first full-scale plant started operation at the end of 1985. Since then, around 120 SCR plants have been installed on coal, oil and gas fired utility power plants. SCR technology for NOx control has also been applied on waste-to-energy plants, wood fired boilers, chemical plants, hazardous waste incinerators, glass smelters, refinery crackers, stationary diesel generators and sewage sludge incinerators. In addition, a special catalyst was developed to control dioxin/furan emissions in waste-to-energy plants, hazardous waste incinerators, sewage sludge incinerators, crematoria, iron ore sintering plants, and other thermal processes requiring dioxin/furan control.

The German NOx emission limit for utility power plants is 200 mg/Nm^3 at 6% O_2 for dry bottom boilers and 5% O_2 for wet bottom boilers or about 117 ppmv NOx at 3% O_2. This is approximately 0.12 lbs/MMBtu. Many German SCR units achieve high online availability on an annual basis.

In the following paper, we will emphasize some aspects of the SCR process:

a) The chemical and physical/chemical properties of the catalyst
b) The chemical engineering design of the catalyst volume
c) The deterioration of catalytic activity with time
d) The effect of NH_3 slip (caused by catalyst deterioration or non-homogeneous NH_3 distribution) and of side reactions

The basis of the SCR technique is described first and each of the above areas is then discussed.

In extrapolating the German SCR experience to U.S. applications, one of the most significant factors will be catalyst deactivation due to the differences in some U.S. coals with high alkaline metals and others with high sulfur and SO_3 contents.

The loss of activity potential of SCR reactors, which is related to material activity constant (K-value) and the geometrically active surface area, can be caused by:

- Excessive heat
- Erosion and pluggage
- Pore blockage
- Accumulation of catalyst poisons like arsenic and alkali metals
- Prevention of gas diffusion by the formation of blinding surface layers

KWH and PreussenElektra have led many developments in the German SCR industry over the past 15 years. Some of the most relevant advancements include:

- Development of new derivative titanium based structures
- Development of new erosive resistant materials
- Optimization of the catalyst pitch
- Development of regeneration programs
- Institution of coal blending programs to extend catalyst life
- Development of catalyst maintenance programs
- Development of improved flow-modeling techniques

These improvements have led to an extended catalyst life for many facilities. This paper will discuss the German SCR experience and how it is being extended to the U.S. power industry.

Introduction

In April 1984, the Environment Ministers of the German states made a decision that all bituminous coal fired power stations in Germany would have to be equipped with SCR-DeNOx reactors (Fig. 1). These regulations applied equally to both new and old stations, insofar as the old stations were to continue operating indefinitely. A concentration of 200 mg/m3 of NOx corresponding to 117 ppmv or ≈ 0.12 lbs/MMBtu must be adhered to as an emission limit for nitrogen oxides for coal fired power plants. From 1985 onwards, power plants producing a total of approximately 30,000 MW have been equipped with SCR technology. Most of these facilities, in particular the retrofitted ones, went into operation about 10 to 15 years ago.

This decision also affected the German electric utility companies such as PreussenElektra and its subsidiary, VEBA Kraftwerke Ruhr AG (VKR) (Fig. 2). PreussenElektra's service area includes large areas of the federal states of Schleswig-Holstein, Lower Saxony and Hessen, while VKR, solely a power producer, is concentrated in the Ruhr area, the home of most of Germany's underground pit coal mining. PreussenElektra and VKR have a combined generating capacity of almost 20,000 MW and have installed SCR-DeNOx reactors in power stations with a capacity of almost 10,000 MW (Fig. 3).

Because of the significance of the SCR technology for VKR, in 1993 it acquired a 49 % share of Katalysorenwerke Hüls GmbH (KWH). KWH produces honeycomb catalysts and plays a leading role in the European market with a market share of over 40% in Germany. Through this business arrangement and its own operating plants, the company has direct access to the entire range of DeNOx expertise including production, engineering, and operation and maintenance experience in all cases where the SCR technology is applicable.

In principle, the reduction of NOx emissions with SCR catalysts is a mature technology, which was developed many years ago. Nevertheless, experience has shown that in many applications, special features were required that necessitate further optimization of the DeNOx system. In particular, standard solutions were often not possible or optimal when retrofitting existing power plants.

In the following discussions, the Staudinger power station near Frankfurt will be used as an example to show how both supplier and operator expertise have contributed to providing technically satisfactory solutions to various problems in the last few years.

Description of the Staudinger Power Station

The Staudinger power plant has five units with a net electrical output capacity of nearly 2,000 MW (Fig. 4). With the exception of unit 4, which is gas fired, all units fire pulverized coal. The two oldest units, 1 and 2, each 250 MW, are equipped with 4 identical cyclone boiler furnaces and have a liquid slag outtake. Unit 3 (300 MW) is also slag tap fired, but is overhead or downshot fired. We would like to point out at this time that the cyclone units in Germany fire pulverized coal not crushed coal like in the U.S.

Unit 5 (510 MW) went into operation in 1992 and is an example of modern German power plant technology. The tower boiler with low NOx opposed firing has dry ash removal, and the cleaned flue gases are discharged to the atmosphere via the cooling tower. All coal boilers have high-dust SCR reactors, electrostatic precipitators and FGD plants. In the following, we will take a closer look at operating experiences in units 1, 2 and 5.

In the face of deregulation in Germany, the Staudinger power plant burns the lowest priced acceptable coal from around the world. The coal burned varies widely in its proximate and ultimate analyses. Coals are blended to optimize the lowest generation cost, to extend SCR catalyst life, and to minimize FGD operating cost.

The range of composition for typical coals purchased for the Staudinger power plant is presented in Table1. Table 2 presents the operating characteristics for each of the plant's SCR reactors.

Operating Experiences DeNOx Reactors Units 1, 2

Units 1 and 2, which were constructed in 1965, are single-line units equipped with a high-dust DeNOx reactor, regenerative air preheater, electrostatic precipitator and wet limestone-based FGD plant (Fig. 5). There are two cyclones per boiler. The coal dust is blown into the cyclones tangentially with adjacent openings for the secondary air intake. The tertiary air is fed in behind the cyclone exhaust of the combustion chamber.

Primary and secondary air is fed into the cyclones sub-stoichiometrically (95% theoretical air), thus achieving a primary NOx reduction. The NOx concentration at the economizer outlet is 650 ppmv. The DeNOx reactors were retrofitted in 1990 and designed for a NOx removal efficiency of 85%. All four reactors were originally equipped with catalysts produced by various manufacturers of differing geometry.

All of the fly ash collected in the electrostatic precipitators is returned to the combustion chamber to be melted into slag.

Bonding of Arsenic as Catalyst Poison Through the Addition of Limestone
The decision to construct the DeNOx reactors in the "high-dust" configuration was made in 1988, after the successful completion of studies into the bonding of arsenic, a catalytic poison contained in the coal. With the complete recirculation of the fly ash (a method often practiced with slag tap firing), the trace element arsenic (As) is concentrated in the fly ash cycle. This results in gaseous arsenic trioxide (As_2O_3), a potent catalyst poison, which is concentrated in the flue gas[1] of wet bottom boilers with fly ash recirculation.

We have developed a process in the Staudinger power station, which involves the addition of small amounts (approximately 1% by weight) of limestone (calcium carbonate, $CaCO_3$) to the coal. During the combustion process the limestone is calcined by liberating CO_2 and highly reactive lime (CaO) is formed.

Calcium rich fly ash is reactive and bonds the arsenic, thus rendering it harmless to the catalysts. It is therefore possible to utilize the economic advantages of a high-dust alternative in contrast to a tail end solution. We have learned that there are several important factors that influence arsenic poisoning of catalyst. Too often engineers look only at the As content of the coal. We have found that in order to evaluate the catalyst life, you also have to consider the following:

- Type of boiler used
- The application of fly ash recirculation
- Concentration of As in the gas phase at the air heater inlet
- The CaO content of the fly ash in addition to the coal

Optimization of the Flue Gas Ducts
The limited space available made a complex arrangement of the flue gas ducts necessary (Fig. 6). Once in operation, it became clear that the duct geometry was not suitable. This duct geometry allowed fly ash deposits to accumulate and potentially drop down "like an avalanche" into the SCR reactor and cover the first rows of modules in the upper catalyst layer. The first stage of optimization involved the installation of short baffle plates close to the ground, "spoilers" to prevent fly ash deposits from building up on the slanted floor of the flue gas duct leading to the reactor inlet hood.

The flue gas velocity in the bottom region was increased but this proved to be insufficient to prevent ash buildup. New deposits formed upstream of the spoiler at a distance of about one-meter (3-feet), and covered the spoiler.

The next modification was a redesign of the complete duct geometry with the assistance of the KWH flow-modeling laboratory. An optimal solution was found using a scaled flow model. The trials were carried out with a two-phase flow stream using original fly ash from the Staudinger station proved effective. In 1994, during inspection work carried out on the unit, the duct diameter was narrowed by the insertion of an intermediate ceiling. As a result, the flue gas velocity in the ducts of the reactor hood was increased from 8 m/s (26 ft/s) to 12 m/s (39 ft/s). In addition, the spoilers and baffle plates were removed and replaced by right-angled flow straighteners. These modifications have completely and permanently prevented fly ash deposits from building up in the reactor inlet.

Combustion Optimization

Another special feature was the occurrence of coarse, distended particles of coke, commonly referred to as popcorn ash, which accumulated on the catalysts and contributed to their clogging (Fig. 7). These particles have a diameter of up to 15 mm and since they cannot pass through the catalyst channels they accumulate on the first catalyst layer.

Under an electron microscope, the pore structure of the coke particles can be identified (Fig. 8). They are completely volatilized and are 70 - 90% carbon.

To prevent popcorn ash from forming, a check measurement of all cyclones was conducted. This check measurement consisted of detailed examination of the pulverization equipment and the coal dust distribution at the pulverizers as well as determining the cyclone fuel and air distribution (Fig. 9). It was determined that the ratio of fuel to air feeding into the region of the cyclone outflow was out of balance, which explained the formation of coke particles. By homogenizing the flow of fuel and air, the formation of Popcorn coke particles was effectively prevented. Moreover, the content of uncombusted carbon in the fly ash was significantly reduced. As an additional measure, low-volatile coal with 18 - 20% volatile constituents was preferred, which, among German coal, has a low swelling index, thus effectively preventing the Popcorn formation.

Boiler and burner adjustments were not sufficient, however, to permanently prevent a clogging of the catalysts (Fig. 10). As the photographs show, both the built-in plate catalysts (on the left side of the photo) and the 7-mm pitch honeycomb catalysts (on the right in the photo) were affected by mass clogging of the catalyst channels or slits. We determined that the pressure drop across the catalyst layers rapidly increased when we did not use a mixture of German and imported South African coal, but instead only burned German Ruhr coal (Fig. 11). In this figure, the correlation between pressure drop and fuel used can clearly be seen. We discovered that the fly ash from the German coal formed highly adhesive deposits, while the portion of South African coal contributed to the formation of a liquefied fly ash.

The reason for this was determined by a chemical analysis of the fly ash (Fig. 12). It can be seen that the content of alkali sulfate, which adheres to the surface of the fly ash particles, favors the tendency to agglomerate. A phase analysis of the deposits revealed crystalline sodium aluminum sulfate and potassium aluminum sulfate ($NaAl(SO_4)_2$; $KAl(SO_4)_2$).

After we determined this, we made South African coal (rich in ash and with a low alkali) a permanent ingredient of the coal mixture. We have also learned that we had to analyze not only for the sodium (Na) and potassium (K) content of the coal but also we need to know if the Na and K compounds are water-soluble. In a water-soluble form, these alkaline metals are highly mobile and will migrate throughout the catalyst material, reducing the active sites. The fly ash from some coals such as Powder River Basin (PRB) can also have high contents of water-soluble alkaline metals.

A further problem also arose at the same time as the catalysts were clogging because of a high-unburned carbon content in the fly ash. The low NOx burner operation and the use of low-volatile coal resulted in the carbon content of the fly ash increasing temporarily to 30%, and not dropping below 10%, even after optimizing the boiler. From the energy production point of view, this is not an issue, since all of the fly ash is returned to the boiler and melted down into the slag. However, the clogging of the catalysts and deposits of ash containing carbon over large areas resulted in local combustion and smoldering fires inside the SCR reactor encouraged by the ventilation of the hot

reactor during shut-downs. The results were a continued increase in pressure drop and damage to the plate-type catalyst, which made it necessary to prematurely replace the plate-type catalyst material with a honeycomb material.

An analysis of the entire range of problems made it advisable to also optimize the catalyst geometry and find a solution, which would prevent the build-up of fly ash deposits. First, test modules were outfitted with honeycomb catalysts with different pitches. In addition to the widely used 7 mm-pitch honeycomb catalyst, a 10 mm-pitch type was also used. These test modules were installed in the reactor at the locations where the risk of deposit accumulation was particularly high. After a long period of trial operations, it was determined that a 10-pitch honeycomb in the first layer prevented deposit accumulation in a nearly ideal manner (Fig. 13). The larger aperture of the catalyst channels in the first layer allowed the ash to fall through also in areas of the reactor with an unfavorable flow distribution. As a matter of fact, another advantage of the honeycomb type is that the channels are open throughout the entire catalyst layer, in other words, ash clogging in the transition zone between stacked catalyst elements is avoided.

Therefore, the station operators decided to equip the reactors progressively with 10-pitch honeycomb catalyst in the first layer of the reactor. In order to maintain a high reactive surface area for NOx reduction, an 8.2-mm pitch KWH honeycomb catalyst was installed in the second and a 7.1-mm pitch KWH honeycomb catalyst in the third layer. This progressive arrangement continues to operate without plugging while meeting the NOx reduction requirement. Consequently, all the plate-type catalyst was replaced by this progressive arrangement with the first 10-mm pitch catalyst layer acting partially as a flow straightener for all the following layers.

Ammonia in the Fly Ash

In addition to noting the pressure drop across the catalyst layers, observing the NH_3 content of the fly ash is another simple and certain method of monitoring the operating performance of a high-dust DeNOx reactor (Fig. 14). The improvement to the fly ash NH_3 content of Unit 1 from 1993 to 1998 is depicted in Fig. 14 and provides a clear overview of the chronological development of the NH_3 slip of the DeNOx reactor.

The results of flue gas cleaning endeavors and changes to the flue gas ducts can clearly been seen. Also, the dramatic decrease in reactor performance is obvious due to the loss of active catalyst surface caused by clogging and local combustion of the fly ash.

After implementing the above-described technical improvements in regard to combustion and flow dynamics, as well as carrying out the two-staged catalyst replacement with 10-mm pitch honeycomb catalyst in the first layer, the NH_3 concentration in the fly ash was permanently reduced.

A similar situation could be observed with the NH_3 content in the wastewater of the FGD plants (Fig. 15). Shown in Fig. 15 are the monthly average values. Here one should note that the Staudinger power station has a central wastewater treatment plant for the FGD plants of all the units and the values shown also include data from units 3 and 5. Here too, one can see that since 1996, changing the catalyst geometry to 10-pitch honeycombs in the first layer has permanently lowered the NH3 slip. Because ammonia is highly toxic to fish, ammonium nitrate is stringently monitored in Germany with a limit of 10 mg/l in the wastewater. Exceeding the limit results in very high wastewater fees and penalties. Using the measures described, the official limits could be maintained,

without having to resort to a costly technical solution for removing ammonia from the FGD wastewater treatment plant.

Operating Experiences with the DeNOx Reactor in Unit 5

Unit 5 of the Staudinger power station commenced operation in 1992 (Fig. 16). The boiler was constructed with low-NOx burners as a tower boiler. The NOx-concentration in the flue gas is 250 ppmv (≈0.3 lbs./MMBtu). The high-dust DeNOx reactor is located directly above the air preheater. Fly ash is removed from the cooled flue gases in a 5-field electrostatic precipitator and the gas is then desulfurized with a limestone-based FGD. The fly ash concentrations at the SCR inlet varied from 10 - 15 g/m3 (4 - 6 gr/acfm).

As a special feature, it should be mentioned that the flue gas is not reheated after passing through the FGD. The purified waste gases are discharged to the atmosphere through the cooling tower of the power station at a temperature of 50°C (122°F).

Unit 5 is fired with a wide range of imported coals from around the world including the U.S. After approximately 8,000 operating hours, fly ash deposits were observed on the 1st catalyst layer. At the same time, an increase in the pressure drop of this catalyst layer was noted (Fig. 17). Here too, the heavy accumulation of deposits made it necessary to replace the catalysts after only 24,000 hours of operation.

During an inspection of the reactor, ash samples were taken from the deposits and examined under a microscope (Fig. 18). These coarse ash particles, in contrast to the ones in units 1 and 2, were not coke, but inorganic ash substance. It was be pointed out that the formation of blistered ash particles was only observed during the combustion of coal or coal mixtures with an ash melting point <1,300°C (2,370°F). This problem was especially pronounced when using American coal from the Appalachians. The blistered popcorn ash particles were up to 6 mm in size and irreversibly clogged the catalyst channels. Here too, switching to a catalyst with a bigger pitch, starting in the first layer provided a permanent solution to the problem.

Conclusions

The example of the DeNOx reactors of the Staudinger power station has shown that in order to arrive at an optimal design, it is necessary to look at the entire power plant, from the fuel to the boiler and the entire path of the flue gas up to the DeNOx reactors (Fig. 19).

Under these conditions, the SCR technology can be mastered, both technologically and economically, including its application as a high-dust SCR system downstream of a wet bottom cyclone fired boiler. The number of iterative steps to an optimal station design can be noticeably reduced, however, if one takes advantage of the expert advice of experienced companies right from the start.

In Germany, KWH and PreussenElektra have gained more than 15 years of full scale SCR operating experience for coal and oil fired utility power plants with a cumulative capacity of over 30,000 MW. The PreussenElektra group owns approximately 30% of these stations. All process-engineering

variations and all types of catalyst available in Germany are represented here. KWH is the largest producer of honeycomb catalysts with a market share of over 40% in Germany. As such its catalysts are used in the majority of German power stations. Thus, it can refer to the operating experiences of many power stations. The knowledge and expertise derived from this experience is available to the U.S. utility market.

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Table 1
Typical Coal & Ash Analysis

Typical Coal Analysis		Ruhr Valley Coals	Imported Coals
Lower Heating Value	MJ/kg	27.6 – 29.8	24.3 – 27.3
Lower Heating Value	Btu/lb	11,900 – 12,800	10,400 – 11,700
Ash	% as received	6 – 8	6 – 16.5
Water	% as received	8 – 10	6 – 13.0
Volatile Matter	% dry basis	19 - 38	21 – 41.0
Chlorine	% as received	0.2	0.01 – 0.35
Sulfur	% as received	0.8 – 1.4	0.3 – 1.5
Nitrogen	% dry basis	1.4 – 1.5	1.2 – 2.0
Typical Coal Ash Analysis			
Fe_2O_3	%	11- 13	2.5 – 20
CaO	%	4	0.54 – 12
MgO	%	2	0.2 – 5.5
K_2O	%	3	0.3 – 5.0
Na_2O	%	1	0.1 – 2.2
SiO_2	%	43 – 45	40 – 55
TiO_2	%	1	0.6 – 3.1
Al_2O_3	%	28 – 29	14 – 37.5
SO_3	%	3	0.3 – 8
P_2O_5	%	1	0.01 – 1.5

Table 2
Individual SCR Reactor Operating Parameters

Flue Gas Flow	Nm^3/h	200,000 – 440,000	scfm	127,000 – 280,000
NOx Reactor Inlet	mg/Nm^3	1,000 – 1,300	ppmdv	487 – 633
NOx Reactor Outlet	mg/Nm^3	185	ppmdv	90
Ammonia Slip	ppmv	2		
H_2O	%	7.2 – 9		
O_2	% dry	1.8 – 3.5		
SO_2	mg/Nm^3	1,400 – 3,500	ppmdv	490 – 1225
SO_3	mg/Nm^3	18 – 70	ppmdv	5 – 20
Fly ash w/o sootblowing Fly ash with sootblowing	g/Nm^3 g/Nm^3	4 – 6 9.2 – 25	gr/dscf gr/dscf	1.6 – 2.4 3.7 – 10.1
Flue Gas Temperature	°C	315 – 440	°F	599 - 824

* Flue gas emissions corrected to 5% O_2.

Figure 1

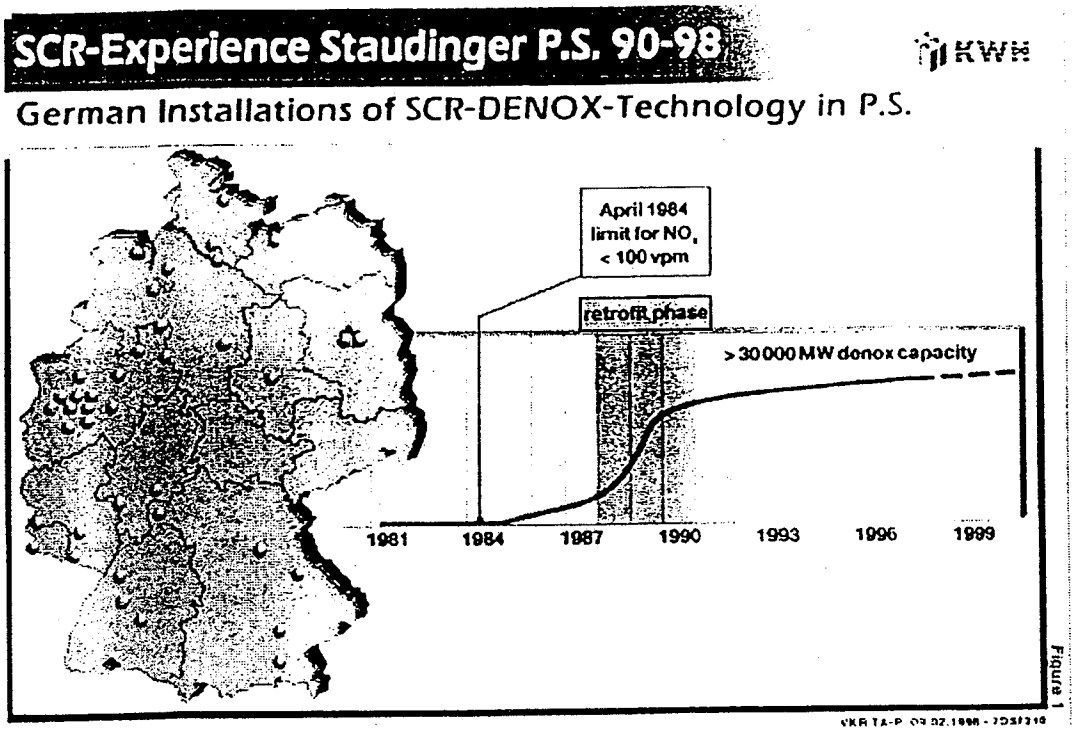
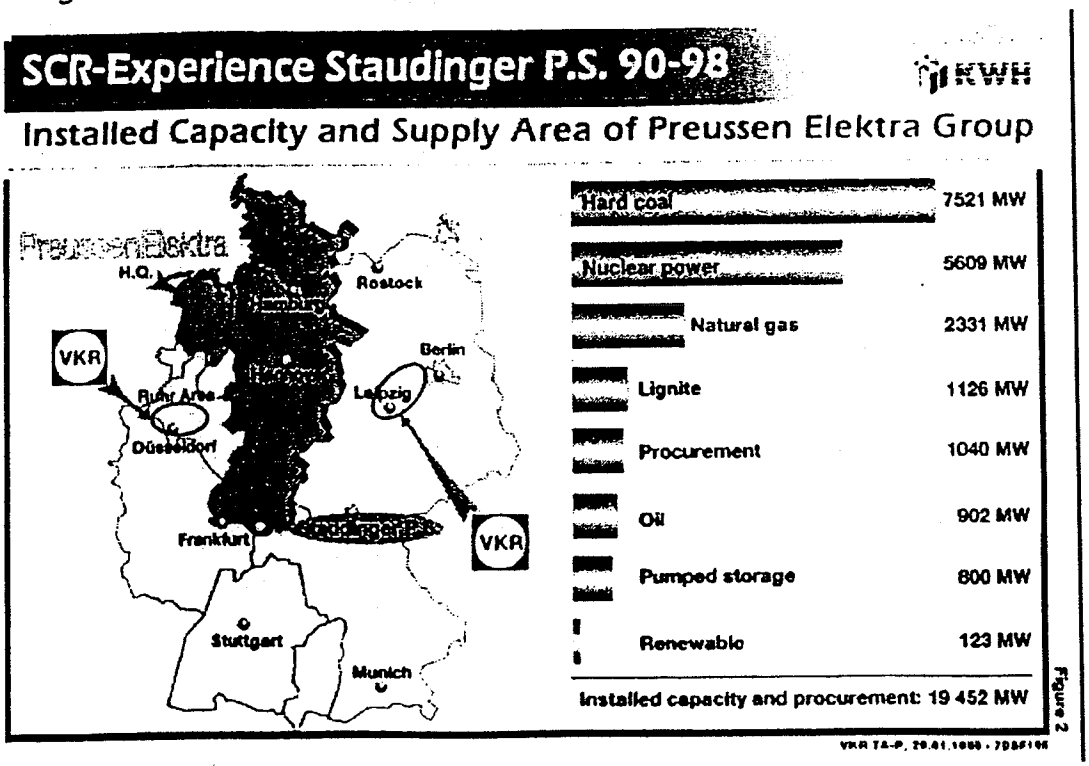


Figure 2



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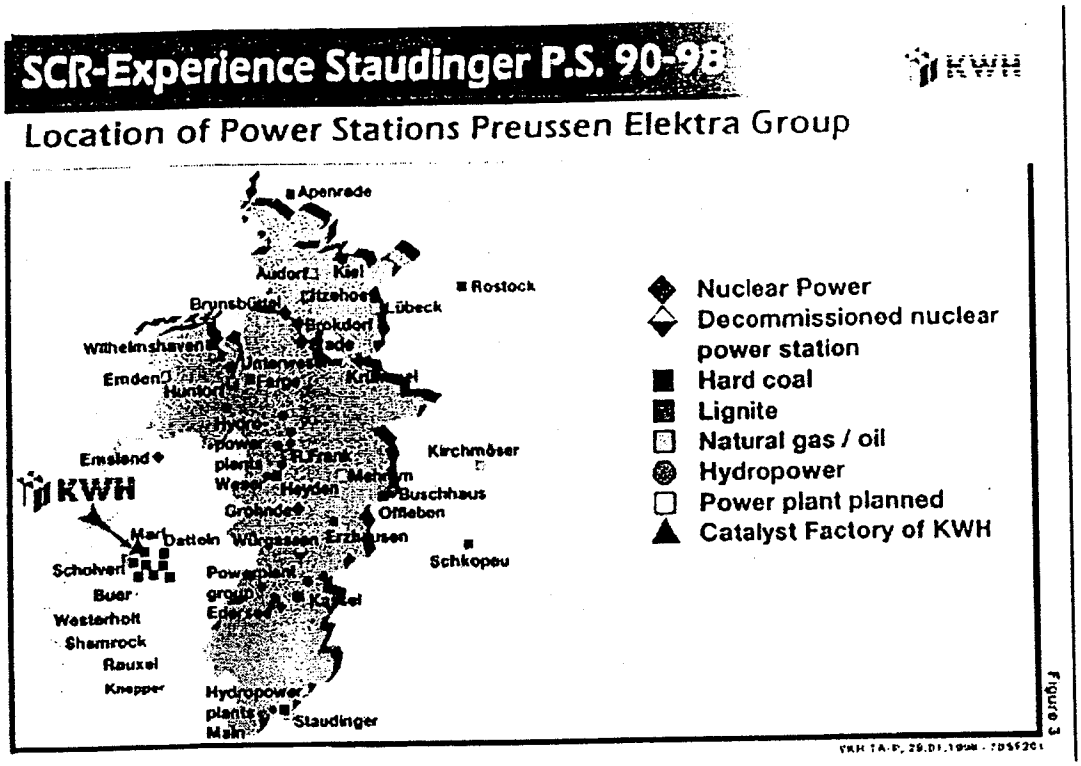

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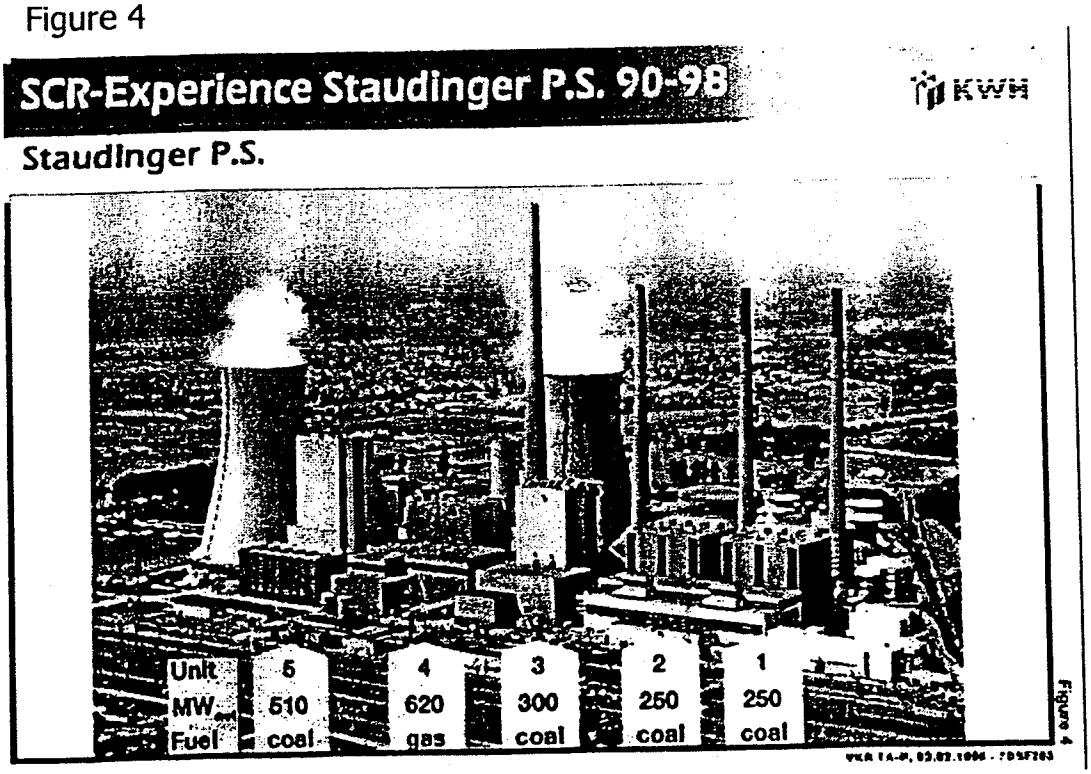

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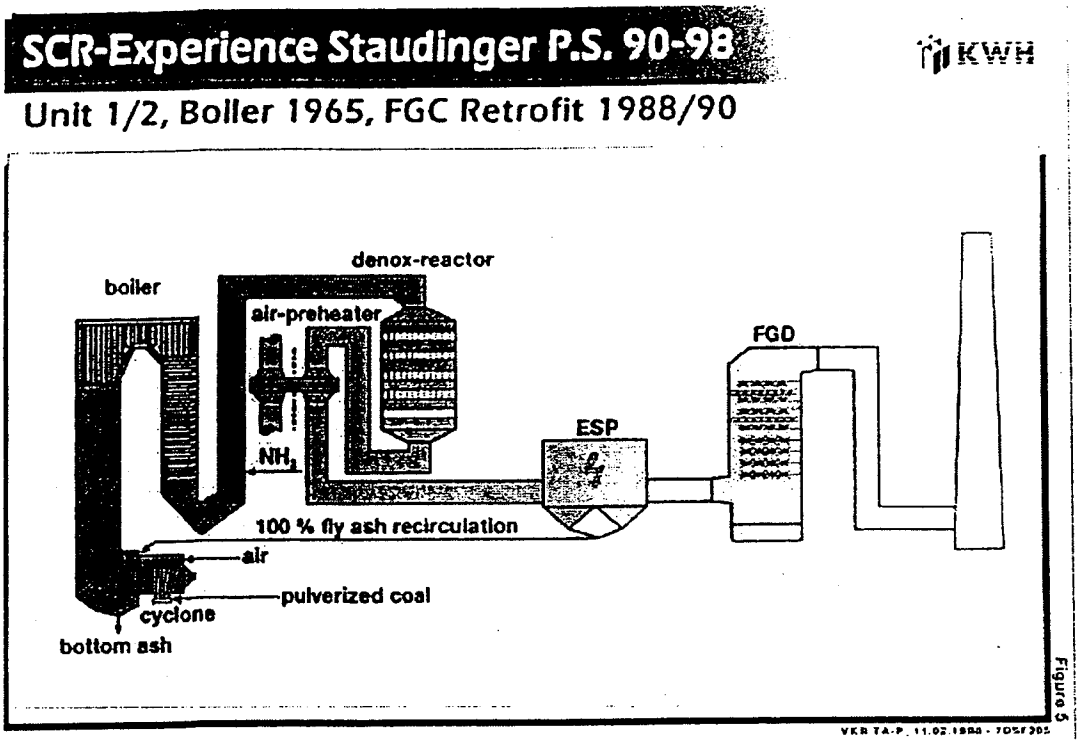


Figure 6

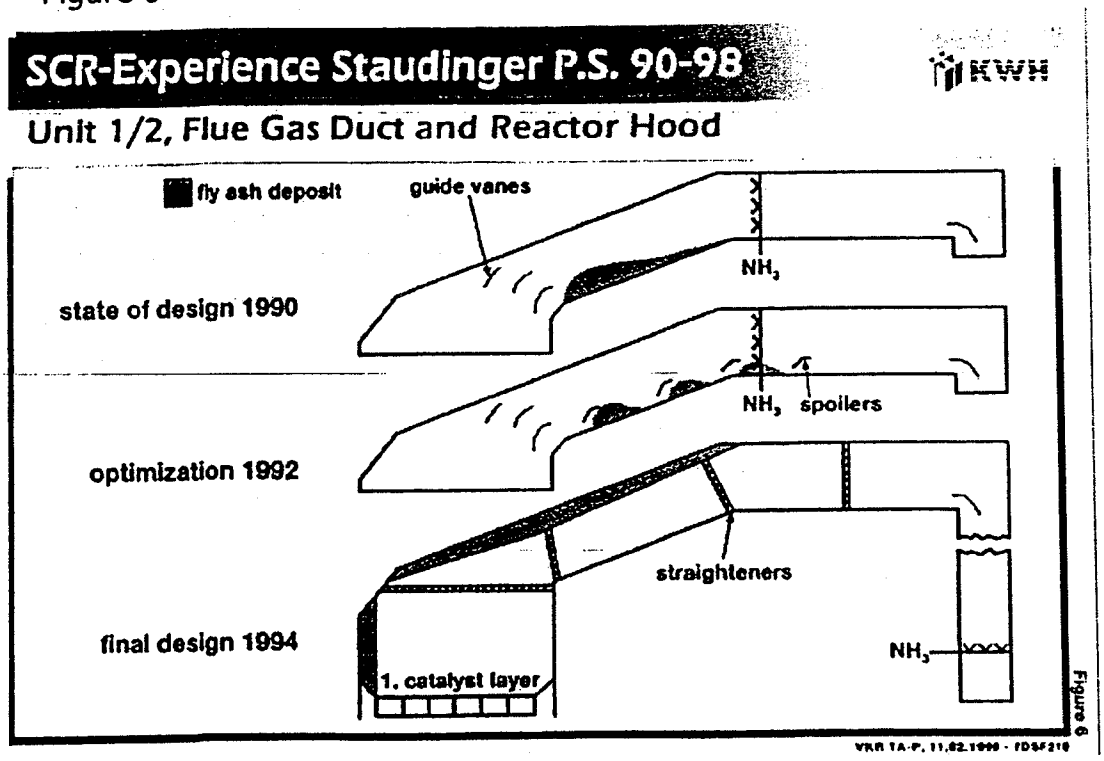


Figure 7

SCR-Experience Staudinger P.S. 90-98

KWH

Unit 1/2, Agglomerated Coke Particles on 1. Catalyst Layer

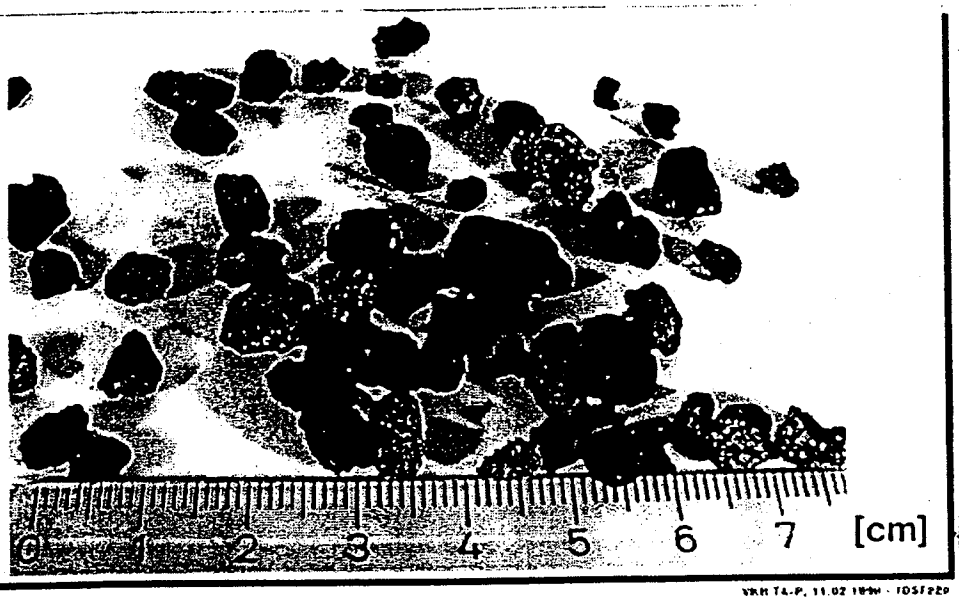


Figure 7

Figure 8

SCR-Experience Staudinger P.S. 90-98

KWH

Unit 1/2, Agglomerated Coke Particles, SEM-Image

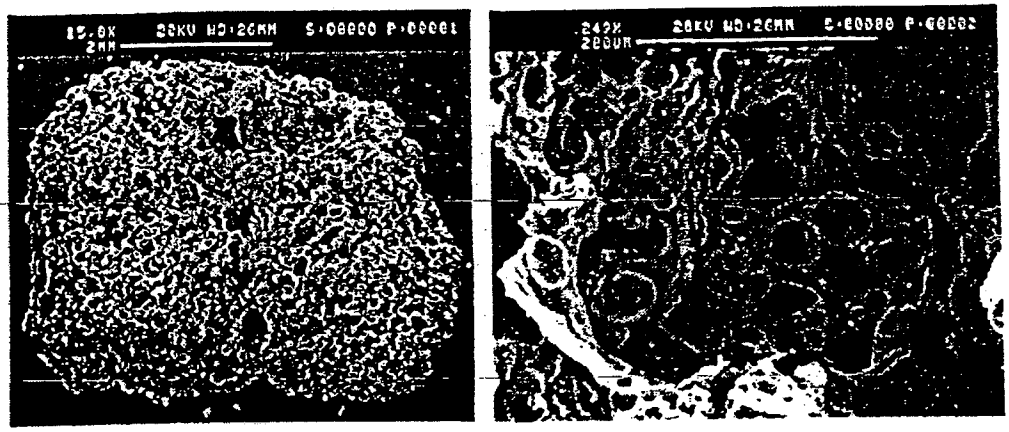


Figure 8

Figure 9

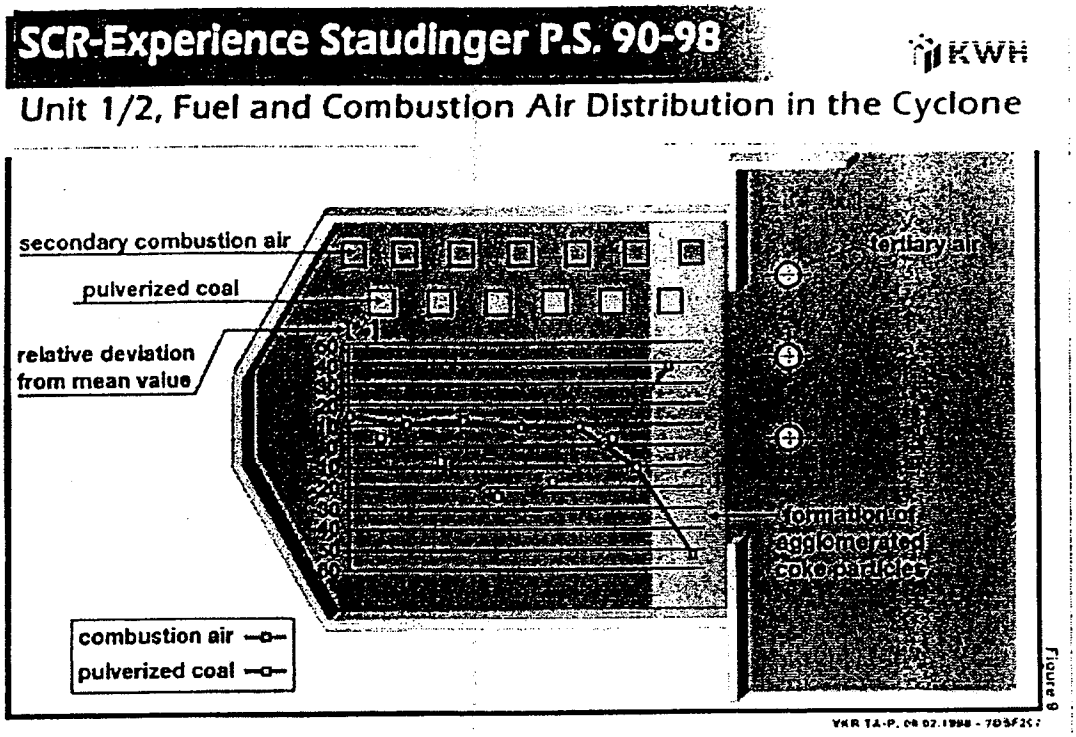
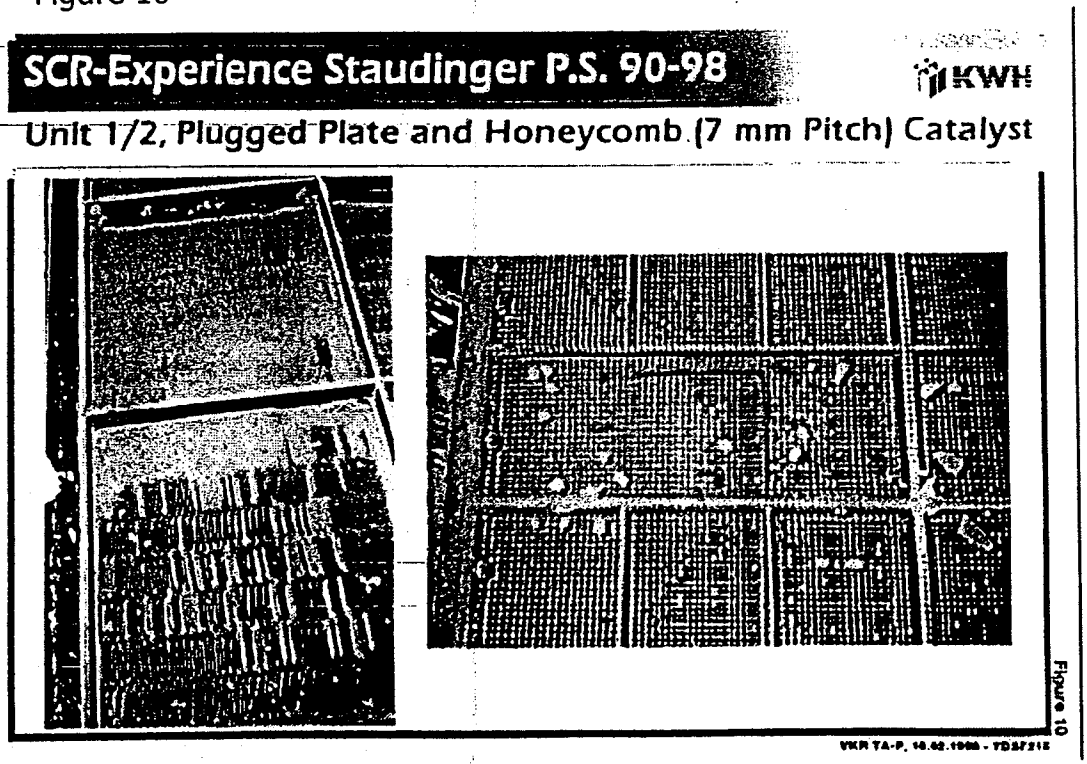


Figure 10



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THE SELECTIVE CATALYTIC REDUCTION OF NO_x EMISSIONS FROM UTILITY BOILERS

Arun B. Mukherjee

Department of Limnology and Environmental Protection, University of Helsinki, SF-00710 Helsinki, Finland

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1. INTRODUCTION

Large amounts of fossil fuels such as coal, oil, natural gas, and to some extent biofuels are used in power production, industrial processes, and transportation. Due to the increase in the use of these fuels, release of sulfur dioxides, nitrogen oxides, and carbon dioxide gases has also increased. In the atmosphere, these gases disperse widely and contribute to tropospheric photochemical smog, ozone formation, wet and dry acid deposition, stratospheric ozone depletion, and the greenhouse effect [Singh et al., 1976; Curtzen et al., 1978; National Academy of Science (NAS), 1979; World Meteorological Organization (WMO), 1986; Tripac, 1987]. Recently, great interest has been shown in oxides of nitrogen, that is, in nitric oxide (NO) and nitrogen dioxide (NO_2), which are jointly termed NO_x because they are pathogenic in humans, animals, and plants and initiate noxious photochemical processes in the atmosphere.

Most NO_x is generated by the combustion of fossil fuels. The global contribution of NO_x from technosystems, calculated as nitrogen, is estimated to be $35-58 \times 10^{12}$ g yr^{-1} (Bosch and Janssen, 1987). In recent decades, both combustion and postcombustion methods have been used to control NO_x from power plants. However, stricter regulations on NO_x emission have forced power plants in many countries to select postcombustion methods such as the ammonia-based selective catalytic reduction (SCR) process.

The SCR process was developed in Japan in the 1970s for the reduction of NO_x emissions from coal-, oil-, and gas-fired boilers (Lowe et al., 1989). The process was put into commercial use in Europe and the United States in the 1980s, and can result in 60 to 90% reduction of NO_x from stationary sources (Sengoku et al., 1980; Slack, 1980; Jones, 1981; Lowe, 1984; Ando, 1985b; Hein et al., 1985; Andreasen and Morsing, 1990). Recent study (Hjalmarsson and Soud, 1991) indicates that as of the end of 1990, SCR systems have been installed on 171 coal-fired power plants having a total capacity of approximately 39.0 GW [gigawatts (electrical)].

This study focuses on SCR NO_x control technology applied to coal-, oil-, and gas-fired boilers and on SCR catalysts and their dimensioning, geometry, maintenance, and poisoning.

2. NITROGEN OXIDE EMISSIONS

2.1. NO_x Formation Mechanisms

There are seven oxides of nitrogen: NO, NO_2, NO_3, N_2O, N_2O_3, N_2O_4, and N_2O_5. Nitric oxide (NO) and nitrogen dioxide (NO_2) known together as NO_x, are emitted mostly from fuel combustion in mobile and stationary sources (Amann, 1989), but the burning of biomass may also be an important source (Logan, 1983).

The mechanisms of NO_x formation during the combustion of fossil fuels are as follows:

- Formation of thermal NO_x by fixation of atmospheric nitrogen with oxygen

Table 1 NO_x Emissions from Both Stationary and Mobile Sources in Europe in 1980

Country	RAINS model	ECE	OECD
		(1000 tonnes as NO_2)	
Albania	28	9	—
Austria	239	216	216
Belgium	439	442	336
Bulgaria	357	150	—
Czechoslovakia	796	1204	—
Denmark	250	247	245
Finland	234	280	278
France	1944	2560	1962
Federal Republic of Germany	2891	2950	2936.
German Democratic Republic	850	965	—
Greece	239	127	217
Hungary	305	270	—
Ireland	89	67	75
Italy	1458	1480	1599
Luxembourg	31	23	23
Netherlands	577	548	551
Norway	169	181	185
Poland	1597	1500	—
Portugal	149	166	165
Romania	661	390	—
Spain	950	950	937
Sweden	333	318	318
Switzerland	186	196	205
Turkey	356	175	—
UK	2394	1916	1924
USSR	9454	2790	—
Yugoslavia	394	190	—

Source: ECE (1988); OECD (1989); Springmann (1989).

- Formation of fuel NO_x
- Formation of prompt NO_x.

2.2. Emission Inventories

Recently estimated global NO_x emissions as well as those for several European countries have been summarized [Organization for Economic Cooperation and Development (OECD), 1983; Economic Commission for Europe (ECE), 1986; Amann, 1989; Sloss, 1990; Ministry of the Environment, U.K., 1990]. About 60% of NO_x emissions are anthropogenic; the rest come from natural sources, mainly the denitrification of bacteria in soils and waters, lightning, and transport from the stratosphere. Hameed and Dignon (1988) have estimated a 4% increase in global NO_x emissions per year since 1950.

Due to the wide range of fuels and combustion techniques used, there are uncertainties in estimating emissions of NO_x from energy production. Singh (1987) estimated total global emissions of NO_x (as $NO + NO_2$) from this source to be between 25 and 75×10^6 tonne yr^{-1}, whereas the Ministry of the Environment, U.K. (1990), estimated it (expressed as NO_2 from anthropogenic and natural sources) to be 153×10^6 tonne yr^{-1}.

Springmann (1989) estimated NO_x emissions based on the RAINS model for 27 countries in Europe. These values are mostly within the quite reasonable range presented by the European Commission for Europe (ECE) and the OECD (Table 1).

3. THE SELECTIVE CATALYTIC REDUCTION PROCESS

3.1. Introduction and Background

In recent decades, the control of NO_x emissions from utility boilers has been both studied and implemented (Ando, 1985b; Shimoto and Muzio, 1986). In the 1970s, the SCR technique for limiting NO_x emissions from stationary sources was developed solely in Japan. This technique claims a higher reduction of NO_x emissions than is presently available from combustion technologies. Due to its high reliability, more than 200 commerical plants in Japan have already adopted this process (Ando, 1987), and the technology has also been exported to Europe and the United States since the end of the 1970s. The first SCR installation in Europe was commissioned in Germany in 1985 (Rentz and Leibfritz, 1987).

3.1.1. Process Description

In the SCR process, NO_x is selectively reduced by NH_3 in the presence of oxygen over any one of a number of catalysts. As described by Kolar (1990), the predominant reactions are as follows:

$$4NO + 4NH_3 + O_2 \longrightarrow 4N_2 + 6H_2O \tag{1}$$

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$
$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$$

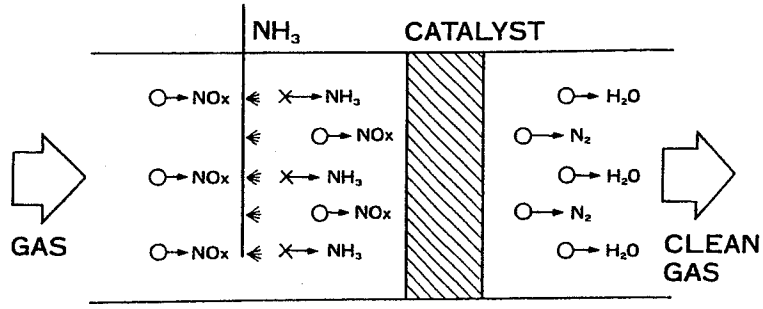


Figure 1. The reduction of NO_x with ammonia by the SCR technique at a temperature between 300 and 400 °C. (From Babcock-Hitachi K.K, with permission.)

$$6NO + 4NH_3 \longrightarrow 5N_2 + 6H_2O \quad (2)$$
$$6NO_2 + 8NH_3 \longrightarrow 7N_2 + 12H_2O \quad (3)$$
$$2NO_2 + 4NH_3 + O_2 \longrightarrow 3N_2 + 6H_2O \quad (4)$$

In the SCR process, the most important component is of course the catalyst. The optimum temperature is between 300 and 400 °C and the main by-products are molecular N_2 and water.

The catalyst is generally mounted in the vertical position with the flue gases flowing from top to bottom. Occasionally, it is placed horizontally. The basic principle of the SCR catalyst reactor is shown in Figure 1 and the whole complex may be divided into three sections: the SCR catalyst, the ammonia storage and injection section, and the flue gas section.

It should be noted that the efficiency of the SCR process depends very much on the catalyst composition and flue gas temperature. In addition, the following parameters also influence the NO_x reduction efficiency:

- Reaction temperature
- Molar ratio of NH_3 to NO_x
- Space velocity of the flue gas passing through the reactor and the area velocity
- Type of catalyst

3.2. The SCR Catalyst

A number of catalysts for reducing NO_x have been studied but mostly parallel-flow-type catalysts of a honeycomb or plate shape are used for utility boilers

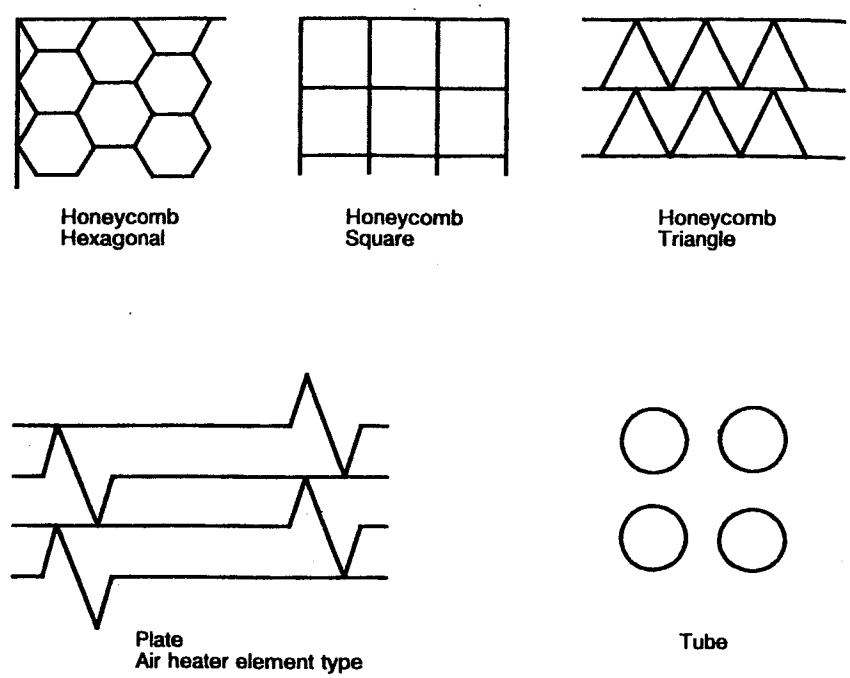
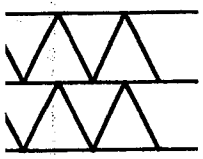


Figure 2. Cross section of a parallel-flow catalyst. (Redrawn from Ando, 1985a.)

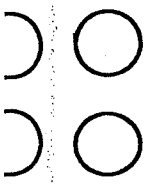
(Klovsky et al., 1980; Sengoku et al., 1980; Lachman, 1986; Bosch and Janssen, 1987).

Occasionally, packed-bed catalysts of activated coke or zeolite pellets are used. The extruded-type catalyst is generally known as honeycomb-shaped. This shape of catalyst is made of a mixture of carrier material, such as TiO_2 or TiO_2/SiO_2, and active components, such as WO_3, V_2O_5, or MoO_3. Besides these compounds, many other types of materials have been extruded into honeycomb-shaped catalysts (Bosch and Janssen, 1987). In this shape of catalyst, pitch or channel diameter and wall thickness are very important. The pitch diameter varies from 4 to 10 mm and wall thickness is generally about 1 mm (Ando, 1985a). Figure 2 shows the major types of parallel-flow catalysts used in the SCR technique; the dimensions of extruded-type catalysts are depicted in Figure 3.

Pitch diameter should be large enough that no blocking occurs, even with a heavy load of fly ash. According to Ando (1985b), in order to minimize dust deposition, a hexagonal honeycomb-type catalyst (angle 120°) offers better service than a triangular (angle 60°) honeycomb type. However, the square (grid) honeycomb-type catalyst is still the most popular. The relative popularity of the different types of catalysts used in Europe is shown in Figure 4. It can be seen that about 96% of catalysts are of the honeycomb type. This large share of the marketing volume is due to large pitch size, which prevents blocking of the catalyst by flue gas laden with fly ash (ECE, 1992).



Honeycomb
Triangle



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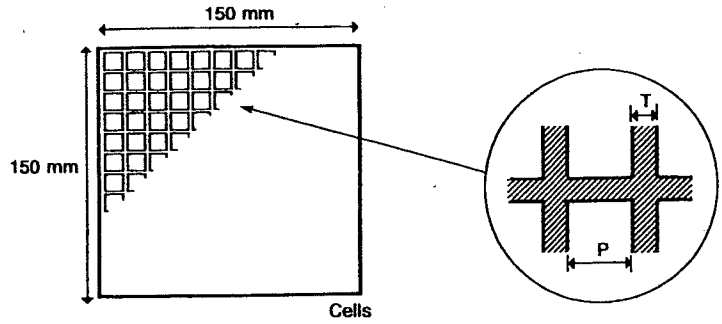

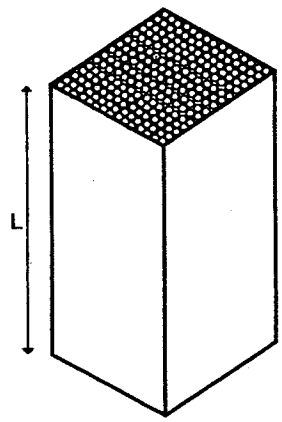

	13×13	15×15	17×17	20×20	21×21	35×35
			Cells			
Pitch (P) mm	9.8	8.0	7.4	6.0	6.0	4.2
Thickness (T) mm	1.8	1.8	1.4	1.4	1.0	0.6
Specific area m^2/m^3	291	312	382	427	470	795

Figure 3. Grid-type catalyst dimensions. (Redrawn from Robie and Ireland, 1990.)

Plate-type catalysts consist of a metal (iron) net on which the active substance is applied. The plates can be corrugated or a mixture of plain and corrugated (Fig. 2). Plate types have higher resistance to deposition and blockage than honeycomb types. The packaging of the plates is such that, due to the difference in physical and mechanical properties of the active and carrier materials, the layers may detach under thermal or mechanical stress (ECE, 1992). On the other hand, Babcock Hitachi (Kuroda, 1985) has developed a plate-type catalyst for coal fired-boiler flue gas that has a lower pressure drop (below 100 mm H_2O) than that in the moving bed pellet-type catalyst (pressure drop 150–200 mm H_2O). Siemens AG (1990) claims that their plate-type catalyst has high thermal and mechanical stability. Their plates also have high erosion resistance. It is further reported that there is less problem of disposal with a plate-type catalyst which can be treated as scrap in a furnace. But before charging into the furnace, the active materials should be removed from the surface of the plates.

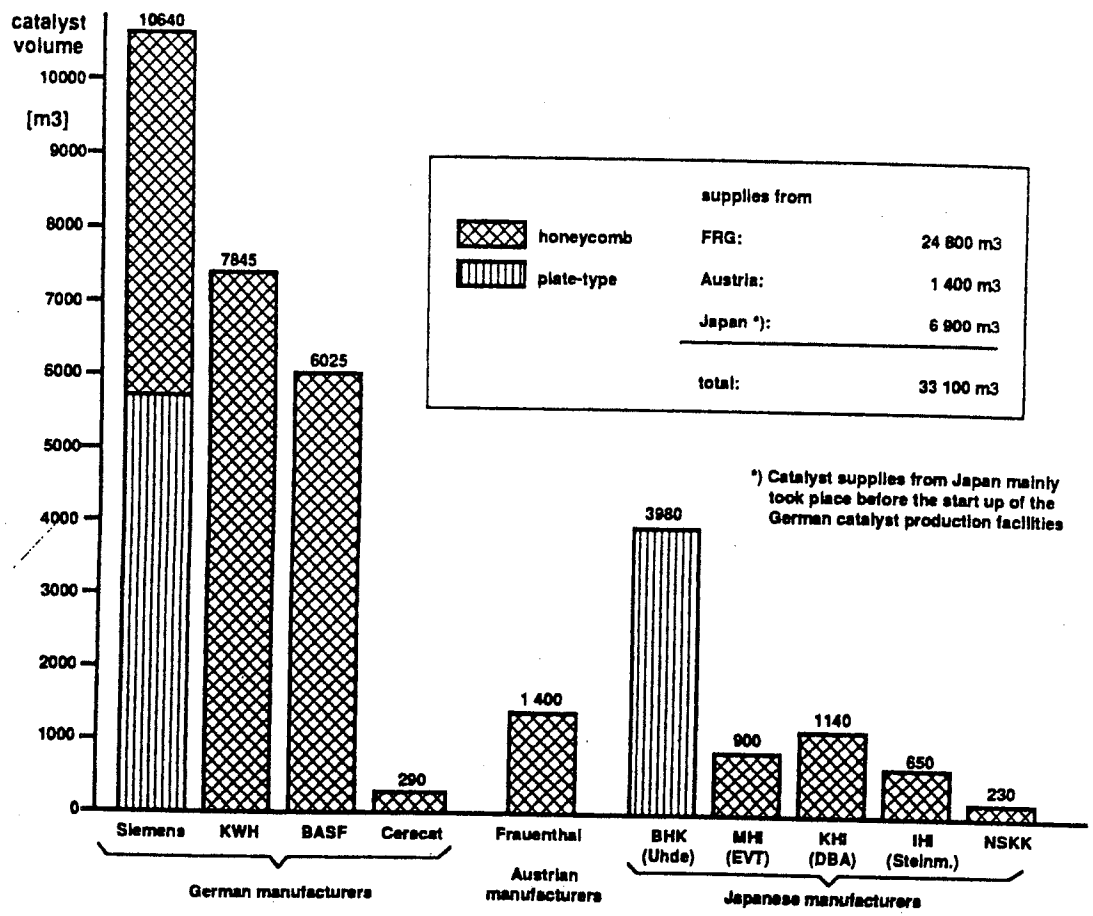

Figure 4. Relative popularity of honeycomb and plate-type catalysts in Europe and their manufacturers. (Siemens AG, 1990, with permission.)

3.2.1. *Catalyst Composition*

Many catalyst compositions are cited for use in the reduction of NO_x and their application range has been widened by the development of new catalyst systems such as low- and high-temperature catalysts (Jones, 1981; Jung et al., 1987; Bosch and Janssen, 1987; Williams et al., 1988). The transition metal oxides of group B in the periodic table mainly act as materials for the catalyst. The metals include: Cu, Ag; Zn; Ti, Zr; V, Ni, Ta; Cr, Mo, W, Mn, Te, Re; and all elements in group VIII (Chen et al., 1990). However, the composition of a catalyst should be specified on the basis of the following: required NO_x reduction, flue gas temperature, dust load, conversion of SO_2 to SO_3, permissible NH_3 slip, presence of alkaline metals, and presence of arsenic.

The following types of catalysts are generally in use in SCR reactors in power plants throughout Japan and Europe (Jones, 1981; Jung et al., 1987; Williams

Table 2 An Example of a Typical Catalyst for the SCR Process

Compensation	
TiO_2	> 90 wt.%
Active Compounds	
V_2O_5	1–5 wt.%
MoO_3 + WO_2	5–10 wt.%
Operating Temperature:	270–400 °C
Dimensions	
Plate Catalyst	
Plate distance	6–10 mm
Plate thickness	1.5–2 mm
Plate length	450–650 mm
Cross-sectional area	464 × 464 mm^2
Specific surface area	250–500 $m^2\,m^{-3}$
Extruded Catalyst	
Pitch size	3.7–7.4 mm
Wall thickness	1.0–2.4 mm
Length	350–1000 mm
Cross-sectional area	150 × 150 mm^2
Specific surface area	427–860 $m^2\,m^{-3}$
Space velocity	
High-dust	1000–3000 $m\,hr^{-1}$
Tail gas	5000–10000 $m\,hr^{-1}$
Oil	5000–10000 $m\,hr^{-1}$
Natural gas	5000–10000 $m\,hr^{-1}$
Area velocity	6–12 $m\,hr^{-1}$

Source: ECE (1992).

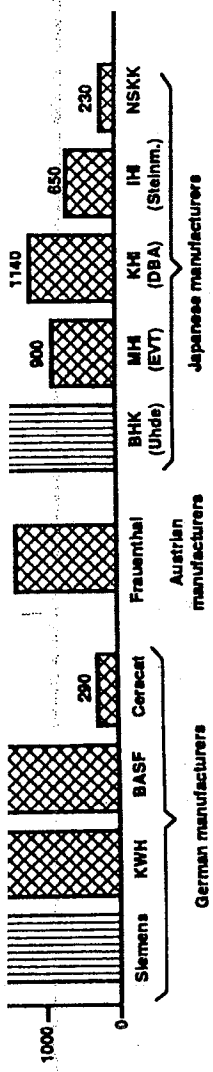

Figure 4. Relative popularity of honeycomb and plate-type catalysts in Europe and their manufacturers. (Siemens AG, 1990, with permission.)

et al., 1988; Hjalmarsson, 1990; ECE, 1992): titanium oxide, iron oxide, zeolite, and activated coke. Details of the active compounds in catalysts are not readily available, but the ECE (1992) has compiled information on the composition and dimensions of a typical TiO_2-based catalyst, as shown in Table 2.

3.2.2. *Catalyst Deactivation*

Catalyst life and activity are adversely affected mainly by poisoning, sintering and dust deposition, and erosion. Coal contains many harmful elements. During the combustion process, the compounds of these elements exist in the flue gas and fly ash and are adsorbed by the active sites of the catalyst, resulting in "catalyst poisoning." These harmful compounds may be subdivided into two groups: alkali metal oxides and heavy metals, especially arsenic.

Alkali Metal Oxides. Deactivation of V_2O_5/TiO_2-based catalysts by alkali metal oxides has been studied in detail (Shikada and Fujimoto, 1983; Yoshida et al., 1984; Kasaoka et al., 1984). When vanadium is used as an active material in the catalyst, it may be deactivated due to the formation of alkali-vanadium compounds (Martin et al., 1988). Chen et al. (1990) observed that the poisoning effect of CaO is less than that of other alkaline metal oxides. Hjalmarsson (1990) pointed out that when fly ash contains less than 10 to 15% (wt %) total alkaline metal oxides (CaO, MgO, Na_2O, and K_2O), its poisonous effect on the catalyst is less. This phenomenon is generally observed with brown coal, in which the CaO in the ash is quite high. In the United States, this problem is also observed with eastern bituminous coal, which contains large amounts of alkali metals. In Finnish coal-fired power plants, the fly ash normally contains about 6.5% CaO, 4.5% MgO, 0.7% Na_2O, and 2.2% K_2O.

Heavy Metals, especially Arsenic. Arsenic is poisonous to SCR catalysts but is less poisonous than the alkali metals, except for lithium (Yang et al., 1989). Arsenic poisoning was reported in wet bottom boilers with ash recycling in Germany (Necker, 1989), as well as in pilot plant tests conducted by Balling and Hein (1989).

Coal contains arsenic, which, when subjected to temperatures above 1300 °C in the boiler, is converted to gaseous arsenic trioxide (As_2O_3) (Schönbucher, 1987).

Arsenic concentration in the flue gas also depends upon the presence of CaO in the fly ash. As_2O_3 reacts with CaO above 500 °C to form calcium arsenite in the following reaction:

$$3CaO + As_2O_3 + O_2 \longrightarrow Ca_3(AsO_4)_2 \qquad (5)$$

Experiments conducted in the Datteln K1 power plant indicate that CaO can suppress arsenic poisoning. A 1% addition of CaO to coal increased the CaO in the granulate by 3.8%; at the same time, the arsenic content of the flue gas dropped from 0.55 to 0.1 mg m^{-3} (Fig. 5) (Gutberlet, 1988). Hence, the CaO

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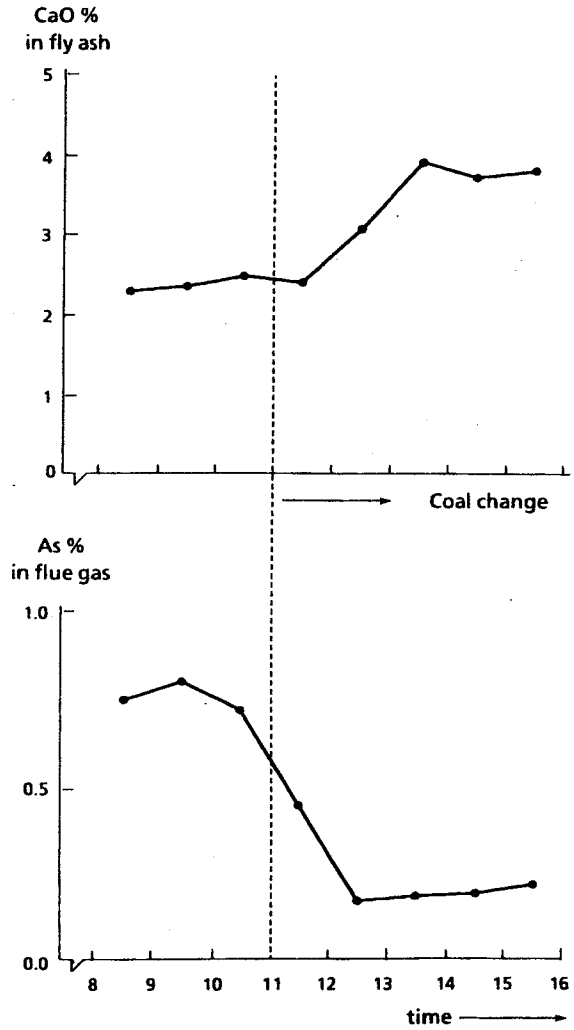


Figure 5. CaO addition to coal decreased gaseous arsenic concentration in flue gas in an SCR reactor at the Datteln K1 power plant in Germany. (Redrawn from Gutberlet, 1988.)

content in coal should be between 3 and 5% to suppress the arsenic content in the flue gas (ECE, 1992).

Siemens AG has also effectively studied the deactivation of catalysts by arsenic poisoning (Balling and Hein, 1989). In dry-bottom boilers, the only source of arsenic is the fuel, whereas in wet-bottom boilers, the fuel, recirculation ash, and melting of ash in the combustion chamber are arsenic sources. Here it was stressed that it is the gaseous arsenic that deactivates the catalyst, and not the

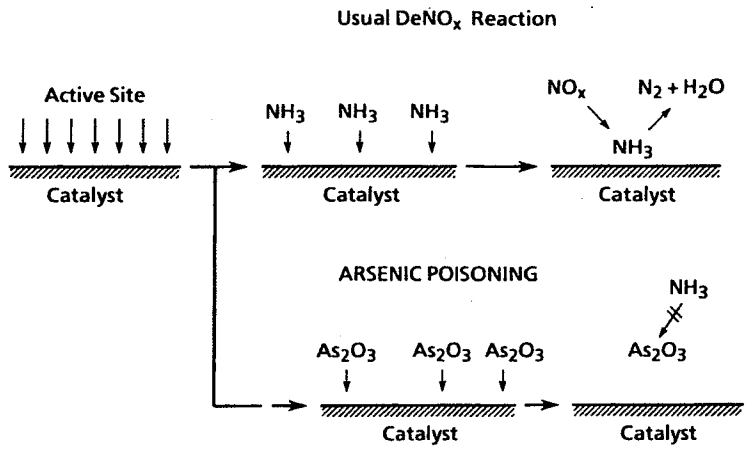


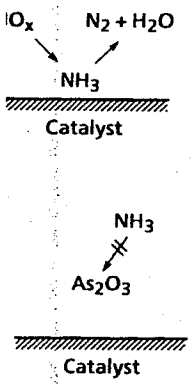
Figure 6. The mechanism of catalyst poisoning by arsenic. (Redrawn from Kuroda et al., 1989.)

arsenic in the ash. It has already been mentioned that it is possible to suppress this problem by adding lime, but pilot plant studies carried out by Siemens AG (1990) indicate that dosing with lime is not a permanent solution to this problem because the activity of the catalyst is eventually affected.

The arsenic content of the coal, the operation mode, and the reactivity of the fly ash may all affect arsenic poisoning. The mechanism of catalyst poisoning by arsenic and how the NO_x efficiency decreases with the increase of arsenic on the active sites of the catalyst are depicted in Figures 6 and 7, respectively. Gaseous arsenic apparently has the strongest poisonous effect on the active surface of the catalyst. But during periods of shutdown, if the moisture (i.e., humidity) cannot be controlled in the SCR reactor, then the arsenic in the fly ash may also have a poisonous effect on the catalyst. However, all these problems can be reduced by the following: less fly ash recycling in the wet-bottom boiler, low ash content in the coal, presence of the active compound in the catalyst, additives in the fly ash, control of humidity in the reactor during shutdown.

Chen et al. (1990) observed the poisoning effect of lead on the SCR catalyst, but it was not as strong as that of other alkali metals. The poisonous effect of selenium is the same as that of arsenic (Gutberlet, 1988), but there is no detailed study of selenium poisoning in fuel-fired power plants.

Dust Deposition and Sintering. The pores of the catalyst may be blocked by the deposition of dusts through capillary condensation and of fine fly ash. Hence, the choice of catalyst geometry and the position of the catalyst in the gas flow line are very important in avoiding pore blockage. On the other hand, condensation of water drops on the surface of the catalyst occurs at lower temperatures and the water may dissolve species of fly ash, thus reducing the activity of the catalyst. However, during SCR processes, it is believed that fine dust deposits on the surface of the catalyst cause a greater deactivation problem than arsenic poison-



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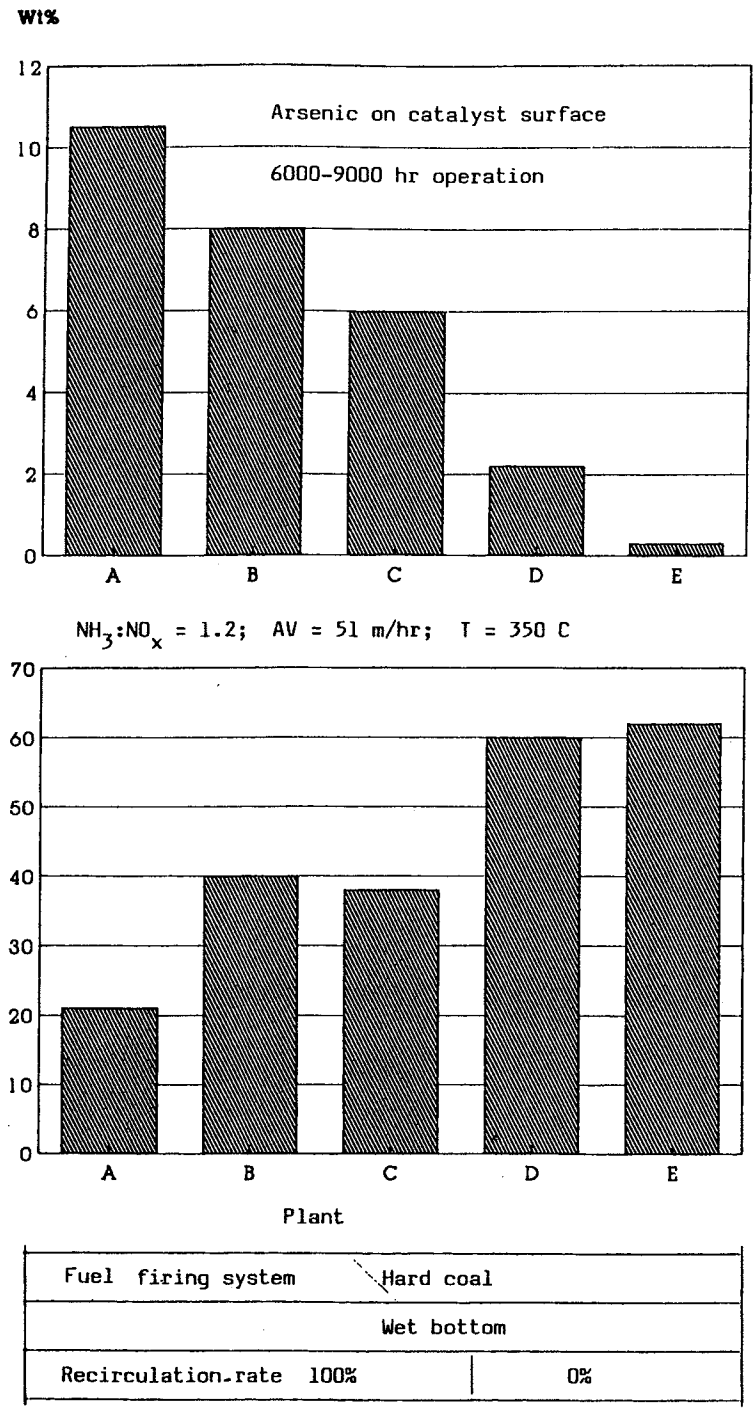

Figure 7. De-NO_x efficiency decreases with increase of arsenic on the catalyst surface. (Redrawn from Kuroda et al., 1989.)

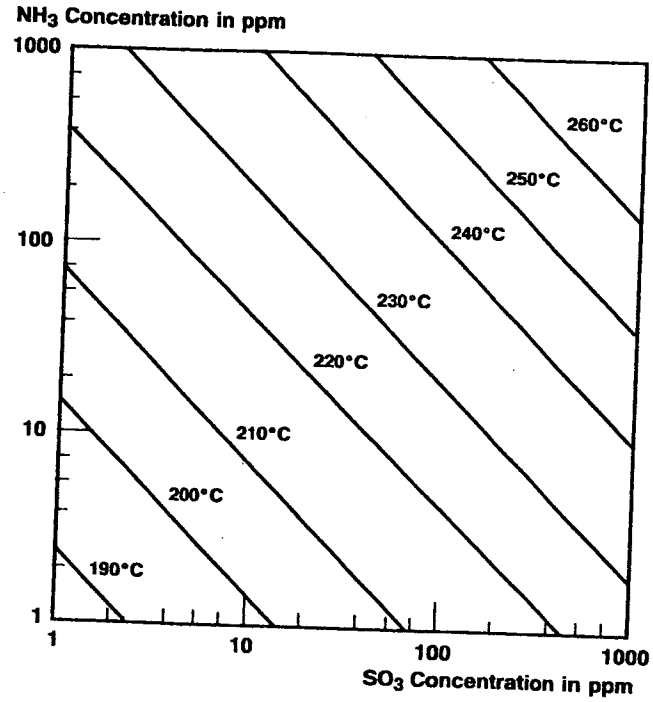

Figure 8. The dew point of ammonium bisulfate. (Redrawn from Ando et al., 1977.)

ing (personal communication with P. A. Lowe, 1991). This is probably due to masking of the surface of the catalyst.

There are many parameters, such as the presence of V_2O_5 in catalysts, process temperature, the fuel firing system, the boiler load, and oxygen concentration, that influence the oxidation of SO_2 in the flue gases. The SO_3 produced reacts with NH_3, forming ammonium sulfate and bisulfate as follows:

$$NH_3 + SO_3 + H_2O \longrightarrow (NH_4)HSO_4 \tag{6}$$

$$NH_3 + (NH_4)HSO_4 \longrightarrow (NH_4)_2SO_4 \tag{7}$$

However, condensation and deposition of ammonium bisulfate generally occur only when the temperature falls below the recommended operation temperature or dew point of this compound (Robie and Ireland, 1990). The dew point of ammonium bisulfate, which depends upon the concentration of NH_3 and SO_3 in the flue gas, is shown in Figure 8.

Sintering of the catalyst, which is a change of crystalline structure, reduces the number of pores and active sites. It generally occurs at higher temperatures. Robie and Ireland (1990) pointed out that under normal operating conditions, catalysts are damaged only slowly by the sintering mechanism. This type of

damage is not recoverable. At higher temperatures, the sintering of dusts and deposition of fly ash may totally destroy the catalyst.

Erosion. Erosion is mainly a function of the gas velocity in the catalyst (Cichanowicz and Offen, 1987). Pilot plant experiments at Rheinisch-Westfälischen Electrizitätswerke indicated that even abrasive fly ash did not cause any erosion problems in catalysts. It must be said, however, that this pilot plant is 25% oversized, which may explain why the catalyst is able to resist erosion. Hjalmarsson (1990) pointed out that the presence of large amounts of fly ash and the uneven concentration of particulates and size distribution may be the main causes of erosion in catalysts.

3.2.3. *Catalyst Lifetime*

Catalyst lifetime strongly affects the cost of the SCR process. The lifetime guarantees vary from one vendor to another, depending especially on a limited number of fuel properties. Catalyst deactivation modes such as surface masking by bisulfate compounds, arsenic poisoning, sulfur content, fly ash, and alkaline metal compounds should also be kept in mind. Experience in Japan suggests that the lifetime of an SCR catalyst is six to seven years for gas-fired boilers, five years for oil-fired boilers, and three years for coal-fired boilers (Ando, 1983). Some recent data on guaranteed and typical expected lifetimes of SCR reactors in western Europe are shown in Table 3. In reality, there will be exceptions. In Germany for example, a wet-bottom boiler with 100% dust recirculation experienced shorter catalyst lifetime due to arsenic poisoning.

3.2.4. *Catalyst Maintenance*

Correct maintenance and repair work will increase plant efficiency and prolong catalyst life. Successful maintenance depends to a great extent on careful study of the daily operation of the plant. The following process data are key to the success

Table 3 Typical Lifetime of SCR Catalyst in Western Europe

Application	Guaranteed Lifetime (Year)	Expected Lifetime (Year)
Coal		
High dust	2	4
Low dust	2	6
Tail end	2	6
Oil	3	6
Natural gas	6	8

Source: Robie and Ireland (1990).

of maintenance: NO_x concentration, inlet and outlet temperature of the flue gas in the reactor, O_2 and SO_2 content in the flue gas, NH_3 injection, mixing air volume, running hours, pressure loss across the catalyst, NH_3 slip, temperature in the catalyst.

3.2.5. Disposal of Deactivated Catalyst

There is no information on the correct disposal of spent catalysts, since nearly all the original catalysts are still in use. As for fuel used, catalyst lifetime increases in the following order: coal < oil < natural gas.

When a catalyst is deactivated, the catalyst manufacturer should collect all the spent catalyst, since its composition is proprietary (Ando, 1985a). Recently, Japanese suppliers have observed that the recovery of metals from the catalyst is quite costly, so they simply crush the spent catalysts and bury them in landfills (personal communication with P. A. Lowe, 1991). It is also reported that in Japan spent catalyst is used as a raw material for portland cement (personal communication with M. Yanai, 1990). In Germany, export of catalyst wastes is prohibited (Cichanowicz and Offen, 1987). In Finland, if the compounds in a catalyst are classified as hazardous, they are treated in the hazardous waste disposal plant in Riihimäki. This means that disposal costs are quite high. However, disposal costs and mode of disposal vary considerably from one country to another.

In the United States, the EPA has classified spent catalyst as a hazardous waste that must be disposed of in a class-one landfill. An independent company in the United States has estimated the disposal costs of spent catalyst to be US$315 per ton (Robie and Ireland, 1990). Research is continuing in Japan and Germany on catalyst recycling techniques (Cichanowicz and Offen, 1987).

3.3. SCR Systems

The arrangement of the catalyst in the flue gas flow depends on the gas temperature and its composition. On this basis, the SCR reactor is placed in one of three different positions known as the high-dust, low-dust, and tail-end configurations. The system arrangements are shown in Figure 9 and the common arrangements in Europe and Japan in Figure 10.

3.3.1. High-dust Configuration

In the high-dust configuration, the NO_x reduction plant is placed just behind the steam generator and upstream of the air preheater, as shown in Figure 9. The main advantage of this arrangement is that preheating of the flue gas is not necessary. But clogging due to dust load and the presence of SO_2 gas from the combustion of coal and oil may reduce the NO_x reduction rate. If the flue dust is recirculated, arsenic poisoning may also occur. If the dust load is abnormal, soot blowers become necessary, adding to capital and operating expenses. The flue gas temperature in the reactor normally varies between 300 and 400 °C but possibly can be reduced to 300 to 350 °C (Lowe et al., 1989). More reactors are needed in this arrangement than in the other two.

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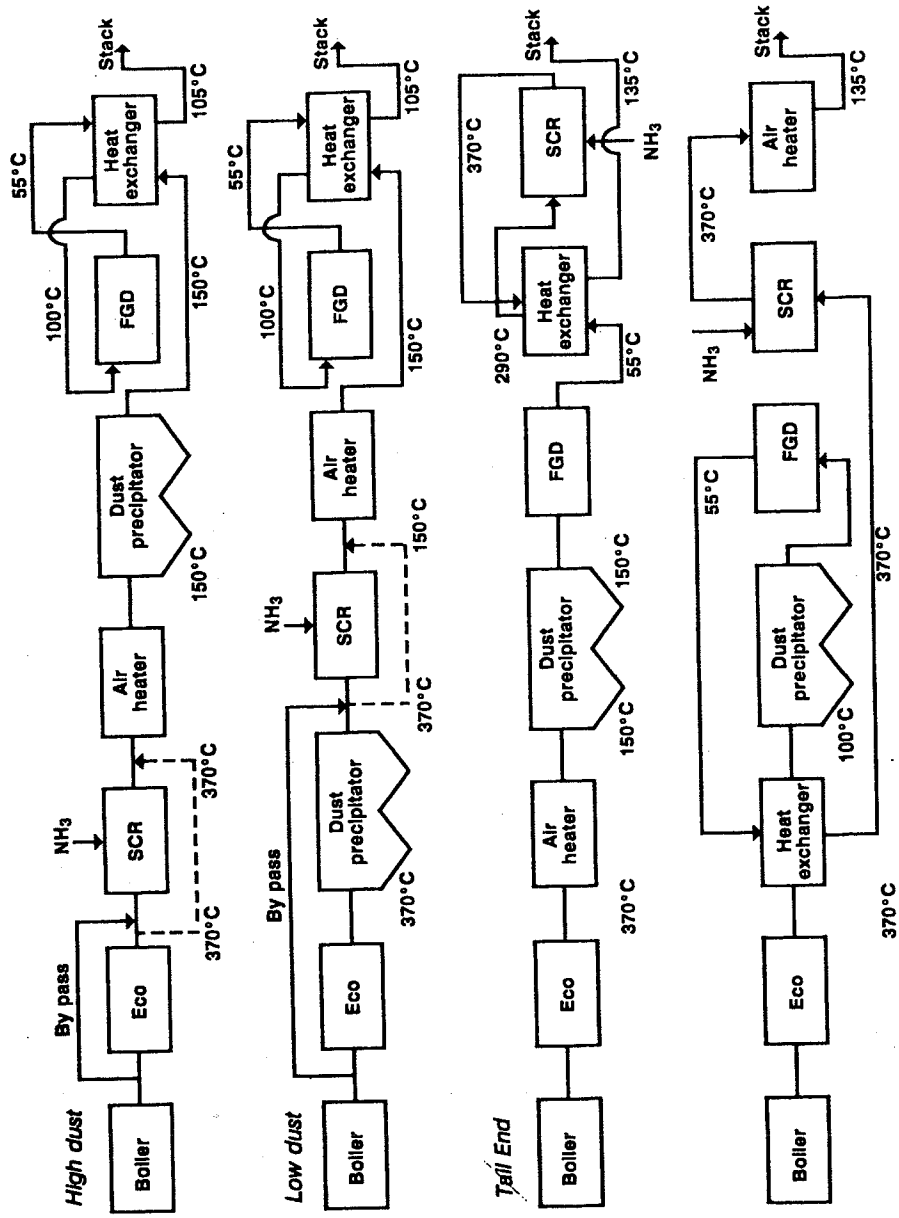

Figure 9. SCR catalyst arrangements. (ECE, 1992.)

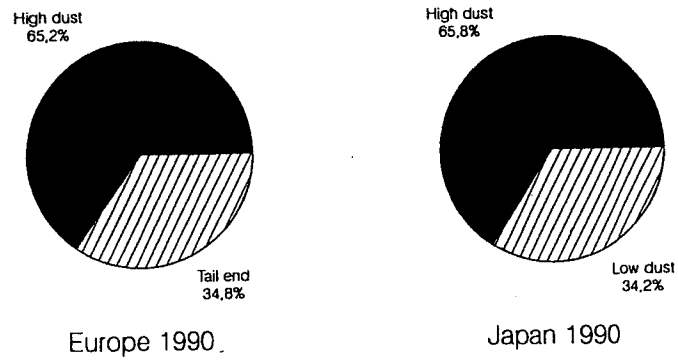

Figure 10. Trends in SCR catalyst arrangements in Europe and Japan. (Redrawn from Hjalmarsson, 1990.)

The principal advantages of the high-dust system are low capital investment and operating costs, provided it is installed in a new plant or integrated into an existing boiler system in such a way that no special problems are encountered (Siemens AG, 1990).

3.3.2. Low-dust Configuration

In this arrangement, the catalyst is situated between the hot dust precipitator and the air preheater. The flue gases entering the SCR reactor therefore contain very little or no dust. But the gases are richer in SO_2. This arrangement is quite common in Japan, where there is no stringent residual dust content requirement. Sooth blowers are necessary in this system because fine particles 0.1 to 3.0 μm in size have a tendency to be deposited or to agglomerate on the surface of the catalyst (Ando, 1985b). In addition, there is a tendency for ammonium bisulfate compounds to be deposited in the air preheater. The induced draft fan may be affected by the ammonium bisulfate compounds, and a special design may therefore be required. Fly ash caught by the cold precipitator may create a disposal problem, as some unreacted ammonia may pass through with the fly ash. To minimize this, NH_3 slip should be kept below 3 ppm (Ando, 1985b).

3.3.3. Tail-end Arrangement

This variant is almost exclusively employed in western Europe due to space limitations and catalyst deactivation, which would result from fly ash recirculation. In this arrangement, the SCR unit is placed at the end of the chain of the flue gas cleaning equipment. [i.e., after the flue gas desulfurization (FGD) unit]. This means that the flue gas contains very little dust and SO_2 when entering the catalyst. After the FGD unit, the flue gas temperature is quite low (55–70 °C), which is not suitable for the catalyst. For this reason, reheating of the flue gas is necessary. This is done partly by utilizing waste heat from the process, but there is still a temperature difference (20–40 °C) that must be compensated for by fuel-fired burners or by a heat exchanger.

3.4. Impact of Ammonia Slip

Ammonia slip is the unreacted ammonia that leaves the catalyst reactor with the flue gases. This unreacted NH_3 can react with SO_3 in the gases, forming ammonium compounds according to Reactions (6) and (7). These compounds have a damaging effect on various parts of the system, including the air preheater, FGD system, induced draft fan, wastewater system, and the management and disposal of the fly ash.

It is noted that problems with ammonium bisulfate are quite serious when using medium or high sulfur-content coals. If the SO_3 concentration exceeds the NH_3 concentration in the flue gas, its deposition on the air preheater tubes accelerates corrosion and increases pressure drop, causing damage or shutdown of the air preheater. In the case of low-sulfur coal or oil, the NH_3 concentration may exceed the SO_3 concentration in the outlet flue gas of the reactor, which will lead to the formation of dry ammonium sulfate powder that will not foul the air preheater (Robie and Ireland, 1990). However, to achieve better reduction of NO_x and a longer lifetime for equipment, NH_3 slip should be kept to a minimum (0.5–2 vppm) (ECE, 1992).

4. ENVIRONMENTAL IMPACT OF THE SCR PROCESS

It is possible to reduce NO_x emissions from utility boilers by 80 to 90% using pollution control technology based on the SCR process, in which NH_3 injection plays an important role. Due to the incomplete reaction of NH_3 with NO_x, some NH_3 will be emitted to the environment from the process. The amount of unreacted NH_3 depends upon the NH_3/NO_x molar ratio and the activity of the catalyst. The reaction of SO_3 with NH_3 and its effects on the downstream equipment have been discussed earlier. It is estimated that 80% of the unreacted NH_3 salts are discharged with the fly ash, as can be seen from the materials balance of NH_3 depicted in Figure 11. In Germany, the removal efficiency depends on the form of the NH_3 in the flue gas, the pH of the scrubbing liquor, and the type of conductor. Here, the NH_3 salt is in the submicron size, for which a high-pressure conductor is more effective.

If the fly ash contains a large amount of NH_3, there is a risk of NH_3 emissions from fly ash to the environment. The process may also have an impact on groundwater if NH_3 leaches from ash that has been used as landfill. The NH_3-bearing wash water from the air preheater and FGD system may also have an effect on the groundwater if it is not denitrified in a wastewater treatment plant before discharge.

It is reported (Jones, 1981; Jones et al., 1982) that NH_3 salts or gaseous NH_3 may form a visible stack plume. The chance of a visible plume forming is minimized when the flue gas passes through a cold electrostatic precipitator, which removes nearly all the NH_3 salts. However, systems using a hot electrostatic precipitator may have the problem of $(NH_4)_2SO_4/NH_4HSO_4$ plume formation. This can be avoided if a high-pressure drop mist eliminator is used in

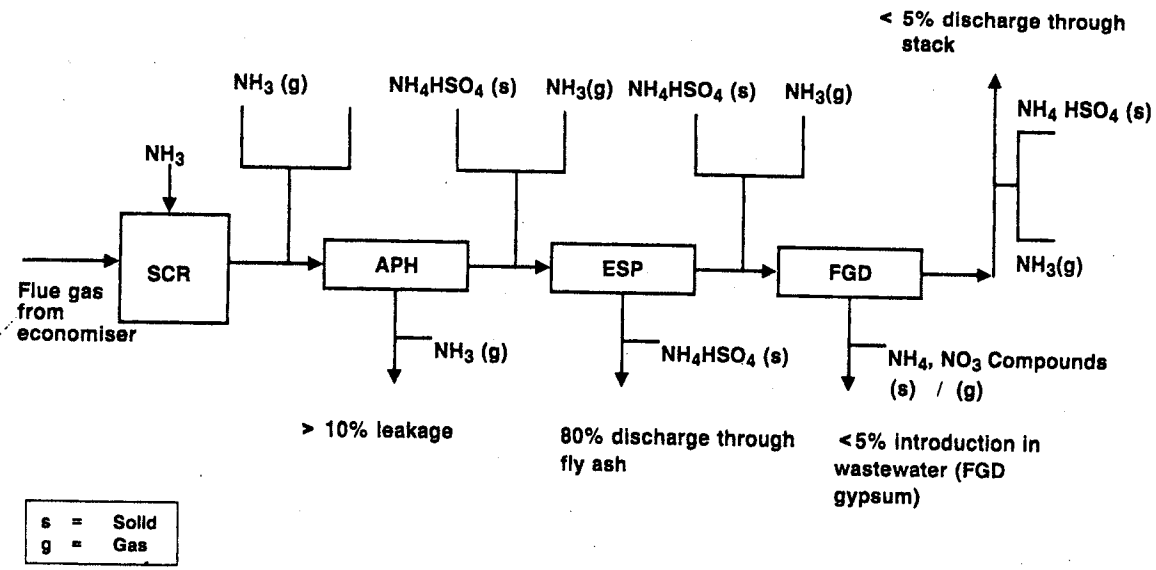

Figure 11. Material balance of NH_3 discharge through downstream equipment. (Hein et al., 1986; Bujak and Gutberlet, 1987; Necker, 1989.)

the FGD equipment. A visible plume may also form due to the reaction of gaseous NH_3 and SO_2 (*g*). This happens only when NH_3 discharge from the stack exceeds 10 ppm (Jones et al., 1982). No reports on plume formation from the SCR process have been cited in the literature, however. Under normal operating conditions, NH_3 emission from the stack is negligible and as a result, the risk plume formation is non-existent or negligible.

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Figure 11. Material balance of NH_3 discharge through downstream equipment. (Hein et al., 1986; Bujak and Gutberlet, 1987; Necker, 1989.)

s = Solid
g = Gas

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SCR Catalyst Design Issues and Operating Experience:
Coals with High Arsenic Concentrations and Coals from the Powder River Basin

Dr. Karina Rigby, Siemens KPW
Mr. Robert Johnson, Siemens Westinghouse
Dr. Ronald Neufert, Siemens KPW
Dr. Günther Pajonk, Siemens KPW
Dr. Erich Hums, Siemens KPW
Mr. Andreas Klatt, Siemens KPW
Mr. Ralf Sigling, Siemens Westinghouse

Selective Catalytic Reduction (SCR) for Nitrogen Oxide emission control is a preferred technology for coal-fired Utility compliance strategies. A large number of installations are scheduled for commercial operation before May, 2003. Within the United States, there is experience on only several installations, and thus many of the SCR-related decisions have been made on the basis of extrapolated data from units with dissimilar operating experience.

Two significant issues currently dominate decision-making for SCR catalyst technology and system engineering: first, the need for catalyst that provides high-efficiency performance under high or varying gaseous arsenic conditions; and second, the need for a technology solution for SCR installations on units firing Powder River Basin (PRB) coal.

1. Gaseous Arsenic and SCR Catalyst Performance

It is well-known that arsenic in gaseous form will poison vanadia-titanium SCR catalysts. The first and most evident cases of poisoning were observed on wet-bottom boilers with fly ash reinjection. In the 1980's, Siemens conducted numerous studies on this phenomenon in German Utility installations. These studies resulted in the development of Siemens' arsenic resistant plate catalyst.

Arsenic in the coal will be vaporized into arsenic oxides, preferably to As-(III), in the boiler. These are very volatile at the operating temperatures of the boiler. These arsenic oxide molecules are very small relative to the typical pore diameters in SCR catalysts. As a result, these can readily penetrate into the pore system of the catalyst where these molecules will react with the vanadia in the catalyst. The resultant vanadia-arsenate compound is so stable that the activity of the vanadia site is lost. This catalyst deactivation can be quite rapid for vanadia-tungsten based catalysts, depending on the concentration of gaseous arsenic in the flue gas.

This catalyst deactivation on wet-bottom boilers in Germany caused some Utilities to install tail-end SCR systems in order to provide a comparatively clean gas (ie low sulfur, dust and arsenic loadings) for the catalyst. These kinds of SCR systems are

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generally more expensive to install, due to the requirements for heat exchangers, and to operate, due to the costs associated with reheating the flue gas. At that time, however, this system became the only option for Utilities to maintain high efficiency SCR performance and relatively long catalyst operating life.

Siemens developed an arsenic resistant catalyst to improve catalyst performance in high dust applications. For German utilities, this catalyst allowed them to choose a high dust SCR for the wet bottom boilers, or to improve operating performance of installed SCRs by maintaining higher removal efficiencies over a longer operating period.

Arsenic Resistance

Deactivation caused by arsenic in the flue gas is a chemical reaction. To make an SCR catalyst resistant to arsenic requires a change in the chemical composition of the catalyst. The purpose is to provide a reaction site for the arsenic oxide other than the vanadia in the pore structure. Research and development work by Siemens proved that the addition of molybdenum to the catalyst composition is effective in protecting the vanadia sites against arsenic attack. The amount of molybdenum and the extent of arsenic resistance are directly proportional. Catalysts with very high molybdenum content deactivate very slowly and show excellent k(t) / k(o) ratios over time. Initial catalyst activity is lower, however.

In a catalyst with molybdenum added, the Mo site is more reactive with arsenic than vanadia. As a result, the vanadia site is shielded from the arsenic since the arsenic will form a stable compound with the molybdenum. Without molybdenum, the arsenic will quickly react with the vanadia. Since the concentration of vanadia in the chemical composition of the catalyst is small, typically less than 1.5%, the deactivation of vanadia sites is quite rapid.

In the same flue gas, ie arsenic concentrations, tungsten-based catalysts will deactivate much faster than a catalyst containing molybdenum. In some German installations, 50% loss of activity has been reported within 10,000 to 15,000 operating hours. With a Siemens titanium molybdenum catalyst on similar applications, the relative activity of the catalyst has declined only 20 to 25%.

Siemens' field experience with tungsten and molybdenum-based catalysts shows the tendencies for lower deactivation rates for Siemens' arsenic-resistant catalysts, and the rapid deactivation for those that are tungsten-based. The trends shown in Figure 1 are based on catalyst samples from full-scale installations, as tested by Siemens or reported by other companies. As arsenic concentrations on the catalyst increase, as a function of operating time and arsenic levels in the flue gas, the relative deactivation between molybdenum and tungsten-based catalysts diverges rapidly.

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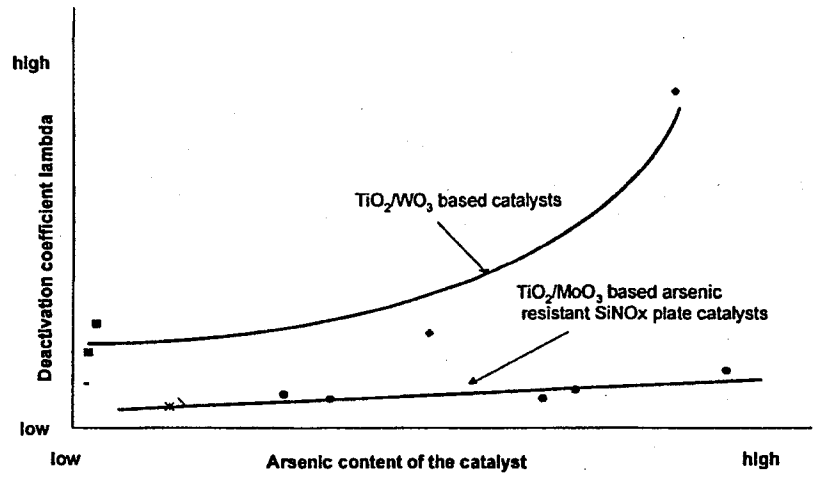

Figure 1. Comparison of Catalyst Deactivation Rates as a Function of Arsenic Content

SCR system design is significantly affected by the catalyst decision, especially on units expected to have high arsenic concentrations. A decision based on an incorrect assessment of expected catalyst deactivation will impact expected operating periods for the catalyst and result in more frequent exchange of catalyst. Understanding the important variables before a catalyst decision will give a Utility a better basis for evaluating expected operation and performance.

The Effect of Calcium Oxide

Extensive development work by Siemens in the late 1980's and early 1990's showed that gaseous arsenic levels in a flue gas are a function of the calcium oxide (CaO) percentage in the coal. Correlations have been formed among these two constituents, boiler type and fly ash recirculation to predict gaseous arsenic concentrations in the flue gas. The importance of this determination is to accurately assess the deactivation rate of the catalyst for catalyst design and volume calculations. Failing to choose the correct deactivation rate will lead to an insufficient initial catalyst volume, a possibly undersized SCR reactor arrangement, and a flawed evaluation of life-cycle operating costs related to catalyst management.

Previous interpretations of these variables by many in the industry, primarily drawn from SCR catalyst performance from Japanese installations firing low arsenic coals and German coals from the Ruhr and Saar Regions with high CaO contents, assumed that catalyst deactivation on dry bottom boilers would be relatively slow. However, Siemens' experience in the United States has shown that arsenic concentrations in the flue gas, based on arsenic content on SCR catalyst samples, vary considerably for dry bottom boilers. Considering the fuel flexibility desired by many Utilities, the impact on catalyst selection is significant. A tungsten-based catalyst will not be able to provide the long-term reduction efficiencies nor control ammonia slip if it deactivates more rapidly due to the high arsenic concentrations. Remedial actions, such as limestone

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injection, limitations on coal selection and a higher frequency of catalyst exchanges, are expensive.

2. Powder River Basin (PRB) Coals and SCR Catalyst Considerations

Cost saving measures as well as strict SO_3 emissions limits have led to an increase in the number of US Utilities burning PRB coal. The subject of PRB coal use is therefore a significant issue in the US Utility market, considering the number of units possibly affected by Title I regulations. Many utilities burning PRB coal are now confronted with the necessity of installing SCR units to meet strict NOx emissions limits.

The uncertainty of long term performance has affected decision-making processes pertaining to SCR system arrangement, life cycle operating costs and commercial guarantees. This situation has prompted Siemens to engage in an extensive research program to study the effects of PRB fly ash on SCR catalysts in high-dust applications, both through independent testing at Siemens as well as through the involvement in partnership research programs with US utilities.

As part of the Siemens PRB research program, more than 400 Siemens test samples have been installed in numerous PRB coal plants across the US. These PRB plants include both pulverized coal (PC) and cyclone power plants. Additional test installations are planned.

The Siemens catalyst samples can be grouped into the following categories:

- Full-size slip-stream samples tested under actual conditions
- Smaller sized slip-stream samples tested under actual conditions
- Coupon samples tested under actual conditions
- Coupon samples tested in flue gas ducts

The goals of the Siemens catalyst testing program for PRB applications are threefold. Our first goal is to quantify the catalyst deactivation rate for various types of PRB applications. Knowledge about catalyst deactivation rates associated with PRB coal forms the basis for a decision on whether a high-dust or tail-end SCR reactor is appropriate and what type of catalyst management plan is necessary.

The second goal of the Siemens catalyst testing program is to gain information on the catalyst deactivation mechanism resulting from PRB fly ash exposure. Knowledge of the physical and/or chemical process leading to catalyst deactivation will provide information on the expected magnitude of activity loss associated with PRB fly ash exposure.

Information on the catalyst deactivation process is also the basis for developing measures to counteract catalyst deactivation in PRB applications. This goal will be addressed in the third phase of the Siemens catalyst testing program.

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Catalyst Deactivation Rate

Activity testing in Siemens semi-bench and pilot scale reactors has been performed on reference catalyst samples and catalyst samples exposed in both PC and cyclone PRB plants under actual SCR conditions. In general, activity testing showed that under worst-case conditions catalyst deactivation can reach more than 50% in less than 5000 operating hours.

Catalysts tested under worst-case conditions showed a sharp initial decrease in activity and a subsequent flattening of the deactivation curve as operating hours increased. This phenomenon will be discussed in more detail below. Deactivation information will continue to be updated as more operating hours on Siemens catalyst test samples are gathered as part of the PRB test program.

Catalyst Deactivation Mechanism

As part of the Siemens PRB investigation, exposed catalyst samples and fly ash specimens were analyzed in order to determine which deactivation mechanism contributes to catalyst deactivation in PRB applications. Catalyst poisoning effects resulting from PRB fly ash were evaluated by performing leaching experiments on fly ash collected from numerous US and European coal plants burning PRB coal, US high-sulfur coal and German hard coal. Leaching tests were performed using water and sulfuric acid to simulate operating conditions in which water or sulfuric acid condenses on the fly ash on the surface of the catalyst. The leached elements were analyzed in both cases and the pH of the leaching solution was measured after the tests performed with water.

The results of the fly ash leaching experiments showed that, except for Na, the concentrations of poisoning constituents in PRB fly ash are lower than or similar to those of other common coal types. The Na concentration will vary depending on the type of PRB fly ash tested. These results show that, although deactivation from poisoning will take place to a limited extent in PRB applications, the extreme catalyst deactivation associated with PRB coal cannot be explained solely be chemical poisoning.

The extent of catalyst masking and plugging resulting from PRB fly ash exposure was also examined as part of the Siemens PRB investigation. Optical microscopy was used to examine the large fly ash particles present on the surface of exposed catalyst samples and scanning electron microscopy (SEM) was used to examine the microscopic surface structure of the catalyst samples (including surface pores, plugging and masking phases). Energy dispersive X-ray analysis (EDX) was used to examine the chemical composition of the catalyst surface and to obtain information about the flue gas constituents deposited on the surface of the catalyst samples.

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Optical microscopy and SEM results showed that the PRB fly ash on the surface of the exposed catalyst samples can generally be divided into two categories. Macroscopic fly ash deposits, observable as ash clumps on the catalyst surface and between the catalyst plates or walls, were found to be loose and showed no signs of cementing. Extreme plugging or fly ash cementation should therefore not be a significant problem in plate- catalyst PRB applications. However, SEM analysis showed that on a microscopic scale, not observable using the naked eye, fly ash on the catalyst surface had reacted to form a masking layer which in some cases was found to be extremely dense. The formation of the masking layer was not found to be connected with catalyst pores, i.e. no individual fly ash particles lodged in catalyst pores were detected. Chemical analysis of the catalyst surface showed that the masking layer formed on the catalyst surface consisted nearly completely of calcium and sulfur. This masking layer prevents nitrogen oxides and ammonia from diffusing into the catalyst sites, resulting in significant catalyst deactivation (Figure 2).

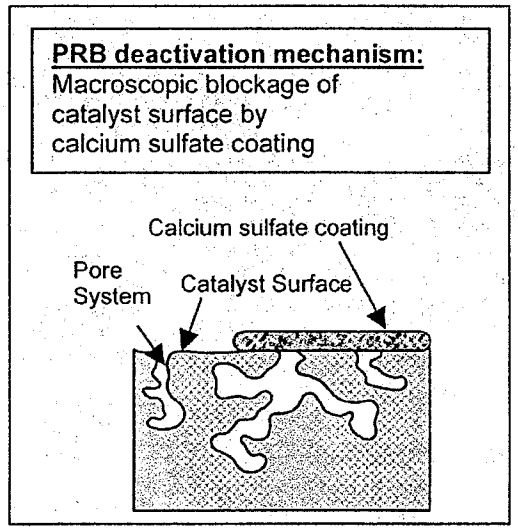

Figure 2: Schematic showing calcium sulfate masking, the main catalyst deactivation mechanism for PRB applications.

If one examines the chemistry of PRB fly ash it is clear why PRB applications are especially susceptible to calcium sulfate surface masking. As discussed previously, one of the main factors driving more and more utilities to switch to PRB coal is the low sulfur content, allowing utilities to meet emissions limits. However, this apparent advantage results in a disadvantage from the standpoint of SCR catalyst operation. The CaO content of PRB coals can be nearly three times that of anthracite or bituminous US coals. When high-sulfur coal having a low CaO content is burned, the calcium compounds react nearly completely with the excess SO_3 present in the boiler to form calcium sulfate and other phases. The calcium sulfate itself is no longer reactive and blows through the catalyst channels as non-reactive fly ash. However, because of the extremely low sulfur content and the extremely high CaO content in PRB coal, there is not enough SO_3 available in the boiler to completely transform the

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CaO phases to calcium sulfate in the boiler. The result is a large percentage of "free" or "active" CaO in PRB fly ash.

The presence of large amounts of free CaO is the essential factor in the calcium sulfate formation mechanism leading to catalyst deactivation in PRB applications. This is illustrated in figure 3.

(1) Free CaO (in fly ash) is deposited onto catalyst surface

(2) SO_2 (in exhaust gas) $\rightarrow$ SO_3 (on catalyst surface)

(3) Free CaO (on catalyst surface) + SO_3 (g) $\rightarrow$ $CaSO_4$ **calcium sulfate coating**

Figure 3: Mechanism leading to the formation of a calcium sulfate surface coating on SCR catalysts in PRB applications

In step 1, the PRB fly ash lands on the catalyst surface as the flue gas passes through the catalyst, as is the case for any type of fly ash. However, as described above, PRB fly ash contains large amounts of reactive free CaO. In step 2, the small amounts of SO_2 present in the flue gas react to SO_3 on the catalyst surface. The presence of both free CaO and SO_3 at the catalyst surface leads to reaction 3, the formation of a $CaSO_4$ layer on the catalyst surface. Because both free CaO and SO_3 are continuously available at the catalyst surface, the $CaSO_4$ layer continues to build up as SCR operating hours increase.

Deactivation resulting from the formation of a calcium sulfate layer on the surface of the catalyst physically explains the sharp initial decrease in catalyst activity and the subsequent flattening of the deactivation curve as operating hours increase. During initial exposure, any calcium sulfate formation which takes place occurs on the active catalyst surface, resulting in deactivation of this surface. As exposure time increases, calcium sulfate formation occurs partially on fresh catalyst surface, but also on top of the already formed calcium sulfate layer, resulting in only a minor increase in deactivation due to thickening of the already present calcium sulfate diffusion barrier. Therefore, for PRB applications, the calcium sulfate formation model is in agreement with the sharp initial activity decrease and subsequent slower catalyst deactivation discussed above. It is expected that continued calcium sulfate formation will result in complete catalyst masking with increased operating hours. As supported by SEM results, fly ash trapping in catalyst pores does not contribute significantly to deactivation.

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Measures to Counteract Catalyst Deactivation

Results gained from the Siemens PRB investigation to date indicate that, in most cases, a high-dust SCR application will result in catalyst deactivation rates which are significantly higher than expected for other coal applications. As discussed above, in such cases a strict catalyst management plan or a tail-end SCR solution may be necessary. A third option, however, is to develop measures to counteract catalyst deactivation resulting from PRB fly ash exposure.

Possible counteraction measures include:

- Coal blending to increase the sulfur to calcium ratio in the fly ash, thereby minimizing free CaO content
- Neutralization of the free CaO before it reaches the catalyst
- Decreasing the SO_3 availability at the catalyst surface
- Removal of the calcium sulfate from the catalyst surface after deposition

These possibilities are currently being investigated as part of the Siemens catalyst testing program for PRB applications.

Conclusions and Catalyst Design Impact for PRB Applications

Commercial SCR catalyst operating experience for PRB applications is very limited at this time, however there has been a substantial amount of development work recently. Siemens has been extensively involved in this area, and has come to some preliminary conclusions. The work indicates that a masking of the catalyst will occur if the catalyst is installed in a conventional high dust location. This masking in essence deactivates the catalyst rapidly, and long term projections of performance become very subjective.

Based on this currently available deactivation information, a tail-end SCR installation would most likely be the best option for meeting the emission limits required at some US utilities burning PRB coal. High-dust SCR systems with deactivation rates as high as those presented here would require an extremely strict catalyst management plan. The pros and cons of a tail-end vs. a high-dust SCR solution will have to be examined by utilities and catalyst manufacturers on a case-by-case basis.

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Optimizing SCR Catalyst Design and Performance for Coal-Fired Boilers

Scot Pritchard
Chris DiFrancesco
Cormetech, Inc.
Durham N.C
(919) 620-3000

Shozo Kaneko
Norihisa Kobayashi
Mitsubishi Heavy Industries, Ltd.
Nagasaki, Japan
(045) 224-9178

Kohei Suyama
Kozo Iida
Mitsubishi Heavy Industries, Ltd.
Nagasaki, Japan
(958) 28-6401

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Scot Pritchard
Chris DiFrancesco
Cormetech, Inc.
5000 International Drive
Durham, NC 27712

Shozo Kaneko
Norihisa Kobayashi
Mitsubishi Heavy Industries, Ltd.
Yokohama, Japan

Kohei Suyama
Kozo Lida
Mitsubishi Heavy Industries, Ltd.
Nagasaki, Japan

Abstract

The design of an SCR system for a coal-fired application is a challenge due to particulate, catalyst poisons, and So_2 in the flue gas. Our experience show that coal-fired SCRs are successful when the system impact and catalyst deterioration factors are understood and specific countermeasure are implemented in system and catalyst design

There are several factors that the system and catalyst must consider in order to assure success. They include: type of boiler, required performance, fuel and ash analysis, ash loading, type of SCR, inlet conditions, Catalyst deactivation mechanisms, and impact on down stream equipment.

This paper explains each system and catalyst deterioration factor that we have experienced. For each factor, it presents the specific countermeasure that has resulted in successful SCR systems. Also, it discusses the design of improved catalyst derived from our experience. Finally, two case studies illustrate the impact of optimized design.

Introduction

Selective Catalyst Reduction (SCR) is recognized worldwide as the most effective NOx Control Technology for utility boilers and combustion turbines when substantial NOx reduction of 50% to 95% is required. In addition to its proven high performance, It has also become an economically viable solution, with current installed cost, in the United States, estimated at between $20/kw for natural gas and $50/kw-$70/kw for coal units. The technology has even given some utilities the capability to achieve lower heat reduction or omission of flue gas recalculation (FGR).

Mitsubishi Heavy Industries (MHI) pioneered the developed and application of SCR technology staring in the late 70's in Japan, and installed the worlds' first High-dust SCR application on a 175 MW coal fired boiler in 1980. MHI transferred their technology through licensing agreement to several companies in Europe and to Cormetech in the United States. Over 319 units including 56 coal fired boilers worldwide operation successfully using this technology.

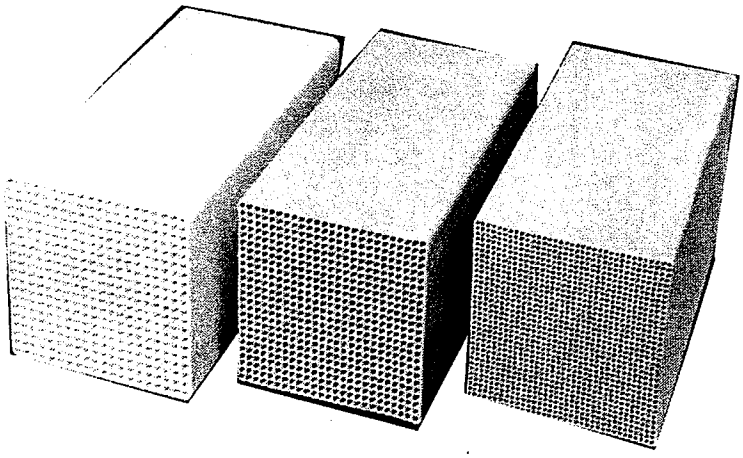

Figure 1
Catalyst for Coal, Oil, and Gas Applications

Cormetech is a joint equity company of Corning Incorporated, MHI, and Mitsubishi Chemical Company (MCC). Cormetech design and Manufactures homogeneous Titanium-Tungsten-Vanadium (Ti-W-V), Extruded honeycomb catalyst for fossil-fuel-fired applications. Figure 1 show a photograph of catalyst for coal, oil, and gas applications. Cormetech draws upon the vast experience database of MHI, the extrusion and catalyst know-how of corning, and catalyst technology of MCC to provide an optimized product to the market.
This paper address the methods successfully implemented to design and optimize catalyst performance in coal fired boiler applications. The basics of deNOx catalysis are

reviewed in preparation for the discussion on system impact, catalyst deterioration, mechanism, and countermeasures that follows. Additionally, catalyst design optimization is presented by a discussion of improved catalysts for coal applications. Two case studies (pulverized coal and cyclone boilers) comparing conventional and improved catalyst are presented.

Background of SCR Reaction

In coal fired boilers in which SOx is presented in the flue gas two chemical reaction that occur in the presence of the SCR catalyst are of most importance to the following discussion

One reaction, of course, is the deNOx reaction:

$$4NO + 4NH_3 + O_2 \xrightarrow{\text{catalyst}} 4NH_2 + 6H_2O \qquad (1)$$

Figure 2 illustrates this primary reaction mechanism. Starting in the upper left-hand corner of the figure and proceeding clockwise is:

1. Active catalyst site (Me = metal)
2. Absorption of ammonia molecule
3. Reaction of NO with NH_3 forming
4. Regeneration of active site by oxidation

The second reaction is oxidation of sulfur dioxide:

$$SO_2 + \tfrac{1}{2} O_2 \xrightarrow{\text{catalyst}} SO_3 \qquad (2)$$

The NOx conversion rate and SO_2 oxidation rate will partly depend upon the rate in which the reactants diffuse through the wall of the porous catalyst to reach active sites where reaction takes place. Through our experience we have determined the rate of chemical reaction is fast reaction for our catalyst. For deNOx conversion the rate of chemical reaction is fast relative to the rate of diffusion. Therefore the catalyst is effective primarily at the surface of the wall. On the other hand, the SO_2 oxidation chemical reaction rate is slow relative to the rate of diffusion so that the reactants diffuse into the entire wall. This conclusion is relevant to the subsequent discussion on the system impacts, catalyst deterioration mechanisms, and countermeasures.

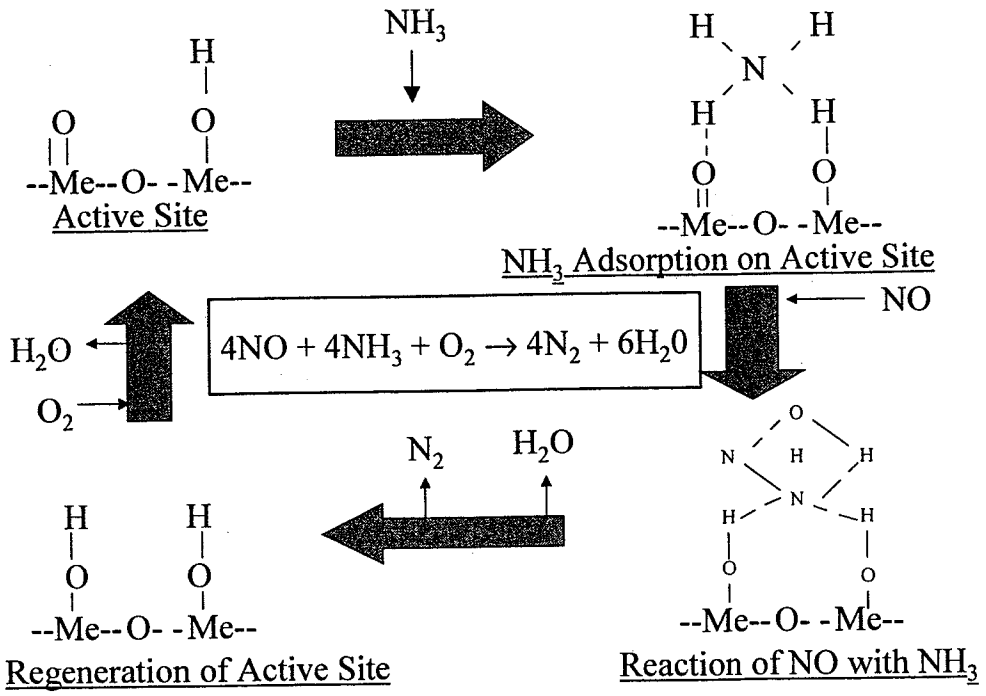

Figure 2
SCR Surface Reaction Mechanism

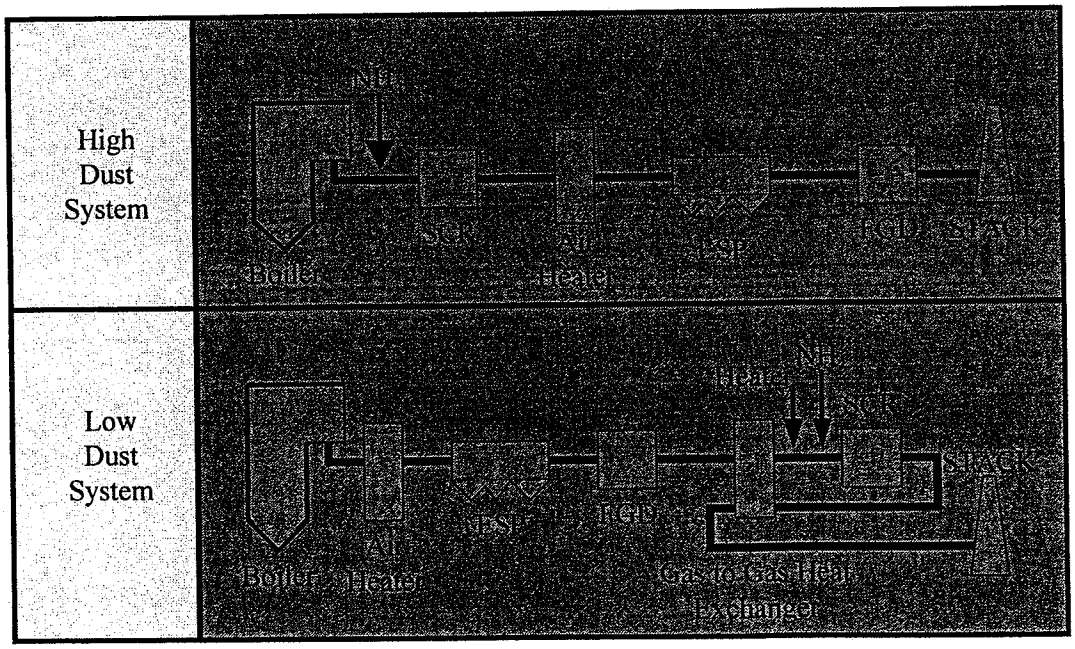

Figure 3
SCR Configurations

System Design Impact & Countermeasures

Figure 3 shows two typical layout of SCR system applied to coal fired boilers. The Low-Dust or Tail End option shows the installation of the SCR reactor after the air preheater (APH), Electrostatic Precipitator (ESP), and flue Gas Desulfurization (FGD) systems. This option requires the flue gas to be reheated to acceptable SCR temperatures, typically 550^{0}F-750^{0}F. Low-Dust designs have primarily been used on wet bottom boilers which have ash re-circulation, due to concern over catalyst degradation caused by arsenic poisoning. The High-Dust option locates the SCR reactor between the economizer exit and the AOH inlet. This is more traditional for dry bottom boilers and less costly, and is now being applied to wet bottom boiler based on economics, advancements in catalyst resistance to arsenic poisoning, and limestone addition to the fuel, which will be discussed later.

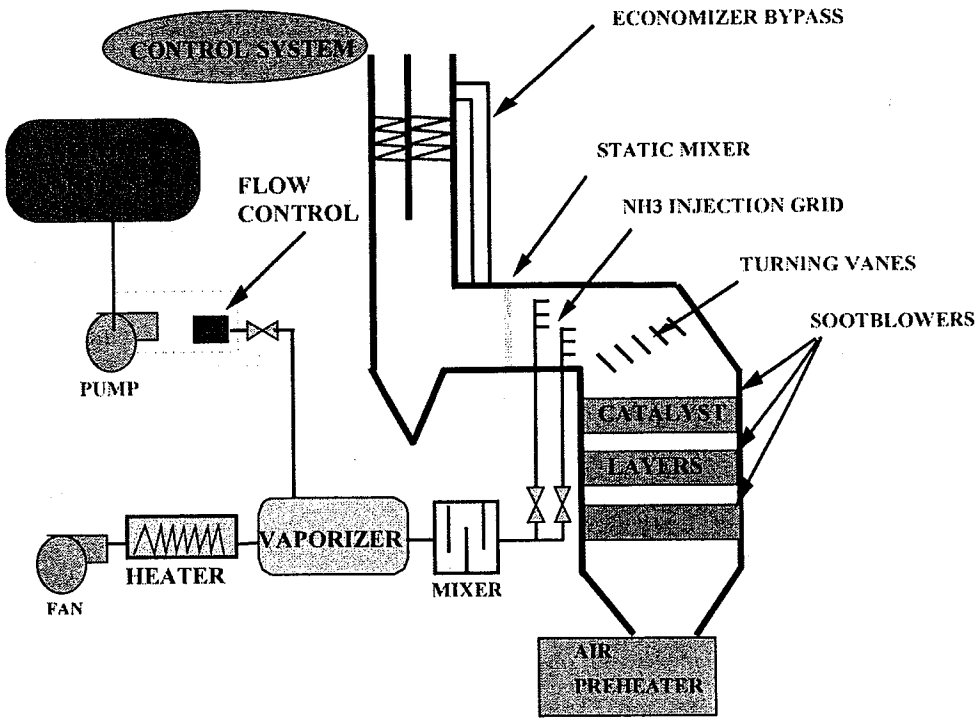

Figure 4
SCR Components

The SCR system consists of many components in addition to the catalyst. *Figure 4* depict a high-dust SCR system which includes the catalyst reactor, economizer bypass used for part-load temperature control, static mixer used for temperature and/or ammonia mixing, turning vanes, ammonia vaporization system, ammonia injection grid (AIG), sootblower, and the control system. Since these components directly influence overall system effectiveness, Cormetech works closely with system equipment suppliers to ensure proper design.

Operational impact of an SCR system on coal fired boilers included drafts loss, SO_3 formation, and ammonia emission, Pressure drop is caused by the installation of the catalyst material in the flue gas and is typically minimized by expanding the flue gas path. Typical pressure value for conventional high dust applications range from 0.5 to 1inch of water per catalyst layer, with 2-3 layers installed with an additional 1-2 inches for the components of the system.

As shown in equation (2) the SCR catalyst will convert a small amount of SO_2 to SO_3. This conversion rate is typically less than 0.55 per layer depending upon the catalyst formulation, deNOx requirements, and operating temperature. If the SO_2 oxidation rate is too high, corrosion and plugging will occur in the (APH) due to the formation of H_2SO_4 and NH_4HSO_4.

As a countermeasure, our catalyst is designed to achieve high deNOx activity while keeping SO_2 oxidation activity low. When considering the catalyst formulation, a high concentration of vanadium will result in a high deNOx activity, but will also result in a high SO_2 oxidation activity. One countermeasure to this is a vanadium concentration is selected such that there is sufficient deNOx activity with an acceptable level of SO_2 oxidation.

As a system countermeasure, the cold end surface of regenerative-type APH may be enameled and/or sootblowing capabilities may be enhanced.

Ammonia slip may contaminate flyash, and combination with $S0_3$ caused (APH) plugging. Designers can combat the effect by considering:

- 2ppm to 5ppm NH_3 slip at end-of-life
- ammonia injection grid with adequate representative NOx input value to control system
- multi-point outlet NOx sampling control grid to assure representative NOx input value to control system.
- permanent measuring grid for AIG tuning to assure proper distribution of ammonia
- Flyash ammonia concentration monitoring.

Catalyst Deterioration Mechanisms & Countermeasures

When designing for a given application, designers must carefully review fuel And ash constituents (*see Table A*). Under ideal conditions the catalyst will reduce NOx for an unlimited period of time. (*Table B*) lists the primary deterioration mechanisms versus the type of coal fired units, wet or dry bottom.

Ash Moisture, %	6-33
Total Sulfur in Coal, %	0.6-1.6*
Trace Material, ppm	
Ni	3-40
Cr	7-46
As	1-25
Cl	41- 1,900
Ash analysis, %	
Sl O2	41-71
As2 O3	2-33
Fe2 O3	2.5-10
CaO	2.4-26
MgO	0.7-49
$Ti0_2$	0.1-1.8
MnO	0.02-0.2
V2 05	0.01-0.1
Na2 O	0.05-1.6
K2O	0.1-4.0
P2 O6	0.06-1.3
SO3	1.6-16.5

***Application Experience on Oil up 5.4% Sulfur**

Table A
Typical Fuel/Ash Composition

Boiler Type	Wet Bottom	Dry Bottom
Sintering	Negligible	Negligible
Accumulation of Alkaline Metal	Small	Small
Accumulation Earth Metal Masking	Large	Large
Accumulation of Arsenic Oxide	Large with Ash Re-circulation	Moderate
Flyash Deposition*	Small	Small
Erosion*	Small	Small

*Highly dependent on proper design of SCR system

Table B
Main Causes of Catalyst Deterioration

Based on a sound understanding of the deterioration mechanisms, specific countermeasures are implemented, such as:

- system design evaluation.
- catalyst formulation.
- catalyst volume selection.
- catalyst geometry.
- catalyst macro and micro pore design.
- catalyst characterization testing and predictive tools.

Thermal Sintering

Thermal sintering is the growth of primary catalyst particle resulting in a reduction of catalyst surface area, which reduces catalyst performance. *Figure 5* illustrate this mechanism. Thermal stability is maximized with the corporation of Tungsten in the catalyst formulation. As a result, sintering is negligible at normal SCR operating temperatures.

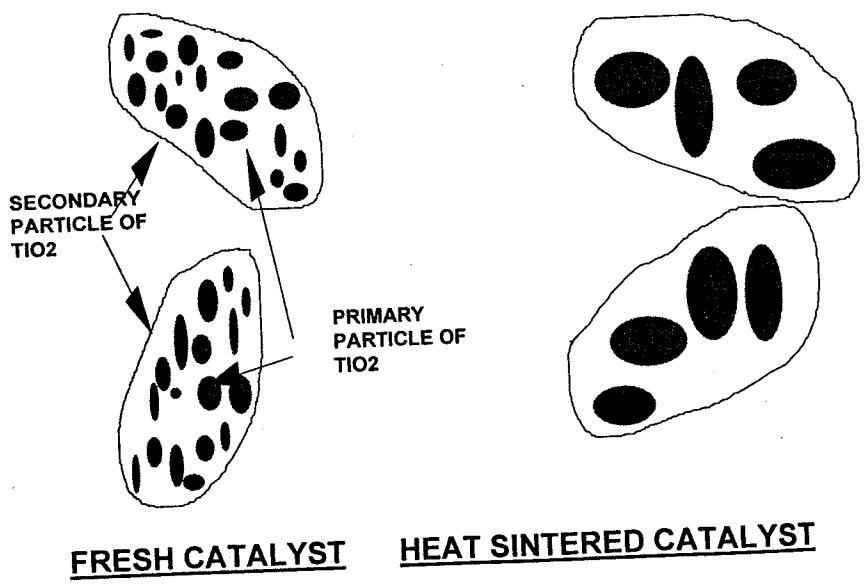

Figure 5
Thermal Sintering

Alkaline Metal (Na, K)

Alkaline metal may directly react with active sites and render them inert as shown in *Figure 6*. Since the deNox reaction takes place primarily on the surface, the degree of deactivation depends on the surface concentration of the alkaline metals. In a water-soluble form, these alkaline metals are highly mobile and will migrate throughout the catalyst material. Since the wall of our catalyst consists entirely of catalyst material, the surface concentration of alkaline metal is diluted by this migration, minimizing the deactivation rate.

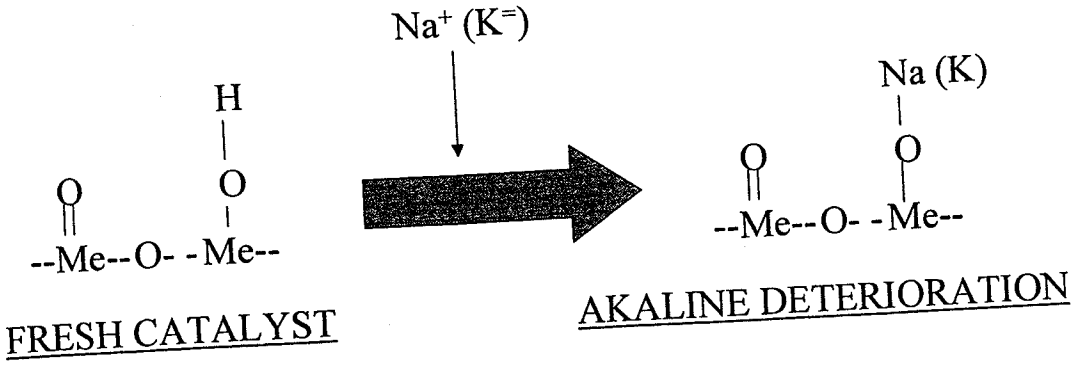

Figure 6
Alkaline Deterioration Mechanism

For the subject catalyst in coal-fired applications, it is our experience that this type of poisoning has a small impact, since most of the alkaline metals in the coal ash are not water soluble. The impact is larger in oil fired applications where the majority of the alkaline metals in the ash are water-soluble or when the thickness of the catalyst material is low. For example, given the same concentration of alkaline metals in the flue gas, this catalyst will have a lower surface poison concentration than a coated product and, thus have a lower deactivation rate and longer useful life as shown in *Figure 7*.

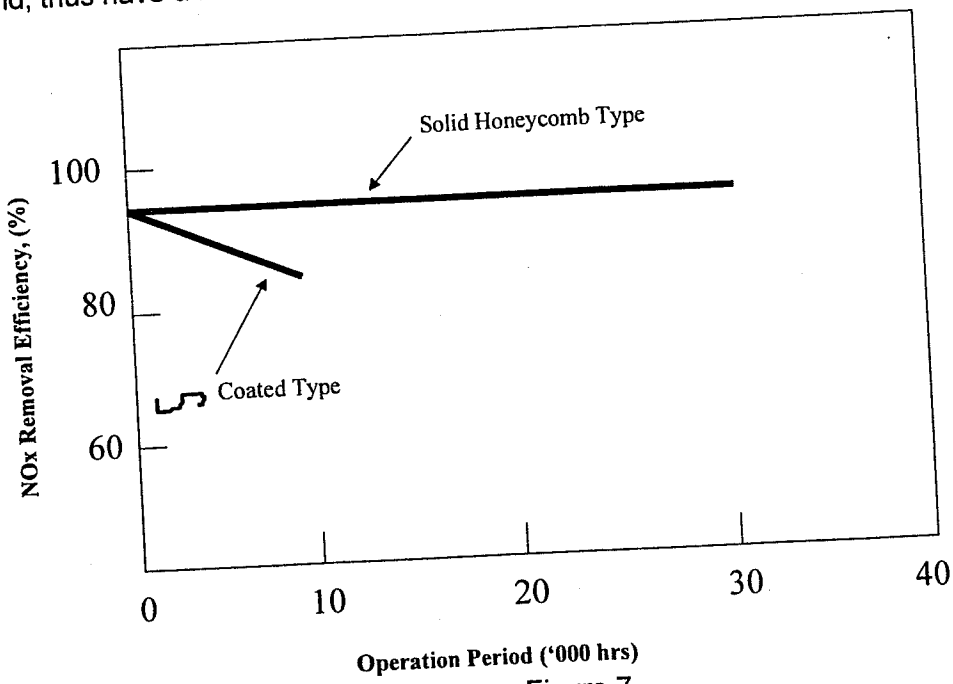

Figure 7
Comparison of Durability (Oil Firing)

Arsenic (As)

Arsenic poisoning is caused by gaseous arsenic As_2O_3 in the flue gas. The As_2O_3 diffuses into the catalyst and solidifies on both active and non-active sites, as shown in *Figure8*.

As with alkaline metals, arsenic poison is best abated by use of homogenous catalyst compositions, which effectively reduce the surface poison concentration. Since the mechanism of arsenic poisoning is more diffusion-limited and subject to capillary condensation, optimized catalyst pore structure also lessens its effects. Further, engineers use accumulation rates determined by both lab and field tests to ensure a proper catalyst volume is provided for each specific application.

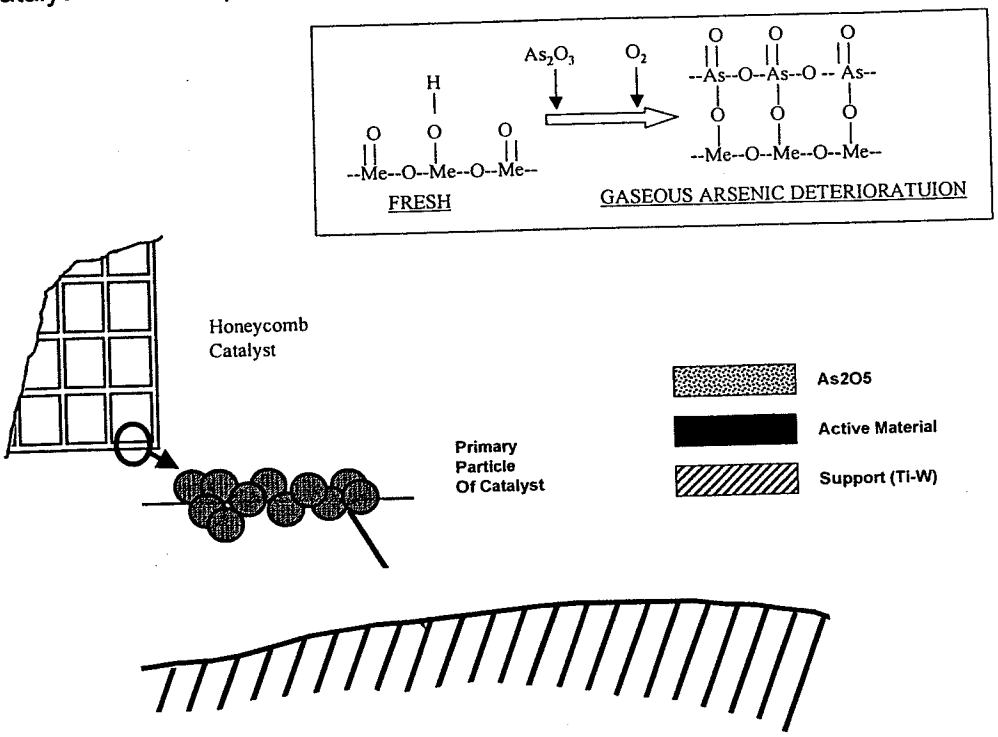

Figure 8
Model of Arsenic Compound Accumulation

A system countermeasure incorporates the use of a fuel additive. As mentioned previously, wet bottom boiler with 100% ash recalculation present a worst case scenario for catalyst deterioration caused by arsenic poisoning. In order to combat the high levels of gaseous arsenic (As_2O_3) in cyclone boilers, limestone may be added to the fuel. A typical limestone to fuel ratio is approximately 1:50. *Figures 9a, 9b, and 10* show how the addition of limestone effectively reduces gaseous arsenic at the entrance to the catalyst. The free CaO in the limestone reacts with arsenic, forming a solid, Ca (AsO_4) which will not poison the catalyst. The impact of adding limestone will be addressed further in the wet bottom boiler case study.

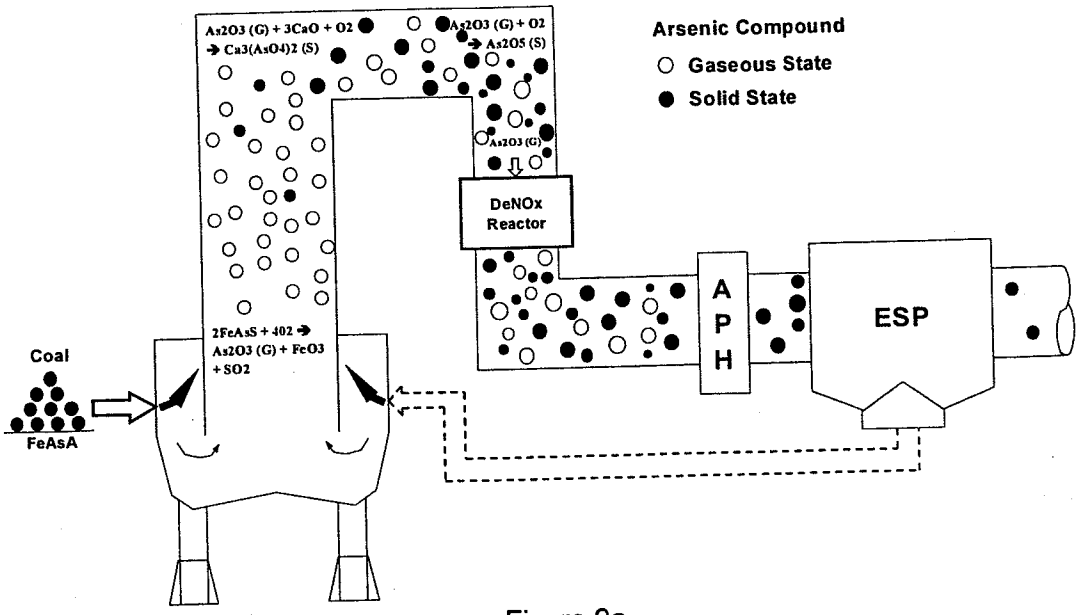

Figure 9a
Arsenic Compound in Flue Gas

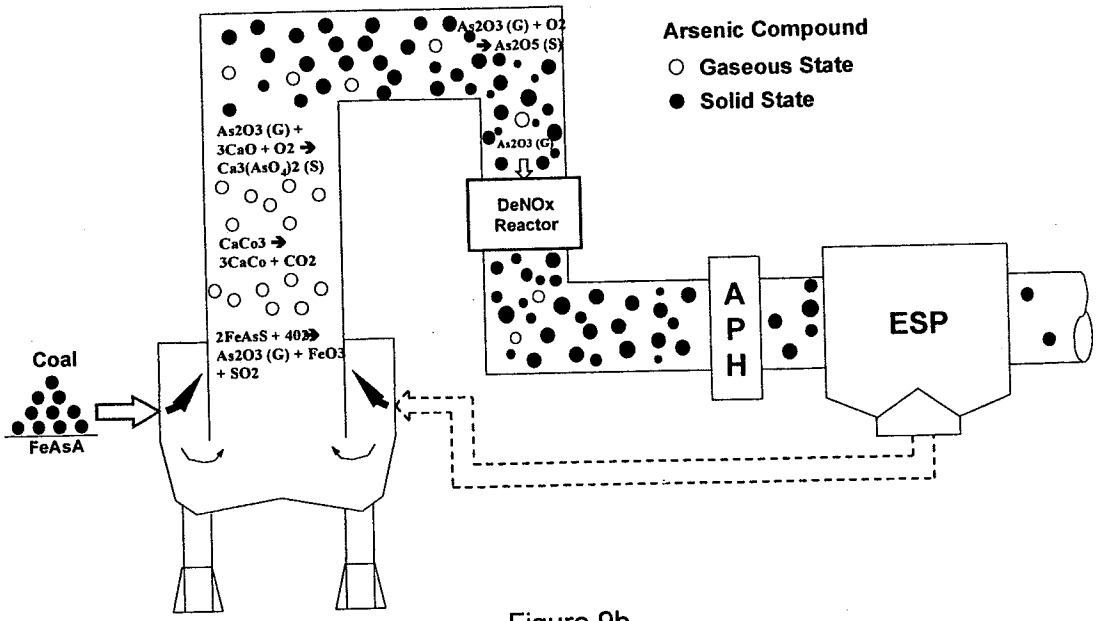

Figure 9b
Effect of Limestone Injection

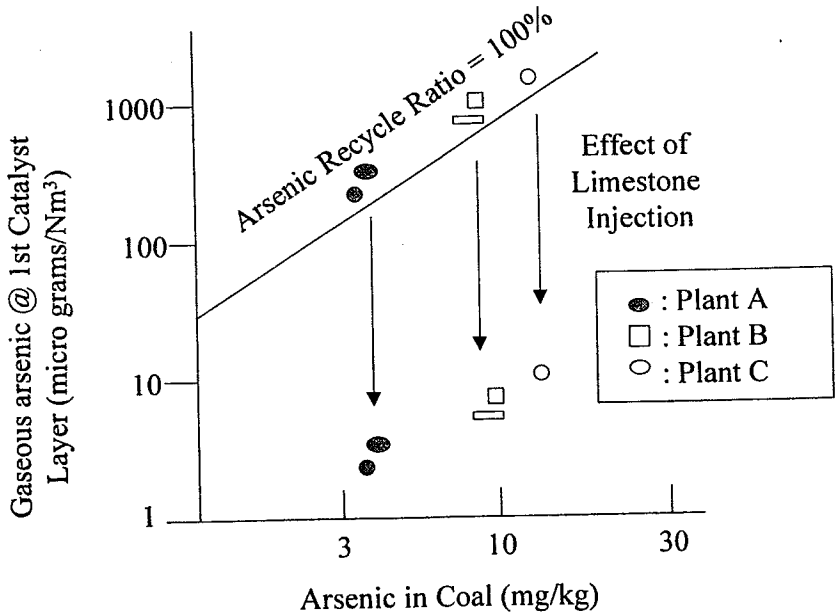

Figure 10
Relationship Between Arsenic in Coal and Gaseous Arsenic

Alkaline Earth Metals (Ca)

Alkaline earth metal poisoning primarily occurs when free CaO in the flyash reacts with SO_3 adsorbed on the catalyst surface forming $CaSO_4$. The $CaSO_4$ may cause catalyst surface masking, preventing the reactants from diffusing in to catalyst surface masking, preventing the reactants from diffusing into catalyst. *Figures 11 and 12* illustrate this mechanism.

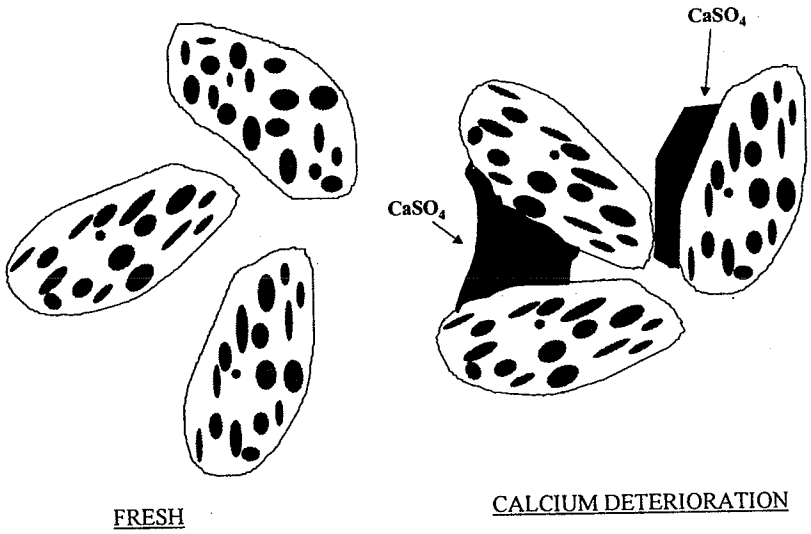

Figure 11
Mechanism of Calcium Deterioration

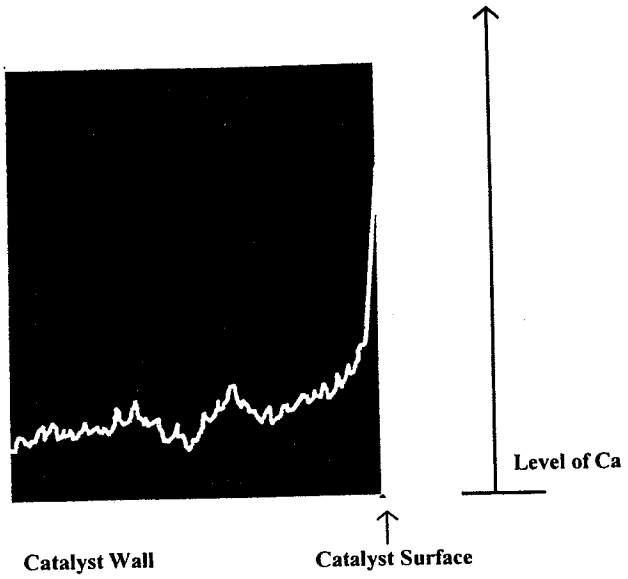

Figure 12
Accumulation of calcium Composition in Catalyst

In order to address masking, particularly in dry bottom boilers where the free CaO content is nearly double that wet bottom boiler (*see Figure 13*), characterization of the mechanism and accurate prediction of deactivation rates is employed. Experience shows that quantity of free CaO in the fly ash governs the amounts of deactivation. Extensive modeling of deactivation from full scale and laboratory data has been development providing high confidence in design to counter this phenomenon.

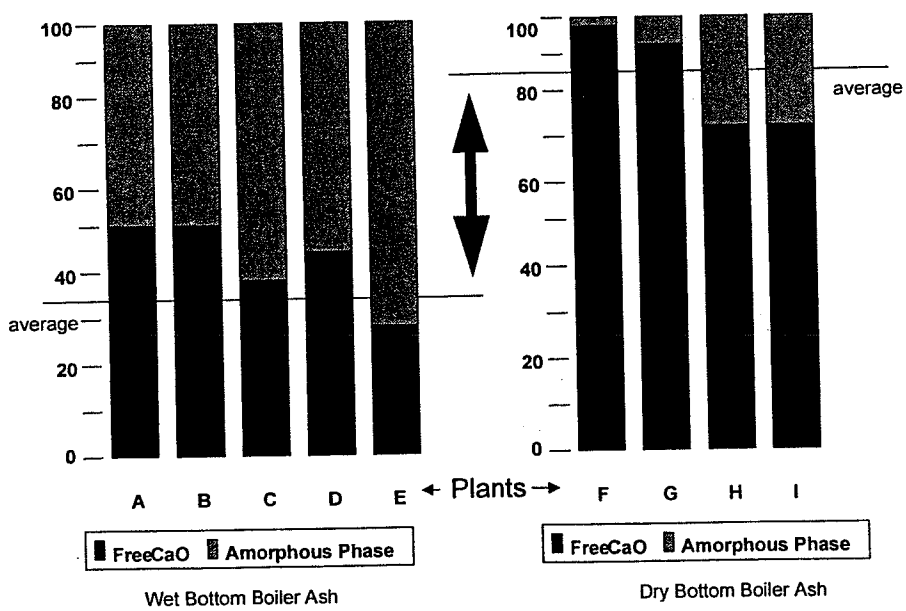

Figure 13
Free CaO Ratio in Fly Ash

Catalyst Plugging

Catalyst plugging has two primary causes: (a) ammonia salt deposition and (b) flight deposition. Proper selection of catalyst pitch and cell opening size minimizes plugging. Good system design is also a primary prevention tool.

Ammonia salt formation/deposition will not occur provided the SCR inlet temperature maintained above the salt formation level. Typically temperature maintenance is only a problem during part load operation and is elevated by installing a water- or gas-side economizer bypass in the system. If a gas bypass is used, careful attention must be paid to provide adequate temperature mixing upstream of AIG. This avoids low temperature streamline, which can cause localized salt formation at the AIG and catalyst.

Flight deposition is minimized through proper flow distribution across the catalyst face. This accomplished through engineering of SCR system flue layout, Computational Fluid Dynamics (CFD) codes, and/or cold flow modeling.

The design limit the number of areas where dust accumulation may occur, i.e.,

- Avoiding flat surface as long leading edge to turning vanes.
- Installing as deflection devices on support beam flanges and sootblower pipes.
- Avoiding flue dead between dampers where ash accumulation may occur in closed position and exhaust onto catalyst when opened, etc.

Erosion

Catalyst erosion is caused by the impingement of flyash on the catalyst face. Catalyst erosion is a function of gas velocity, ash character, angle of impingement, and catalyst properties. Cormetech has experience with flyash loading as high as 30g/Nm^3 and flue gas velocities up to 6.2 m/s.

Experience has proven that no significant erosion will occur with proper system design, catalyst material durability, and catalyst edge hardening. Poor flow and ash distribution at the inlet to the catalyst has been the source of most problems, and has improved significantly over the entire SCR experience history. Careful attention must be paid to utilize flow modeling (CFD and cold flow rectifier grid should be installed to straighten flow into the catalyst bed. Since most catalyst erosion occurs at the catalyst leading edge, which is exposed, to the direct impingement of dust particle the catalyst may also be hardened at the entrance region to provide further protection as shown in *Figure 14*.

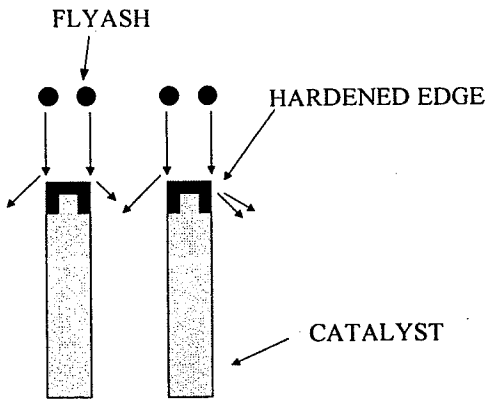

Figure 14
Honeycomb Catalyst with Hardened Edge

Although in most cases In-Duct SCR is not attractive due to extremely high system draft loss and difficulty in control of gas flow and ammonia distribution, some utility site are considering the concept due to site plan limitations. Therefore, we will pilot test our hardened edge catalyst at velocities > 12m/s in 1995.

Catastrophic Failure of SCR Catalyst

Catastrophic Failure is defined as sudden and permanent loss of catalyst performance based on our experience, catastrophic failure are extremely rare. The primary cause is associated with the ignition of ash buildup. The intense heat of a fire can irreversibly damage any SCR catalyst. Cormetech's ceramic honeycomb catalyst, unlike plate catalyst with stainless steel mesh substrates, will not promote oxidation; therefore fires are less likely to spread and are more easily contained.

Coal Catalyst Developments

Based on our understanding of reaction and deactivation mechanisms we are improving our catalyst. The objective is to increase the deNOx reaction rate without increasing the SO_2 oxidation rate. One method is to modify the pore structure of the catalyst wall in order to reduce diffusion resistance. The other is novel method and requires further explanation.

Since the deNOx reaction is only effective at the surface, we have developed an improved catalyst of the same composition as our conventional catalyst with the exception that the vanadium is preferentially distributed to the surface if the catalyst wall. In this manner, we can maximize the concentration of vanadium in the effective fraction of the wall, maximizing deNOx activity without incurring high SO_2 oxidation. *Figure 15* shows the performance of this improved catalyst compared to that of conventional catalyst. Since the product is still made entirely of catalytic material, resistance to poisons in maintained.

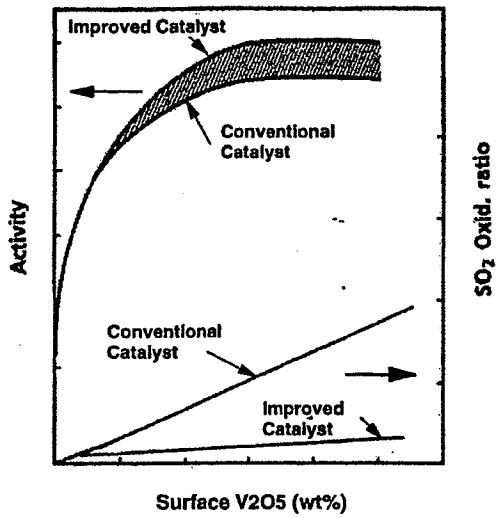

Figure 15
Comparison of Catalyst Performance

Development and Qualification of Improved Coal Catalysts

We are developing the improved coal catalyst described according to the schedule shown in *Figure 16*.

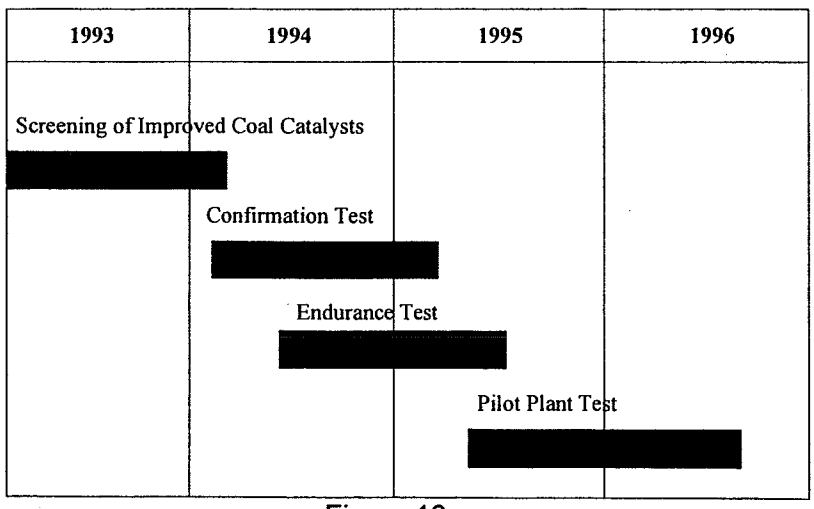

Figure 16
Improved Coal Catalyst R&D Schedule

We have already completed laboratory performance confirmation and durability tests. The performance of the improved catalyst is approximately 15% higher that our conventional catalyst, without impact on SO_2 oxidation.

We have tested durability to gaseous arsenic poisoning by an accelerated method using the apparatus in *Figure 17*. The test results are shown in *Figure 18*. The improved catalyst maintains its performance advantage over conventional catalyst at any arsenic poisoning level.

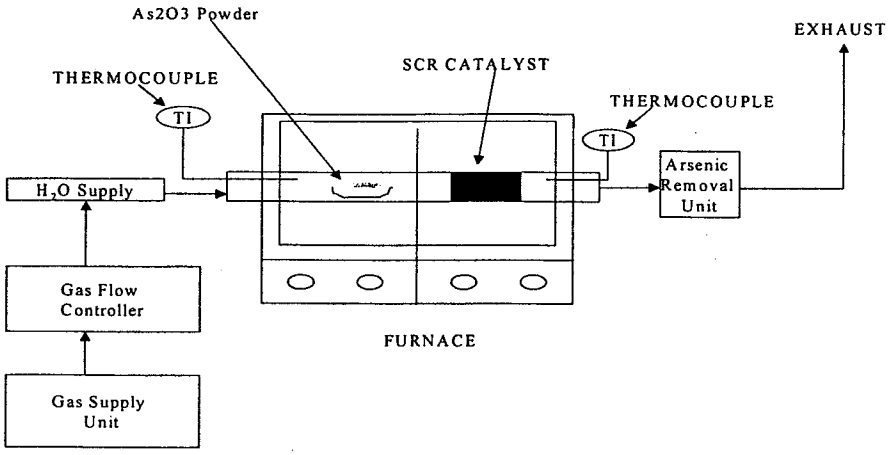

Figure 17
Schematic of Arsenic Testing Apparatus

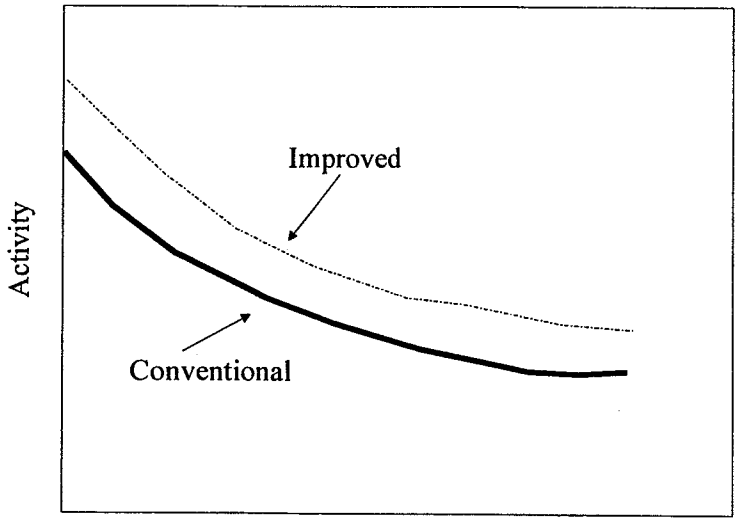

Figure 18
Arsenic Durability

Since the degree of Deactivation due to surface masking by $CaSO_4$ is dependent only on the fraction of surface masked we expected that the rate is deactivation is the same for both conventional and improved catalyst. Therefore, given the same installed catalyst volume, the improved catalyst will maintain field performance much longer due to the higher initial activity, as shown in *Figure 19*.

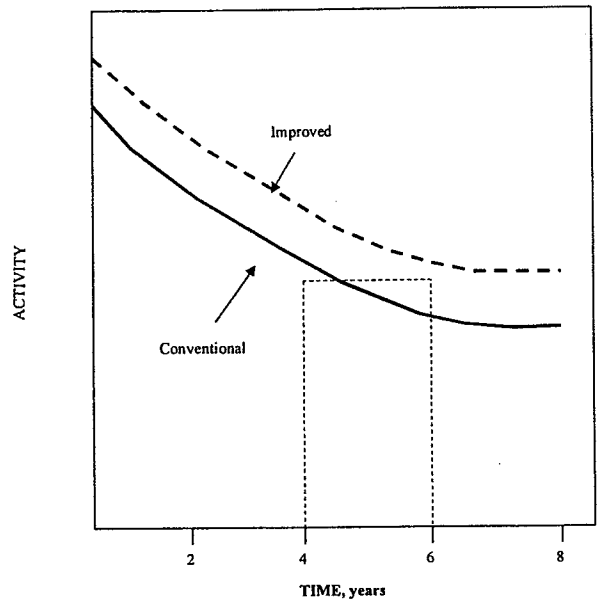

Figure 19
CaO Durability

Before Commercialization, the endurance of the catalyst will be confirmed by operation in actual plant. Initial endurance tests will start by charging catalyst samples into commercial SCR plants in Japan. During 1995 catalyst samples will be charged into a coal unit in the United States and three coal units in Germany. The performance of the catalyst sample after aging in the commercial plants will be compared to fresh performance in order to evaluate endurance.

Impact of Improved Coal Catalyst on SCR Design for Coal Fired

Whether achieving an increase in performance by optimizing the pore structure of the catalyst on the SCR design, two SCR case studies are described below comparing improved with conventional catalyst.

Case Study 1: Dry Bottom Boiler

A 250 MW unit is selected as an example unit. *Table C* shows the design data for this unit. *Figure20* shows the 10-year catalyst volume of the improved catalyst is higher by 15%, the catalyst volume of the improved catalyst is decreased by approximately 15% from the conventional catalyst volume.

Design Condition;	
Fuel	Coal
Plant Output, MW	250
Flue Gas FlowRate,Nm3/hr	784,000
NOx inlet, ppmvd @ 3% O2	154
NOx outlet, ppmvd @ 3% O2	31
NOx Removal Efficiency, %	80
Ammonia Slip, ppmvd @ 3% O2	5
Specification:	
Type of System	SCR
Type of Reactor	Vertical Flow-Fixed Bed
Type catalyst	Honeycomb
Number of reactor	1

Table C
Dry Bottom Boiler

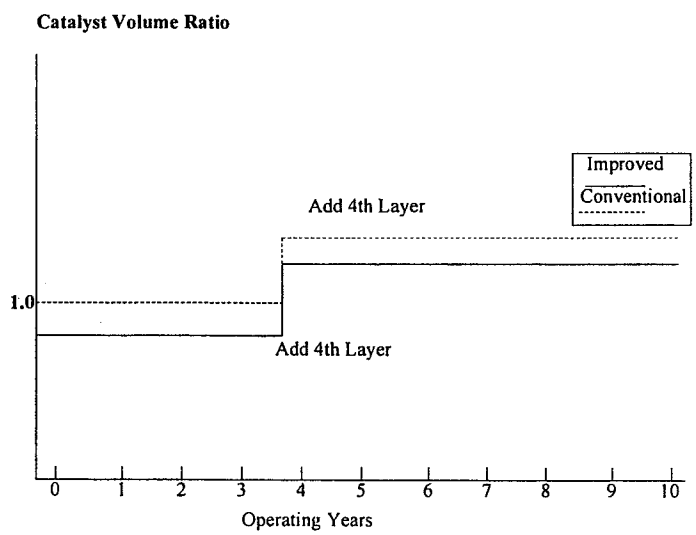

Figure 20
Impact of Improved Catalyst
Dry Bottom Boiler

Case Study 2: Wet Bottom with Ash Recalculation

A 320 MW unit is selected as an example unit. *Table D* shows data for this unit. *Figure 21* shows the 10 years catalyst management plan. The total catalyst volume of the improved catalyst for ten years of operation is two-thirds that of the conventional catalyst. The impact on the catalyst management plan is shown in *Figure22*. With Limestone Injection, the need for addition and replacements of catalyst are significantly delayed.

Design Condition	Coal
Fuel	320
Plant Output, MW	1,125,000
Flue Gas Flow Rate,Nm^3/hr	1,652
NOx Inlet, ppmvd @ 3% O2	530
NOx removal efficiency, %	68
Ammonia Slip, ppmvd @ 3% O2	5
Flash recalculation Rate, %	100
Specification:	
Type of System	SCR
Type of Reactor	vertical flow-fixed bed
Type of Catalyst	honeycomb
Number Of Reactors	1

Table D
Wet Bottom Boiler

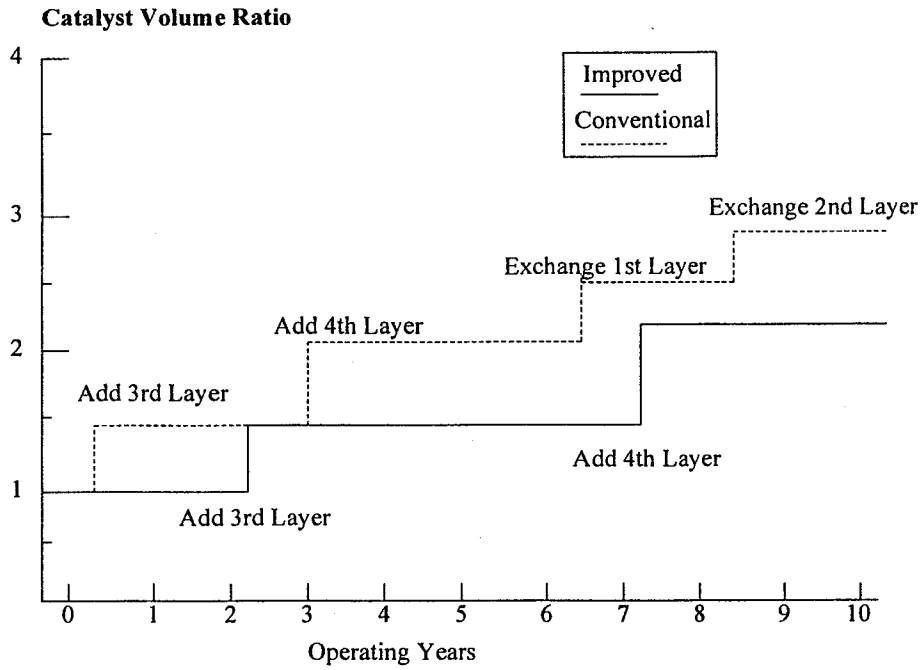

Figure 21
Impact of Improved Catalyst
Wet Bottom Boiler

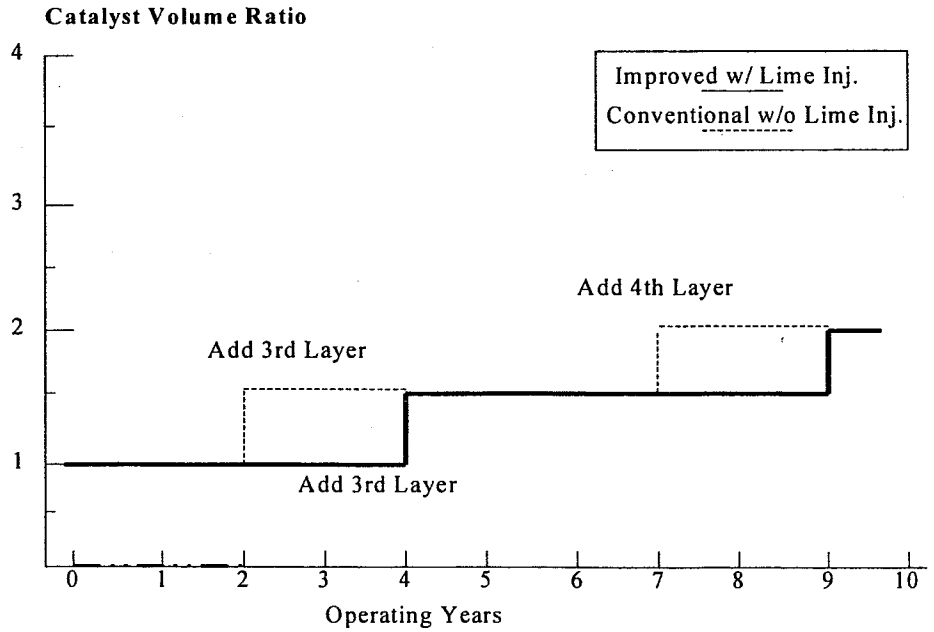

Figure 22
Impact Of Limestone
Wet Bottom Boiler

Conclusions

Our experience shows that coal-fired SCRs are successful when proper attention is paid to system and catalyst design.

Proper system design is crucial to Maximizing Catalyst performance potential and achieving lowest annualized cost.

By exploiting the experience and know-how gained on existing facilities it is possible to further optimize catalyst design.

NOx BEST AVAILABLE CONTROL TECHNOLOGY ANALYSIS STUDY

for

Milton R. Young Station Unit 1
Minnkota Power Cooperative, Inc.

Revised Final Report

October 2006

31777

Minnkota Power
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NOx Best Available Control Technology Analysis Study for Milton R. Young Station Unit 1

prepared for

Minnkota Power Cooperative, Inc.

October 2006

Project No. 31777

Revised Final Report

prepared by

Burns & McDonnell Engineering Company, Inc.
Kansas City, Missouri

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* * * * *

EXECUTIVE SUMMARY

The Milton R. Young Station of Minnkota Power Cooperative, Inc. (Minnkota) and Square Butte Electric Cooperative (Square Butte) includes two cyclone-furnace, lignite-fired steam-electric generating units (SEGUs). The units both fire North Dakota lignite supplied from the adjacent mine, near Center, North Dakota. Unit 1 has a nominal 235 MW net design output capacity rating, is typically capable of sustained output of approximately 250 MW_g (gross), and has a gross design output capacity rating of 257 MW_g. Unit 1 is owned and operated entirely by Minnkota. Unit 2 has a nominal 439 MW net design output capacity rating, is capable of sustained output of approximately 460 MW_g (gross), and has a gross design output capacity rating of 477 MW_g. Unit 2 is owned by Square Butte Electric Cooperative (Square Butte), and operated by Minnkota.

A Notice of Violation (NOV) from the United States Environmental Protection Agency (US EPA or EPA) was issued to Minnkota Power Cooperative on June 21, 2002. The NOV alleged that modifications had been made at the Milton R. Young Station that would have required a construction permit under New Source Review (Code of Federal Regulations 40 CFR 52.21, and North Dakota Administrative Code NDAC 33-15). As a result of this allegation, a civil complaint was filed by the United States of America and the State of North Dakota against Minnkota Power Cooperative Inc. ("Minnkota") and Square Butte Electric Cooperative ("Square Butte") in the United States District Court for the District of North Dakota. A Consent Decree (CD) has been approved that represents a final negotiated settlement of the United States' and North Dakota's claims against Minnkota and Square Butte. The Consent Decree requires Minnkota and Square Butte to perform a "NO_X Top-Down Best Available Control Technology (BACT) Analysis" to describe the emission limits for NO_X that will be required at Units 1 and 2, expressed as a 30-Day Rolling Average NO_X Emission Rate [Consent Decree paragraph 24, page 7, and paragraph 5, page 4].

Burns & McDonnell was retained to conduct a Top-Down BACT Analysis for nitrogen oxides (NO_X) at the Milton R. Young Station. The results of the BACT analysis are presented in this study report.

The procedures mandated by the Consent Decree for performing a Top-Down BACT Analysis are outlined in Chapter B of the U.S. EPA's New Source Review Workshop Manual: Prevention of Significant Deterioration and Nonattainment Area Permitting, Draft, October 1990 ("EPA's NSR Manual"). The MRY Station BACT analysis was performed in accordance with this procedure. The

EPA's NSR Manual outlines five basic steps that are to be followed in this BACT analysis. These basic steps for such a BACT analysis are summarized as follows:

Step 1 – Identify All Control Technologies
Step 2 – Eliminate Technically Infeasible Options
Step 3 – Rank Remaining Control Technologies by Control Effectiveness
Step 4 – Evaluate Most Effective Controls and Document Results
Step 5 – Select BACT

A Best Available Control Technology (BACT) analysis was performed for Milton R. Young Unit 2 for NO_X using the EPA's "top-down" approach. Best Available Control Technology is defined as "an emissions limitation (including a visible emission standard) based on the maximum degree of reduction for each pollutant subject to regulation under Act which would be emitted from any proposed major stationary source or major modification which the Administrator, on a case-by-case basis, taking into account energy, environmental, and economic impacts and other costs, determines is achievable for such source or modification through application of production processes or available methods, systems, and techniques, including fuel cleaning or treatment or innovative fuel combustion techniques for control of such pollutant" (40 CFR 52.21, NSR Manual B.1).

Unit 1 at Milton R. Young Station is a cyclone-fired boiler that burns North Dakota lignite. The method of firing is very significant in analyzing control options for NO_X emissions. A cyclone boiler produces inherently higher uncontrolled NO_X levels than pulverized-coal and circulating fluidized bed boilers. There have been no new coal-burning cyclone-fired boilers built and installed in the United States since the early 1980's. Consequently, there are no examples of BACT control options listed in the RACT/BACT/LAER Clearinghouse database for consideration and direct application of published NO_X emission permit limits on the Milton R. Young cyclone-fired boilers.

Step 1 – Identify All Control Technologies

The Consent Decree requires that the NO_X Top-Down BACT Analysis for the Milton R. Young Station "include an evaluation of Selective Catalytic Reduction (SCR), Selective Non-Catalytic Reduction (SNCR), Overfire Air (OFA), Rich Reagent Injection (RRI), as well as other NO_X control technologies" potentially applicable for lignite-fired cyclone boilers [Consent Decree paragraph 65, page 19]. Other identified control techniques, such as fuel switching and fuel cleaning, and combustion-related emission control technologies, such as fuel reburn and oxygen-enhanced combustion, were also considered.

Step 2 – Eliminate Technically Infeasible Options

The BACT evaluation determined that not all the technologies identified were considered available and applicable. The technically infeasible alternatives were eliminated from further evaluation, along with feasible technologies with economic impacts that were unreasonable compared to other cost-efficient alternatives to control NO_X emissions for MRY Station Unit 1.

The technical feasibility of applying NO_X emission reduction techniques and technologies at Milton R. Young Station is dominated by the composition and combustion characteristics of the North Dakota lignite supplied solely from a surface mine adjacent to the plant. This mine is the only supplier of solid fuel for this station, as there are no railroad facilities provided to service the Milton R. Young plant. North Dakota lignite has high moisture and high sodium content, moderate higher heating values, and can have a widely variable and high ash content compared to other coals. These characteristics create difficulties in promoting consistent, steady combustion and slag formation in the cyclone burners. It also results in producing a flyash that has severe deposition characteristics.

Both boilers include a unique coal conditioning system (drying, crushing, and feeding) for each cyclone furnace specifically designed to aid in proper combustion of the lignite fuel. This method of firing solid fuel significantly influences the resulting nitrogen oxide concentration of the flue gases emitted from the boilers.

Ash deposition in each boiler and air preheater is a significant operational challenge for the facility. Significant equipment and manpower resources are devoted to on-going removal of fireside ash accumulations. Unit outages must be conducted at regular intervals to clean each boiler (approximately every 80-120 days). There are a number of issues that make selective catalytic reduction (SCR) technically infeasible for NO_X emission control for Milton R. Young Unit 1. The consistent long-term operation of SCR technology on lignite-fired cyclone boilers will be drastically inhibited by the susceptibility of the SCR catalyst to severe fouling, deactivation, and erosion resulting from the actions of the emitted flue gases and flyash, and ash deposit removal operations. SCR technology is considered technically infeasible for application on the cyclone boilers at the Milton R. Young Station.

Rich Reagent Injection has been demonstrated on boilers burning bituminous and subbituminous coal. However, it has not been commercially installed and placed in continuous operation on a cyclone-fired boiler burning lignite coal with high fouling and slag temperature sensitivities associated and a highly

variable heat content. RRI adds urea reagent to the hot furnace gases near the cyclones, which must be devoid of free oxygen in order to avoid oxidation of the urea, and thus creating NO_X. While RRI is specifically intended for NO_X emissions control on cyclone boilers, RRI is considered technically infeasible for application on the lignite fired cyclone boilers at the Milton R. Young Station due to the variable heat content of the lignite fuel which allows the creation of oxygen-rich conditions in the boiler.

The application of separated overfire air (SOFA) for NOx emissions control on Milton R. Young Unit 1's boiler was evaluated as part of the BACT analysis. A version of separated overfire air specifically designed for increased NO_X emission reduction performance for lignite-fired cyclone boilers, referred to as "Advanced SOFA" in this analysis, can be installed on both units at M.R. Young Station. This highest-performing form of SOFA can be applied alone and in combination with other technologies. Key aspects of successfully applying and operating a separated overfire air system on a cyclone-fired boiler are the ability to:

- Accurately measure the fuel heat input rate (BTUs) and combustion air inputs on a real-time, individual cyclone by cyclone basis, to allow the ability to determine and control the desired air/fuel ratio, especially when "starved air" (i.e. substoichiometric) combustion conditions are required.
- Maintain adequate molten coal ash (slag) formation and flow within the barrels and slag taps.

The degree to which the individual cyclone furnaces can be operated with less-than-theoretical (substoichiometric) combustion air, which corresponds to operation of a SOFA system, directly contributes to less combustion-related NO_X formation and further in-furnace emission reduction but also risks solidification of the molten coal ash. This places great emphasis on achieving tight control over the air/fuel ratios on each cyclone during air-staged combustion operation with SOFA in order for air-staged combustion to be successful in producing significant additional NOx emissions reduction on lignite-fired cyclone boilers.

In the case of MRY Station Unit 1's boiler, air-staged combustion must be sufficient to reduce NO_X emissions while releasing enough heat to continue to melt the fuel ash so that it flows effectively within and from the cyclone burners. Due to the short-term variability of the combustible and ash components of North Dakota lignite supplied from the current mine near Center, ND, and the complex behavior of lignite ash when exposed to high temperatures, the extent of air-staging and thus the level of NO_X control while operating the highest-performing version of SOFA system is expected to be modest.

Selective Non-Catalytic Reduction (SNCR) technology has been used to reduce NO_X emissions ı numerous utility boilers burning eastern bituminous coal, midwestern bituminous coal, and, to a lı extent, western subbituminous coal. SNCR has also been used on fuel oil and natural gas-fired uni SNCR does not appear to be dependent directly on the type of burners (wall-fired, tangentially-fired, cyclone-fired) employed in the boilers where it has been installed, with or without air-staged combust with overfire air in full operation.

There are significant concerns associated with effective long-term SOFA operation for Milton R. Young Station Unit1's boiler. The ability of basic combustion equipment and improvements to precisely measure the boiler's heat input rate in real-time on an individual cyclone by cyclone basis with compensation for the short-term variability of the combustible content of the Center lignite to consistently maintain substoichiometric operation of every cyclone during air-staged combustion is unproven.

Several other techniques and technologies were considered technically feasible for NOx emissions control at MRY Station: Fuel Blending/Switching; Basic Combustion Control Improvements; and various forms of Fuel Reburn. Fuel switching/blending was not evaluated further because of expected unreasonably high capital and operating costs and no additional emission reduction compared to continued lignite firing.

Other NOx emissions control techniques and technologies for MRY Station that were evaluated and determined to be technically infeasible were: Fuel Cleaning; Low NOx Burners (LNB); Flue Gas Recirculation; Oxygen-enhanced Combustion (OEC); Water/steam injection (combustion tempering); and Electro-Catalytic Oxidation (ECO®).

Step 3 – Rank Remaining Control Technologies by Control Effectiveness

The third step in the "top-down" BACT evaluation ranked the remaining control technologies by effectiveness. The purpose of ranking the control technologies was to establish a hierarchy that places at the "top" the control technology that achieves the lowest emission level. The technologies in order of their effectiveness, from highest to lowest, are: SNCR with ASOFA; Gas Reburn with ASOFA; Lignite Reburn with ASOFA; Fuel Lean Gas Reburn with ASOFA; and Advanced Separated Overfire Air (ASOFA). None of these control options has been installed on a cyclone-fired boiler burning North Dakota lignite. As such, the expressed control percentages reflect the use of engineering judgment, based on the listed technique or technology application.

Step 4 – Evaluate Most Effective Controls and Document Results

Additional criteria besides technical feasibility were utilized for technology selection in this BACT analysis. These included estimates of control effectiveness (i.e. percent pollutant removed), capital plus operating and maintenance costs, annual emission reduction (tons per year), energy impacts, average and incremental cost effectiveness ($/ton), and environmental impacts (other media and emissions of toxic and hazardous air pollutants).

The economic analysis examined the capital cost of each feasible BACT alternative evaluated and any other powerplant upgrade costs necessary to implement the alternative. In addition, the economic analysis examined the operating and maintenance cost associated with the highest-performing forms of each feasible BACT alternative evaluated. These costs were then combined into a levelized total annual cost for a comparative assessment of the total implementation cost of each alternative. Finally, as part of the top-down analysis, a dominant controls cost curve was plotted and the unit control cost for each alternative was evaluated.

Two alternatives were on the dominant controls cost curve and thus were identified as the more cost effective alternatives. The two BACT NO_X control alternatives evaluated for incremental cost, energy, and environmental impacts applicable to Milton R. Young Station Unit 1 were:

- Selective Non-Catalytic Reduction (SNCR) combined with a special form of separated overfire air (SOFA) specifically for lignite-fired cyclone boilers (referred to as Advanced SOFA or ASOFA); and
- ASOFA alone.

The two most cost-effective feasible control alternatives for reduction of NO_X emissions were reviewed to determine if the use of the technique or technology would result in any significant or unusual energy penalties or benefits. Potential increase in power plant energy consumption or net generation reductions, for ASOFA alone, or ASOFA with SNCR were relatively small.

The predicted environmental impacts from implementation of the two most cost-effective feasible NO_X emissions control alternatives from slightly higher unburned carbon in the emitted fly ash, carbon monoxide, and excess ammonia ("slip") emissions was expected to be small in comparison with the

significant anticipated reduction in far-field ozone and improvement in atmospheric visibility as a result of the overall NO_X emission reduction.

Step 5 – Select BACT

Taking into account technical feasibility, energy, environmental, and economic impacts and other costs, the recommended Best Available Control Technologies and associated emission rates for nitrogen oxides emissions produced by Milton R. Young Station Unit 1 boiler are provided in the table below.

NO_X Emission Control Technology and Rate Recommended as BACT

Control Technology and Emission Rate Recommended as BACT			
Unit	**Pollutant**	**Control Method**	**12-Month Rolling Average NOx Emission Rate (lb/ million Btu)**
1	NO_X	Selective Non-Catalytic Reduction with Advanced Separated Overfire Air (ASOFA)	0.355

This recommended BACT 12-month NO_X emission rate is based upon a historic pre-control 12-month baseline average annual NO_X emission rate used in the control and cost-effectiveness analysis of 0.849 lb/mmBtu for Unit 1. The baseline emission was determined from the 12 consecutive month period with the highest historic summation of NO_X mass emissions (pounds) reported for actual operation between January 1,2001 and December 31, 2005.

To complete the BACT determination process, the Consent Decree (CD) requires that "specific control technologies to be installed and a specific Phase II 30-day Rolling Average NO_X Emission Rate limitation (lbs/MMBtu)" must be established for each subject emission Unit [CD Paragraph 66, pg 20]. Because there are expected to be minor short term variations in operating conditions where Minnkota has not, in fact, materially changed any of their normal daily operating practices, a margin between the 12-month average operating conditions and the 30-day permit limit is proposed. This recommended emission rate should be suitably higher such that operation consistent with the technological limitations, manufacturer's specifications, and good engineering and maintenance practices to the extent practicable for the recommended NOx BACT alternative would not result in an exceedance (violation) of an enforceable emission permit limit.

The Consent Decree also requires that the North Dakota Department of Health's (NDDH) NO_X BACT Determination address specific emission limitations during Unit startups at Milton R. Young Station [CD Paragraph 66, pg 20]. The type and duration of firing during startups, and the limited ability of available and feasible technologies to control startup NO_X emissions, both significantly influence the 30-day rolling average BACT NO_X emission rate limit recommended for Milton R. Young Station boilers. A 24-hour rolling average NO_X emission rate limit applied to startup periods is also recommended for Milton R. Young Station boilers.

The SEGU startup operating period is usually not defined in emission permits. However, for the purpose of this NO_X BACT analysis, Unit startup was defined as the period from initial fuel combustion to the point in time when:

- the measured Heat Input to the boiler on a 6-hour rolling average basis is greater than or equal to 2500 million BTU/hr for Unit 1; or
- the amount of time reported for the longest individual Unit 1 startup period during actual operation between January 1, 2001 and December 31, 2005 elapses, whichever occurs first; or
- fuel firing is discontinued prior to satisfying either previous criteria.

For MRYS Unit 1, the recommended 30-day rolling average NO_X emission permit limit rate that includes the impact of startups is based upon recognized operational factors and equipment designs that influence whether the startup emissions result in higher 30-day emissions compared to normal continuous operation excluding such startup periods:

- The uncontrolled emission rate (i.e. without separated OFA or SNCR in operation) and its variability during operation from a cold startup up to and including maximum continuous rated output;
- The operating conditions that are required to exist for the selected NO_X BACT control techniques to be initiated and be effective; and
- The effectiveness of these two particular control techniques if invoked at less-than-MCR steady-state operating conditions.
- The number of startups and their range of typical durations per 30-day period time frame.

The Consent Decree and the EPA's NSR Manual do not describe the method for determining a 30-day Rolling Average NO_X Emission Rate permit limitation (CD Phase II) that reflects BACT applied to Milton R. Young Station Unit 1. The approach taken in this analysis was to establish a historic pre-control 30-day baseline average NO_X emission rate (lb/mmBtu) from the 30-consecutive day period with

the highest historic unit NO_X mass emissions (pounds) reported for actual operation between January 1,2001 and December 31, 2005. This reflects unit NO_X emissions that were generated during periods of high unit operations, not affected by unit shutdowns, startups, or malfunctions. This was then compared to the 12-month historic pre-control baseline average NO_X emission rate (lb/mmBtu) from the 12-consecutive month period with the highest historic unit NO_X mass emissions (pounds) reported for actual operation during the same 5-year look-back period. An estimate of NO_X emission reduction for the proposed BACT NO_X alternative operating at the historic pre-control 30-day baseline average NO_X emission rate (lb/mmBtu) was made. This rate considered recognized operational factors and equipment designs applied to "steady state" conditions with sustained output close to maximum continuous capacity ratings. The potential impact of startups, recognizing operational and technical limitations on NO_X emission control performance, was then applied to the steady-state rate, to establish a recommended 30-day Rolling Average NO_X Emission Rate permit limitation (CD Phase II) that reflects BACT for Milton R. Young Station Unit 1. This is summarized below.

Recommended NO_X BACT Control Method and 30-Day Rolling Average NO_X Emission Rate Limit Without Startups

Unit	Pollutant	Control Method	30-day Rolling Average NOx Emission Rate Limit Excluding Startups (lb/million Btu)
1	NO_X	Selective Non-Catalytic Reduction with Advanced Separated Overfire Air (ASOFA)	0.360

This recommended BACT 30-day NO_X emission rate limit is based upon a historic pre-control 30-day baseline average NO_X emission rate of 0.884 lb/mmBtu for Unit 1. The baseline emission was determined from the 30-consecutive day period with the highest historic unit NO_X emissions rate reported for actual operation between January 1,2001 and December 31, 2005.

An incremental adjustment to the proposed 30-day rolling average steady-state unit NO_X BACT emission rate without startups of 0.36 lb/mmBtu for Unit 1 is recommended for the 30-day rolling average NO_X emission permit limit periods as defined and applied to Milton R. Young Station. This is summarized in the table below.

Recommended BACT 30-Day Rolling Average NO_X Emission Rate Limit and Startup Impact

Unit	30-day Rolling Average NOx Emission Rate Limit Excluding Startups (lb/million Btu)	Impact on 30-day Rolling Average NOx Emission Rate Limit Due to Startups (lb/million Btu)
1	0.360	+0.041 per startup

This recommended adjustment to the proposed 30-day rolling average steady-state NO_X BACT emission rate limit without startups is based upon average historic pre-control NO_X emission rates of 0.766 lb/mmBtu for Unit 1 reported for the longest individual Unit 1 startup period during actual operation between January 1, 2001 and December 31, 2005. These emissions occurred during the 61-hour June 27-29, 2005 startup for Unit 1.

A 24-hour rolling average BACT NO_X emission rate limit applied to startup periods is also recommended for each of the Milton R. Young Station boilers.

This is summarized in the table below.

Recommended 24-Hour Rolling Average NO_X Emission Rate Limit During Startups

Unit	24-hour Rolling Average NOx Emission Rate Limit During Startups (lb/million Btu)
1	0.980

These emissions occurred during the 61-hour June 27-29, 2005 startup for Unit 1.

Compliance with these emission rate would be measured at the stack of the Unit, verified with Continuous Emission Monitoring (CEM) systems in accordance with the reference methods specified in 40 C.F.R. Part 75, and would be determined on a 30 consecutive Operating Day and 24-consecutive hour rolling average basis, respectively.

A trial demonstration period of 18 months after the completion of Consent Decree Phase II NO_X emission reduction system installation commissioning at Milton R. Young Station is recommended. It is proposed to allow Minnkota to demonstrate the actual control system capabilities of the combined NO_X BACT emissions reduction system. Operating experience during the trial period will:

- confirm steady-state control performance of the combined NO_X BACT emissions reduction system;
- allow determination of the ability to further control Unit start-up emissions;
- allow the determination of the permitted 30-day rolling average NO_X emission limit including startups, shutdowns, and malfunctions; and
- address the specific emission limitations during Unit startups at Milton R. Young Station and their impact on the proposed 30-day rolling average emission rate limit (without startups).

Based upon the information obtained during the trial period, final emission limits can then be determined.

The means that will be employed to minimize emissions during startup will primarily be based on operating procedures, both before and after the level of upper furnace gas temperatures and/or heat input rate are considered sufficient to start the NO_X controls and operating conditions are conducive for effective emissions reduction. These could be similar to Minnkota's current MRYS practices, or could be different, depending upon the capabilities of the NO_X controls and their impacts on Unit operations.

* * * * *

1.0 INTRODUCTION

The Milton R. Young Station of Minnkota Power Cooperative, Inc. (Minnkota) and Square Butte Electric Cooperative (Square Butte) includes two cyclone-furnace, lignite-fired boilers producing steam for electric generation. Both units fire North Dakota lignite supplied from an adjacent mine, near Center, North Dakota.

A Notice of Violation (NOV) from the United States Environmental Protection Agency (US EPA or EPA) was issued to Minnkota on June 21, 2002. The NOV alleged that modifications have been made at the Milton R. Young Station that would require a construction permit under New Source Review (Code of Federal Regulations 40CFR52.21, and North Dakota Administrative Code NDAC 33-15). As a result of this allegation, a civil complaint was filed by the United States of America and the State of North Dakota against Minnkota Power Cooperative Inc. ("Minnkota") and Square Butte Electric Cooperative ("Square Butte") in the United States District Court for the District of North Dakota. A Consent Decree[1] has been entered that represents a final negotiated settlement of the United States and North Dakota's claims against Minnkota and Square Butte. The Consent Decree requires Minnkota and Square Butte to perform a NO_X "Top-Down" Best Available Control Technology (BACT) Analysis to describe the emission limits for NO_X that will be required at Units 1 and 2, expressed as a 30-Day Rolling Average Emission Rate (lbs/million Btu)[2].

Burns & McDonnell was retained by Minnkota to conduct a "Top-Down" Best Available Control Technology (BACT) Analysis for nitrogen oxides (NO_X) at the Milton R. Young Station. Burns & McDonnell is a full service engineering, architectural, construction and environmental firm. The company plans, designs and constructs electric generating facilities and has been providing environmental services since the 1970s. As part of those services, Burns & McDonnell has extensive experience in permitting, Best Available Control Technology (BACT) studies and control technology analysis. The results of the BACT analysis are presented in this report.

[1] In the United States District Court For The District Of North Dakota, United States Of America and State Of North Dakota, Plaintiffs, v. Minnkota Power Cooperative, Inc. and Square Butte Electric Cooperative, Defendants, Civil Action No. 1:06-CV-034

[2] Ibid – footnote number 1, CD paragraph 65, page 19.

The primary guidance utilized in preparation of this BACT analysis is the U.S. EPA's New Source Review Workshop Manual: Prevention of Significant Deterioration and Nonattainment Area Permitting, Draft, October 1990[3] ("NSR Manual").

In the next section of the report, the approach to the BACT Analysis is described. Following that, a quick summary of the plant conditions and report basis is given and then the BACT Analysis begins. The impact portion of the report is broken down into separate subsections. Within the last section, the results of all of the BACT Analysis steps are summarized for NO_X control options for Unit 1's boiler at the Milton R. Young Station.

* * * * *

[3] Chapter B of the U.S. EPA's New Source Review Workshop Manual: Prevention of Significant Deterioration and Nonattainment Area Permitting, Draft, October 1990.

2.0 "TOP-DOWN" NO_X BACT ANALYSIS APPROACH

Best Available Control Technology (BACT) is an emissions limitation for each pollutant from a source determined to be achievable using control technologies(s) that provide the "maximum degree of emission reduction...taking into account energy, environmental, and economic impacts"[4]. A BACT review does not result in an emissions removal efficiency requirement. The generally accepted procedures for performing a BACT analysis are outlined in the EPA's draft NSR Manual. The BACT analysis for Milton R. Young Station Unit 1's boiler NO_X emissions was performed in accordance with this procedure. The EPA's draft NSR Manual outlines five basic steps that are to be followed in the "top-down" BACT evaluation. These steps are as follows:

Step 1 – Identify All Control Technologies
Step 2 – Eliminate Technically Infeasible Options
Step 3 – Rank Remaining Control Technologies by Control Effectiveness
Step 4 – Evaluate Most Effective Controls and Document Results
Step 5 – Select BACT

The predefined steps of a BACT analysis are described in this section, and results presented. Available NO_X control techniques and technologies are defined, identified, and a technical description of the emission reduction process and capabilities are reviewed in the following section. Subsequently, those techniques and technologies deemed feasible for retrofit application are ranked according to nominal NO_X control capability. An engineering analysis reviews the estimated capital and operations and maintenance (O&M) costs for each feasible alternative, including taking a look at Balance of Plant (BOP) requirements. Following the cost impact determination, the energy and environmental impacts are reviewed for each feasible technology. Finally, the results of the engineering analyses are tabulated and a NO_X BACT selection is recommended for each unit.

2.1 STEP 1 – IDENTIFY ALL CONTROL TECHNOLOGIES

The first step in a "top-down" NO_X BACT analysis is to identify, for the emissions unit in question, a comprehensive list of all "available" control options. In the EPA's draft NSR Manual,

> "available control options are those air pollution control technologies or techniques with a practical potential for application to the emissions unit and the regulated pollutant under evaluation. Air pollution control technologies and techniques include the application of

[4] Ibid footnote number 2, NSR Manual B.1

production process or available methods, systems, and techniques, including fuel cleaning or treatment or innovative fuel combustion techniques for control of the affected pollutant"[5].

According to the EPA's draft NSR Manual, "a technology is considered "available" if it can be obtained by the applicant through commercial channels or is otherwise available within the common sense meaning of the term"[6]. Also, "a control technique is considered available, within the context presented above, if it has reached the licensing and commercial sales stage of development"[7].

In order to identify available NO_X emission control technologies and techniques appropriate for potential application to MRY Station units, the following information sources were reviewed for coal-fired electric generating unit powerplants:

- EPA's RACT/BACT/LAER Clearinghouse (RBLC) database and Control Technology Center (website).
- Federal (EPA) and State, including North Dakota Department of Health internet websites for air emission permits and recently-submitted applications, including BACT Evaluations following New Source Review procedures.
- Federal (EPA and Department of Justice) and State, including North Dakota Department of Health internet websites for Consent Decrees issued as a result of legal actions taken by the United States government for alleged violations of the Prevention of Significant Deterioration (PSD) provisions and New Source Review provisions of the Clean Air Act, and/or federally-approved and enforceable State Implementation Plans.
- Control technology vendor information.
- Published and available information from technical, engineering, and environmental consultants.
- Technical literature found in journals, reports, internet websites, newsletters, proceedings of technical seminars and conferences pertaining to studies, engineering, designs, and testing of air pollution controls.

[5] Ibid, NSR Manual B.5
[6] Ibid, NSR Manual B.17
[7] Ibid, NSR Manual B.18

2.2 STEP 2 – ELIMINATE TECHNICALLY INFEASIBLE OPTIONS

The second step of the "top-down" BACT process is to evaluate the available NO_X control technologies and techniques identified in Step 1 in terms of the specific factors that apply to the emissions unit in question. In accordance with EPA's draft NSR Manual, "an available technology is "applicable" if it can be reasonably installed and operated on the source type under consideration. A technology that is available and applicable is technically feasible[8]".

The EPA's NSR Manual states a technology may be determined to be not applicable if "a technical assessment considering physical, chemical and engineering principles and/or empirical data showing the technology would not work on the emissions unit under review or that unsolvable technical difficulties would preclude the successful deployment of the technique"[9]. Also, a "showing of unresolvable technical difficulty with applying the control would constitute a showing of technical infeasibility (e.g., size of the unit, location of the proposed site, and operating problems related to specific circumstances of the source)"[10]. After a determination is made that any of the processes are technically infeasible, options are eliminated if technical challenges would preclude or prevent the successful long-term use of the control option or technique on the emission unit under consideration. This is performed prior to any economic analysis.

However, the EPA's NSR Manual also states "...control options incapable of meeting an applicable New Source Performance Standard (NSPS) or State Implementation Plan (SIP) limit would not meet the definition of BACT under any circumstances. The applicant does not need to consider them in the BACT analysis"[11]. Also, it states "An NSPS simply defines the minimum level of control to be considered in the BACT analysis"[12]. The NSR Manual further states "When developing a list of possible BACT alternatives, the only reason for comparing control options to an NSPS is to determine whether the control option would result in an emission level less stringent than the NSPS. If so, the option is unacceptable"[13]. New Source Performance Standards (NSPS) for NO_X emissions from EGUs firing North Dakota lignite are 0.8 lb/mmBtu. The EPA Acid Rain Program's Title IV NO_X emission limit for Group 2, cyclone-fired coal boilers with outputs greater than 155 MWe is 0.86 lb/mmBtu.

[8] Ibid, NSR Manual B.17
[9] Ibid, NSR Manual B.20
[10] Ibid, NSR Manual B.19
[11] Ibid, NSR Manual B.12
[12] Ibid, NSR Manual B.12
[13] Ibid, NSR Manual B.12

EPA's draft NSR Manual also states "A source would not be required to experience extended time delays or resource penalties to allow research to be conducted on a new technique. Neither is it expected that an applicant would be required to experience extended trials to learn how to apply a technology on a totally new and dissimilar source type. Consequently, technologies in the pilot scale testing stages of development would not be considered available for BACT review"[14].

Also in the EPA's draft NSR Manual is a qualification for technical feasibility, as described by the statement "Commercial availability by itself, however, is not necessarily a sufficient basis for concluding a technology to be applicable and therefore technically feasible. Technical feasibility, as determined in Step 2, also means a control option may reasonably be deployed on or "applicable" to the source type under consideration"[15].

2.3 STEP 3 – RANK REMAINING CONTROL TECHNOLOGIES BY CONTROL EFFECTIVENESS

The third step in the "top-down" BACT evaluation is to rank the control technologies remaining after the feasibility analysis by control effectiveness. The purpose of ranking the control technologies is to establish a hierarchy that "places at the "top", the control technology that achieves the lowest emission level"[16].

Selecting common units in order to compare emissions performance levels amongst options is one of the two key issues that must be addressed in a BACT analysis. EPA's draft NSR Manual states "it is generally most effective to express emissions performance as an average steady state emissions level per unit of product produced or processed"[17]. For fossil fuel-fired boilers, pounds of nitrogen oxides per unit of fuel heat input (i.e. lb/mmBtu), is a common means of comparing and calculating NO_X emissions.

Many control techniques, including both add-on controls and inherently lower polluting processes can perform at a wide range of levels. The EPA's draft NSR Manual states "It is not the EPA's intention to require analysis of each possible level of efficiency for a control technique, as such an analysis would

[14] Ibid, NSR Manual B.18
[15] Ibid, NSR Manual B.18
[16] Ibid, NSR Manual B.25
[17] Ibid, NSR Manual B.22

result in a large number of options"[18]. Also, "manufacturer's data, engineering estimates, and the experience of other sources provide the basis for determining achievable limits"[19].

2.4 STEP 4 – EVALUATE THE MOST EFFECTIVE CONTROLS AND DOCUMENT RESULTS

The fourth step of a "top-down" BACT review is to evaluate the technically-feasible emission controls, beginning with the most effective. Economic, energy, and environmental impacts are to be assessed and quantified, where possible, in the control technology analysis. The purpose of the evaluation is to determine if there are any identified impacts that would eliminate the top control technology from consideration. In the case where the most effective control alternative is determined to incur or produce adverse energy, economic or environmental impacts, the basis of the determination is documented, and the next most stringent control alternative is evaluated. This analysis process continues until the control technology under consideration cannot be eliminated by identification of any source-specific adverse energy, economic or environmental impacts.

The economic impacts are based on estimates of capital equipment pricing, procurement, installation and estimated operating and maintenance costs. The total installed capital costs along with the operating costs for each control technology are summarized in the economics of each respective section. The Levelized Total Annual Cost (LTAC) represents the levelized cost of procurement, construction, operation and maintenance over an assumed service life. Cost effectiveness ($/ton) of a control technique or technology is calculated by dividing the LTAC ($/yr) by the annual amount of NO_X removed (tons/yr). Baseline pre-control emissions are calculated using realistic upper boundary operating assumptions, considering inherent physical or operational constraints on the source. Plotting of the annual amount of NO_X removed (tons/yr) versus the levelized total annual control cost ($/yr) for the various control options on an x-y graph allows visualization of the cost-effectiveness. A "least-cost envelope" can be readily identified to indicate the inferior control options which should not be considered in the subsequent analyses. The incremental cost-effectiveness (difference in $/ton) between control techniques or technologies can also be calculated and compared. This allows evaluation of the dominant controls included on the least-cost envelope (curve).

[18] Ibid, NSR Manual B.23
[19] Ibid, NSR Manual B.24

2.5 STEP 5 – SELECT BACT

The final step in the "top-down" evaluation process is to select BACT for the applicable pollutant and emission unit. Per the EPA guidance document, BACT is "the most effective control technology not eliminated in Step 4"[20]. The methodology described above was applied to the Milton R. Young Station Unit 1's boiler for emissions of nitrogen oxides.

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[20] Ibid, NSR Manual B.53

3.0 BACT ANALYSIS for MRY STATION UNIT 1 NO_X EMISSIONS

The approach taken in this BACT analysis for Milton R. Young Station included a technical analysis of demonstrated control alternatives for NO_X emissions. This approach followed the predefined steps of a BACT analysis process as generally described in Section 2. Potential NO_X control techniques and technologies were identified, and a technical description of the emission reduction process and capabilities were provided. Subsequently, those techniques and technologies deemed available and feasible for retrofit application were ranked according to nominal NO_X control capability. The engineering analysis then developed the estimated capital and O&M costs for each alternative, including taking a look at Balance of Plant (BOP) requirements. Finally, the cost effectiveness points for each feasible technology were plotted, and those that comprise the dominant controls curve were identified.

For the feasible techniques and technologies considered for determining NO_X control cost-effectiveness for the two steam electric generating units at the MRY Station, estimates were produced for predicted NOx reductions that represent achievable long-term expectations of the alternative reduction techniques and technologies being presented in the technical analysis. Each were tabulated and graphed.

3.0.1 EMISSION UNIT DESCRIPTION

Milton R. Young Station Unit 1 is owned and operated entirely by Minnkota. MRY Station Unit 1 includes a Babcock and Wilcox steam generator installed in 1970. The steam generator is a lignite-fired boiler with multiple cyclone-furnaces installed in parallel using balanced-draft and natural circulation. Original unit design steam generating capacity is 1.714 million lbs/hr at 1,920 psi with a fuel heat input of 2,510 mmBtu/hr. The boiler is fired by seven ten-foot diameter cyclone burners, arranged "three over four" across the front wall of the lower furnace. The unit has a tubular air heater installed between the boiler and the flue gas ductwork leading to the electrostatic precipitator (ESP). Exhaust gases leave the air heater and pass through an ESP for particulate collection and removal prior to the two induced draft fans (installed in parallel) which discharge to the stack. Unit 1 has a nominal 235 MW net design output capacity rating, is typically capable of sustained output of approximately 253 MW gross, and has an ultimate short-term maximum gross output (URGE) rating of 278 MW.

The EPA's Technical Support Document[21] published in the Edocket (EPA's internet website) for the Final BART Guidelines lists nameplate steam turbine-generator capacity of MRY Station Unit 1 as 257 MW (gross), which was assumed for calculating capital cost estimates for control alternatives.

The Unit 1 boiler at M.R. Young Station includes a unique coal conditioning system (drying, crushing, and feeding) for each cyclone furnace specifically designed to aid in proper combustion of the lignite fuel. This method of firing solid fuel significantly influences the resulting nitrogen oxide concentration of the flue gases emitted from the boilers.

Milton R. Young Station Unit 1's boiler design, combustion performance, and NO_X emissions are dominated by the composition and combustion characteristics of the North Dakota lignite supplied solely from a surface mine adjacent to the plant. This mine is the only supplier of solid fuel for this station, as there are no railroad facilities provided to service the Milton R. Young plant. North Dakota lignite has high moisture and high sodium content, moderate higher heating values, and can have a widely variable and high ash content compared to other coals. These characteristics create difficulties in promoting consistent, steady combustion and slag formation in the cyclone burners. It also results in producing a flyash that has severe deposition characteristics.

The design unit operating conditions for this study are presented in Table 3-1. The historical average lignite coal analysis is shown in Table 3-2.

Table 3-1 – Unit Design Parameters

Design Unit Operating Characteristics	Unit 1 Design
Boiler Type	Subcritical(1)
Combustion System	Cyclone
Number of Cyclones; arrangement, location	7; 3 over 4, front
Unit Design Capacity Electrical Output(2), MW (net/gross)	235 / 257

(1) – Balanced draft, single drum, superheated steam with single stage of steam reheat.
(2) – These values were established by the original equipment manufacturers, prior to construction.

[21] EPA Docket OAR-2002-0076-0446 Technical Support Document for BART NOx Limits for Electric Generating Units Excel Spreadsheet 6/15/2005, posted on their website: from EDOCKET at http://docket.epa.gov/edkpub/do/EDKStaffItemDetailView?objectId=090007d48084562b; this is associated with EPA Acid Rain Program Clean Air Markets Division, Technical Support Document – Methodology For Developing BART NO_x Presumptive Limits, June 15, 2005, OAR-2002-0076-0445
[23] Ibid, footnote number 2, NSR Manual page B.11

Table 3-2 – Historical Average Lignite Coal Analysis

Lignite - Center Mine Ultimate Coal Analysis: (as received)	Average % by mass
Moisture	37.29
Carbon	38.69
Hydrogen	2.50
Nitrogen	0.57
Sulfur	0.81
Ash	8.74
Oxygen	11.40
Total	100.00
Higher Heating Value, Btu/lb	6,662

3.0.2 NITROGEN OXIDES EMISSION FORMATION

Nitrogen oxides (NO_X) are produced when nitrogen in the fuel and combustion air are exposed to high temperatures. There are two primary sources of NO_X emissions, referred to as "thermal" NO_X and "fuel" NO_X. Thermal NO_X emissions are produced when elemental nitrogen in the combustion air is admitted to a high temperature zone and oxidized. Fuel NO_X emissions are created during the rapid oxidation of the fuel containing nitrogen compounds. For most coal-fired units, thermal NO_X emission typically represents approximately 20% and fuel NO_X about 80% of the total NO_X formed. Nitrogen oxide (NO) is typically the most predominant form of NO_X emissions from fossil fuel combustion, along with nitrogen dioxide (NO_2). The formation of these compounds in utility powerplant boilers is sensitive to the method of firing and combustion controls utilized. The techniques employed for mixing the combustion air and fuel, which creates flames and high temperature combustion products, results from the rapid oxidization of carbon, hydrogen, and other exothermic reactions. Cyclone-fired boilers, by design, create intense heat release rates to melt and fluidize the coal ash introduced into the barrel-shaped furnaces. This produces high temperature flue gases and results in very high uncontrolled NO_X emissions. The amount of thermal NO_X emissions produced by cyclone boilers can be considerably higher than fuel NO_X emissions.

3.1 IDENTIFICATION OF NO_X CONTROL OPTIONS FOR MILTON R. YOUNG STATION

The first step in the BACT evaluation is to identify all "demonstrated and potentially applicable control technology alternatives"[23] according to the EPA's draft NSR Manual. In identifying control technologies, "the applicant needs to survey the range of potentially available control options"[24].

[24] Ibid, NSR Manual page B.11

3.1.1 REVIEW OF RETROFIT INSTALLATIONS

The BACT determinations listed in the EPA's RACT/BACT/LAER Clearinghouse (RBLC) database are for new facilities. The Milton R. Young Station is an existing powerplant facility with two coal-fired EGUs. A BACT evaluation for retrofitting control equipment to coal-fired EGUs in an existing facility will be substantially different than an analysis for installing control equipment on coal-fired EGUs in a new facility. Consequently, in performing the BACT analysis for existing boilers at Milton R. Young Station, it is important to review powerplant facilities, especially cyclone-fired coal boilers, which have retrofitted NO_X control equipment in recent years.

In 1998, EPA issued a NO_X SIP (State Implementation Plan) call. Under the SIP call, utility boilers in the eastern United States were required to substantially reduce NO_X emissions during the "ozone season". The compliance date for the NO_X SIP call is May 31, 2004. A high percentage of the fired electric generation facilities in the eastern United States have or are in the process of retrofitting NO_X controls to comply with the NO_X SIP call. The EPA's NO_X SIP call was not applicable to North Dakota utility boilers.

There are a number of fossil fuel-fired EGU powerplants around the United States that have implemented or are planning to implement modifications to reduce NO_X emissions. The NO_X emission control system installations are in response to Acid Rain requirements, EPA's NO_X SIP call, the Clean Air Interstate Rule (CAIR), the Regional Haze Rule (RHR), and local regulations.

In addition to the facilities that have had to retrofit emissions controls as a result of the Title IV Part 76 Acid Rain requirements and/or EPA's NO_X SIP call, a few installations have had to retrofit controls in recent years as the result of court decisions resulting from litigation and regulatory action. None of the boilers associated with identified consent decrees are cyclone-fired. They are also located in a region requiring compliance with an EPA-approved State Implementation Plan for nitrogen oxides emissions controls (i.e. NO_X SIP call). As mentioned above, North Dakota utility boilers were not subject to the EPA's NO_X SIP call.

3.1.2 POTENTIALLY FEASIBLE NOx CONTROL OPTIONS FOR MILTON R. YOUNG STATION

A review of available information on retrofit installations performed at utility and industrial coal-fired powerplants during the past fifteen years was undertaken. NO_X emission control technologies and techniques with potential application to Milton R. Young Station boilers were identified, and are listed in Table 3-3.

TABLE 3-3 – Potentially Available NO_X Control Technologies Identified for BACT Analysis

NOx Control Technology
Pre-Combustion Controls
Fuel Cleaning/Blending/Switching
Combustion Controls
Basic Combustion Control Improvements
Low NOx Burners (LNB)
Separated Overfire Air (SOFA)(1)
Flue Gas Recirculation
Fuel Reburn
Oxygen-enhanced combustion (OEC)
Water/steam injection (combustion tempering)
Post-Combustion Controls
Selective Non-Catalytic Reduction (SNCR)(2)
Selective Catalytic Reduction (SCR)
Electro-Catalytic Oxidation (ECO®)(3)

Notes: these are basic forms of the identified techniques.
Not all variations or combinations are included.
(1) – SOFA technologies include Boosted SOFA and Rotating Opposed Fired Air (ROFA)
(2) – SNCR technologies include Rich Reagent Injection, and Hydrocarbon-enhanced SNCR, commercially available as "NOxStar™".
(3) – Multi-pollutant control technology currently under commercial development by Powerspan Corp.

A comprehensive literature search, with sources including technical papers and presentations made at conferences by nationally-recognized technical organizations, utilities and other parties involved with design, construction, and testing of NO_X control techniques, plus hardware supplier experience lists, was performed. The results of this search are presented in Appendix A2, which includes a summary of various selected U.S. NO_X emission reduction retrofit projects.

3.2 FEASIBILITY ANALYSIS

The second step of the "top-down" BACT process is to evaluate the control processes that have been identified and determine if any of the processes are technically infeasible.

An available technology is "applicable" if it can be reasonably be installed and operated on the source type under consideration. Also, a control technique is considered available if it has reached the stage of licensing and commercial availability. For the purposes of this analysis, the term "commercial" is further defined to mean "capable of establishing a full contractual agreement with commercial and performance guarantees supported by appropriate financial backing" for the implementation of full-scale, full-time systems of the technique or technology application. A technology that is available and applicable is technically feasible.

There are three basic categories of NO_X emission control techniques and technologies:

- Pre-combustion controls;
- Combustion controls; and
- Post-combustion controls

Uncontrolled NO_X emissions from a coal-fired electric generating unit are highly dependent on type of firing method, amount of solid fuel fired per unit time and furnace volume, and the fuel's basic combustion properties and elemental composition. The basic methods for reduction of such emissions:

- either prevent pollution, i.e. use inherently lower-emitting processes/practices which produce fewer NO_X emissions during the power generation process; or
- involve improvements to, or provide new add-on controls that, reduce emissions after they are produced before they are emitted from the facility; or
- are combinations of inherently lower-emitting processes and add-on controls.

Most of the identified control options have been commercially-available, installed, and operating in many full-scale, permanent coal-fired utility boiler installations in the United States for five years or more.

Pre-combustion controls, such as fuel switching, fuel blending, and fuel cleaning have been practiced and performed at numerous utility power plants, typically for operational and sulfur emissions control reasons.

Combustion controls, such as low-NO_X burners (LNBs) and overfire air systems, are very commonly applied to reduce NO_X emissions from fossil fuel-fired powerplants. Low-NO_X Burners are typically applied to pulverized coal, gaseous and liquid fuel-fired boilers. They are not applicable to cyclone-fired boilers. Flue gas recirculation (FGR) has been practiced and performed at numerous natural gas and fuel oil-fired utility and industrial powerplants for NO_X emissions control reasons. On large coal-fired utility boilers, FGR has primarily been applied for steam temperature control purposes, not for emissions control. Conventional Gas Reburn (CGR) with overfire air has been installed and placed in commercial operation on several cyclone-fired boilers, primarily in the eastern region of the United States. Coal Reburn (CR) with overfire air has been successfully demonstrated on two cyclone-fired boilers and commercially installed on three pulverized coal-fired boilers in the United States. Combustion tempering (water/steam injection) has been tested but has not been continuously practiced on cyclone-fired coal boilers. Oxygen-enhanced combustion has only been demonstrated and/or installed on a limited number of pulverized coal-fired powerplants, not on any coal-fired cyclone boilers.

Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) are post-combustion technologies that have been applied predominantly on eastern or midwestern bituminous coal-fired boilers. Others, mostly comprised of a combination of available emission reduction technologies, are often referred to as "hybrid" or "layered" controls. Variations of SNCR, such as Rich Reagent Injection (RRI) with and without SNCR, have only been installed or demonstrated on a limited number of cyclone-fired boilers. Other technologies, such as Fuel Lean Gas Reburn™ with SNCR, hydrocarbon-enhanced SNCR (commercially available as NO_XStar™), and Conventional Gas Reburn with SNCR have only been demonstrated and/or installed on a limited number of pulverized coal-fired power plants.

Emerging post-combustion multi-pollutant control technologies, such as Powerspan's Electro-Catalytic Oxidation (ECO®), which include NO_X control, were also identified. These are typically in the large pilot-scale commercial development phase, and have not been successfully demonstrated on a full scale basis on any pulverized coal, cyclone, or circulating fluid bed boilers.

In most of the combination or "layered" and emerging control cases, the NO_X control technology has been demonstrated to be capable of controlling the targeted pollutant(s) on either:

- a full-scale basis, but only with temporary equipment; or
- a full-scale basis, with permanent equipment but in a limited number of installations; or

- with less than full-scale and full-time application.

3.2.1 SUMMARY OF RETROFIT INSTALLATIONS OF NO_X CONTROL TECHNOLOGIES

There are a number of facilities around the country that have implemented or are planning to implement modifications to reduce NO_X emissions. Table 3-4 summarizes the various NO_X emission control system installations currently installed, or that have been demonstrated on a full-scale, short-term basis, in response to Acid Rain requirements, EPA's NO_X SIP call and local regulations, or a utility investigating the technology.

TABLE 3-4 – Identified NO_X Control System Retrofits on Cyclone Coal-fired Boilers

No. of Units(1)	Cyclone NO_X Control Technology Description
1	Fuel Switching/Blending
39(2)	Separated Overfire Air (SOFA)
2	Selective Non-Catalytic Reduction, with or without SOFA
2(3)	Rich Reagent Injection, with SOFA
7(4)	Conventional fuel reburn (pulverized or micronized coal, gas), w/ SOFA
1(5)	Fuel lean gas reburn, with or without SOFA
22(6)	High-dust or low-dust SCR, with or without other technologies
1(6)	Tail-gas SCR, with or without other technologies

(1) – This list of known NOx control retrofit installations is primarily focused on units in the United States. There may be other installations that are similar but were not identified.
(2) – Installed for NOx control (without fuel reburn). A list of known cyclone boiler SOFA installations is included in Appendix A2.
(3) – RRI has only been demonstrated with temporary equipment for testing. See technical literature references in Appendix A1 and A2 for details.
(4) – Several conventional coal and gas reburn retrofits have discontinued reburn demonstration or routine operation. See Technical Literature Reference list and Appendix A3 for further details.
(5) – Only one example of fuel lean gas reburn retrofit (without OFA) on a cyclone-fired boiler has been demonstrated. This system was installed for short-term reburn testing and has been removed.
(6) – High-dust SCR technology has been retrofitted on sixteen U.S. cyclone-fired boilers, all believed to have SOFA. Low-dust SCRs in U.S. have only been installed only on pulverized coal-fired boilers, none on cyclones. One tail-gas SCR installation on a coal-fired cyclone boiler found in Germany; none in the U.S. See technical literature references in Appendix A1 and A2 for details.

A more detailed description of the various control technology retrofits and their claimed effectiveness is included in the technical descriptions and reference literature in the technical feasibility assessment of

Appendix A1, and Appendix A2, which includes a summary of various selected U.S. NO_X emission reduction retrofit projects.

3.2.2 SUMMARY OF FEASIBLE NO_X CONTROL TECHNOLOGIES FOR MRY STATION

One example of fuel switching applied to a cyclone-fired boiler was identified. Ottertail's Big Stone Unit 1 was originally designed to burn North Dakota lignite and was switched to western subbituminous (PRB) coal for reasons unrelated to NO_X emissions reduction. Big Stone Unit 1 and M.R. Young Station Unit 2 have similar boiler designs, and MRYS Unit 1's boiler is approximately 60% as large as MRYS Unit 2's boiler. Thus, conversion of Milton R. Young Station Unit 1's boiler to fire PRB coal or a lignite/PRB blend is technically possible. There are no railroad facilities provided to service the Milton R. Young plant. Additional operational and capital costs to bring in large quantities of PRB coal will be significant. Based on a comparison of available emission data between Ottertail's Big Stone Unit 1 and M.R. Station Young Unit 1, there is no expected reduction in baseline (i.e. uncontrolled) NO_X emissions from switching to PRB from lignite at Milton R. Young Station. Although fuel switching at Milton R. Young Station is technically feasible, this alternative will not be economically competitive with other NO_X control technologies that offer better results for a much lower combination of capital and operational costs. For these reasons, it has not been considered further as an effective NO_X emissions control option for MRY Station Unit 1 boiler.

Separated Overfire Air (SOFA) is the most commonly-applied, combustion-related NO_X emission reduction technology that has been proven effective on cyclone-fired boilers. A version of separated overfire air specifically designed for increased NO_X emission reduction performance for lignite-fired cyclone boilers, referred to as "Advanced SOFA" in this analysis, can be installed on both units at M.R. Young Station. The potential operational limitations mentioned in the detailed feasibility discussions included in Appendix A1 for deeply air-staged cyclones associated with separated overfire air are expected to limit the control effectiveness of this technique, alone and in combination with other feasible NO_X control options.

Selective Non-Catalytic Reduction (SNCR) technology is a form of post-combustion NO_X emission control that has been successfully applied on numerous utility boilers burning eastern bituminous coal, midwestern bituminous coal, and, to a lesser extent, western subbituminous coal to reduce NO_X emissions. SNCR has also been used on fuel oil and natural gas-fired units. SNCR does not appear to be

dependent directly on the type of burners (wall-fired, tangentially-fired, and cyclone-fired) employed in the boilers where it has been installed, with or without air-staged combustion with overfire air in full operation. This control technology adds urea (or ammonia) reagent to the hot furnace gases in the upper furnace to chemically reduce nitrogen oxides. SNCR was considered technically feasible for application on both units at M.R. Young Station. SNCR can be operated with and without SOFA. Variations of SNCR technologies such as Hydrocarbon-enhanced SNCR (HE-SNCR) and "Rotamix" have been installed on pulverized coal-fired boilers but are not proven on cyclone boilers. This is described in detail in Appendix A1.

Rich Reagent Injection (RRI) is a form of SNCR under development specifically intended for NOx emissions control on cyclone boilers. As of October 2006, RRI has been demonstrated but has not been commercially installed and placed in continuous operation on a cyclone-fired boiler, especially one burning coal with high fouling and slag temperature sensitivities associated with lignite supplied from the Center mine. RRI adds aqueous urea reagent to the hot furnace gases near the cyclones, which must be devoid of free oxygen in order to avoid oxidation of the urea which will increase NOx emissions. RRI is considered technically infeasible for application on the cyclone boilers at the Milton R. Young Station at the present time. This is described in detail in Appendix A1.

Various forms of fuel reburn with and without overfire air are types of combustion-related technologies that have been demonstrated and commercially installed on pulverized coal, fuel oil-fired, and cyclone utility and industrial boilers. Natural gas-consuming variations such as Conventional Gas Reburn (CGR) and Fuel-Lean Gas Reburn (FLGR™) have been applied to cyclone boilers burning bituminous and subbituminous coals. High capital costs expected for installing a natural gas pipeline and high operating costs from consumption of large volumes of such fuel make these alternatives economically unfavorable for both units at M.R. Young Station. Pulverized or micronized coal reburn, in combination with SOFA, are technically feasible but will require extensive capital, operating and maintenance costs for fuel grinding equipment and facilities when installed and operated for both units at M.R. Young Station. This is described in detail in Appendix A1.

Fuel cleaning is a technique normally applied to reduce the sulfur or ash content of a fossil fuel prior to combustion. No examples of fuel cleaning of North Dakota lignite or western subbituminous coal strictly for NO_X emissions reduction were found in available technical literature. This technique is considered infeasible for NO_X emissions control of M.R. Young Station boilers at the present time.

High-dust, low-dust, and tail-gas variations of selective catalytic reduction (SCR) technology have been applied on pulverized coal and cyclone boilers as a post-combustion type of NO_X emission control throughout the world and in the United States, except on units firing North Dakota lignite. The severity of catalyst blinding and pluggage from particulate matter and flue gases emitted from cyclone-fired boilers burning North Dakota lignite precludes the technical feasibility for successful application of such SCR technology on the EGUs at the Milton R. Young Station. This is described in detail in Appendix A1 with supporting documentation in Appendix B.

The results of Step 2 of the NO_X BACT Analysis for determining the technical feasibility of potential control technologies, including various "layered" combinations, are listed in Tables 3-5 and 3-6.

TABLE 3-5 – Technically-Feasible Potential NO_X Control Technologies for M.R. Young Station Cyclone Boilers

Control Technology(1)	In Permanent, Full-Scale Service on Existing Coal-Fired Cyclone Utility Boilers?	Technically Feasible on M.R. Young Station Unit 1 boiler?
Selective Non-Catalytic Reduction (SNCR)	Yes(2)	Yes
Conventional Gas Reburn	Yes(3)	Yes(3); Requires SOFA or ASOFA
Coal Reburn	Yes(4)	Yes(4); Requires SOFA or ASOFA
Fuel Lean Gas Reburn	No(5)	Yes(5) (w/ or w/out SOFA or ASOFA)
Advanced SOFA	No(6)	Yes(6). Includes relocated lignite drying vent ports
Separated OFA (basic SOFA)	Yes(6)	Yes(6)
Combustion Improvements	Yes	Yes(7); typically included with separated OFA
Flue Gas Recirculation	Not for NOx control	Yes(8) (not expected to reduce NOx further)
Fuel Switching / Blending	Yes	Yes(9) (not expected to reduce NOx further)

See technical feasibility details and literature References in Appendix A for details.

(1) – All potential combinations of technologies not listed. See discussion of "layered" technologies.

(2) – Assumes use of urea for reagent. Limited number of active installations on cyclone-fired boilers burning western subbituminous (i.e. Powder River Basin or PRB coal).

(3) – Limited number of active conventional gas reburn (CGR) installations on cyclone-fired boilers burning PRB coal.

(4) – Limited number of demonstrations or active installations of pulverized or micronized coal reburn on cyclone-fired boilers. One demonstration of pulverized coal reburning with PRB coal has been performed on a cyclone-fired boiler, no longer active. Only one active permanent coal reburn installation on cyclone-fired boiler burning eastern bituminous coal, none burning western subbituminous coal or lignite.

(5) – Only one short-term test demonstration of FLGR™ on a cyclone-fired boiler burning coal with separated overfire air.

(6) – No cyclone boilers firing North Dakota lignite have installed basic or advanced SOFA. See Appendix A.

(7) – Considered part of SOFA installation for coal boilers without combustion controls for NOx reduction.

(8) – No examples of using recirculated flue gas on coal-fired boilers for NOx emissions control were found in available technical literature. Zero additional NO_X reduction potential expected from this technique alone for MRY Station Unit 1 / 2. Potential NO_X reduction improvement on MRY Unit 1 / 2 considered part of "advanced" SOFA.

(9) – Zero additional NO_X reduction potential expected from this technique (switching from lignite to lignite/PRB blends or 100% PRB) alone for MRY Station Unit 1 / 2.

TABLE 3-6 – Technically Infeasible Potential NO_X Control Technologies for M.R. Young Station Cyclone Boilers

Control Technology(1)	In Permanent, Full-Scale Service on Existing Coal-Fired Cyclone Utility Boilers?	Technically Feasible on M.R. Young Station Unit 1 boiler?
Selective Catalytic Reduction (SCR): conventional (high dust); Low-dust; Tail-gas	Yes(2) / No / Yes(3)	No(4) - Unresolvable fouling and catalyst deactivation problems expected. See discussion of SCR feasibility for ND lignite.
Electro-Catalytic Oxidation (ECO®)	No	No, has not been demonstrated full-scale nor reached commercial availability
HE-SNCR (using ammonia)	No(5)	No(5). Has not been demonstrated on cyclone.
Rotamix (ROFA + SNCR)	No(6)	No(6). Has not been demonstrated on cyclone.
Rich Reagent Injection (RRI) with ASOFA	No(7)	No(7). Requires oxygen-free furnace environment, varying air/fuel would increase NOx emissions.
RRI + SNCR with ASOFA	No(7)	No(7). See footnote and feasibility discussion.
Advanced Conventional Gas Reburn (ACGR) + SNCR	No(8)	No. Has not been demonstrated on cyclone.
Coal Reburn + SNCR	No(8)	No. Has not been demonstrated on cyclone.
Fuel Lean Gas Reburn + SNCR	No(8)	No. Has not been demonstrated on cyclone.
Rotating Opposed-Fired Air	No(6)	No. Has not been demonstrated on cyclone.
Oxygen Enhanced Combustion	No(9)	No. Has not been demonstrated on cyclone.
Water Injection	No(10)	No(10)
Fuel Cleaning	Not for NOx control	No(11) (not expected to reduce NOx further)

See technical feasibility details and literature References in Appendix A for details.

(1) – All potential combinations of technologies not listed. See discussion of "layered" technologies.

(2) – Limited number of active installations on cyclone-fired boilers burning western subbituminous coal.

(3) – No identified installations on coal-fired boilers in the United States. One tail-end SCR on cyclone boiler in Germany.

(4) – See discussion of SCR feasibility for ND lignite in Appendix A1 and Appendix B.

(5) – Hydrocarbon-enhanced SNCR has not been demonstrated on a cyclone-fired boiler, nor any boiler firing western subbituminous coal or lignite.

(6) – Rotating Opposed-Fired Air with or without SNCR has not been demonstrated on a cyclone-fired boiler. No apparent significant advantages over SOFA on cyclone-fired boilers.

(7) – Rich Reagent Injection has been successfully demonstrated for brief periods with SOFA with and without SNCR at two cyclone powerplants. There are no permanent RRI installations completed and operational as of May 2006. Difficulties in maintaining an oxygen-free furnace environment in MRY Station boilers where the urea reagent would be injected due to cyclone air/fuel imbalances during air-starved combustion would increase NOx emissions.

(8) – No known demonstrations or permanent installations of Advanced conventional gas reburn (CGR) or FLGR™ or pulverized/micronized coal reburn (PCR/mCR) in combination with SNCR on cyclone-fired boilers. CGR and PCR/mCR require separated overfire air. FLGR™ has been applied to pulverized coal firing with and without SOFA, with and without SNCR; FLGR™ with SNCR is also called amine-enhanced fuel lean gas reburn (AEFLGR™).

(9) – No known demonstrations or permanent installations of oxygen-enhanced combustion (OEC) on cyclone-fired boilers.

(10) – No permanently installed examples of using this technique continuously on coal-fired boilers were found in available technical literature. Not suitable for high-moisture lignite fuels.

(11) – No known demonstrations or permanent installations of using this technique continuously on coal-fired boilers for NOx emissions control were found in available technical literature.

Additional criteria besides technical feasibility are utilized for technology selection in a BACT analysis have been included in the following sections summarizing control effectiveness estimates, capital plus operating and maintenance cost estimates, energy impacts, and environmental impacts:

- Control effectiveness (i.e. percent pollutant removed)
- Expected emission rate (see Tables 3-7, 3-8) and emission reduction (tons per year)
- Economic impacts (total cost and incremental cost effectiveness)
- Energy impacts
- Environmental impacts (other media and emissions of toxic and hazardous air pollutants)

3.3 RANK OF TECHNICALLY FEASIBLE NO_X CONTROL OPTIONS BY EFFECTIVENESS

The third step in the "top-down" BACT evaluation is to rank the remaining control technologies by effectiveness. The purpose of ranking the control technologies is to establish a hierarchy that "places at the "top" the control technology that achieves the lowest emission level."

The emission reduction (control effectiveness) percentages developed for ranking the available NO_X emission control options considered feasible for Milton R. Young Station Unit 1 are shown in Table 3-7. These are estimates based upon engineering judgments with considerations of:

- Boiler heat input rates associated with realistic upper boundary operating assumptions;
- baseline emission rates corresponding to the realistic upper boundary operating assumptions;
- the general combustion properties of North Dakota lignite;
- published and available emission reduction performance achieved at other similar utility powerplants (cyclone-fired boilers);
- computer-derived predictions; and
- inclusion of performance margins to allow for variations in fuel, weather, equipment condition, and other factors that prevent the ultimate peak short-term performance from being reliably sustained over the course of long-term operation.

These NO_X emission level and reduction percentage estimates include adjustments of previously demonstrated or predicted performance that reflect differences between North Dakota lignite and eastern or midwestern bituminous and western subbituminous coals.

The numbers assume the estimated capability of the employed technique is achievable and sustainable (long-term) and that potential operational limitations mentioned in the feasibility discussions allow the successful practice of the technique or technology. None of the remaining control options has been installed on a cyclone-fired boiler burning North Dakota lignite. As such, the expressed control percentages reflect the use of engineering judgment, based on the listed technique or technology application. This is particularly pertinent to all control options that involve air-staged combustion associated with various forms of separated overfire air. SOFA-based controls for cyclone-fired coal-burning boilers have typically reduced NO_X emission levels significantly from the precontrol baseline, and which allow or enhance further reductions when combined with other control techniques and technologies.

3.3.1 ESTABLISHING BASELINE NO_X EMISSIONS FOR RANKING CONTROL OPTIONS

Before the various feasible NO_X emission control alternatives can be estimated and ranked in order of effectiveness, the precontrol baseline level of emissions and its basis must be determined. The EPA's NSR Manual provides general guidance for establishing estimated baseline emissions to be used for the purpose of calculating and comparing the control and cost-effectiveness of a control option:

> "The baseline emissions rate represents a realistic scenario of upper boundary uncontrolled emissions from the source. The NSPS/NESHAP requirements or the application of controls, including other controls necessary to comply with State or local air pollution regulations, are not considered in calculating the baseline emissions. In other words, baseline emissions are essentially uncontrolled emissions, calculated using realistic upper boundary operating assumptions. When calculating the cost effectiveness of added post-process emissions controls to certain inherently lower polluting processes, baseline emissions may be assumed to be the emissions from the lower polluting process itself. In other words, emission reduction credit can be taken for the use of inherently lower polluting processes"[25].

Also stated in the EPA's NSR Manual:

> "Estimating realistic upper bound case scenario does not mean that the source operates in an absolute worst-case manner all the time. For example, in developing a realistic upper boundary case, baseline emissions calculations can also consider inherent physical or operational constraints on the source. Such constraints should accurately reflect the true

[25] Ibid, NSR Manual B.37

upper boundary of the source's ability to physically operate and the applicant should submit documentation to verify these constraints"[26].

Establishing estimated baseline NO_X emissions for a new or existing source involves determining the design or operational basis of the emission rate. A useful means of comparing such emission rates is to establish the unit emission rate, expressed in pounds of pollutant per unit of process output. For processes such as steam-electric generating powerplants utilizing combustion in boilers, the desired process output (kilowatts or megawatts) can be related to the pollutant-bearing flue gas created by the combustion of fuel. Units of fuel heat input (millions of BTUs) required to create a unit of desired electrical output (kW) and thus the efficiency of converting the fuel heat to such electrical output (unit heat rate, Btu/kW-hr) are important.

A review of reported hourly NO_X emissions for MRY Station Unit 1 boiler, including unit mass rates (lb/mmBtu and lb/hr), boiler heat input (mmBtu/hr), and gross electrical output in megawatts (MW_g), was performed for the operating periods in years 2001-2005 inclusive. A realistic upper bound emission case scenario for each boiler's baseline emissions at Milton R. Young Station determined the highest summation of any rolling 12-month period NO_X mass emissions (pounds), along with the summation of the gross heat input (mmBtus) and the boiler operating hours for the same rolling 12-month period corresponding to the highest NO_X pounds. Dividing the summation of the rolling 12-month NO_X pounds by heat input results in a average unit emission rates (lb/mmBtu). Likewise, the summation of the rolling 12-month gross heat input (mmBtus) divided by the boiler operating hours yields an average gross heat input rate (mmBtu/hr). This emission evaluation revealed that:

- Unit 1 at Milton R. Young Station is typically operated in a base-loaded manner;
- MRYS Unit 1's highest 12-month NO_X mass emissions summation divided by the summation of the same 12-month period's heat input averaged 0.849 lb/mmBtu at a corresponding average unit heat input rate of 2,744 mmBtu/hr and unit gross electrical output of 244.5 MW_g.

3.3.2 ESTIMATING CONTROL-EFFECTIVENESS OF NO_X EMISSIONS CONTROL OPTIONS

The degree of success in operation of separated overfire air alone and in combination with the other selected feasible alternatives is important to the amount of NO_X emission reduction achieved. The emission control performance from the advanced version of separated overfire air (ASOFA) is highly

[26] Ibid, NSR Manual B.37

dependent on the degree of success in admitting combustion air insufficient for complete combustion in the cyclones without causing related negative impacts. The control percentages estimated for firing North Dakota lignite in the MRY Station boilers reflect the belief that operating the existing cyclones much below an average cyclone stoichiometric ratio of approximately 0.95 (95% of the theoretical amount of combustion air required for complete combustion) will not be successful. This is due primarily to the expected "starved air" combustion causing a reduction in cyclone furnace gas temperatures, thus creating a strong potential for molten slag solidifying in the cyclone barrels, slag taps, and lower furnace floor openings. This would impose a great interruption to steam production since forced outages would be required to remove this physical obstruction before full load boiler operation could be reestablished. The EPA's draft NSR Manual states "It is not the EPA's intention to require analysis of each possible level of efficiency for a control technique, as such an analysis would result in a large number of options"[27].

The potential operational limitations for deeply air-staged cyclones associated with separated overfire air and coal reburn alternatives are expected to limit the amount of NO_X control potential possible from successful practice of the particular technique or technology. This is described in the detailed feasibility discussions included in Appendix A1.

The advanced form of separated overfire air is expected to be effective in NO_X emission reduction and can be combined with other feasible combustion-related and post-combustion control alternatives for these lignite-fired cyclone boilers. The basic form of SOFA in combination with coal reburn, gas reburn options, and SNCR, was not included in the detailed control effectiveness analysis in order to limit the number of options that were evaluated.

Using an advanced form of SOFA system, M.R. Young Station's Unit 1's boiler operating at MCR is expected to achieve a NO_X emission level of 0.51 lb/mmBtu when operating modestly air-staged cyclone furnaces with suitable combustion controls. This level of NO_X reduction from ASOFA operation, approximately forty percent, is based on the expected ability to reduce emissions without incurring potential significant negative impacts of this technique. This reduction estimate includes the additional amounts of control potential available from operating with relocated lignite drying system vent ports associated with ASOFA operation with modestly air-staged cyclone furnaces.

[27] Ibid, NSR Manual B.37

Coal reburn with ASOFA is estimated to reduce NO_X emissions for M.R. Young Station's Unit 1's boiler operating at MCR slightly less than 55 percent from the pre-control baseline NO_X emission rate, considering similar control levels demonstrated by previous coal-reburn retrofits on cyclone-fired boilers and limitations previously discussed with ASOFA.

Conventional Gas Reburn and Fuel Lean Gas Reburn options were both assumed to be installed with ASOFA. NO_X reduction from CGR with ASOFA operation is expected to be approximately fifty six percent. FLGR with ASOFA is expected to reduce NO_X emissions approximately forty six percent. Estimates for NO_X emissions for M.R. Young Station's Unit 1's boiler considered similar control levels demonstrated by previous gas-reburn retrofits on cyclone-fired boilers with modestly air-staged cyclone furnaces and limitations previously discussed with ASOFA.

The NO_X emission rate for Selective Non-Catalytic Reduction (SNCR) (using urea) with ASOFA is expected to be approximately 0.355 / 0.33, resulting from a reduction in NO_X emissions of approximately 58 percent from the 12-month average pre-control baseline NO_X emission rate.

Included in the feasible control option ranking of Table 3-7 are layered alternatives that were shown in Table 3-5. The highest-performing NO_X control alternatives remaining in consideration are ranked in declining order of expected emission reduction. These combined control options refer to "advanced" SOFA, which is expected to have significantly lower NO_X emissions than a typical SOFA system as applied to the Milton R. Young cyclone boilers.

TABLE 3-7 – Ranked NO_X Control Options Feasible for MRY Station Unit 1 Boiler with Expected Control Performance

Alt. Label(1)	NO_X Control Technique	Emission Rate (lb/mmBtu)	Control Percentage(2)
E	SNCR (using urea) w/ ASOFA	0.355	58.1
D	Gas Reburn with ASOFA	0.374	56.0
C	Lignite Reburn w/ ASOFA	0.385	54.6
B	Fuel Lean Gas Reburn with ASOFA	0.460	45.9
A	Advanced Separated Overfire Air (ASOFA)	0.513	39.5
-	Baseline	0.849	-

(1) - Alternative designation assigned from highest to lowest unit NOx emission rate.
(2) - Control percentages are relative to an average pre-control emission baseline of 0.849 lb/mmBtu based on annual operation at highest pre-control 12-month rolling NOx summation mass emissions divided by the 12-month heat input summation.

The annual emission levels developed for Table 3-7's ranking the feasible alternatives assume that the highest 12-month average pre-retrofit level of unit NO_X emissions for M.R. Young Station's Unit 1's boiler is a baseline of 0.849 lb/mmBtu. This was determined from the highest reported rolling 12 consecutive month period's summation of hourly NO_X emissions (lbs).

The hourly gross fuel heat input (mmBtu) was summed over that same 12-month time period, and divided by the number of boiler operating hours to yield an annual average gross fuel heat input rate (mmBtu/hr). Multiplying the 12-month average heat input rate (mmBtu/hr) by the baseline or control alternative's 12-month average unit emission rate (lb/mmBtu) equals a 12-month average hourly NO_X emissions rate (lb/hr). Annual NO_X emissions (tons) for the baseline pre-control condition were calculated by multiplying the 12-month summation for boiler operating hours during the same period as the highest NO_X emissions by the 12-month average emission rate (lb/hr). The annual tons for the control options were calculated by multiplying the alternative's average annual emission rate (lb/yr) by a reduction factor (if applicable) for heat input or running plant capacity and adjusting boiler operating hours by an annual uptime (availability) factor. Details for these adjustments are included in Appendix C3. Based on these calculations, the annual emissions for M.R. Young Station's Unit 1's boiler are shown in Table 3-8.

3.4 NO_X CONTROLS ANALYSIS AND IMPACTS EVALUATION

The fourth step of a "top-down" BACT review is to evaluate the most effective emission controls. Energy, economic, and environmental impacts are to be considered in the control technology evaluation. The purpose of the evaluation is to determine if there are any energy, economic or environmental impacts that would eliminate the top control technologies from consideration.

3.4.1 NO_X CONTROL ECONOMIC IMPACTS FOR MRY STATION UNIT 1

An evaluation was performed to determine the various cost impacts of installing feasible NO_X control alternatives on Milton R. Young Unit 1. This evaluation includes estimated:

- Capital costs;
- Fixed and variable operating and maintenance costs; and
- Levelized total annual costs

to engineer, procure, construct, install, startup, test, and place into commercial operation the particular control technology. The results of this evaluation are summarized in Tables 3-9 through 3-13.

3.4.1.1 CAPITAL COST ESTIMATES FOR NO_X CONTROL ALTERNATIVES

The capital costs to implement the various NO_X control technologies were largely estimated from unit output capital cost factors ($/kW) published in technical papers discussing those control technologies. In the cases of SNCR, preliminary vendor budgetary cost information was obtained and used in place of, or to adjust, the published unit output cost factors. These cost estimates were considered to be study grade, which is + or – 30% accuracy.

The unit nameplate output capacity (gross electrical output in megawatts) assumed for the NO_X control technologies capital cost estimate basis was 257 MW_g for MRY Station Unit 1[28].

A review of the unit capital cost factor range and single point factors applicable to MRY Station Unit 1 NO_X control technologies are presented in Table 3-9. The estimated installed and levelized capital costs for the highest-performing form of the various feasible NO_X emission reduction technologies evaluated for cost-effectiveness are shown in Table 3.10. These are listed in order of control effectiveness, with the highest ranked option at the top.

[28] Ibid footnote number 23.

TABLE 3-9 – Unit Capital Cost Factors of Feasible NO_X Control Options for MRY Station Unit 1

Alt. Label[1]	NO_X Control Technique	Range[2] ($/kW)	Single Point Unit Capital Cost Factor[3], ($/kW) MRYS Unit 1
E	SNCR (using urea) w/ ASOFA	20-35[4]	31.6[4],[5]
D	Gas Reburn w/ ASOFA	15-30[6]	70.1[5],[6],[7]
C	Lignite Reburn w/ ASOFA	30-60[6]	181.5[5],[8]
B	Fuel Lean Gas Reburn w/ ASOFA	--[9]	41.4[4],[5],[9]
A	Advanced Separated Overfire Air (ASOFA)	5-10[6]	16.6[5]

(1) – Alternative designation has been assigned from highest to lowest unit NOx emission rate.
(2) – Unit capital cost factors ($/kW) of these individual technologies combined by simple addition. Actual installed costs may differ this due to positive or negative synergistic effects. Range based on published values or vendor proposals.
(3) – Single point cost factor is best estimate for determination of total capital cost for a particular technology or combination, assuming maximum unit capacity is based on EPA's nameplate rating. Single point cost figures in 2006 dollars.
(4) – Estimated capital cost for SNCR point estimate and FLGR point estimate derived from December 2004 budgetary proposal by Fuel Tech. See Appendix C2 for details.
(5) – The single point unit capital cost factor shown for the "advanced" version of SOFA derived from Burns & McDonnell internal database and cost estimate for North Dakota lignite-fired cyclone boilers.
(6) – NESCAUM 2005 Technical Paper, posted at their website. See technical references in Appendix A1 for details.
(7) – The single point unit capital cost factor shown for a conventional gas reburn system includes the estimated capital cost to install a high-pressure natural gas supply pipeline (31.4 $/kW), and that both boilers share the capital cost in proportion to their respective rated MW gross output capacities.
(8) – The single point unit capital cost factor shown for a lignite reburn system is highly site-specific, and assumes that new pulverizers and building enclosures are required. The general cost range for pulverized coal-fired boilers is included in the NESCAUM 2005 Technical Paper; for cyclone boilers is included in the 2005 WRAP Draft Report, posted at their website. The single point unit capital cost factor for this alternative for increased PM collection capacity included in lignite reburn option is 91.7 $/kW. See technical references in Appendix A1 for details.
(9) – The unit capital cost factor range for FLGR applications on boilers without an existing a high-pressure natural gas supply was not found in available technical literature. The single point unit capital cost factor shown for a fuel lean gas reburn system includes the estimated capital cost to install a high-pressure natural gas supply pipeline (15.7 $/kW), and that both boilers share the capital cost in proportion to their respective rated MW gross output capacities.

TABLE 3-10 – Estimated Capital Costs for NO_X Control Alternatives - MRY Station Unit 1

Alt. Label(1)	NOx Control Alternative	Installed Capital Cost(2) $1,000	Annualized Capital Cost(3) $1,000
E	SNCR w/ ASOFA	8,113	707
D	Gas Reburn w/ ASOFA(4)	18,006	1,570
C	Lignite Reburn w/ ASOFA(5)	46,656	4,068
B	Fuel Lean Gas Reburn w/ ASOFA(4)	10,639	928
A	Advanced SOFA (ASOFA)	4,277	373
	Baseline	0	0

(1) - Alternative label has been assigned from highest to lowest unit NOx emission rate.
(2) - Installed capital cost is estimated for determination of total capital cost for a particular technology or combination, assuming 257 MWg unit capacity rating. All cost figures in 2006 dollars.
(3) - Annualized capital cost = Installed capital cost x 0.08718 annualized capital cost factor.
(4) - Costs for gas reburn options include high-pressure natural gas supply pipeline installed capital cost of $8,075,000 for CGR and $4,038,000 for FLGR; and annualized capital cost of $704,000/yr for CGR and $352,000 for FLGR. See footnotes #8 and 10 under Table 3-9.
(5) - Costs for increased PM collection capacity included in lignite reburn option are $23,561,000 for installed capital cost, and $2,054,000/yr annualized capital cost.

3.4.1.2 Operating and Maintenance Cost Estimates for MRY Station NO_X Controls

The operational and maintenance costs to implement the various NO_X control technologies were largely estimated from cost factors (percentages of installed capital costs) established in the EPA's Air Pollution Control Cost Manual (OAQPS) for SNCR[29], and from published in technical papers discussing those control technologies. In the cases including various forms of SNCR, preliminary vendor quotes were obtained and used in place of, or to adjust the OAQPS cost factors. These cost estimates were considered to be study grade, which is + or – 30% accuracy.

Fixed and variable operating and maintenance costs considered and included in each NO_X control technology's annual O&M costs are estimates of:

- Auxiliary electrical power consumption for operating the additional control equipment;
- Reagent consumption, and reagent unit cost for SNCR alternatives; and
- Reagent dilution water consumption and unit cost for SNCR alternatives.

[29] EPA Office of Air Quality Planning and Standards (OAQPS) publication EPA/452/B-02-001, Section 4.2, NO_X Controls – NO_X Post-Combustion, Chapter 1 - Selective Non-Catalytic Reduction, dated October 2000, posted at their website: http://www.epa.gov/ttn/catc/dir1/cs4-2 ch1.pdf

- Increases or savings in auxiliary electrical power consumption for changes in coal preparation equipment and loading, primarily for fuel reburn cases;
- General operating labor, plus maintenance labor and materials devoted to the additional emission control equipment and its impact on existing boiler equipment.
- Reductions in revenue expected to result from loss of unit availability, i.e. outages attributable to the control option, which reduce annual net electrical generation available for sale (revenue).

For economic evaluation purposes, an annual average running plant capacity factor of 96.6 percent compared to a nominal unit output capacity of 253 MW_g combined with an average annual availability (uptime) of 8,528 operating hours (97.3 percent of 8760 hours per year) resulting in an annual unit capacity factor of 94.1% were assumed for Unit 1's pre-control baseline annual operation. A heat input rate of 2,744 mmBtu/hr and a NO_X emission rate of 0.849 lb/mmBtu were assumed for calculating control and cost-effectiveness from pre-control maximum rolling 12 month summation of nitrogen oxides' mass emissions for MRY Station Unit 1.

Table 3-11 show the estimated annual operating and maintenance costs and levelized annual O&M cost values for the highest-performing form of the various feasible NO_X emission reduction technologies. These are listed in order of control effectiveness, with the highest ranked options at the top. The cost methodology summarized in Appendix C3 provides more details for the levelized annual O&M cost calculations and cost factors.

TABLE 3-11 – Estimated O&M Costs for NO_X Control Alternatives - MRY Station Unit 1

Alt. Label(1)	NOx Control Alternative	Annual O&M Cost(2) $1,000	Levelized Annual O&M Cost(3) $1,000
E	SNCR w/ ASOFA	5,417	6,764
D	Gas Reburn w/ ASOFA	28,641	35,765
C	Lignite Reburn w/ ASOFA	5,862	7,320
B	FLGR w/ ASOFA	12,863	16,062
A	Advanced SOFA (ASOFA)	1,695	2,117
	Baseline	0	0

(1) - Alternative label has been assigned from highest to lowest unit NOx emission rate.
(2) - Annual operating and maintenance cost for a particular technology or combination is compared to unit baseline operation at an average unit output (244.5 MWg) and assumes a 97.3% average annual availability, which is highest consecutive 12-months of operation from 2001-2005. All cost figures in 2006 dollars.
(3) - Levelized annual O&M cost = Annual O&M cost x 1.24873 annualized O&M cost factor.

TABLE 3-8 – Expected Annual NO_X Control Performance for MRY Station Unit 1 Alternatives

		EMISSIONS				NOx Removal Efficiency[5] %
Alt. Label[1]	NOx Control Alternative	Emission Rate lb/mmBtu	Hourly Emission[2] lbs/hr	Annual Emission[3] tons/yr	Emission Reduction[4] tons/yr	
E	SNCR (using urea) w/ ASOFA	0.355	975	4,025	5,909	58.1
D	Gas Reburn w/ ASOFA	0.374	1,025	4,275	5,659	56.0
C	Lignite Reburn w/ ASOFA	0.385	1,058	4,343	5,591	54.6
B	Fuel Lean Gas Reburn w/ ASOFA	0.460	1,261	5,260	4,674	45.9
A	Advanced Separated Overfire Air (ASOFA)	0.513	1,409	5,874	4,060	39.5
-	Baseline	0.849	2,330	9,934	0	-

(1) - Alternative label has been assigned from highest to lowest unit NOx emission rate.
(2) - Hourly NO_X emission estimates (lb/hr) were calculated based upon average annual unit emission rate (lb/mmBtu) x 2,744 mmBtu/hr heat input.
(3) - Estimated annual emission tons assume an annual unit availability factor specific to each alternative; 97.3% was assumed for the baseline case. See Appendix C3.
(4) - Estimated annual tons of emission reduction is the difference between annual baseline tons and each alternative's annual emissions (tons).
(5) - Estimated NO_X control level percentage reductions relative to 0.849 lb/mmBtu emission baseline at 2,744 mmBtu/hr MCR heat input.

(4) - Costs for increased PM collection capacity included in lignite reburn option are $2,024,000/yr for annual O&M cost, and $2,527,000/yr annualized O&M cost.

3.4.1.3 LEVELIZED TOTAL ANNUAL COST ESTIMATES FOR MRY STATION NO_X CONTROLS

In order to compare a particular NO_X emission reduction alternative during the initial engineering analysis portion of the BACT selection process, the sum of estimated annualized installed capital plus levelized annual operating and maintenance costs, which is referred to as "Levelized Total Annual Cost" (LTAC) of expected pollutant removal by implementing that alternative was calculated. The LTAC for all NO_X control alternatives was calculated based on the same economic conditions and a 20 year project life (see Appendix C1 for methodology). The unit control cost was then determined as the LTAC divided by annual tons of pollutant emissions that would be avoided by implementation of the respective alternative. The control alternatives were also compared by calculating the change in unit cost (incremental cost) per incremental ton removed for the next most stringent alternative. This identified which alternatives produced the highest increment of expected pollutant reduction for the estimated lowest average annual cost increment compared with the baseline emission rate. The expected annual number of tons of pollutant removed versus estimated LTAC for each remaining control alternative was then plotted.

The comparison of the cost-effectiveness of the remaining NO_X emission reduction technologies was made and is shown in Table 3-12 and Figures 3-1 and 3-2 for MRY Station Unit 1. These figures plot estimated annual amount of NO_X removal (emission reduction) in tons per year on the ordinate (horizontal axis) and the estimated levelized total annual cost in thousands of U.S. dollars per year on the abscissa (vertical axis), for each of the remaining NO_X control technologies. Points on the graph that are farthest to the right and closest to the horizontal axis are deemed more cost-effective, since they represent controls that achieve more NO_X removal per dollar required for total annual costs of operation, maintenance, and capital recovery (depreciation).

Although the NSR Manual repeatedly prescribes following a "top down" analysis approach for BACT determination, the development of a least cost envelope with dominant controls (as seen in NSR Manual Figure B-1, page B.42) clearly labels points with lower emissions reductions and total annual costs first, i.e. "A", "B", etc. then proceeding with labeling and connecting points plotted further away from the zero emission reduction point. This "bottom-up" approach is for plotting the least-cost (dominant) control curve. The labeling of each unit's NOx control technique alternative has followed this approach.

TABLE 3-12 – Estimated Annual Emissions and Levelized Total Annual Cost for NO_X Control Alternatives - MRY Station Unit 1

Alt. Label(1)	NOx Control Alternative	Annual NOx Emissions(2) Tons/yr	Annual NOx Emissions Reduction(3) Tons/yr	Levelized Total Annual Cost(4) $1,000	Average Control Cost(5) $/ton
E	SNCR w/ ASOFA	4,025	5,909	7,472	1,265
D	Gas Reburn w/ ASOFA	4,275	5,659	37,334(6)	6,597
C	Lignite Reburn w/ ASOFA	4,343	5,591	11,388(7)	2,037
B	FLGR w/ ASOFA	5,260	4,674	16,990(6)	3,635
A	Advanced SOFA (ASOFA)	5,874	4,060	2,489	613
	Baseline	9,934	0	0	

(1) - Alternative label has been assigned from highest to lowest unit NOx emission rate.

(2) - Estimated annual emission tons assume an annual capacity factor specific to each alternative; 94.1% was assumed for the baseline case.

(3) - Estimated annual tons of emission reduction is the difference between annual baseline tons and each alternative's annual emissions (tons).

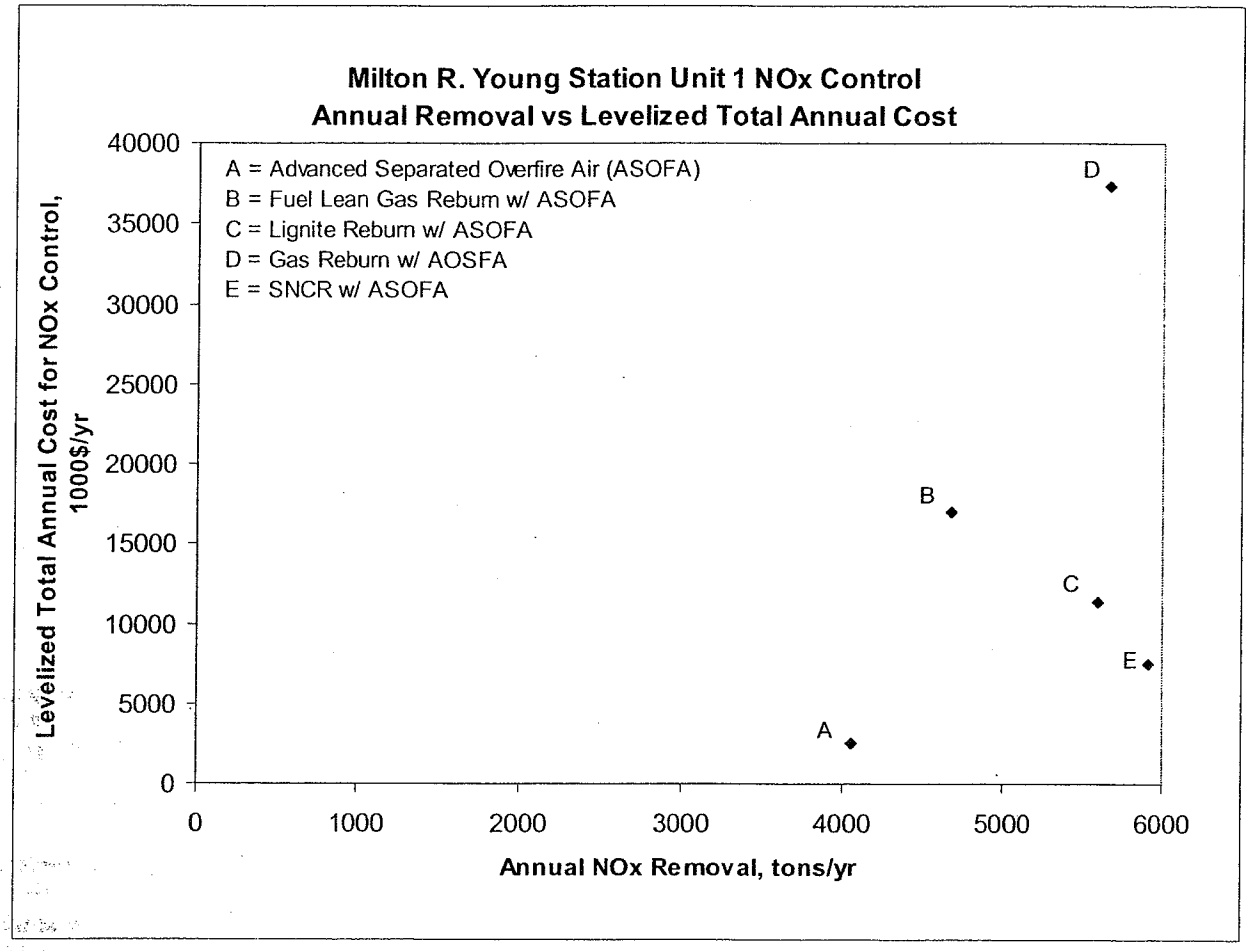
(4) - Levelized Total Annual Cost = Annualized Installed Capital Cost + Levelized Annual O&M cost. See note #3 for Tables 3-10 and 3-11 for annualized cost factors. Emissions are calculated from unit emission rates, control percentage, hourly heat input, and annual hrs/yr operation compared to pre-control baseline based on annual operation at highest allowable pre-control NOx emission rate.

(5) - Average Control Cost Effectiveness ($/ton) is the Levelized Total Annual Cost (1000$/yr) divided by Annual Emission Reduction (tons/yr). All cost figures in 2006 dollars.

(6) - LTAC for gas reburn options include high-pressure natural gas supply pipeline annualized capital cost of $704,000/yr for CGR and $352,000 for FLGR. See footnotes #8 and 10 under Table 3-9.1

(7) - LTAC for increased PM collection capacity included in lignite reburn option are approximately $2,054,000 for annualized capital cost plus $2,527,000/yr for annualized O&M cost, for a LTAC subtotal of $4,581,000/yr.

Figure 3-1 – NO_X Control Cost Effectiveness - MRY Station Unit 1(1)



(1) - All cost figures in 2006 dollars. Numbers are listed and qualifiers are noted in Table 3-12.

The purpose of Figure 3-1 is to show the range of control and cost for all feasible NO_X reduction alternatives evaluated. A dominant set of control alternatives were determined by generating what is called the "envelope of least-cost alternatives". The dominant controls cost curve is the best fit line through the points forming the rightmost boundary of the data zone on a scatter plot of the annual NO_X removal tonnage versus LTAC for the various remaining BACT alternatives. Following a "bottom-up" graphical comparison approach, each of the NO_X control technologies represented by a data point to the left of and above the least cost envelope are inferior control alternatives per the NSR Manual and should be excluded from further analysis on a cost efficiency basis.

Of the technically feasible NO_X control alternatives considered for MRY Station Unit 1, data points for conventional gas reburn (Point D) and fuel-lean gas reburn (Point B) with advanced separated overfire air, and lignite reburn with ASOFA (Point C), lay distinctly left and above the other points of the control cost points' scatter plot of Figure 3-1. These control options are inferior and therefore were eliminated from further control cost-effectiveness analysis.

Average and incremental annual costs and NO_X emission reductions for the dominant least-cost control alternatives remaining after the elimination of the obviously inferior options are listed in Table 3-13. The annual NO_X control tons per year, divided by the total levelized annual cost, yields an average unit cost ($/ton). Incremental cost effectiveness is a measure of the increase in marginal cost effectiveness between two specific alternatives. The additional tons per year of NO_X control relative to the previous apparent least-cost curve point, divided by the increase in levelized annual cost, yields an incremental unit cost ($/ton). Alternatively, the incremental cost effectiveness analysis identifies the rate of change of cost effectiveness with respect to removal benefits (i.e., the slope of the envelope of least-cost control alternatives, also called the dominant controls cost curve or DCCC) between successively more effective alternatives which are considered technically feasible for Milton R. Young Station boilers.

TABLE 3-13 – Dominant Controls Cost Curve Points for Feasible BACT NO_X Alternatives - MRY Station Unit 1

Alt. Label(1)	NOx Control Technique	Levelized Total Annual Cost(2),(3) ($1,000/yr)	Annual Emission Reduction(3) (tpy)	Incremental Levelized Total Annual Cost(2),(4) ($1,000/yr)	Incremental Annual Emission Reduction(4) (tpy)	Incremental Control Cost Effectiveness ($/ton)(2),(4)
E	SNCR w/ ASOFA	7,472	5,909	4,982	1,849	2,694
A	Advanced SOFA (ASOFA)	2,489	4,060	2,489	4,060	613

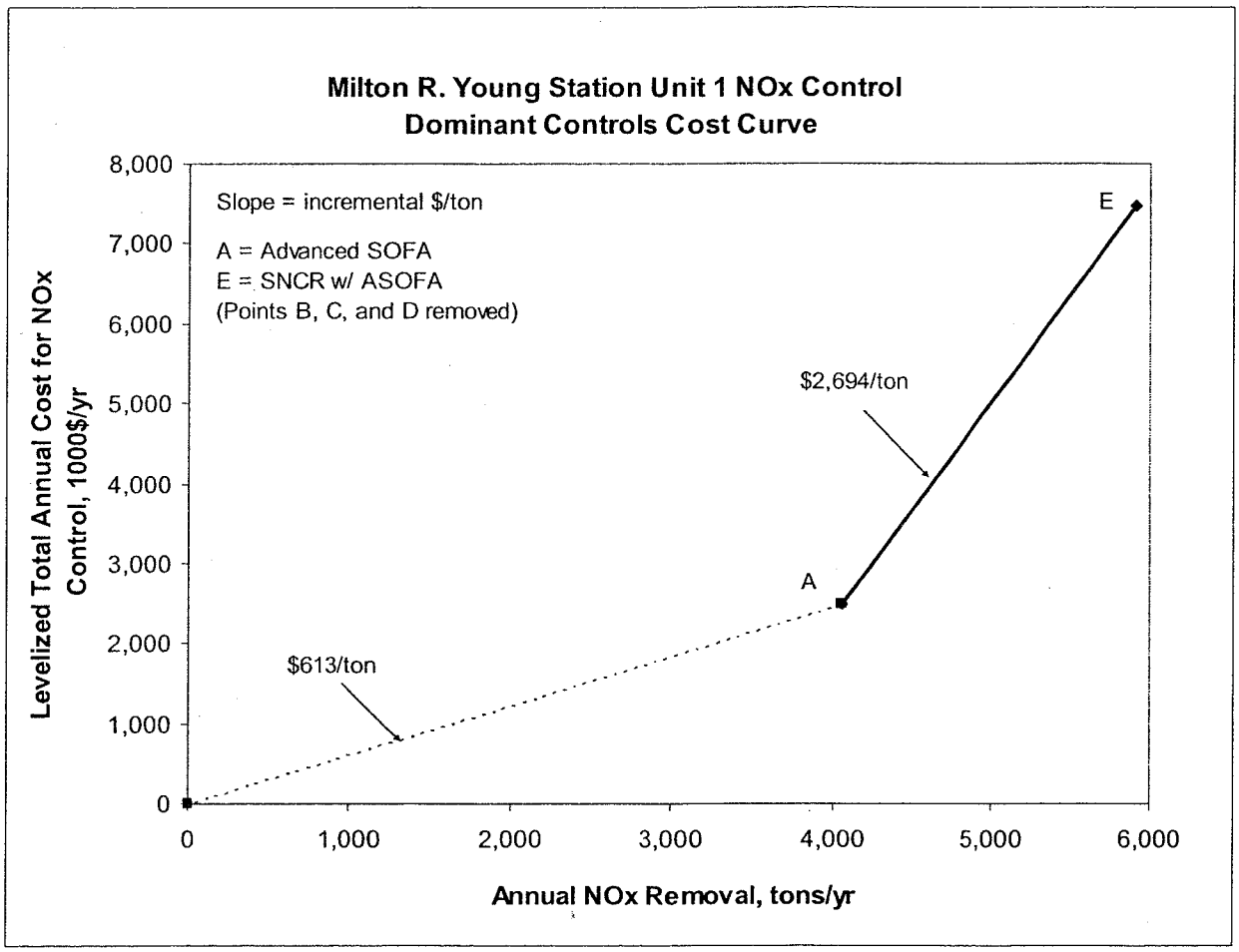
(1) – Dominant controls cost curve points from lowest (ASOFA) to highest (SNCR w/ ASOFA) are labeled the same as in Table 3-12, and on the graphs that accompany this table (Points B, C, and D were eliminated).
(2) – All cost figures in 2006 dollars.
(3) – Annual emission reduction and levelized control cost of these alternatives is relative to current costs and pre-control unit MCR baseline emission rate.
(4) – Increment based upon comparison between consecutive alternatives (points) from lowest to highest, except as noted.

The incremental cost analysis indicates that from a cost effectiveness viewpoint, the SNCR with ASOFA alternative incurs a significant annual (levelized) incremental cost compared to the ASOFA NO_X control

technique (slope from zero baseline to ASOFA, Point A was $613/ton for MRYS Unit 1; the incremental cost (slope) from ASOFA, Point A to SNCR with ASOFA, Point E was $2,694/ton for MRYS Unit 1.

Figure 3-2 contains a repetition of the levelized total annual cost and NO_X control information from Figure 3-1 for MRY Station Unit 1, with Point B (FLGR™ with ASOFA) , Point C (Lignite Reburn with ASOFA) and Point D (conventional gas reburn with ASOFA) removed. This is the dominant controls cost curve for MRY Station Unit 1 NO_X emissions alternatives.

Figure 3-2 – MRY Station Unit 1 NO_X Control Alternatives BACT Dominant Controls Cost Curve(1)



(1) - All cost figures in 2006 dollars. Numbers are listed and qualifiers are noted in Table 3-13.

In the U.S. EPA's NSR Manual, the EPA does not specify acceptable or unacceptable ranges for average (unit control costs) and incremental cost effectiveness values. As can be seen from a review of Table 3-14, the average levelized control cost effectiveness (called the unit control cost in this report) ranges from approximately $613/ton to $6,597/ton of MRYS Unit 1's NO_X emissions removed. It should be noted,

however, that the highest estimated average control costs involve gas reburn technologies that were shown to be inferior options (not on the dominant controls cost curve) and thus were eliminated from further impacts analysis.

The incremental cost effectiveness is a measure of the increase in marginal cost effectiveness between two specific alternatives. Alternatively, the incremental cost effectiveness analysis identifies the rate of change of cost effectiveness with respect to removal benefits (i.e., the slope of the least-cost envelope of dominant control alternatives or dominant controls cost curve) between successively more effective alternatives. The economic impact analysis indicates that from a cost effectiveness viewpoint, the highest performing alternative is SNCR with ASOFA (Point E). This control option is considered technically feasible for Milton R. Young Station Unit 1 boiler but incurs a significant annual (levelized) incremental cost relative to the next highest feasible NO_X control technique, ASOFA (Point A) when ASOFA is compared against the pre-control baseline. The Advanced Separated Overfire Air alternative has an average unit control cost ($613/ton) approximately 48% of the highest performing feasible alternative on the dominant controls cost curve (SNCR with ASOFA, $1,265/ton). ASOFA also has a much lower incremental cost per ton relative to the pre-control baseline (slope from zero to Point A, $613/ton) compared to SNCR with ASOFA (Point E) versus ASOFA (Point A); the slope from Point A to Point E was $2,694/ton.

The other elements of the fourth step of a BACT analysis following economic impacts are to evaluate the following impacts of feasible emission controls:

- The energy impacts.
- The environmental impacts.

TABLE 3-14 – Estimated Emissions and Economic Impacts Summary for NO_X Control Alternatives - MRY Station Unit 1

Summary of Estimated Annual Emissions and Economics for NOx Control Alternatives Evaluated for Milton R. Young Station Unit 1

		EMISSIONS(2)					ECONOMIC IMPACTS			
Alt. Label(1)	NOx Control Alternative	Emission Rate lb/mmBtu	Hourly Emission lbs/hr	Annual Emission tons/yr	Emission Reduction tons/yr	NOx Removal Efficiency(2) %	Installed Capital Cost(3) $1,000	Annual O & M Cost(4) $1,000	Levelized Total Annualized Cost(5) $1,000	Average Control Cost(6) $/ton
E	SNCR w/ ASOFA	0.355	975	4,025	5,909	58.1	8,113	5,417	7,472	1,265
D	Gas Reburn w/ ASOFA	0.374	1,025	4,275	5,659	56.0	18,006	28,641	37,334(7)	6,597
C	Lignite Reburn w/ ASOFA	0.385	1,058	4,343	5,591	54.6	46,656	5,862	11,388(7)	2,037
B	FLGR w/ ASOFA	0.460	1,261	5,260	4,674	45.9	10,639	12,863	16,990(7)	3,635
A	Advanced SOFA (ASOFA)	0.513	1,409	5,874	4,060	39.5	4,277	1,695	2,489	613
	Baseline	0.849	2,330	9,934	0	0.0	0	0	0	

(1) - Alternative label has been assigned from highest to lowest unit NOx emission rate.

(2) - Estimated NO_X control level reductions relative to average annual unit emission baseline of 0.849 lb/mmBtu at 2,744 mmBtu/hr MCR heat input. Emissions are calculated from unit emission rates, control percentage, hourly heat input, and annual hrs/yr operation compared to pre-control baseline based on annual operation at a gross unit electrical output of 244.5 MWg and assumes a 97.3% average annual availability. Values from reported emission data for the 12 month operating period during 2001-2005 with the highest rolling summation of NOx pounds.

(3) - Installed capital cost is estimated for determination of total capital cost for a particular technology or combination, assuming 257 MWg unit capacity rating. All cost figures in 2006 dollars. Costs for gas reburn options include high-pressure natural gas supply pipeline installed capital cost of $8,075,000 for CGR and $4,038,000 for FLGR. Costs for increased PM collection capacity included in lignite reburn option are $23,561,000 for installed capital cost.

(4) - Annual operating and maintenance cost for a particular technology or combination is compared to unit baseline operation at a gross unit electrical output of 244.5 MWg and assumes a 96.6% average running plant capacity factor compared to nominal unit gross electrical output capacity of 253 MWg. All cost figures in 2006 dollars. Costs for increased PM collection capacity included in lignite reburn option are $1,909,000/yr for annual O&M cost.

(5) - Levelized Total Annual Cost = Annualized Installed Capital Cost + Levelized Annual O&M cost. Annualized capital cost = Installed capital cost x 0.08718 annualized capital cost factor. Levelized annual O&M cost = Annual O&M cost x 1.24873 annualized O&M cost factor.

(6) - Average Control Cost Effectiveness ($/ton) is the Levelized Total Annual Cost (1000$) divided by Annual Emission Reduction (tons). All cost figures in 2006 dollars.

(7) - LTAC for reburn options include high-pressure natural gas supply pipeline annualized capital cost of $704,000/yr for CGR and $352,000 for FLGR; LTAC for increased PM collection capacity included in lignite reburn option are $2,054,000 for annualized capital cost plus $2,384,000/yr for annualized O&M cost, for a total of $4,438,000/yr.

3.4.2 ENERGY IMPACTS OF MRY STATION NO_X CONTROLS

Operation of the most cost-effective NO_X control technologies considered feasible for potential application at the Milton R. Young Station impose direct impacts on the consumption of energy required for the production of electrical power at the facility. The details of estimated energy usage and costs for the various NO_X control alternatives are summarized in Appendix C3.

Control alternatives for reduction of NO_X emissions were reviewed to determine if the use of the technique or technology will result in any significant or unusual energy penalties or benefits. There are several basic kinds of energy impacts for NO_X emissions controls:

- Potential increase or decrease in power plant energy consumption resulting from a change in thermal (heat) energy to net electrical output conversion efficiency of the unit, usually expressed as an hourly unit heat rate (Btu/kW-hr) or the inverse of pounds of pollutant per unit electrical power output (MW-hr). This may or may not change the net electrical output (MW) capacity of the EGU, depending on if there are physical or imposed limits on the total heat input to the boiler or electrical power output.
- Potential increase or decrease in net electrical output of the unit, resulting from changes in physical operational limitations imposed on the ability to sustain a fuel heat input rate (mmBtu/hr) which results in a potentially lower or higher unit net electrical output (MW) capacity. This is effectively a change in net electrical output (MW) capacity of the EGU.
- Potential increase or decrease in net electrical output of the unit, resulting from changes in auxiliary electrical power demand and usage (kW, kW-hrs). This is effectively a change in net electrical output (MW) capacity of the EGU.
- Potential increase or decrease in reliability and availability to generate electrical power. This results in a change to the number of hours of annual operation, not necessarily a change in net electrical output (MW) capacity of the EGU.

3.4.2.1 ENERGY IMPACTS OF SOFA TECHNOLOGY

There should not be a major impact on energy consumption resulting from the operation of the advanced variation of a separated overfire air system. SOFA does not significantly change the total amount of air introduced into the boiler, only the location where it is introduced. Damper resistance and supply pressure impacts of the SOFA system on fan power consumption should be insignificant. The amount of flyash emitted from the boiler is expected to be reduced (less than five percent) from the baseline level

when the SOFA system is in full operation. Slightly higher levels of unburned carbon in the flyash may occur with the operation of a SOFA system. This could have a small negative impact on the plant heat rate (higher Btu/kw-hr). These changes are expected to be within the typical range of current operation.

There is a potential reduction in reliability and availability of a lignite-fired cyclone boiler to generate steam for production of electrical power as a result of installing and operating a separated overfire air system. Typical SOFA operation on bituminous or western subbituminous coal-fired cyclone boilers does not carry a significant additional risk of causing insufficient or excessive accumulation of slag within the cyclone barrels or furnace bottom compared with non air-staged combustion. Reliable boiler operation depends on avoiding such adverse conditions in the cyclones and lower furnace, which could require a forced outage to remove the solidified slag prior to returning the boiler to generation production service.

The challenges of maintaining adequate slag layer development and flow while firing lignite in MRY Unit 1's cyclones under excess air conditions have been significant during the operating history of the powerplant. Minimizing forced outages resulting from cyclone slag issues have largely been successful through operational practices that do not affect day-to-day boiler reliability and availability. Due to the variability of combustion characteristics of lignite supplied from the Center mine, and the dependency of the slag flow on the temperature within the cyclone barrels or furnace bottom, conditions may occur during ASOFA operation that exceed the ability to adjust operational practices sufficiently to avoid forced outages to remove the solidified slag.

The potential impact on annual unit operating time due to cyclone slag issues associated with air-staged cyclones/ASOFA system operation was estimated to be approximately 2% reduction from the assumed pre-control baseline availability, i.e. 0.97-0.02=0.95. The estimated electrical generation production lost due to the reduction in MRY Unit 1's annual availability is shown in Table 3-16.

3.4.2.2 ENERGY IMPACTS OF SNCR TECHNOLOGY

For SNCR, the injection of a diluted urea solution will require some additional auxiliary power for heating and pumping the liquid and using compressed air for atomization and cooling the reagent injection nozzles/lances, on the order of 70 to 200 kW. The injection of water (used for urea dilution) into the boiler flue gas also will have a small negative impact on the plant heat rate (higher Btu/kw-hr), although the vendor of SNCR systems advises that the heat released from the oxidation of a portion of the

injected urea compensates for this impact. The impact of additional flue gas created by operation of an SNCR-related system on fan power consumption should be small.

There is a potential reduction in reliability and availability of a lignite-fired cyclone boiler to generate steam for production of electrical power as a result of installing and operating a SNCR-related system. Typical SNCR operation with low ammonia slip when firing low-sulfur western subbituminous coal in cyclone-fired boilers does not carry a significant additional risk of causing excessive fouling of the tubular air preheater compared with non-SNCR operation. Reliable boiler operation depends on avoiding adverse fouling conditions in the air preheater, which could require a forced outage to remove the ash deposits prior to returning the boiler to generation production service.

The challenges of maintaining open passages through the air preheater tubes while firing lignite in MRY Unit 1's cyclones under typical conditions have been minor during the operating history of the powerplant. Minimizing forced outages resulting from ash deposits within the air preheater have largely been successful through operational practices that do not affect day-to-day boiler reliability and availability. Due to the variability of fouling characteristics of lignite supplied from the Center mine, and the dependency of the fouling within the air preheater on sodium, sulfur, and ammonia slip emission levels, conditions may occur during SNCR operation that exceed the ability to adjust operational practices sufficiently to avoid forced outages to remove the air preheater deposits.

The potential impact on annual unit operating time due to air preheater fouling and other potential issues associated with SNCR system operation was estimated to be an incremental 1% reduction from the assumed pre-control baseline or ASOFA availability. The estimated electrical generation production lost due to the reduction in MRY Unit 1's annual availability is shown in Table 3-16.

TABLE 3-15 – Expected Auxiliary Electrical Power Impacts for NO_X Controls - MRY Station Unit 1

Alt. Label(1)	NOx Control Technique	Estimated Annual Average Auxiliary Electrical Power Demand and Consumption for NOx Control Equipment	
		Gross Demand(2) kW	Power Usage(3) kW-hrs/yr
E	SNCR w/ ASOFA	73	582,411
A	Advanced SOFA (ASOFA)	1	8,058

(1) – Alternative number has been previously assigned from highest to lowest unit NOx emission rate.
(2) – The APC NOx equipment gross auxiliary electrical power demand of alternatives is the sum of individual technologies combined by simple addition. Actual power demands may differ from this due to positive or negative synergistic effects.
(3) – The annual change in APC NOx equipment auxiliary electrical power demand electricity usage in kW-hrs/yr for these alternatives is the net power demand multiplied by the estimated annual operating time and running plant capacity factor which reflects the adjustment for any expected reliability and capacity impacts from the implementation of the control technique. A negative reduction in generation is an increase in annual new electrical power available for sale.

TABLE 3-16 – Expected Electrical Power Generation Availability and Capacity Impacts for NO_X Controls - MRY Station Unit 1

Alt. Label(1)	NOx Control Technique	Estimated Annual Average Availability(2)	Estimated Annual Average Operating Time Reduction, hrs/yr(3)	Estimated Annual Average Running Plant Capacity Factor(4)	Estimated Annual Average Electricity Generation Reduction kW-hrs/yr(5)
E	SNCR w/ ASOFA	0.956	273	0.965	67,660,606
A	Advanced SOFA (ASOFA)	0.952	188	0.966	46,586.546

(1) – Alternative number has been previously assigned from least removal to highest removal percentage.
(2) – Baseline availability is assumed at 97.3 percent. These values reflect estimated amounts of negative reliability impact expected from the implementation of the individual NOx control technique.
(3) – Annual lost operating time resulting from the implementation of the individual NOx control technique is the difference between the baseline and expected annual outage times.
(4) – Baseline running plant capacity factor is assumed at 96.6 percent. These values reflect estimated amounts of negative reliability impact expected from the implementation of the individual NOx control technique.
(5) – Annual electricity generation reduction is annual reduction of operating time multiplied by the annual running plant capacity factor resulting from the implementation of the individual NOx control technique multiplied by the MCR capacity rating of 253 MW (MCR gross unit electrical output capacity).

TABLE 3-17 – Expected Total Electrical Power Generation Impacts for NO_X Controls - MRY Station Unit 1

Alt. Label[1]	NOx Control Technique	Power Usage[2] kW-hrs/yr	Estimated Annual Average Electricity Generation Reduction[3] kW-hrs/yr	Est. Total Annual Change in Net Electrical Power Generation Available for Sale[4] kW-hrs/yr
E	SNCR w/ ASOFA	582,411	67,660.606	68,243,017
A	Advanced SOFA (ASOFA)	8,058	46,586.546	46,594,605

(1) – Alternative number has been previously assigned from least removal to highest removal percentage.
(2) – The annual change in APC NOx equipment auxiliary electrical power demand electricity usage in kW-hrs/yr for these alternatives is the net power demand multiplied by the estimated annual operating time and running plant capacity factor which reflects the adjustment for any expected reliability and capacity impacts from the implementation of the control technique. A negative reduction in generation is an increase in annual new electrical power available for sale.
(3) – Annual electricity generation reduction is annual reduction of operating time multiplied by the annual running plant capacity factor resulting from the implementation of the individual NOx control technique multiplied by the MCR capacity rating of 253 MW (MCR gross unit electrical output capacity).
(4) – Annual change in net electrical power generation available for sale is arithmetic sum of annual power generation reduction due to a change in the auxiliary electrical power consumed plus the annual generation reduction from a decrease in annual operating time and average annual running plant capacity factor resulting from the implementation of the individual NOx control technique, compared with baseline.

3.4.3 ENVIRONMENTAL IMPACTS OF NOx CONTROLS - MRY STATION

Nitrogen oxides react with oxygen in the atmosphere to produce elemental nitrogen and ozone (O_3). This is one of the common causes of visible pollution in the atmosphere referred to as "smog". Operation of the various NO_X control technologies considered for potential application at the Milton R. Young Station impose direct and indirect impacts on the environment. The most pronounced direct environmental impact expected from operation of any of the NO_X control options considered is the reduction of ozone and improvement in atmospheric visibility (i.e. reduced visibility impairment) downwind of the facility.

3.4.3.1 ENVIRONMENTAL IMPACTS OF SOFA TECHNOLOGY

The operation of a separated overfire air system is expected to slightly increase carbon monoxide concentrations in the stack flue gas. The advanced form of SOFA alternative is expected to slightly lower the amount of particulate matter emitted from the boiler and may raise the amount of unburned carbon in the flyash collected for land disposal and emitted to the atmosphere by small increments. Alternatives involving forms of gas reburn should experience lower particulate emissions, and a reduction in the amount of boiler bottom and flyash requiring disposal.

The environmental impact from potential reduction of annual unit operating time by approximately two percent due to cyclone slag issues associated with air-staged cyclones/ASOFA system operation will be to reduce the annual amount (tons) of nitrogen oxides emitted, and therefore the annual number of NO_X tons removed will increase, by approximately two percent.

3.4.3.2 ENVIRONMENTAL IMPACTS OF SNCR TECHNOLOGY

Operation of a conventional SNCR system is not expected to significantly impact emissions of CO or volatile organic compounds (VOCs).

Operation of an SNCR system will normally create a small amount of unreacted urea or ammonia to be emitted. The amount of ammonia slip produced by SNCR depends on the amount of reagent utilization and location of the injection points. Higher SNCR NO_X reduction performance involves greater amounts of reagent usage and ammonia slip. This is typically controlled to less than 10 ppmvd, especially when the possible formation of sulfates such as ammonium sulfate [$(NH_4)_2SO_4$] and ammonium bisulfate [NH_4HSO_4] will be more problematic at higher slip levels. Sulfur trioxide (SO_3) formed during combustion in the boiler can combine with ammonia during passage through the flue gas ductwork to form the sulfates.

Some of the unreacted ammonia from SNCR operation will be collected with the flyash in the electrostatic precipitator. Any remaining ammonia slip that is not collected or condensed in the air pollution control system will be emitted from the stack as an aerosol or condensable particulate. This has the potential to increase atmospheric visibility impairment downwind of the facility compared with a pristine condition. Although the predicted amount of such potential impact from ammonia slip emissions has not been determined, it is expected to be small in comparison with the significant anticipated reduction in far-field ozone and improvement in atmospheric visibility as a result of the overall NOx emission reduction.

Delivery of the urea reagent to the powerplant facility and storage of aqueous urea reagent on-site creates the potential for accidents, leaks, and subsequent releases to air, ground, and surface water immediately surrounding the facility. Urea is much less volatile than anhydrous or aqueous ammonia, and these risks are expected to be manageable. Emergency planning and community communications are part of the management plan requirements for such reagent usage.

The environmental impact from potential reduction of annual unit operating time by approximately one percent due to air preheater fouling issues associated with SNCR system operation will be to reduce the annual amount (tons) of nitrogen oxides emitted, and therefore the annual number of NO_X tons eliminated relative to the constant pre-control emission baseline will increase by approximately one percent.

3.4.4 SUMMARY OF ECONOMIC, ENERGY AND ENVIRONMENTAL IMPACTS OF MRY STATION NO_X CONTROLS

The economic, energy, and environmental impacts of each feasible BACT alternative evaluated for this study is summarized in this Section. Table 3-18 summarizes the various impacts discussed in Sections 3.4.1 through 3.4.3. The economic analysis examined the capital cost of each feasible BACT alternative evaluated and any other powerplant upgrade costs necessary to implement the alternative. In addition, the economic analysis examined the operating and maintenance cost associated with the highest-performing forms of each feasible BACT alternative evaluated. These costs were then combined into the levelized total annual cost for a comparative assessment of the total implementation cost of each alternative. Finally, as part of the top-down analysis, a dominant controls cost curve was plotted and the unit control cost for each alternative was evaluated. Two alternatives were on the dominant controls cost curve and thus were identified as the more cost effective alternatives. The two BACT NO_X control alternatives evaluated for incremental cost, energy, and environmental impacts applicable to Milton R. Young Station Unit 1 were:

- Selective Non-Catalytic Reduction (SNCR) combined with a special form of separated overfire air (SOFA) specifically for lignite-fired cyclone boilers (referred to as Advanced SOFA or ASOFA); and
- ASOFA alone.

TABLE 3-18 – Summary of Top-Down B

Alt. Label[1]	NOx Control Alternative	Emission Rate lb/mmBtu	PACTS: Incremental Annual Aux. Power Usage Generation Reduction[8], kW-hrs/yr	ENVIRONMENTAL IMPACTS: Non-Air Increase	ENVIRONMENTAL IMPACTS: Toxic Air Increase
E	SNCR w/ ASOFA	0.355	68,243,017	Flyash UBC	CO, NH_3
A	Advanced SOFA (ASOFA)	0.513	46,594,605	Flyash UBC	CO
	Baseline	0.849			

(1) - Alternative label has been assigned from highest to lc
(2) - Estimated NO_X control level reductions relative to avt, and annual hrs/yr operation compared to pre-control baseline based on
(3) - Installed capital cost is estimated for determination on capacity included in lignite reburn option are $23,561,000 for installed ca
(4) - Annual operating and maintenance cost for a particulch is the highest consecutive 12-months of operation from 2001-200
(5) - Levelized Total Annual Cost = Annualized Installed ual O&M cost x 1.24873 annualized O&M cost factor.
(6) - Average Control Cost Effectiveness ($/ton) is the Le
(7) - Incremental Control Cost Effectiveness ($/ton) is the
(8) - Energy impacts are incremental auxiliary electrical p(kW-hrs/yr).
(9) - Environmental impacts summarize expected non-air centrations likely will increase with air-staging cyclones. Excess unreacte

3.5 BACT RECOMMENDATIONS AND CONTROL LEVELS – MRY STATION UNIT 1

This report presents the analysis of control technologies for nitrogen oxides (NO_X) for Minnkota Power Cooperative's (MPC's) Milton R. Young Station Unit 1 using the EPA's "top-down" BACT approach. BACT is an emissions limitation for each pollutant from a source determined to be achievable using control technologies(s) that provide the "maximum degree of emission reduction…taking into account energy, environmental, and economic impacts"[30]. A BACT review does not result in a percent removal efficiency requirement. The generally accepted procedures for performing a BACT analysis are outlined in the EPA's draft NSR Manual. The BACT analysis for Milton R. Young Station NO_X emissions was performed in accordance with this procedure. The EPA's draft NSR Manual outlines five basic steps that are to be followed in the "top-down" BACT evaluation. These steps were as follows:

Step 1 – Identify All Control Technologies
Step 2 – Eliminate Technically Infeasible Options
Step 3 – Rank Remaining Control Technologies by Control Effectiveness
Step 4 – Evaluate Most Effective Controls and Document Results
Step 5 – Select BACT

The final result of this analysis is a recommendation of the BACT alternative and the associated NO_X emission rate for Minnkota Power Cooperative's Milton R. Young Station Unit 1. The emission limitations for a generation facility are expressed in a pounds per million British Thermal Units (lb/mmBtu) basis.

3.5.1 UNIT 1 NO_X BACT

In step one of the technology evaluation, three basic categories of NO_X controls for EGUs were-identified: pre-combustion, combustion, and post-combustion. Eleven basic types of NO_X control processes were identified within these three categories. Twenty four variations of these eleven processes were reviewed for availability and applicability to cyclone-fired EGUs burning North Dakota lignite. An "advanced" form of Separated Overfire Air, alone and in various combinations with Lignite Reburn, Selective Non-Catalytic Reduction (SNCR), Conventional Gas Reburn and

[30] Ibid, NSR Manual B.1

Fuel Lean Gas Reburn™, was evaluated for cost-effectiveness. The cost-effectiveness analysis indicated that ASOFA alone, and ASOFA with SNCR were cost effective alternatives for MRY Station Unit 1 NO_X control. The energy and environmental impacts analysis for MRY Station Unit 1's cost-effective NO_X control alternatives were generally insignificant.

Based upon the definition of BACT and the results of the BACT analysis, Selective Non-Catalytic Reduction (SNCR) in combination with a special form of separated overfire air (SOFA) specifically for lignite-fired cyclone boilers (referred to as Advanced SOFA or ASOFA) is recommended as the Best Available Control Technology for nitrogen oxides emissions from Minnkota Power Cooperative's Milton R. Young Station Unit 1. The unit BACT NO_X emissions rate for MRYS Unit 1 is 0.355 lb/mmBtu , determined as a rolling 12-month average. This is shown in Table 3-19.

TABLE 3-19 – NO_X Emission Control Technology and Rate Recommended as BACT for Milton R. Young Station Unit 1

Control Technology and Emission Rate Recommended as BACT			
Unit	**Pollutant**	**BACT Control Method**	**12-Month Rolling Average BACT NOx Emission Rate (lb/mmBtu)**
1	NO_X	Selective Non-Catalytic Reduction with Advanced Separated Overfire Air (ASOFA)	0.355

3.5.2 EMISSION RATE LIMITATION RECOMMENDATION

To complete the BACT determination process, the Consent Decree (CD) requires that "specific control technologies to be installed and a specific Phase II 30-day Rolling Average NO_X Emission Rate limitation (lbs/MMBtu)"[31] (pounds per million Btu) must be established for each subject emission Unit. The CD also states that "a "30-day Rolling Average Emission Rate" shall be determined by calculating an arithmetic average of all hourly emission rates in lbs/MMBtu for the current Operating Day and the previous 29 Operating Days. A new 30-day Rolling Average Emission Rate shall be calculated for each new Operating Day. Each 30-day Rolling Average Emission Rate shall include startup, shutdown, and Malfunction periods within each Operating Day"[32].

[31] Ibid footnote number 1, Paragraph 66, page 20.
[32] Ibid footnote number 1, Paragraph 5, page 4.

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A recent SEGU proposed PSD permit has included a definition of startup as "the period beginning with ignition and lasting until the equipment has reached a continuous operating level and operating permit limits"[36]. Similarly, a shutdown is defined as "the period beginning with the lowering of equipment from base load and lasting until fuel is no longer added to the boiler and combustion has ceased"[37]. Based on the referenced definitions of a startup period and a shutdown period, the amount of time required for a SEGU's load (boiler steam output or generator electrical output) to increase beyond such minimum sustainable operating levels can be considered part of startup events if the SEGU is typically base-loaded at full load or MCR output. This is the case with both MRY Station SEGUs.

Startups of SEGUs may be labeled as cold, warm, and hot to account for the amount of residual heat remaining in the boiler and steam turbine equipment. The various types of starts are dependent upon the amount of time the SEGU has been out-of-service (i.e. without boiler fuel firing or generator megawatt output). Cold starts have been defined as starts after the boiler has been without fuel firing for more than 72 hours, warm starts are more than 8 hours and less than 72 hours, and hot starts are less than 8 hours[38].

Although the definition of a startup event and the corresponding startup period is not required by the Consent Decree, defining start-ups is recommended. This helps to address the specific emission limitations during Unit startups at Milton R. Young Station and determine the impact of such operations on 30-day rolling average NO_X emissions. For the purpose of this NO_X BACT analysis, a Unit startup was defined as the period from initial fuel combustion to the point in time when:

- the measured Heat Input to the boiler on a 6-hour rolling average basis is greater than or equal to 2500 million BTU/hr for Unit 1; or
- the amount of time reported for the longest individual Unit 1 startup period during actual operation between January 1, 2001 and December 31, 2005 elapses, whichever occurs first; or
- fuel firing is discontinued prior to satisfying either previous criteria.

This startup definition for MRY Station Unit 1 accounts for conditions where cyclone refractory materials replaced during boiler overhauls must be cured by extended low-firing heating cycles,

[36] Desert Rock Energy Center (AZP04-01) Proposed PSD Permit Conditions, page 7. (http://www.epa.gov/region09/air/permit/desertrock/#permit)
[37] Ibid, page 7.
[38] Application for Prevention of Significant Deterioration Permit for the Desert Rock Energy Facility, Document Number 09417-360-250R1, May 2004, page 5-1.

unit controls are upgraded and must be adjusted during low-load operation, or for boiler feedwater quality to improve after boiler maintenance has been performed that affects the insides of the waterwall and superheated steam tubes. It also allows for a failed or interrupted start sequence which can require considerably less or more time to elapse than an average startup duration.

Analysis of MRY Station Unit 1 operations data from 2001 through 2005 revealed:

- There were 60 total startups in the five year period;
- Minimum startup was 10 hours for a "hot" start following a boiler master fuel interruption (Unit "trip");
- Maximum startup with an extended ramp-up period until full load was reached was 61 hours.

Unit 1 had a start-up that began on June 27, 2005 that lasted for 61 hours. This startup included initial firing in the 5th hour of 6/27 (0500 hours being the beginning of the startup period), and which ended at the end of the 17th hour (i.e. at 1800 hours) on June 29th, 2005 upon reaching a generator output of 245 MW (gross) rather than a 6-hour average heat input rate of more than 2500 million Btu per hour.

There are certain boiler operating conditions that need to exist before the BACT NOx control techniques and technologies can be effectively operated:

1. The furnace gas temperature in the region where a urea reagent solution is injected for SNCR-based NO_X control must be between 1700°F and 2100°F. This region is expected to be in the vicinity of the furnace exit, which is commonly defined as either the horizontal plane extending from the furnace rear wall arch ("nose") to the front wall of the boiler, or the vertical plane from the nose up to the furnace roof, upstream of the gas inlet to the superheater tube banks. The gas temperature (FEGT) range in this furnace region is dependent on boiler heat input rate and cleanliness of the firesides of the furnace walls, which affects the amount of radiant energy absorbed by the wall tubes and transferred to the water within.
2. The numbers of active cyclones and continuous coal firing rates must be enough to establish sufficient:
   a. coverage of molten slag on the actively-fired cyclone barrel surfaces and drainage of the slag from the bottom of the boiler; and

b. combustion airflow through the actively-fired cyclones to allow a portion to be diverted to the separated overfire air system above the amount required for idle cyclone cooling and SOFA nozzle cooling.

As previously discussed, furnace exit flue gas temperatures (FEGTs) will need to be measured or determined empirically during operation of the MRY Station boilers in order to be able to effectively control NO_X emissions using SNCR technology. The design and operation of the SNCR systems at MRYS for CD Phase II emissions control should include features that accommodate cyclone boiler startups and low-load operation with "clean" or "dirty" boiler heat transfer surfaces as soon as conditions occur that are technically practicable, i.e. within the SNCR system vendor's recommended operating guidelines, as well as full-load conditions in order to minimize NO_X emissions.

The amount and duration of sustained boiler heat input required to establish the operating conditions described in item 2 above is more difficult to precisely determine. Lignite heat content variability and inability to accurately determine the actual air/fuel ratio on a cyclone-by-cyclone basis in real-time, and the slagging and fouling characteristics of the lignite ash, cause (and are expected to continue to cause) difficulties with stable combustion performance. The minimum firing rates of the MRY Station boilers required to successfully initiate the effective operation of the SOFA system are specific to each individual boiler, and are not currently known. Due to such operating problems and emission control limitations, the ability to effectively limit NO_X emissions during startup periods and low-load operation following implementation of advanced SOFA (CD Phase I control) and/or an SNCR system (CD Phase II control) is uncertain.

Because there are expected to be minor short term variations in operating conditions during startups where Minnkota has not, in fact, materially changed any of their normal startup operating practices and criteria, a margin between the 30-day rolling average steady-state NO_X emission rate (which does not include the impacts of startups) and the proposed 30-day rolling average NO_X emission permit limit that includes startup emissions is recommended. This rate considered recognized operational factors and equipment designs applied to steady state conditions with sustained output close to maximum continuous capacity ratings. The recommended 30-day Rolling Average NO_X Emission Rate permit limitation excluding the impact of startups that reflects BACT for Milton R. Young Station Unit 1 is shown in the table below.

TABLE 3-20 – Recommended NO_X BACT Control Method and 30-Day Rolling Average NO_X Emission Rate Limit Without Startups

Unit	Pollutant	Control Method	30-day Rolling Average NOx Emission Rate Limit Excluding Startups (lb/million Btu)
1	NO_X	Selective Non-Catalytic Reduction with Advanced Separated Overfire Air (ASOFA)	0.360

This recommended BACT 30-day NO_X emission rate limit is based upon a historic pre-control 30-day baseline average NO_X emission rate of 0.884 lb/mmBtu for Unit 1. The baseline emission was determined from the 30-consecutive day period with the highest historic unit NO_X emissions rate reported for actual operation between January 1,2001 and December 31, 2005.

A recommended BACT 30-day NO_X emission rate limit that includes the impact of startup emissions should be suitably higher such that operation consistent with the technological limitations, manufacturer's specifications, and good engineering and maintenance practices to the extent practicable for the MRY Station boilers would not result in an exceedance (violation) of an enforceable 30-day rolling average NO_X emission permit limit.

For MRYS Unit 1, the recommended 30-day rolling average NO_X emission permit limit rate that includes the impact of startups is based upon recognized operational factors and equipment designs that influence whether the startup emissions result in higher 30-day emissions compared to normal continuous operation without or excluding such startup periods:

1. The uncontrolled emission rate (i.e. without separated OFA or SNCR in operation) and its variability during operation from a cold, warm, or hot startup up to and including maximum continuous rated output;
2. The operating conditions that are required to exist for the selected NO_X BACT control techniques to be initiated and be effective; and
3. The effectiveness of these two particular control techniques if invoked at less-than-MCR steady-state operating conditions.
4. The number of startups and their range of typical durations per 30-day period time frame.

The June 27-29, 2005 startup was chosen for additional evaluation as the start-up for MRY Station Unit 1.

An incremental adjustment to the proposed 30-day rolling average steady-state unit NO_X BACT emission rate without startups of 0.36 lb/mmBtu for Unit 1 is recommended for the 30-day rolling average NO_X emission permit limit periods as defined and applied to Milton R. Young Station. This is summarized in the table below.

TABLE 3-21 – Recommended BACT 30-Day Rolling Average NO_X Emission Rate Limit and Startup Impact

Unit	30-day Rolling Average NOx Emission Rate Limit Excluding Startups (lb/million Btu)	Impact on 30-day Rolling Average NOx Emission Rate Limit Due to Startups (lb/million Btu)
1	0.360	+0.041 per startup

This recommended adjustment to the proposed 30-day rolling average steady-state NO_X BACT emission rate limit without startups is based upon average historic pre-control NO_X emission rates of 0.766 lb/mmBtu for Unit 1 reported for the longest individual Unit 1 startup period during actual operation between January 1, 2001 and December 31, 2005. These emissions occurred during the 61-hour June 27-29, 2005 startup for Unit 1.

A 24-hour rolling average BACT NO_X emission rate limit applied to startup periods is also recommended for each of the Milton R. Young Station boilers.

This is summarized in the table below.

TABLE 3-22 – Recommended 24-Hour Rolling Average NO_X Emission Rate Limit During Startups

Unit	24-hour Rolling Average NOx Emission Rate Limit During Startups (lb/million Btu)
1	0.980

These emissions occurred during the 61-hour June 27-29, 2005 startup for Unit 1.

Compliance with these emission rates would be measured at the stack of the Unit, verified with Continuous Emission Monitoring (CEM) systems in accordance with the reference methods specified in 40 C.F.R. Part 75, and would be determined on a 30 consecutive Operating Day and 24-consecutive hour rolling average basis, respectively.

A trial demonstration operating period of 18 months after the completion of Consent Decree Phase II NO_X emission reduction system installation commissioning at Milton R. Young Station is recommended. It is proposed to allow Minnkota to demonstrate the actual control system capabilities of the combined NO_X BACT emissions reduction system. Operating experience during the trial period will:

- confirm steady-state control performance of the combined NO_X BACT emissions reduction system;
- allow determination of the ability to further control Unit start-up emissions;
- allow the determination of the permitted 30-day rolling average NO_X emission limit including startups, shutdowns, and malfunctions; and
- address the specific emission limitations during Unit startups at Milton R. Young Station and their impact on the proposed 30-day rolling average emission rate limit (without startups).

Based upon the information obtained during the trail period, final emission limits can then be determined.

The means that will be employed to minimize emissions during startup will primarily be based on operating procedures, both before and after the level of upper furnace gas temperatures and/or heat input rate are considered sufficient to start the NO_X controls and operating conditions are conducive for effective emissions reduction. These could be similar to Minnkota's current MRYS practices, or could be different, depending upon the capabilities of the NO_X controls and their impacts on Unit operations.

References:

1. In the United States District Court For The District Of North Dakota, United States Of America and State Of North Dakota, Plaintiffs, v. Minnkota Power Cooperative, Inc. and Square Butte Electric Cooperative, Defendants, Civil Action No.1:06-CV-034.

2. EPA New Source Review Workshop Manual, Prevention of Significant Deterioration and Nonattainment Area Permitting, Draft October 1990 (The "NSR Manual").

3. EPA Docket OAR-2002-0076-0446 Technical Support Document for BART NOx Limits for Electric Generating Units Excel Spreadsheet 6/15/2005, posted on their website: from EDOCKET at http://docket.epa.gov/edkpub/do/EDKStaffItemDetailView?objectId=090007d48084562b; this is associated with EPA Acid Rain Program Clean Air Markets Division, Technical Support Document – Methodology For Developing BART NO_x Presumptive Limits, June 15, 2005, OAR-2002-0076-0445.

4. EPA Office of Air Quality Planning and Standards (OAQPS) publication EPA/452/B-02-001, Section 4.2, NO_X Controls – NO_X Post-Combustion, Chapter 1 - Selective Non-Catalytic Reduction, dated October 2000, posted at their website: http://www.epa.gov/ttn/catc/dir1/cs4-2 ch1.pdf

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APPENDIX A

Technical Feasibility Assessment Details for NO_X Control Technologies (A1)

U.S. Coal Cyclone NO_X Reduction Projects Summary

With Retrofit NO_X Control Projects' Technical Literature Summary (A2)

A.1 Technical Feasibility Assessment of NO_X Control Alternatives

A.1.1 Pre-Combustion Fuel Treatment/Switching

Fuel switching can be a viable method of NO_X emission reduction in certain situations. Often, coal combustion facilities are constructed to take maximum advantage of the particular combustion characteristics of a specific fuel. In the case of MRY Station, the Unit 1 and 2 boilers were designed and constructed specifically for firing North Dakota lignite, which has a fuel higher heating value (Btu/lb) approximately 20% lower than typical Powder River Basin (PRB) coal. A cyclone–fired boiler (Ottertail's Big Stone Unit 1) that is similar in geometry and steam generation design to MRY Station Unit 2 fires PRB coal. Based on a comparison of available emission data between Big Stone Unit 1 and MR Young Unit 2, there is no expected reduction in baseline (i.e. uncontrolled) NO_X emissions from switching to PRB from lignite at Milton R. Young Station.

Conversion of Milton R. Young Station Unit 1 boiler to fire PRB coal is technically possible. It is expected that major plant modifications will be required. Rail service is not presently installed at this site, so the additional operational and capital costs to bring in large quantities of PRB coal will be significant. Investigation of the specific source, distance, and costs for supplying necessary quantities of PRB coal via rail or trucks to M.R. Young station has not been performed. With zero baseline NO_X emissions reduction expected from application of fuel switching, this alternative will not be economically competitive with other NO_X control technologies that offer better results for a much lower combination of capital and operational costs. Although fuel switching is technically feasible, it has not been considered further as an effective NO_X emissions control option for MRY Station Unit 1 boiler.

A.1.2 Combustion Controls

Combustion controls comprise the most numerous category of NO_X emission reduction technologies. These techniques employ methods that reduce the amount of NO_X emissions created in the combustion zone of the boiler prior to exhausting the flue gases from the furnace (upstream of the convective heat transfer zones). These controls result in fewer emissions to atmosphere or that may require subsequent reduction from additional applicable combustion and/or post-combustion techniques.

As the boilers in question were designed for firing North Dakota lignite fuel, they were furnished with suitably-sized furnaces and limited back-end economizer heat transfer surfaces upstream of the air preheaters. This provides high temperature air to aid the evaporation of excess moisture from the crushed coal particles in the pre-combustion drying systems, and long residence times for solid and gaseous fuel

particles to burn essentially to completion prior to leaving the furnaces. The latter feature is especially advantageous for applying various forms of combustion modifications which are conducive in reducing NO_X emissions.

A.1.2.1 Basic Combustion Improvements

Combustion improvements are commonly-applied techniques which may produce modest incremental NO_X emissions reductions. In their most basic form, these typically provide improvements to combustion air flow distribution, measurement, and pressure, together with fuel flow measurement and metering, to promote consistent combustion performance by burning fuel with more accuracy in maintaining a desired fuel/air ratio.

These improvements may allow, or be combined with, the practice of several other NO_X control techniques. Separated overfire air (discussed below), with or without "low excess air" (LEA), burners out-of-service (BOOS) and biased firing (BF) operation of the cyclones, cause a decrease in the ratio of combustion air to fuel supplied to the cyclones (burners), thus reducing the amount of thermal NO_X emissions produced during combustion. The amount of potential NO_X emission reduction achievable from these basic techniques is highly-dependent on the specific type of firing, fuel, and conditions which apply to the boiler(s) being reviewed.

Making lignite drying system air adjustments and adding improvements to the boiler combustion controls and reducing combustion air inputs have already reduced uncontrolled NO_X emissions at Milton R. Young Station boilers approximately 10%. Further incremental improvements from additional combustion controls that allow operation with modest amounts of cyclone air staging, similar to the effect of a separated overfire air system, are possible. Incremental NO_X emissions reductions are expected from such improvements being incorporated into another feasible alternative, such as separated overfire air. This alternative was not considered as a stand-alone option for additional NO_X reduction at Milton R. Young Station for the Unit 1 boiler.

A.1.2.2 Low NO_X Burners (LNB)

Low NO_X burners (LNBs) of various designs have been commonly applied to pulverized coal-fired utility and industrial boilers for more than ten years. However, they are not installed on cyclone-fired boilers. This technology is infeasible on cyclone boilers[1], and was eliminated from consideration for additional NO_X reduction at Milton R. Young Station Unit 1's boiler.

A.1.2.3 Separated Overfire Air (SOFA)

Separated overfire air (SOFA) is a combustion-related NO_X emission reduction technology frequently-applied with and without low NO_X burners to utility and industrial boilers for more than twenty five years. Separated Overfire Air (SOFA) is an air-staging NO_X emission reduction combustion technique that is typically based on withholding 15 to 20 percent of the total combustion air conventionally supplied to the firing zone. The diverted combustion air is then injected in the upper furnace, where combustion is completed. For typical cyclone coal-fired boilers, this involves diverting approximately 20 percent of the secondary combustion air, forcing the cyclones to operate fuel-rich. Starved-air combustion causes fewer NO_X emissions to be produced.

At least thirty nine existing cyclone-fired boilers, firing eastern bituminous, midwestern bituminous, and western subbituminous ("Powder River Basin") coals in units ranging in size from 50 to 1150 MW, have been retrofitted with commercial SOFA since 1998. A summary of several of the first SOFA (and reburn) retrofits to cyclone-fired boilers is described in published technical papers[1,2]. Cyclone boiler retrofit SOFA installations are included in the EPA's BART technical support document[3] and listed later in Appendix A2.

A basic form of separated overfire air (SOFA) can be applied and installed on MRY Station Units 1. There are potential impacts and limitations unique to the firing of North Dakota lignite in cyclone-fired boilers that should be recognized as part of this emission reduction technology application.

Key aspects of successfully applying and operating a separated overfire air system on a cyclone-fired boiler are the ability to:

- Accurately measure the fuel heat input rate (BTUs) and combustion air inputs on a real-time, individual cyclone by cyclone basis, to allow the ability to determine and control the desired air/fuel ratio, especially when "starved air" (i.e. substoichiometric) combustion conditions are required.
- Maintain adequate molten coal ash (slag) formation and flow within the barrels and slag taps.

The degree to which the cyclone furnaces can be operated with less than theoretical (substoichiometric) combustion air directly contributes to less NO_X formation and further in-furnace emission reduction but also risks solidification of the molten coal ash. In the case of MRY Station Unit 1 boiler, cyclone combustion must be sufficiently air-staged to reduce NO_X emissions while releasing enough heat to continue to melt the fuel ash so that it flows effectively within and from the cyclone burners.

In the case of MRY Station boilers, there is a significant amount of variability in the combustible and ash components of North Dakota lignite supplied from the current mine near Center, ND. Analysis of several hundred coal feed samples taken simultaneously from multiple cyclones of MRY Station Unit 2's boiler revealed that the maximum differential of the lignite heating values from cyclone-to-cyclone was just over 12% of the average heating value of all the samples. Assuming an operating case occurred where the maximum cyclone-to-cyclone differential heating value was for two cyclones at the opposite ends of the fuel heat content range, there would be a plus or minus 6% variation in fuel heat content for either of the individual cyclones from the overall average. If the desired average cyclone air/fuel (stoichiometric) ratio was 0.95 when operating with air-staged cyclones associated with separated overfire air, and the amount of secondary combustion air to each cyclone was equal, there would be a stoichiometric ratio of approximately 1.01 in one cyclone and a stoichiometric ratio around 0.89 in another cyclone at the same time. The modestly air-staged cyclone would produce higher than average NOx emissions. The deeply staged cyclone would produce less than average NOx emissions and potentially insufficient amounts of heat release, and raise the risk of solidifying the fuel ash so that it accumulates within the cyclone barrel. This could result in firing auxiliary fuel oil in the deeply-staged cyclone or taking the boiler out-of-service to remove the pluggage. Neither of these conditions is desirable because they result in lower emissions removal performance and higher operating costs. Thus, due to the variability of the fuel heat content and the complex behavior of lignite ash when exposed to high temperatures, the extent of air-staging and thus the level of NO_X control in MRY Station boilers is expected to be modest while firing lignite coals.

In order to potentially achieve lower NO_X emission rates with modestly air-staged combustion for MRY Station boilers, additional combustion improvements can be installed. One potential improvement is to implement a unique form of SOFA for North Dakota-lignite–fired cyclone boilers. This includes relocated lignite drying system vent ports. This will be referred to as "Advanced SOFA" (ASOFA). There are several design challenges anticipated for implementing the advanced version (with the described port relocations) of separated OFA. These are believed to be solvable.

Both forms of separated overfire air as a combustion-related NO_X control technique are considered feasible for application to Milton R. Young Station cyclone boilers. Since the advanced SOFA is the highest-performing form of this technology, only this ASOFA version of the alternative was considered for additional NO_X reduction at Milton R. Young Station boilers.

Another form of separated overfire air being marketed commercially is "Rotating Opposed Fire Air" (ROFA). For utility applications in the United States, this has only been applied to pulverized coal-fired boilers, primarily tangentially-fired units[4]. It is different than basic SOFA in that it includes a hot air booster fan, and injects the overfire air in an offset fashion from opposite sides of the furnace at high velocities, with multi-port nozzles located at high elevations relative to the top burner row. The vendor (Mobotec USA) claims ROFA maximizes air-staged in-furnace combustion NOx reduction while minimizing negative impacts on carbon monoxide and flyash unburned carbon.

While this variation of separated overfire air could potentially be applicable to cyclone boilers, it has not been marketed to serve such applications. Because cyclone boilers do not require the addition of hot air booster fans for SOFA, this technique is not distinct enough from basic SOFA from functional and air-staged cyclone NO_X reduction performance standpoints to warrant individual consideration. ROFA technology lacks demonstrated cyclone-fired boiler experience, and thus was considered infeasible and not included in the control effectiveness and cost-effectiveness sections of the main report.

A.1.2.4 Oxygen-Enhanced Combustion

A supplier of liquid oxygen (Praxair) has developed a method of replacing some of the combustion air supplied to the burners with pure oxygen. Combustion air, which is normally input through the secondary air system ductwork downstream of the forced draft (FD) fan and air heater, is supplemented with pure oxygen directly injected into the burners. Oxygen-enhanced combustion (OEC) can reduce boiler NO_X emissions resulting from " thermal NO_X", a reaction of the nitrogen in the combustion air admitted to the burners with the available oxygen in the air in the flame or peak temperature regions of the fuel combustion process. The use of pure oxygen instead of air reduces the availability of nitrogen from the air to be oxidized in the high temperature regions, thus reducing formation of thermal NO_X. This technique has only been demonstrated in a boiler with pulverized fuel burners firing bituminous coal[5].

The lack of adequate experience on any cyclone-fired coal-burning boiler, on a temporary demonstration or permanent full-scale basis, and for a coal-fired facility of this size, precludes consideration of oxygen-enhanced combustion at MRY Station Unit 1's boiler. This is deemed to be infeasible technology at this location at the present time.

A.1.2.5 Flue Gas Recirculation

Flue gas recirculation (FGR) has been commonly applied to coal-fired boilers, primarily to inject into the lower furnace, just above the burners, supplied from the boiler's economizer flue gas outlet via a hot gas booster fan. This modifies the amount and temperature of hot furnace gas either in the lower-middle or upper furnace and convection heat transfer zones. As this flue gas typically has an oxygen content around 2-5%, it limits the availability of oxygen in a high temperature, possibly fuel-rich lower furnace zone. Flue gas recirculation for NO_X control is most commonly applied with gaseous or liquid fossil fuels to reduce the high temperatures which convert nitrogen in the combustion air to nitrogen oxides. No examples of using or installing FGR on cyclone-fired boilers strictly for NO_X emissions control were found in available technical literature.

For MRY Station Unit 1's boiler, FGR was originally supplied from the outlet of the induced draft fans, but has since been discontinued and removed. Since it is not operational on Unit 1, and therefore does not affect the potential performance of separated overfire air (in an "advanced" form), it would not be expected to reduce NO_X emissions if reinstalled alone or in combination with SOFA. Although FGR is technically feasible, it has not been considered further as an effective NO_X emissions control option for MRY Station Unit 1's boiler.

A.1.2.6 Water/Steam Injection (Combustion Tempering)

When applied to older gas-fired and oil-fired utility and industrial boilers, water and/or steam injection adds moisture into the lower furnace, concurrent with or near (to the side or slightly above) the burners, supplied from the boiler's treated feedwater or auxiliary steam systems via a metering pump or valve. There has been some limited testing of water injection for NO_X emissions control on natural gas-fired and coal-fired cyclone boilers[6,1]. For coal-fired cyclones, this technique is most effective on boilers burning bituminous coal; however, it has not been permanently installed and continuously operated in such applications. Successful long-term operation of water injection would be difficult for lignite-fired cyclone boilers, due to the high moisture levels in the coal and the need to readily ignite and sustain stable combustion and molten slag formation in the cyclone furnaces. For these reasons, water/steam injection is considered technically infeasible for NO_X control application at Milton R. Young Station.

A.1.2.7 Fuel Reburn

Another combustion technology that may be applicable to control NO_X emissions from the Milton R. Young Station units is fuel reburn. In a similar manner that overfire air diverts a portion of the combustion air input to the main firing zone, the reburning process involves supplying a portion of the fuel heat input to the boiler at a higher elevation in the furnace. This creates an upper furnace atmosphere where the reburn fuel's combustion products causes some of the NO_X formed in the main burner combustion zone and reburn zone to be converted into molecular nitrogen. Depending on the amount of reburn fuel added and the amount of oxygen available in the furnace gases to combine with the reburn fuel introduced, additional combustion air may be supplied as supplemental or overfire air. Downstream of the air injection elevation, the intention is to complete the reaction of any remaining carbon monoxide (CO) to carbon dioxide (CO_2), plus reduce the amount of combustible matter remaining in the entrained flyash.

The most common forms of reburn technology applied to utility powerplant boilers are:

- Pulverized or micronized coal reburn (PCR or MiCR); and
- Gas reburn (GR).

Pulverized coal reburning and micronized coal reburning have been applied to pulverized coal and cyclone-fired boilers. NO_X reduction efficiencies of 50 to 60 percent have been demonstrated on eastern bituminous coal and midwestern bituminous and Powder River Basin (PRB) western subbituminous coals while supplying up to approximately 20-30% of the boiler's total fuel heat input to the reburn zone[7,8].

For utility powerplant boiler applications, natural gas has been utilized as reburn fuel most often, demonstrated in two basic approaches:

- Conventional gas reburn (CGR); and
- Fuel-lean gas reburn (FLGR™).

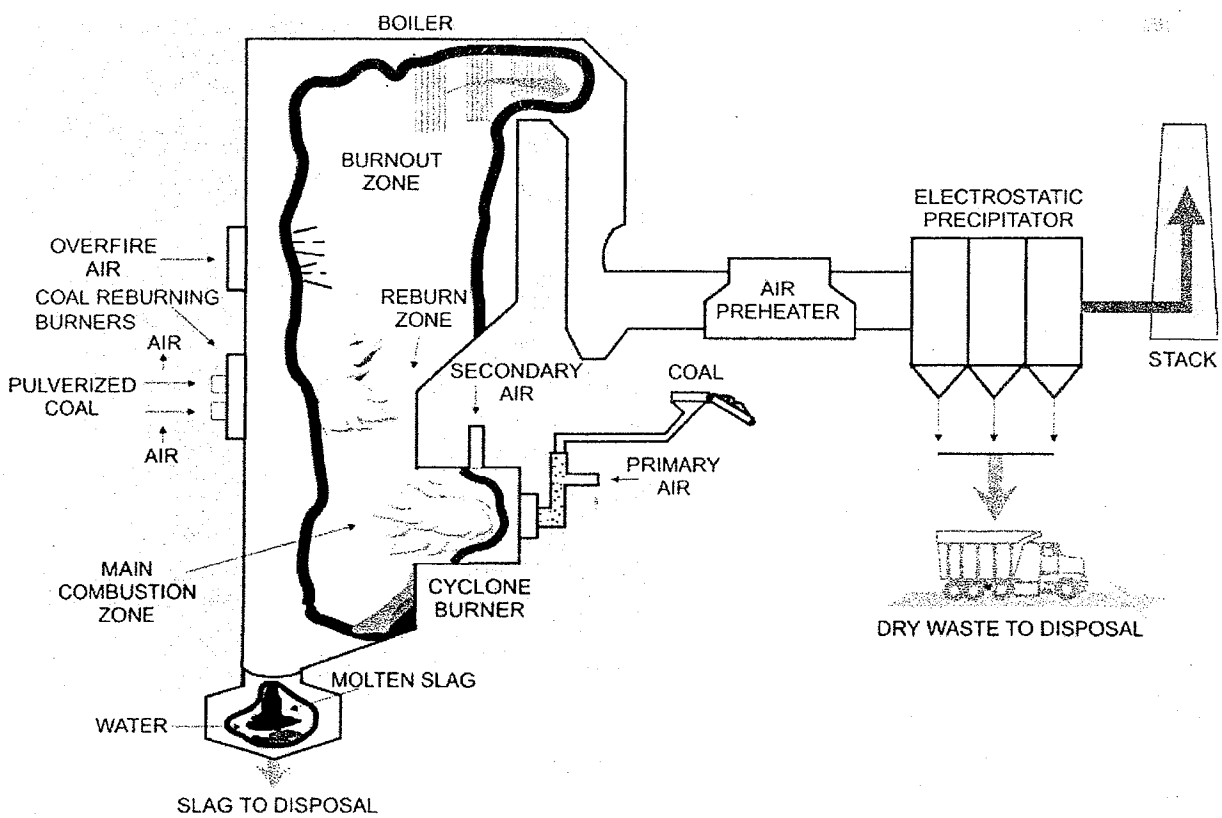
Either natural gas or pulverized coal (lignite) can be used as the reburn fuel. A sufficient quantity of natural gas is not currently available at the Milton R. Young Station plant site. Supplying enough natural gas to provide 6 to 25% of the total heat input to either or both boilers at MRY Station is expected to be technically feasible, although transport pipeline installation capital costs, and current and predicted unit natural gas costs and operating economics, are likely to be unfavorable.

Various forms of fuel reburning have been demonstrated and operated routinely on cyclone boilers for NO_X emission controls. This has been applied to units firing eastern bituminous coal, and western subbituminous or PRB/bituminous coal blends, using pulverized or micronized coal or natural gas as the most common reburn fuel. Reburning for NO_X emissions reduction has not been demonstrated on a unit firing high moisture, low heat content North Dakota lignite. Pulverized/micronized coal, along with conventional and fuel lean gas reburn technologies, are discussed below.

A.1.2.7.1 Coal Reburn

In the case of applying conventional coal reburn to cyclone boilers, the existing cyclones are supplied with the majority of the fuel, with either natural gas or pulverized coal (lignite) used as the reburn fuel such that the total heat input to the boiler is essentially the same as without fuel reburn. Separated OFA ports are located above the reburn fuel injection section of the furnace. These SOFA ports provide sufficient oxygen in a conventional fuel reburn installation to complete the combustion process that begins in the main combustion zone and is supplemented in the reburn and burnout zones. This is shown schematically for a pulverized coal reburn application on a cyclone-fired boiler with SOFA in Figure A.1-1.

Figure A.1-1 Pulverized Coal Reburn Application on Cyclone Boiler With Overfire Air[8]



In the United States, pulverized coal reburning and micronized coal reburning techniques for utility powerplant NO_X emissions reduction have been applied on a very limited full-scale, full-time basis to cyclone-fired boilers in field demonstration tests and longer-term demonstration operation, respectively. There have been only two known pulverized or micronized coal reburn installations in the United States on cyclone boilers, one on a utility boiler in Wisconsin, and one on a small industrial-size cyclone boiler in New York state[7,8,9,10,11,12,13,14]. NO_X emissions reduction efficiencies of 57 percent have been demonstrated on cyclone boilers firing eastern bituminous coal, or midwestern bituminous and Powder River Basin (PRB) western subbituminous coals while supplying up to approximately 20-30% of the boiler's total fuel heat input to the reburn zone. With the exception of the U.S. Department of Energy's (DOE) Clean Coal Technology Program demonstration projects[7,8,9], no known commercially-available coal reburn systems have been installed and are routinely operated on cyclone boilers in the United States to date. The DOE-CCTP projects for coal reburn applied to cyclone boilers are described below.

Pulverized coal reburning for NO_X emissions reduction in a cyclone-fired boiler was demonstrated on the 110 MW Nelson Dewey Unit 2 for Wisconsin Power & Light in 1991-1992. Reburn fuel preparation and handling, reburn burners with flue gas recirculation, and a separated overfire air system were added. Coal reburn tests were conducted on this unit while firing bituminous and PRB coals. NO_X emission control efficiencies of 50 to 60 percent, with reductions from 0.75-0.83 lb/mmBtu baselines to around 0.38 lb/mmBtu, but as low as 0.29 to 0.32 lb/mmBtu, with PRB coal at full load with approximately 25-30% of the total fuel heat input from reburn fuel were demonstrated[9,11,12]. The reburn system is no longer operated on Nelson Dewey Unit 2.

Micronized coal reburning has been demonstrated in 1997-1998, and continues to operate year-round on a small industrial cyclone boiler (400,000 lb/hr steam output, 50 MW gross equivalent) for Eastman Kodak Company at their Kodak Park facility in Rochester, NY. This unit (Boiler #15) achieves a NO_X reduction efficiency of approximately 57 percent on eastern bituminous coal, involving limited cyclone air-staging (cyclones believed to be slightly above 0% excess air) and a modest amount of overfire air injection downstream of the micronized reburn fuel input nozzles. Approximately 17% of the boiler's total fuel heat input is typically supplied to the reburn zone. This coal reburn system continues to operate routinely at this facility. This installation is reported to use a Fuller MicroMill to produce micronized coal with 80% passing through a 325 mesh screen[7,9,13].

If a coal reburn system was applied to MRY Station boilers, the existing cyclones would be supplied with the majority of the fuel in the form of crushed coal, and the balance of fuel would be supplied to a pair of dedicated pulverizers to feed the reburn injection ports, such that the total heat input to the boiler is essentially the same as without fuel reburn. In a conventional fuel reburn installation, OFA ports located above the reburn section of the furnace provide sufficient oxygen to complete the combustion process that begins in the main combustion zone and is supplemented in the reburn and burnout zones.

Similar to the application of separated overfire air, there are potential impacts and limitations unique to the firing of North Dakota lignite in cyclone-fired boilers that should be recognized as part of this emission reduction technology application. As a reburn fuel, lignite is expected to behave appropriately upon introduction in the lower middle furnace to help reduce NO_X emissions. The concerns are that the diversion of a significant amount of heat input from the cyclone barrels to use as a source of reburn fuel in the form of pulverized or micronized lignite may reduce cyclone temperatures enough to inhibit slag formation and flow, especially as boiler load is reduced. Air-staging the cyclones with the use of separated overfire air to further complement combustion NO_X reduction as part of this reburn technique will further risk slag "freezing" in the barrels and lower furnace. Reducing the number of active cyclones which are air- and fuel-staged to accommodate reduced firing rates while operating a coal-fired boiler with reburn and separated overfire air is the typical approach to avoid slag tapping problems.

Potential NO_X emissions reduction performance is expected to be limited on lignite-fired cyclone boilers with a basic form of separated overfire air system, since the reburn fuel injection location is expected to coincide with the existing lignite pre-drying system vent ports. The amount of oxygen introduced by the vent ports will be disruptive to any conventional reburn process in that it would require much higher reburn fuel injection rates to create a substoichiometric atmosphere in the lower secondary furnace that is conducive to promoting in-furnace NO_X reduction.

Significant additions to the fuel preparation equipment in the existing plant facilities will be required. The coal reburn system expected to be applied to MRY Station boilers may use two new fine-grind pulverizers and dynamic classifiers to achieve the level of coal particle size distribution required.

Higher unburned carbon levels in the flyash exhausted from the boiler may occur, especially when the reburn fuel is coal, and the regular burners are fired with less than theoretical amounts or combustion air commonly practiced with the use of overfire air. Lowering the reburn fuel injection elevation, decreasing

the amount of reburn fuel, and grinding the reburn coal to a greater degree of fineness can help to offset some of the increase in flyash unburned carbon content. Flue gas opacity from the stack may increase if the particulate removal equipment is an electrostatic precipitator, due primarily to reduced resistivity and smaller particle sizes of the flyash.

An issue that affects the feasibility of lignite reburning is the uptime required for the lignite reburn fuel pulverizing system, and impact of the reburn system on effectiveness in reducing NO_X emissions during load changes and lower loads. Typically, one new pulverizer is dedicated to prepare reburn fuel in existing pulverized fuel-fired boiler applications. Cyclones may be fired with less fuel or deactivated during boiler operation in order to accommodate changes in fuel combustion characteristics, boiler load, and for scheduled or unscheduled individual crusher maintenance. Milton R. Young Station Unit 1 has seven crushers for cyclone coal grinding, each dedicated to one of the seven cyclone furnaces. Diverting as much as 30% of the total heat input as reburn fuel could require two of the existing cyclones to be deactivated, and two new MPS-89 pulverizers to be dedicated to reburn fuel preparation. As each of these mills requires periodic maintenance, boiler emissions and/or load could be negatively impacted during individual reburn mill outage periods while the boiler remained in service. A high level of fineness of coal particles from the reburn mills is important to achieve and maintain in order to limit increases in flyash combustibles. A minimum of 60 percent passing through 200 mesh fineness is recommended by one of the reburn technology vendors (B&W) for pulverized lignite reburn. Micronized coal reburn requires even greater fineness: 70-80 percent passing through a 325 mesh screen.

Pulverized or micronized coal reburn with the advanced form of separated overfire air (ASOFA) can be applied and installed on MRY Station Unit 1's boiler. These combined techniques are expected to reduce NO_X emissions approximately 54% from current pre-control baseline levels (down to 0.385 lb/mmBtu) for the MRY Station Unit 1 boiler. These levels of NO_X reduction depend on the advanced form of separated overfire air technique to achieve the expected NO_X reduction percentages when applied to lignite-fired cyclone boilers, which may not be successful given the concerns expressed about the potential impacts of this technique. Using finely pulverized lignite for reburn fuel is considered technically feasible for NO_X emissions control under evaluation for application to MRY Station Unit 1's boiler.

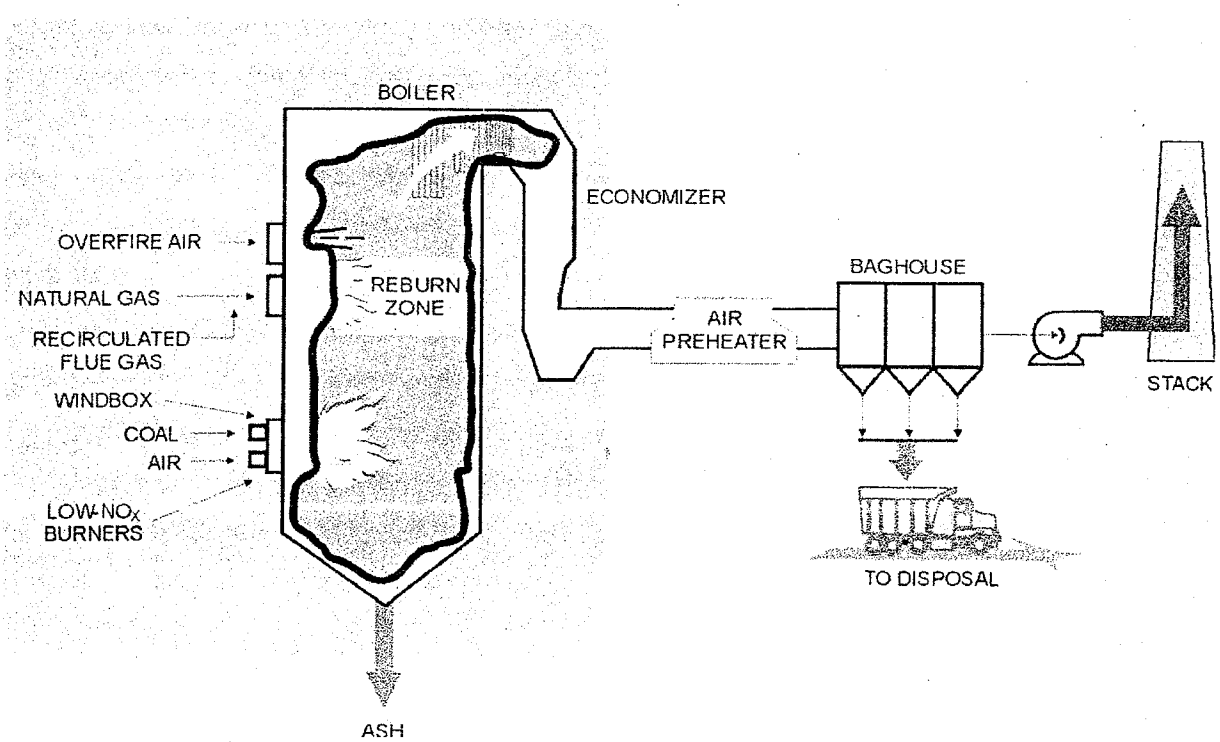
A.1.2.7.2 Conventional Gas Reburn

Natural gas has been preferred as the reburn fuel of choice. Natural gas has been utilized for reburn fuel in two basic approaches: conventional reburn and fuel-lean gas reburn. In the conventional approach, up to 30% of the boiler's total fuel heat input is supplied to the reburn zone, followed by a significant amount of overfire air for completion of combustion prior to flue gases exiting the boiler.

Conventional gas reburning in a cyclone-fired boiler has been available at Tennessee Valley Authority's Allen Station Boiler #1 (300 MW) since 1998. The reburn technology provider (vendor) claims NO_X emissions were reduced 67% from a full-load baseline of 1.29 (down to 0.42) lb/mmBtu when firing a blend of western bituminous and PRB coals[14]. Conventional gas reburn fuel input rates were not available from the technology vendor's literature. Another reference source of information stated NO_X emissions were reduced 65% from a full-load baseline of 0.86 (down to 0.30) lb/mmBtu with 7 percent of the total fuel heat input supplied as reburn fuel[9].

A schematic graphic of conventional gas reburn on a pulverized coal-fired boiler is shown in Figure A.1-2.

Figure A.1-2 Natural Gas Reburn Application on Wall-Fired Pulverized Coal Boiler with Overfire Air[8]



Similar to the application of separated overfire air, there are potential impacts and limitations unique to the firing of North Dakota lignite in cyclone-fired boilers that should be recognized as part of this emission reduction technology application. For the most effective NO_X reduction by applying the various available forms of fuel reburn, the injection of fuel is usually performed using recirculated flue gas as a diluent and carrier media to aid dispersion and avoid completely oxidizing the carbon and nitrogen components in the fuel and furnace gases from staged burners/cyclones. Improved gas reburn designs have reduced or eliminated FGR with higher gas injection pressures. For lignite-fired cyclone boilers, reburn fuel firing with a basic form of separated overfire air is expected to be much less effective in reducing NO_X emissions than previously demonstrated elsewhere. This is related to the likelihood that the injection of reburn fuel will be near the elevation of the existing lignite drying system vent ports, and that the oxygen introduced with the lignite drying system's vented moisture will disrupt the desired in-furnace nitrogen oxides reduction process.

It should be recognized that application of air-staged cyclones with basic or advanced forms of SOFA with reburn techniques will require the overfire air injection ports to be located at a somewhat lower elevation of the furnace compared with air-staged cyclones without reburning. This means that less air-staging of the cyclones may be practiced, or that less residence time will be available for the in-furnace NO_X reduction process to occur.

Similar to coal reburning, there are concerns that withholding a significant amount of heat input from the cyclone barrels to use natural gas as a source of reburn fuel may reduce cyclone temperatures enough to inhibit slag formation and flow, especially as boiler load is reduced. Air-staging the cyclones for use of separated overfire air to further complement combustion NO_X reduction as part of this reburn technique will further risk slag "freezing" in the barrels and lower furnace. Reducing the number of active cyclones which are air- and fuel-staged to accommodate reduced firing rates while operating a coal-fired boiler with conventional reburn and separated overfire air systems is the typical approach to avoid slag tapping problems. Natural gas reburn with the advanced form of separated overfire air (ASOFA) can be applied and installed on Milton R. Young Station's Unit 1 boiler.

Although the unit operating and capital costs to supply large quantities of gaseous fuel not currently available at this site are economic disadvantages, using high-pressure natural gas for reburn fuel is considered technically feasible for NO_X emissions control under evaluation for application to MRY Station Unit 1's boiler.

A.1.2.7.3 Fuel Lean Gas Reburn

Another approach to gas reburning is "fuel-lean gas reburn" (FLGR™) technology, which injects limited amounts of natural gas (approximately 3-10 percent of the total fuel heat input) above the burners (or cyclones) with or without significant air-staging of the burners (cyclones) or the addition of overfire air upstream of the fuel injection elevation. FLGR's first field-test on a cyclone-fired boiler was at Commonwealth Edison's Joliet Unit 6 (327 MW), a 9-cyclone-furnace boiler[15]. NO_X emissions reduction with FLGR (without SOFA) was believed to be approximately 35-40% with 7% of the boiler's total fuel heat input supplied in the reburn zone. This test yielded 0.59 lb/mmBtu NO_X emissions from a baseline of 0.98[16]. One other cyclone boiler has been modeled using computational fluid dynamics (CFD) as part of a study looking at applying FLGR at Owensboro Municipal Utilities' Elmer Smith Station Unit 1 (150 MW single-wall, eastern bituminous coal-fired boiler). This model predicted that NO_X emissions could be reduced by 25-30% over that achievable from overfire air and SNCR[17].

More commonly, FLGR™ has been applied on medium to large pulverized coal wall-fired boilers burning eastern bituminous or western subbituminous coals. On Wisconsin Electric Power Company's (WEPCO's) Pleasant Prairie Unit 1, a 620 MWg Riley turbo-fired wet-bottom (slagging) boiler, FLGR™ alone was predicted to reduce NO_X emissions by 35-39 percent at a gas reburn rate of 7-8 percent but only achieved 20% from a baseline of 0.45 lb/mmBtu[16,18]. This is presumably without burner air-staging or SOFA. It has also been applied in combination with SNCR at this WEPCO site.

A potential advantage of FLGR™ over conventional gas reburn is that the former is generally compatible with, but does not require, the installation and operation of SOFA. The staged reburn fuel is introduced into an oxygen-rich atmosphere downstream of the burners and any OFA injection points. The amount of reburn fuel injected is typically limited by acceptable carbon monoxide levels in the boiler exit flue gas.

There are potential impacts and limitations unique to the firing of North Dakota lignite in cyclone-fired boilers that should be recognized as part of this emission reduction technology application. This is significant, especially for alternatives with FLGR™ technology when combined with basic or advanced SOFA to allow the natural gas introduced above the SOFA ports to burn completely prior to the furnace exit plane. In either case, the amount of additional potential NOx reduction possible with FLGR™ is limited, since the reburn fuel injection location is expected to coincide with the existing lignite pre-drying system vent ports. The amount of oxygen introduced by the vent ports will be disruptive to the fuel-lean

reburn process in that it would require much higher reburn fuel injection rates in the lower secondary furnace to promote in-furnace NO_X reduction. There are reduced concerns that the withholding of a modest amount of heat input from the cyclone barrels to use natural gas as a source of reburn fuel may reduce cyclone temperatures enough to inhibit slag formation and flow, especially as boiler load is reduced. Air-staging the cyclones with the use of separated overfire air to further complement combustion NO_X reduction is an optional part of this reburn technique which will further risk slag "freezing" in the barrels and lower furnace.

Fuel lean gas reburn can be applied and installed on MRY Station Unit 1's boiler with or without SOFA/ASOFA. This technique is considered technically feasible for application to MRY Station Unit 1's boiler. Expected NO_X reduction will be modest for FLGR™ without SOFA and FLGR™ with a basic form of SOFA. Unit operating and capital costs to supply large quantities of gaseous fuel not currently available at this site are economic disadvantages. Because of these factors, these variations of this technology will not be cost-effective compared to other alternatives with similar control effectiveness. FLGR™ without SOFA and FLGR™ with a basic form of SOFA were not included in the control effectiveness and cost-effectiveness sections of the main report.

Other demonstrated forms of fuel lean gas reburning in combination with post-combustion technologies, such as amine-enhanced fuel lean gas reburn (FLGR™ with SNCR), are discussed under the layered technologies section.

A.1.2.7.4 Fuel Oil Reburn

Fuel oil has been substituted for natural gas in a conventional reburn application. This is much less common in the United States than using natural gas as a reburn fuel, due to the general lack of demand and difficulties in supplying the volume of fuel oil which would be required. It has been installed commercially on three 350 MW oil-fired boilers in New Brunswick (Canada) at the Coleson Cove plant. NO_X emissions reduction with reburn and SOFA was 78% with 25% of the boiler's total fuel heat input supplied in the reburn zone. This yielded 0.22 lb/mmBtu NO_X emissions from a baseline of 1.0 lb/mmBtu[9]. No examples of conventional fuel oil reburn applied to a coal-fired cyclone boiler were found in available literature.

Fuel oil reburn could potentially be considered for application to MRY Station Unit 1 and Unit 2 boilers. Investigation of the specific source, distance, and costs for supplying significantly increased quantities of fuel oil via transport trucks hauling tanker trailers or underground pipeline to M.R. Young station has not

been performed. The unit operating and capital costs to supply large quantities of high-volume liquid fossil fuel at this site are economic disadvantages. The concerns regarding potential impacts and limitations unique to the firing of North Dakota lignite in cyclone-fired boilers that should be recognized as part of this emission reduction technology application are similar to those expressed for conventional gas reburn. It is believed that potential NO_X control with oil reburn would be slightly less than comparable conventional gas reburn systems.

Although fuel oil reburn could potentially be considered for application to MRY Station Unit 1's boiler, the lack of any distinct potential NO_X reduction advantages and demonstration on cyclone-fired boilers does not appear to support its consideration. This alternative was not included in the NO_X control and cost-effectiveness analysis.

A.1.3 Post-Combustion Controls

Post-combustion controls deal with techniques that thermally or chemically-treat the flue gases to reduce NO_X emissions after they have exited the boiler's lower furnace. In the case of Milton R. Young Station Unit 1, this primarily involves forms of selective catalytic reduction (SCR) and selective non-catalytic reduction (SCR) technologies. Another emerging technology that has recently entered the commercial market is Powerspan's Electro Catalytic Oxidation®, which treats utility boiler flue gas for removal of nitrogen oxides, sulfur oxides, and mercury. Another emerging technology that has recently entered the commercial utility air pollution control market is Powerspan's Electro Catalytic Oxidation®, which treats boiler flue gas for removal of nitrogen oxides, sulfur oxides, and mercury.

A.1.3.1 Selective Non-Catalytic Reduction (SNCR)

Selective Non-Catalytic Reduction (SNCR), and variations such as hydrocarbon-enhanced SNCR (sold under the trade name of NOxStar™), and Rich Reagent Injection (RRI), are all post-combustion types of boiler NO_X emission controls. While these technologies are insensitive to the specific fuel types whose combustion products are being treated, the large majority of boiler applications to date have been on pulverized coal-fired units burning eastern bituminous fuels. SNCR has been used to reduce NO_X emissions on numerous utility boilers burning eastern bituminous coal, midwestern bituminous coal, and, to a lesser extent, western subbituminous coal. SNCR has also been used with fuel oil and natural gas-fired units. SNCR (and hydrocarbon-enhanced SNCR) technologies can each be applied to cyclone boilers with or without the use of a SOFA system. SNCR does not appear to be dependent directly on the type of burners (wall-fired, tangentially-fired, and cyclone-fired) employed in the boilers where it has

been installed, with or without overfire air in full operation. Operation at these plants has demonstrated that SNCR can decrease NO_X emissions as much as 15-40% at full load, most typically between 25-35 percent[19].

In the conventional SNCR process, urea or ammonia is injected into the boiler in a region where the combustion gas temperature is in the 1700 to 2100 degrees F range. Under these temperature conditions, the urea reagent [$CO(NH_2)_2$] or ammonia [NH_3] reacts with the NO_X, forming N_2 and water, reducing NO_X emissions.

Long-term examples where SNCR has been used to reduce NO_X emissions on two cyclone-fired boilers are on a 138 MW unit and 160 MW unit burning eastern bituminous coal at Conectiv's B.L England Station (Units 1 and 2) since 1995 and 1996, respectively. Tests at these plants demonstrated that SNCR can decrease NO_X emissions as much as 30-36% at full load, from around 1.3-1.4 lb/mmBtu respectively to as low as 0.85 lb/mmBtu (without overfire air)[18,19,20]. These boilers, located near Atlantic City, New Jersey, continue to operate SNCR (with OFA) for annual NOx emissions around 0.55 and 0.45 lb/mmBtu, respectively.

SNCR can be applied and installed on MRY Station boilers. Estimated NO_X emission rates for using SNCR with North Dakota lignite considered published levels achieved by cyclone-fired units firing western subbituminous coal, and vendor predictions. SNCR alone is expected to reduce NO_X emissions approximately 37% from MCR baseline levels (down to around 0.5 lb/mmBtu) for the MRY Station Unit 1 boiler with ammonia slip limited to approximately 5 ppmvd. Because of the operating costs of the consumed reagent, this technology will not be cost-effective compared to other alternatives with similar control effectiveness (i.e. SOFA), SNCR alone was not included in the control effectiveness and cost-effectiveness sections of the main report.

Other demonstrated forms of SNCR-related technologies, such as Rich Reagent Injection with SNCR, and amine-enhanced fuel lean gas reburn (FLGR™ with SNCR), are discussed under the layered technologies section.

A.1.3.2 Hydrocarbon-enhanced SNCR (NOxStar™)

Hydrocarbon-enhanced SNCR technology, commercially marketed as NO_XStar™, is offered by a single vendor (Mitsui Babcock) as a post-combustion type of enhanced SNCR technology, whereby an

ammonia-based reagent is continuously injected into the superheater/reheater pass of an operating boiler with small amounts of gaseous hydrocarbon (typically either natural gas or propane) and air or steam to provide lance cooling and aid reagent dispersion. The targeted combustion gas temperature range is between 1500°F and 2000°F. The amount of gaseous hydrocarbon introduced is small enough (0.1 to 0.2% of total fuel heat input) that this is not intended to act as a form of reburn or staged fuel combustion. An array of permanently-installed injection lances are located within the boiler convection pass, divided into numerous discrete zones across the full width and height of the duct. The hydrocarbon auto-ignites, forming hydroxyl (OH) radicals which react with the NO_X and ammonia to produce elemental nitrogen (N_2) and water vapor (H_2O).

NO_XStar™ was demonstrated at Tennessee Valley Authority's Kingston Power Station Unit 9 (tangentially-fired 200 MW twin-furnace boiler firing eastern bituminous coal) in 2002[21]. This technology was subsequently permanently-installed at TVA's Colbert Station Unit 4 in late 2003 on a 192 MW wall-fired boiler burning eastern bituminous coal[22]. NO_X reduction was stated as 68-80% for these applications, which included the impact of overfire air and air-staged combustion upstream of the ammonia and propane injection locations.

An example of a hydrocarbon-enhanced SNCR installation on a wall-fired pulverized fuel boiler is shown as a sectional side elevation view of the upper furnace in Figure A.1-3.

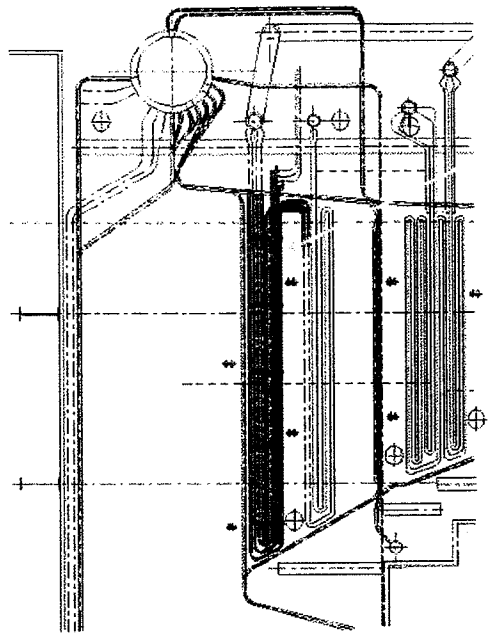


Figure A.1-3 Hydrocarbon-enhanced SNCR Application on PC-fired Boiler[22]

The supplier (Mitsui Babcock) of hydrocarbon-enhanced SNCR technology claims there is little sensitivity to the type fuel (coal) or burners this technique can be potentially applied to in order to reduce NO_X emissions. The chemical reagent injection for hydrocarbon-enhanced SNCR (NO_XStar™) NO_X control technology must be precisely located and carefully controlled to be effective. Operation outside of the required operating ranges can even result in increased NO_X emissions. Extensive computational fluid dynamic (CFD) model simulations are needed to determine the optimum injection points and spray patterns. Boiler operating conditions change with unit load and varying fuel characteristics. The NO_XStar™ process control system must be able to adjust for these changing conditions in order to be effective throughout the intended load range and firing conditions encountered. Non-retractable ammonia injection lances arranged in a parallel-series manner are permanently mounted inside the upper furnace zone, attached to convective tube elements. Different sections of the injection "grid" can be turned off or on, depending on load and firing conditions and amount of NO_X reduction required. Injection nozzles are continuously purged and cooled by extracted superheated steam from the boiler's main steam outlet, whether ammonia reagent is being introduced into the flue gas stream or not. Ammonia slip can be minimized by injecting less reagent, although NO_X control performance will be reduced.

There are a number of issues with firing North Dakota lignite that make the applicability of hydrocarbon-enhanced SNCR infeasible compared to previous experience in other coal-fired powerplants. These issues include:

- Hydrocarbon-enhanced SNCR (NOxStar™) technology has not been applied to cyclone boilers (with or without the use of a SOFA system). It has been only applied to date on pulverized coal-fired boilers burning eastern bituminous fuels.
- There is no successful demonstrated full-scale experience in continuous service of hydrocarbon-enhanced SNCR (NO_XStar™) technology on units firing high-slagging coals such as western subbituminous (PRB) and lignite. The heat transfer surfaces in the convective heat transfer zone where the reagent mixture is injected are prone to severe fouling from flyash constituents common in North Dakota lignite coals. Flyash deposit accumulation on the outside of the NO_XStar™ lances in Milton R. Young Station Unit 1 boiler's upper furnace is expected to be significant, potentially occurring within a matter of a few weeks from startup and nearly impossible to prevent or remove effectively during boiler operation. Such buildup is expected to cause maldistribution of the NO_X reduction chemical reagent from the injection nozzles. Effective on-line removal of these deposits from the injection nozzles is anticipated to be insufficient to maintain effective injection distribution and volume control. It is anticipated that this would significantly reduce the NO_X emission reduction performance consistently achieved on a sustainable basis.

The lack of experience with cyclone boilers, especially those firing coal with severe deposition characteristics such as North Dakota lignite, makes this technology technically infeasible for application on the Milton R. Young Station Unit 1 boiler.

A.1.3.3 Rich Reagent Injection (RRI)

Rich Reagent Injection (RRI) is a NO_X control process that has been developed and demonstrated specifically for use on cyclone boilers. Rich Reagent Injection is an SNCR process that involves the injection of aqueous urea into the lower furnace between the cyclones and the SOFA ports. RRI targets a high temperature, fuel-rich zone within the boiler-furnace environment immediately adjacent to the cyclone burners, and requires temperatures in the range of 2400 to 3100 degrees F.

The three zones of a Rich Reagent Injection SNCR application on a boiler with separated overfire air are shown as a sectional side elevation view of the furnace in Figure A.1-4.

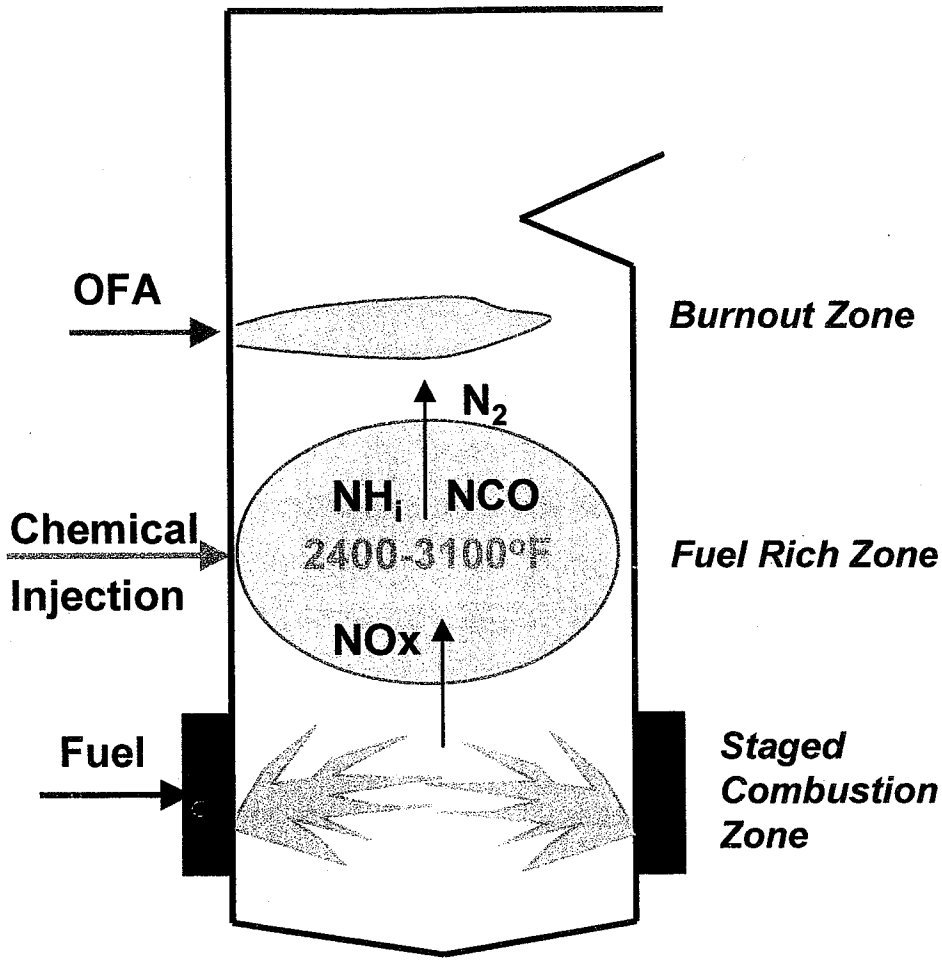


Figure A.1-4 Rich Reagent Injection Application on Boiler With Overfire Air[23]

The Rich Reagent Injection (RRI) process has been successfully demonstrated on at least two cyclone-fired boilers, with the most recent installation at Ameren's Sioux Unit 1, a 500 MW boiler firing a blend of PRB and midwestern bituminous coals. Generally, the heat content of these coals typically varies very little. Short-term testing of the RRI process has been performed alone and in combination with SNCR on B.L. England Unit 1 in 1999[24,25], and more recently at Ameren's Sioux Unit 1 in 2002[23,25], in 2004[26] (alone), and in the first half of 2005[27] (alone, and with SNCR).

The RRI process is intended to be used only with air-starved (substoichiometric staged-air) cyclone combustion, in conjunction with the installation and operation of an OFA system. The RRI process has not been demonstrated on any unit that fires North Dakota lignite. As of May 2006, no commercial installation of a permanent Rich Reagent Injection system has been made at any cyclone-fired boiler.

There is only one holder of a commercial license for modeling and conceptually designing RRI (Reaction Engineering International), with two vendors sub-licensed to design and sell RRI equipment (Fuel Tech and Combustion Components Associates). Since these license agreements are in place, and considering that successful demonstration testing has been performed at two cyclone-fired boiler powerplants, this technology is considered to be applicable and commercially available for potential application on cyclone boilers which burn coals with heat contents that are relatively constant. However, due to the variable heat content of lignite coal, RRI is considered to be technically-infeasible for application on North Dakota lignite-fired boilers. Technical feasibility and expected NO_X emissions from RRI for application on the Milton R. Young Station Unit 1 boiler are included in the "Layered NO_X Reduction Technologies" section.

A.1.3.4 Selective Catalytic Reduction (SCR)

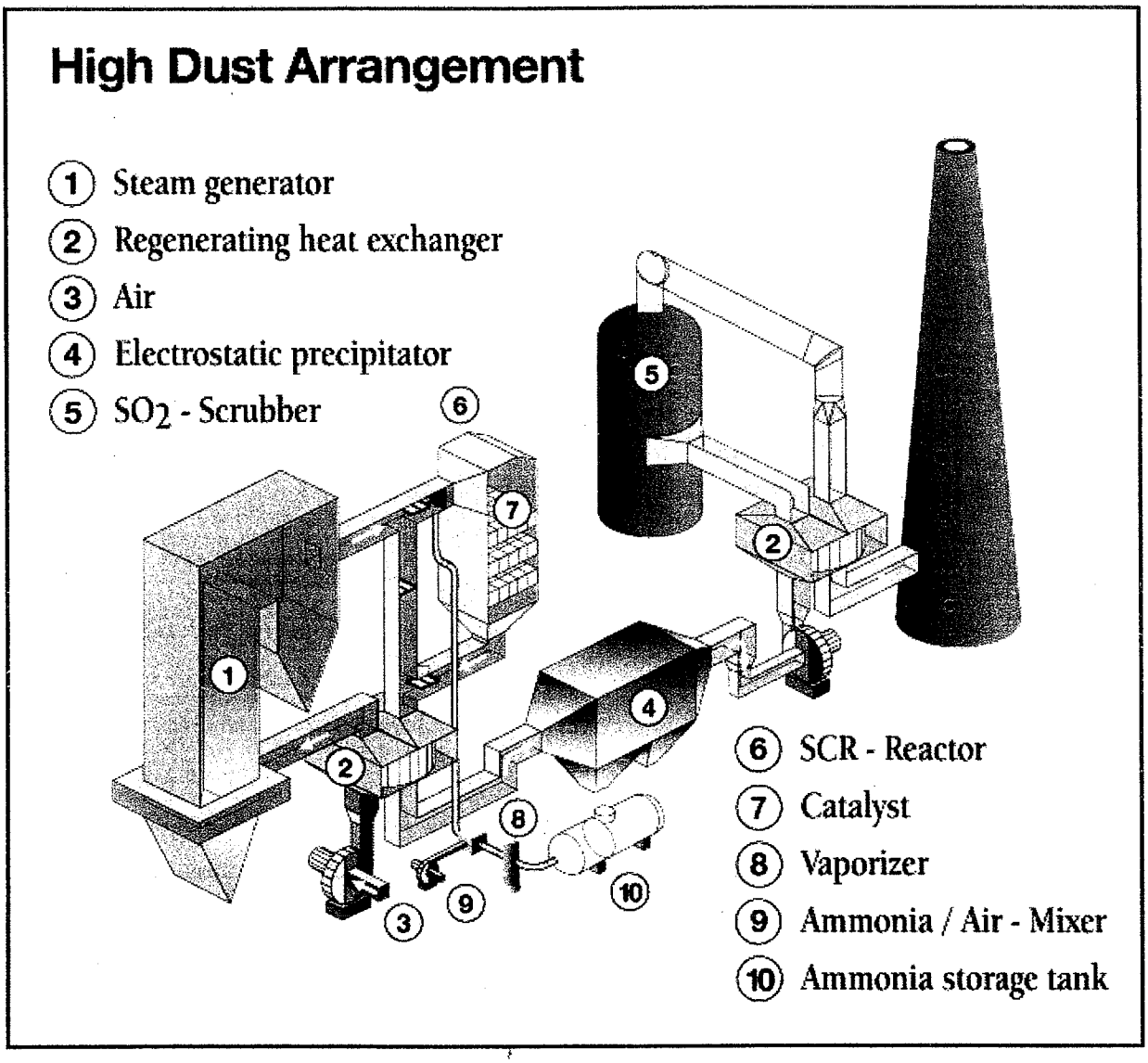
The lowest NOx emission levels from coal-fired utility boilers are typically achieved by installing and operating selective catalytic reduction (SCR) technology. In the SCR process, the gas stream is passed through a catalyst bed in the presence of ammonia to reduce NO_X to molecular nitrogen and water. The process is termed "selective" because the ammonia preferentially reacts with the NO_X rather than with the oxygen in the flue gas. A catalyst is used to enhance NO_X reduction and ammonia utilization at appropriate flue gas temperatures. SCR is usually applied to flue gas in the 600°F to 750°F temperature range. There are variations in the SCR process for coal-fired boilers that mostly involve locations in the flue gas path where the catalyst is placed in order to promote the desired NO_X emission reduction effect. These are described below.

A.1.3.4.1 High-Dust Selective Catalytic Reduction (HD-SCR)

For coal-fired boilers, a conventional SCR reactor utilizes readily-available catalyst materials and reagent in the form of ammonia. A conventional SCR reactor is commonly installed in a high-dust, hot-side arrangement, located between the economizer outlet and air heater inlet, where the flue gas temperature is within the desired operating range for the SCR catalyst. The conventional SCR reactor arrangement is preferred for most coal-fired applications in utility boilers because it avoids the added expense of reheating the flue gas if placed after the air heaters which cool the flue gas, and downstream of any flue gas treatment to remove acid gases. Conventional SCR technology uses an ammonia injection grid (AIG), which consists of multiple nozzles, for distributing the reagent into the flue gas at the boiler's economizer flue gas outlet.

A schematic graphic diagram for a conventional high-dust, hot-side SCR system on a boiler with a flue gas desulfurization system and stack gas reheat is provided in Figure A.1-5.

Figure A.1-5 Conventional High-Dust SCR Arrangement with FGD Scrubber Outlet Reheat



(figure copied from Wheelabrator Air Pollution Control literature)

Conventional high-dust, hot-side SCR technology has been installed on several pulverized coal and cyclone boilers firing bituminous and subbituminous coal in the United States. There are also a limited number of European SCR installations on steam electric generating units (SEGUs) firing lower grade (brown) coal. There are, however, no existing full-scale SCR installations on units that fire North Dakota

lignite. There are approximately 50 cyclone-fired units located in the states affected by EPA's NO_X SIP call. Over half of these units are planning to install conventional high-dust, hot-side SCR systems in response to the SIP call. The installation of conventional high-dust, hot-side SCR systems has been completed on approximately 22 of these units. Appendix A2 lists several conventional high-dust hot-side U.S. SCR installations on pulverized coal and cyclone-fired utility boilers, along with measured NO_X emissions. Initial data from these units indicate that conventional high-dust, hot-side SCR systems operated on suitable cyclone-fired units may be able to reduce NO_X emissions to as low as 0.07 lbs/mmBtu. Several SCR installations have been retrofit on existing cyclone-fired boilers burning western subbituminous coal (or PRB blended with midwestern bituminous coal). For cyclone coal-fired utility boilers retrofitted with SCR technology, all were originally designed to burn bituminous coal.

The EPA NO_X SIP call only applies to units in the eastern United States. There are no facilities firing North Dakota lignite in the EPA NO_X SIP call region. SCR system operation is currently only needed during the ozone season (June – September) for units installing control equipment solely to meet the EPA NO_X SIP call requirements. Limited annual operation is a significant factor with respect to SCR equipment reliability, maintenance, operational costs, and catalyst life. The demands on the SCR system are much more severe if the equipment is required to operate on a full-time, annual basis.

Two byproducts from the high-dust, hot-side SCR process are ammonia slip and SO_3:

- Ammonia Slip: Slip is ammonia that is unreacted in the NO_x emission reduction process. Maximum ammonia slip for a gas fired unit is usually 10 ppmvd whereas, on a coal fired unit, ammonia slip below 5 ppm is desired. For certain applications, this concentration can be problematic, therefore requiring more catalyst to reduce slip. Most new SCR applications have ammonia slip guaranteed at a 2 ppmvd maximum for an initial operating period.
- SO_3: Due to the composition of typical SCR catalysts, a small percentage of inherent SO_2 will be oxidized to SO_3. This oxidation can be controlled by catalyst selection and can be less than one percent. SO_2 to SO_3 oxidation must be carefully controlled to avoid creating SO_3 levels sufficiently high to raise the possibility of air heater fouling. A unit firing high-sulfur coal with SCR technology is especially vulnerable to SO_3 oxidation and ammonia slip-related fouling problems. The deposition and fouling is due to formation of solid ammonium sulfate ($(NH_4)_2SO_4$) and liquid ammonium bisulfate (NH_4HSO_4). The most important design variable is optimizing the catalyst selection and amount of catalyst that will reduce NO_X emissions, control ammonia slip, and minimize SO_2 oxidation.

Recent technology has allowed catalyst suppliers to make more rigorous and lengthy guarantees. A reasonable initial operating period for conventional catalysts in high-dust reactor arrangements on boilers firing eastern or midwestern bituminous coal is around 24,000 active operating hours (i.e. when ammonia reagent is being injected). Factors that need to be taken into account in design of a high-dust, hot-side SCR application that affect the need for catalyst replacement are:

- Pressure drop: The amount of restriction to flue gas flow through the SCR inlet, ammonia injection grid, SCR reactor, and downstream ductwork directly increases induced draft fan horsepower required to maintain adequate boiler draft. This is an important parameter to consider and minimize during the design stage. Pressure drop is a function of the average and maximum SCR reactor duct velocities, the amount of restriction caused by flow distribution correction devices (baffles or vanes), and the number and geometrical aspects of the catalyst layers. Many retrofit SCR installations require a booster fan or upgraded induced draft fan to overcome the added flow resistance. This increases operating cost for the increase in auxiliary power consumption and loss of saleable electric power. The type and pitch of the catalyst are factors most influential in determining the amount of pressure drop.
    - Catalyst type: The most common types or forms of catalyst material are honeycomb or plate. The former offers more surface area per volume, but can be more restrictive and prone to pluggage from ash deposits. The latter is usually less restrictive but requires more catalyst per layer or more layers to achieve the active surface needed to achieve the intended NO_X emission reduction.
    - Catalyst pitch: The pitch of the catalyst, a term used to describe the size of the gas path openings through the catalyst, varies depending on the manufacturer and design dust loading. Pitch is generally on the order of 5 to 7 millimeters. Potential pluggage of flow channels within the catalysts layers is therefore an issue that must be dealt with during design.
- Catalyst performance: The amount of NO_X emission reduction expected is a function of the specific activity level of the catalyst material and the amount of catalyst installed, over a given period of time. Catalyst formulation selection and features of construction have a significant impact on long-term NO_X emission reduction and subsequent costs for reagent and catalysts replacement. The frequency of catalyst replacement is influenced strongly by:
    - Catalyst erosion: Erosion of the catalyst material in coal fired units from entrained flyash or sootblowing action reduces the amount of active surface available for reacting with the reagent and flue gas, and can cause distortions in gas distribution ("channeling") through the

SCR reactor. Catalyst material is fragile and can be easily damaged. Some catalyst is provided with erosion-resistant top edges to mitigate this tendency.

- Moisture absorption: Many types of catalyst are damaged by absorption of moisture. The reactor must be kept above ambient dewpoint temperatures or protected from freezing during outages in order to protect the catalyst from moisture damage. Spare catalyst must be carefully packaged to keep it dry and must be handled delicately to prevent damage.
- Thermal degradation: The specific active elements of the catalyst surface, or the matrix structure itself upon which the catalyst material is applied, can degrade when exposed to flue gas temperatures greater than the intended design of the formulation. High flue gas temperatures within the reactor causes sintering, leading to a permanent loss of catalyst activity due to a change in the pore structure of the catalyst. Proper selection and manufacturing control of the catalyst structure and formulation can minimize thermal degradation.
- Catalyst poisoning: The loss of performance or activity of the catalyst over time can be due to chemical damage or poisoning. Two elements especially detrimental to the life of common titanium-supported vanadium pentoxide SCR catalyst are arsenic and zinc. Vanadia/tungsten-based catalysts are particularly susceptible to rapid deactivation due to gaseous arsenic poisoning. In some German SCR installations, a 50% loss of activity has been reported within 10,000-15,000 operating hours. Addition of molybdenum to a vanadia-titanium SCR catalyst on similar applications shows relative activity reductions of 20-25%. Progressive loss of SCR NO_X reduction performance from catalyst deactivation due to poisoning is not possible to restore without effective cleaning to remove the deposits, or eventual replacement.
- Catalyst fouling: The surface area potentially exposed to the reagent (ammonia) and nitrogen oxides in the flue gas can become fouled with flyash or sulfur-related compounds. The presence of excess calcium oxide in the presence of sulfur in the flue gas can form a calcium sulfate surface coating that can be extremely dense, masking the pores of the catalyst. Progressive loss of SCR NO_X reduction performance from catalyst deactivation due to fouling is difficult to restore without effective cleaning to remove the deposits, or eventual replacement.

SCR technology has been installed on numerous coal-fired utility boiler facilities around the world and there are a large number of manufacturers that market the catalysts. The question is whether SCR is a

feasible technology for a unit firing North Dakota lignite. There are serious concerns whether installation of SCR technology on a North Dakota lignite-fired unit can be successful, especially in a conventional "hot-side, high-dust" configuration. The effectiveness of the SCR process is highly dependent upon the ability of the nitrogen oxides in the flue gas being able to contact the active sites within microscopic pores of the catalyst in the presence of ammonia reagent with minimal interference from contaminants.

A recent technical paper "Ash and Mercury Behavior in SCR Catalysts When Firing Subbituminous and Lignite Coals" by the Energy & Environmental Research Center (EERC) of the University of North Dakota was published in the February 2005 issue of Fuel Processing Technology magazine[28]. This paper summarized the results of SCR slipstream testing at two PRB-fired plants and one North Dakota lignite-fired powerplant. The evaluation included determination of impacts of ash on SCR plugging and blinding. Flue gas was isokinetically extracted from the convective pass of the boiler upstream of the air heater. Pressure drop across the catalyst was measured during the initial two-month test period, and the two consecutive two-month test periods following the initial trial, while holding flue gas flow and temperatures constant. Ammonia was injected downstream of a screen, upstream of a flow straightener and air pulse section. Compressed air was injected ahead of the reactor, and was periodically pulsed to simulate sootblowing to minimize ash deposit accumulation.

This slipstream SCR testing examined the significance of ash accumulations on SCR catalyst on both the macroscopic and microscopic levels. Very small flyash particles were found bonded together by a matrix of sodium-, calcium-, and sulfur-rich materials, likely in the form of calcium sulfate. North Dakota lignite coal contains many alkali and alkaline-earth elements, and sulfur. The firing of lignite coal which produces fine (less than 5-μm diameter) flyash particles creates conditions that enter the pores of the catalyst, react with SO_3 in the flue gas, and form sulfates which bind other ash particles into the matrix.

As posted on Electric Power Research Institute Inc.'s (EPRI's) website regarding the impact of coal type on SCR catalyst life and performance, a recent EPRI study[29] produced field data analyzed from an "In-Situ Mini SCR Reactor" system installed in a typical "high-dust" location at seven different test sites, including four firing PRB coal, one firing Texas lignite, one firing high-sulfur eastern bituminous coal, and one firing a PRB/eastern bituminous coal blend. The PRB/bituminous coal blend test was performed at AmerenUE's Sioux Station, on one of the two 500 MW cyclone-fired boilers. This study found that the cyclone unit firing the PRB/bituminous coal blend exhibited the fastest rate of catalyst activity degradation. Also, the higher deactivation rates seen at this site were due to economizer exit flue gas

temperatures being significantly higher than at the other sites. A comparison of the Texas lignite and one of the PRB-fired sites with two different catalysts, deactivation was more a function of trace elements in the flue gas and flyash than the specific catalyst type or formulation.

North Dakota lignite produces an ash that is very sticky and creates severe ash deposition problems. There have been no installations of SCR systems (full-scale) on units that fire North Dakota lignite. A technical assessment was conducted for the installation of SCR technology on a North Dakota lignite unit. In order to further evaluate the feasibility of installing a conventional SCR system on a North Dakota lignite fired unit, the Energy & Environmental Research Center (EERC) at the University of North Dakota was consulted. EERC has extensive experience investigating the deposition characteristics of North Dakota lignite ash.

Technical difficulties and anticipated operating problems that are unresolved with respect to installing conventional SCR technology at Milton R. Young Station include the impacts of erosion, severe ash deposition, and "popcorn ash" on the catalyst. According the EERC's study (see Appendix B), "the most significant problems that prohibit the successful operation of SCR catalysts to lignite coal is the formation of low-temperature sodium-calcium-magnesium sulfates and phosphates that will form on the surfaces of catalysts and the carryover of deposits that will plug the catalyst openings, resulting in increased pressure drop and decreased efficiency". For these reasons, application of available conventional high-dust SCR technology is considered technically infeasible for Milton R. Young Station Unit 1 and Unit 2 boilers. These concerns can be divided into four categories. Each category is addressed below. An explanation of the factors that make conventional SCR technology infeasible for these boilers follows:

1. Ash Deposition: North Dakota lignite contains a variable and complex variety of inorganic compounds that contribute to ash deposition. This fuel produces ash with severe deposition characteristics that are not typical with other coals. When exposed to the heat of the combustion process inside the cyclone burners, the majority of the fuel ash becomes molten and flows into the bottom of the furnace. A significant portion of the fuel ash is entrained into the flue gas exiting the cyclone barrels at high velocity, where it comes into contact with the lower furnace waterwalls. The portion that is carried with the rising flue gas cools and some is deposited on heat transfer surfaces in the upper furnace and boiler convection pass. Ash deposition on heat transfer surfaces is a substantial problem for units that fire North Dakota lignite. The problem is so severe at Milton R. Young that the Unit 1 boiler must be shut down at 120-day intervals to

allow for cleaning of ash deposits from the boiler heat transfer surfaces in order to restore reasonable furnace exit gas velocities and temperatures.

Sodium is a significant contributor to the "stickiness" of the ash produced from firing North Dakota lignite. Sodium content of the lignite ash averages approximately 4.4%, and can nearly double this value for some of the lignite produced from the Center mine. PRB coal typically averages around 1.5% sodium content. Boilers firing North Dakota lignite typically have a 2.5% higher heat rate (million Btu per kilowatt of electric generation) than a typical boiler firing PRB coal, thus requiring more heat input and firing more fuel per megawatt of electricity output. A cyclone boiler firing North Dakota lignite also converts approximately 50% of the fuel ash to flyash, compared with a 35% conversion rate for PRB coal-fired cyclone boilers. Overall, this results in an amount of sodium emitted from a cyclone boiler firing North Dakota lignite of approximately 7.3 lbs/MW-hr compared with 0.9 lbs/MW-hr for a PRB-fired cyclone boiler.

→ Ratio is 26:1 (much higher)

The catalysts in coal-fired boiler SCR reactors are highly susceptible to ash deposition. In a typical conventional high-dust SCR reactor, the flue gas typically passes through two to four layers of catalyst modules. The catalyst modules have numerous narrow passages to provide intimate contact between the flue gas, ammonia and catalyst. The clearance (pitch) in these passages is typically 6-10 millimeters. A typical catalyst layer is approximately 1 to 1.5 meters deep. The catalysts in coal-fired boiler SCR reactors must be cleaned frequently using soot blowers and/or sonic horns. This is true even on units firing fuels that do not produce a sticky ash that contributes to ash deposition. Ash deposition on the catalyst in a high-dust SCR application would be severe for a unit firing North Dakota lignite.

Sulfur in the coal is oxidized during excess air combustion to form sulfur dioxide (SO_2), and a small amount of sulfur trioxide (SO_3). Some of the ammonia-based reagent injected upstream of the SCR reactor will combine with SO_3 to form ammonium bisulfate. The catalyst in the SCR reactor will also oxidize a portion of the SO_2 to SO_3. Excess unreacted ammonia reagent carryover ("ammonia slip") from the SCR reactor will also react with these sulfuric acid compounds in a similar fashion. The deposition characteristics for a unit burning North Dakota lignite will create difficult-to-remove ash deposits and pluggage of a conventional high-dust catalyst, and increase the probability that the air preheater downstream and flue gas ductwork will be prone to accumulations which could be severe. High-dust SCR performance and catalyst life

will be severely impacted. It is anticipated that a high-dust SCR's catalyst life will be shortened from 3-6 years (typical) to as little as 2-12 months, requiring extended, frequent outages for replacement.

Hot-side air preheaters are susceptible to fouling. Tubular air pre heaters originally supplied with all cyclone boilers also tolerate moderate dust loadings, since their height and size make them difficult to maintain cleanliness. Leak tightness of the air preheater is important on cyclone-fired boilers with relatively high forced draft fan discharge (combustion air supply) pressures. A high-dust SCR installation will be prone to air preheater tube fouling and pluggage, requiring extended, frequent outages for cleaning.

2. "Popcorn Ash": A second consideration in the application of conventional high-dust SCR technology on a lignite-fired unit is the potential of the SCR reactor catalyst pluggage resulting from carry over of "popcorn ash" from the boiler. Boilers firing North Dakota lignite have severe problems with ash deposition on boiler surfaces. North Dakota lignite has a high propensity to form deposits on the boiler's furnace and convection pass fireside surfaces. For lignite-fired units, the boiler's heat transfer surfaces must be cleaned by sootblowing and other methods (e.g. water lances) frequently to maintain satisfactory boiler operation. Some of the removed deposits released by the cleaning action within the boiler and convection passes form "popcorn ash", which will be entrained in the flue gas. Carry over of boiler ash deposits will contribute to pluggage of the "popcorn ash" screen ahead of the top layer of SCR reactor catalyst. This can cause distortions in gas distribution ("channeling") through the SCR reactor, which will aggravate erosion in the high velocity areas and ineffective performance of the catalyst.

3. Temperature: A third issue that impacts the feasibility of installing high-dust SCR technology on the North Dakota lignite-fired units is catalyst operating temperature. The performance of any SCR catalyst is highly dependent on the temperature of the flue gas passing through the reactor. Typically, a temperature of 600 – 750 degrees F is required to obtain satisfactory operation of an SCR reactor. Operation of commonly supplied catalyst suitable for a high-dust SCR reactor at temperatures above 750 degrees results in severe and rapid deterioration of the catalyst and SCR reactor's NO_X emission reduction performance. For bituminous and sub-bituminous coal-fired units, boiler flue gas passing between the economizer outlet and air heater inlet is generally

within a temperature range acceptable for conventional SCR catalysts without additional heating or cooling of the flow stream.

North Dakota lignite-fired cyclone boilers, including those at Milton R. Young Station, have high temperatures at the economizer's flue gas outlet by design. The highest gas temperatures downstream of the convection pass economizer sections and upstream of the air heater inlets in Milton R. Young Unit 1's boiler are much higher than 750 degrees.

High gas temperatures at the air heater inlet are required to produce the high air temperatures (700°F) needed for the pre-combustion lignite drying system, along with primary and secondary combustion air supplied to the cyclones. Such air preheater arrangements and capabilities have been taken into account in the design of the North Dakota lignite-fired cyclone boilers. Reducing this high gas temperature to accommodate conventional catalysts for a conventional high-dust SCR reactor would result in pre-combustion air temperatures that are too low to provide satisfactory drying and rapid ignition of the high-moisture fuel. This will seriously impact reliable combustion, slag formation and tapping in the cyclone burners. Consequently, it is not feasible to modify the Milton R. Young Unit 1's boiler to operate with the lower economizer outlet flue gas temperature.

Catalysts for a conventional high-dust, hot-side SCR system have not been installed nor successfully demonstrated in a full-scale installation of an operating solid fuel-fired unit that are designed to continuously operate at the high temperatures (above 750 degrees F) that exist between the convection pass economizer and air heater on the Milton R. Young Unit 1's boiler.

4. Erosion: A final consideration on whether hot-side, high-dust SCR technology can be successful on a North Dakota lignite-fired unit is the potential for erosion of the SCR catalyst. North Dakota lignite supplied from the Center mine has an average fuel ash content of 10.5%, and can have an ash content up to 25.5 percent. PRB coal fuel ash content typically averages approximately 5 percent. As previously stated, a cyclone boiler firing North Dakota lignite converts a significantly greater amount of flyash than a PRB-fired cyclone boiler. Overall, this results in a flyash output rate from a cyclone boiler firing North Dakota lignite of approximately 83 lbs/MW-hr compared with 21 lbs/MW-hr for a PRB-fired cyclone boiler. High ash contents in the flue gas stream can result in physical erosion of the catalyst. In addition, effective on-line cleaning of the

high-dust catalyst will likely require steam or compressed air sootblowing. Cleaning cycles of the catalyst will be required much more frequently than a typical conventional SCR installation due to the ash deposition characteristics of the North Dakota lignite and the expected buildup and pluggage resulting from the carry over of "popcorn ash". Frequent sootblowing of the catalyst to remove fouling deposits and ash accumulations will contribute to erosion and decreased catalyst life. There is some European experience with high ash brown coals that catalyst manufacturers will be able to draw upon. This experience, however, will not be directly applicable to these United States units because of the severe deposition characteristics of the North Dakota lignite ash compared to brown coal.

The EPA's NSR Manual states that for a technology to be feasible it must "available and applicable". SCR technology is an available technology which has been installed on numerous powerplant facilities around the world and there are a large number of manufacturers that market the technology. The question is whether SCR technology is "applicable" for a unit firing North Dakota lignite.

In accordance with EPA's NSR Manual, a technology is "applicable" if it has been installed on a "similar unit". Hot-side, high-dust SCR technology has been retrofit on coal-fired units featuring cyclone boilers. However, there are no SCR installations in operation or planned on units that include cyclone burners firing North Dakota lignite with severe slagging and fouling tendencies combined with such high boiler economizer outlet gas temperatures (over 750°F) required for high-moisture fuel pre-drying systems and tubular air preheaters.

The EPA's NSR Manual also states a technology may be determined to be not applicable if "a technical assessment considering physical, chemical and engineering principles and/or empirical data showing the technology would not work on the emissions unit under review or that unsolvable technical difficulties would preclude the successful deployment of the technique." In this SCR technology application, it appears that a facility utility powerplant firing North Dakota lignite would experience extended time delays or be required to devote significant internal resources and engage outside research, followed by extended field trials to learn how to apply a conventional high-dust, hot-side SCR technology on a such a fuel source.

Based upon this technical assessment that looked at the various design and operational issues associated with the installation of hot-side, high-dust SCR technology on a North Dakota lignite-fired steam-electric

generating unit, this control option is considered technically infeasible for Unit 1's boiler at Milton R. Young Station.

A.1.3.4.2 Low-Dust Selective Catalytic Reduction (LD-SCR)

Low-dust SCR (LD SCR) technology could potentially be applicable to North Dakota lignite-fired boilers for NOx emission control. Low-dust SCR refers to the location of the SCR system downstream of a particulate collection system, such as an electrostatic precipitator or a fabric filter. If the low-dust SCR is downstream of a hot-side electrostatic precipitator and prior to the air preheater, flue gas reheating is unnecessary. This has been the prevalent form of alternative retrofit SCRs in the United States for coal-fired utility boilers. There are ten known hot-side low-dust SCR installations (without flue gas reheat) operating in the United States as of July 2005. These are listed in Appendix A2. If applied to MRY Station Unit 1's boiler, the low-dust SCR equipment would be downstream of a cold-side electrostatic precipitator; flue gas reheat prior to the LD SCR reactor inlet would be required for proper NO_X emission reduction performance.

For a cold-side LD SCR, the ESP outlet flue gas passes through a low-dust gas-to-gas heat exchanger (LD GTG-HE), prior to passing to the low-dust SCR reactor. After the LD GTG-HE, the flue gas will travel through the new duct, receiving hot flue gases from a direct-fired gas burner or set of high-pressure steam coils, leading to an ammonia injection grid, turning vanes and then into the LD SCR reactor. The flue gas entering the inlet to the LD GTG HE is expected to be near the air heater outlet temperature (330-340°F) in a cold-side LD SCR application. The supplemental heat added downstream of the LD GTG-HE can be supplied from high temperature steam coils (indirect heat exchange) or directly from natural gas-fired duct burners. The flue gas must be heated to a minimum of approximately 600°F for the LD SCR NO_X–ammonia reaction to be effective. The LD gas-to-gas heat exchanger is used to recover part of that supplied heat, prior to exhausting to the FGD system (if applicable) and stack. The use of rotary regenerative-type heat exchangers has been applied in European LD SCRs. With this design, there will be leakage between the untreated and treated gas streams such that the exit flue gas has higher NO_X concentrations than the LD SCR outlet gas. The direct-fired flue gas reheat duct burners will also create NO_X emissions, which will add to the amount emitted from the boiler and input into the LD SCR reactor. The LD SCR reactor, GTG HE, and connecting ductwork will increase the pressure drop through the flue gas system. This normally requires an induced draft fan upgrade or a booster fan addition.

The factors that make low-dust SCR technology infeasible for the Milton R. Young Station Unit 1's boiler with existing particulate collection via electrostatic precipitators are as follows:

- Catalyst Fouling and Deactivation: An existing electrostatic precipitator upstream of a low dust SCR reactor will still expose the catalyst to the acid gas content and fine particulate containing trace metals and the high alkali mineral content of the entrained lignite flyash not removed by the ESP upstream. Although the total amount of flyash carryover into the LD-SCR reactor is greatly reduced compared with a high-dust design, it is anticipated that the low-dust SCR catalyst life will still be unacceptably short. The small particle flyash passing into the reactor will be sufficient to cause pluggage of the catalyst pores, resulting in deactivation of the catalyst. The firing of lignite coal produces fine (less than 5-μm diameter) flyash particles, which are also least likely to be removed by the existing particulate collection equipment (e.g. ESP) upstream of a low-dust SCR. This creates conditions that allow these small flyash particles to enter the pores of the catalyst, react with SO_3 in the flue gas, and form sulfates which bind other ash particles into a matrix of sodium-, calcium-, and sulfur-rich materials (likely in a form of calcium sulfate). Once such a matrix forms within the catalyst, it can be extremely tenacious and difficult to remove. One catalyst vendor's has stated it is their "experience that low-dust catalyst is more difficult to clean than that from high-dust"[30]. Low-dust SCR performance and catalyst life could be severely negatively impacted. Shortened lifespans of the LD SCR catalyst will require premature, extended, frequent outages for replacement.
- Site Space Constraints: The installation of a low-dust SCR system with flue gas reheat requires a substantial amount of space for installation and operation. A low-dust SCR system will likely use a regenerative gas-to-gas heat exchanger (reheater) to raise the temperature of the flue gas at the SCR inlet. A GTG HE will transfer heat from the flue gas at the SCR reactor outlet to the flue gas entering the SCR reactor in order to minimize the supplemental SCR energy usage. The gas-to-gas heat exchanger dictates the footprint of the cold-side low-dust SCR system. Space is required for the GTG HE and for ductwork in and out of the reheater. Sufficient free space around the reheater and SCR is also required for maintenance.

  The area around Units 1 and 2 at the M.R. Young station is extremely congested in the areas where low-dust SCR systems must be located. The situation is particularly severe for Unit No. 2. Equipment that impacts the feasibility of installing a low-dust SCR system on Units 1 and 2 includes the Unit 2 absorbers, Unit 2 flue gas desulfurization (FGD) dewatering equipment, fly ash handling equipment, fuel storage and transfer equipment, stacks, fans and ductwork. It would be extremely

disruptive to the continued economic operation of both boilers to relocate all the mentioned equipment to create space for the low-dust SCR systems at the M.R. Young Station. Stacks, fans and ductwork and the Unit 2 FGD system cannot be readily relocated due to adjacent structures and the need to continue operation while constructing the retrofit installations. The fuel handling equipment includes a coal storage barn and the main conveyors supplying lignite to the units. Relocating the coal handling equipment currently occupying space needed for the low dust SCR systems would be quite difficult given the site configuration. It is conceivable that the fly ash equipment located west of Unit 1 could be relocated to provide some of the space needed for the low-dust SCR. However, the availability of this space is doubtful, since avoiding the likelihood of severe SCR catalyst sulfate fouling will require a new Unit 1 FGD system to be installed. If a new FGD system is installed for Unit 1, the FGD system would need to occupy the space that can be made available by relocating ash handling equipment. This space subsequently would not be available for a low-dust SCR system.

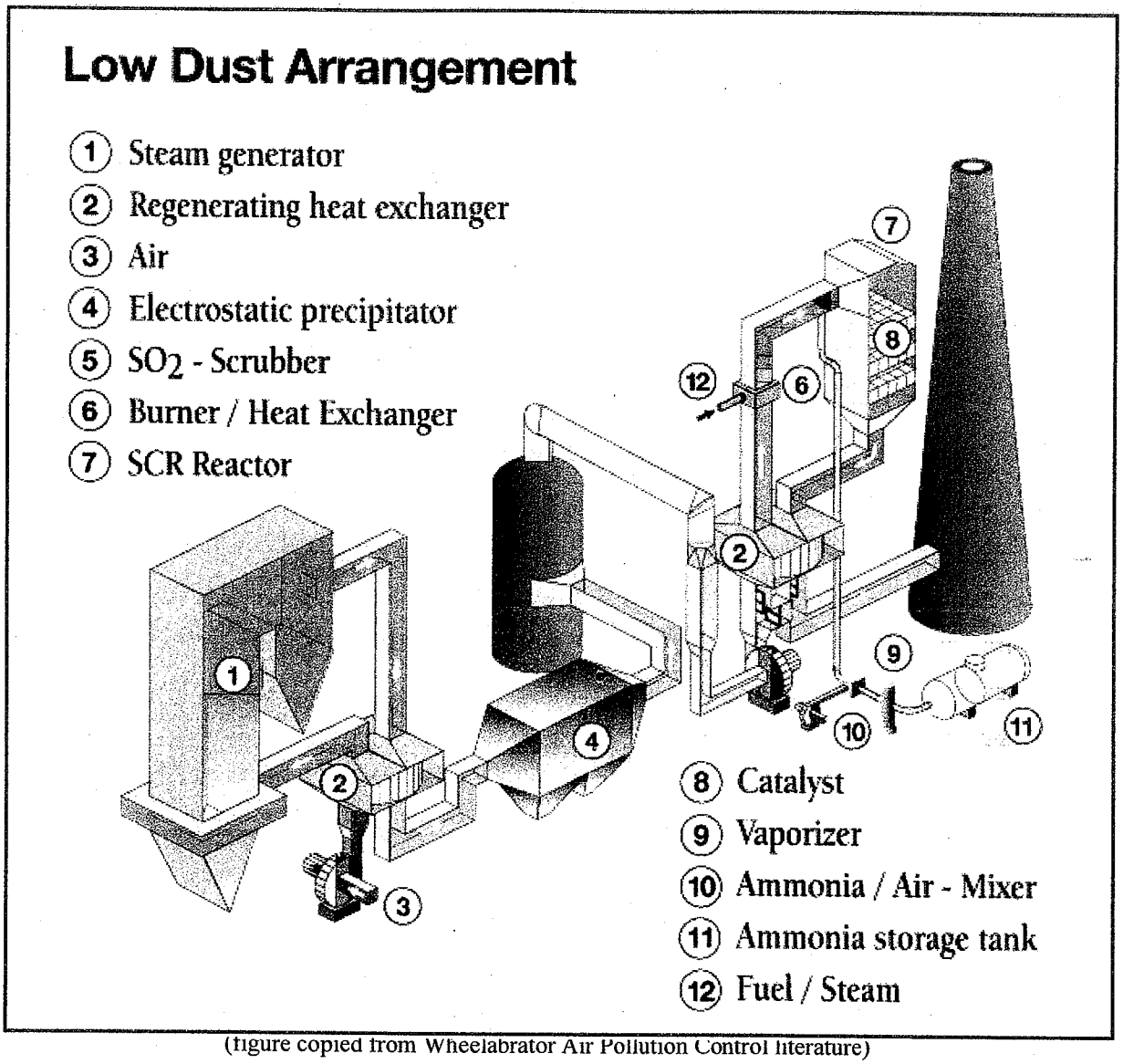
Based upon a technical assessment that looked at the various design and operational issues associated with the installation of low-dust SCR technology on a North Dakota lignite-fired steam-electric generating unit, this control option is considered technically infeasible for the Milton R. Young Station Unit 1's boiler.

A.1.3.4.3 Tail-Gas Selective Catalytic Reduction (LD-SCR)

A tail-gas (TG) SCR is a low-dust SCR system where the LD SCR reactor is installed downstream of a FGD scrubber. The FGD outlet flue gas passes through a gas-to-gas heat exchanger (GTG-HE), prior to passing to the tail-gas SCR reactor. The flue gas will travel through new or modified ductwork leading to an ammonia injection grid, turning vanes and then into the TG SCR reactor. The TG SCR reactor, GTG HE, and connecting ductwork will increase the pressure drop through the flue gas system. This normally requires an induced draft fan upgrade or a booster fan addition.

A schematic graphic diagram for a low dust arrangement is shown in Figure A.1-6.

Figure A.1-6 Tail-Gas SCR Arrangement



(figure copied from Wheelabrator Air Pollution Control literature)

The flue gas from a wet FGD scrubber outlet entering the inlet to the gas-to-gas heat exchanger is expected to be near the saturation temperature (140°F) in a cold-side TG SCR application. The supplemental heat added downstream of the TG GTG-HE can be supplied from high temperature steam coils (indirect heat exchange) or directly from natural gas-fired duct burners. The flue gas must be heated to a minimum of approximately 600°F for the TG SCR NO_X– ammonia reaction to be effective. The TG gas-to-gas heat exchanger is used to recover part of that supplied heat, prior to exhausting to the stack. With a rotary regenerative-type gas-to-gas heat exchanger, there will be internal leakage between the untreated and treated gas streams such that the stack exit flue gas has higher NO_X concentrations than the

TG SCR reactor outlet gas. Using direct-fired flue gas reheat duct burners will also create NO_X emissions, which will add to the amount emitted from the boiler and input into the TG SCR reactor.

There is limited technical information published in English for coal-fired steam-electric generating units (SEGU) with low-dust/tail-gas SCR technology in applications requiring full flue gas reheat prior to the reactor inlet. There is no experience with TG SCR on eastern bituminous, western subbituminous coal or lignite-fired SEGUs in the United States. As of 1997, there was one low-dust/tail-gas SCR on a 220 MWe German cyclone-fired boiler with a 1988 retrofit installation. This boiler was reported to be operating without combustion controls or FGD, burning low sulfur, low ash, moderate moisture bituminous coal with an average pre-SCR NO_X emission rate of approximately 1.07 lb/mmBtu, and was meeting a 30-day rolling average emission limit of approximately 0.16 lb/mmBtu (85% reduction)[31].

Milton R. Young Station Unit 1 does not currently incorporate any flue gas desulfurization equipment, which would place the reactor catalyst in a low-dust SCR configuration, which is considered infeasible when burning North Dakota lignite. A new FGD system for Unit 1 would be required in order to avoid or significantly reduce expected sulfate formation within the catalyst and gas-to-gas heat exchanger when combined with ammonia required for the TG SCR. Unit 2 currently employs a wet scrubber which currently treats approximately 83% of the total flue gas flow from the boiler. Flue gas reheat is currently provided by the FGD bypass (i.e. warm, untreated flue gas is mixed with the cool scrubbed gas).

The factors that make tail-gas SCR technology infeasible for both Milton R. Young Station boilers with existing particulate collection via electrostatic precipitators are as follows:

- Catalyst Fouling and Deactivation: The TG SCR reactor downstream of a flue gas desulfurization (FGD) scrubber will still be susceptible to fouling, contamination, pluggage, and catalyst deactivation.
    - An existing electrostatic precipitator (ESP) upstream of a tail-gas SCR reactor will still expose the catalyst to fine particulate containing trace metals and the high alkali mineral content of the entrained lignite flyash not removed by the ESP upstream. Although the total amount of flyash carryover into the TG-SCR reactor is greatly reduced compared with a high-dust design, it is anticipated that the tail-gas SCR catalyst life will still be unacceptably short.
    - The firing of lignite coal produces fine (less than 5-μm diameter) flyash particles, which are also least likely to be removed by the existing particulate collection equipment (e.g. ESP) upstream of

a TG-SCR. Flue gas with entrained fine particulate matter, including some involving sodium and sulfur-containing compounds, will pass through and be carried-over from a wet FGD scrubber. This treated gas stream will carry sodium sulfate particles, formed by homogenous condensation after exiting the boiler and not removed by the FGD system, into the catalyst layers of the TG-SCR reactor. A dry FGD system followed by a fabric filter upstream of the TG-SCR will still allow sulfur-bearing flue gas and fine particles to enter the catalyst. There is serious concern that fine particles passing into the reactor will accumulate within the catalyst, and be resistant to removal by conventional sootblowers and other cleaning technologies. This creates conditions that allow these small flyash particles to enter the pores of the catalyst, react with SO_2 and/or SO_3 in the flue gas, and form sulfates which bind other ash particles into a matrix of sodium-, calcium-, and sulfur-rich materials (likely in a form of calcium sulfate). Once such a matrix forms within the catalyst, it can be extremely tenacious and difficult to remove. Catalyst that is exposed to such conditions will be ineffective at maintaining adequate activity upon which the performance of the TG-SCR's NO_X removal is based.

- These entrained particles will also deposit on the gas-to-gas heat exchanger ahead of the tail gas SCR reactor. This deposition will decrease heat transfer between the incoming (cool) flue gas and the outgoing (warm) flue gas. Sootblowers could be used to remove the accumulated deposits from the GTG HE, but the SCR reactor could still suffer catalyst fouling from the deposits dislodged from the GTG HE cleaning cycle becoming reentrained in the reheated flue gas. Tail-gas SCR performance and catalyst life could be severely negatively impacted. Shortened lifespans of the TG SCR catalyst will require premature, extended, frequent outages for replacement.

- Site Space Constraints: The installation of a tail-gas SCR system with flue gas reheat requires a substantial amount of space for installation and operation. A tail-gas SCR system will likely use a regenerative gas-to-gas heat exchanger (reheater) to raise the temperature of the flue gas at the SCR inlet. A GTG HE will transfer heat from the flue gas at the TG SCR reactor outlet to the scrubbed flue gas entering the SCR reactor in order to minimize the supplemental SCR energy usage. The gas-to-gas heat exchanger dictates the footprint of the TG SCR system. Space is required for the GTG HE and for ductwork in and out of the reheater. Sufficient free space around the reheater and SCR system is also required for maintenance.

The area around Units 1 and 2 at the M.R. Young station is extremely congested in the areas where TG SCR systems must be located. A flue gas desulfurization system will be needed for Unit 1 in the

near future to comply with the Consent Decree. When a new FGD system is installed for Unit 1, the FGD system would need to occupy the space that can be made available by relocating ash handling equipment. This space subsequently would not be available for a tail-gas SCR system. Thus, the availability of adequate space for all the new FGD and TG-SCR system equipment and structures while accommodating existing coal storage and handling needs for both existing boilers at Milton R. Young Station is doubtful.

The challenges for installation of new ductwork, SCR reactors, and flue gas reheating equipment and the lack of pertinent experience with all aspects of design, construction, operation and maintenance of tail-gas SCRs on such high-fouling coals as North Dakota lignite are significant. The flue gas conditions that the TG-SCR catalyst will be exposed to will create unresolvable fouling and blinding that makes successful application of this technology difficult, expensive, and uncertain.

The risk of failure and uncertainty of successfully applying low-dust, tail-gas SCR technology to a cyclone-fired utility powerplant firing North Dakota lignite appear substantial.

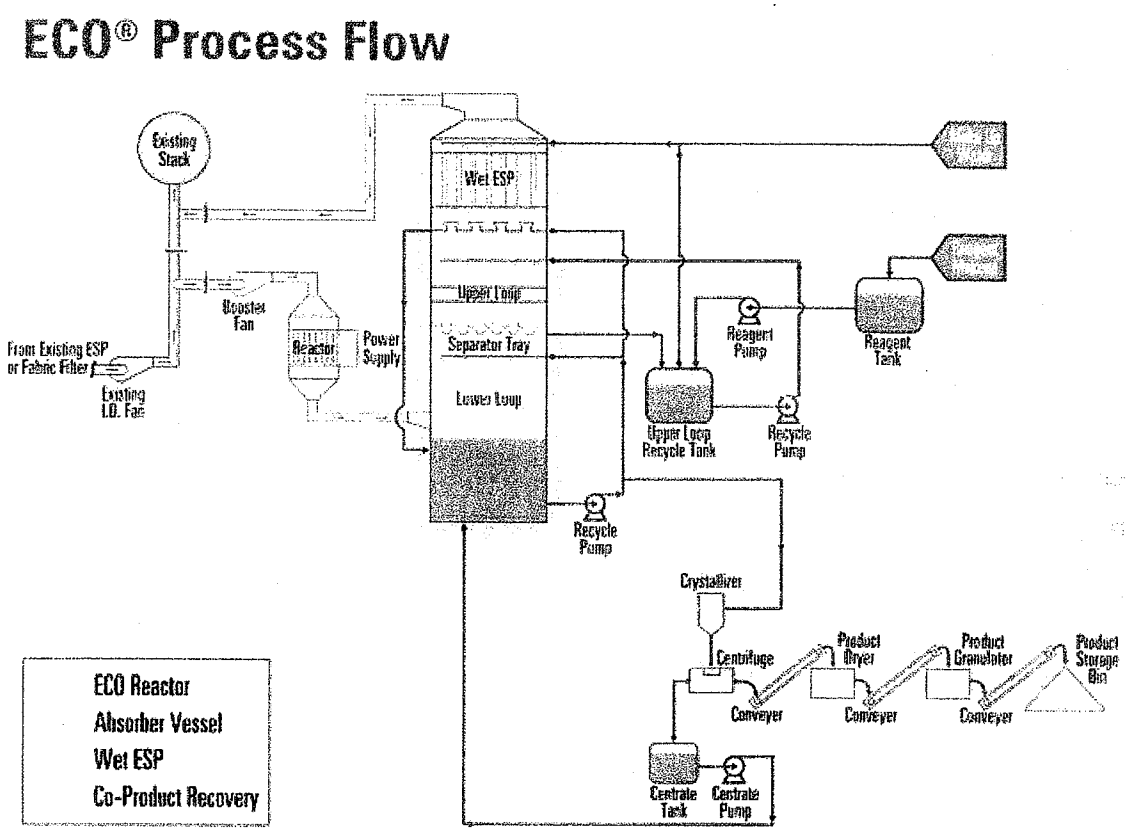
Based upon a technical assessment that looked at the various design and operational issues associated with the installation of tail-gas SCR technology on a North Dakota lignite-fired steam-electric generating unit including a cyclone boiler, this control option is considered technically infeasible for the Milton R. Young Station Unit 1's boiler.

A.1.3.5 Electro-Catalytic Oxidation (ECO®)

Powerspan's Electro-Catalytic Oxidation (ECO®) system is a multi-pollutant technology designed to control emissions of NO_X, SO_2, fine particulate, mercury and certain Hazardous Air Pollutants (HAPs). The ECO® process has two main process vessels, a barrier discharge reactor, and a multi-level wet scrubber. The barrier discharge reactor utilizes an electrical discharge to create oxygen and hydroxide radicals which then react with NO_X, and other constituents in the flue gas stream. The flue gas stream then enters the bottom of the ECO® scrubber where the lower loop cools the flue gas and removes a portion of the acid gasses [sulfur trioxide (SO_3), sulfuric acid (H_2SO_4), nitric acid (HNO_3)] produced in the barrier reactor and oxidized metals such as mercury, with a low pH aqueous ammonia reagent. A second scrubbing loop is then entered where additional SO_2, NO_2, acid gases and oxidized metals are removed with an aqueous ammonia reagent, though at a higher pH. Above the second scrubber loop is an absorber section for absorbing fugitive ammonia from the first and second scrubbing loops. The final

step in the ECO® process is a wet electrostatic precipitator (WESP) which collects fine particulate matter, aerosols generated in the scrubber and additional mercury. An updated schematic process flow diagram for the basic ECO® process is shown in Figure A.1-7.

Figure A.1-7 – Electro-Catalytic Oxidation (ECO®) Process Flow Diagram
(copied from http://www.epa.gov/appcdwww/aptb/EPA600R03110.pdf)



Powerspan has been involved in an extended ECO® process demonstration using a 28 MW Commercial Demonstration Unit (CDU) at R.E. Burger Station Units 4&5. The ECO® CDU project treated a slipstream and demonstrated performance, reliability and economics for approximately one year. The demonstration program started in January, 2004. NO_X removal is stated to be up to 90% with a claimed 0.05 lb NO_X/mmBtu outlet condition achievable for the front-end of the ECO® process. Further sustained operational tests of the ECO® CDU are underway during the second and third quarters of 2005.

As this is a post-combustion multi-pollutant control technology, it is claimed that there is little sensitivity to the type boiler or burners that Powerspan's Electro-Catalytic Oxidation (ECO®) process can be

potentially applied to in order to reduce NO_X emissions. The effectiveness of this ECO® process for NO_X control has been demonstrated on a slip-stream commercial demonstration unit (CDU) associated with pulverized fuel boilers firing midwestern or eastern bituminous coal.

Powerspan's published data from the commercial demonstration unit's performance of up to 90% when treating flue gas with an inlet NO_X concentration around 0.5 lb/mmBtu. This would result in a stack NO_X emission around 0.05 lb/mmBtu.

The ECO® process has not been demonstrated in a full-scale configuration on any unit, nor tested in a slipstream configuration on any boiler that fires western subbituminous coals or North Dakota lignite. It has also not been applied to emissions from a cyclone-fired boiler. According the EPA's Draft NSR Manual, "Technologies which have not been applied to (or permitted for) full scale operations need not be considered available: an applicant should be able to purchase or construct a process or control device that has already been demonstrated in practice".

There are a number of issues with firing North Dakota lignite that make the applicability of the ECO® process technically infeasible for MRY Station boilers. These issues include:

- Deposits and Pluggage: The flyash deposition characteristics of the North Dakota lignite are extremely severe. Anything that contributes to flyash deposition and pluggage within the barrier reactor is expected to have a detrimental impact on the multi-pollutant control performance of the ECO® process, and thus could have a serious impact on MRY Station operations. The lack of demonstrated operation on treating the emissions from a boiler firing coal with a high slagging index precludes the use of the ECO® process as technically feasible for BACT as applied to a boiler firing North Dakota lignite.
- Reliability and Availability: Milton R. Young Station's major planned outages for each unit are scheduled to occur once every three years. Any NO_X control technology selected as BACT will need to operate year-round, year in and year out, on a routine basis, while performing at high levels of pollutant reduction. The Powerspan ECO® system is a new technology and is not as highly developed as other more common NO_X and SO_2 control technologies such as SCR or SNCR plus wet or semi-dry flue gas desulfurization (FGD). It is expected to require a full-time, full-scale application with sustained continuous operation to confirm levels of currently demonstrated reliability and availability from the ECO® CDU are acceptable to meet the

expectation of infrequent major outages over long time periods while maintaining high levels of control.

There are additional factors that make the application of the ECO® process potentially more difficult than other established emission control technologies available for coal-fired powerplants:

- There is a lack of experience with the ECO® downstream ammonia scrubber's coproduct crystallization and granulization equipment design, operation, and maintenance, which was not included with the initial commercial demonstration unit. The coproduct stream that would normally feed into the crystallization and granulation processes was collected and transported offsite for this process step during CDU operation. Because crystallization and granulation of ammonium sulfate from an ammonia scrubber solution is not a new technological process, this was not considered a technical feasibility deficiency. For instance, the Dakota Gasification Company (DGC) in Beulah, ND currently operates an SO_2 scrubber utilizing ammonia as a reagent. Following the generation of ammonium sulfate, DGC crystallizes and granulates a fertilizer product on site. However, at MRY Station, considerable costs would be incurred for interim storage and shipment of the ECO® process scrubber's liquid bleedstream until sufficient experience has identified and eliminated potential failures and repairs for the crystallization and granulation equipment should it prove to be unreliable.

- Size of the barrier reactor: Powerspan recently indicated that they would scale the reactor for optimum cost and space arrangement based upon lessons learned from the CDU plant operation. The number of individual passages within a barrier reactor sized for either of MRY Station boilers' maximum flue gas flow and gas stream constituents is expected to require a cross-sectional area comparable to half of a large electrostatic precipitator. Although this has not been closely examined for all aspects of design, construction, operation and maintenance, the amount of physical space required to hold the barrier reactor and inlet and outlet ductwork is believed to not be available for potential retrofit to MRY Station units. Site space constraints are considered to be a barrier to technical feasibility for potential application of the ECO® process at Milton R. Young Station for Unit 1 and Unit 2's boilers.

- Additional station auxiliary power consumption: The barrier reactor, plus the ammonia scrubber and wet electrostatic precipitator additions by an ECO™ system, require an increase in station

auxiliary power consumption. For NO_X control, this includes more horsepower required by the booster fan needed to compensate for the flue gas pressure drop created across the barrier reactor. It also includes the power consumed by the electrodes of the barrier reactor itself.

Because of the technical feasibility issues and lack of commercial availability and full-scale experience, especially on such high fouling coals, the ECO® system was considered technically infeasible as a BACT alternative for Milton R. Young Station for Unit 1's boiler.

A.1.4 "Layered" NOx Reduction Technologies

Many of the NO_X emission reduction technologies which involve furnace or convection pass areas for their introduction into the flue gas stream have been, or can potentially be, applied in combinations so as to result in an overall higher level of removal. Separated overfire air, various types of fuel reburn, and various forms of SNCR could potentially be combined in series to reduce NO_X emissions prior to boiler's flue gas exit. However, all the possible NO_X control technology combinations have not been installed on coal-fired powerplants, so actual feasibility of some combinations have not been demonstrated as viable, particularly in consideration of the special challenges posed by cyclone boilers firing lignite coal.

A.1.4.1 SOFA Combined With Other NO_X Reduction Technologies

Separated Overfire Air can be favorably combined with every other method in order to reduce the amount of reagent or reburn fuel required to achieve the resulting level of NO_X emission reduction. Some control technologies, especially conventional fuel reburn systems, require overfire air to complete the combustion of the staged fuel admitted to the upper furnace. Fuel lean gas reburn can be applied with or without SOFA, as this limited amount of staged fuel is introduced into an oxygen-rich atmosphere downstream of the cyclone burners and any overfire air injection points.

A.1.4.1.1 SOFA with SNCR

Selective non catalytic reduction technologies are post-combustion, in-furnace NO_X control alternatives that have been installed in numerous boilers of various designs, fuel types, with and without overfire air. It is usually advantageous to apply overfire air so that the amount of chemical reagent consumption can be minimized in order to achieve the targeted NO_X emission rate from the boiler outlet.

Tests at Conectiv's B.L England Station (Units 1 and 2) demonstrated that SNCR can decrease NO_X emissions as much as 31% at full load, from 0.55 to 0.38 lb/mmBtu, over and above the reduction possible from overfire air alone (approximately 60% drop, from 1.3 to 1.4 down to 0.55) in full operation. This is an overall NO_X emission reduction of 72% from pre-retrofit baseline[24].

SNCR can be applied alone or combined with either the basic or the advanced forms of separated overfire air (ASOFA) on MRY Station boilers. Air-staging the cyclones with the use of separated overfire air to further complement combustion NO_X reduction is an optional part of this technique. However, as previously explained in the discussion of SOFA alternatives, this will risk slag "freezing" in the barrels and lower furnace. Estimated NO_X emission rates for using SNCR techniques with North Dakota lignite considered published levels achieved by cyclone-fired units firing western subbituminous coal, and vendor estimates. SNCR with ASOFA is expected to reduce NO_X emissions approximately 31% below NO_X levels predicted for ASOFA operation, and potentially 58% overall from current baseline level for the MRY Station Unit 1 boiler with ammonia slip limited to approximately 5 ppmvd. This highest performing basic SNCR system is potentially able to achieve a NO_X emission rate of 0.355 lb/mmBtu, when combined with the advanced form of SOFA on MRY Station Units 1 boiler during operation at the pre-control baseline (near MCR load). These levels of NO_X reduction depend on the advanced form of separated overfire air technique to achieve the expected NO_X reduction percentages when applied to lignite-fired cyclone boilers.

Another form of SNCR is combined with separated overfire air. This is currently being marketed commercially as "Rotating Mixing" (Rotamix). In the United States' utilities industry, this has only been applied to pulverized coal-fired boilers. It is different than basic SNCR in that it includes a hot air booster fan and a small ambient air fan, and injects the ammonia (or urea) reagent into the high-pressure overfire air flow stream ahead of the ROFA nozzles' outlets. This mixture is imparted into the boiler in an offset fashion from opposite sides of the furnace at high velocities, with multi-port nozzles located at high elevations relative to the top burner row. This vendor (Mobotec USA) claims that Rotamix (rotating opposed fire air or ROFA + SNCR) helps to distribute the reagent across the furnace cross section, which maximizes in-furnace NOx reduction while minimizing negative impacts on carbon monoxide and flyash unburned carbon. Three tangentially-fired utility boilers burning eastern bituminous coal or Illinois bituminous coal were retrofitted with Rotamix, each achieving a NO_X reduction of approximately zero to 55 percent beyond the levels produced by ROFA alone, from pre-SNCR baselines of 0.22 to 0.28 lb/mmBtu down to 0.10 to 0.23 lb/mmBtu without low-NO_X burners[4,32,33,34].

While this variation of SNCR combined with separated overfire air could potentially be applicable to cyclone boilers, it has not been marketed to serve such applications. Since cyclone boilers do not require the addition of hot air booster fans for SOFA, and optimum injection locations for both SOFA and SNCR reagent may not coincide, Rotamix may not perform as well as, or significantly better than, a well-designed combination of conventional SOFA and SNCR. This technique is not distinct enough from basic SNCR from functional and air-staged cyclone NO_X reduction performance standpoints to warrant individual consideration for Milton R. Young Station boilers. Because of a lack of cyclone-fired boiler experience with ROFA and Rotamix, the latter was considered infeasible and thus was not included in the control effectiveness and cost-effectiveness sections of the main report.

A.1.4.1.2 SOFA with RRI

Rich Reagent Injection must be used in an oxygen-deprived atmosphere in order to effectively reduce nitrogen oxide emissions. This requires air-staged cyclones and separated overfire air operation. The NO_X emission reduction reagent injection for RRI processes must be precisely located and carefully controlled to be effective. Operation outside of the required operating ranges can even result in increased NO_X emissions. Extensive computational fluid dynamic (CFD) simulations are needed to determine the optimum injection points. Boiler operating conditions will change with unit load and varying fuel characteristics. The RRI process control systems must be able to adjust for these changing conditions.

RRI has the potential to provide a moderate degree of NO_X reduction on coal-fired boilers. Data from B.L. England and Sioux plants show this technology can reduce NO_X emissions between zero and 39 percent beyond the amount attributable to overfire air system operation[23,24,25,26,27]. During initial demonstration testing of RRI at Ameren's Sioux Unit 1 boiler, a 500 MW unit firing a blend of PRB and midwestern bituminous coals (without SNCR), with SOFA in August 2001 at a lower furnace SR of approximately 0.99, NO_X emissions were reduced approximately 55% to 0.55 lb/mmBtu w/ SOFA only, with zero to 15% additional NO_X reduction from RRI (down to 0.47 lb/mmBtu) with zero ammonia slip[25]. Results of this initial RRI testing at Sioux plant were poor at cyclone stoichiometric ratios close to 0.99 because inconsistent, sporadic, and non-repeatable NO_X emissions reductions between zero and 15% were measured. Subsequent RRI testing at Sioux Unit 1 in March 2002 with SOFA at an average cyclone stoichiometric ratio around 0.95 showed NO_X emissions reduction of 29 percent (down to 0.27 lb/mmBtu) beyond those achieved with a modest amount of cyclone air-staging with SOFA (68% drop down to 0.38 lb/mmBtu from SOFA alone), for an 80% overall decrease from uncontrolled baseline; RRI CFD model

predictions for these conditions were NO_X emissions reduction of 31% with FGR and 37% without FGR operation. Tested NO_X emissions with RRI+SOFA in 2002 were with a reagent normalized stoichiometric ratio (NSR) of 3 (lbs NH_3 per lb NO_X)[25].

Parametric testing at Sioux Unit 1 in May 2005 reduced NO_X emissions between 15-38% with RRI, down to 0.15 to 0.20 lb/mmBtu. Reagent NSR between 1.0 and 4.0 and low ammonia slip levels less than 2 ppm from an established baseline condition of 0.20 to 0.285 lb/mmBtu level achieved NO_X emissions as low as 0.12 lb/mmBtu with deep cyclone air-staging and SOFA operation firing an 80:20 PRB/Illinois coal blend at 480 MWg unit output[27].

The intent of the RRI process for NO_X reduction is that it must be used in conjunction with air-starved (substoichiometric staged-air) cyclone combustion resulting from the installation and operation of an OFA system, with or without SNCR. The cyclones' air/fuel stoichiometry must be carefully controlled to maintain fuel-rich conditions for the RRI process to be effective. The combustion gases in the vicinity of the RRI urea injection ports must be essentially devoid of free oxygen, in order to avoid oxidizing the nitrogen contained in the injected reagent, which will increase NO_X emissions. For lignite-fired cyclone boilers, the basic form of separated overfire air (without relocated lignite drying system vent ports) is incompatible with RRI. Reagent injection will be near the elevation of the existing lignite drying system vent ports in the lower front and rear walls of a lignite-fired cyclone boiler located immediately above the top rows of cyclones. The oxygen introduced with the lignite drying system's vented moisture-laden airstreams will cause the urea to be oxidized, creating NO_X emissions.

The advanced form of SOFA relocates these lignite drying system vent ports from the lower to the middle furnace, enhancing the desired in-furnace nitrogen oxides reduction process. Therefore, in order for RRI to be even moderately effective in reducing NO_X emissions from a lignite-fired cyclone boiler, this technology must be combined with an advanced form of separated overfire air, whether installed with or without SNCR.

As mentioned in the feasibility discussion of applying separated overfire air to lignite-fired cyclone boilers, the degree to which each and every individual cyclone furnace can be successfully operated with less than theoretical (substoichiometric) combustion air directly impacts potential NO_X formation and further in-furnace emission reduction. Because the heat content of lignite from the Center mine is not

consistent from hour to hour, there can be substantial deviations in air/fuel ratios for individual cyclones from the overall average.

In the case of MRY Station boilers, Minnkota has simultaneously sampled the unprepared lignite feed to several cyclones' lignite drying systems in order to determine the variability in the combustible and ash components of North Dakota lignite. This investigation found that fuel quality variations can result in individual samples' heating values to have a maximum differential of over 12% of the lignite samples' average.

TABLE A1-1 – Lignite Heating Values and Variations for Milton R. Young Station (Unit 2)

M.R. Young Station Individual Cyclone Lignite Samples		Differences Between Individual Cyclone Lignite Samples	
Higher Heating Values, Btu/lb	Percentage of Average HHV	HHV Differential, Btu/lb	Percentage of Average HHV
Minimum HHV: 5,852	88.9%	Minimum : 4	0.06%
Maximum HHV: 7,101	~~1.08%~~ 108%	Maximum : 797	12.1%
Average HHV: 6,584	100%	Average: 165	2.51%

When operating with air-staged conditions associated with separated overfire air, any individual cyclone with lignite heat input lower than average can allow significant amounts of oxygen to oxidize the urea reagent at high temperatures, thus increasing NOx emissions in that zone at that time. Cyclones with lignite heat inputs higher than average would produce lower stoichiometric air/fuel ratios and less NOx emissions. Less complete combustion in the deeply staged cyclones may release insufficient amounts of heat, thus raising the risk of solidifying the fuel ash so that it accumulates within the cyclone barrel. This could result in firing auxiliary fuel oil or taking the boiler out-of-service to remove the pluggage. Neither of these conditions is desirable because they result in increased emissions, lower performance, and higher operating costs.

The MRY Station Unit 1 boiler's cyclone air/fuel ratios vary in real-time based on significant changes in combustible content on an individual cyclone by cyclone basis. Adjustment of individual cyclone combustion air inputs to compensate for the variability in individual cyclone lignite heat input rates for Unit 1's boiler would be necessary to maintain consistent substoichiometric operation of every cyclone during air-staged combustion. This places great emphasis on achieving tight control over the air/fuel

ratios on each cyclone during air-staged combustion operation in order for ASOFA to be successful in producing significant additional NOx emissions reduction on lignite-fired cyclone boilers.

There is no equipment available for coal-fired boilers that can measure the fuel heat input at the prepared feed injection point on such a variable fuel to allow the determination of reasonably accurate air/fuel ratios on individual cyclones in real time. Without being able to measure the cyclone air and heat inputs to allow for control of air/fuel proportions and emissions, the stoichiometric ratios of individual cyclones can not be established accurately to produce combustion products essentially devoid of free oxygen. This requirement is especially necessary when employing RRI to avoid increasing, rather than reducing, NO_X emissions on the Milton R. Young Station Unit 1 boiler.

Because of the significant insurmountable problems discussed above which would increase NOx emission rates, RRI is considered technically infeasible for application on the Unit 1 cyclone boiler at the Milton R. Young Station.

A.1.4.1.3 SOFA with RRI and SNCR

When RRI is combined with separated overfire air and SNCR, it has demonstrated very high NO_X emissions reduction at Conectiv's B.L. England Unit 1 boiler during short-term testing firing eastern bituminous coal, on the order of 80% from an uncontrolled baseline around 1.2 lb/mmBtu[24]. In May 2005, testing RRI+SNCR+SOFA at Ameren's Sioux Unit 1 boiler firing a high PRB-blend coal demonstrated NO_X emissions as low as 0.12 lb/mmBtu. This was from an established baseline condition of 0.20 lb/mmBtu level achieved with deep cyclone air-staging and SOFA operation. These testing results when firing an 80%:20% PRB/Illinois coal blend at 480 MWg unit output with a reagent NSR of 4 and ammonia slip limited to less than 5 ppmvd, showed an overall 90% reduction with no apparent adverse short-term impacts of deeper air-staged combustion together with overfire air, RRI and SNCR applications[27].

Because of the significant insurmountable problems regarding RRI as mentioned above, RRI with SNCR and ASOFA is considered technically infeasible for application on the Unit 1 cyclone boiler at the Milton R. Young Station due to the variable heat content of the lignite fuel which allows the creation of oxygen-rich conditions in the boiler.

A.1.4.2 SNCR and Reburn

Various forms of SNCR could potentially be installed downstream of separated overfire air and various types of fuel reburn, to reduce NO_X emissions prior to a boiler's flue gas exit. Several of these examples were already described[7,8,9,10,11,1213,14]. Conventional gas (CGR) or coal reburn systems, by and large, have not been combined with forms of SNCR, although at least one vendor (GE Energy) has promoted a combination of conventional gas reburn with SNCR and overfire air systems as "advanced" gas reburn. Only one example of permanent installation of SNCR with conventional gas reburn (and overfire air) on a tangentially-fired boiler was found in available technical literature[10] and vendor experience lists[14]. The vendor (GE Energy) that provided the advanced gas reburn system at 120 MW NRG Somerset Station claimed NO_X emissions were reduced by 44% from a baseline of 0.45 down to 0.25 lb/mmBtu with overfire air alone; an additional reduction of 20% resulting from conventional gas reburn with overfire air, down to 0.20 lb/mmBtu; and further decrease of 45% down to 0.11 lb/mmBtu using gas reburn with SNCR with an unstated amount of ammonia slip, for an overall reduction of 75% from uncontrolled baseline[14].

No examples of actual demonstration or permanent installation of SNCR with conventional gas or coal reburn (and overfire air) on cyclone-fired boilers were found in a search of published and proprietary technical literature. The lack of experience with these combinations on a cyclone-fired boiler, especially for lignite-firing, makes the application for MRY Station's boilers infeasible.

FLGR™ has been installed with SNCR for NO_X emission reduction on several pulverized coal boilers, as discussed in the following subsection. A potential advantage of FLGR™ over conventional coal or gas reburn techniques is that the former is generally compatible with, but does not require, the installation and operation of SOFA.

Rich Reagent Injection would appear to be less capable of being combined with fuel reburn, especially conventional fuel reburn alternatives with high amounts of reburn fuel injection. This is due to the expected need to idle (e.g. not fire) up to two of the seven cyclones when operating the reburn system at full boiler load. In this case, the cooling air introduced into the idle cyclones, and any conveying air injected with pulverized reburn coal (or if natural gas is injected with recirculated flue gas), are expected to counteract the fuel-rich conditions of the air-and fuel-staged cyclones operating substoichiometrically. This will cause a portion of the amine reagent to be oxidized in the lower furnace, creating NO_X emissions instead of converting them to nitrogen and water. No example of actual demonstration or permanent installation of RRI with reburn (and overfire air) on cyclone-fired boilers was found in

available technical literature or vendor experience lists. This combination is considered infeasible at the present time.

Hydrocarbon-enhanced SNCR (e.g. NO_XStar™) may potentially be combined with all types and forms of reburn previously discussed, since the location of the enhanced ammonia injection nozzles will be above (beyond) the elevation in the middle furnace where any reburn fuel should be reacted. No example of actual demonstration or permanent installation of HE-SNCR with reburn (and overfire air) on any coal-fired utility boilers, especially cyclone-fired units, was found in available technical literature or vendor experience lists. The advantage that HE-SNCR presents is the potential for greater-than-SNCR-levels of NOx reduction without significant amounts of gaseous hydrocarbon being required. Because of a lack of experience with HE SNCR applied to cyclone boilers, and none with significant amounts of fuel reburn, this combination has not been investigated further, and was not included in the control and cost-effectiveness analysis for NO_X controls.

A.1.4.2.1 Amine-Enhanced FLGR™ (AEFLGR™) or FLGR™ + SNCR

Fuel-lean gas reburn has been combined with SNCR as a hybrid form of amine reagent technologies on at least five pulverized coal-fired utility powerplants retrofit installations within the United States. This combination of technologies allows the boiler to be operated with FLGR™ alone, FLGR™ and SNCR simultaneously, or SNCR only (without SOFA) for the specific level of control desired or required.

No examples of actual demonstration or permanent installation of FLGR™ + SNCR (with or without overfire air) applied to a cyclone-fired boiler were found in available technical literature or vendor experience lists. The vendor (Fuel Tech) that provided the AEFLGR™ system at Mercer Station claimed NO_X emissions were reduced by 60% (from a baseline of 1.4 down to 0.56 lb/mmBtu) with 5 ppm ammonia slip without overfire air. A technical paper provides more details[18]. Another technical paper stated that FLGR™ alone only reduced NO_X emissions approximately 27% from the 1.4 lb/mmBtu baseline, down to 1.03 lb/mmBtu[35].

An AEFLGR™ system (with or without SOFA or ASOFA) may be potentially applied to a cyclone-fired boiler. The high capital and operating costs associated with applying fuel lean gas reburn is expected to make this economically unattractive, and the existing lignite pre-drying vent ports will likely limit the NO_X emission reduction potential of the FLGR™ component if installed without the advanced form of

SOFA. The lack of experience with this combination on any cyclone-fired boiler, especially fo firing, makes this combination infeasible for MRY Station Unit 1 boiler.

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A.2.1 - U.S. Cyclone NOx Reduction Projects Summary

SELECTIVE NON-CATALYTIC REDUCTION/ RICH REAGENT INJECTION

Cyclone-Fired Boilers

Conectiv (formerly Atlantic Electric)

BL England Unit 1	Crushed Coal, single-wall cyclone-fired	1962 vintage
138 MW B&W boiler	aqueous urea SNCR, 1995 startup	eastern bituminous coal

Boiler has only 3 cyclone burners, arranged "1 over 2" style.
RJM implemented commercial Fuel Tech urea-based SNCR system installation in 1995 after short-term (3-month demonstration test) in 1993-1994. 31 % NOx reduction claimed, from 1.31 lb/mmBtu NOx baseline[(1)] for SNCR only; RJM claimed 35% reduction from 1.31 lb/mmBtu down to 0.85 lb/mmBtu (without overfire air) with urea-to-NOx NSR = 0.85 (RJM experience list).

Added eight temporary RRI ports (three nozzles on each lower sidewall, and two nozzles on the upper rear wall, and performed one month demonstration parametric testing of overfire air only (without SNCR or RRI), at 120 MW nominal boiler load and cyclone S.R. = 0.90 in 1999. REI claimed 55% NOx reduction from a 1.2 lb/mmBtu uncontrolled NOx baseline to 0.55 lb/mmBtu with OFA only, with stack CO emissions below 50 ppm. For Rich Reagent Injection; REI claimed 25-30% NOx reduction for RRI down to 0.38 lb/mmBtu from controlled baseline w/ OFA alone of 0.55 lb/mmBtu NOx and a RRI urea-to-NOx NSR = 2; also showed RRI+SNCR w/ OFA reduced NOx 55% to 0.25 lb/mmBtu (34% beyond RRI w/ OFA), for an overall 79% NOx reduction with a SNCR urea-to-NOx NSR = 1. Measured less than 1 ppm ammonia slip during RRI testing, < 5 ppm slip for RRI + SNCR. No significant increase in CO emissions during RRI testing[(2)].
Source: [(1)] ICAC White Paper; RJM experience list; [(2)] REI 2001 Technical Paper.

Conectiv (formerly Atlantic Electric)

BL England Unit 2	Crushed Coal, cyclone-fired, single-wall-fired	1964 vintage
160 MW B&W boiler	SNCR, 1996 startup eastern bituminous coal	

RJM implemented commercial Fuel Tech urea-based SNCR system in 1996, claimed 36% reduction from 1.36 lb/mmBtu down to 0.85 lb/mmBtu, urea-to-NOx NSR = 0.85 (without overfire air) [(1)].
An OFA system was added in 1998, resulting in NOx emissions of 0.33 lb/mmBtu, for an overall NOx reduction of 76%.
Source: RJM experience list. (Also listed in [(1)] ICAC White Paper).

AmerenUE (formerly Union Electric Co.)

Sioux Unit 1	Crushed Coal, opposed-wall cyclone-fired	1969 vintage
500 MW B&W boiler	Rich Reagent Injection demonstration testing in 2001	

Boiler has 10 cyclone burners, arranged "2 over 3" style, on opposite walls, and fires a blend of 85% to 50% western subbituminous (PRB) coal, with Illinois bituminous coal, petroleum coke, and tire-derived fuel.

Installed twenty temporary RRI ports (six nozzles on each lower sidewall, and four nozzles on each front and rear wall), and performed one month demonstration parametric testing of overfire air only and initial testing with RRI in August 2001, followed by additional testing in March 2002, and the second quarter of 2004. Added 8 RRI ports (1 in each sidewall, 4 in each front and rear wall) and 14 SNCR ports (5 on upper front wall, 9 on upper rear wall) to the furnace in early 2005, followed by three weeks of parametric testing and 3 days of continuous testing of RRI with SNCR and deeper-staged OFA.
Tested in August 2001 at lower furnace SR approx.=1.0, 0.55 lb/mmBtu w/ OFA only, only 15% NOx reduction w/ RRI, zero ammonia slip.

Tested in March 2002 at lower furnace SR approx.=0.95, from 0.38 lb/mmBtu baseline w/ OFA only, achieved 29% NOx reduction w/ RRI down to 0.27 lb/mmBtu, NSR=3, zero ammonia slip[3].
(assume blend of PRB and Illinois bituminous coal w/ tire-derived fuel and petroleum coke)[3].
Operation in the second quarter 2004 showed actual stack NOx averaged around of 0.30 lb/mmBtu with OFA only and lower furnace at a cyclone SR around 0.88 burning a 85% PRB, 15% Illinois #6 bituminous coal blend, presumably at 440 MW. This is a 75% NOx reduction from a 1.19 lb/mmBtu pre-control baseline. REI using CFD modeling predicted NOx down to 0.18 lb/mmBtu with RRI+OFA, and below 0.15 with RRI+SNCR under similar deep cyclone air-staging (1.19 to 0.28 lb/mmBtu is 76% reduction, 0.18 vs 0.28 is an additional 36% reduction w/ RRI, and 0.14 vs 0.28 is a 50% reduction w/ RRI+SNCR, for an overall reduction of 88%)[4].
Tested in May 2005 at 480 MWg with lower furnace SR approx. = 0.85-0.88, 76-83% reduction from 1.2 lb/mmBtu baseline down to as low as 0.20 lb/mmBtu w/ SOFA only firing 80% PRB, 20% Illinois #6 bituminous coal blend; additional 15-39% NOx reduction w/ RRI, to as low as 0.15 lb/mmBtu from 0.20-0.28 lb/mmBtu baseline w/ SOFA only at urea NSR varied between 1 and 4, with one ppm ammonia slip; achieved additional NOx reduction w/ RRI +SNCR down to 0.12 lb/mmBtu, NSR=4, ammonia slip10 ppm or less. RRI+SNCR w/ SOFA NOx reduction percentage varied from 15% to 50% below SOFA-only levels, with NSRs between 1 and 4.5. SNCR alone had 13% (NSR=1) to 32% (NSR=1) NOx reduction with ammonia slip around 1-2 ppm*.
Source: [3] REI 2002 and 2003 Technical Papers; [4] REI 2004 Technical paper;* REI 2005 Technical paper.

REBURN – GAS, CONVENTIONAL
Cyclone-Fired Boilers
Constellation Energy (formerly Baltimore Gas & Electric)
C.P. Crane Station, Units 1 & 2 (MD) Crushed Coal, cyclone-fired, eastern bituminous coal
2 x 200 MW B&W boilers (four cyclones each) 1961, 1963 vintage
GE-EER Conventional Gas Reburn, 1999 startup
Added gas supply piping, metering, hangers, supports; reburn injectors and cooling air ductwork, OFA ductwork, injection nozzles and wall ports, field (assume eastern bituminous coal)
GE-EER claimed Gas Reburn with OFA lowered NOx between 60% and 65% from baselines of 1.50 lb/mmBtu to between 0.60 and 0.52 lb/mmBtu, at full load with reburn operation. No claims of percent reburn fuel or percent OFA included in GE-EER's experience list.
Another technical paper showed this installation of CGR operated with 25 percent reburn fuel[5].
Source: Sept. 2005 GE-EER experience list; [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

City Water, Light & Power
Lakeside Unit 7 Crushed Coal, front-wall cyclone-fired, midwestern bituminous coal
300,000 lb/hr steam B&W boiler (approx. 33 MWe equivalent, two cyclones) 1961 vintage
Springfield, IL DOE Clean Coal demonstration project (included sorbent injection)
GE-EER conventional gas reburn w/ OFA 1992 startup (CGR not currently operating)
Vendor claimed to lower NOx by 66% from 0.95 lb/mmBtu baseline to 0.32 lb/mmBtu. A GE-EER 2004 technical paper showed 25% reburn fuel yielded minimum NOx emissions[6].
A DOE NETL technical paper showed this demonstration of CGR from 5/93-10/94 (assume with OFA) with 23 percent reburn fuel reduced NOx 60% from 0.97 to 0.39 lb/mmBtu [5].
Source: Sept. 2005 GE-EER experience list; [6] GE-EER 2004 Technical paper; [5] DOE-NETL 2004 Reburn Conference Technical paper.

Eastman Kodak Company
Kodak Park Boilers 41 & 42 Crushed Coal, front-wall cyclone-fired, 1964 & 1966 vintage

400,000 lb/hr steam B&W boilers (approx. 50 MWe equivalent, two 8-ft dia. cyclones)
Rochester, NY eastern bituminous coal
B&W conventional gas reburn w/ OFA December 1998, July 1998 startups (still operating)
Commercial installation of CGR, with (1) gas burner added to each sidewall + (2) large and (2) small OFA ports added to front wall above cyclones, utilizing higher reburn gas pressure (vs. Boiler #43) requires no flue gas recirculation; {Very small furnace w/ cyclone SR not <1.0}.
B&W claimed reburn with OFA lowered NOx by 50% from 1.20 lb/mmBtu baseline to 0.6 lb/mmBtu.
B&W graph shows 10-12% percent reburn fuel to achieve 0.6 lb/mmBtu and 23-24% reburn gas input to reach 0.33 lb/mmBtu NOx (73% reduction) [7].
Another technical paper showed NOx lowered by 52% from 1.25 lb/mmBtu baseline to 0.60 lb/mmBtu with 18 percent reburn fuel[5].
Source: [7] B&W Technical Paper; [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

REBURN – GAS, CONVENTIONAL
Cyclone-Fired Boilers, continued
Eastman Kodak Company
Kodak Park Boiler 43 Crushed Coal, front-wall cyclone-fired 1968 vintage
600,000 lb/hr steam B&W boiler (approx. 60 MWe equivalent, two cyclones)
Rochester, NY eastern bituminous coal
B&W conventional gas reburn 1995 startup (still operating)
Commercial installation of CGR, with flue gas recirculation (FGR) for injection mass momentum w/ (1) FGR fan; (1) gas burner added to each sidewall + (2) OFA ports added front wall above cyclones. {Very small furnace/low residence time w/ cyclone SR not <1.0}
B&W claimed reburn with OFA & FGR lowered NOx by 50% from 1.20 lb/mmBtu baseline to 0.6 lb/mmBtu. B&W graph shows 18% percent reburn fuel to achieve 0.6 lb/mmBtu and 29% reburn gas input to reach 0.36 lb/mmBtu NOx (70% reduction) [7].
Another technical paper showed NOx lowered by 56% from 1.35 lb/mmBtu baseline to 0.60 lb/mmBtu with 18 percent reburn fuel[5].
Source: [7] B&W Technical Paper; [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

Tennessee Valley Authority (TVA)
Allen Station Unit 1 (TN) Crushed Coal, cyclone-fired (seven cyclones) 1959 vintage
300 MW B&W boiler PRB &western bituminous coal blend fired
GE-EER Conventional Gas Reburn, 1998 startup
Commercial installation added gas supply piping, metering, hangers, supports; reburn injectors and cooling air piping, OFA ductwork, injection nozzles and wall ports, field I&C devices.
Reburn with OFA claimed to lower NOx 65% from baseline 1.20 lb/mmBtu to 0.42 lb/mmBtu) at full load with reburn operation. No claims of percent reburn fuel included. (TVA also installed duplicate OFA systems on Allen Units 2 & 3 boilers).
Another technical paper showed NOx lowered by 65% from 0.86 lb/mmBtu baseline (to 0.30 lb/mmBtu) with 7 percent reburn fuel[5].
Source: Sept. 2005 GE-EER experience list; [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

REBURN – COAL, CONVENTIONAL
Cyclone-Fired Boilers
Alliant Energy (formerly Wisconsin Power & Light)
Nelson Dewey Station Unit 2 Crushed Coal, cyclone-fired, PRB coal 1962 vintage

110 MW B&W boiler 3-cyclones across front wall, 4 reburn burners +
4 OFA ports across rear wall, aligned vertically in columns.

US DOE Clean Coal Demonstration project of B&W's Conventional Coal Reburn, 1991 startup (since discontinued) added coal supply piping, reburn burners with flue gas recirculation, OFA ductwork + dual zone ports; coal feeder, pulverizer & PA fan, tested with PRB and bituminous coals. (western subbituminous coal)

B&W claimed reburn operation lowered NOx by 57% from baseline of 0.83 mmBtu to 0.38 lb/mmBtu at full load[7]. Approx. 30% percent of total fuel input supplied as reburn fuel. Increased unit output by 10 MW, increased flyash unburned carbon by 4% (13-22% vs 9-18%), decreased furnace exit gas temperature (FEGT). OFA ports listed in B&W experience list.

B&W shows full load NOx w/o reburn was 0.75 lb/mmBtu, and 0.29-0.32 lb/mmBtu w/ PRB fuel during reburn operation (57% decrease). At 75% load, 0.64 vs 0.29-0.32 lb/mmBtu. At 55% load, 0.62 vs 0.29-0.31 lb/mmBtu without and with reburn activated[8].

Another technical paper showed NOx lowered by 52-55% from 0.82 lb/mmBtu baseline (to 0.39-0.34 lb/mmBtu) with 25-30 percent reburn fuel[5].

Source: [7] 2004 B&W Technical Paper; [5] DOE-NETL 2004 Reburn Conference Technical paper; [8] B&W case history (from website, dated 1997).

REBURN – COAL, MICRONIZED, CONVENTIONAL

Cyclone-Fired Boilers

Eastman Kodak Company
Kodak Park #15 Boiler Crushed Coal, front-wall cyclone-fired, 1956 vintage
400,000 lb/hr steam B&W boiler (approx. 50 MWe equivalent, two cyclones)
Rochester, NY eastern bituminous coal
GE-EER micronized coal reburn1996 initial startup (operating since 1997)

Demonstration project performed with Dept. of Energy's US Clean Coal Technology Program. Project added flue gas recirculation for injection mass momentum, FGR fan and two micronized coal pulverizers; (6) reburn coal injectors added to rear wall + (1) reburn coal injector on each of the sidewalls, with (4) OFA ports added across front wall above cyclones[9]. GE-EER designed and fabricated the coal injectors and OFA ports. {Extremely small furnace and low residence time}.

GE-EER claimed reburn + OFA w/ FGR reduced NOx by 50% from 1.20 lb/mmBtu baseline to 0.6 lb/mmBtu. No claims of percent reburn fuel included.

Another technical paper showed this demonstration of micronized coal reburn from 4/97-10/98 lowered NOx by 57% from 1.36 lb/mmBtu baseline (to 0.59 lb/mmBtu) with 17 percent reburn fuel[5].

Source: [9] DOE Topical Report Number 14 (May 1999); GE-EER experience list; [5] DOE-NETL 2004 Reburn Conference Technical paper.

REBURN – FUEL LEAN GAS REBURN

Cyclone-Fired Boilers

Midwest Generation (formerly Commonwealth Edison)
Joliet Station 9, Unit 6 Crushed Coal, opposed-wall cyclone-fired (nine cyclones)
340 MW B&W boiler 1959 vintage, 1997 startup (FLGR has since been decommissioned)

Energy Systems Associates demonstrated 25-30% NOx reduction using 5-10% of total heat input as reburn natural gas injected (without OFA)[5].

Another technical paper showed this demonstration in collaboration with Gas Research Institute of FLGR lowered NOx by 28-43% from 1.36 lb/mmBtu baseline (to 0.59 lb/mmBtu) with 7 percent reburn fuel[10].

Source: [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference); [10] NGB Technologies Technical Paper.

REBURN – FUEL LEAN GAS REBURN w/ SNCR continued

Cyclone-Fired Boilers

Owensboro Municipal Utilities (KY) Crushed Coal, front-wall cyclone-fired
Elmer Smith Unit 1 (three cyclones) 1965 vintage
150 MW B&W boiler
CFD model study only predicted NOx reductions from 1.59 to 0.39 lb/mmBtu with OFA only (75% reduction, 0.90 SR); 25-30% NOx reduction using 6% of total heat input as reburn natural gas injected above OFA; 40-45% NOx reduction from SNCR with <5 ppm ammonia slip[11].
Source: [11] REI Technical paper.

Separated OVERFIRE AIR

Cyclone-Fired Boilers

Tennessee Valley Authority (TVA) Crushed Coal, cyclone-fired, 1959 vintage
Allen Station Units 2 & 3 (TN) (seven cyclones)
300 MW B&W boilers PRB &western bituminous coal blend
GE-EER Overfire air (duplicate of Allen 1), 1999 startup
GE-EER claimed to lower NOx with OFA alone up to 29% from baseline 1.20 lb/mmBtu to 0.85 lb/mmBtu on Units #2 and 3 at full load.
Source: Sept. 2005 GE-EER experience list.

AmerenUE (formerly Union Electric Co.)
Sioux Unit 1 Crushed Coal, opposed-wall cyclone-fired 1969 vintage
500 MW B&W boiler PRB/Illinois Coal blend
Boiler has 10 cyclone burners, arranged "2 over 3" style, on opposite walls, and fires a blend of 85% to 50% western subbituminous (PRB) coal, with Illinois bituminous coal, petroleum coke, and tire-derived fuel.
A ten-port OFA system (five ports on each front and rear wall) began operation in mid-2001, which reduced NOx emissions approx. 40-50% reduction from 1.1-1.3 (assume average of 1.19) down to 0.7 lb/mmBtu with moderate cyclone air-staging (cyclone SR from 1.19 to 1.0).[3] Subsequent testing and full load operation at deeper cyclone air-staging (SRs ≤0.90) has dropped NO_X with SOFA alone to around 0.3 lb/mmBtu in 2004[4].
Source: [3] REI 2002 and 2003 Technical Papers; [4] REI 2004 Technical paper;* REI 2005 Technical paper

Coal burning cyclone-fired utility boilers in the United States that have been retrofitted with Separated Overfire Air CR technology are listed in Table A.2-1. A large majority of the cyclone-fired boilers listed burn western subbituminous coal (or PRB blended with midwestern bituminous coal).

TABLE A.2-1 – Cyclone-Fired Boiler Overfire Air Retrofit Installations[12]

Facility Name	Installation Date	Comments
Allen Station Units 1	Installed 1998*	OFA w/ CGR retrofit; has SCR
Allen Station Unit 2	Installed 1999*	(Similar to Unit 1, w/o CGR) have SCR
Allen Station Unit 3	Installed 1999*	(Similar to Unit 1, w/o CGR) have SCR
Asbury Unit 1	Installed 5/10/1999	Empire District, BART-eligible
Bailly Unit 7	Installed 2003[13]	SCR to be installed in 2006-7
Bailly Unit 8	Installed 5/31/2000	SCR retrofit 5/11/2004
Baldwin Unit 1	Installed 12/31/1999	SCR retrofit 4/28/2003
Baldwin Unit 2	Installed 5/8/2000	SCR retrofit 4/12/2002
Big Stone Unit 1	Installed 10/22/1997	part of conversion to PRB
BL England Unit 2	Installed 1998*	previous SNCR retrofit in 1996
CP Crane Unit 2	Installed 2/1/1999	OFA w/ CGR retrofit
Coffeen Unit 1	Installed 2/1/2001	SCR retrofit 4/21/2003
Coffeen Unit 2	Installed 2/9/2000	SCR retrofit 4/09/2002
Edgewater Unit 3	Installed 11/2001[13]	
Edgewater Unit 4	Installed 6/19/2001	
Joliet 9 Unit 6	Installed 2000[13]	
Kincaid Unit 1	Installed 4/28/2000	SCR retrofit 12/17/2002
Kincaid Unit 2	Installed 5/24/2000	SCR retrofit 6/07/2002
Allen S. King Unit 1	Installed 11/30/1999	
LaCygne Unit 1	Installed 2/28/2000	
Lake Road Unit 6	Installed 6/01/2002	
Michigan City Unit 12	Installed 4/1998[13]	SCR retrofit 5/01/2003
Nelson Dewey Unit 1	Installed 2002[13]	
Nelson Dewey Unit 2	Installed 2002[13]	
Paradise Unit 1	Installed 11/14/1998	SCR retrofit 5/01/2001
Paradise Unit 2	Installed 12/8/1999	SCR retrofit 5/01/2000
Paradise Unit 3	Installed 5/4/2000	SCR retrofit 3/10/2004
Powerton Unit 5-1	Installed 6/1/2003	
Powerton Unit 5-2	Installed 6/1/2003	
Powerton Unit 6-1	Installed 6/1/2002	
Powerton Unit 6-2	Installed 5/4/1999	
Schahfer Unit 14	Installed early 2000[13]	SCR retrofit 5/11/2004
Sibley Unit 2	Installed 5/24/2002	
Sibley Unit 3	Installed 5/4/1999	
Sioux Unit 1	Installed 4/30/2001	SNCR demo May 2005
Sioux Unit 2	Installed 4/30/1997	
State Line Unit 4	Installed 11/2001[13]	Similar to Joliet 9 Unit 6
Tanners Creek Unit 4	Installed 5/12/2002	
Thomas Hill Unit 1	Installed June 2004[13]	
Thomas Hill Unit 2	Installed November 2000[13]	

Note: This table does not include every installed U.S. coal-fired cyclone boiler OFA retrofit project.
Source: [12] US EPA Docket OAR-2002-0076-0446 Technical Support Document for BART NOx Limits for Electric Generating Units Excel Spreadsheet 6/15/2005 (except as noted below)
* Vendor experience list (GE Energy for Allen Station Units 1-3; RJM for BL England Unit 2)
[13] Burns & McDonnell internal database.

Coal burning cyclone-fired utility boilers in the United States that have been retrofitted with SCR technology are listed in Table A.2-2. This list includes at least eighteen cyclone-fired boilers burning western subbituminous coal (or PRB blended with midwestern bituminous coal). The highest emission

reductions listed in Table A.2-2 for SCR systems are for clean reactor catalyst and ideal operating conditions.

TABLE A.2-2 – Cyclone-Fired Boiler High-Dust SCR Installations

Facility[1]	Unit Size[2],MW	Tested Control Efficiency[3]	Tested Outlet NO_X Emission Rate (lb/mmBtu)[3]	2003 Ozone Season Average NO_X Emission Rate[4] (lb/mmBtu)
Allen 1, 2, & 3[5,6]	330 ea.	91.1/NAD[7]/88.7	0.070/NAD[7]/0.088	0.088/0.077/0.086
Baldwin 1[5,6]	600[3]	82.9	0.072	0.238
Baldwin 2[5,6]	605[3]	83.5	0.067	0.286
Bailly 8[5,6]	422	NAD[7]	NAD[7]	0.84
Coffeen 1[5,6]	389	NAD[7]	NAD[7]	0.114
Coffeen 2[5,6]	617	NAD[7]	NAD[7]	0.120
Dallman 31 & 32	207	NAD[6]	NAD[6]	0.149/0.146
Kincaid 1 & 2[5,6]	660[3] ea.	89/89	0.079/0.079	0.181/1.198
Marion 4	173	94.3	0.067	0.252
Merrimack 1[5,8]	114	50.5[9]	0.148	0.158
Merrimack 2	346	51.3[9]	0.155	0.171
Michigan City 12[5,10]	540	84.2	0.109	0.418
New Madrid 1 & 2[8,10]	600 ea.	87.4/88.1	0.149/0.147	0.319/1.172
Paradise 1 & 2[5,6]	704 ea.	87.7/87.7	0.102/0.101	0.124/0.113
Paradise 3[5,6]	1150	89.1	0.088	0.658
Schahfer 14[5,10]	540	83.5	0.106	0.478

[1] – original design fuel for all listed cyclone boilers was bituminous coal
[2] – Generator nameplate rating, March 2002 Energy Information Administration report DOE/EIA-0095(2000). Actual unit MW output rating may be higher or lower than nameplate.
[3] – Burns & McDonnell internal database.
[4] – as reported to US EPA, available from their website at http://cfpub.epa.gov/gdm/index.cfm
[5] – includes application of separated overfire air for combustion NO_X control
[6] – current fuel believed to be a blend of subbituminous and bituminous coals
[7] – NAD = no published data from SCR emission testing found on these units.
[8] – original air preheaters were tubular-type; changed to rotary-type during SCR retrofit
[9] – Design NO_X removal efficiency is higher, approx. 90%.
[10] – current fuel believed to be subbituminous coal

For Merrimack Unit 1's SCR, inlet (i.e. uncontrolled) NO_X was 1.34 lb/mmBtu, for a blend of high sulfur bituminous and medium or low sulfur bituminous coals, and requires year-round SCR operation for compliance. The catalyst was designed for 88.9% NO_X removal efficiency

SELECTIVE NON-CATALYTIC REDUCTION

Pulverized coal-fired boilers

American Electric Power (AEP) Pulverized Coal, cell-burner, opposed wall-fired B&W boiler
Cardinal Unit 1 1967 vintage; Low NO_x burners installed in October 1998
600 MW (nominal) Brilliant, Ohio
Fuel Tech urea-based SNCR installed in October 1998.
Fuel Tech, DOE, EPRI-member utilities SNCR demonstration project. Tested in March-April 1999, claimed 65% reduction with LNBs + SNCR w/ 5 ppm NH_3 slip, (from pre-LNB retrofit baseline of 1.20 lb/mmBtu*) down to 0.52 lb/mmBtu at 620 MW (100% MCR). SNCR reduced NO_X 31% below LNBs alone (0.75 lb/mmBtu baseline), at 620 MWg (100% MCR), 34% reduction at 75% MCR (450 MWg), and 42% reduction at minimum load (340 MWg, 55% MCR) ≤5% ammonia slip[17], burning eastern bituminous coal. Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005; [1]ICAC White Paper, [17] 2000 Fuel Tech technical paper, *Riley Power (Babcock Power Inc.) experience list 8/16/04.

Carolina Power & Light (Progress Energy)
Asheville Unit 1 Pulverized Coal, front wall fired
200 MWe DB Riley boiler 1964 vintage, eastern bituminous coal, June 2000 SNCR startup
Fuel Tech commercial SNCR installation claimed 25% NOx reduction from low-NO_X burner w/o OFA baseline of 0.58 lb/mmBtu (down to 0.44 lb/mmBtu on SNCR alone). Urea-to-NOx NSR not stated. (Also see FLGR + SNCR installation summaries for pulverized coal boilers).
Source: Fuel Tech experience list dated 1/28/2005.

Carolina Power & Light (Progress Energy) Pulverized Coal, Tangentially-fired
Cape Fear Unit 5 1956 vintage; eastern bituminous coal
154 MW CE boiler SNCR startup in 2002
Mobotec USA "Rotamix" ammonia-based SNCR system injects aqueous ammonia liquid into a high velocity boosted separated overfire air (ROFA) system at the boiler.
CP&L technical paper claimed to lower NO_X from 0.28 lb/mmBtu baseline by 43% to 0.16 lb/mmBtu in 2002 with 5 ppm NH_3 slip following the installation of ROFA in 2000.
Overall reduction 73% from full-load pre-ROFA baseline 0.60 lb/mmBtu to 0.16 lb/mmBtu[18].
Mobotec claimed further NO_X reduction was possible by injecting urea in place of ammonia, achieving 0.13 lb/mmBtu instead of 0.18 lb/mmBtu, which would be 54% decrease from 0.28 lb/mmBtu with ROFA alone, or 78% overall decrease[19]. Ammonia-to-NOx NSR not stated.
Source: [18] CP&L 2002 Technical paper; [19] Mobotec 2003 technical paper.

Carolina Power & Light (Progress Energy) Pulverized Coal, Tangentially-fired
Cape Fear Unit 6 twin-furnace (eight corner), 1958 vintage; eastern bituminous coal
175 MW CE boiler SNCR startup in 2001
Mobotec USA "Rotamix" ammonia-based SNCR system, injects aqueous ammonia liquid into a high velocity boosted separated overfire air ("ROFA") system at the boiler.
CP&L technical paper claimed to lower NO_X from 0.23 lb/mmBtu baseline by 22% to 0.18 lb/mmBtu with 5 ppm NH_3 slip following the installation of ROFA+SNCR in 2001[18]. Presentation slide graph shows no reduction for Rotamix beyond ROFA alone at full load NO_X emission rate of 0.23 lb/mmBtu. Ammonia-to-NOx NSR not stated.
Overall reduction 67% from full-load pre-ROFA baseline 0.54 lb/mmBtu to 0.18 lb/mmBtu.
Mobotec claimed further NO_X reduction was possible by injecting urea in place of ammonia, achieving 0.10 lb/mmBtu instead of 0.18 lb/mmBtu, which would be 56% decrease from 0.23 lb/mmBtu with ROFA alone, or 81% overall decrease[19]. Urea-to-NOx NSR not stated.
Source: [18] CP&L 2002 Technical paper; [19] Mobotec 2003 technical paper.

TABLE A-3 – Low-Dust Pulverized Coal-Fired Boiler SCR Installations

Operator/Facility[1,2]	SCR Startup Date[3]	Average NO_X Emission Rates[4] (lb/mmBtu)	Unit Size[5], MW
AEP/Cardinal Unit 3[6]	5/01/03	0.74 / 0.34 / 0.135	650
Carolina P&L/Mayo Unit 1[7]		- / (0.36) / N/A	368 x 2
Carolina P&L/Roxboro Unit 4[7,8]	5/07/01	0.57 / 0.26 / 0.081	372 x 2
Cinergy/East Bend Unit 1	4/01/02	- / (0.28) / 0.067	648
Constellation/Brandon Shores Unit 1[8]	(2001)	0.47 /0.33 / 0.126	685
Constellation/Brandon Shores Unit 2[8]	(2000)	0.45 / 0.31 / 0.094	685
Dayton P&L/Killen Station Unit 2	11/01/03	- / (0.48) / 0.06[9]	666
Dynegy Midwest Gen/Havana Unit 6[10]	(2000)	0.46 /0.20 / 0.102[9]	488
PSEG Power LLC / Mercer Unit 1[11]	(2005)	- / (0.63) / N/A	320
PSEG Power LLC / Mercer Unit 2[11]	(2004)	- / (0.76) / N/A	320

[1] – Burns & McDonnell internal database.
[2] – Current fuel is eastern or midwestern bituminous coal, except Havana
[3] – US EPA Docket OAR-2002-0076-0446 Technical Support Document for BART NOx Limits for Electric Generating Units Excel Spreadsheet 6/15/2005, except where noted. Dates in () are believed to be accurate but have not been confirmed.
[4] – The three values are "Pre-control average", "2004 annual average", and "2003 ozone season average" NO_X emission rates, as reported to US EPA. Pre-control and year 2004 annual average data as shown in US EPA Docket OAR-2002-0076-0446 Technical Support Document for BART NOx Limits for Electric Generating Units Excel Spreadsheet 6/15/2005, posted on their website: http://docket.epa.gov/edkpub/do/EDKStaffItemDetailView?objectId=090007d48084562b. Values shown in parentheses are year 2003 annual average where 2004 data is not available. Year 2003 and 2003 ozone season data is available from the EPA's website at http://cfpub.epa.gov/gdm/index.cfm, includes application of separated overfire air for combustion NO_X control where applicable.
[5] – Generator nameplate rating, March 2002 Energy Information Administration report DOE/EIA-0095(2000). Actual unit MW output rating may be higher or lower than nameplate.
[6] – This boiler has low-NOx burners for combustion controls.
[7] – Carolina Power & Light plants listed here have two boilers per unit, total nameplate for Mayo is 736 MW, Roxboro is 745 MW; emission numbers are the average of both boilers.
[8] – This boiler has low-NOx burners and overfire air for combustion controls.
[9] – This is preliminary data reported to the US EPA for 2004 ozone season average emission rate.
[10] – This boiler's current fuel is believed to be subbituminous coal.
[11] – Mercer boilers listed have low-dust SCR with flue gas reheat. Unit size is approximate, not nameplate.
N/A = complete 2004 ozone season data is not available, and 2003 ozone season data is not representative of the post-SCR installation emission rate.

SELECTIVE NON-CATALYTIC REDUCTION

Pulverized coal-fired boilers

American Electric Power (AEP) Pulverized Coal, cell-burner, opposed wall-fired B&W boiler
Cardinal Unit 1 1967 vintage; Low NO_x burners installed in October 1998
600 MW (nominal) Brilliant, Ohio
Fuel Tech urea-based SNCR installed in October 1998.
Fuel Tech, DOE, EPRI-member utilities SNCR demonstration project. Tested in March-April 1999, claimed 65% reduction with LNBs + SNCR w/ 5 ppm NH_3 slip, (from pre-LNB retrofit baseline of 1.20 lb/mmBtu*) down to 0.52 lb/mmBtu at 620 MW (100% MCR). SNCR reduced NO_X 31% below LNBs alone (0.75 lb/mmBtu baseline), at 620 MWg (100% MCR), 34% reduction at 75% MCR (450 MWg), and 42% reduction at minimum load (340 MWg, 55% MCR) ≤5% ammonia slip[17], burning eastern bituminous coal. Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005; [1]ICAC White Paper, [17] 2000 Fuel Tech technical paper, *Riley Power (Babcock Power Inc.) experience list 8/16/04.

Carolina Power & Light (Progress Energy)
Asheville Unit 1 Pulverized Coal, front wall fired
200 MWe DB Riley boiler 1964 vintage, eastern bituminous coal, June 2000 SNCR startup
Fuel Tech commercial SNCR installation claimed 25% NOx reduction from low-NO_X burner w/o OFA baseline of 0.58 lb/mmBtu (down to 0.44 lb/mmBtu on SNCR alone). Urea-to-NOx NSR not stated.
(Also see FLGR + SNCR installation summaries for pulverized coal boilers).
Source: Fuel Tech experience list dated 1/28/2005.

Carolina Power & Light (Progress Energy) Pulverized Coal, Tangentially-fired
Cape Fear Unit 5 1956 vintage; eastern bituminous coal
154 MW CE boiler SNCR startup in 2002
Mobotec USA "Rotamix" ammonia-based SNCR system injects aqueous ammonia liquid into a high velocity boosted separated overfire air (ROFA) system at the boiler.
CP&L technical paper claimed to lower NO_X from 0.28 lb/mmBtu baseline by 43% to 0.16 lb/mmBtu in 2002 with 5 ppm NH_3 slip following the installation of ROFA in 2000.
Overall reduction 73% from full-load pre-ROFA baseline 0.60 lb/mmBtu to 0.16 lb/mmBtu[18].
Mobotec claimed further NO_X reduction was possible by injecting urea in place of ammonia, achieving 0.13 lb/mmBtu instead of 0.18 lb/mmBtu, which would be 54% decrease from 0.28 lb/mmBtu with ROFA alone, or 78% overall decrease[19]. Ammonia-to-NOx NSR not stated.
Source: [18] CP&L 2002 Technical paper; [19] Mobotec 2003 technical paper.

Carolina Power & Light (Progress Energy) Pulverized Coal, Tangentially-fired
Cape Fear Unit 6 twin-furnace (eight corner), 1958 vintage; eastern bituminous coal
175 MW CE boiler SNCR startup in 2001
Mobotec USA "Rotamix" ammonia-based SNCR system, injects aqueous ammonia liquid into a high velocity boosted separated overfire air ("ROFA") system at the boiler.
CP&L technical paper claimed to lower NO_X from 0.23 lb/mmBtu baseline by 22% to 0.18 lb/mmBtu with 5 ppm NH_3 slip following the installation of ROFA+SNCR in 2001[18]. Presentation slide graph shows no reduction for Rotamix beyond ROFA alone at full load NO_X emission rate of 0.23 lb/mmBtu. Ammonia-to-NOx NSR not stated.
Overall reduction 67% from full-load pre-ROFA baseline 0.54 lb/mmBtu to 0.18 lb/mmBtu.
Mobotec claimed further NO_X reduction was possible by injecting urea in place of ammonia, achieving 0.10 lb/mmBtu instead of 0.18 lb/mmBtu, which would be 56% decrease from 0.23 lb/mmBtu with ROFA alone, or 81% overall decrease[19]. Urea-to-NOx NSR not stated.
Source: [18] CP&L 2002 Technical paper; [19] Mobotec 2003 technical paper.

SELECTIVE NON-CATALYTIC REDUCTION continued

Pulverized coal-fired boilers

Cinergy (formerly Cincinnati G&E) — Pulverized Coal, Tangentially-fired,
Miami Fort Unit 6 (Ohio) — 1960 vintage; startup prior to 2000
163 MW CE boiler
Fuel Tech urea-based SNCR system, claimed to lower NOx by 35% from 0.55 lb/mmBtu baseline[(1)].(assume eastern bituminous coal). Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005, [(1)] ICAC White Paper.

Conectiv (formerly Delmarva Power & Light)
Edgemoor Unit 3 — Pulverized Coal, Tangentially-fired, 1954 vintage
84 MW CE boiler — mid-March 1996 startup; (assume eastern bituminous coal)
Hamon Research-Cottrell supplied a urea-based SNCR system. HRC claimed 35% NOx reduction with less than 10 ppm ammonia slip. Urea-to-NOx NSR not stated.
Another source shows a 30% reduction from 0.54 lb/mmBtu baseline[(1)].
Source: Hamon experience list (not listed by Fuel Tech); [(1)] ICAC White Paper.

Conectiv (formerly Delmarva Power & Light) — Pulverized Coal
Indian River Units 3 & 4 (Millsboro, DE) — Unit 3 is front wall-fired, 1974 vintage
178MW and 440 MW — Unit 4 is turbo-fired opposed-wall, 1980 vintage
B&W, DB Riley boilers — Spring 2000 startup (eastern bituminous coal)
Hamon Research-Cottrell supplied a urea-based SNCR system (not listed by Fuel Tech) on both units. HRC claimed 35% NO_X reduction with less than 5 ppm ammonia slip. Urea-to-NOx NSR not stated.
An REI 1999 technical paper shows a pre-SNCR baseline of 0.37 and 0.44 lb/mmBtu, respectively. [(20)]
Another source listed these units as having a pre-control NO_X baseline of 0.97 and 0.57 lb/mmBtu, and 2004 post-SNCR startup average of 0.32 and 0.33 lb/mmBtu, respectively. [(12)]
Source: Hamon experience list (not listed by Fuel Tech); [(20)] REI 1999 technical paper;
[(12)] US EPA Docket OAR-2002-0076-0446 Excel Spreadsheet 6/15/2005.

Dominion Generation (Virginia E&P Co.) — Pulverized Coal, Tangentially-fired
Clover Station, Units 1 & 2 (VA) — ABB/CE boilers, 1995, 1996 vintage
2 x 465 MW — (eastern bituminous coal)
Urea-based SNCR (Fuel Tech system) — 1995, 1996 startup (initial commercial)
Fuel Tech claimed NOx reduced by 25% from 0.32 lb/mmBtu baseline (to 0.24 lb/mmBtu).
Source: Fuel Tech experience list dated 1/28/2005. Urea-to-NOx NSR not stated.

Dynegy Midwest Generation (formerly Illinois Power) — Pulverized Coal, Tangentially-fired
Vermillion Station, Unit 1 — 1955 vintage
82 MW — CE boiler, bituminous Illinois coal
Mobotec USA "Rotamix" urea-based SNCR system with rotating opposed fired air (ROFA).
Mobotec 2004 technical paper claimed to lower NO_X by 55% from 0.22 lb/mmBtu baseline to 0.10 lb/mmBtu in April 2004 with urea-based Rotamix SNCR and < 5 ppm CO. NH_3 slip not mentioned.
Overall reduction 83% from full-load pre-ROFA baseline 0.58 lb/mmBtu to 0.10 lb/mmBtu [(21)]. Urea-to-NOx NSR not stated.
Source: [(21)] Mobotec 2004 technical paper.

Source: Fuel Tech experience list dated 1/28/2005; also listed in [1]ICAC White Paper. (Also see FLGR+SNCR installation summaries for pulverized coal boilers)

SELECTIVE NON-CATALYTIC REDUCTION continued

Pulverized coal-fired boilers

Reliant Energy (formerly GPU Genco)	Pulverized Coal
(formerly Sithe, formerly Penelec)	Tangentially-fired
Seward # 15 (PA)	mid-1990's SNCR startup
Units 4 & 5	eastern bituminous coal
62 & 156 MW CE boilers	1950 & 1957 vintage

Urea-based SNCR (Fuel Tech system), later installed an in-duct SCR to reduce NH_3 slip.
Fuel Tech claimed to lower NOx 35% for SNCR only (55% for combined SNCR/SCR from 0.78 lb/mmBtu baseline). Boilers have since been demolished and replaced with CFBs. Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005, [1]ICAC White Paper.

Rochester Gas & Electric	Pulverized Coal, Tangentially-fired
Russell Station, Units 1-4 (NY)	1948, 1950, 1953, 1957 vintage
1 x 50 MW, 2 x 65 MW, 1 x 85 MW CE boilers	eastern bituminous coal
Urea-based SNCR (Fuel Tech system)	SNCR startup prior to 2000

Vendor claimed to lower NOx by 15-27.5% from 0.28 – 0.42 lb/mmBtu baselines. Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005.

HYDROCARBON-ENHANCED AMMONIA SNCR (NOxStar™)

Pulverized coal-fired boilers

Tennessee Valley Authority (TVA)	Pulverized Coal twin-furnace, tangentially-fired,
Kingston Power Station (TN)	1955 vintage eastern bituminous coal
Unit 9, 200 MWe CE boiler	NOxStar™ startup January 2002

Demonstration of NOxStar™ hydrocarbon-enhanced ammonia-based SNCR installation.
Mitsui Babcock claimed 68% NOx reduction from baseline of 0.55 lb/mmBtu down to 0.17 lb/mmBtu with boosted OFA and NOxStar™ with < 5 ppm ammonia slip; NOxStar™ alone reduced NOx by 53%[22]; boosted OFA only reduced NOx from 0.55 to 0.45 lb/mmBtu (18% reduction). Ammonia-to-NOx NSR not stated.
TVA's website reported that "an earlier version of NOxStar was installed at Kingston Fossil Plant Unit 9 in 2002 with mixed results. NOx reductions were achieved, but the boiler was damaged" (http://www.tva.gov/environment/repotrs/envreports/aer/2003/env_compliance.htm)
Source: [22] Mitsui Babcock Technical paper, October 2003.

Tennessee Valley Authority (TVA)	Pulverized Coal, wall-fired
Colbert Station (AL)	1955 vintage

Unit 4, 192 MWe twin-furnace B&W boiler w/ FGR eastern bituminous coal
First commercial installation of NOxStar™ hydrocarbon-enhanced ammonia-based SNCR technology.
Mitsui Babcock showed 80% NOx reduction from baseline of 0.50 to 0.10 lb/mmBtu; using < 0.1% of total boiler heat input for propane input and 1% of total steam flow generated in the boiler for lance cooling[23]; 2004 SNCR system startup. Ammonia-to-NOx NSR not stated.
Source: [23] Mitsui Babcock 2004 Technical paper.

RJM claimed 50% reduction from 0.50 lb/mmBtu pre-SNCR baseline to 0.25 lb/mmBtu for SNCR coal-firing operation; NO_X baseline 0.82 lb/mmBtu prior to RJM's LNB modifications installed in 1994, 1992, & 1994 (39% reduction); Urea-to-NOx NSR not stated.
Fuel Tech claimed 30% NO_X reduction for SNCR from baseline of 153 ppm firing #6 fuel oil on Units 4 & 6 only.
Source: RJM experience list, Fuel Tech experience list dated 1/28/2005.

SELECTIVE NON-CATALYTIC REDUCTION continued

Pulverized coal-fired boilers

Owensboro Municipal Utilities (KY) Pulverized Coal, Tangentially-fired,
Elmer Smith Unit 2 1974 vintage
300 MW CE boiler eastern bituminous coal
Hamon Research-Cottrell supplied an ammonia-based SNCR system but stated no claims for NOx reduction; (this project is not listed in ICAC White Paper[(1)]). Ammonia-to-NOx NSR not stated.
Source: Hamon experience list.

PECO Energy (formerly Philadelphia Electric Company)
Cromby Unit 1 Pulverized Coal, front wall-fired divided furnace
160 MWe B&W boiler 1954 vintage eastern bituminous coal
RJM installed Fuel Tech urea-based SNCR with low NO_X burner modifications & OFA in 1999, June 1999 startup.
RJM claimed 29% SNCR NO_X reduction from baseline of 0.35 lb/mmBtu, down to 0.25 lb/mmBtu with urea NSR = 0.8; RJM provided burner modifications of B&W XCL low-NOx burners installed in 1994 + OFA; this reduced NO_X from 0.50 to 0.35 lb/mmBtu (30% reduction) without SNCR. Urea-to-NOx NSR not stated.
Source: RJM experience list; [(1)]ICAC White Paper.

Exelon (formerly PECO Energy/ Pennsylvania Electric Company)
Eddystone Units 1 & 2 Pulverized Coal Tangentially-fired, 1954 vintage
318, 333 MW each CE boilers 1999 SNCR startup, eastern bituminous coal
Fuel Tech claimed 30% NOx reduction from baseline of 0.26 lb/mmBtu.
Source: Fuel Tech experience list dated 1/28/2005.

Public Service Enterprise Group (PSEG) Power LLC [formerly Public Service Electric & Gas of New Jersey (PSE&G)]
Hudson Station, Unit 2 Pulverized Coal, opposed-wall-fired, 1968 vintage
660 MWe Foster Wheeler boiler eastern bituminous coal March 1999 startup
Fuel Tech urea-based commercial SNCR installation claimed 25% (initial) NOx reduction for SNCR alone from baseline of 0.65 lb/mmBtu (down to 0.49 lb/mmBtu). Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005, also listed in [(1)]ICAC White Paper. (Also see FLGR+SNCR installation summaries for pulverized coal boilers).

Public Service Enterprise Group (PSEG) Power LLC [formerly Public Service Electric & Gas of New Jersey (PSE&G)]
Mercer Station (2) twin-furnace boilers, 320 MWe each, DB Riley turbo-fired
Unit 1 and Unit 2 front wall PC, wet-bottom (slagging ash) eastern bituminous coal
Furnace #11 & #12 1960 vintage April 1999 startup
Furnace #21 & 22 1961 vintage May 1999 startup
Fuel Tech urea-based commercial SNCR installation claimed 30-35% NOx reduction from baseline of 2.0 lb/mmBtu on SNCR alone, down to 1.4 lb/mmBtu. Urea-to-NOx NSR not stated.

Source: Fuel Tech experience list dated 1/28/2005; also listed in [1]ICAC White Paper. (Also see FLGR+SNCR installation summaries for pulverized coal boilers)

SELECTIVE NON-CATALYTIC REDUCTION continued

Pulverized coal-fired boilers

Reliant Energy (formerly GPU Genco) — Pulverized Coal
(formerly Sithe, formerly Penelec) — Tangentially-fired
Seward # 15 (PA) — mid-1990's SNCR startup
Units 4 & 5 — eastern bituminous coal
62 & 156 MW CE boilers — 1950 & 1957 vintage
Urea-based SNCR (Fuel Tech system), later installed an in-duct SCR to reduce NH_3 slip.
Fuel Tech claimed to lower NOx 35% for SNCR only (55% for combined SNCR/SCR from 0.78 lb/mmBtu baseline). Boilers have since been demolished and replaced with CFBs. Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005, [1]ICAC White Paper.

Rochester Gas & Electric — Pulverized Coal, Tangentially-fired
Russell Station, Units 1-4 (NY) 1948, 1950, 1953, 1957 vintage
1 x 50 MW, 2 x 65 MW, 1 x 85 MW CE boilers — eastern bituminous coal
Urea-based SNCR (Fuel Tech system) — SNCR startup prior to 2000
Vendor claimed to lower NOx by 15-27.5% from 0.28 – 0.42 lb/mmBtu baselines. Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005.

HYDROCARBON-ENHANCED AMMONIA SNCR (NOxStar™)

Pulverized coal-fired boilers

Tennessee Valley Authority (TVA) — Pulverized Coal twin-furnace, tangentially-fired,
Kingston Power Station (TN) — 1955 vintage eastern bituminous coal
Unit 9, 200 MWe CE boiler — NOxStar™ startup January 2002
Demonstration of NOxStar™ hydrocarbon-enhanced ammonia-based SNCR installation.
Mitsui Babcock claimed 68% NOx reduction from baseline of 0.55 lb/mmBtu down to 0.17 lb/mmBtu with boosted OFA and NOxStar™ with < 5 ppm ammonia slip; NOxStar™ alone reduced NOx by 53%[22]; boosted OFA only reduced NOx from 0.55 to 0.45 lb/mmBtu (18% reduction). Ammonia-to-NOx NSR not stated.
TVA's website reported that "an earlier version of NOxStar was installed at Kingston Fossil Plant Unit 9 in 2002 with mixed results. NOx reductions were achieved, but the boiler was damaged" (http://www.tva.gov/environment/repotrs/envreports/aer/2003/env_compliance.htm)
Source: [22] Mitsui Babcock Technical paper, October 2003.

Tennessee Valley Authority (TVA) — Pulverized Coal, wall-fired
Colbert Station (AL) — 1955 vintage
Unit 4, 192 MWe twin-furnace B&W boiler w/ FGR eastern bituminous coal
First commercial installation of NOxStar™ hydrocarbon-enhanced ammonia-based SNCR technology.
Mitsui Babcock showed 80% NOx reduction from baseline of 0.50 to 0.10 lb/mmBtu; using < 0.1% of total boiler heat input for propane input and 1% of total steam flow generated in the boiler for lance cooling[23]; 2004 SNCR system startup. Ammonia-to-NOx NSR not stated.
Source: [23] Mitsui Babcock 2004 Technical paper.

REBURN – GAS, CONVENTIONAL

Pulverized coal-fired boilers

Allegheny Power (formerly West Pennsylvania Power)
Hatfield's Ferry Station
Units 2 & 3, 600 MW (nominal) each (B&W boilers)
GE-EER Gas Reburn; 1999 startup (Unit 2) & 2003 (Unit 3)

Pulverized Coal, opposed wall-fired
cell-burner, 1969 & 1972 vintage
eastern bituminous coal

GE-EER Low NOx burners, boosted OFA, gas reburn system.
GE-EER claimed to lower NOx up to 67% from baseline of 0.60 lb/mmBtu to 0.20 lb/mmBtu at full load with reburn operation on Unit 2, 68% from 0.62 lb/mmBtu to 0.20 lb/mmBtu on Unit 3. No claims of percent reburn fuel included.
GE-EER technical paper shows approx. 35% NOx reduction at 600 MW load with LNB + OFA w/o reburn fuel, and an additional 50% reduction to 0.20 lb/mmBtu with reburn fuel[24].
B&W added 20 OFA ports in 1994 per B&W's experience list. No NOx reduction claims. Source: Sept. 2005 GE-EER experience list; [24] GE-EER 2004 Technical paper. Unit 2 and Unit 3 listed in [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

REBURN – GAS, CONVENTIONAL continued

Pulverized coal-fired boilers)

Conectiv (formerly Delmarva Power & Light)
Edgemoor Unit 4
160 MW CE boiler

Pulverized Coal, Tangentially-fired
1966 vintage, eastern bituminous coal
1999 startup

GE-EER Gas Reburn project added gas supply piping, metering, hangers, supports, reburn injectors and cooling air piping; OFA ductwork, injection nozzles and wall ports, field instrumentation. No FGR or OFA booster fans.
Vendor claimed to lower NOx up to 48% from baseline of 0.32 lb/mmBtu to 0.16 lb/mmBtu) at full load with reburn operation. No claims of percent reburn fuel included.
GE-EER technical paper shows approx. 32% NOx reduction for gas reburn with 4-mill operation at 160 MW load from 0.31 lb/mmBtu LNB + OFA baseline w/o reburn fuel (down to 0.21 lb/mmBtu), and 48% NOx reduction for gas reburn with 3-mill operation, to 0.16 lb/mmBtu [24].
Source: Sept. 2005 GE-EER experience list; [24] GE-EER 2004 Technical paper. Listed in [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference)

Dynegy (formerly Illinois Power)
Hennepin Unit 1
71 MW CE boiler

Pulverized Coal, Tangentially-fired
1966 vintage
eastern bituminous coal

GE-EER Gas Reburn, 1990 startup (not currently operating); GE-EER Orimulsion Reburn, 1997.
DOE Clean Coal demonstration project (included sorbent injection).
Vendor claimed gas reburn w/ OFA lowered NOx up to 67% from baseline of 0.75 lb/mmBtu to 0.25 lb/mmBtu) at full load; 65% reduction from baseline of 0.75 lb/mmBtu down to 0.26 lb/mmBtu with subsequent Orimulsion reburn operation.
GE-EER 2004 technical paper shows 18% gas reburn fuel yielded minimum NOx emissions[6].
Another technical paper showed this 80 MW US DOE Clean Coal demonstration project in January 1991-January 1993 lowered NOx by 67% from 0.75 lb/mmBtu baseline (to 0.25 lb/mmBtu) with 18 percent reburn fuel[5].
Source: Sept. 2005 GE-EER experience list; [6] GE-EER 2004 Technical paper; [5] DOE-NETL 2004 Reburn Conference technical paper, and DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference). (Also see Conventional Oil reburn installation summaries for pulverized coal boilers).

REBURN – COAL, MICRONIZED, CONVENTIONAL continued

Pulverized coal-fired boilers

E. ON US Holdings (formerly Louisville Gas and Electric)

R.D. Green Station Units 1 & 2 (KY)	wall-fired, pulverized coal, vintage unknown
293 MWe, 2 boilers	eastern bituminous coal
GE-EER coal reburn system	Startup dates: 2003 & 2002, respectively

Vendor claimed to lower NOx up to 57% from baseline of 0.45 lb/mmBtu to 0.20 lb/mmBtu at full load with reburn operation.

Reburn system listed on EPA's "Scorecard on Reburning 6/1/2004" shows NOx lowered by 44% from baseline of 0.45 lb/mmBtu down to 0.25 lb/mmBtu (with unknown reburn fuel input[(5)]).

Another technical paper showed baseline NOx with existing low-NOx burners was 0.45 lb/mmBtu, and reduced NOx emission 40% to 0.27 lb/mmBtu with OFA, and further reduced NOx emissions 22% down to 0.21 lb/mmBtu with the coal reburn system in operation[26].

Source: [(5)] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference); [(24)] GE Energy 2004 Technical paper, and [(26)] March 2004 Modern Power Systems issue.

Cheng Loong (not in United States)

Unit #1, 250 MWe	wall-fired, bituminous pulverized coal, vintage & mfr unknown
GE-EER coal reburn system	2000 Startup (still operating)

Source: GE-EER experience list

Vendor claimed to lower NOx 44% from baseline 0.45 lb/mmBtu to 0.25 lb/mmBtu) at full load with OFA alone; further reduced NOx 28% to 0.18 lb/mmBtu, for 60% overall reduction. Recent (2004) data shows NOx down to 0.14 lb/mmBtu (69% overall) with up to 30 percent reburn fuel[(24)].

Source: [(24)] GE Energy 2004 Technical paper; GE-EER experience list. Listed in [(5)] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

REBURN – GAS, CONVENTIONAL w SNCR

Pulverized coal-fired boilers)

NRG Somerset	Pulverized Coal, Tangentially-fired,	vintage
Unit 6 Boiler 8 (NY)	GE-EER Conventional Gas Reburn,	
120 MW CE boiler	Fuel Tech SNCR, 2003 startup	

Reburn vendor claimed to lower NOx 55% from 0.45 lb/mmBtu baseline to 0.20 lb/mmBtu at full load with reburn operation burning Venezuelan coal. The SNCR system further reduced NOx emissions 45% down to 0.11 lb/mmBtu, for an overall reduction of 77%.[(26)].

Source: Sept. 2005 GE Energy experience list; [(26)] March 2004 Modern Power Systems issue.

REBURN – FUEL LEAN GAS REBURN (FLGR)

Pulverized coal-fired boilers

Duke Power Company	tangentially-fired, pulverized coal	
Riverbend Unit 7	eastern bituminous coal	1954 vintage
140 MWe, CE boiler	1998 FLGR startup, gas reburn decommissioned since then	

Previously installed ABB/CE's Low NOx Concentric Firing System (LNCFS-1) with Close-Coupled Overfire Air (CCOFA); (pre-mod NOx + combustion mods date not known).

Commercial FLGR installation claimed 34% NOx reduction from full-load baseline of 0.42 lb/mmBtu down to 0.29 lb/mmBtu w/ the combustion modifications and FLGR gas reburn fuel at 7% of total boiler heat input. CO emissions were above 1000 ppm corrected to 3% O_2.[(27)]

Vendor claimed to lower NOx 57% from 0.47 lb/mmBtu baseline to 0.20 lb/mmBtu) at full load with separated OFA alone; further reduced NOx 45% to 0.11 lb/mmBtu with low-NOx burners, OFA, gas reburn, and SNCR, for 77% overall reduction; no claims for amount of reburn fuel[(24)].

REBURN – OIL, CONVENTIONAL

Pulverized coal-fired boilers

Dynegy (formerly Illinois Power) Pulverized Coal, Tangentially-fired
Hennepin Unit 1 1966 vintage, eastern bituminous coal
71 MW CE boiler 1997 startup
GE-EER Orimulsion Reburn system w/ OFA, claimed orimulsion reburn lowered NOx up to 65% from baseline of 0.75 lb/mmBtu to 0.26 lb/mmBtu at full load with Orimulsion reburn operation (installed after gas reburn was demonstrated in early 1990's). No claims for percent reburn fuel included.
GE-EER 2004 technical paper shows 60% reduction with subsequent Orimulsion reburn [(6)].
Source: GE-EER experience list; [(6)] GE-EER 2004 Technical paper. Orimulsion not mentioned in [(5)] DOE-NETL 2004 Reburn Conference technical paper or DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference). (Also see Conventional Gas Reburn installation summaries for pulverized coal boilers).

New Brunswick Power
Coleson Cove, Bunker C/Orimulsion–fired, opposed-wall
St. John, New Brunswick, Canada
3x 350 MW B&W Boilers
Sixteen new low-NO_X oil/Orimulsion burners, eight reburn burners, nine SOFA ports, two combustion air booster fans, reburn and OFA wall penetration openings, OFA windboxes, ductwork, dampers, and accessories were added[(7)].
Another technical paper showed this reburn system lowered NOx by 78% from 1.0 lb/mmBtu baseline to 0.22 lb/mmBtu at 25 percent reburn fuel input[(5)].
Source: [(7)] B&W 2004 Technical Paper;[(5)] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

Georgia Power Pulverized Coal, Tangentially-fired
Scherer Unit 1 1982 vintage
887 MW CE boiler 2000 oil reburn startup
GE-EER Oil Reburn system, claimed to lower NOx from baseline of 0.36 lb/mmBtu.
GE-EER 2004 Technical paper shows reduction up to 48% (to 0.19 lb/mmBtu) at 800 MW load with oil reburn operation. No claims of percent reburn fuel included[(24)].
Source: Sept. 2005 GE-EER experience list shows this as a coal reburn project with eastern bituminous coal, reducing NO_X emissions 33% from 0.36 to 0.24 lb/mmBtu;
[(24)] GE-EER 2004 Technical paper. Not listed in [(5)] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

REBURN – COAL, MICRONIZED, CONVENTIONAL

Pulverized coal-fired boilers

AES (formerly New York State Electric and Gas Milliken Station Unit 1)
Cayuga tangentially-fired, pulverized coal, 1956 vintage
148 MWe, CE boiler eastern bituminous coal
GE-EER micronized coal reburn system 1996 startup (still operating)
US DOE Clean Coal demonstration project from March 1997-April 1999 lowered NOx with this reburn system by 29% from 0.35 lb/mmBtu baseline to 0.25 lb/mmBtu at 14 percent reburn fuel input[(5)]. Not listed in GE-EER's experience list nor in their 2004 technical paper.
Source: [(5)] DOE-NETL 2004 Reburn Conference technical paper and DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

REBURN – COAL, MICRONIZED, CONVENTIONAL continued

Pulverized coal-fired boilers

E. ON US Holdings (formerly Louisville Gas and Electric)

R.D. Green Station Units 1 & 2 (KY)	wall-fired, pulverized coal, vintage unknown
293 MWe, 2 boilers	eastern bituminous coal
GE-EER coal reburn system	Startup dates: 2003 & 2002, respectively

Vendor claimed to lower NOx up to 57% from baseline of 0.45 lb/mmBtu to 0.20 lb/mmBtu at full load with reburn operation.

Reburn system listed on EPA's "Scorecard on Reburning 6/1/2004" shows NOx lowered by 44% from baseline of 0.45 lb/mmBtu down to 0.25 lb/mmBtu (with unknown reburn fuel input[5]).

Another technical paper showed baseline NOx with existing low-NOx burners was 0.45 lb/mmBtu, and reduced NOx emission 40% to 0.27 lb/mmBtu with OFA, and further reduced NOx emissions 22% down to 0.21 lb/mmBtu with the coal reburn system in operation[26].

Source: [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference); [24] GE Energy 2004 Technical paper, and [26] March 2004 Modern Power Systems issue.

Cheng Loong (not in United States)

Unit #1, 250 MWe	wall-fired, bituminous pulverized coal, vintage & mfr unknown
GE-EER coal reburn system	2000 Startup (still operating)

Source: GE-EER experience list

Vendor claimed to lower NOx 44% from baseline 0.45 lb/mmBtu to 0.25 lb/mmBtu) at full load with OFA alone; further reduced NOx 28% to 0.18 lb/mmBtu, for 60% overall reduction. Recent (2004) data shows NOx down to 0.14 lb/mmBtu (69% overall) with up to 30 percent reburn fuel[24].

Source: [24] GE Energy 2004 Technical paper; GE-EER experience list. Listed in [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

REBURN – GAS, CONVENTIONAL w SNCR

Pulverized coal-fired boilers)

NRG Somerset	Pulverized Coal, Tangentially-fired,	vintage
Unit 6 Boiler 8 (NY)	GE-EER Conventional Gas Reburn,	
120 MW CE boiler	Fuel Tech SNCR, 2003 startup	

Reburn vendor claimed to lower NOx 55% from 0.45 lb/mmBtu baseline to 0.20 lb/mmBtu at full load with reburn operation burning Venezuelan coal. The SNCR system further reduced NOx emissions 45% down to 0.11 lb/mmBtu, for an overall reduction of 77%.[26].

Source: Sept. 2005 GE Energy experience list; [26] March 2004 Modern Power Systems issue.

REBURN – FUEL LEAN GAS REBURN (FLGR)

Pulverized coal-fired boilers

Duke Power Company	tangentially-fired, pulverized coal	
Riverbend Unit 7	eastern bituminous coal	1954 vintage
140 MWe, CE boiler	1998 FLGR startup, gas reburn decommissioned since then	

Previously installed ABB/CE's Low NOx Concentric Firing System (LNCFS-1) with Close-Coupled Overfire Air (CCOFA); (pre-mod NOx + combustion mods date not known).

Commercial FLGR installation claimed 34% NOx reduction from full-load baseline of 0.42 lb/mmBtu down to 0.29 lb/mmBtu w/ the combustion modifications and FLGR gas reburn fuel at 7% of total boiler heat input. CO emissions were above 1000 ppm corrected to 3% O_2.[27]

Vendor claimed to lower NOx 57% from 0.47 lb/mmBtu baseline to 0.20 lb/mmBtu) at full load with separated OFA alone; further reduced NOx 45% to 0.11 lb/mmBtu with low-NOx burners, OFA, gas reburn, and SNCR, for 77% overall reduction; no claims for amount of reburn fuel[24].

EPA's "Scorecard on Reburning 6/1/2004" showed this reburn system lowered NOx by 25-30% with 5-10 percent reburn fuel input[5].
Source: [27] ESA, GRI, NGB 1998 Technical paper; [24] GE Energy 2004 Technical paper; [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

REBURN – FUEL LEAN GAS REBURN (FLGR) continued

Pulverized coal-fired boilers

Wisconsin Electric Power Company (WEPCO)
Pleasant Prairie Unit 1 DB Riley, turbo-fired PC, Powder River Basin coal
620 MWg 1980 vintage 1999 startup
Fuel Tech listed FLGR installation and claimed 20% NOx reduction from baseline of 0.45 lb/mmBtu (to 0.36 lb/mmBtu). No claims of percent reburn fuel input included.
Source: Fuel Tech experience list dated 1/28/2005. [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference). (Also see FLGR + SNCR installation summaries for pulverized coal boilers).

REBURN – FUEL LEAN GAS REBURN w/ SNCR (Amine-Enhanced FLGR)

Pulverized coal-fired boilers

Carolina Power & Light (Progress Energy)
Asheville Unit 1 Pulverized Coal, front wall fired
200 MWe DB Riley boiler 1964 vintage, eastern bituminous coal, June 2000 startup
Commercial urea-based Fuel Tech SNCR +FLGR installation claimed 50% NOx reduction from baseline of 0.58 lb/mmBtu (426 ppm) down to 0.29 lb./mmBtu w/ 5 ppm ammonia slip[1]. Low NO_X burners were previously retrofitted in 1997 without separated overfire air[28]. This is 33 % lower than 0.44 lb/mmBtu baseline for SNCR alone. (Also see SNCR installation summaries for pulverized coal boilers). Urea-to-NOx NSR not stated.
EPA's "Scorecard on Reburning 6/1/2004" showed this SNCR-enhanced reburn system lowered NOx by 25-30% with 5-10 percent reburn fuel input in 2000, but not currently operating[5].
Another technical paper showed 52% NOx reduction down to 0.28 lb/mmBtu at all loads, from 99 MWg to 207 MWg (48% to 100% MCR) with an average NH_3 slip of 3 ppm. FLGR alone achieved 23% NOx reduction with 6% reburn fuel and < 400 ppm CO at full load. [28]
Source: Fuel Tech experience list, [1]ICAC White Paper; [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference); [28] CP&L and Fuel Tech 2001 Technical paper.
(Also see SNCR installation summaries for pulverized coal boilers).

Public Service Enterprise Group (PSEG) Power LLC [formerly Public Service Electric & Gas of New Jersey (PSE&G)]
Hudson Station, Unit 2 Pulverized Coal, opposed-wall-fired, 1968 vintage
660 MWe Foster Wheeler boiler eastern bituminous coal March 1999 startup
Commercial SNCR + FLGR urea-based Fuel Tech installation claimed 40% NOx reduction from baseline of 0.65 lb/mmBtu (down to 0.39 lb/mmBtu) w/ 10 ppm ammonia slip[1]. This is 20 % lower than 0.49 lb/mmBtu baseline for SNCR alone. Urea-to-NOx NSR not stated.
EPA's "Scorecard on Reburning 6/1/2004" showed this SNCR-enhanced reburn system lowered NOx by 25-30% with 5-10 percent reburn fuel input in 2000, but not currently operating[5].
Source: Fuel Tech experience list, [1]ICAC White Paper;[5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).
(Also see SNCR installation summaries for pulverized coal boilers).

REBURN – FUEL LEAN GAS REBURN w/ SNCR (Amine-Enhanced FLGR) continued

Pulverized coal-fired boilers

Public Service Enterprise Group (PSEG) Power LLC [formerly Public Service Electric & Gas of New Jersey (PSE&G)]

Mercer Station	(2) twin-furnace boilers, 320 MWe each, DB Riley turbo-fired	
Unit 1 and Unit 2	front wall PC, wet-bottom (slagging ash) eastern bituminous coal	
Furnace #11 & #12	1960 vintage	May 1999 startup
Furnace #21 & 22	1961 vintage	May 1999 startup

Commercial urea-based Fuel Tech SNCR + FLGR installation claimed 60% NOx reduction from baseline of 1.4 lb/mmBtu (down to 0.56 lb/mmBtu) w/ 5 ppm ammonia slip [1]. This is 72 % lower than 2.0 lb/mmBtu baseline without control. Initial demonstration of AEFLGR coinjected amine-enhanced natural gas into Furnace 22 in 1998. Subsequently installed AEFLGR on both units to reduce NOx starting in May 1999 using (2) levels of AEFLGR retractable gas injectors and (2) levels of SNCR injectors[29]. Urea-to-NOx NSR not stated, goal was NSR < 1.25.

{Note both units have since been retrofitted with low-dust tail-end SCRs in 2004; SNCR systems are still capable and operated as needed, mostly for flyash conditioning to aid ESP performance}

EPA's "Scorecard on Reburning 6/1/2004" showed this SNCR-enhanced reburn system lowered NOx by 25-30% with 5-10 percent reburn fuel input in 1999, but not currently operating[5].

Source: Fuel Tech experience list, [1]ICAC White Paper; [29] PSE&G, FT and ESA 2000 Technical paper;[5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

Wisconsin Electric Power Company (WEPCO)

Pleasant Prairie Unit 1	DB Riley, turbo-fired PC, Powder River Basin coal	
620 MWg	1980 vintage	1999 startup

Fuel Tech urea-based SNCR +FLGR demonstration installation claimed 56% NOx reduction from baseline of 0.45 lb/mmBtu to 0.20 lb/mmBtu w/ 5 ppm ammonia slip[1]. This is 44 % lower than 0.36 lb/mmBtu baseline for FLGR alone.

EPA's "Scorecard on Reburning 6/1/2004" showed this SNCR-enhanced reburn system lowered NOx by 25-30% with 5-10 percent reburn fuel input in 2000, but not currently operating[5].

Source: Fuel Tech experience list, [1]ICAC White Paper and F.T. experience list 0207;
[5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

LOW NO_x BURNERS (Replacement or modifications) w/ and w/o OVERFIRE AIR

Pulverized coal-fired boilers

AEP Cardinal Unit 1	Pulverized Coal	cell-burner, opposed wall-fired B&W boiler
600 MW (nominal)	1967 vintage; Low NO_x burners installed in October 1998	

Produced 0.75 lb/mmBtu NOx post-LNB install baseline at full load.

LNBs reduced NO_X 57% from 1.20 down to 0.52*, produce NO_X at approx. 0.57 lb/mmBtu at min. load w/o SNCR (range 0.51 to 0.65) and produce 0.75 lb/mmBtu NO_X at approx. 585 MW (top of load range tested, NO_X range 0.73 to 0.86 lb/mmBtu) [17].

(50) original B&W circular burners were recently replaced on Cardinal Units 2 & 3 by Buckeye Power with DB Riley (now Babcock Power) CCV type low NOx burners.

Source: *Riley Power (Babcock Power Inc.) 8/16/04 experience list; [17] 2000 Fuel Tech technical paper. (Also see SNCR installation summaries for pulverized coal boilers).

Carolina Power & Light (Progress Energy)

Asheville Unit 1	Pulverized Coal, front wall fired
200 MWe DB Riley boiler	1964 vintage, eastern bituminous coal, June 2000 startup

Low NO_X burners were previously retrofitted in 1997 without separated overfire air[22]. NOx reduction was 46% from pre-LNB installation baseline of 1.08 lb/mmBtu [12] down to 0.58 lb./mmBtu [28].

(Also see SNCR, and FLGR with SNCR installation summaries for pulverized coal boilers).
Source: [12] 2005 US EPA Docket OAR-2002-0076-0446 Technical Support Document spreadsheet; [28] CP&L and Fuel Tech 2001 Technical paper.

LOW NO_x BURNERS (Replacement or modifications) w/ and w/o OVERFIRE AIR continued

Pulverized coal-fired boilers

Carolina Power & Light (Progress Energy) Pulverized Coal, Tangentially-fired
Cape Fear Unit 5 1956 vintage; eastern bituminous coal
154 MW CE boiler ROFA startup in 2000
Mobotec USA's Rotating Opposed Fire Air (ROFA) is a high velocity boosted separated overfire air system claimed to lower NO_X without retrofitting low-NOx burners. This was the first U.S. installation of Mobotec USA's "Rotating Opposed Fire Air" (ROFA) on a utility boiler, which utilizes a booster fan. CP&L technical paper claimed to lower NO_X 53% from full-load pre-ROFA baseline 0.60 lb/mmBtu to 0.28 lb/mmBtu with ROFA alone following the installation of ROFA in 2000[18].
Source: [18] CP&L 2002 Technical paper. (Also see SNCR installation summaries for pulverized coal boilers).

Carolina Power & Light (Progress Energy) Pulverized Coal, Tangentially-fired
Cape Fear Unit 6 twin-furnace (eight corner), 1958 vintage; eastern bituminous coal
175 MW CE boiler ROFA startup in 2001
This unit's "ROFA" system was installed as part of a "Rotamix" SNCR + ROFA system.
CP&L technical paper shows ROFA alone reduced NOx 57% from full-load pre-ROFA baseline 0.54 lb/mmBtu to a NO_X emission rate of 0.23 lb/mmBtu. [18]
Source: [18] CP&L 2002 Technical paper. (Also see SNCR installation summaries for pulverized coal boilers).

Conectiv (formerly Delmarva Power & Light)
Indian River Units 3 & 4 (Millsboro, DE) Unit 3 is front wall-fired, 1974 vintage
178MW and 440 MW Unit 4 is turbo-fired opposed-wall, 1980 vintage
B&W, DB Riley boilers eastern bituminous coal
REI performed CFD modeling on both units for potential SNCR application.
Unit 3 has Riley Low NOx burners (16), (8) front wall and (8) rear wall OFA ports, (8) wall boundary air ports, (66) side wall OFA slots, claimed baseline NOx around 0.37 lb/mmBtu w/o SNCR [20].
Unit 4 has (24) front and rear wall down-fired burners, (28) front and rear wall SOFA ports, claimed NOx around 0.44 lb/mmBtu w/o SNCR [20] {furnace has "Mae West" belt}.
Riley provided 16 CCV low-NOx burners for Unit 3 in 1994, and claimed to reduce NOx emissions by 67% from pre-LNB baseline of 1.05 lb/mmBtu down to 0.34 lb/mmBtu.
Source: [20]REI 1999 Technical Paper; Riley Power (Babcock Power Inc.) 8/16/04 experience list. (Also see SNCR installation summaries for pulverized coal boilers).

Dayton Power & Light Pulverized Coal, Tangentially-fired
Killen Station, Unit 2 1955 vintage
632 MW CE boiler, bituminous Illinois coal
GE-EER provided low-NOx burners in 1999. Vendor claimed full load NO_X was reduced by 23% from a 0.57 lb/mmBtu baseline down to 0.44 lb/mmBtu.
Source: GE-EER Experience list 2/1/02. (Also see low-dust SCR installation list for pulverized coal boilers)

LOW NO_x BURNERS (Replacement or modifications) w/ and w/o OVERFIRE AIR continued

Pulverized coal-fired boilers

Dynegy Midwest Generation (formerly Illinois Power) Pulverized Coal, wall-fired
Havana Station, Unit 6 1978 vintage
460 MW B&W boiler, bituminous Illinois coal
GE-EER provided modifications to the original B&W dual-register burners, and an OFA system in 2000.
Vendor claimed full load NO_X was unchanged from 0.38 lb/mmBtu baseline.
Source: GE-EER Experience list 2/1/02. (Also see low-dust SCR installation list for pulverized coal boilers)

Dynegy Midwest Generation (formerly Illinois Power) Pulverized Coal, Tangentially-fired
Vermillion Station, Unit 1 1955 vintage
82 MW CE boiler, bituminous Illinois coal
This rotating opposed fire air (Mobotec USA ROFA) system was installed in July 2002, as part of a "Rotamix" SNCR + ROFA system, without low-NOx burners.
Mobotec 2004 technical paper claimed to lower full load NO_X by 62% from 0.58 lb/mmBtu baseline to 0.22 lb/mmBtu in July 2002 (without LNB or SNCR).[21]
Source: [21] Mobotec 2004 technical paper. (Also see SNCR installation summaries for pulverized coal boilers).

Georgia Power Pulverized coal, opposed wall-fired,
Harlee Branch Unit 1 250 MW B&W boiler, 1965 vintage 2003 startup
Harlee Branch Unit 2 359 MW Riley boiler, 1967 vintage 1998 startup
B&W provided 24 DRB-4Z low NOx burners for Unit 1 B&W boiler, 24 DRB-XCL low NOx burners for Unit 2 Riley boiler (believe southeast coast lignite is primary fuel).
Source: B&W's experience list. No NOx reduction claims.

Kansas City Power & Light Pulverized coal, opposed wall-fired, 600 MW B&W boiler
Hawthorn Unit 5 30 burners, 2001 vintage, (Powder River Basin coal)
B&W provided 30 DRB-4Z low NOx burners and 11 OFA ports with the new boiler.
Source: B&W's experience list. No NOx reduction claims.

New England Power Company (NEPCO)
Salem Harbor Station Pulverized Coal, front wall-fired,
Units 1, 2 & 3 1952, 1952, 1958 vintage (eastern bit. coal)
84 MWe x 2, & 156 MWe B&W boilers LNBs startup in 1995, 1995, and 1993
Riley claimed Unit 1 LNBs reduced NOx emissions by 57% from baseline of 1.10 lb/mmBtu down to 0.42 lb/mmBtu; Unit 2's LNBs achieved 42% NOx reduction from a baseline of 0.95 lb/mmBtu down to 0.55 lb/mmBtu; Unit 3's LNBs achieved 60% NOx reduction from a baseline of 1.05 lb/mmBtu down to 0.42 lb/mmBtu.
Source: Riley Power (Babcock Power Inc.) 8/16/04 experience list.
(Also see SNCR installation summaries for pulverized coal boilers).

Northeast Utilities (formerly Public Service of New Hampshire)
Shiller Station Pulverized Coal/#6 Fuel oil, front-wall-fired
Units 4, 5, & 6 1952, 1955, 1957 vintage
50 MWe x 3 Foster Wheeler boilers
RJM provided (6) Low NO_x burner modifications per boiler in 1994, 1992, & 1994 respectively;
LNBs reduced NOx 43% from 0.85 to 0.48, 50% from 1.0 to 0.50, and 51% from 0.82 to 0.40 lb/mmBtu.
Source: RJM experience list

LOW NO_x BURNERS (Replacement or modifications) w/ and w/o OVERFIRE AIR continued

Pulverized coal-fired boilers

Potomac Electric Power (formerly West Pennsylvania Power)

Chalk Point Station	Pulverized Coal	opposed wall-fired
Units 1 & 2	1964, 1965 vintage	eastern bituminous coal
360 MW (nominal)	B&W boilers	

DB Riley (now Babcock Power) CCV type low NOx burners retrofitted in 1993 and 1994, respectively. Vendor claimed to lower NOx up to 52% and 50% from 1.35 and 1.40 lb/mmBtu baselines (to 0.65 and 0.70 lb/mmBtu, assumed at full load).
Source: Riley Power (Babcock Power Inc.) 8/16/04 experience list. (Also see Conventional Gas Reburn installation summaries for pulverized coal boilers).

Xcel Energy (formerly Public Service Company of Colorado)

Cherokee Unit 3	Pulverized coal, wall-fired, B&W boiler, 16 burners, 1962 vintage
175 MW	October 1992 baseline testing started (western bituminous coal)

Installed (16) Foster Wheeler Controlled Flow/Split Flame low NO_x replacement burners as part of a DOE Clean Coal Technology gas reburn demonstration performed with Gas Research Institute 1992-1995.
Uncontrolled NOx w/ original B&W flare-type burners was 0.73 lb/mmBtu. Replacement LNBs (assuming OFA included) reduced NO_X 37% to 0.46 lb/mmBtu[25].
Source: [25] DOE NETL 2001 Technical paper.

A.2.2 Technical Literature References for U.S. NOx Control Retrofit Projects:

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[4] REI 2004 Technical paper, "Evaluation of Cost Effective Non-SCR Options for NOx Control in PRB Fired Cyclone Boilers" by Marc A. Cremer and David H. Wang, and Bradley R. Adams, Reaction Engineering International, David E. Boll and Kenneth B. Stuckmeyer, AmerenUE, presented at the Western Fuels Symposium, 19th International Conference on Lignite, Brown, and Subbituminous Coals (formerly Low-Rank Fuels), October 12-14, 2004, Billings, MT.

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(5) DOE-NETL 2004Technical Paper "Reburning Projects in the Department of Energy's Clean Coal Technology Demonstration Program", by Al Mann and Tom Ruppel, Parsons Corporation, and Tom Sarkus, National Energy Technical Laboratory, presented at the 2004 DOE-NETL Conference on Reburning for NOx Control, Morgantown, WV, May 18, 2004. A reburn-related document (an updated version of a poster from the May 18 Conference) is titled "Scorecard on Reburning 6/1/2004" by Al Mann and Tom Ruppel, Parsons Corporation, available on-line at: http://www.netl.doe.gov/publications/proceedings/04/NOx/posters/Reburning%20Scorecard.pdf

(6) GE Energy 2004 Technical paper "Reburn Technology Application Guidelines", by David Moyeda, GE Energy, presented at the 2004 DOE-NETL Conference on Reburning for NOx Control", Morgantown, WV, May 18, 2004.

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APPENDIX B

EERC REPORT

Ash Impacts on SCR Catalyst Performance

ASH IMPACTS ON SCR CATALYST PERFORMANCE

Prepared by:

Steven A. Benson, Ph.D.

Energy & Environmental Research Center
University of North Dakota
PO Box 9018
Grand Forks, ND 58202-9018

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ASH IMPACTS ON SCR CATALYST PERFORMANCE

EXECUTIVE SUMMARY

The ash deposition behavior of the lignites from North Dakota is the most complex and severe of any coals in the world, and installation of catalysts for NO_x reduction is going to be plagued with problems. The Center lignite fired at the Milton R. Young (MRY) Power Station is highly variable in abundance of various types of ash/slag-forming components. Ash-forming components consist of inorganic elements (sodium, magnesium, calcium, and potassium) associated with oxygen functional in the organic matrix and mineral grains (quartz, clays, carbonates, sulfates, and sulfides). Upon combustion, the inorganic components undergo chemical and physical transformations that produce intermediate inorganic species in the form of inorganic gases, liquids, and solids. The alkali and alkaline-earth elements combine with minerals during combustion, resulting in low-melting-point phases that cause a wide range of fireside deposition problems. In addition, the alkali and alkaline-earth elements also form very small particles that are carried into the backpasses of the combustion system and react with flue gas to form sulfates that can cause deposition, blinding, and plugging problems in selective catalytic reduction (SCR) systems. This report analyzes these problems, and concludes that SCR is not a feasible option to control NOx emissions at MRY Power Station because of the high sodium levels present in the coal.

Following is a list of the key problems that are associated with Center lignite which have not been overcome and, in our opinion, make the installation of SCR at the MRY plant technically infeasible for NO_x control.

- Blinding of Catalyst Pores by High Sodium Compounds

  X High levels of alkali and alkaline-earth elements present in the coal fired at the MRY plant produce small particles that react to form sulfates that blind the catalyst pores. The high levels of sodium in the coals combined with calcium will produce low-melting-point eutectic sulfate compounds that will form and melt inside the pores of the catalyst.

  - Alkali and alkaline earth sulfates are enhanced by cyclone fired system. The cyclone firing results in partitioning of the ash between bottom slag and the body of the boiler. The sulfate forming materials are more concentrated in the ash as a a result of cyclone firing.

  - Sulfate formation is enhanced by the presence of an SCR catalyst; this accelerates the sulfation reactions, causing blinding of the catalyst.

  - The sulfate reactions are more severe at MRY because of the high temperature where an SCR would be installed. The higher temperature increases the rate of formation of sulfates and rate of pore plugging.

  - The testing conducted by the Germans found catalyst deactivation and blinding occurs when firing coals with lignite or brown coals that have ashes that are rich in alkali and alkaline-earth elements. .

- The findings by the Germans were confirmed by recent SCR catalyst slipstream testing that showed significant evidence of sodium and calcium-rich sulfate formation that fill and plug the catalyst at both lignite- and subbituminous-coal-fired power plants. The results of this recent testing showed that the presence of sodium significantly enhanced the formation of bonding of particles and more rapid sulfation, filling of pores, and rapid increase in pressure drop across the catalyst.

- Deposit carryover, or "popcorn ash," plugging the top of the SCR catalyst is a significant problem because of the extremely high deposition rates of the Center coal. When firing Center coal, deposits form on various parts of the boiler requiring continuous sootblowing. The sootblowing of upstream heat-exchange equipment will cause deposit fragments to be carried back to the SCR catalyst, resulting in plugging. In addition, during sootblowing of the SCR catalyst, the entrainment of deposit fragments along with the sootblowing media will result in significant erosion of the catalyst surfaces.

- Recent testing with subbituminous and lignitic coals indicated a significantly higher level of pore filling and plugging in the catalyst exposed to lignite ash as compare to subbituminous coal ash. The catalyst pores as well as the catalyst surface in the lignite tests were completely coated with a sodium calcium sulfate material, while only pore filling was found in the subbituminous coal testing. The pressure drop across the catalyst exhibited for lignite was 4 to 5 times greater than that found for a catalyst exposed to subbituminous coal ash. The plugging occurred over a 1000 hour test period.

➢ Cold Side SCR Installation

- High-sodium lignite coal from the Center Mine Hagel A and B seam coal produces significant levels of homogeneously condensed sodium sulfate that pass through the ESP and wet scrubber.

- These small particles have been shown to pass through a wet scrubber and will accumulate on surfaces of tail-end SCR systems. The accumulated materials require sootblowing to remove the particulate and will result in increased opacity.

- Liquid pyrosulfate materials at temperatures as low as 535°F from sodium sulfate materials occurs in coal-fired power systems and is well documented. Pyrosulfates will form and cause blinding of tail-end SCR devices. In addition, SCR systems are known to catalyze the formation of SO_3 from SO_2. The presence of SO_3 significantly enhances the formation of the pyrosulfates.

ASH IMPACTS ON SCR CATALYST PERFORMANCE

INTRODUCTION

Ash produced during combustion of coal in conventional power systems is a major problem that results in decreased efficiency, unscheduled outages, equipment failures, and increased cleaning. The many ways in which the detrimental effects of ash manifest themselves in a boiler system include fireside ash deposition on heat-transfer surfaces, corrosion and erosion of boiler parts, poor slag flow, and production of fine particulates that are difficult to collect. Decades of research have been conducted to develop a better understanding of the chemical and physical processes of ash formation and deposition in combustion systems. Overviews of ash-related issues and compilations of work by many investigators can be found by referring to the work of Mehta and Benson (1), Schobert (2), Baxter and DeSollar (3), Couch (4), Williamson and Wigley (5), Benson and others (6), Benson (7), Bryers and Vorres (8), Raask (9, 10), and Benson (11). This work has led to a detailed understanding of ash formation and behavior in combustion systems as well as the development of predictive methods (12, 13).

The chemical composition and physical characteristics of ash-forming or inorganic components (mineral and organically associated elements) of the fuel(s) fired have an influence on the following processes in the combustion systems:

- Firing conditions such as cyclone, pulverized coal, and low-NO_x burners
- Transformations of coal inorganic components to ash particulate and vapor-phase species
- Boiler design characteristics, including number of burners, radiant section area, tube bank spacing, access for cleaning, and number of sootblowers
- Ash transport to heat-transfer surfaces in utility boilers
- Erosion wear and sticking
- Ash deposit growth and impact on heat transfer
- Ash blinding and plugging of selective catalytic reduction (SCR) catalysts
- Ash deposit removability

The ash deposition in North Dakota lignite-fired power plants is a major problem that impacts all fireside surfaces of the power plant. The ash problems are due to the variable and complex nature of inorganic components associated with lignite coals (2). Upon combustion, the inorganic components undergo chemical and physical transformations that produce intermediate inorganic species in the form of inorganic gases, liquids, and solids. During the gas-cooling processes in the boiler, the gas-phase species condense and the liquid-phase materials solidify. The abundance of these gas-phase and liquid materials entrained in the bulk gas flow is highly dependent upon coal composition and system operating conditions. The inorganic materials are transported to heat-transfer and catalyst surfaces by diffusion, electrophoresis, thermophoresis,

and inertial impaction. The particle sticking and accumulation rates are dependent upon the quantity of ash and the abundance and viscosity of the liquid-phase components. In high-temperature regions of the boiler, high-temperature sodium–calcium–aluminosilicate liquid phases act as the sticky material, causing deposit initiation, growth, and development of deposit strength. As the temperature of the flue gases decreases, the condensation and reaction of flame-volatilized species play a more significant role in the formation of deposits from lignite coals. The formation of sodium and/or calcium magnesium sulfates dominates the deposit accumulation mechanisms at lower temperatures. The aluminosilicate phases are dominant above about 1800°F. Below about 1800°F, the sulfate phases become stable, with an optimum temperature of formation of about 1400°F, and can form at temperatures as low as 300°F.

The most significant problems that prohibit the successful operation of SCR catalysts to lignite coal is the formation of low-temperature sodium–calcium–magnesium sulfates and phosphates that will form on the surfaces of catalysts and the carryover of deposits that will plug the catalyst openings, resulting in increased pressure drop and decreased efficiency (14 16).

INORGANIC COMPOSITION OF LOW-RANK COALS

Inorganic elements in coal occur as discrete minerals, organically associated cations, and cations dissolved in pore water. The fraction of inorganic components that are organically associated varies with coal rank. Lower-ranked subbituminous and lignitic coals have high levels of oxygen, which act as bonding sites for cations such as sodium, magnesium, calcium, potassium, strontium, and barium (other minor and trace elements may also be present in this form). In higher-ranked coals, bituminous and anthracite, inorganic components consist mainly of minerals. Mineral grains are usually the most abundant inorganic component in coal. The major mineral groups found in coals include silicates, aluminosilicates, carbonates, sulfides, sulfates, phosphates, and some oxides.

The behavior of ash produced during coal combustion is related to the abundance, size, and association of mineral grains in the coal. In addition, the association of the mineral grain with the coal matrix influences the temperature and gaseous environment the mineral is exposed to during combustion. A mineral associated with the organic part of a coal particle is said to be included. A mineral that is not associated with organic material is referred to as excluded. The behavior of the organically associated elements, those elements that are atomically dispersed in the coal matrix, must also be measured as to their abundance in the coal. The organically associated elements will react and interact with the other ash-forming constituents during combustion.

The Center lignite is highly variable in abundance of various types of ash/slag-forming constituents. Ash-forming components in the Center lignite are of two types. The first form may constitute up to 50% of the ash and is derived from inorganic elements (sodium, magnesium, calcium, and potassium) associated with oxygen functional in the organic matrix of the coal. The second type consists of mineral grains (sand, clay, limestone, and pyrite). The minerals are discrete particles of ash-forming species and the sources of silicon, aluminum, iron, titanium, and minor amounts of the calcium and potassium. The Center lignite fired at the Milton R. Young (MRY) plant has been examined extensively because of its problem with ash behavior. Analyses

of as-fired and drill core samples have been conducted. The mean and the range of selected components are shown in Figure 1. The results indicate that both the abundance of ash and the abundance of major oxides in the ash vary significantly. In addition, the abundance of alkali and alkaline-earth elements (Na and Ca) varied dramatically. Variations in Si were found to be the most significant. High levels of Ca and/or Na were found for lower-ash coals as compared to high levels of Al and Si associated with higher-ash coals (17, 18).

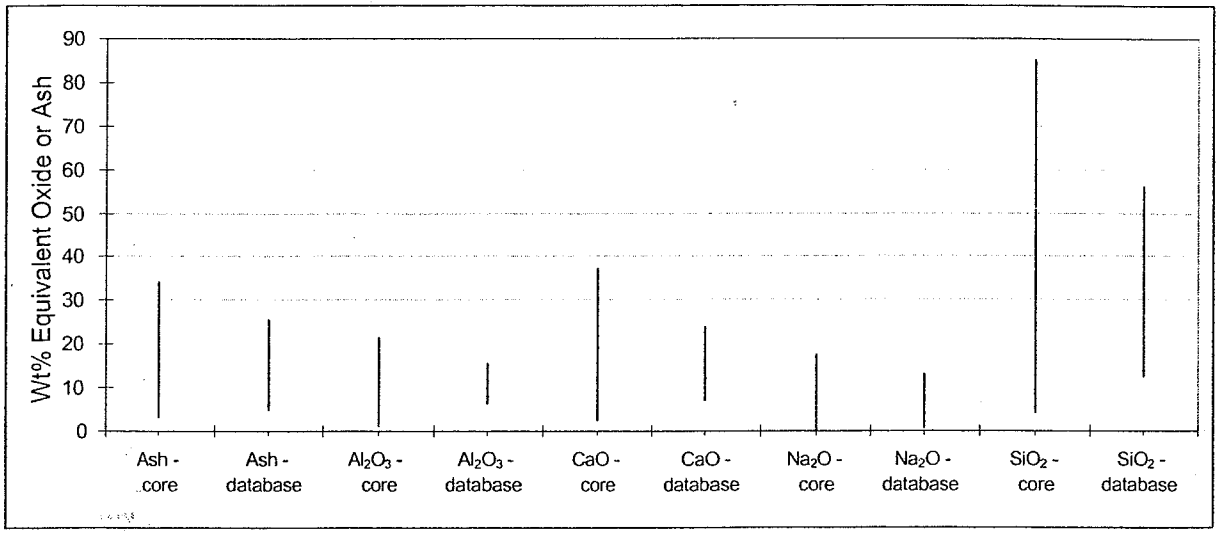

Figure 1. Variability of ash and selected constituents in core analysis database provided by BNI Coal, Ltd. and Minnkota as fired coal analysis database.

The variability of the ash-forming components has been examined for the approximately 5000 samples characterized to date. Wide variations in ash contents and the major ash-forming constituents are observed. During the mining processes, the inorganic components are mixed, and some of the extreme characteristics are diluted (17).

INORGANIC TRANSFORMATIONS AND ASH FORMATION

The inorganic coal components undergo complex chemical and physical transformations during combustion to produce intermediate ash species. The inorganic species consist of vapors, liquids, and solids. The partitioning of the inorganic components during combustion to form ash intermediates depends upon the association and chemical characteristics of the inorganic components, the physical characteristics of the coal particles, the physical characteristics of the coal minerals, and the combustion conditions.

The physical transformation of inorganic constituents depends on the inorganic composition of the coal and combustion conditions. The inorganic components can consist of organically associated cations, mineral grains that are included in coal particles, and excluded mineral grains. There is a wide range of combinations of mineral–mineral, mineral–coal,

mineral–cation–coal, and mineral–mineral–cation–coal associations in coal. These associations are unique to each coal sample.

The physical transformations involved in fly ash formation include 1) coalescence of individual mineral grains within a char particle, 2) shedding of the ash particles from the surface of the chars, 3) incomplete coalescence due to disintegration of the char, 4) convective transport of ash from the char surface during devolatilization, 5) fragmentation of the inorganic mineral particles, 6) formation of cenospheres, and 7) vaporization and subsequent condensation of the inorganic components upon gas cooling. As a result of these interactions, the ash has a bimodal size distribution. The submicron component is largely a result of the condensation of flame-volatilized inorganic components. The mass mean diameter of the larger particles is approximately 12 to 15 μm, depending upon the coal and combustion conditions. The larger-size particles have been called the residual ash by some investigators (19) because these ash particles resemble, to a limited degree, the original minerals in the coal. Processes such as ash mineral coalescence, partial coalescence, ash shedding, and char fragmentation during char combustion and mineral fragmentation, all play an important role in the size and composition of the final fly ash. Loehden and others (20) and Zygarlicke and others (21) indicate that three potential modes for fly ash generation can be used to describe fly ash particle-size and composition evolution. The first, "fine limit," assumes that each mineral grain forms a fly ash particle and that the organically associated elements form fly ash particles of less than 2 μm. The second, "total coalescence," assumes one fly ash particle forms per coal particle. The third, "partial coalescence," suggests that the fly ash composition and particle size evolve because of partial coalescence.

The transformations of excluded minerals are dependent upon the physical characteristics of the mineral. Excluded minerals such as quartz (SiO_2) can be carried through the combustion system with its angular structure still intact. Excluded clay minerals can fragment during dehydration, melt, and form cenospheres. The behavior of excluded pyrite depends upon its morphology. Some of the pyrite may be present as framboids. Framboidal pyrite may fragment more easily than massive pyrite particles. In addition, the decomposition of pyrite is very exothermic, and it transforms to pyrrhotite and oxidizes to FeO, Fe_3O_4, and Fe_2O_3 during combustion.

ASH DEPOSITION ON HEAT-TRANSFER AND OTHER SURFACES EXPOSED TO ASH AND FLUE GAS

The characteristics of a deposit depend upon the chemical and physical characteristics of the intermediate ash species, geometry of the system (gas flow patterns), gas temperature, gas composition, and gas velocity. Figure 2 illustrates the ash deposition phenomena in utility boilers. Ash particle accumulations occur via transport of particles to the fireside surfaces (heat transfer, ceramic materials, support materials, SCR catalysts, baghouse materials, and ESP wires and plates) and sticking of the particles. The transport mechanisms important for ash deposition include small-particle mechanisms for particles less than 10 μm that involve thermophoresis, electrophoresis, and vapor-phase and small-particle diffusion; and large-particle mechanisms for particles greater than 10 μm that involve inertial impaction. The ability of larger particles to stick depends upon the quantity and viscosity of the liquid phase on the particle surface.

Thermophoresis is a phenomenon that involves the transport of very small particles as a result of a thermal gradient from hot gases to cooler surfaces. Electrophoresis is the transport of particles because of a difference in charge. Vapor-phase and small-particle diffusion occurs in the boundary layer next to the surface and results in transport of ash to the surface. Inertial impaction is a larger-particle phenomenon where the particles are of a sufficient size and density to leave airflow patterns around the tube and impinge upon the surface of a tube or deposit. Deposits that form in high-temperature regions of the boiler, such as the radiant section, are called slag deposits. Deposits that form in lower-temperature regions of the boiler, such as in the convective pass on steam tubes and lower-temperature surfaces such as SCR catalysts, are called fouling deposits. Slag deposits are usually associated with a high level of liquid-phase components and are exposed to radiation from the flame. This is a description that many researchers use to aid in classification of deposits since some engineers call any type of deposit "slag". Slag deposits are typically dominated by silicate liquid phases, but may also contain moderate to high levels of reduced iron phases such as FeO and FeS. The liquid characteristics of the silicates are highly dependent upon the quantities of Na, Mg, Ca, K, and Fe ash on the silicates. In addition, the initiating layers of slag deposits may consist of very fine particulate and can produce a reflective ash layer. This phenomenon is especially evident when high organically associated calcium subbituminous coal is fired. These coals produce small CaO particles that usually form the initiating layers.

Fouling deposits form in the lower-temperature regions of the boilers and, in most cases, do not contain the high levels of liquid phases that are usually associated with slagging-type deposits. Fouling deposits contain lower levels of liquid phases as compared to slag deposits. The fouling deposit liquid phases usually consist mainly of sulfates that bind the particles together. Fouling deposits typically form as a result of the reaction of gas-phase sulfur oxide species with particles rich in alkali and alkaline-earth elements.

ASH-RELATED EXPERIENCES AT MRY FACILITY

The MRY is a minemouth electrical generating plant located near Center, North Dakota. The station consists of two units: Unit 1, rated at 276 MWg, began production in 1970; Unit 2, rated at 506 MWg, began production in 1977. Both Units 1 and 2 are equipped with B&W cyclone-fired boilers; the Unit 1 boiler has seven cyclones, and the Unit 2 boiler has twelve cyclones. Annual station gross generation is approximately 5.5 million MWh.

BNI Coal Ltd. is the sole coal supplier for the MRY Station. Coal is mined from the nearby Center mine, which consists of three distinct seams varying from 2½–9 feet thick. Coal is strip-mined using two draglines and is loaded with front-end loaders and delivered to the plant with bottom-dump haul trucks. Annual coal production is 4.3 million tons per year.

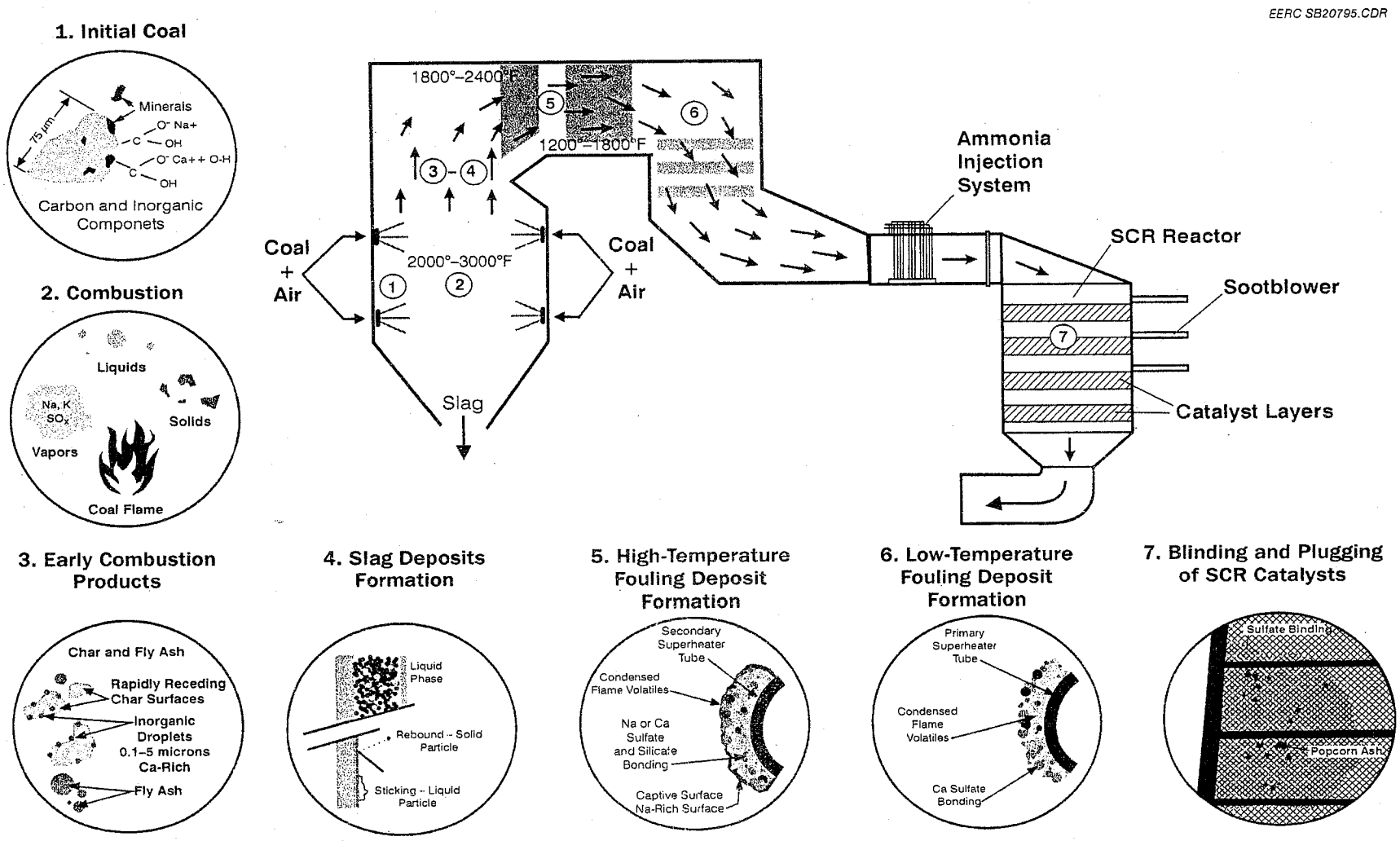

Figure 2. Overall processes of ash deposition typical of a lignite- or subbituminous-fired boiler.

History of Furnace Slagging/Fouling

Prior to 1991, besides annual maintenance outages, load reductions and forced outages due to furnace slagging/fouling were the largest cause of production loss. In 1985, operating guidelines were established that reduced furnace slagging/fouling, including deslagging outages scheduled every six months.

In 1991, a 3-month boiler cleaning cycle was proposed and initiated. The goal of this program was to increase annual generation by running the units at higher sustained loads and scheduling boiler-cleaning outages at 3-month intervals. However, furnace slagging/fouling continued to have a significant impact on plant operations. Success was measured in the number of production days between boiler-cleaning outages.

During the mid-1990s, a major outage every third year was scheduled for each unit. In addition, Unit 1 cleaning outages were scheduled for 80–90-day runs (four cleaning outages per year), and Unit 2 cleaning outages were scheduled for 65–75-day runs (five cleaning outages per year). The problem was that furnace and convection-pass surfaces gradually become coated with ash deposits, which, over time, sootblowers cannot remove. Some of the contributors to the ash deposits were as follows:

- Organically associated sodium is a primary contributor to deposition problems. Sodium is vaporized in the cyclones and condenses on other ash particles, causing them to become sticky and deposit at the furnace exit. The problem is associated with sulfate formation and occurs in the convective pass, including the economizer. Samples show that sodium in the ash varies from 0.6%–13.0%.

- Organically associated calcium is another component that causes deposition problems. Unlike sodium, calcium does not produce a vapor-phase component. Calcium does react with silicate (derived from clays) to cause low-melting-point phases that produce wall deposits and deposits in the high-temperature regions of the convective pass. Calcium also produces very small particles that will be transported to heat-transfer surfaces, resulting in the formation of thin, light-colored layers called reflective ash. These small particles of ash are carried through to the back passes where they are sulfated and can combine with sodium to cause the formation of strongly bonded sulfate-based deposits. Samples show that calcium in the ash varies from 6.8%–24.0%.

- Clay minerals and quartz – Center lignite can contain high levels of illite, which has a 1:3 Al:Si ratio and high levels of potassium, both of which cause wall slagging and high-temperature fouling. Quartz and other clays can significantly contribute to the mass of the deposits. Samples show that ash content varies from 5.0%–25.5%.

Advanced Boiler Performance Indices

Advanced indices are used to relate the coal characteristics as determined by computer-controlled scanning electron microscopy (CCSEM) and chemical fractionation to ash behavior in a coal-fired utility boiler (12). Fuel performance is estimated in terms of slag flow behavior,

abrasion and erosion wear, wall slagging, high-temperature silicate-based convective pass fouling, and low-temperature sulfate-based convective pass fouling. The following indices are used to assess the effects of ash behavior on utility boiler performance:

- Convective-Pass Fouling Indices

Sulfation Index: Indicates the propensity of deposit to form in the convective pass of the utility boiler in the temperature range from 1000°–1750°F. This index is based on the availability of alkali (Na and K) and alkaline-earth (Ca and Mg) elements to react with SO_2 and SO_3 to form sulfates. The sulfates are the primary materials that cause particle-to-particle bonding in high-calcium coals. The sulfates are thermodynamically stable at temperatures below about 1650°F. Index values range from 1 (low) to 10 (severe).

Silicate Index: Indicates the propensity of deposits to form from 1600°–2400°F. This index is related to the formation of deposits in which the silicate material is the primary component that bonds the deposits together. The information used to derive the index includes the size of the minerals such as quartz and clay minerals, availability of alkali and alkaline-earth elements, and viscosity of the silicate liquid phase. Index values range from 1 (low) to 200 (severe).

- Waterwall Slagging

Slagging Index: Indicates the propensity of a deposit to form on the radiant walls from 2000°–3000°F. The basis of the slagging index is the size of the minerals (especially the illite, quartz, and pyrite), association of the calcium (calcite can contribute to slagging), and viscosity of the silicate-based liquid phase. Index values range from 1 (low) to 20 (severe).

- Wear Indices

Abrasion Index: This index indicates the potential for wear of fuel preparation and handling equipment. The wear is related to the hardness of minerals in the coal. The primary minerals of concern include quartz and pyrite. The index values range from 0.1 (low) to 10 (severe).

Erosion Index: This index indicates the potential for wear of boiler parts due to the impaction of fly ash particles. The erosion index is dependent upon the size of the ash/mineral particle, size of the particle, and velocity of the particle. The index values range from 0.1 (low) to 1.0 (severe).

- Cyclone Slagging Index: This index provides information on the slag flow behavior in cyclones. The factors that are included in this index include the partitioning of the ash in the cyclone based on size and association of the ash-forming components in the coal. The partitioning of the ash between the slag and entrained ash can significantly influence the flow behavior of the slag. Standard partitioning criteria have been developed to provide the composition of the slag. The composition is used to estimate the viscosity of the slag as a function of temperature. The index values have several ranges as follows: 1 (low viscosity), 1.5–2.5 (optimum viscosity), >3.0 (slag freezing).

- Strength Development Index: The strength index is based on the ability of the deposited material to develop strength. Strength development is primarily dependent upon the abundance and viscosity of the liquid-phase components in the deposits. Index values less than 0.25 indicate that the material will produce weak deposits; index values of 0.25–0.34 indicate weak-to-moderate-strength deposits; index values of 0.34–0.41 indicate high-strength deposits; and index values >0.41 indicate flowing slag.

Indices were calculated for a range of coals from the Center mine, and the propensity for ash deposition in various portions of the boiler indicates wide variations, as shown in Table 1. The BNI numbers indicate the location in the seams where the coal originated: Kinneman Creek seam (KC), Hagel A (HA), and Hagel (HB). Each seam has a different distribution of minerals and organically associated elements that can have a significant impact on the formation of deposits in the system. Comparison of Center lignite to subbituminous and bituminous coals from other regions of the United States, shown in Table 2, indicates significant differences in the potential to form deposits in the boilers. In all cases, the lignite (not the worst coal from Center mine) from the Center mine has a high propensity to produce deposits as compared to the other coals.

Another indication of the variability of lignites can be illustrated based on the calculation of the temperature where the slag flow would occur. This is defined as the T250 temperature, where the slag viscosity is 250 poise. Frequency distributions of the T250 values for all the data for coals analyzed are illustrated in Figure 3. Calculations of T250 values for 1212 samples obtained from the Center mine database (17) were made using empirical relations derived from CCSEM and chemical fractionation data and knowledge of how ash partitions in the cyclone. Figure 3 shows a bimodal distribution in the T250 based on the Urbain equation calculations. The primary mode was at a value of 2000°F. The secondary mode was at about 2700°F. The results indicate that many of the coals have a sufficiently low T250 for good slag flow. However, coals with T250 at 2700°F are not suitable for maintaining good slag flow.

Figures 4 through 6 illustrate the variations in T250 for the various seams of coals characterized. The HA and HB seam coals appear to have large numbers of samples, with T250 values at or near 2000°F. The KC seam coal, as illustrated in Figure 6, has extremely high T250 values. Based on these data, the KC coals are not favored relative to the slag flow behavior of the ash.

Frequency distributions of cyclone slagging index values indicated significant variations in slagging potentials of coals mined from the three seams, KC, HA, and HB. This information proved particularly useful in planning the mining and firing of coal from the KC seam.

During a July 1999 test burn, the composition of the cores was used to examine and illustrate the variability of the delivered coal quality based on base-to-acid ratio calculated from the ash composition. Figure 7 shows the variation in the base-to-acid-ratio and the seam where the coal was loaded. The base-to-acid ratios were calculated from core data that corresponded to the location in the seam where the coal was mined. There is a significant variation in the base-to-acid ratio for the coals. The coals that have the highest base-to-acid ratio are typically from the HA seam. HB seam coals generally have an intermediate base-to-acid ratio. KC or top-seam coal has the lowest base-to-acid ratio. Lower base-to-acid-ratio coals typically produce slag with high viscosities.

Table 1. Characteristics and Indices Calculated for Selected Center Lignite Samples

BNI No.	41-132HB	41-44KC	41-144HA	41-144HB	41-168KC	41-168HA	41-168HB	41-180KC	41-180HA	41-180HB	41-192KC	41-192HA
Mineral wt%, mineral basis												
Total Quartz Content			18.8	9.8	30.3	8.7	8.8	11.4	20.0	3.9	15.0	17.4
Quartz <10 microns		10.8		6.4	24.6	4.4	4.0	6.8	3.3	2.6	9.7	12.7
Total Kaolinite Content		10.6		10.8	7.7	6.4	1.7	9.5	4.4	2.4	14.3	28.0
Kaolinite Content <10 microns		5.1		6.3	4.5	2.6	0.9	4.8	1.1	0.9	10.2	20.8
Total Montmorillonite		10.7		2.7	6.5	1.7	6.1	7.0	2.3	2.4	7.6	5.1
Total Illite		14.1		9.3	6.6	0.2	28.0	19.1	10.2	1.6	6.8	1.9
Total Pyrite		8.0		26.7	18.9	67.1	19.7	9.1	10.9	57.2	22.6	32.3
Pyrite Content <10 microns		4.5		10.5	2.8	9.8	4.7	2.5	2.5	17.0	6.6	7.0
Gypsum Content		6.5		0.0	1.6	2.7	0.8	5.4	0.0	16.1	2.2	0.0
Proximate (wt% as received)												
Moisture		30.95		41.66	36.24	38.23	37.50	37.90	37.99	38.21	37.85	39.52
Volatile Matter		27.26		25.74	26.32	25.90	24.55	25.11	24.42	25.88	26.13	24.27
Fixed Carbon		26.56		27.97	28.18	29.65	30.37	27.94	29.53	31.54	29.15	30.30
Ash		10.30		4.63	9.26	6.22	7.58	9.05	8.1	4.37	6.88	5.91
Total Sulfur (% as received)		0.94		0.55	1.49	1.08	0.75	0.99	0.64	0.86	0.90	0.85
Btu/lb		6597		6593	6791	6957	6806	6584	6653	7194	6881	6835
% Ash (dry basis)	11.64	10.30		7.94	14.52	10.07	12.13	14.57	13.00	7.07	11.07	9.77
Ash Comp. (wt% equiv. Oxide)												
Na_2O		0.50		10.65	0.82	9.25	8.02	0.46	8.15	11.99	1.48	9.69
MgO		3.30		5.74	3.72	4.90	4.45	3.90	5.00	4.59	6.13	5.10
Al_2O_3		11.90		10.37	9.34	5.64	11.81	12.12	10.19	5.23	10.59	7.46
SiO_2		30.60		14.70	33.71	8.47	30.74	35.57	36.25	5.31	25.80	13.06
P_2O_5		0.20		0.06	0.15	0.42	0.25	0.07	0.26	0.23	0.25	0.24
SO_3		23.00		25.50	21.28	35.25	21.05	18.32	15.93	35.75	24.15	32.75
K_2O		1.20		0.96	0.47	0.62	1.52	1.03	1.22	0.47	0.55	0.60
CaO		16.80		21.00	15.31	18.94	12.10	17.15	14.87	15.43	20.01	18.98
TiO_2		1.30		0.39	0.72	0.29	0.40	0.51	0.29	0.16	0.48	0.28
MnO		0.20		0.03	0.07	0.05	0.04	0.10	0.07	0.04	0.07	0.12
Fe_2O_3		10.30		8.43	14.87	15.95	10.44	7.80	6.84	18.88	10.12	13.29
Cyclone Slagging Index		2.77		1.28	2.5	1.1	2.6	3.3	2.9	0.4	2.2	1.3
Silicate		10.71		102.43	29.47	108.33	109.93	16.29	176.22	137.49	14.19	149.54
Sulfate		9.43		3.57	2.2	5.01	3.46	1.75	3.98	4.4	2.21	3.24
Wall Slagging Index		1.18		11	2.67	10.68	9.27	1.79	8.83	12.63	2.2	10.53
Erosion Index		0.19		0.15	0.17	0.19	0.22	0.21	0.27	0.17	0.17	0.17
Abrasion Index		2.14		0.71	6.46	1.55	1.41	2.25	1.93	0.83	1.75	1.68
Strength Index		0.32		0.66	0.35	1.11	0.35	0.3	0.33	1.32	0.43	0.63

Continued . .

Table 2. Advanced Index Values for Other Coals (12)

Advanced Indices	Lignite North Dakota	Powder River Basin	Bituminous Illinois	Bituminous Appalachian
Cyclone Slagging Index	1.6	2.1	3.5	3.2
Convective Pass Fouling				
Silicate	61.8	23.99	10.36	14.21
Sulfate	4.09	2.88	0	0
Wall Slagging Index	9.28	1.85	1.53	1.66
Erosion Index	0.15	0.17	0.14	0.17
Abrasion Index	0.71	1.96	3.94	1.96

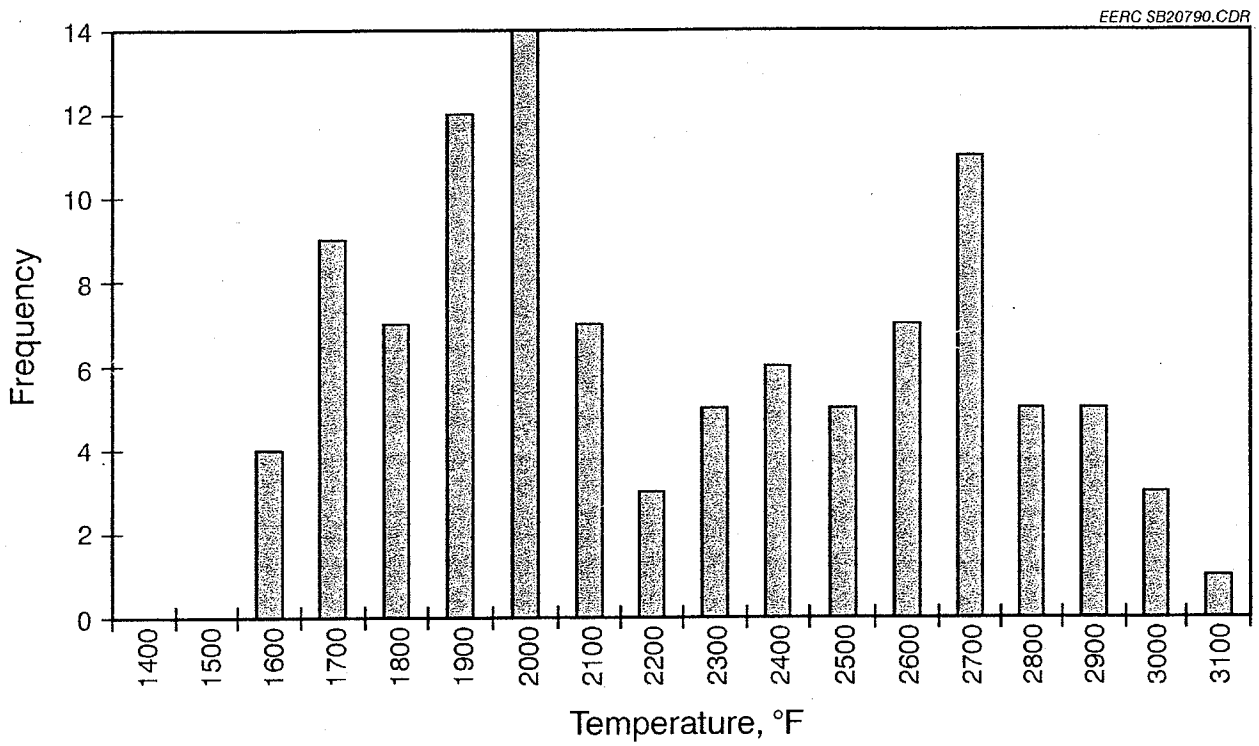

Figure 3. T_{250} frequency distribution for all Coal Quality Management System (CQMS) data, °F.

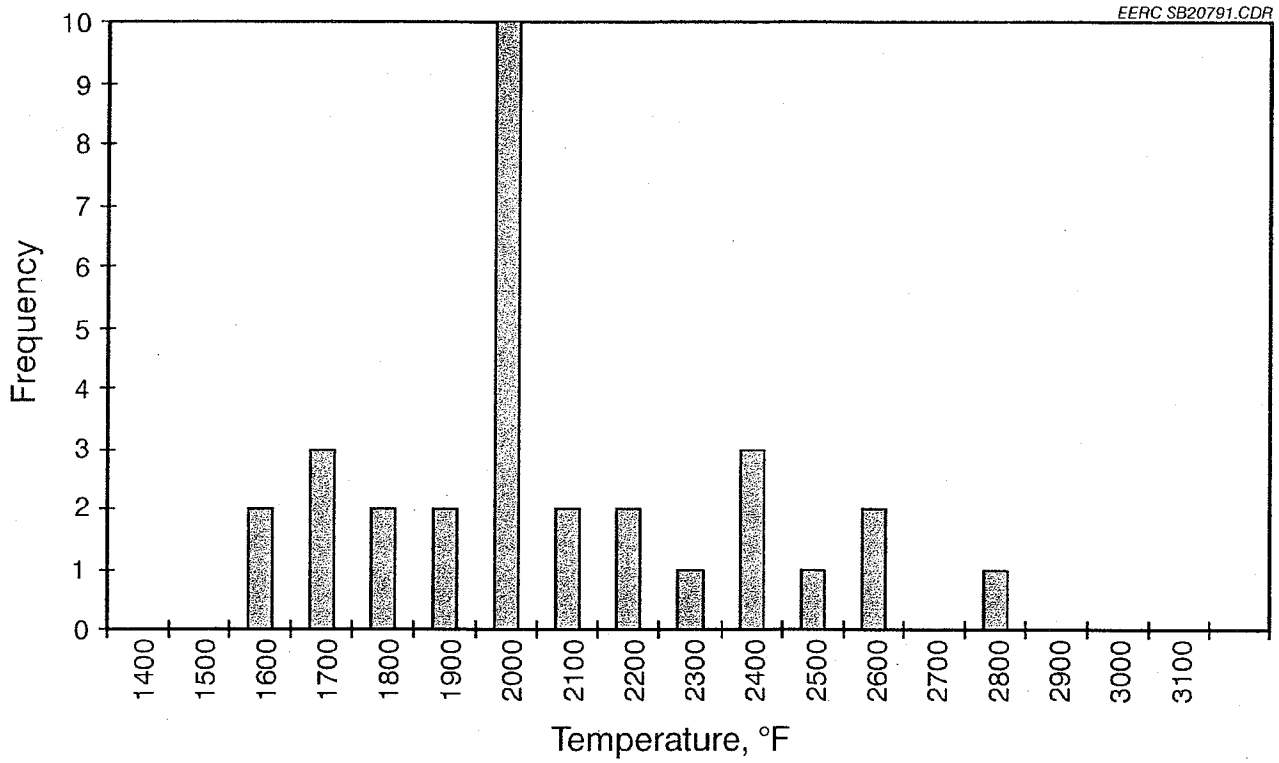

Figure 4. T_{250} distribution for HA seam coal.

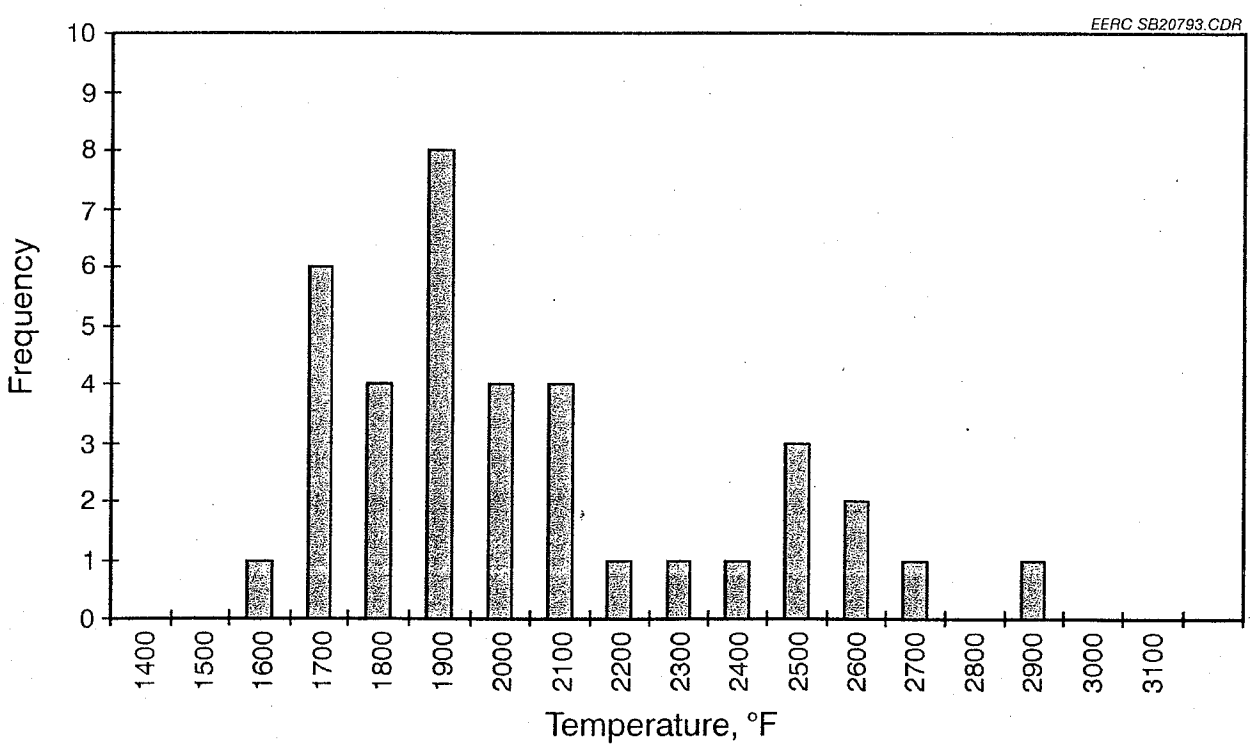

Figure 5. T_{250} distribution for HB seam coal.

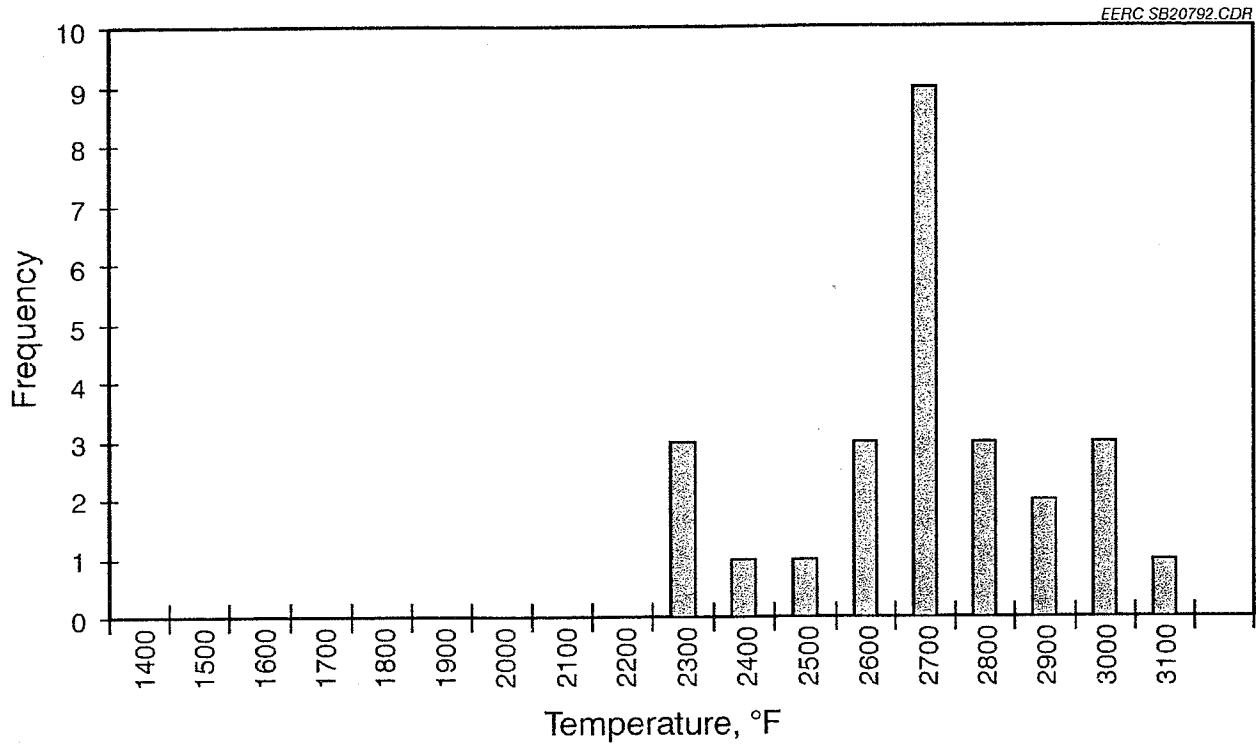

Figure 6. T_{250} distribution for KC seam coal.

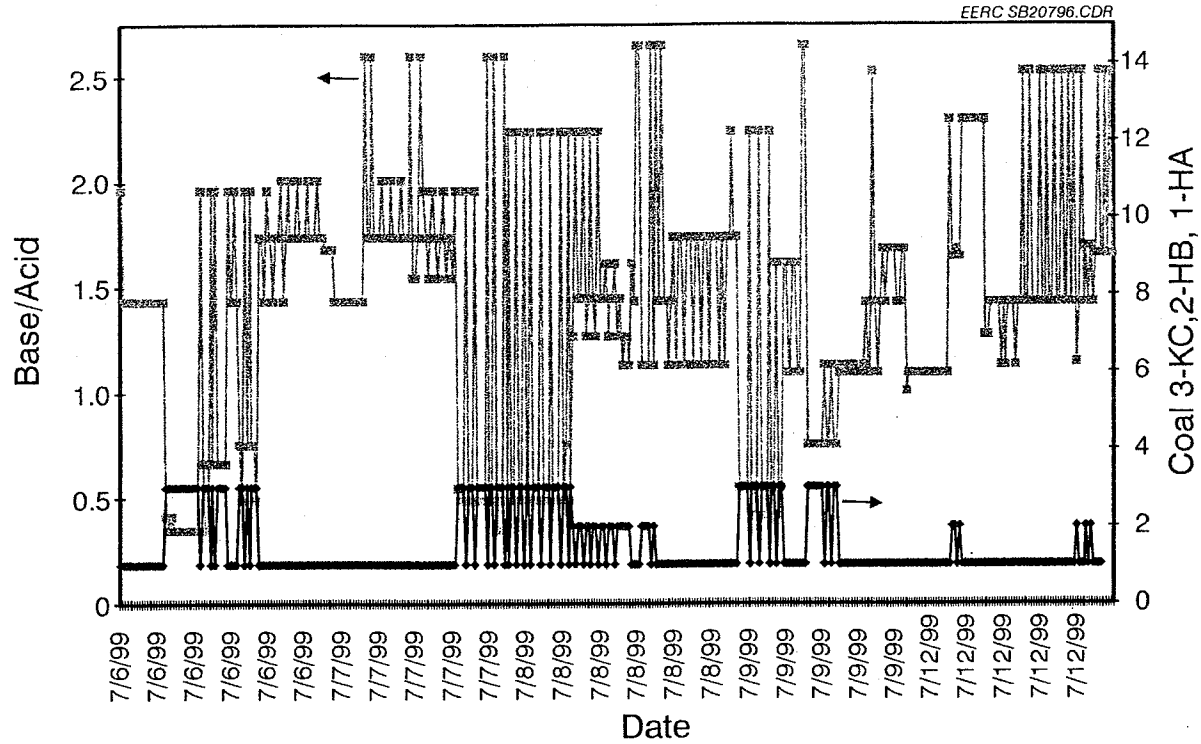

Figure 7. Variations in the delivered coal quality during a test burn period.

Figure 7 shows the sequence of deliveries beginning on July 6 and ending on July 12, 2004. During this period, the majority of the coal delivered was from the HA seam, followed by KC, and HB. Most of the deliveries alternated between KC and HA. Figure 6 shows several instances where significant quantities of KC coal were delivered, on July 6 through July 9. The quantity of KC coal delivered will have the potential to increase the viscosity of the slag and result in poor slag flow from the cyclones.

ASH-RELATED IMPACTS ON SCR CATALYST PERFORMANCE

Ash-related impacts on SCR catalyst performance will depend upon the composition of the coal, the type of firing systems, flue gas temperature, and catalyst design (14–16, 22). The problems currently being experienced on SCR catalysts include the following:

- Formation of sulfate- and phosphate-based blinding materials on the surface of catalysts.
- Carrying of deposit fragments, or popcorn ash, from other parts of the boiler and depositing on top of the SCR catalysts.

Licata and others (14) conducted tests on a South African and German Ruhr coal and found that the German Ruhr coal significantly increased the pressure drop across the catalyst because of the accumulation of ash. They found that the German coal produced a highly adhesive ash consisting of alkali (K and Na) sulfates. In addition, they reported that the alkali elements are in a water-soluble form and highly mobile and will migrate throughout the catalyst material, reducing active sites. The water-soluble form is typical of organically associated alkali elements in coals. The German Ruhr Valley coal has about 9.5% ash and 0.9 % S on an as-received basis, and the ash consists mainly of Si (38.9%), Al (23.2%), Fe (11.6%), and Ca (9.7%), with lower levels of K (1.85%) and Na (0.85%) (15). Cichanosicz and Muzio (16) summarized the experience in Japan and Germany and indicated that the alkali elements (K and Na) reduced the acidity of the catalyst sites for total alkali content (K+Na+Ca+Mg) of 8%–15% of the ash in European power plants. They also found that alkaline-earth elements such as calcium react with SO_3 on the catalyst, resulting in plugging of pores and a decrease in the ability of NH_3 to bond to catalyst sites. The levels of calcium in the coals that caused blinding ranged from 3%–5% of the ash.

The mechanisms for this type of low-temperature deposition have been examined and modeled in detail at the Energy & Environmental Research Center (EERC) in work termed Project Sodium and Project Calcium in the early 1990s; however, the focus of those projects was specific to primary superheater and economizer regions of boilers and not SCR systems (22, 23). Deposit buildup of this type can effectively blind or mask the catalyst, diminishing its reactivity for converting NO_2 to N_2 and water and potentially creating increased ammonia slip (14). Arsenic and phosphates, which are not uncommon in low-rank coals, may also play a role in catalyst degeneration. Arsenic is a known catalyst poison (14) in applications such as catalytic oxidation for pollution control. Phosphates can occur in low-temperature ash deposits to create blinding effects, and they also occur with arsenic and can cause catalyst poisoning (23).

Lignite and subbituminous coals produce ash that plugs and blinds catalysts (25–28). The problems currently experienced with SCR catalysts include the formation of sulfate- and phosphate-based blinding materials on the surface of catalysts and the carrying of deposit fragments, or popcorn ash, from other parts of the boiler and depositing them on top of the SCR catalysts (14). The most significant problem that limits the successful application of SCR catalysts to lignite coal is the formation of low-temperature sodium–calcium–magnesium sulfates, phosphates, and possibly carbonates that will form on the surfaces of catalysts and the carryover of deposits that will plug the catalyst openings, resulting in increased pressure drop and decreased efficiency (14–16, 27–28). The degree of the ash-related impacts on SCR catalyst performance depends upon the composition of the coal, the type of firing systems, flue gas temperature, and catalyst design (15–16, 24, 27–28).

In studies (7) the impacts of temperature and the presence of catalyst on the ability of ash to sulfate were examined. The tests were conducted using a thermogravimetric analyzer (TGA). TGA testing was conducted using a <5-μm-size fraction of ash produced from Powder River Basin (PRB) coals and lignites and exposing them to vapor-phase sulfur dioxide with and without catalyst at several temperatures. The aim of the testing was to determine the potential of the formation of sulfates to cause particle-to-particle bonding that leads to the formation of deposits in the temperature range where SCR catalysts are used. The TGA testing is focused on determining the reactivity of the <5-μm ash produced from selected PRB and blends to sulfur dioxide and gas-phase phosphorus species as a function of temperature. Testing was conducted to determine the weight gain with flue gas containing ammonia. The impact temperature on the weight gain due to the formation of sulfates for a PRB blend is shown in Figure 8. The rates of sulfation were found to increase with increased temperature. The results show an increase in the weight gains when ammonia and phosphorus were added. Ground catalyst was mixed with PRB and placed in the TGA. Increases in weight gain were observed when catalyst was added as compared to baseline cases for 100% PRB, as shown in Figures 8 and 9, respectively. The presence of catalyst enhances the formation of sulfates.

Full-Scale Slipstream Testing

More recently (8), the behavior of ash and mercury in flue gas produced from the combustion of lignite and subbituminous coals from the United States of America in selective catalytic reduction (SCR) systems for nitrogen oxide removal has been examined. Typically, these coals contain ash-forming components that consist of inorganic elements (sodium, magnesium, calcium, and potassium) associated with the organic matrix and mineral grains (quartz, clays, carbonates, sulfates, and sulfides). Upon combustion, these coals produce ash that has an abundance of alkali and alkaline-earth-rich oxide particles (<5 μm) that are carried into the backpasses of the combustion system and react with flue gas to form sulfates and possibly carbonates. The forms of mercury in the flue gas produced from the lignite and subbituminous coals are dominated by the elemental form. Slipstream testing was conducted at two subbituminous-fired power plants and one lignite-fired power plant to determine the impacts of ash on SCR plugging, blinding, and mercury oxidation.

The SCR slipstream system consists of two primary components: the control room and the SCR reactor. The reactor section consists of a catalyst section, an ammonia injection system, and sampling ports for NO_x at the inlet and exit of the catalyst section. The control room houses a computer system that logs data and controls the gas flow rates, temperatures, pressure drop across the catalyst, and sootblowing cycles. The computer is programmed to maintain constant temperature of the catalyst, gas flow rates, sootblowing cycles, and ammonia injection. The computer is equipped with a modem that allows for downloading of data and modification of the operation of the reactor from a remote computer located at the EERC.

Flue gas is isokinetically extracted from the convective pass of the boiler upstream of the air heater. The temperature is typically about 790°F. The flue gases pass through a 4-inch pipe equipped with sampling, thermocouple, and pressure ports. Ammonia is injected into the piping upstream of the reactor section. The reactor consists of a steel housing that is approximately 8.5 inches square and 8 feet long. The reactor section has three components, including a flow straightener, a pulse section or sootblower, and a catalyst test section. A metal honeycomb is used as a flow straightener upstream of the catalyst section and is about 6 inches long. A purge section was installed ahead of the catalyst test section to remove accumulated dust and deposits. The catalyst test section is located downstream of the purge section. The entire catalyst section is insulated and equipped with strip heaters for temperature control. The catalyst test section is 3.28 ft (1 m) in length and houses three catalyst sections. Thermocouple and pressure taps are located in the purge sections for measurements before and after each section.

The induced-draft fan is used to extract approximately 400 acfm (200 scfm) of flue gas from the convective pass of the utility boiler to achieve an approach velocity of 5.2 m/s (17.0 ft/s). The gas velocity is similar to that found in full-scale applications. The total gas flow through the reactor represents a thermal load of approximately 300 kW.

The range of operating conditions for the reactor is listed below:

- X Gas temperature: ~700°–800°F
- X Gas flow rate: 400–500 acfm
- X Approach velocity range: 5.0–5.5 m/sec
- X Ammonia injection rate: 0.5:1 with NO_x level
- X Tempering air for fan: ~ 50–200 scfm
- X Catalyst dP: 0.5–1.0 inches water column
- X Fan sized for up to 30 inches water column

The catalyst installed at the Baldwin and Coyote Stations was the Haldor Topsoe catalyst. Topsoe's DNX-series of catalysts comprises SCR DENOX catalysts tailored to suit a comprehensive range of process requirements. DNX-series catalysts are based on a corrugated, fiber-reinforced titanium dioxide (TiO_2) carrier impregnated with the active components vanadium pentoxide (V_2O_5) and tungsten trioxide (WO_3). The catalyst is shaped to a monolithic structure with a large number of parallel channels. The unique catalyst design provides a highly porous structure with a large surface area and an ensuing large number of active sites. The pitch of the catalyst was approximately 6 mm.

The catalyst installed at the Columbia Station was a Babcock Hitachi plate-type catalyst. This catalyst is a TiO_2-based plate catalyst, developed and manufactured by Hitachi. The pitch of the catalyst was approximately 10 mm.

The coals produced ash that had significant accumulations of ash on the catalyst on both macroscopic and microscopic levels. On a macroscopic level, there were significant observable accumulations that plugged the entrance as well as the exit of the catalyst sections. On a microscopic level, the ash materials filled pores in the catalyst and, in many cases, completely masked the pores within 4 months of operation.

The deposits on the surfaces and within the pores of the catalyst consisted of mainly alkali and alkaline-earth element-rich phases that have been sulfated. The results of this testing found that the <5-μm ash rich in alkali and alkaline-earth elements is captured on the surface and within the catalyst pores. These materials react with SO_2/SO_3 in the flue gas, resulting in the formation of a continuous phase that blinds the catalyst. The ability of elemental mercury to be oxidized across the SCR catalyst was investigated at a North Dakota lignite-fired plant. These results showed no oxidation of mercury across the SCR catalyst.

The reactor was installed at the Baldwin Station and operated for a 6-month time period on the Haldor Topsoe catalyst. The information obtained from testing included pressure drop, sootblowing cycles, and reactor temperatures. Figure 10 show the pressure drop across the catalyst test periods from 0 to 2 months. During the first two months of operation, the pressure was about 0.5 inches of water; at the end of two months, the pressure drop was about 0.8 inches of water, indicating plugging had occurred. The air was pulsed a minimum of every 8 hours in an attempt to maintain cleanliness. The reactor was monitored on a daily basis, and adjustments in pulsing cycles were made in order to minimize deposit accumulation. However, for the first two months, the pressure drop steadily increased. There are several periods where the unit was taken off-line; during those times, the temperature of the catalyst was maintained. At 2-month intervals, a section of catalyst was removed and replaced with a new one.

For Months 2 through 4, the pressure drop was highly variable initially but was about 0.8 inches of water. From Months 4 through 6, the pressure drop was maintained between 0.6 and 0.8 inches of water. This is due to the installation of a fresh catalyst section and leaving two thirds of the catalysts in place that were partially plugged. The gas velocity in the single section of new, clean catalyst was high because of channeling, and the result of the high gas flow was less deposition and accumulation. Gas velocity has a significant impact on the potential for deposits to form. However, at high gas velocity, low NO_x conversion is likely.

The reactor was installed at the Columbia Station and operated for a 6-month period of time with the Babcock Hitachi catalyst. The information obtained from the testing included pressure drop information, sootblowing cycles, and reactor temperature. Figure 11 shows the test periods from 0 to 2 months. The pressure drop across the SCR upon installation was about 0.4 inches of water and increased to an average of about 0.5 inches of water, but ranged from less than 0.4 to greater than 0.8 inches of water. The pressure drop for Months 2 to 4 increased from about 0.5 to 0.7 inches of water because of accumulation of ash. After cleaning the reactor and replacing one catalyst section, the pressure drop was about 0.3 but increased to over

0.6 inches of water up to about 4100 hours. There was an outage at the plant, and aggressive pulsing of the reactor was conducted; the pressure drop was brought back down to 0.3 but rapidly increased to over 0.5 inches of water within 500 hours.

The same reactor that was installed at the Baldwin Station was moved and installed at the Coyote Station. In addition, the same Haldor Topsoe catalyst type was used in the reactor. The reactor was operated for a 6-month period of time. Figure 12 shows the test periods from 0 to 2 months. As this paper is being prepared, the reactor is still operating on-site. The pressure drop across the catalyst upon installation was about 0.4 inches of water. After only 750 hours, the pressure drop was 1.5 inches of water, indicating significant plugging and blinding. Very aggressive air pulsing was conducted, with little success in removing the deposits. The pressure drop for the catalyst was over two times greater than the pressure drop observed for the Baldwin Station utilizing the same reactor and same catalyst. At about 1700 hours, the reactor was cleaned, and a section of catalyst was removed for characterization. The pressure drop after cleaning was about 0.8 to 1.0 inches of water. The pressure drop did not increase as rapidly because of the higher velocities through the clean section of the catalyst.

The tops of the catalysts were photographed during inspection and sampling of the catalyst sections. Figure 13 shows the ash materials that accumulated on the catalyst inlet after 2 months of operation. The most significant accumulation was noted for the Coyote Station, followed by Columbia and Baldwin. The Coyote Station had some larger pieces of ash deposit material on the surface as well as plugging of the catalyst passages. The Baldwin Station showed some obvious deposition along the walls of the reactor and some accumulation on the inlet sections. The Columbia Station showed more significant accumulation and plugging than the Baldwin Station.

After 4 months, the tops of the catalysts were photographed during inspection and sampling of the catalyst sections, as shown in Figure 14. The most significant accumulation was noted for the Coyote Station and some accumulation for the Baldwin Station.

SCR Ash Deposit Characterization

The characteristics of the ash materials that collected on the catalyst surfaces and pores were characterized by SEM and x-ray microanalysis and, in selected cases, XRD was used to determine the crystalline phases present. The catalysts were sampled after 2, 4, and 6 months. The sections were sampled, and approximately 2.5-cm squares were mounted for SEM analysis on double-stick tape and in epoxy resin. The double-stick tape samples allowed for characterization of the external morphology of the particles and catalyst surface. The samples mounted in resin were cross-sectioned and polished, which allowed for more detailed and quantitative analysis of the bonding materials and materials that accumulated in the pores of the catalyst. Detailed information on all the samples can be found elsewhere (add FPT reference). Examples of two deposit and catalyst analysis are presented here.

The 6-month sample from the Baldwin Station showed extensive sulfation of the alkaline-earth elements present in the deposits. Figures 15a and 15b show regions of the catalyst where all the pores were blocked and a minimal amount of deposit on the surface of the catalyst. Figure

15c shows a higher-magnification view of the deposit that is filling the catalyst pore. The deposit consists of particles of fly ash bonded together by a matrix of calcium- and sulfur-rich material, likely in the form of calcium sulfate. The chemical compositions of selected points that indicate the presence of high levels of calcium and sulfur are listed in Table 3. There is much more extensive bonding of the materials with the sulfate matrix as compared to the 2-month sample. In addition, there are some regions of high levels of calcium, aluminum, and sulfur present. The calcium aluminum materials are likely derived from the calcium aluminum phosphate minerals found in the coal fired at this plant.

The 4-month sample from the Coyote Station showed particles adhering to the surface and filling pores in the catalyst. Figure 16 shows the 4-month sample from the Coyote Station. The catalyst showed particles adhering to the surface and completely filling and masking the pores in the catalyst. The external morphology of the catalyst surface shows the masking of the catalyst surface. Chemical compositions of selected points are shown in Table 4. The 4-month sample shows more sulfation than the two months of exposure samples. Figures 16b and 16c shows a higher-magnification view of the deposit that is filling the catalyst pore. The deposit consists of particles of fly ash bonded together by a matrix of sodium-, calcium-, and sulfur-rich material, likely in the form of calcium sulfate. Significant sodium was found in the deposits, as shown in Table 4. The sample shows significant evidence of sulfation after 4 months of exposure and was much more pronounced than the samples for the Baldwin and Columbia Stations that are fired on PRB coals. The presence of sodium enhances the bonding and sulfation of the particles to form a strongly bonded matrix (22).

SCR Deposit Formation Mechanisms

The mechanism for the formation of deposits that blind SCR catalysts involves the transport of very small particles rich in alkali and alkaline-earth elements, the surface of the catalyst, and reactions with SO_2/SO_3 to form sulfates. The formation of SO_3 from SO_2 is catalyzed by the SCR; this, in turn, increases the reaction rate of SO_3 to form sulfates. In some cases, the alkali and alkaline-earth elements will also react with CO_2 to form carbonates. XRD analysis identified $CaSO_4$ as a major phase and $Ca_3Mg(SiO_4)_2$ and $CaCO_3$ as minor phases.

Lignite and subbituminous coals contain high levels of organically associated alkali and alkaline-earth elements including sodium, magnesium, calcium, and potassium, in addition to mineral phases. The primary minerals present in these coals include quartz, clay minerals, carbonates, sulfates, sulfides, and phosphorus-containing minerals (6).

During combustion, the inorganic components in the coal are partitioned into various size fractions based on the type of inorganic component, their association in the coal, and combustion system design and operating conditions. Significant research has been conducted on ash formation mechanisms and relationships to impacts on power plant performance (1–6, 9–13, 19–21, 29). During combustion, the inorganic components associated with western subbituminous and lignite coal typically are distributed into various size fractions of ash. The smaller size fractions of ash are dominated by partially sulfated alkali and alkaline-earth elements. These ash particles are largely derived from the organically associated cations in the coal. The larger size

fraction has higher levels of aluminum and silicon derived from the mineral fraction of the ash-forming component of the coal. Entrained ash was extracted from the Columbia Station at the point of the inlet to the SCR reactor and was aerodynamically classified and analyzed. The composition of the size fractions was compared to the chemical composition of the ash deposited on and in the catalyst, as shown in Figure 17. The comparison shows that the composition of the particle captured in the SCR catalyst is very similar to the <5-μm size fraction. The deposited material shows significantly more sulfation than the entrained-ash size fraction, indicating that the sulfation process occurs after the particles are deposited in the catalyst.

The mechanism of SCR catalyst blinding when firing lignite or subbituminous coals is shown in Figure 18 (30). The requirements for the formation of deposits that blind SCR catalyst include firing a coal that produces significant levels of <5-μm-sized particles. The particles are transported into the pores of the catalyst and subsequently react with SO_3 to form sulfates. The sulfate forms a matrix that bonds other ash particles. The SCR catalyzes the formation of SO_3 and thereby increases the rate of sulfation (24, 25). The sulfation of CaO increases the molar volume, resulting in the filling of the pore. For coals that have high sodium contents, formation of low-melting-point phases such as pyrosulfates is possible (31). Pyrosulfate materials can melt at temperatures as low as 535°F in coal-fired power systems.

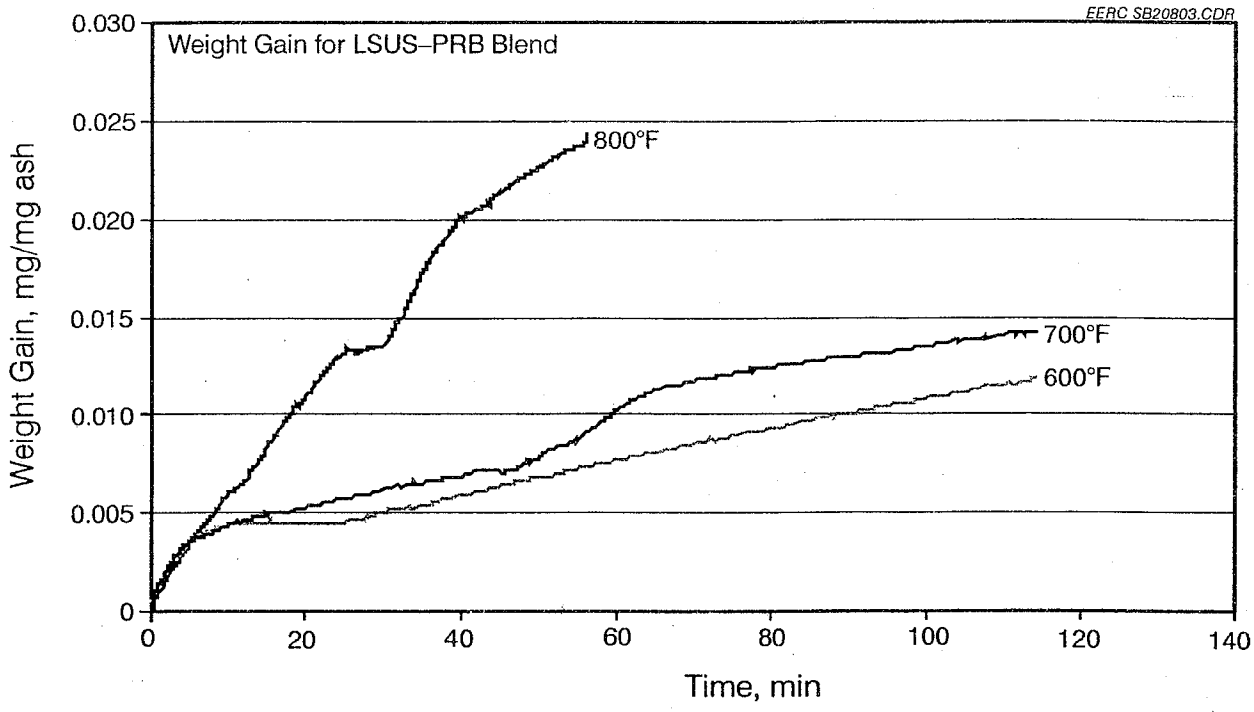

Figure 8. Weight changes for PRB-blend coal ash exposed to flue gases and ammonia at three temperatures.

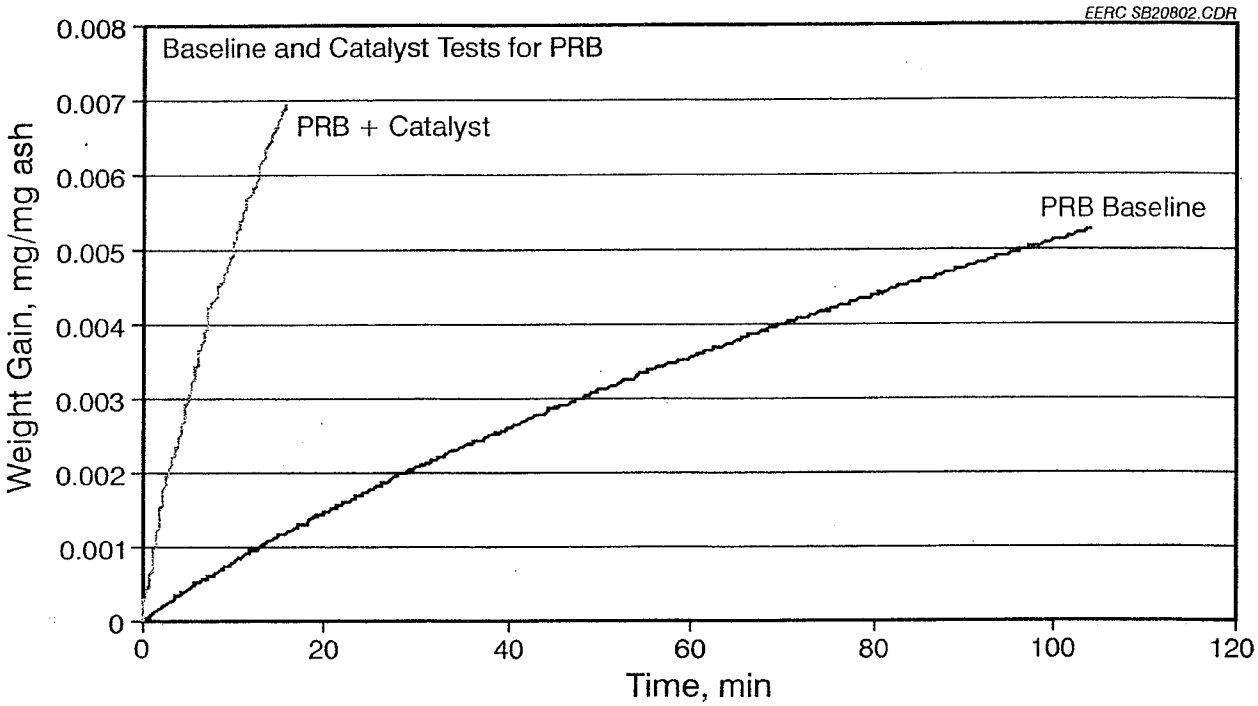

Figure 9. Weight changes for PRB-blend coal ash exposed to flue gases and ammonia with and without SCR catalyst present.

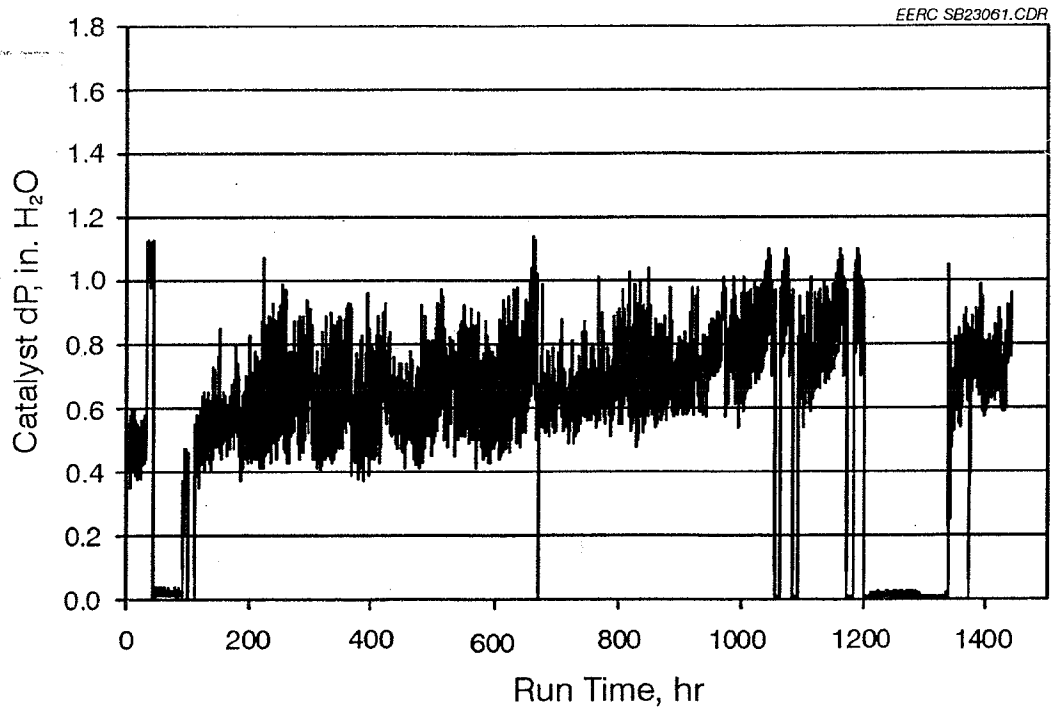

Figure 10. Catalyst pressure drop at Baldwin Station at 0 to 2 months of operation.

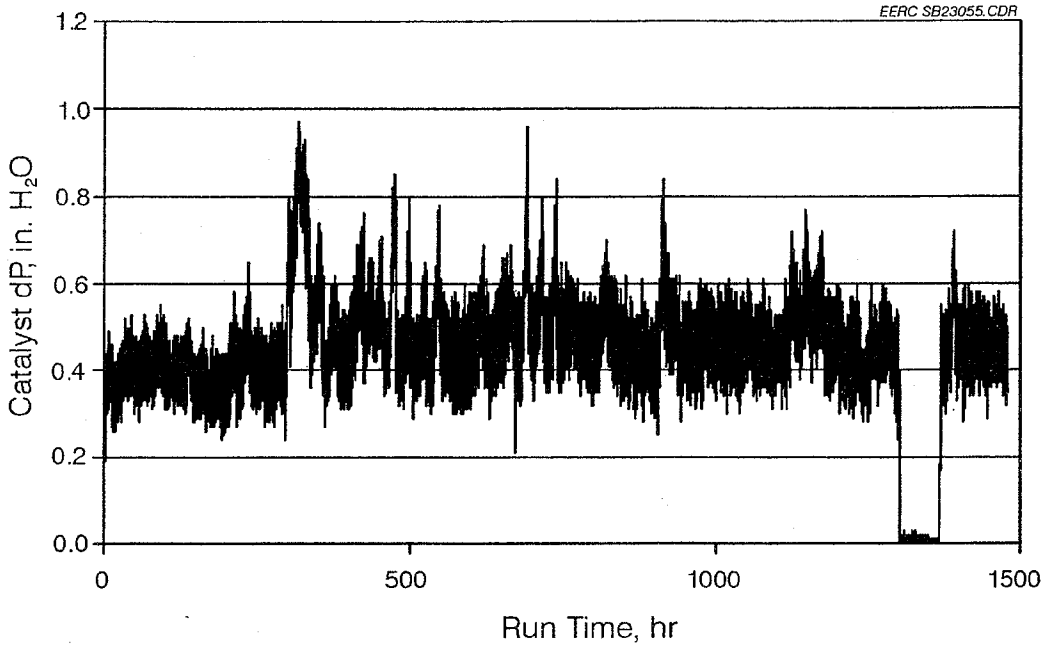

Figure 11. Catalyst pressure drop at Columbia Station at 0 to 2 months of operation.

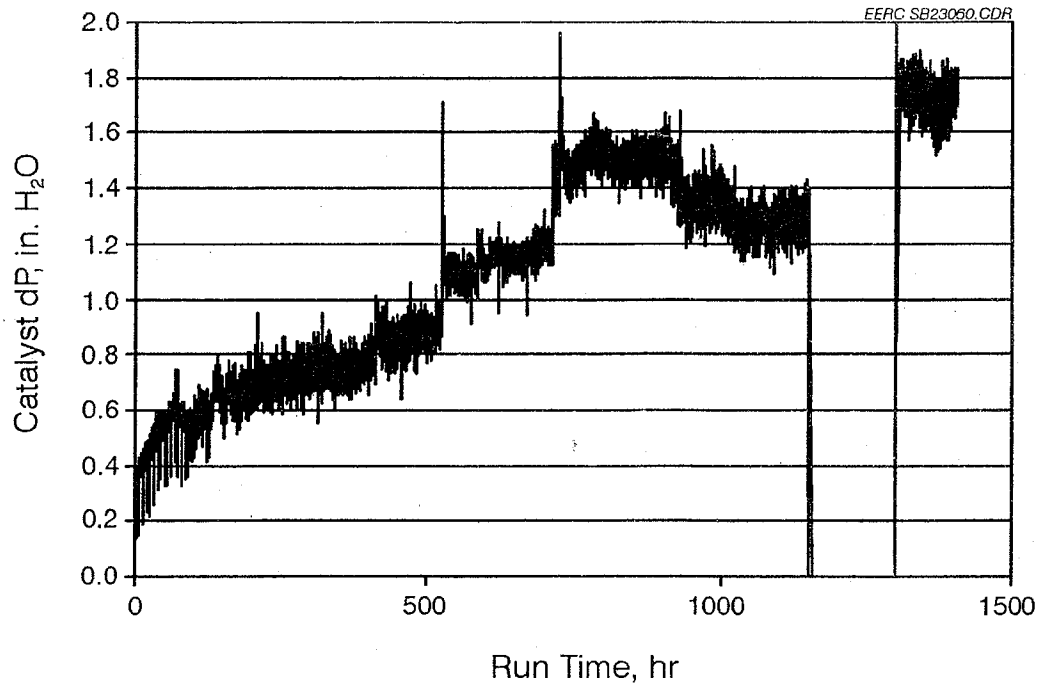

Figure 12. Catalyst pressure drop at Coyote Station at 0 to 2 months of operation.

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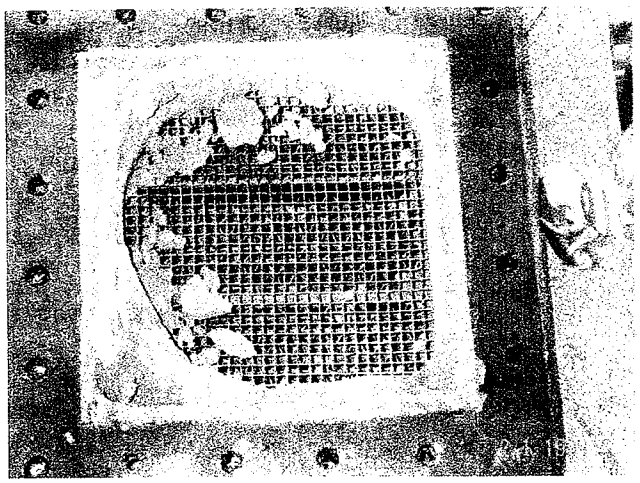
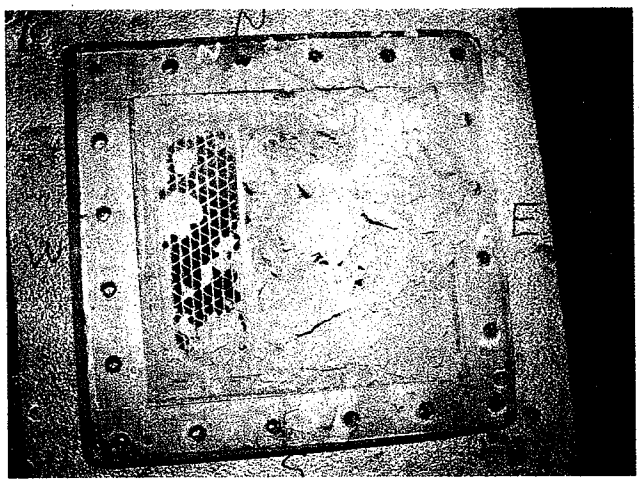
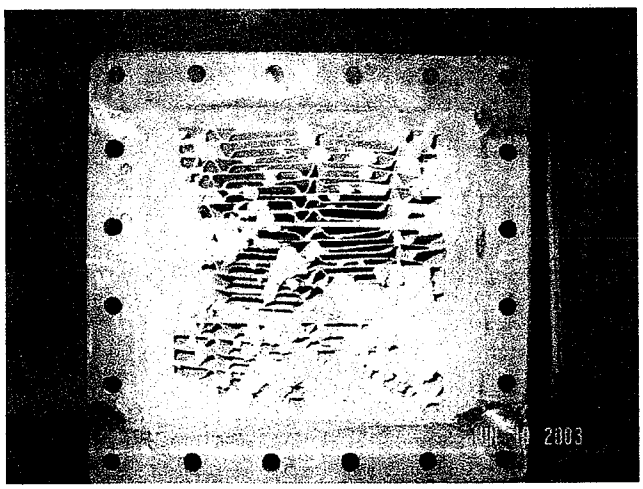


Baldwin Station after 2 months



Coyote Station after 2 months



Columbia Station after 2 months

Figure 13. Pictures of catalyst inlet after about 2 months of testing at each plant.

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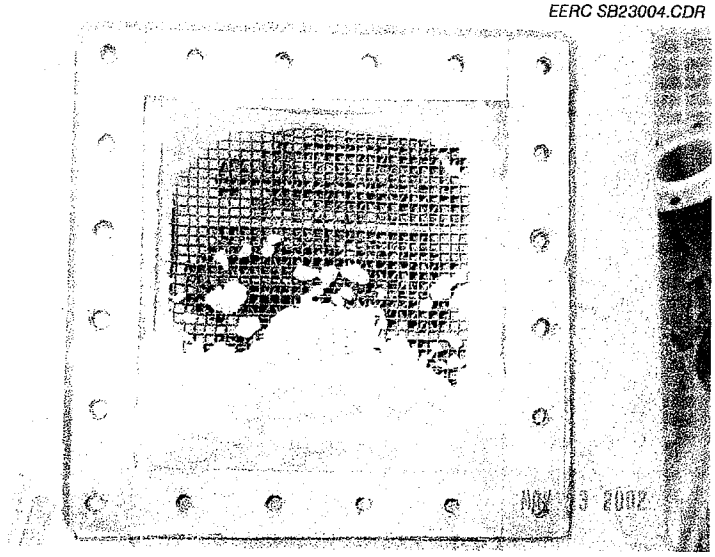
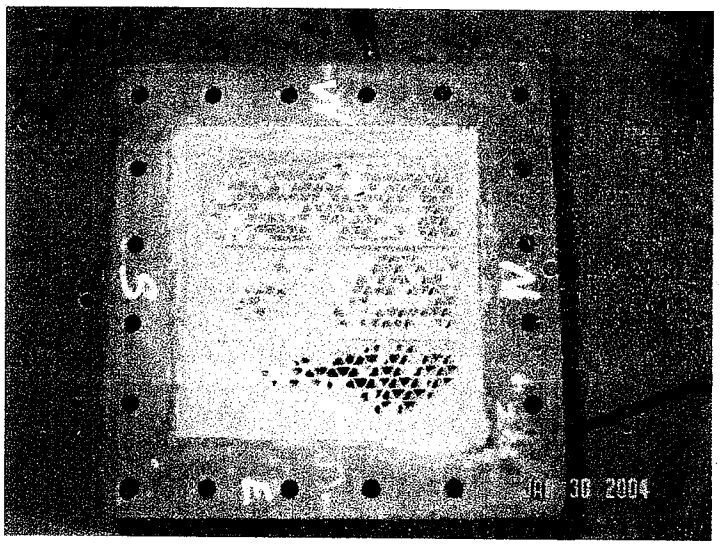
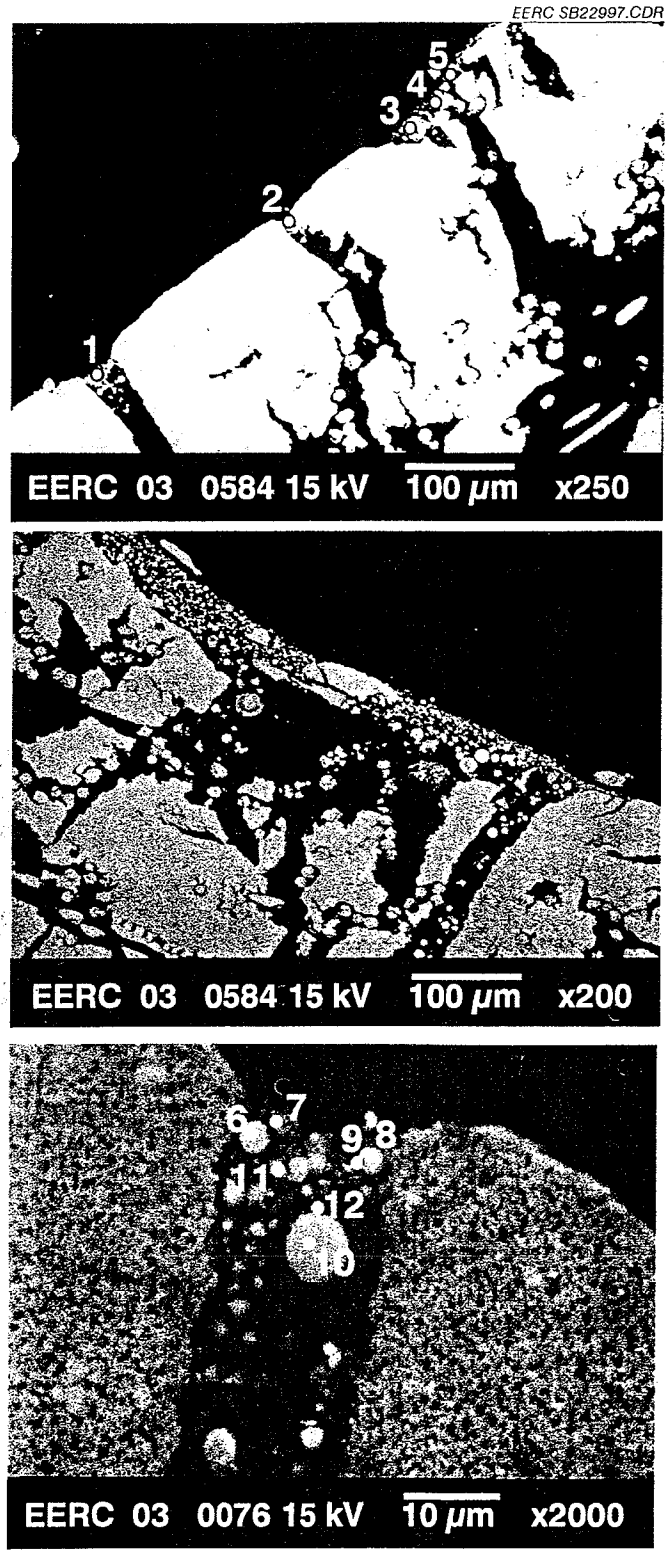


Baldwin Station after 4 months



Coyote Station after 4 months

Figure 14. Pictures of catalyst inlet after about 4 months of exposure to flue gas and particulate.



A

B

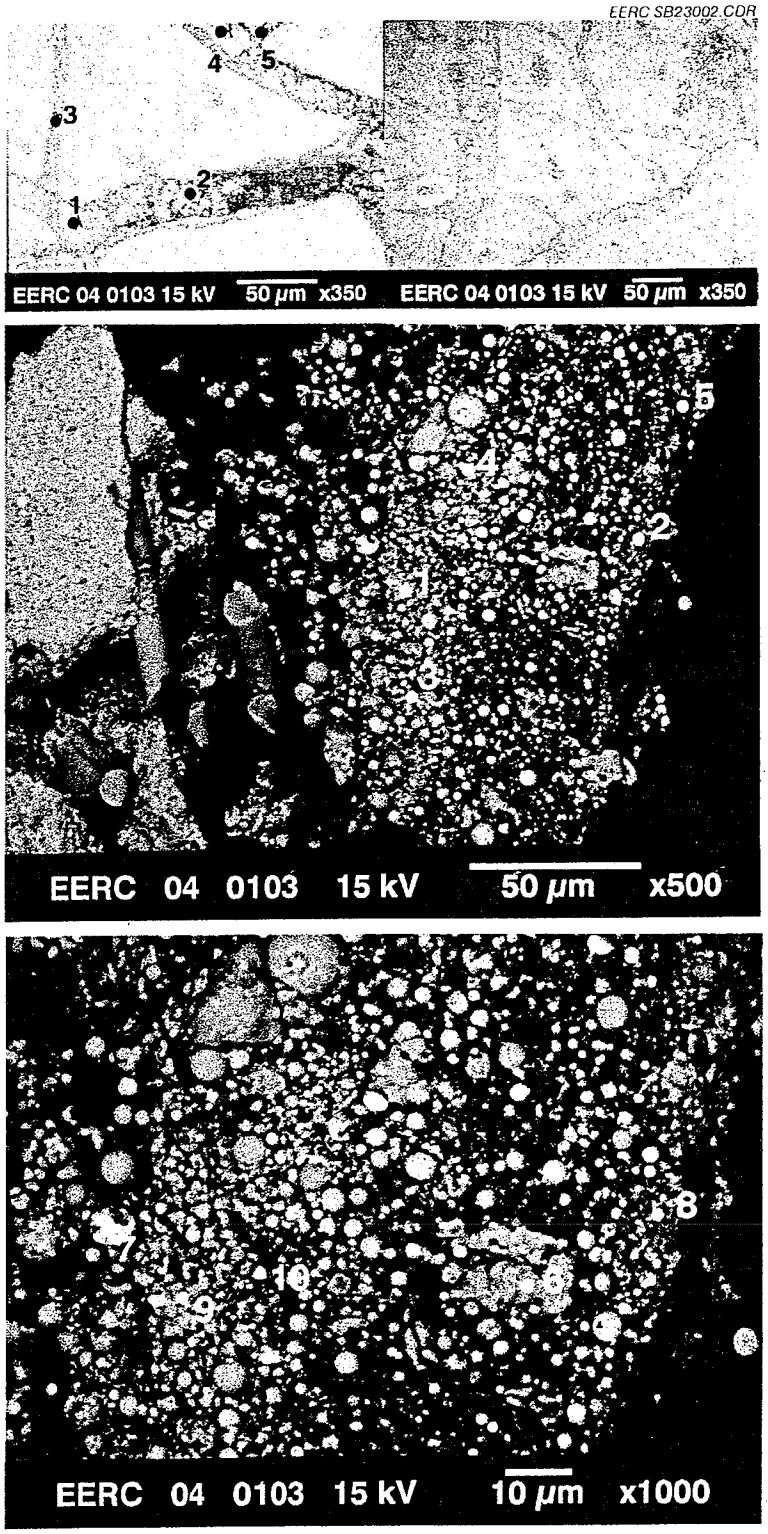
C

Figure 15. SEM images of ash collected on catalyst surface at the Baldwin Station after 6 months of exposure. A) and B) low-magnification images of ash deposit on catalyst surface

and C) high-magnification image of polished cross section showing particles in a matrix of calcium- and sulfur-rich materials.

Table 3. Chemical Composition of Selected Points and Areas in Figure 15

	Chemical composition (normalized wt% equivalent oxide)					
Oxide	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
1.1.1						
	0.6	1.0	2.1	0.3	0.5	2.7
Na_2O	4.3	2.5	6.3	0.7	1.6	7.6
MgO	14.8	16.0	15.6	15.5	14.7	0.9
Al_2O_3	3.3	7.8	18.8	57.7	7.7	47.3
SiO_2	2.3	2.1	0.5	0.6	1.8	0.0
P_2O_5	30.7	20.4	17.7	0.0	29.0	0.8
SO_3	0.7	0.0	1.0	0.4	0.9	0.9
K_2O	28.8	28.7	28.1	22.5	34.9	28.4
CaO	2.0	7.2	2.2	0.3	1.3	1.1
TiO_2	11.4	12.9	6.2	0.0	7.6	7.9
Fe_2O_3	1.1	1.4	1.4	2.0	0.0	2.5
BaO						
Total	100	100	100	100	100	100
Oxide	Point 7	Point 8	Point 9	Point 10	Point 11	Point 12
1.1.2						
	1.7	0.4	0.5	2.2	1.3	1.7
Na_2O	4.5	6.4	5.9	5.0	3.4	6.4
MgO	5.0	2.4	3.0	19.2	10.8	3.8
Al_2O_3	8.4	18.4	18.5	31.0	17.9	16.7
SiO_2	1.8	0.9	1.0	0.0	1.7	1.2
P_2O_5	37.9	1.7	5.3	0.0	22.5	13.9
SO_3	0.4	0.0	0.0	0.9	0.8	0.0
K_2O	31.4	52.6	49.0	28.9	30.6	45.4
CaO	1.9	6.9	7.4	2.4	2.0	1.1
TiO_2	7.1	5.7	6.0	6.3	6.1	6.5
Fe_2O_3	0.0	4.6	3.5	4.2	2.9	3.3
BaO						
Total	100	100	100	100	100	100



A

B

C

Figure 16. SEM images of ash collected on catalyst surface at the Coyote Station after 4 months of exposure. A) low-magnification image of ash deposit on catalyst surface, B) low-

magnification image of polished cross section showing particles in a matrix of calcium- and sulfur-rich materials, and C) higher-magnification image of bonding.

1.1.2.1 Table 4. Chemical Composition of Selected Points and Areas in Figure 16

	Chemical composition (normalized wt% equivalent oxide)				
Oxide	Point 1	Point 2	Point 3	Point 4	Point 5
1.1.3					
	6.7	1.9	7.1	6.2	3.1
Na_2O	1.1	1.7	1.1	2.6	3.2
MgO	2.6	8.8	4.0	4.8	10.5
Al_2O_3	7.0	21.1	11.3	5.6	32.2
SiO_2	0.2	2.4	0.0	0.2	0.9
P_2O_5	54.7	38.5	56.4	57.5	30.4
SO_3	2.0	2.8	0.7	2.8	2.4
K_2O	18.0	3.4	15.8	9.3	2.3
CaO	0.6	0.8	1.1	1.3	1.5
TiO_2	5.8	5.1	2.1	6.5	9.8
Fe_2O_3	1.4	13.5	0.5	3.4	3.6
BaO					
Total	100	100	100	100	100
Oxide	Point 6	Point 7	Point 8	Point 9	Point 10
1.1.4					
	9.5	2.6	10.4	8.9	4.4
Na_2O	1.2	1.9	1.3	3.0	3.7
MgO	2.6	8.6	4.2	4.9	10.6
Al_2O_3	6.3	18.2	10.5	5.0	28.9
SiO_2	0.1	1.9	0.0	0.1	0.7
P_2O_5	41.8	28.4	44.9	44.5	23.4
SO_3	3.2	4.3	1.2	4.4	3.8
K_2O	24.5	4.4	22.5	12.8	3.1
CaO	0.6	0.8	1.3	1.5	1.8
TiO_2	7.7	6.6	2.9	8.9	13.2
Fe_2O_3	2.4	22.3	0.9	5.9	6.3
BaO					
Total	100	100	100	100	100

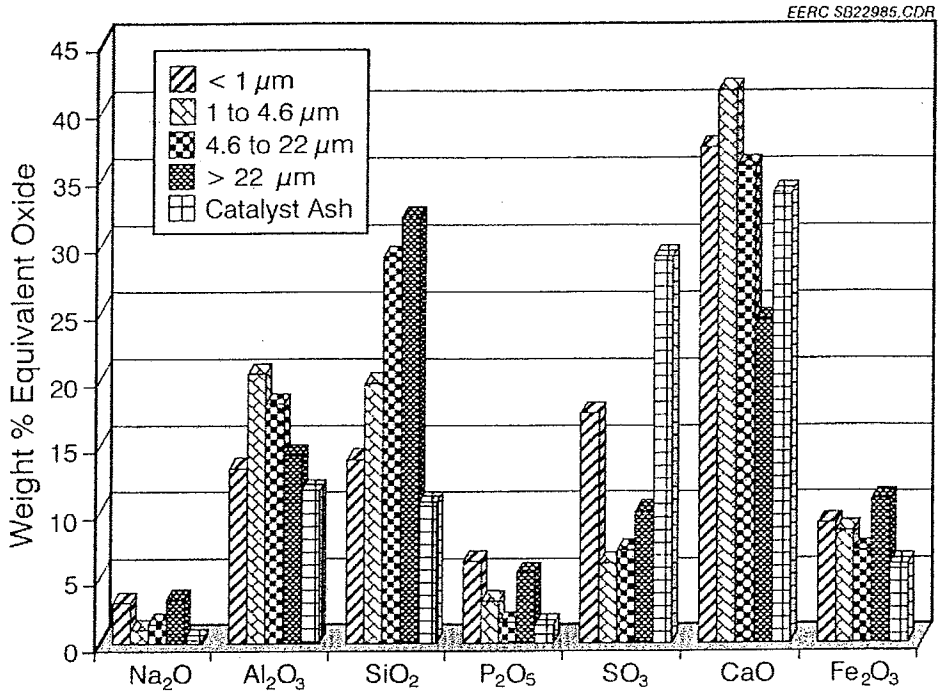


Figure 17. Comparison of entrained ash and deposited ash on catalyst for Columbia Station.

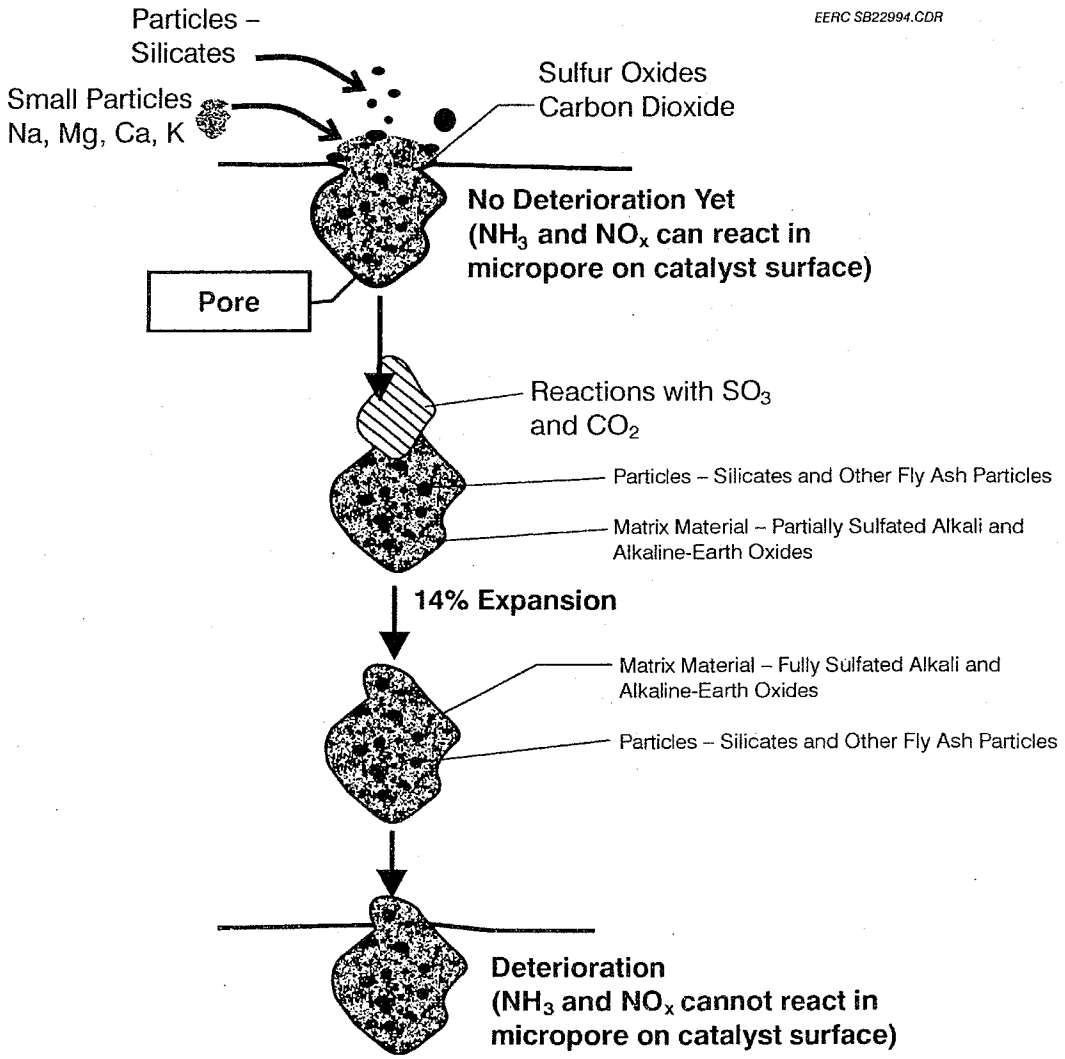


Figure 18. Mechanism of SCR catalyst blinding via the formation of sulfates and carbonates (modified after Pritchard and others [30]).

Low-Temperature Pyrosulfates

The presence of sodium sulfate in the flue gas exiting a scrubber will cause problems to low-dust and tail-end devices such as selective catalytic reduction (SCR) systems for NO_x reduction. There are two problems associated with the fine particulate rich in sodium sulfate on downstream devices. These include accumulation of fine particles on the SCR that, when sootblown, will cause opacity problems, and that the fine particles on the SCR will form pyrosulfates such as $(K_{1.5}Na_{0.5})S_2O_7$ that have melting points as low as 535°F (31) that will blind the catalyst. The presence of these compounds in low-temperature corrosion deposits is well known (32). In addition, the presence of SO_3 enhances the formation of the low-melting-point pyrosulfates (31). The sodium sulfate materials will cause opacity and SCR catalyst

blinding problems that limit the feasibility of the low-dust or tail-end SCR technology for use with high-sodium lignite coals.

The sodium sulfate materials will be transported to the catalyst surfaces by diffusion, electrophoresis, and, possibly, inertial impaction. The particles are held in place by weak electrostatic and van der Waals forces. Once accumulation takes place, the sodium sulfate particles will react with flue gas components, resulting in the formation of pyrosulfates. The formation of pyrosulfates involves the following processes (31):

1. Formation of sulfates such as Na_2SO_4 and K_2SO_4

2. Conversion of SO_2 to SO_3 in the bulk gas phase – catalytically active surface such as an SCR catalyst – $SO_2 + \frac{1}{2} O_2 \rightarrow SO_3$

3. Pyrosulfate formation – $Na_2SO_4 + SO_3 \rightarrow Na_2S_2O_7$

The melting points of selected pyrosulfate phases are shown in Table 5.

Table 5. Melting Points of Selected Pyrosulfate Compounds

Compound	Temperature, °C	Temperature, °F
$K_3Fe(SO_4)_3$	618	1144
$K_3Al(SO_4)_3$	654	1209
$KFe(SO_4)_2$	694	1281
$Na_3Fe(SO_4)_3$	624	1155
$Na_3Al(SO_4)_3$	646	1195
$NaFe(SO_4)_2$	690	1274
$Na_2S_2O_7$	401	754
$K_2S_2O_7$	300	572
$(K_{1.5}Na_{0.5})S_2O_7$	279	535

Melting points for pyrosulfates between 535° and 770°F have been reported in the literature. Much of the past work has focused on the formation of these phases on tube surfaces. These species contribute to the corrosion of heat-transfer surfaces in coal-fired power plants. The exact melting point depends on the relative amounts of sodium and/or potassium.

There is significant evidence for the formation of sodium-rich fine particulate in full-scale power plants when firing high-sodium-containing coals. For example, Minnesota Power's Boswell Energy Station found that when it fired high-sodium, lower-ash subbituminous coal, it experienced increases in opacity. Hurley and Katrinak (33) conducted a field-testing project on Unit No. 4, a pulverized coal-fired boiler equipped with an electrostatic precipitator and a wet scrubber, to better understand the reasons for the opacity problems. During the field testing, sampling of the coals, flue gases, and scrubber materials was conducted. The particulate in flue gases downstream of the scrubber was aerodynamically classified using an impactor and

multicyclone. The sized fractions were analyzed to determine the composition of the submicron-sized fraction.

The results of the study indicated that the particulate collected downstream of the scrubber was coal-related and caused by the high sodium content of one of the coals. Vapor-phase sodium condenses in the convective pass to form fine sodium sulfate particles or other Na species that later react with ash particles. Pure Na_2SO_4 particles are too small to be removed by scrubbing.

CONCLUSION: SCR IS NOT FEASIBLE FOR NO_X REDUCTION AT MILTON R. YOUNG

The ash deposition behavior of the lignites from North Dakota is the most complex and severe of any coals in the world, and installation of catalysts for NO_x reduction is going to be impossible because of the formation of sodium calcium sulfates in the pores of the catalyst. Following is a list of the key roadblocks associated with lignites which have not been overcome and, in our opinion, make the installation of SCR catalyst at the MRY plant technically infeasible for NO_x control.

- High alkali and alkaline-earth elements present in the coal fired at the MRY plant form sulfates that blind the catalyst.
    - Cyclone-firing partitions the ash during combustion. As a result the level of sodium and calcium in the fly ash is enhanced and will increase the SCR catalyst blinding.
    - Sulfate reactions increase with increasing temperature, and the suggested temperature of installation at the MRY facility is higher than typical installations; therefore, sulfation problems are enhanced.
    - Sulfate formation is also enhanced by the presence of an SCR catalyst; this accelerates the sulfation reactions, causing blinding of the catalyst.
    - The high levels of sodium in the coals combined with calcium produces low-melting-point eutectic compounds that will melt on the surface.
    - Sulfates form on the surfaces of catalysts firing PRB coals. Lignites will be several orders of magnitude worse because of the higher levels of sodium.

- The ash components to impact SCR performance in Japan and Europe (14–16) include alkali and alkaline-earth elements that result in sulfate formation. The total calcium content and the sum of the calcium, magnesium, potassium, and sodium provide an indication of the problems that occur. For the coals fired at the MRY power plant, the CaO content ranges from 6.8%–19.99%, and the sum of the alkali and alkaline-earth elements range from 9.33%–29.87% of the ash. The levels of calcium in Center lignite are 2 to 4 times higher than the problematic coals in Japan and Europe.

- The finding or work conducted in Germany and Japan were confirmed by recent SCR catalyst slipstream testing that showed significant evidence of sodium and calcium-

rich sulfate formation that fill and plug the catalyst at both lignite (North Dakota)- and subbituminous-coal-fired power plants. The results of this recent testing showed that the presence of sodium significantly enhanced the formation of bonding of particles and more rapid sulfation, filling of pores, and rapid increase in pressure drop across the catalyst.

- Deposit carryover, or popcorn ash, plugging the top of the SCR catalyst with deposit fragments, is a significant problem because of the extremely high deposition potential of the coal. The formation of deposits in various parts of the boiler requires continuous sootblowing. The deposit fragments are likely going to be carried with the bulk gas flow to the SCR catalyst, resulting in plugging.

- The variability of the lignite is a problem of unique concern at MRY. The deposition potential of the coal is always changing rapidly, resulting in rapid growth and formation of deposits in various sections of the boiler. Aggressive sootblowing of all fireside surfaces is already required to maintain full-load operation. The sootblowing of upstream heat exchange equipment will cause deposit fragments to be carried back to the SCR catalyst, and during sootblowing of the SCR catalyst, the entrainment of deposit fragments along with the sootblowing media will result in significant erosion of the catalyst surfaces.

The ash-related impacts of the lignites from North Dakota are the most complex and severe of any coals in the world, and installation of tail-end SCR systems for NO_x reduction will not be possible. The key problems associated with lignites that have not been overcome and, in our opinion, make the installation of tail-end SCR systems at the MRY plant technically infeasible for NO_x control at MRY's Units 1 and 2 are listed below:

X High-sodium lignite coal from the Center Mine Hagel A and B seam coal produces extreme levels of homogeneously condensed sodium sulfate that pass through the wet scrubber. In addition, the cyclone-firing system captures much of the ash as slag, resulting in a decrease in ash that is available for providing condensation sites for vapor-phase sodium compounds upon gas cooling. This results in an increased homogeneous condensation of sodium sulfate.

X These small particles pass through a wet scrubber and will accumulate on surfaces of tail-end SCR systems. The accumulated materials cannot feasibly be resolved through conventional sootblowing and cleaning technologies to remove the particulate.

X Recent testing with subbituminous and lignitic coals indicated a significantly higher level of pore filling and plugging in the catalyst exposed to lignite ash as compare to subbituminous coal ash. The catalyst pores as well as the catalyst surface in the lignite tests were completely coated with a sodium calcium sulfate material, while only pore filling was found in the subbituminous coal testing. The pressure drop across the catalyst exhibited for lignite was 4 to 5 times greater than that found for a catalyst exposed to subbituminous coal ash. The plugging occurred over a 1000 hour test period.

The formation of liquid pyrosulfate materials at temperatures as low as 535°F from sodium sulfate materials occurs in coal-fired power systems and is well documented. Pyrosulfates will form and cause blinding of tail-end SCR devices. In addition, SCR systems catalyze the formation of SO_3 from SO_2. The presence of SO_3 significantly enhances the formation of the pyrosulfates at MRY to an extreme level that cannot be dealt with effectively using cleaning technologies that exist today.

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APPENDIX C

COST METHODOLOGY

CAPITAL COST ESTIMATE DETAILS FOR NO_X CONTROLS

O&M COST ESTIMATE DETAILS FOR NO_X CONTROLS

C.1 METHODOLOGY FOR ESTIMATED COSTS

The summary economic evaluations of each alternative are presented in the cost impact sections of the main report. Capital and O&M cost estimates for each alternative are presented individually. The Levelized Total Annual Cost (LTAC) for all the alternatives for control of a single pollutant (i.e. NO_X) from a single unit is then presented together with Unit Control Costs. The Levelized Total Annual Cost (LTAC) represents the levelized annual cost of procurement, construction and operation over a 20 year design life, again in current (2006) dollars. As a minimum, the design life for any alternative was taken to be that recommended by "The EPA Air Pollution Control Cost Manual", Sixth Edition, January 2002, EPA/452/B-02-001[i].

The LTAC is also used to calculate the average annual and incremental cost effectiveness of each alternative. The LTAC represents an annual payment in current day dollars sufficient to finance the project over its entire life.

In determining the LTAC a Capital Recovery Factor and an O&M Levelization Factor were calculated from the project economic conditions and then applied separately to the estimated capital and O&M costs. The equation used is shown below.

$$LACC / NPV = \left(\frac{i(1+i)^n}{(1+i)^n - 1} \right) = CRF$$

Where,
LACC = Levelized Annual Capital Cost
NPV = Net Present Value of the capital investments required.
i = discount rate
n = design life in years
CRF = Capital Recovery Factor

Therefore:

$$LACC = CRF \times NPV$$

For the economic conditions described in Table C.1-1 the Capital Recovery Factor was calculated to be 0.08718.

In determining the levelized annual O&M cost the estimated annual O&M cost, the inflation rate, the discount rate, and the equipment life are taken into account. The O&M Levelization Factor (OMLF) was calculated as follows.

$$LAOMC / A_1 = \left(\frac{1+i_d}{1+i_i} - 1\right)\left(\frac{i_d(1+i_d)^n}{(1+i_d)^n - 1}\right) = OMLF$$

Where,
A = Levelized Annual O&M Cost (LAOMC)
A_1 = Total annual O&M cost in current dollars
i_d = discount rate
i_i = inflation rate
n = design life in years

Therefore:

$$LAOMC = OMLF \times A_1$$

For the economic conditions described in Table C.1-1 the Operating and Maintenance Levelization Factor was calculated to be 1.24873.

The Levelized Total Annual Cost, or LTAC is the sum of the levelized capital cost and the levelized O&M cost. Therefore:

$$LTAC = LACC + LAOMC = (CRF \times P) + (OMLF \times A_1) = 0.08718 \times P + 1.24873 \times A_1$$

The differences between alternatives are also presented graphically in the form of a plot of the annual emissions reduction (tpy) versus the LTAC for each alternative. This form of plot graphically depicts the cost effectiveness or Unit Control Cost (in $/ton of pollutant reduction) of each alternative relative to all of the others. The cost effectiveness is also referred to as the Unit Control Cost and defined as the LTAC divided by the annual emissions reduction (ton/yr). The area on the plot indicated by the various data points represents the cost effectiveness envelope for the alternatives under consideration. A smooth line is drawn on this plot connecting the rightmost points (those with the lowest cost for a given level of emissions reduction). This line is referred to as the Dominant Control Curve (DCC). The DCC defines the right hand boundary of the envelope encompassing all of the alternatives considered. The DCC is used as a screening tool between considered alternatives. Those alternatives whose plotted position is above and/or to the left of the DCC are not as cost effective as those forming the line and thus can be eliminated from further analysis if desired.

In order to compare various pollutant control alternatives, the Unit Control Cost and the incremental Unit Control Cost of each alternative were also calculated and tabulated for comparison purposes. The Unit

Control Cost compares control technologies on a basis of dollars expended per ton of pollutant reduced ($/ton). This relationship is graphically depicted in the DCC chart.

To more accurately compare between alternatives with different costs and control efficiencies, the incremental cost effectiveness is also determined for those alternatives on the DCC. The incremental cost effectiveness is defined as the LTAC of a given control option minus the LTAC of an alternative, divided by the difference between the annual emissions reduction (tpy) of the given control option and the alternative being evaluated. The combination of these two economic analyses can be used as an argument for the elimination of control technologies with significantly greater marginal control costs than the given case. The equation used for the incremental cost effectiveness is shown below.

$$ICF = \frac{(LTAC_1 - LTAC_2)}{(AE_1 - AE_2)}$$

Where,

ICF = Incremental cost effectiveness ($/incremental ton removed)
$LTAC_1$ = Levelized Total Annual Cost of control alternative No. 1 ($/yr)
$LTAC_2$ = Levelized Total Annual Cost of control alternative No. 2 ($/yr)
AE_1 = Control option No. 1 Annual Emissions Reduction (ton/yr)
AE_2 = Control option No. 2 Annual Emissions Reduction (ton/yr)
(The higher cost, more effective control option is subscript 1 in this equation.)

The economic analyses presented in this report not only include the estimated capital and O&M costs for each alternative, but also the LTAC for economic comparison of the various alternatives. In addition, the Unit Control Cost or cost effectiveness is presented for each alternative. Finally, a comparison between alternatives, in the form of the marginal cost effectiveness, is presented in both numerical and graphical form. Thus a comprehensive comparison of the economic impacts of each alternative, as well as the differences in economic impact between alternatives is clearly presented.

Table C.1-1 – Economic Factors(1),(2)

Total Possible Operating Hours per Year	8,760
Amortization Life, Years	20
Cost of Money	6%
Property Taxes, Insurance, %	NA
Conversion Tax (in lieu of property tax)	NA
Amortization Rate for APC Capital Costs	6%
Interest During Construction (IDC)	6%
Discount Rate (used to calculate NPV)	6%
Construction Cost Escalation	3%
Non-Fuel O&M Escalation	2.5%
Fuel (coal and natural gas) Escalation	2.5%
Auxiliary Electric Power Cost, $/MW-hr	$35.00
Urea Cost, ($/ton delivered, 50% aqueous solution)	$380.00
Natural Gas ($/mmBtu)	$7.98

(1) - All financial percentages and unit auxiliary electric power cost were provided by MPC.
(2) - All costs are in 2006 dollars unless noted otherwise.

C.2 NOx CONTROLS - CAPITAL COST ESTIMATES

The capital costs to implement the various NO_X control technologies were largely estimated from unit output capital cost factors ($/kW) published in technical papers discussing those control technologies. In the cases of SNCR and FLGR, preliminary vendor budgetary cost information was obtained and used in place of, or to adjust, the published unit output cost factors. These cost estimates were considered to be study grade, which is + or – 30% accuracy, or better.

The limitations of these capital cost estimates developed from unit capital cost factors multiplied by unit output are:

- Scope basis uncertainty – inability to precisely determine what scope of supply, including such things as balance-of-plant (BOP) systems and equipment improvements were required, assumed, or accounted for when developing the unit cost factors. Some alternatives may have higher indirect or BOP capital costs than others. Similarly, the inclusion of general facilities, preproduction and inventory costs, and other indirect costs is not known. It is likely that the utility owner's final total expenditure for the implementation of the alternatives, especially options that are most capital cost-intensive, will be greater than the calculated cost estimates.
- Location-specific influences – most NO_X control techniques have been applied primarily to eastern bituminous coal-fired plants located near large metropolitan areas, not in largely rural, upper midwestern United States locales. The amount of space available is dependent on the existing powerplant equipment and building layout and property plot area, versus what is expected to be required for implementing various control technologies. Transportation and local/regional labor costs are also variables.
- Size influences – some technologies' capital costs are more sensitive to "economies of scale" than others.
- Capacity margins – some technologies' may require higher capacity margins to allow sustained operation at high throughput rates over extended periods of time.
- Reliability concerns – some technologies' have been refined to a higher degree, and others may require more component redundancy than others in order to avoid performance reductions and potential outages for failures and repairs or replacements.
- Inflationary influences – the significant increases in 2004-2005 for raw material costs, especially steel and alloys for fabrication of structural and mechanical components, has occurred after many of these technologies were installed in projects upon which the referenced unit capital cost factors were based.

- Market conditions – as demand increases for emission controls, some alternatives become more cost-competitive, while others do not. This can be influenced by the relative supply and demand for the technology and number of suppliers who can furnish it. The demand for some alternatives can also be strongly influenced by the stringency of the local, state, and national regulatory requirements. Schedule for implementation and availability of local/regional labor for installation contractors are also market-driven factors.

The estimated NO_X control costs are in addition to capital costs to provide normal replacements of the existing Milton R. Young Station's major power generating equipment.

C.2.1 Separated Overfire Air Capital Cost Estimates

Installation of separated overfire air systems typically includes windbox and/or secondary combustion air supply duct modifications, boiler waterwall tube openings, airflow distribution devices (dampers/registers), airflow controls and measurement instrumentation, and related structural and electrical tie-ins to the existing plant facilities. A basic separated overfire air retrofit system installed on a lignite-fired cyclone boiler includes ports across the front and rear walls of the upper furnace. The unit capital cost factor is expected to be above the high end of the typical published cost range of $5-10/kW[ii] ($12.0/kW or $3,080,000[iii] for MRYS Unit 1), due to the large ducts, relatively tall furnace (compared to typical bituminous coal-fired cyclone boilers), and the need to avoid existing obstructions within the boiler house.

An advanced form of SOFA unique to North Dakota lignite-fired boilers will include relocation of the existing lignite drying system vent port openings from the lower primary furnace to the upper furnace, to be placed at the same elevation as the new SOFA ports. This requires extension of the existing cyclones' lignite drying systems' vent piping to supply the new boiler furnace ports. This is expected to cost in the area of +$4.7/kW or approximately $1,200,000 for Unit 1's additional capital cost over and above the basic SOFA system. Overall, the advanced version of separated overfire air technology is estimated to have an installed capital cost of approximately $16.6/kW ($4.3Million) for MRYS Unit 1.

C.2.2 Reburn Capital Cost Estimates

C.2.2.1 Coal Reburn Capital Cost Estimates

There is one alternative that includes a new coal reburn system. Capital cost estimates for coal reburn systems are highly dependent on the requirements for reburn fuel preparation and feeding to the boiler. For the purposes of this analysis, the application of a pulverized coal reburn system assumed the need to make extensive additions to the existing fuel preparation equipment in the existing plant facilities and feeding to new furnace injectors. At least two new fine-grind pulverizers, or MPS-89 standard pulverizers followed by dynamic classifiers are expected to supply the amount of finely ground reburn coal for this method.

Addition of new electrical loads for the pulverized coal preparation equipment to the existing plant facilities will be required. For the purposes of this preliminary study, it is assumed that additional plant auxiliary electrical power will be available for powering the new pulverizers/micro-mills and related new coal reburn equipment, but this has not been confirmed.

The existing crusher bays do not have floor space available to allow the new milling equipment for reburn fuel preparation to be located adjacent to the existing coal crushers. This will require a separate building or addition to the existing powerhouse to be built to provide sufficient space to enclose the new milling and coal silo/handling equipment. Separate modified pulverized coal-style burners or coal injectors will be installed through new openings in the upper furnace front and rear waterwalls at or above the elevation of the existing lignite drying system vent ports, along with new overfire air ports located at a higher elevation, above the reburn fuel injectors. This would have the capacity to supply approximately up to thirty percent of the total full load fuel heat input to the boiler through the coal reburn injectors. This coal reburn system design was not expected to change the existing cyclone silo/feeder arrangement, such that all cyclones would remain operational. To achieve maximum NO_X emission control, only the advanced form of SOFA for pulverized coal reburn was included. Confirmation of these concepts and cost estimates requires more detailed equipment design and plant layout than has been performed for the purposes of this BACT analysis.

The installed capital cost of pulverized coal reburn for the cyclone boilers at Milton R. Young Station used in this cost effectiveness analysis was estimated based upon a Clean Air Markets Division [CAMD] of the US EPA dollar per kilowatt unit capital cost factor for cyclones. The installed capital cost estimate of $21,900,000 for MRY Station Unit 1's pulverized coal reburn alternative used in this cost effectiveness analysis was estimated based upon applying a 3.5% assumed inflation cost adjustment to the CAMD unit

capital cost factor for cyclones of $82.33/kW (x 1.035 = $85.2/kW) included in a WRAP (Western Regional Air Partnership) draft report[iv] published on their website, dated April 26, 2005. The cost to relocate the lignite drying system vent ports (+$4.7/kW) was added to the inflation-adjusted CAMD number ($85.2 + $4.7/kW = $89.9/kW), since coal reburn is expected to include separated overfire air but not the extra costs for the special improvements identified for air-staged lignite-firing in cyclone boilers. This increased the installed capital cost by $1,200,000 for MRY Station Unit 1's coal reburn system to a total of $23,561,000. This does not include the additional particulate matter collection capacity considered necessary to limit the expected negative impact on opacity from this option.

To control particulate matter (PM) emissions that would be expected to increase from installation and operation of pulverized or micronized coal reburn, additional PM collection capacity will be required. A hybrid form of PM collection that supplements the existing electrostatic precipitator's performance, referred to as COHPAC (COmpact Hybrid PArticulate Collector). This was estimated in 2002 dollars at $20,191,000 for MRY Station Unit 1's COHPAC[3]. Adjusted by an escalation factor of 1.2623, the installed capital cost of the COHPAC addition was estimated to be $23,561,000 for MRY Station Unit 1 in 2006 dollars. When the COHPAC addition was combined with the Lignite Reburn and ASOFA alternatives, the resulting total estimated capital costs were $46,656,000 for MRYS Unit 1 ($89.9 + $91.7 = $181.5 /kW).

C.2.2.1 Gas Reburn Capital Cost Estimates

Conventional gas reburn options assume that seventeen percent of the total fuel heat input to the boiler is through the new gas reburn injectors to be located in the lower secondary furnace above the top rows of cyclones. Eight to twelve gas reburn injectors would be expected to be required in this case. Seven percent of the total fuel heat input to the boiler through the gas reburn injectors is assumed to be supplied for the fuel lean gas reburn alternatives. Four to eight gas reburn injectors could be assumed in FLGR™ cases. Gas reburn options assume that a new high-pressure gas pipeline would be brought from near Bismarck, ND approximately twenty six miles. The pipeline diameter is proportional to the amount of fuel required for the specific alternative, ranging from 24 inches for conventional gas reburn to 12 inches for fuel lean gas reburn cases. A station gas main, with new gas trains, consisting of valves, metering, and safety shutoff valves for the front and rear boiler for the gas injectors' supply, would be furnished and installed.

The capital costs for conventional gas reburn alternatives were estimated considering unit capital costs published in published technical literature. One vendor that has supplied numerous domestic utility boiler gas reburn systems (GE Energy, formerly GE-EER) published $10/kW for gas reburn in a 2001 technical paper[v]. Another source published a 2005 technical paper[vi] that provided a unit capital cost range for gas reburn of $15/kW to $30/kW. Neither source included a detailed scope description nor cost breakdown for engineering, equipment, materials, and labor to install a gas reburn system.

Site-specific needs and challenges identified for applying conventional gas reburn to Milton R. Young Station, and lack of detailed gas reburn project scope and equipment descriptions available in published technical literature leads to a much greater degree of uncertainty with regards to an accurate capital cost estimate for this alternative. For the purposes of this study, the estimated installed capital cost for a conventional gas reburn system with advanced SOFA on MRYS Unit 1 is expected to be approximately $9.9M ($38.6/kW), which is above the top end of the previously stated range, before adding the new underground gas pipeline capital costs. This study assumed an average unit capacity capital cost factor of $22/kW for conventional gas reburn, plus the additional costs for the advanced from of SOFA over basic SOFA (+$1.2M or +$4.6/kW) and the new high-pressure gas pipeline. This results in a an estimated installed capital cost for conventional gas reburn system with advanced SOFA on MRYS Unit 1 of $11.1M ($25.7/kW) plus the new high-pressure gas pipeline costs. Confirmation of these concepts and cost estimates requires more detailed equipment design and plant layout than has been performed for the purposes of this BACT analysis.

Fuel lean gas reburn (without SOFA) capital cost estimates were based upon a late 2004 budgetary proposal[vii] by a vendor (Fuel Tech) with experience in supplying FLGR™ equipment, typically combined with an SNCR system. Estimated capital costs of $3M include budgetary numbers for the equipment installation, including installation management, material and labor, with a –43% price adjustment assumed for 257 vs 450 MW for a fuel lean gas reburn system without SOFA on MRY Unit 1, not including the capital cost for the gas supply pipeline. Costs for work outside the vendor's scope, such as balance-of-plant additions plus other indirect costs were estimated to add approximately $0.5M (25% plus 10% contingency) to the adjusted vendor's estimated installed cost of $1.7M for their scope of supply. These adjustments result in a total installed capital cost for FLGR (without SOFA) estimated to be $2.2M plus the capital cost for the gas supply pipeline. Adding the incremental costs for the advanced from of SOFA over no SOFA (+$4.3M (+$16.6/kW) results in an estimated installed capital cost for a fuel gas reburn system with advanced SOFA on MRYS Unit 1 of $6.6M ($25.7/kW) plus the new high-pressure gas pipeline costs.

The capital cost estimates for the new high-pressure underground gas supply pipeline assumed $7 per inch of diameter per foot of length. This was calculated to be approximately $23M for conventional gas reburning and $11.5M for FLGR™. The cost analysis for each NO_X control alternative involving a particular form of gas reburn assumed that both boilers at Milton R. Young Station select the same alternative that burns natural gas. Therefore, the estimated capital costs for gas reburn alternatives reflect a capacity-based proportional share of the gas pipeline capital costs, avoiding double-counting. This results in an estimated installed capital cost for MRYS Unit 1's share of the gas pipeline to be $8.1M / for the conventional gas reburn alternative and $4M for fuel-lean gas reburn alternatives.

The total installed capital costs for conventional gas reburn (with ASOFA) with MRYS Unit 1's share of the total capital cost for the gas supply pipeline estimated to be $18M ($70.6/kW). The total installed capital costs for FLGR™ (with ASOFA) with MRYS Unit 1's share of the total capital cost for the gas supply pipeline were estimated to be $10.6M ($41.4/kW). Confirmation of these concepts and cost estimates requires more detailed equipment design and plant layout than has been performed for the purposes of this BACT analysis.

C.2.3 SNCR Capital Cost Estimate

The alternatives that include selective non-catalytic reduction systems assume the use of urea unless noted otherwise. The SNCR systems' preliminary design and estimated capital costs were based upon a 450 MW lignite-fired cyclone boiler in a late 2004 budgetary proposal[7] by a vendor (Fuel Tech) with experience in supplying SNCR equipment. Circulation, metering, dilution, control, and injection equipment is included. A 180,000 gallon field-erected stainless steel storage tank will hold the 50% urea solution (as delivered by truck). Individual and multiple nozzle lances with multiple levels of urea reagent injection will be designed and located to optimize distribution and accommodate various boiler load conditions. Estimated capital costs of $4.9 Million include budgetary numbers for equipment installation, including installation management, material and labor assumed for a SNCR system applied to a 450 MW boiler. Costs for work outside the vendor's scope, such as outdoor reagent storage tank and building enclosure/equipment foundations and containment, and balance-of-plant additions plus other indirect costs were estimated to add approximately $1.9 Million (25% plus 10% contingency) to the vendor's estimated installed cost for their scope of supply. This results in an estimated total capital cost for SNCR (without SOFA) of $6.8M for a 450 MW lignite-fired cyclone boiler.

Applying these adjustments to a 257 MW boiler, estimated direct capital costs of $2.800,000, plus $1,000,000 for indirect costs yields a total installed capital cost for applying SNCR to MRY Station Unit 1 of approximately $3,836,000 ($14.9/kW).

C2.5 Layered Technology Capital Cost Estimates

Capital costs were generally estimated based upon simple arithmetic addition of individual unit output capital cost factors for combinations of available NO_X reduction technologies, such as SNCR with ASOFA. An advanced form of separated overfire air system included the lignite-fired cyclone boiler equipment changes within the estimated unit capital cost factors.

Adding the advanced SOFA capital cost of $4.3 Million to the previous estimated installed capital cost of $3.8 Million yields a total estimated installed capital cost of $8.113 Million ($31.6/kW) for the SNCR with ASOFA alternative for MRYS Unit 1.

As previously discussed, Lignite (coal) reburn (CR) was assumed to be combined with advanced SOFA and a COHPAC addition considered necessary to limit the expected negative impact on opacity from this option. The installed capital cost of the COHPAC addition was estimated to be $23,561,000 for MRY Station Unit 1. When the COHPAC addition was combined with the Lignite Reburn and ASOFA alternatives, the resulting total estimated capital costs were $46,656,000 for MRYS Unit 1 ($89.9 + $91.7 = $181.5 /kW).

C.3 Operating and Maintenance Cost Estimates for MRY Station NO_X Control

An evaluation was performed to determine the estimated operating and maintenance cost impacts of installing and continuously operating various feasible NO_X control technologies on Milton R. Young Station Unit 1. These were estimated to be in addition to existing O&M costs to operate and maintain the MRY Station equipment.

The expected loss of electrical power sales from the operation of the specific NO_X control alternative was included as an annualized cost, assuming $35 per megawatt-hour. This was determined to include estimates for:

- Reduction in annual unit output due to an expected negative reliability (i.e. uptime availability) impact for each alternative. This generation reduction was calculated by multiplying the estimated additional numbers of outage hours per year by the average running plant capacity factor for that specific alternative, multiplied by the historic 12-month average unit gross electrical power output (MW_g) determined during the same period as the highest 12-month rolling summation NO_X pounds.
- Net additional auxiliary electric power demand for the added control equipment for each specific alternative based on assumptions for gross horsepower, plus additional power demand for existing fans caused by flue gas pressure drop (COHPAC for additional PM collection capacity), with adjustment for expected reductions in power demand (such as a decrease in existing coal crusher and feeder electric demand for the pulverized coal reburn case).
- The average running plant capacity factor for each alternative, which may also include an expected negative impact on the unit capacity from operation of the technology. This assumes that the control technique limits the gross electrical power output of the Unit (such as causing an increase in flue gas flow) such that the firing rate of the boiler cannot be maintained or raised to compensate for the load impact. Examples are lower boiler thermal efficiency (higher unit heat rate) when firing natural gas (due to higher moisture content of the flue gas).

For the SNCR alternative that involves a chemical reagent injected for NOx control, such as urea, the annual reagent consumption based on an assumed actual stoichiometric ratio (ASR) of moles of equivalent NH_3 injected per mole of uncontrolled NO_X emission estimated at the point of injection, converted to a mass rate (lbs/hr) by multiplying by the estimated annual number of hours of operation and the estimated NOx reduction fraction, and then multiplied by unit reagent cost (for a specific inlet NO_X concentration, emission reduction percentage and ammonia slip level).

General annual maintenance costs were assumed to be 1.5 percent of the estimated installed capital cost for each alternative, except for the coal conveying and grinding equipment portion of the coal reburn alternative, which was assumed to be 3 percent. The periodic bag replacement costs and other COHPAC system maintenance costs were estimated to be approximately 5.3% of the installed capital cost of the additional particulate matter collection equipment.

Additional operating labor costs directly attributable to each alternative were assumed to be zero for all alternatives.

Other operating costs include:

- Reagent dilution water for those alternatives that involve a chemical reagent injected for NOx control, typically four times the amount of urea consumption (assumes urea is a 50% solution as delivered and is injected as a 10% solution); this follows EPA OAQPS convention[1].
- Heat required for urea reagent storage, for those alternatives that involve a chemical reagent injected for NOx control; the source of heat is assumed to be auxiliary electrical power, but could be auxiliary steam (depending on heat source availability and plant preference).
- Additional coal consumption for those alternatives that involve a chemical reagent injected for NOx control to compensate for the heat of vaporization of the reagent dilution water; This follows EPA OAQPS convention[1], but is not accepted practice by an experienced SNCR vendor (Fuel Tech) who claims that the heat produced from the exothermic reaction of urea and NO_X is approximately equal to the heat required to evaporate the dilution water. For the purposes of this study, this additional coal consumption has been included in the annual O&M costs.

The sum of the estimated annual O&M costs was multiplied by the O&M levelization factor (1.24873) for each alternative to yield levelized total annual O&M costs.

C.3.1 Separated Overfire Air O&M Cost Estimate

Operation of SOFA is expected to add a small amount of O&M cost, primarily electricity consumed by the conventional SOFA damper electric drive actuator and airflow measuring system transmitter on each port. Using the existing forced draft, induced draft, and flue gas recirculation fans is not expected to change the overall amount of fan horsepower demand to be supplied by those fans' electric motors. Maintenance of the new overfire air ports and relocated lignite drying system vent ports is included,

assumed to be 1.5 percent of the installed capital cost. This is included in every control alternative's estimated O&M cost.

SOFA is not expected to significantly reduce unit reliability and availability to generate electrical power, assuming consistent combustion and continuous slag tapping under substoichiometric air/fuel operating conditions for MRYS boilers can be routinely established. A Unit availability reduction of 2.2% (188 hours per year), for M.R. Young Station Unit 1 was assumed, which allows for forced or extended scheduled boiler outages that may result from problematic cyclone slag tapping operational conditions encountered during substoichiometric cyclone operation with SOFA. The expected loss of electrical power sales from the reduction in annual electrical power output due to a decrease in expected Unit availability from ASOFA operation is included in every control alternative's estimated O&M cost.

Boiler furnace waterwall tube maintenance may increase slightly as a result of more fireside corrosion due to substoichiometric cyclone operation with SOFA. There may be some changes in the degradation rate of the boiler's furnace waterwall tubes resulting from exposure of more area of the furnace walls to slightly air-starved conditions during SOFA operation. Such conditions can promote corrosion from sulfur compounds in the furnace gases being created above the cyclones and below the SOFA injection ports. Due to the relatively moderate amounts of sulfur content in the lignite, modest amount of air-staging of the existing cyclones during SOFA operation, and the potential use of recirculated flue gas along the lower furnace walls, the expected change in corrosion rate of the boiler tubes should be minor. This degradation is expected to occur over many years of operation, and normally requires periodic replacement of the deteriorated sections of boiler furnace waterwall tubes to avoid forced outages to repair tube leaks or failed sections. The additional costs associated with potential change in the frequency of furnace wall tube failures and changeouts are difficult to estimate, and have not been quantified.

C.3.2 Reburn O&M Cost Estimates

The alternatives that include a new coal reburn system assume the use of new equipment for preparing the reburn fuel to replace 25% of the MRY Station Unit 1 boiler's total fuel heat input. Two additional lignite silos, with coal feeders and fine-grind pulverizers followed by dynamic classifier(s), are assumed to be located in a new separate building or powerhouse enclosure. Booster fan(s) addition was included because the existing forced draft fans were assumed to be incapable supplying the additional amount of primary air to the fine-grind pulverizers and dynamic classifier(s) for processing and conveying the reburn fuel. Using the existing forced draft, induced draft, and flue gas recirculation fans is not expected

to significantly change the overall amount of fan horsepower demand to be supplied by those fans' electric motors. The expected loss of electrical power sales from the additional auxiliary electric power demand for the reburn milling equipment from an estimated 0.6% (1.5 MW) reduction in net output was included as a cost, assuming $35 per megawatt-hour for MRY Station Unit 1. Electrical power consumed by the increased load on boiler fans to overcome the higher flue gas system pressure drop, plus the COHPAC particulate collection system support equipment was estimated to be a 1.2% (3.2 MW) reduction in net output for Unit 1.

Maintenance of the separate reburn coal injectors, fuel and primary air piping, and reburn fuel milling equipment is expected to be similar to the expenses associated with typical pulverized coal burners. The estimated additional annual maintenance costs for a new micronized coal reburn system was assumed to be 3.0 percent of the installed capital cost, or roughly $693,000 per year, for MRY Station Unit 1. The estimated additional annual maintenance costs (inflation adjusted from 2002 to 2006 $) for the COHPAC system was approximately $1,223,000 for MRYS Unit 1. Boiler furnace waterwall tube and superheater/reheater tube maintenance may increase slightly as a result of more erosion due to increased particulate emissions or fouling by flyash deposits resulting from coal reburn operation with ASOFA. The additional costs associated with potential change in the frequency of boiler tube failures and changeouts are difficult to estimate, and have not been quantified.

The estimated impacts on operation and maintenance costs for the coal reburn alternative that include a new pulverized or micronized coal reburn system are approximate. The seven (Unit 1) existing coal crushers for preparing the main (cyclone) fuel fraction will have slightly lower electrical demand. This was estimated as -0.26 MW (-0.1%) for MRYS Unit 1. Addition of new electrical loads for the micronized coal preparation equipment to the existing plant facilities will be required. For the purposes of this preliminary study, it is assumed that additional plant auxiliary electrical power will be available for powering the new pulverizers/classifiers and related new coal reburn equipment, but this has not been confirmed.

Coal Reburn with ASOFA is not expected to significantly reduce unit reliability and availability to generate electrical power, assuming consistent combustion and continuous slag tapping under substoichiometric air/fuel operating conditions for MRYS boilers can be routinely established. A Unit availability reduction of 3.7% (316 hrs/yr), for M.R. Young Station Unit 1 was assumed, which allows for forced or extended scheduled boiler outages that may result from problematic operational conditions encountered during coal reburn operation with ASOFA. This reduction in annual electrical power output

due to a decrease in expected Unit availability is included in the coal reburn control alternative's estimated O&M cost.

A Running Plant Capacity Factor reduction of 0.5% of annual gross electrical output was assumed for the coal reburn alternative. This would result in an estimated 1.2 MW average load decrease for M.R. Young Station Unit 1. This expected loss of electrical power sales from the reduction in net output due to this plant capacity impact was included in the estimated annual O&M costs.

Conventional and fuel-lean gas reburn options will involve higher operating costs compared with the existing operation of M.R. Young Station. Natural gas supply was assumed to be available near Bismarck, ND, but this has not been confirmed. The estimated unit cost of this natural gas was assumed to average $7.98/million Btu on a levelized annual cost basis, with a "credit" of $0.71 per mmBtu for avoided cost of consumption of lignite coal reduced by the natural gas heat input. The estimated annual cost of natural gas for the conventional gas reburning alternative applied to MRYS Unit 1 is approximately $29.7M per year. The estimated annual cost of natural gas for the FLGR™ alternative applied to MRYS Unit 1 is approximately $12.3M per year.

The new gas reburn injectors, station gas main and injector gas trains would add a minor amount of expense to current maintenance requirements, assumed to be 1.5 percent of the installed capital cost. Maintenance of separated overfire air nozzles is expected to be similar to the expenses associated with Unit 2's existing flue gas recirculation ports.

C.3.3 SNCR O&M Cost Estimate

The alternatives that include selective non-catalytic reduction systems will involve higher operating costs compared with the existing operation of MRY Station Unit 1. Urea reagent supply was confirmed to be available regionally. The estimated unit cost of this 50% aqueous urea solution was assumed to average approximately $379/ton delivered (2006$). Consumption of urea reagent for SNCR with ASOFA was based upon preliminary numbers allowing for a boiler flue gas exit ammonia slip of 5 ppmvd. These were estimated as approximately 200 gph for SNCR when applied to MRY Station Unit 1 with ASOFA.

New electrical loads are required for high flow urea circulation, in-line and storage tank heating, water dilution, and reagent metering equipment. These auxiliary electrical demands and reagent dilution water usage were calculated based upon equations published in EPA Office of Air Quality Planning and

Standards (OAQPS) publication EPA/452/B-02-001, Section 4.2, NOx Controls – NOx Post-Combustion, Chapter 1 - Selective Non-Catalytic Oxidation[1]. Compressed air for reagent atomization and lance purging and cooling, as well as multiple nozzle lance water cooling are additional demands on the existing plant facilities. These powerhouse building service supplies were assumed to be available, but this has not been confirmed. The new urea reagent injection nozzle lances, reagent pumps, dilution water pumps, and distribution piping/valve trains would add a minor amount of expense to current maintenance requirements, assumed to be 1.5 percent of the installed capital cost.

SNCR with ASOFA is not expected to significantly reduce unit reliability and availability to generate electrical power, assuming urea injection does not impact the ability to maintain consistent combustion and continuous slag tapping under substoichiometric air/fuel operating conditions for MRYS boilers. A Unit availability reduction of 3.2% (273 hrs/yr), for M.R. Young Station Unit 1 was assumed, which allows for forced or extended scheduled boiler outages that may result from problematic operational conditions encountered during SNCR-related operation with ASOFA. This reduction in annual electrical power output due to a decrease in expected Unit availability is included in the these control alternatives' estimated O&M costs.

A Running Plant Capacity Factor reduction of 0.15% of annual gross electrical output was assumed for the SNCR with ASOFA alternative. This would result in an estimated 0.37 MW average load decrease for M.R. Young Station Unit 1. This expected loss of electrical power sales from the reduction in net output due to this plant capacity impact was included in the estimated annual O&M costs.

C.3.4 Layered Technology O&M Cost Estimates

Operating and maintenance costs for combinations of available NO_X reduction technologies were estimated based upon simple arithmetic addition of individual cost estimates. SNCR was combined with advanced SOFA, as previously shown. Pulverized coal reburn was assumed to be combined with advanced SOFA (and a COHPAC addition for PM control). The auxiliary electrical demands and reagent dilution water usage for SNCR with ASOFA were calculated based upon equations published in EPA Office of Air Quality Planning and Standards (OAQPS) publication EPA/452/B-02-001, Section 4.2, NOx Controls – NOx Post-Combustion, Chapter 1 - Selective Non-Catalytic Oxidation[1].

C.3.5 Summary of O&M Costs Estimates for MRY Station NOx Control

The results of this evaluation for estimated variable operating and maintenance costs for the individual NOx control alternatives are summarized in this section. The expected reductions in Unit availability (uptime) and capacity are included in Tables C.3-1 through C.3-4 for MRYS Unit 1. Tables C.3-5 and C.3-6 for MRYS Unit 1 include the estimated urea reagent and dilution water usage rates and costs for the alternatives that involve SNCR with ASOFA NO_X control technologies.

TABLE C.3-1 – Expected Availability Reductions for MRY Unit 1 NO_X Controls

Alt.[1]	NOx Control Technique	Estimated Annual Average Unit Operating Time			
		Unit Availability[2]	Unit Operating Time[3], hrs/yr	Unit Outage Time[4], hrs/yr	Unit Operating Time Reduction[5], hrs/yr
E	SNCR w/ ASOFA	0.942	8255	505	273
D	Gas Reburn w/ ASOFA	0.952	8340	420	188
C	Coal Reburn w/ ASOFA	0.937	8212	548	316
B	FLGR w/ ASOFA	0.952	8340	420	188
A	Advanced SOFA (ASOFA)	0.952	8340	420	188
	Baseline	0.973	8528	232	0

1 – Alternative number has been previously assigned from least removal to highest removal percentage.
2 – 12-month baseline availability is assumed at 97.3 percent. These values reflect estimated amounts of negative reliability impact expected from the implementation of the individual NOx control technique.
3 – Annual operating time is annual average availability multiplied by 8760 hrs/yr of possible uptime.
4 – Annual outage time is 8760 hrs/yr possible operating time minus estimated annual operating time.
5 – Annual operating time reduction resulting from the implementation of the individual NOx control technique is the difference between the baseline and expected annual outage times.

TABLE C.3-2 – Expected Capacity Reductions for MRY Unit 1 NO_X Controls

Alt. Label(1)	NOx Control Technique	Estimated Annual Average Unit Electrical Power Generation Reduction from Operating Time Reduction		
		Unit Running Plant Capacity Factor(2)	Unit Generation Reduction(3) kW-hrs/yr	Unit Generation Reduction Cost(4), 1000$/yr
E	SNCR w/ ASOFA	0.965	67,660,606	2,368
D	Gas Reburn w/ ASOFA	0.957	46,120,681	1,614
C	Coal Reburn w/ ASOFA	0.961	77,958,350	2,729
B	FLGR w/ ASOFA	0.962	46,400,200	1,624
A	Advanced SOFA (ASOFA)	0.966	46,586,546	1,631
	Baseline	0.966	0	0

(1) – Alternative designation has been previously assigned from least removal to highest removal percentage.
(2) – 12-month baseline running plant capacity factor is assumed at 96.6 percent. These values reflect estimated amounts of negative reliability impact expected from the implementation of the individual NOx control technique.
(3) – Annual electricity generation reduction is annual operating time reduction multiplied by the annual running plant capacity factor resulting from the implementation of the individual NOx control technique multiplied by the 12-month average gross output of 244.4 MW.
(4) – Annual electricity generation reduction cost is the annual electricity generation reduction (kW-hrs/yr) resulting from the implementation of the individual NOx control technique multiplied by the incremental value of electricity generation, assumed to be $35.00/MW-hr. All cost figures in 2006 dollars.

TABLE C.3-3 – Expected Auxiliary Electrical Power Demand Changes for MRY Unit 1 NO_X Controls

Alt. Label(1)	NOx Control Technique	Estimated Annual Average APC NOx Equipment Auxiliary Electrical Power Demand and Usage				
		Gross Demand (2) kW	Credit(3) kW	Total Net Demand(4) kW	Power Usage(5) kW-hrs/yr	Power Usage Cost(6), 1000$/yr
E	SNCR w/ ASOFA	73.1	0	73.1	582,411	20
D	Gas Reburn w/ ASOFA	1	133	(132)	(1,054,343)	(37)
C	Coal Reburn w/ ASOFA	4,666	261	4,405	11,905,082	1,217
B	FLGR w/ ASOFA	1	73	(72)	(578,744)	(20)
A	Advanced SOFA (ASOFA)	1	0	1	8,058	0.3

(1) – Alternative designation has been previously assigned from least removal to highest removal percentage.
(2) – The APC NOx equipment gross auxiliary electrical power demand of alternatives is the sum of individual technologies combined by simple addition. Actual power demands may differ from this due to positive or negative synergistic effects. Coal reburn includes 1,507 kW for feed preparation and conveying equipment demand plus 3,158 kW for the COHPAC system addition for PM control.
(3) – The APC NOx equipment auxiliary electrical power demand credit of coal reburn alternatives is the estimated result of lower cyclone coal preparation and feeder power demand due to lower boiler cyclone coal equipment loading. Actual power demands may differ from this due to accuracy of estimates for assumed amount of operating horsepower reduction.
(4) – The total net auxiliary electrical power demand is the sum of the gross demand and credit.
(5) – The annual change in APC NOx equipment auxiliary electrical power demand electricity usage in kW-hrs/yr for these alternatives is the net power demand multiplied by the estimated annual operating time and running plant capacity factor which reflects the adjustment for any expected reliability and capacity impacts from the implementation of the control technique.
(6) – The annual change in APC NOx equipment auxiliary electrical power demand electricity cost is the annual change in kW-hrs/yr for these alternatives resulting from the implementation of the individual NOx control technique multiplied by the incremental value of auxiliary electricity generation, assumed to be $35.00/MW-hr. All cost figures in 2006 dollars.

TABLE C.3-4 – Expected Auxiliary Electrical Power Demand and Generation Reduction Cost Changes for MRY Unit 1 NO_X Controls

Alt. Label[1]	NOx Control Technique	Estimated Annual Change in Unit Generation Due to APC NOx Equipment Auxiliary Power Electricity Demand and Generation Reduction			
		APC Electrical Power Usage[2] kW-hrs/yr	Unit Generation Reduction[3] kW-hrs/yr	Total Unit Electrical Power Generation Change[4] kW-hrs/yr	Total Unit Electrical Power Generation Change Cost[5] 1000$/yr
E	SNCR w/ ASOFA	582,411	67,660,606	68,243,017	2,389
D	Gas Reburn w/ ASOFA	(1,054,343)	46,120,681	45,066,338	1,577
C	Coal Reburn w/ ASOFA	11,905,082	77,958,350	89,863,432	3,946
B	FLGR w/ ASOFA	(578,744)	46,400,200	45,821,456	1,604
A	Advanced SOFA (ASOFA)	8,058	46,586,546	46,594,605	1,631

(1) – Alternative designation has been previously assigned from least removal to highest removal percentage.
(2) – The annual change in APC NOx equipment auxiliary electrical power demand electricity usage in kW-hrs/yr for these alternatives is the net power demand multiplied by the estimated annual operating time and running plant capacity factor which reflects the adjustment for any expected reliability and capacity impacts from the implementation of the control technique.
(3) – Annual electricity generation reduction is annual operating time reduction multiplied by the annual running plant capacity factor resulting from the implementation of the individual NOx control technique multiplied by the 12-month average gross output of 244.4 MW.
(4) – The total unit electrical power generation change is the sum of the annual change in APC NOx equipment auxiliary electrical power demand electricity usage plus the annual electricity generation reduction resulting from the implementation of the individual NOx control technique.
(5) – The total unit electrical power generation change cost is the total generation change (kw-hrs/yr) multiplied by the incremental value of electricity generation, assumed to be $35.00/MW-hr. All cost figures in 2006 dollars.

TABLE C.3-5 – Expected NOx Reagent Usage and Cost Estimates for MRY Unit 1 NO_X Controls

Alt. Label[1]	NOx Control Technique	NOx Reduction Reagent Urea Usage[2]			NOx Reduction Reagent Dilution Water Usage[3]	
		lbs/hr	tons/yr	1000$/yr	1000 gal/yr	1000$/yr
E	SNCR w/ ASOFA	1,894	7,544	2,861	7,232	7

(1) – Alternative designation has been previously assigned from least removal to highest removal percentage.
(2) – All cost figures in 2006 dollars.
(3) – Reagent dilution water usage assumes potable water is added to create a 10% urea concentration (4 parts water to 1 part urea solution at 50% concentration) prior to injection. Dilution water unit cost assumed to be $1.00 per thousand gallons.

TABLE C.3-6 – Expected Heat Input and Equivalent Coal Cost to Evaporate Aqueous Urea for MRY Unit 1 NO_X Controls

Alt. Label[1]	NOx Control Technique	Estimated Annual Average Unit Equivalent Coal Consumption Cost for Aqueous Urea Evaporation		
		Heat Required to Evaporate Aqueous Urea[2], mmBtu/yr	Equivalent Coal Consumption for Heat Input[2], Tons/yr	Coal Consumption Cost[2], 1000$/yr
E	SNCR w/ ASOFA	54,315	4,077	38

(1) – Alternative designation has been previously assigned from least removal to highest removal percentage.
(2) – Heat required to evaporate urea reagent dilution water assumes 900 Btu/lb required based on a 10% urea concentration (4 parts water to 1 part urea solution at 50% concentration) injected for the estimated amount of urea usage. Coal heat content of 6,662 Btu/lb, unit cost of $0.71/mmBtu.

Appendix C References:

[i] EPA Office of Air Quality Planning and Standards (OAQPS) publication EPA/452/B-02-001, Section 4.2, NOx Controls – NOx Post-Combustion, Chapter 1 - Selective Non-Catalytic Reduction, dated October 2000, posted at their website: http://www.epa.gov/ttn/catc/dir1/cs4-2 ch1.pdf, Chapter 2 - Selective Catalytic Reduction, dated October 2000, posted at their website: http://www.epa.gov/ttn/catc/dir1/cs4-2 ch2.pdf.

[ii] "Stationary Source NOx and PM Emissions in the WRAP Region: An Initial Assessment of Emissions, Controls, and Air Quality Impacts", October 1, 2003 Western Regional Air Partnership Final Report of the WRAP Market Trading Forum, Section VI: Summary of Emission Controls Available for Large Stationary Sources of NOx and PM (by Reaction Engineering International), available at http://www.wrapair.org/forums/mtf/nox-pm.html

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NOx BEST AVAILABLE CONTROL TECHNOLOGY ANALYSIS STUDY

for

Milton R. Young Station Unit 2

Minnkota Power Cooperative, Inc.

Operating Agent for

Square Butte Electric Cooperative

Owner

Revised Final Report

October 2006

31777

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NOx Best Available Control Technology Analysis Study for Milton R. Young Station Unit 2

prepared for

Minnkota Power Cooperative, Inc. and Square Butte Electric Cooperative

October 2006

Project No. 31777

Revised Final Report

prepared by

Burns & McDonnell Engineering Company, Inc.
Kansas City, Missouri

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INDEX AND CERTIFICATION

Minnkota Power Cooperative, Inc. and Square Butte Electric Cooperative
Milton R. Young Station Unit 2
NO_X Best Available Control Technology Analysis Study

Project 31777

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Certification

I hereby certify, as a Professional Engineer in the state of North Dakota, that the information in this document was assembled under my direct personal charge. This report is not intended or represented to be suitable for reuse by Minnkota Power Cooperative, Inc. and Square Butte Electric Cooperative or others without specific verification or adaptation by the Engineer. This certification is made in accordance with the provisions of the laws and rules of the North Dakota State Board of Registration under Title 28 Administrative Code.

STEPHEN W. VOSS
REGISTERED
PROFESSIONAL
4945
ENGINEER
NORTH DAKOTA

10-4-06

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* * * * *

EXECUTIVE SUMMARY

The Milton R. Young Station of Minnkota Power Cooperative, Inc. (Minnkota) and Square Butte Electric Cooperative (Square Butte) includes two cyclone-furnace, lignite-fired steam-electric generating units (SEGUs). The units both fire North Dakota lignite supplied from the adjacent mine, near Center, North Dakota. Unit 1 has a nominal 235 MW net design output capacity rating, is typically capable of sustained output of approximately 250 MW_g (gross), and has a gross design output capacity rating of 257 MW_g. Unit 1 is owned and operated entirely by Minnkota. Unit 2 has a nominal 439 MW net design output capacity rating, is capable of sustained output of approximately 460 MW_g (gross), and has a gross design output capacity rating of 477 MW_g. Unit 2 is owned by Square Butte Electric Cooperative (Square Butte), and operated by Minnkota.

A Notice of Violation (NOV) from the United States Environmental Protection Agency (US EPA or EPA) was issued to Minnkota Power Cooperative on June 21, 2002. The NOV alleged that modifications had been made at the Milton R. Young Station that would have required a construction permit under New Source Review (Code of Federal Regulations 40 CFR 52.21, and North Dakota Administrative Code NDAC 33-15). As a result of this allegation, a civil complaint was filed by the United States of America and the State of North Dakota against Minnkota Power Cooperative Inc. ("Minnkota") and Square Butte Electric Cooperative ("Square Butte") in the United States District Court for the District of North Dakota. A Consent Decree (CD) has been approved that represents a final negotiated settlement of the United States' and North Dakota's claims against Minnkota and Square Butte. The Consent Decree requires Minnkota and Square Butte to perform a "NO_X Top-Down Best Available Control Technology (BACT) Analysis" to describe the emission limits for NO_X that will be required at Units 1 and 2, expressed as a 30-Day Rolling Average NO_X Emission Rate [Consent Decree paragraph 24, page 7, and paragraph 5, page 4].

Burns & McDonnell was retained to conduct a Top-Down BACT Analysis for nitrogen oxides (NO_X) at the Milton R. Young Station. The results of the BACT analysis are presented in this study report.

The procedures mandated by the Consent Decree for performing a Top-Down BACT Analysis are outlined in Chapter B of the U.S. EPA's New Source Review Workshop Manual: Prevention of Significant Deterioration and Nonattainment Area Permitting, Draft, October 1990 ("EPA's NSR Manual"). The MRY Station BACT analysis was performed in accordance with this procedure. The

EPA's NSR Manual outlines five basic steps that are to be followed in this BACT analysis. These basic steps for such a BACT analysis are summarized as follows:

Step 1 – Identify All Control Technologies
Step 2 – Eliminate Technically Infeasible Options
Step 3 – Rank Remaining Control Technologies by Control Effectiveness
Step 4 – Evaluate Most Effective Controls and Document Results
Step 5 – Select BACT

A Best Available Control Technology (BACT) analysis was performed for Milton R. Young Unit 2 for NO_X using the EPA's "top-down" approach. Best Available Control Technology is defined as "an emissions limitation (including a visible emission standard) based on the maximum degree of reduction for each pollutant subject to regulation under Act which would be emitted from any proposed major stationary source or major modification which the Administrator, on a case-by-case basis, taking into account energy, environmental, and economic impacts and other costs, determines is achievable for such source or modification through application of production processes or available methods, systems, and techniques, including fuel cleaning or treatment or innovative fuel combustion techniques for control of such pollutant" (40 CFR 52.21, NSR Manual B.1).

Unit 2 at Milton R. Young Station is a cyclone-fired boiler that burns North Dakota lignite. The method of firing is very significant in analyzing control options for NO_X emissions. A cyclone boiler produces inherently higher uncontrolled NO_X levels than pulverized-coal and circulating fluidized bed boilers. There have been no new coal-burning cyclone-fired boilers built and installed in the United States since the early 1980's. Consequently, there are no examples of BACT control options listed in the RACT/BACT/LAER Clearinghouse database for consideration and direct application of published NO_X emission permit limits on the Milton R. Young cyclone-fired boilers.

Step 1 – Identify All Control Technologies

The Consent Decree requires that the NO_X Top-Down BACT Analysis for the Milton R. Young Station "include an evaluation of Selective Catalytic Reduction (SCR), Selective Non-Catalytic Reduction (SNCR), Overfire Air (OFA), Rich Reagent Injection (RRI), as well as other NO_X control technologies" potentially applicable for lignite-fired cyclone boilers [Consent Decree paragraph 65, page 19]. Other identified control techniques, such as fuel switching and fuel cleaning, and combustion-related emission control technologies, such as fuel reburn and oxygen-enhanced combustion, were also considered.

Step 2 – Eliminate Technically Infeasible Options

The BACT evaluation determined that not all the technologies identified were considered available and applicable. The technically infeasible alternatives were eliminated from further evaluation, along with feasible technologies with economic impacts that were unreasonable compared to other cost-efficient alternatives to control NO_X emissions for MRY Station Unit 2.

The technical feasibility of applying NO_X emission reduction techniques and technologies at Milton R. Young Station is dominated by the composition and combustion characteristics of the North Dakota lignite supplied solely from a surface mine adjacent to the plant. This mine is the only supplier of solid fuel for this station, as there are no railroad facilities provided to service the Milton R. Young plant. North Dakota lignite has high moisture and high sodium content, moderate higher heating values, and can have a widely variable and high ash content compared to other coals. These characteristics create difficulties in promoting consistent, steady combustion and slag formation in the cyclone burners. It also results in producing a flyash that has severe deposition characteristics.

Both boilers include a unique coal conditioning system (drying, crushing, and feeding) for each cyclone furnace specifically designed to aid in proper combustion of the lignite fuel. This method of firing solid fuel significantly influences the resulting nitrogen oxide concentration of the flue gases emitted from the boilers.

Ash deposition in each boiler and air preheater is a significant operational challenge for the facility. Significant equipment and manpower resources are devoted to on-going removal of fireside ash accumulations. Unit outages must be conducted at regular intervals to clean each boiler (approximately every 80-120 days). There are a number of issues that make selective catalytic reduction (SCR) technically infeasible for NO_X emission control for Milton R. Young Unit 2. The consistent long-term operation of SCR technology on lignite-fired cyclone boilers will be drastically inhibited by the susceptibility of the SCR catalyst to severe fouling, deactivation, and erosion resulting from the actions of the emitted flue gases and flyash, and ash deposit removal operations. SCR technology is considered technically infeasible for application on the cyclone boilers at the Milton R. Young Station.

Rich Reagent Injection has been demonstrated on boilers burning bituminous and subbituminous coal. However, it has not been commercially installed and placed in continuous operation on a cyclone-fired boiler burning lignite coal with high fouling and slag temperature sensitivities associated and a highly

variable heat content. RRI adds urea reagent to the hot furnace gases near the cyclones, which must be devoid of free oxygen in order to avoid oxidation of the urea, and thus creating NO_X. While RRI is specifically intended for NO_X emissions control on cyclone boilers, RRI is considered technically infeasible for application on the lignite fired cyclone boilers at the Milton R. Young Station due to the variable heat content of the lignite fuel which allows the creation of oxygen-rich conditions in the boiler.

The application of separated overfire air (SOFA) for NOx emissions control on Milton R. Young Unit 2's boiler was evaluated as part of the BACT analysis. A version of separated overfire air specifically designed for increased NO_X emission reduction performance for lignite-fired cyclone boilers, referred to as "Advanced SOFA" in this analysis, can be installed on both units at M.R. Young Station. This highest-performing form of SOFA can be applied alone and in combination with other technologies. Key aspects of successfully applying and operating a separated overfire air system on a cyclone-fired boiler are the ability to:

- Accurately measure the fuel heat input rate (BTUs) and combustion air inputs on a real-time, individual cyclone by cyclone basis, to allow the ability to determine and control the desired air/fuel ratio, especially when "starved air" (i.e. substoichiometric) combustion conditions are required.
- Maintain adequate molten coal ash (slag) formation and flow within the barrels and slag taps.

The degree to which the individual cyclone furnaces can be operated with less-than-theoretical (substoichiometric) combustion air, which corresponds to operation of a SOFA system, directly contributes to less combustion-related NO_X formation and further in-furnace emission reduction but also risks solidification of the molten coal ash. This places great emphasis on achieving tight control over the air/fuel ratios on each cyclone during air-staged combustion operation with SOFA in order for air-staged combustion to be successful in producing significant additional NOx emissions reduction on lignite-fired cyclone boilers.

In the case of MRY Station Unit 2's boiler, air-staged combustion must be sufficient to reduce NO_X emissions while releasing enough heat to continue to melt the fuel ash so that it flows effectively within and from the cyclone burners. Due to the short-term variability of the combustible and ash components of North Dakota lignite supplied from the current mine near Center, ND, and the complex behavior of lignite ash when exposed to high temperatures, the extent of air-staging and thus the level of NO_X control while operating the highest-performing version of SOFA system is expected to be modest.

Selective Non-Catalytic Reduction (SNCR) technology has been used to reduce NO_X emissions on numerous utility boilers burning eastern bituminous coal, midwestern bituminous coal, and, to a lesser extent, western subbituminous coal. SNCR has also been used on fuel oil and natural gas-fired units. SNCR does not appear to be dependent directly on the type of burners (wall-fired, tangentially-fired, and cyclone-fired) employed in the boilers where it has been installed, with or without air-staged combustion with overfire air in full operation.

There are significant concerns associated with effective long-term SOFA operation for Milton R. Young Station Unit 2's boiler. The ability of basic combustion equipment and improvements to precisely measure the boiler's heat input rate in real-time on an individual cyclone by cyclone basis with compensation for the short-term variability of the combustible content of the Center lignite to consistently maintain substoichiometric operation of every cyclone during air-staged combustion is unproven.

Several other techniques and technologies were considered technically feasible for NOx emissions control at MRY Station: Fuel Blending/Switching; Basic Combustion Control Improvements; and various forms of Fuel Reburn. Fuel switching/blending was not evaluated further because of expected unreasonably high capital and operating costs and no additional emission reduction compared to continued lignite firing.

Other NOx emissions control techniques and technologies for MRY Station that were evaluated and determined to be technically infeasible were: Fuel Cleaning; Low NOx Burners (LNB); Flue Gas Recirculation; Oxygen-enhanced Combustion (OEC); Water/steam injection (combustion tempering); and Electro-Catalytic Oxidation (ECO®).

Step 3 – Rank Remaining Control Technologies by Control Effectiveness

The third step in the "top-down" BACT evaluation ranked the remaining control technologies by effectiveness. The purpose of ranking the control technologies was to establish a hierarchy that places at the "top" the control technology that achieves the lowest emission level. The technologies in order of their effectiveness, from highest to lowest, are: SNCR with ASOFA; Gas Reburn with ASOFA; Lignite Reburn with ASOFA; Fuel Lean Gas Reburn with ASOFA; and Advanced Separated Overfire Air (ASOFA). None of these control options has been installed on a cyclone-fired boiler burning North Dakota lignite. As such, the expressed control percentages reflect the use of engineering judgment, based on the listed technique or technology application.

Step 4 – Evaluate Most Effective Controls and Document Results

Additional criteria besides technical feasibility were utilized for technology selection in this BACT analysis. These included estimates of control effectiveness (i.e. percent pollutant removed), capital plus operating and maintenance costs, annual emission reduction (tons per year), energy impacts, average and incremental cost effectiveness ($/ton), and environmental impacts (other media and emissions of toxic and hazardous air pollutants).

The economic analysis examined the capital cost of each feasible BACT alternative evaluated and any other powerplant upgrade costs necessary to implement the alternative. In addition, the economic analysis examined the operating and maintenance cost associated with the highest-performing forms of each feasible BACT alternative evaluated. These costs were then combined into a levelized total annual cost for a comparative assessment of the total implementation cost of each alternative. Finally, as part of the top-down analysis, a dominant controls cost curve was plotted and the unit control cost for each alternative was evaluated.

Two alternatives were on the dominant controls cost curve and thus were identified as the more cost effective alternatives. The two BACT NO_X control alternatives evaluated for incremental cost, energy, and environmental impacts applicable to Milton R. Young Station Unit 2were:

- Selective Non-Catalytic Reduction (SNCR) combined with a special form of separated overfire air (SOFA) specifically for lignite-fired cyclone boilers (referred to as Advanced SOFA or ASOFA); and
- ASOFA alone.

The two most cost-effective feasible control alternatives for reduction of NO_X emissions were reviewed to determine if the use of the technique or technology would result in any significant or unusual energy penalties or benefits. Potential increase in power plant energy consumption or net generation reductions, for ASOFA alone, or ASOFA with SNCR were relatively small.

The predicted environmental impacts from implementation of the two most cost-effective feasible NO_X emissions control alternatives from slightly higher unburned carbon in the emitted fly ash, carbon monoxide, and excess ammonia ("slip") emissions was expected to be small in comparison with the

significant anticipated reduction in far-field ozone and improvement in atmospheric visibility as a result of the overall NO_X emission reduction.

Step 5 – Select BACT

Taking into account technical feasibility, energy, environmental, and economic impacts and other costs, the recommended Best Available Control Technologies and associated emission rates for nitrogen oxides emissions produced by Milton R. Young Station Unit 2 boiler are provided in the table below.

NO_X Emission Control Technology and Rate Recommended as BACT

Control Technology and Emission Rate Recommended as BACT			
Unit	**Pollutant**	**Control Method**	**12-Month Rolling Average NOx Emission Rate (lb/ million Btu)**
2	NO_X	Selective Non-Catalytic Reduction with Advanced Separated Overfire Air (ASOFA)	0.330

This recommended BACT 12-month NO_X emission rate is based upon a historic pre-control 12-month baseline average annual NO_X emission rate used in the control and cost-effectiveness analysis of 0.786 lb/mmBtu for Unit 2. The baseline emission was determined from the 12 consecutive month period with the highest historic summation of NO_X mass emissions (pounds) reported for actual operation between January 1,2001 and December 31, 2005.

To complete the BACT determination process, the Consent Decree (CD) requires that "specific control technologies to be installed and a specific Phase II 30-day Rolling Average NO_X Emission Rate limitation (lbs/MMBtu)" must be established for each subject emission Unit [CD Paragraph 66, pg 20]. Because there are expected to be minor short term variations in operating conditions where Minnkota has not, in fact, materially changed any of their normal daily operating practices, a margin between the 12-month average operating conditions and the 30-day permit limit is proposed. This recommended emission rate should be suitably higher such that operation consistent with the technological limitations, manufacturer's specifications, and good engineering and maintenance practices to the extent practicable for the recommended NOx BACT alternative would not result in an exceedance (violation) of an enforceable emission permit limit.

The Consent Decree also requires that the North Dakota Department of Health's (NDDH) NO_X BACT Determination address specific emission limitations during Unit startups at Milton R. Young Station [CD Paragraph 66, pg 20]. The type and duration of firing during startups, and the limited ability of available and feasible technologies to control startup NO_X emissions, both significantly influence the 30-day rolling average BACT NO_X emission rate limit recommended for Milton R. Young Station boilers. A 24-hour rolling average NO_X emission rate limit applied to startup periods is also recommended for Milton R. Young Station boilers.

The SEGU startup operating period is usually not defined in emission permits. However, for the purpose of this NO_X BACT analysis, Unit startup was defined as the period from initial fuel combustion to the point in time when:

- the measured Heat Input to the boiler on a 6-hour rolling average basis is greater than or equal to 4800 million BTU/hr for Unit 2; or
- the amount of time reported for the longest individual Unit 2 startup period during actual operation between January 1, 2001 and December 31, 2005 elapses, whichever occurs first; or
- fuel firing is discontinued prior to satisfying either previous criteria.

For MRYS Unit 2, the recommended 30-day rolling average NO_X emission permit limit rate that includes the impact of startups is based upon recognized operational factors and equipment designs that influence whether the startup emissions result in higher 30-day emissions compared to normal continuous operation excluding such startup periods:

- The uncontrolled emission rate (i.e. without separated OFA or SNCR in operation) and its variability during operation from a cold startup up to and including maximum continuous rated output;
- The operating conditions that are required to exist for the selected NO_X BACT control techniques to be initiated and be effective; and
- The effectiveness of these two particular control techniques if invoked at less-than-MCR steady-state operating conditions.
- The number of startups and their range of typical durations per 30-day period time frame.

The Consent Decree and the EPA's NSR Manual do not describe the method for determining a 30-day Rolling Average NO_X Emission Rate permit limitation (CD Phase II) that reflects BACT applied to Milton R. Young Station Unit 2. The approach taken in this analysis was to establish a historic pre-control 30-day baseline average NO_X emission rate (lb/mmBtu) from the 30-consecutive day period with

the highest historic unit NO_X mass emissions (pounds) reported for actual operation between January 1,2001 and December 31, 2005. This reflects unit NO_X emissions that were generated during periods of high unit operations, not affected by unit shutdowns, startups, or malfunctions. This was then compared to the 12-month historic pre-control baseline average NO_X emission rate (lb/mmBtu) from the 12-consecutive month period with the highest historic unit NO_X mass emissions (pounds) reported for actual operation during the same 5-year look-back period. An estimate of NO_X emission reduction for the proposed BACT NO_X alternative operating at the historic pre-control 30-day baseline average NO_X emission rate (lb/mmBtu) was made. This rate considered recognized operational factors and equipment designs applied to "steady state" conditions with sustained output close to maximum continuous capacity ratings. The potential impact of startups, recognizing operational and technical limitations on NO_X emission control performance, was then applied to the steady-state rate, to establish a recommended 30-day Rolling Average NO_X Emission Rate permit limitation (CD Phase II) that reflects BACT for Milton R. Young Station Unit 2. This is summarized below.

Recommended NO_X BACT Control Method and 30-Day Rolling Average NO_X Emission Rate Limit Without Startups

Unit	Pollutant	Control Method	30-day Rolling Average NOx Emission Rate Limit Excluding Startups (lb/million Btu)
2	NO_X	Selective Non-Catalytic Reduction with Advanced Separated Overfire Air (ASOFA)	0.350

This recommended BACT 30-day NO_X emission rate limit is based upon a historic pre-control 30-day baseline average NO_X emission rate of 0.874 lb/mmBtu for Unit 2. The baseline emission was determined from the 30-consecutive day period with the highest historic unit NO_X emissions rate reported for actual operation between January 1,2001 and December 31, 2005.

An incremental adjustment to the proposed 30-day rolling average steady-state unit NO_X BACT emission rate without startups of 0.35 lb/mmBtu for Unit 2 is recommended for the 30-day rolling average NO_X emission permit limit periods as defined and applied to Milton R. Young Station. This is summarized in the table below.

Recommended BACT 30-Day Rolling Average NO_X Emission Rate Limit and Startup Impact

Unit	30-day Rolling Average NOx Emission Rate Limit Excluding Startups (lb/million Btu)	Impact on 30-day Rolling Average NOx Emission Rate Limit Due to Startups (lb/million Btu)
2	0.350	+0.102 per startup

This recommended adjustment to the proposed 30-day rolling average steady-state NO_X BACT emission rate limit without startups is based upon average historic pre-control NO_X emission rates of 0.959 lb/mmBtu for Unit 2 reported for the longest individual Unit 2 startup period during actual operation between January 1, 2001 and December 31, 2005. These emissions occurred during the 115-hour October 25-30, 2001 startup for Unit 2.

A 24-hour rolling average BACT NO_X emission rate limit applied to startup periods is also recommended for each of the Milton R. Young Station boilers.

This is summarized in the table below.

Recommended 24-Hour Rolling Average NO_X Emission Rate Limit During Startups

Unit	24-hour Rolling Average NOx Emission Rate Limit During Startups (lb/million Btu)
2	1.064

These emissions occurred during the 115-hour October 25-30, 2001 startup for Unit 2.

Compliance with these emission rate would be measured at the stack of the Unit, verified with Continuous Emission Monitoring (CEM) systems in accordance with the reference methods specified in 40 C.F.R. Part 75, and would be determined on a 30 consecutive Operating Day and 24-consecutive hour rolling average basis, respectively.

A trial demonstration period of 18 months after the completion of Consent Decree Phase II NO_X emission reduction system installation commissioning at Milton R. Young Station is recommended. It is proposed to allow Minnkota (for Square Butte) to demonstrate the actual control system capabilities of the combined NO_X BACT emissions reduction system. Operating experience during the trial period will:

- confirm steady-state control performance of the combined NO_X BACT emissions reduction system;
- allow determination of the ability to further control Unit start-up emissions;
- allow the determination of the permitted 30-day rolling average NO_X emission limit including startups, shutdowns, and malfunctions; and
- address the specific emission limitations during Unit startups at Milton R. Young Station and their impact on the proposed 30-day rolling average emission rate limit (without startups).

Based upon the information obtained during the trial period, final emission limits can then be determined.

The means that will be employed to minimize emissions during startup will primarily be based on operating procedures, both before and after the level of upper furnace gas temperatures and/or heat input rate are considered sufficient to start the NO_X controls and operating conditions are conducive for effective emissions reduction. These could be similar to Minnkota's current MRYS practices, or could be different, depending upon the capabilities of the NO_X controls and their impacts on Unit operations.

* * * * *

1.0 INTRODUCTION

The Milton R. Young Station of Minnkota Power Cooperative, Inc. (Minnkota) and Square Butte Electric Cooperative (Square Butte) includes two cyclone-furnace, lignite-fired boilers producing steam for electric generation. Both units fire North Dakota lignite supplied from an adjacent mine, near Center, North Dakota.

A Notice of Violation (NOV) from the United States Environmental Protection Agency (US EPA or EPA) was issued to Minnkota on June 21, 2002. The NOV alleged that modifications have been made at the Milton R. Young Station that would require a construction permit under New Source Review (Code of Federal Regulations 40CFR52.21, and North Dakota Administrative Code NDAC 33-15). As a result of this allegation, a civil complaint was filed by the United States of America and the State of North Dakota against Minnkota Power Cooperative Inc. ("Minnkota") and Square Butte Electric Cooperative ("Square Butte") in the United States District Court for the District of North Dakota. A Consent Decree[1] has been entered that represents a final negotiated settlement of the United States and North Dakota's claims against Minnkota and Square Butte. The Consent Decree requires Minnkota and Square Butte to perform a NO_X "Top-Down" Best Available Control Technology (BACT) Analysis to describe the emission limits for NO_X that will be required at Units 1 and 2, expressed as a 30-Day Rolling Average Emission Rate (lbs/million Btu)[2].

Burns & McDonnell was retained by Minnkota to conduct a "Top-Down" Best Available Control Technology (BACT) Analysis for nitrogen oxides (NO_X) at the Milton R. Young Station. Burns & McDonnell is a full service engineering, architectural, construction and environmental firm. The company plans, designs and constructs electric generating facilities and has been providing environmental services since the 1970s. As part of those services, Burns & McDonnell has extensive experience in permitting, Best Available Control Technology (BACT) studies and control technology analysis. The results of the BACT analysis are presented in this report.

[1] In the United States District Court For The District Of North Dakota, United States Of America and State Of North Dakota, Plaintiffs, v. Minnkota Power Cooperative, Inc. and Square Butte Electric Cooperative, Defendants, Civil Action No. 1:06-CV-034

[2] Ibid – footnote number 1, CD paragraph 65, page 19.

The primary guidance utilized in preparation of this BACT analysis is the U.S. EPA's New Source Review Workshop Manual: Prevention of Significant Deterioration and Nonattainment Area Permitting, Draft, October 1990[3] ("NSR Manual").

In the next section of the report, the approach to the BACT Analysis is described. Following that, a quick summary of the plant conditions and report basis is given and then the BACT Analysis begins. The impact portion of the report is broken down into separate subsections. Within the last section, the results of all of the BACT Analysis steps are summarized for NO_X control options for Unit 2's boiler at the Milton R. Young Station.

* * * * *

[3] Chapter B of the U.S. EPA's New Source Review Workshop Manual: Prevention of Significant Deterioration and Nonattainment Area Permitting, Draft, October 1990.

2.0 "TOP-DOWN" NO_X BACT ANALYSIS APPROACH

Best Available Control Technology (BACT) is an emissions limitation for each pollutant from a source determined to be achievable using control technologies(s) that provide the "maximum degree of emission reduction...taking into account energy, environmental, and economic impacts"[4]. A BACT review does not result in an emissions removal efficiency requirement. The generally accepted procedures for performing a BACT analysis are outlined in the EPA's draft NSR Manual. The BACT analysis for Milton R. Young Station Unit 2's boiler NO_X emissions was performed in accordance with this procedure. The EPA's draft NSR Manual outlines five basic steps that are to be followed in the "top-down" BACT evaluation. These steps are as follows:

Step 1 – Identify All Control Technologies
Step 2 – Eliminate Technically Infeasible Options
Step 3 – Rank Remaining Control Technologies by Control Effectiveness
Step 4 – Evaluate Most Effective Controls and Document Results
Step 5 – Select BACT

The predefined steps of a BACT analysis are described in this section, and results presented. Available NO_X control techniques and technologies are defined, identified, and a technical description of the emission reduction process and capabilities are reviewed in the following section. Subsequently, those techniques and technologies deemed feasible for retrofit application are ranked according to nominal NO_X control capability. An engineering analysis reviews the estimated capital and operations and maintenance (O&M) costs for each feasible alternative, including taking a look at Balance of Plant (BOP) requirements. Following the cost impact determination, the energy and environmental impacts are reviewed for each feasible technology. Finally, the results of the engineering analyses are tabulated and a NO_X BACT selection is recommended for each unit.

2.1 STEP 1 – IDENTIFY ALL CONTROL TECHNOLOGIES

The first step in a "top-down" NO_X BACT analysis is to identify, for the emissions unit in question, a comprehensive list of all "available" control options. In the EPA's draft NSR Manual,

> "available control options are those air pollution control technologies or techniques with a practical potential for application to the emissions unit and the regulated pollutant under evaluation. Air pollution control technologies and techniques include the application of

[4] Ibid footnote number 2, NSR Manual B.1

production process or available methods, systems, and techniques, including fuel cleaning or treatment or innovative fuel combustion techniques for control of the affected pollutant"[5].

According to the EPA's draft NSR Manual, "a technology is considered "available" if it can be obtained by the applicant through commercial channels or is otherwise available within the common sense meaning of the term"[6]. Also, "a control technique is considered available, within the context presented above, if it has reached the licensing and commercial sales stage of development"[7].

In order to identify available NO_X emission control technologies and techniques appropriate for potential application to MRY Station units, the following information sources were reviewed for coal-fired electric generating unit powerplants:

- EPA's RACT/BACT/LAER Clearinghouse (RBLC) database and Control Technology Center (website).
- Federal (EPA) and State, including North Dakota Department of Health internet websites for air emission permits and recently-submitted applications, including BACT Evaluations following New Source Review procedures.
- Federal (EPA and Department of Justice) and State, including North Dakota Department of Health internet websites for Consent Decrees issued as a result of legal actions taken by the United States government for alleged violations of the Prevention of Significant Deterioration (PSD) provisions and New Source Review provisions of the Clean Air Act, and/or federally-approved and enforceable State Implementation Plans.
- Control technology vendor information.
- Published and available information from technical, engineering, and environmental consultants.
- Technical literature found in journals, reports, internet websites, newsletters, proceedings of technical seminars and conferences pertaining to studies, engineering, designs, and testing of air pollution controls.

[5] Ibid, NSR Manual B.5
[6] Ibid, NSR Manual B.17
[7] Ibid, NSR Manual B.18

2.2 STEP 2 – ELIMINATE TECHNICALLY INFEASIBLE OPTIONS

The second step of the "top-down" BACT process is to evaluate the available NO_X control technologies and techniques identified in Step 1 in terms of the specific factors that apply to the emissions unit in question. In accordance with EPA's draft NSR Manual, "an available technology is "applicable" if it can be reasonably installed and operated on the source type under consideration. A technology that is available and applicable is technically feasible[8]".

The EPA's NSR Manual states a technology may be determined to be not applicable if "a technical assessment considering physical, chemical and engineering principles and/or empirical data showing the technology would not work on the emissions unit under review or that unsolvable technical difficulties would preclude the successful deployment of the technique"[9]. Also, a "showing of unresolvable technical difficulty with applying the control would constitute a showing of technical infeasibility (e.g., size of the unit, location of the proposed site, and operating problems related to specific circumstances of the source)"[10]. After a determination is made that any of the processes are technically infeasible, options are eliminated if technical challenges would preclude or prevent the successful long-term use of the control option or technique on the emission unit under consideration. This is performed prior to any economic analysis.

However, the EPA's NSR Manual also states "...control options incapable of meeting an applicable New Source Performance Standard (NSPS) or State Implementation Plan (SIP) limit would not meet the definition of BACT under any circumstances. The applicant does not need to consider them in the BACT analysis"[11]. Also, it states "An NSPS simply defines the minimum level of control to be considered in the BACT analysis"[12]. The NSR Manual further states "When developing a list of possible BACT alternatives, the only reason for comparing control options to an NSPS is to determine whether the control option would result in an emission level less stringent than the NSPS. If so, the option is unacceptable"[13]. New Source Performance Standards (NSPS) for NO_X emissions from EGUs firing North Dakota lignite are 0.8 lb/mmBtu. The EPA Acid Rain Program's Title IV NO_X emission limit for Group 2, cyclone-fired coal boilers with outputs greater than 155 MWe is 0.86 lb/mmBtu.

[8] Ibid, NSR Manual B.17
[9] Ibid, NSR Manual B.20
[10] Ibid, NSR Manual B.19
[11] Ibid, NSR Manual B.12
[12] Ibid, NSR Manual B.12
[13] Ibid, NSR Manual B.12

EPA's draft NSR Manual also states "A source would not be required to experience extended time delays or resource penalties to allow research to be conducted on a new technique. Neither is it expected that an applicant would be required to experience extended trials to learn how to apply a technology on a totally new and dissimilar source type. Consequently, technologies in the pilot scale testing stages of development would not be considered available for BACT review"[14].

Also in the EPA's draft NSR Manual is a qualification for technical feasibility, as described by the statement "Commercial availability by itself, however, is not necessarily a sufficient basis for concluding a technology to be applicable and therefore technically feasible. Technical feasibility, as determined in Step 2, also means a control option may reasonably be deployed on or "applicable" to the source type under consideration"[15].

2.3 STEP 3 – RANK REMAINING CONTROL TECHNOLOGIES BY CONTROL EFFECTIVENESS

The third step in the "top-down" BACT evaluation is to rank the control technologies remaining after the feasibility analysis by control effectiveness. The purpose of ranking the control technologies is to establish a hierarchy that "places at the "top", the control technology that achieves the lowest emission level"[16].

Selecting common units in order to compare emissions performance levels amongst options is one of the two key issues that must be addressed in a BACT analysis. EPA's draft NSR Manual states "it is generally most effective to express emissions performance as an average steady state emissions level per unit of product produced or processed"[17]. For fossil fuel-fired boilers, pounds of nitrogen oxides per unit of fuel heat input (i.e. lb/mmBtu), is a common means of comparing and calculating NO_X emissions.

Many control techniques, including both add-on controls and inherently lower polluting processes can perform at a wide range of levels. The EPA's draft NSR Manual states "It is not the EPA's intention to require analysis of each possible level of efficiency for a control technique, as such an analysis would

[14] Ibid, NSR Manual B.18
[15] Ibid, NSR Manual B.18
[16] Ibid, NSR Manual B.25
[17] Ibid, NSR Manual B.22

result in a large number of options"[18]. Also, "manufacturer's data, engineering estimates, and the experience of other sources provide the basis for determining achievable limits"[19].

2.4 STEP 4 – EVALUATE THE MOST EFFECTIVE CONTROLS AND DOCUMENT RESULTS

The fourth step of a "top-down" BACT review is to evaluate the technically-feasible emission controls, beginning with the most effective. Economic, energy, and environmental impacts are to be assessed and quantified, where possible, in the control technology analysis. The purpose of the evaluation is to determine if there are any identified impacts that would eliminate the top control technology from consideration. In the case where the most effective control alternative is determined to incur or produce adverse energy, economic or environmental impacts, the basis of the determination is documented, and the next most stringent control alternative is evaluated. This analysis process continues until the control technology under consideration cannot be eliminated by identification of any source-specific adverse energy, economic or environmental impacts.

The economic impacts are based on estimates of capital equipment pricing, procurement, installation and estimated operating and maintenance costs. The total installed capital costs along with the operating costs for each control technology are summarized in the economics of each respective section. The Levelized Total Annual Cost (LTAC) represents the levelized cost of procurement, construction, operation and maintenance over an assumed service life. Cost effectiveness ($/ton) of a control technique or technology is calculated by dividing the LTAC ($/yr) by the annual amount of NO_X removed (tons/yr). Baseline pre-control emissions are calculated using realistic upper boundary operating assumptions, considering inherent physical or operational constraints on the source. Plotting of the annual amount of NO_X removed (tons/yr) versus the levelized total annual control cost ($/yr) for the various control options on an x-y graph allows visualization of the cost-effectiveness. A "least-cost envelope" can be readily identified to indicate the inferior control options which should not be considered in the subsequent analyses. The incremental cost-effectiveness (difference in $/ton) between control techniques or technologies can also be calculated and compared. This allows evaluation of the dominant controls included on the least-cost envelope (curve).

[18] Ibid, NSR Manual B.23
[19] Ibid, NSR Manual B.24

2.5 STEP 5 – SELECT BACT

The final step in the "top-down" evaluation process is to select BACT for the applicable pollutant and emission unit. Per the EPA guidance document, BACT is "the most effective control technology not eliminated in Step 4"[20]. The methodology described above was applied to the Milton R. Young Station Unit 2's boiler for emissions of nitrogen oxides.

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[20] Ibid, NSR Manual B.53

3.0 BACT ANALYSIS for MRY STATION UNIT 2 NO_X EMISSIONS

The approach taken in this BACT analysis for Milton R. Young Station included a technical analysis of demonstrated control alternatives for NO_X emissions. This approach followed the predefined steps of a BACT analysis process as generally described in Section 2. Potential NO_X control techniques and technologies were identified, and a technical description of the emission reduction process and capabilities were provided. Subsequently, those techniques and technologies deemed available and feasible for retrofit application were ranked according to nominal NO_X control capability. The engineering analysis then developed the estimated capital and O&M costs for each alternative, including taking a look at Balance of Plant (BOP) requirements. Finally, the cost effectiveness points for each feasible technology were plotted, and those that comprise the dominant controls curve were identified.

For the feasible techniques and technologies considered for determining NO_X control cost-effectiveness for the two steam electric generating units at the MRY Station, estimates were produced for predicted NOx reductions that represent achievable long-term expectations of the alternative reduction techniques and technologies being presented in the technical analysis. Each were tabulated and graphed.

3.0.1 EMISSION UNIT DESCRIPTION

Milton R. Young Unit 2 is a Babcock and Wilcox steam generator installed in 1977. The steam generator is a lignite-fired boiler with multiple cyclone-furnaces installed in parallel using balanced-draft and natural circulation assisted with circulation pumps. Original unit design steam generating capacity is 3.20 million lbs/hr at 2,620 psi with a fuel heat input of 4,696 mmBtu/hr. The boiler is fired by twelve ten-foot diameter cyclone burners, arranged "three over three" across the front and rear walls of the lower furnace. The unit has a tubular air heater installed between the boiler and the flue gas ductwork leading to the ESP. Exhaust gases leave the air heater and pass through an ESP for particulate collection and removal followed by the two induced draft fans (installed in parallel) prior to a wet flue gas desulfurization (FGD) system which discharges to the stack. The current air pollution control system's configuration allows a portion of the low dust flue gas to reheat the stack gas, thus bypassing the FGD system. Unit 2 has a nominal 439 MW net design output capacity rating, is capable of sustained output of approximately 462 MW gross, and has an ultimate short-term maximum gross output (URGE) of 512 MW.

The EPA's Technical Support Document[22] lists nameplate steam turbine-generator capacity of MRY Station Unit 2 as 477 MW (gross), which was assumed for calculating capital cost estimates for control alternatives.

The Unit 2 boiler at M.R. Young Station includes a unique coal conditioning system (drying, crushing, and feeding) for each cyclone furnace specifically designed to aid in proper combustion of the lignite fuel. This method of firing solid fuel significantly influences the resulting nitrogen oxide concentration of the flue gases emitted from the boilers.

Milton R. Young Station Unit 2's boiler design, combustion performance, and NO_X emissions are dominated by the composition and combustion characteristics of the North Dakota lignite supplied solely from a surface mine adjacent to the plant. This mine is the only supplier of solid fuel for this station, as there are no railroad facilities provided to service the Milton R. Young plant. North Dakota lignite has high moisture and high sodium content, moderate higher heating values, and can have a widely variable and high ash content compared to other coals. These characteristics create difficulties in promoting consistent, steady combustion and slag formation in the cyclone burners. It also results in producing a flyash that has severe deposition characteristics.

The design unit operating conditions for this study are presented in Table 3-1. The historical average lignite coal analysis is shown in Table 3-2.

Table 3-1 – Unit Design Parameters

Design Unit Operating Characteristics	Unit 2 Design
Boiler Type	Subcritical(1)
Combustion System	Cyclone
Number of Cyclones; arrangement, location	12; 3 over 3, opposed
Unit Design Capacity Electrical Output(2), MW (net/gross)	439 / 477

(1) – Balanced draft, single drum, superheated steam with single stage of steam reheat.
(2) – These values were established by the original equipment manufacturers, prior to construction.

[22] Ibid

Table 3-2 – Historical Average Lignite Coal Analysis

Lignite - Center Mine Ultimate Coal Analysis: (as received)	Average % by mass
Moisture	37.29
Carbon	38.69
Hydrogen	2.50
Nitrogen	0.57
Sulfur	0.81
Ash	8.74
Oxygen	11.40
Total	100.00
Higher Heating Value, Btu/lb	6,662

3.0.2 NITROGEN OXIDES EMISSION FORMATION

Nitrogen oxides (NO_X) are produced when nitrogen in the fuel and combustion air are exposed to high temperatures. There are two primary sources of NO_X emissions, referred to as "thermal" NO_X and "fuel" NO_X. Thermal NO_X emissions are produced when elemental nitrogen in the combustion air is admitted to a high temperature zone and oxidized. Fuel NO_X emissions are created during the rapid oxidation of the fuel containing nitrogen compounds. For most coal-fired units, thermal NO_X emission typically represents approximately 20% and fuel NO_X about 80% of the total NO_X formed. Nitrogen oxide (NO) is typically the most predominant form of NO_X emissions from fossil fuel combustion, along with nitrogen dioxide (NO_2). The formation of these compounds in utility powerplant boilers is sensitive to the method of firing and combustion controls utilized. The techniques employed for mixing the combustion air and fuel, which creates flames and high temperature combustion products, results from the rapid oxidization of carbon, hydrogen, and other exothermic reactions. Cyclone-fired boilers, by design, create intense heat release rates to melt and fluidize the coal ash introduced into the barrel-shaped furnaces. This produces high temperature flue gases and results in very high uncontrolled NO_X emissions. The amount of thermal NO_X emissions produced by cyclone boilers can be considerably higher than fuel NO_X emissions.

3.1 IDENTIFICATION OF NO_X CONTROL OPTIONS FOR MILTON R. YOUNG STATION

The first step in the BACT evaluation is to identify all "demonstrated and potentially applicable control technology alternatives"[23] according to the EPA's draft NSR Manual. In identifying control technologies, "the applicant needs to survey the range of potentially available control options"[24].

[23] Ibid, footnote number 2, NSR Manual page B.11

3.1.1 REVIEW OF RETROFIT INSTALLATIONS

The BACT determinations listed in the EPA's RACT/BACT/LAER Clearinghouse (RBLC) database are for new facilities. The Milton R. Young Station is an existing powerplant facility with two coal-fired EGUs. A BACT evaluation for retrofitting control equipment to coal-fired EGUs in an existing facility will be substantially different than an analysis for installing control equipment on coal-fired EGUs in a new facility. Consequently, in performing the BACT analysis for existing boilers at Milton R. Young Station, it is important to review powerplant facilities, especially cyclone-fired coal boilers, which have retrofitted NO_X control equipment in recent years.

In 1998, EPA issued a NO_X SIP (State Implementation Plan) call. Under the SIP call, utility boilers in the eastern United States were required to substantially reduce NO_X emissions during the "ozone season". The compliance date for the NO_X SIP call is May 31, 2004. A high percentage of the fired electric generation facilities in the eastern United States have or are in the process of retrofitting NO_X controls to comply with the NO_X SIP call. The EPA's NO_X SIP call was not applicable to North Dakota utility boilers.

There are a number of fossil fuel-fired EGU powerplants around the United States that have implemented or are planning to implement modifications to reduce NO_X emissions. The NO_X emission control system installations are in response to Acid Rain requirements, EPA's NO_X SIP call, the Clean Air Interstate Rule (CAIR), the Regional Haze Rule (RHR), and local regulations.

In addition to the facilities that have had to retrofit emissions controls as a result of the Title IV Part 76 Acid Rain requirements and/or EPA's NO_X SIP call, a few installations have had to retrofit controls in recent years as the result of court decisions resulting from litigation and regulatory action. None of the boilers associated with identified consent decrees are cyclone-fired. They are also located in a region requiring compliance with an EPA-approved State Implementation Plan for nitrogen oxides emissions controls (i.e. NO_X SIP call). As mentioned above, North Dakota utility boilers were not subject to the EPA's NO_X SIP call.

[24] Ibid, NSR Manual page B.11

3.1.2 POTENTIALLY FEASIBLE NOx CONTROL OPTIONS FOR MILTON R. YOUNG STATION

A review of available information on retrofit installations performed at utility and industrial coal-fired powerplants during the past fifteen years was undertaken. NO_X emission control technologies and techniques with potential application to Milton R. Young Station boilers were identified, and are listed in Table 3-3.

TABLE 3-3 – Potentially Available NO_X Control Technologies Identified for BACT Analysis

NOx Control Technology
Pre-Combustion Controls
Fuel Cleaning/Blending/Switching
Combustion Controls
Basic Combustion Control Improvements
Low NOx Burners (LNB)
Separated Overfire Air (SOFA)(1)
Flue Gas Recirculation
Fuel Reburn
Oxygen-enhanced combustion (OEC)
Water/steam injection (combustion tempering)
Post-Combustion Controls
Selective Non-Catalytic Reduction (SNCR)(2)
Selective Catalytic Reduction (SCR)
Electro-Catalytic Oxidation (ECO®)(3)

Notes: these are basic forms of the identified techniques.
Not all variations or combinations are included.
(1) – SOFA technologies include Boosted SOFA and Rotating Opposed Fired Air (ROFA)
(2) – SNCR technologies include Rich Reagent Injection, and Hydrocarbon-enhanced SNCR, commercially available as "NOxStar™".
(3) – Multi-pollutant control technology currently under commercial development by Powerspan Corp.

A comprehensive literature search, with sources including technical papers and presentations made at conferences by nationally-recognized technical organizations, utilities and other parties involved with design, construction, and testing of NO_X control techniques, plus hardware supplier experience lists, was performed. The results of this search are presented in Appendix A2, which includes a summary of various selected U.S. NO_X emission reduction retrofit projects.

3.2 FEASIBILITY ANALYSIS

The second step of the "top-down" BACT process is to evaluate the control processes that have been identified and determine if any of the processes are technically infeasible.

An available technology is "applicable" if it can be reasonably be installed and operated on the source type under consideration. Also, a control technique is considered available if it has reached the stage of licensing and commercial availability. For the purposes of this analysis, the term "commercial" is further defined to mean "capable of establishing a full contractual agreement with commercial and performance guarantees supported by appropriate financial backing" for the implementation of full-scale, full-time systems of the technique or technology application. A technology that is available and applicable is technically feasible.

There are three basic categories of NO_X emission control techniques and technologies:

- Pre-combustion controls;
- Combustion controls; and
- Post-combustion controls

Uncontrolled NO_X emissions from a coal-fired electric generating unit are highly dependent on type of firing method, amount of solid fuel fired per unit time and furnace volume, and the fuel's basic combustion properties and elemental composition. The basic methods for reduction of such emissions:

- either prevent pollution, i.e. use inherently lower-emitting processes/practices which produce fewer NO_X emissions during the power generation process; or
- involve improvements to, or provide new add-on controls that, reduce emissions after they are produced before they are emitted from the facility; or
- are combinations of inherently lower-emitting processes and add-on controls.

Most of the identified control options have been commercially-available, installed, and operating in many full-scale, permanent coal-fired utility boiler installations in the United States for five years or more.

Pre-combustion controls, such as fuel switching, fuel blending, and fuel cleaning have been practiced and performed at numerous utility power plants, typically for operational and sulfur emissions control reasons.

Combustion controls, such as low-NO_X burners (LNBs) and overfire air systems, are very commonly applied to reduce NO_X emissions from fossil fuel-fired powerplants. Low-NO_X Burners are typically applied to pulverized coal, gaseous and liquid fuel-fired boilers. They are not applicable to cyclone-fired boilers. Flue gas recirculation (FGR) has been practiced and performed at numerous natural gas and fuel oil-fired utility and industrial powerplants for NO_X emissions control reasons. On large coal-fired utility boilers, FGR has primarily been applied for steam temperature control purposes, not for emissions control. Conventional Gas Reburn (CGR) with overfire air has been installed and placed in commercial operation on several cyclone-fired boilers, primarily in the eastern region of the United States. Coal Reburn (CR) with overfire air has been successfully demonstrated on two cyclone-fired boilers and commercially installed on three pulverized coal-fired boilers in the United States. Combustion tempering (water/steam injection) has been tested but has not been continuously practiced on cyclone-fired coal boilers. Oxygen-enhanced combustion has only been demonstrated and/or installed on a limited number of pulverized coal-fired powerplants, not on any coal-fired cyclone boilers.

Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) are post-combustion technologies that have been applied predominantly on eastern or midwestern bituminous coal-fired boilers. Others, mostly comprised of a combination of available emission reduction technologies, are often referred to as "hybrid" or "layered" controls. Variations of SNCR, such as Rich Reagent Injection (RRI) with and without SNCR, have only been installed or demonstrated on a limited number of cyclone-fired boilers. Other technologies, such as Fuel Lean Gas Reburn™ with SNCR, hydrocarbon-enhanced SNCR (commercially available as NO_XStar™), and Conventional Gas Reburn with SNCR have only been demonstrated and/or installed on a limited number of pulverized coal-fired power plants.

Emerging post-combustion multi-pollutant control technologies, such as Powerspan's Electro-Catalytic Oxidation (ECO®), which include NO_X control, were also identified. These are typically in the large pilot-scale commercial development phase, and have not been successfully demonstrated on a full scale basis on any pulverized coal, cyclone, or circulating fluid bed boilers.

In most of the combination or "layered" and emerging control cases, the NO_X control technology has been demonstrated to be capable of controlling the targeted pollutant(s) on either:

- a full-scale basis, but only with temporary equipment; or
- a full-scale basis, with permanent equipment but in a limited number of installations; or

- with less than full-scale and full-time application.

3.2.1 SUMMARY OF RETROFIT INSTALLATIONS OF NO_X CONTROL TECHNOLOGIES

There are a number of facilities around the country that have implemented or are planning to implement modifications to reduce NO_X emissions. Table 3-4 summarizes the various NO_X emission control system installations currently installed, or that have been demonstrated on a full-scale, short-term basis, in response to Acid Rain requirements, EPA's NO_X SIP call and local regulations, or a utility investigating the technology.

TABLE 3-4 – Identified NO_X Control System Retrofits on Cyclone Coal-fired Boilers

No. of Units(1)	Cyclone NO_X Control Technology Description
1	Fuel Switching/Blending
39(2)	Separated Overfire Air (SOFA)
2	Selective Non-Catalytic Reduction, with or without SOFA
2(3)	Rich Reagent Injection, with SOFA
7(4)	Conventional fuel reburn (pulverized or micronized coal, gas), w/ SOFA
1(5)	Fuel lean gas reburn, with or without SOFA
22(6)	High-dust or low-dust SCR, with or without other technologies
1(6)	Tail-gas SCR, with or without other technologies

(1) – This list of known NOx control retrofit installations is primarily focused on units in the United States. There may be other installations that are similar but were not identified.
(2) – Installed for NOx control (without fuel reburn). A list of known cyclone boiler SOFA installations is included in Appendix A2.
(3) – RRI has only been demonstrated with temporary equipment for testing. See technical literature references in Appendix A1 and A2 for details.
(4) – Several conventional coal and gas reburn retrofits have discontinued reburn demonstration or routine operation. See Technical Literature Reference list and Appendix A3 for further details.
(5) – Only one example of fuel lean gas reburn retrofit (without OFA) on a cyclone-fired boiler has been demonstrated. This system was installed for short-term reburn testing and has been removed.
(6) – High-dust SCR technology has been retrofitted on sixteen U.S. cyclone-fired boilers, all believed to have SOFA. Low-dust SCRs in U.S. have only been installed only on pulverized coal-fired boilers, none on cyclones. One tail-gas SCR installation on a coal-fired cyclone boiler found in Germany; none in the U.S. See technical literature references in Appendix A1 and A2 for details.

A more detailed description of the various control technology retrofits and their claimed effectiveness is included in the technical descriptions and reference literature in the technical feasibility assessment of

Appendix A1, and Appendix A2, which includes a summary of various selected U.S. NO_X emission reduction retrofit projects.

3.2.2 SUMMARY OF FEASIBLE NO_X CONTROL TECHNOLOGIES FOR MRY STATION

One example of fuel switching applied to a cyclone-fired boiler was identified. Ottertail's Big Stone Unit 1 was originally designed to burn North Dakota lignite and was switched to western subbituminous (PRB) coal for reasons unrelated to NO_X emissions reduction. Big Stone Unit 1 and M.R. Young Station Unit 2 have similar boiler designs. Thus, conversion of Milton R. Young Station Unit 2's boiler to fire PRB coal or a lignite/PRB blend is technically possible. There are no railroad facilities provided to service the Milton R. Young plant. Additional operational and capital costs to bring in large quantities of PRB coal will be significant. Based on a comparison of available emission data between Ottertail's Big Stone Unit 1 and M.R. Station Young Unit 2, there is no expected reduction in baseline (i.e. uncontrolled) NO_X emissions from switching to PRB from lignite at Milton R. Young Station. Although fuel switching at Milton R. Young Station is technically feasible, this alternative will not be economically competitive with other NO_X control technologies that offer better results for a much lower combination of capital and operational costs. For these reasons, it has not been considered further as an effective NO_X emissions control option for MRY Station Unit 2 boiler.

Separated Overfire Air (SOFA) is the most commonly-applied, combustion-related NO_X emission reduction technology that has been proven effective on cyclone-fired boilers. A version of separated overfire air specifically designed for increased NO_X emission reduction performance for lignite-fired cyclone boilers, referred to as "Advanced SOFA" in this analysis, can be installed on both units at M.R. Young Station. The potential operational limitations mentioned in the detailed feasibility discussions included in Appendix A1 for deeply air-staged cyclones associated with separated overfire air are expected to limit the control effectiveness of this technique, alone and in combination with other feasible NO_X control options.

Selective Non-Catalytic Reduction (SNCR) technology is a form of post-combustion NO_X emission control that has been successfully applied on numerous utility boilers burning eastern bituminous coal, midwestern bituminous coal, and, to a lesser extent, western subbituminous coal to reduce NO_X emissions. SNCR has also been used on fuel oil and natural gas-fired units. SNCR does not appear to be dependent directly on the type of burners (wall-fired, tangentially-fired, and cyclone-fired) employed in

the boilers where it has been installed, with or without air-staged combustion with overfire air in full operation. This control technology adds urea (or ammonia) reagent to the hot furnace gases in the upper furnace to chemically reduce nitrogen oxides. SNCR was considered technically feasible for application on both units at M.R. Young Station. SNCR can be operated with and without SOFA. Variations of SNCR technologies such as Hydrocarbon-enhanced SNCR (HE-SNCR) and "Rotamix" have been installed on pulverized coal-fired boilers but are not proven on cyclone boilers. This is described in detail in Appendix A1.

Rich Reagent Injection (RRI) is a form of SNCR under development specifically intended for NOx emissions control on cyclone boilers. As of October 2006, RRI has been demonstrated but has not been commercially installed and placed in continuous operation on a cyclone-fired boiler, especially one burning coal with high fouling and slag temperature sensitivities associated with lignite supplied from the Center mine. RRI adds aqueous urea reagent to the hot furnace gases near the cyclones, which must be devoid of free oxygen in order to avoid oxidation of the urea which will increase NOx emissions. RRI is considered technically infeasible for application on the cyclone boilers at the Milton R. Young Station at the present time. This is described in detail in Appendix A1.

Various forms of fuel reburn with and without overfire air are types of combustion-related technologies that have been demonstrated and commercially installed on pulverized coal, fuel oil-fired, and cyclone utility and industrial boilers. Natural gas-consuming variations such as Conventional Gas Reburn (CGR) and Fuel-Lean Gas Reburn (FLGR™) have been applied to cyclone boilers burning bituminous and subbituminous coals. High capital costs expected for installing a natural gas pipeline and high operating costs from consumption of large volumes of such fuel make these alternatives economically unfavorable for both units at M.R. Young Station. Pulverized or micronized coal reburn, in combination with SOFA, are technically feasible but will require extensive capital, operating and maintenance costs for fuel grinding equipment and facilities when installed and operated for both units at M.R. Young Station. This is described in detail in Appendix A1.

Fuel cleaning is a technique normally applied to reduce the sulfur or ash content of a fossil fuel prior to combustion. No examples of fuel cleaning of North Dakota lignite or western subbituminous coal strictly for NO_X emissions reduction were found in available technical literature. This technique is considered infeasible for NO_X emissions control of M.R. Young Station boilers at the present time.

High-dust, low-dust, and tail-gas variations of selective catalytic reduction (SCR) technology have been applied on pulverized coal and cyclone boilers as a post-combustion type of NO_X emission control throughout the world and in the United States, except on units firing North Dakota lignite. The severity of catalyst blinding and pluggage from particulate matter and flue gases emitted from cyclone-fired boilers burning North Dakota lignite precludes the technical feasibility for successful application of such SCR technology on the EGUs at the Milton R. Young Station. This is described in detail in Appendix A1 with supporting documentation in Appendix B.

The results of Step 2 of the NO_X BACT Analysis for determining the technical feasibility of potential control technologies, including various "layered" combinations, are listed in Tables 3-5 and 3-6.

TABLE 3-5 – Technically-Feasible Potential NO_X Control Technologies for M.R. Young Station Unit 2 Cyclone Boiler

Control Technology(1)	In Permanent, Full-Scale Service on Existing Coal-Fired Cyclone Utility Boilers?	Technically Feasible on M.R. Young Station Unit 2 boiler?
Selective Non-Catalytic Reduction (SNCR)	Yes(2)	Yes
Conventional Gas Reburn	Yes(3)	Yes(3); Requires SOFA or ASOFA
Coal Reburn	Yes(4)	Yes(4); Requires SOFA or ASOFA
Fuel Lean Gas Reburn	No(5)	Yes(5) (w/ or w/out SOFA or ASOFA)
Advanced SOFA	No(6)	Yes(6). Includes relocated lignite drying vent ports
Separated OFA (basic SOFA)	Yes(6)	Yes(6)
Combustion Improvements	Yes	Yes(7); typically included with separated OFA
Flue Gas Recirculation	Not for NOx control	Yes(8) (not expected to reduce NOx further)
Fuel Switching / Blending	Yes	Yes(9) (not expected to reduce NOx further)

See technical feasibility details and literature References in Appendix A for details.

(1) – All potential combinations of technologies not listed. See discussion of "layered" technologies.

(2) – Assumes use of urea for reagent. Limited number of active installations on cyclone-fired boilers burning western subbituminous (i.e. Powder River Basin or PRB) coal.

(3) – Limited number of active conventional gas reburn (CGR) installations on cyclone-fired boilers burning PRB coal.

(4) – Limited number of demonstrations or active installations of pulverized or micronized coal reburn on cyclone-fired boilers. One demonstration of pulverized coal reburning with PRB coal has been performed on a cyclone-fired boiler, no longer active. Only one active permanent coal reburn installation on cyclone-fired boiler burning eastern bituminous coal, none burning PRB coal or lignite.

(5) – Only one short-term test demonstration of FLGR™ on a cyclone-fired boiler burning coal with separated overfire air.

(6) – No cyclone boilers firing North Dakota lignite have installed basic or advanced SOFA. See Appendix A.

(7) – Considered part of SOFA installation for coal boilers without combustion controls for NOx reduction.

(8) – No examples of using recirculated flue gas on coal-fired boilers for NOx emissions control were found in available technical literature. Zero additional NO_X reduction potential expected from this technique alone for MRY Station Unit 2. Potential NO_X reduction improvement on MRY Unit 2 considered part of "advanced" SOFA.

(9) – Zero additional NO_X reduction potential expected from this technique (switching from lignite to lignite/PRB blends or 100% PRB) alone for MRY Station Unit 2.

TABLE 3-6 – Technically Infeasible Potential NO_X Control Technologies for M.R. Young Station Unit 2 Cyclone Boiler

Control Technology(1)	In Permanent, Full-Scale Service on Existing Coal-Fired Cyclone Utility Boilers?	Technically Feasible on M.R. Young Station Unit 2 boiler?
Selective Catalytic Reduction (SCR): conventional (high dust); Low-dust; Tail-gas	Yes(2) / No / Yes(3)	No(4) - Unresolvable fouling and catalyst deactivation problems expected. See discussion of SCR feasibility for ND lignite.
Electro-Catalytic Oxidation (ECO®)	No	No, has not been demonstrated full-scale nor reached commercial availability
HE-SNCR (using ammonia)	No(5)	No(5). Has not been demonstrated on cyclone.
Rotamix (ROFA + SNCR)	No(6)	No(6). Has not been demonstrated on cyclone.
Rich Reagent Injection (RRI) with ASOFA	No(7)	No(7). Requires oxygen-free furnace environment, varying air/fuel would increase NOx emissions.
RRI + SNCR with ASOFA	No(7)	No(7). See footnote and feasibility discussion.
Advanced Conventional Gas Reburn (ACGR) + SNCR	No(8)	No. Has not been demonstrated on cyclone.
Coal Reburn + SNCR	No(8)	No. Has not been demonstrated on cyclone.
Fuel Lean Gas Reburn + SNCR	No(8)	No. Has not been demonstrated on cyclone.
Rotating Opposed-Fired Air	No(6)	No. Has not been demonstrated on cyclone.
Oxygen Enhanced Combustion	No(9)	No. Has not been demonstrated on cyclone.
Water Injection	No(10)	No(10)
Fuel Cleaning	Not for NOx control	No(11) (not expected to reduce NOx further)

See technical feasibility details and literature References in Appendix A for details.

(1) – All potential combinations of technologies not listed. See discussion of "layered" technologies.

(2) – Limited number of active installations on cyclone-fired boilers burning western subbituminous coal.

(3) – No identified installations on coal-fired boilers in the United States. One tail-end SCR on cyclone boiler in Germany.

(4) – See discussion of SCR feasibility for ND lignite in Appendix A1 and Appendix B.

(5) – Hydrocarbon-enhanced SNCR has not been demonstrated on a cyclone-fired boiler, nor any boiler firing western subbituminous coal or lignite.

(6) – Rotating Opposed-Fired Air with or without SNCR has not been demonstrated on a cyclone-fired boiler. No apparent significant advantages over SOFA on cyclone-fired boilers.

(7) – Rich Reagent Injection has been successfully demonstrated for brief periods with SOFA with and without SNCR at two cyclone powerplants. There are no permanent RRI installations completed and operational as of May 2006. Difficulties in maintaining an oxygen-free furnace environment in MRY Station boilers where the urea reagent would be injected due to cyclone air/fuel imbalances during air-starved combustion would increase NOx emissions.

(8) – No known demonstrations or permanent installations of Advanced conventional gas reburn (CGR) or FLGR™ or pulverized/micronized coal reburn (PCR/mCR) in combination with SNCR on cyclone-fired boilers. CGR and PCR/mCR require separated overfire air. FLGR™ has been applied to pulverized coal firing with and without SOFA, with and without SNCR; FLGR™ with SNCR is also called amine-enhanced fuel lean gas reburn (AEFLGR™).

(9) – No known demonstrations or permanent installations of oxygen-enhanced combustion (OEC) on cyclone-fired boilers.

(10) – No permanently installed examples of using this technique continuously on coal-fired boilers were found in available technical literature. Not suitable for high-moisture lignite fuels.

(11) – No known demonstrations or permanent installations of using this technique continuously on coal-fired boilers for NOx emissions control were found in available technical literature.

Additional criteria besides technical feasibility are utilized for technology selection in a BACT analysis have been included in the following sections summarizing control effectiveness estimates, capital plus operating and maintenance cost estimates, energy impacts, and environmental impacts:

- Control effectiveness (i.e. percent pollutant removed)
- Expected emission rate (see Tables 3-7, 3-8) and emission reduction (tons per year)
- Economic impacts (total cost and incremental cost effectiveness)
- Energy impacts
- Environmental impacts (other media and emissions of toxic and hazardous air pollutants)

3.3 RANK OF TECHNICALLY FEASIBLE NO_X CONTROL OPTIONS BY EFFECTIVENESS

The third step in the "top-down" BACT evaluation is to rank the remaining control technologies by effectiveness. The purpose of ranking the control technologies is to establish a hierarchy that "places at the "top" the control technology that achieves the lowest emission level."

The emission reduction (control effectiveness) percentages developed for ranking the available NO_X emission control options considered feasible for Milton R. Young Station Unit 2 are shown in Table 3-7. These are estimates based upon engineering judgments with considerations of:

- Boiler heat input rates associated with realistic upper boundary operating assumptions;
- baseline emission rates corresponding to the realistic upper boundary operating assumptions;
- the general combustion properties of North Dakota lignite;
- published and available emission reduction performance achieved at other similar utility powerplants (cyclone-fired boilers);
- computer-derived predictions; and
- inclusion of performance margins to allow for variations in fuel, weather, equipment condition, and other factors that prevent the ultimate peak short-term performance from being reliably sustained over the course of long-term operation.

These NO_X emission level and reduction percentage estimates include adjustments of previously demonstrated or predicted performance that reflect differences between North Dakota lignite and eastern or midwestern bituminous and western subbituminous coals.

The numbers assume the estimated capability of the employed technique is achievable and sustainable (long-term) and that potential operational limitations mentioned in the feasibility discussions allow the successful practice of the technique or technology. None of the remaining control options has been installed on a cyclone-fired boiler burning North Dakota lignite. As such, the expressed control percentages reflect the use of engineering judgment, based on the listed technique or technology application. This is particularly pertinent to all control options that involve air-staged combustion associated with various forms of separated overfire air. SOFA-based controls for cyclone-fired coal-burning boilers have typically reduced NO_X emission levels significantly from the precontrol baseline, and which allow or enhance further reductions when combined with other control techniques and technologies.

3.3.1 ESTABLISHING BASELINE NO_X EMISSIONS FOR RANKING CONTROL OPTIONS

Before the various feasible NO_X emission control alternatives can be estimated and ranked in order of effectiveness, the precontrol baseline level of emissions and its basis must be determined. The EPA's NSR Manual provides general guidance for establishing estimated baseline emissions to be used for the purpose of calculating and comparing the control and cost-effectiveness of a control option:

> "The baseline emissions rate represents a realistic scenario of upper boundary uncontrolled emissions from the source. The NSPS/NESHAP requirements or the application of controls, including other controls necessary to comply with State or local air pollution regulations, are not considered in calculating the baseline emissions. In other words, baseline emissions are essentially uncontrolled emissions, calculated using realistic upper boundary operating assumptions. When calculating the cost effectiveness of added post-process emissions controls to certain inherently lower polluting processes, baseline emissions may be assumed to be the emissions from the lower polluting process itself. In other words, emission reduction credit can be taken for the use of inherently lower polluting processes"[25].

Also stated in the EPA's NSR Manual:

> "Estimating realistic upper bound case scenario does not mean that the source operates in an absolute worst-case manner all the time. For example, in developing a realistic upper boundary case, baseline emissions calculations can also consider inherent physical or operational constraints on the source. Such constraints should accurately reflect the true

[25] Ibid, NSR Manual B.37

upper boundary of the source's ability to physically operate and the applicant should submit documentation to verify these constraints"[26].

Establishing estimated baseline NO_X emissions for a new or existing source involves determining the design or operational basis of the emission rate. A useful means of comparing such emission rates is to establish the unit emission rate, expressed in pounds of pollutant per unit of process output. For processes such as steam-electric generating powerplants utilizing combustion in boilers, the desired process output (kilowatts or megawatts) can be related to the pollutant-bearing flue gas created by the combustion of fuel. Units of fuel heat input (millions of BTUs) required to create a unit of desired electrical output (kW) and thus the efficiency of converting the fuel heat to such electrical output (unit heat rate, Btu/kW-hr) are important.

A review of reported hourly NO_X emissions for MRY Station Unit 2 boiler, including unit mass rates (lb/mmBtu and lb/hr), boiler heat input (mmBtu/hr), and gross electrical output in megawatts (MW_g), was performed for the operating periods in years 2001-2005 inclusive. A realistic upper bound emission case scenario for each boiler's baseline emissions at Milton R. Young Station determined the highest summation of any rolling 12-month period NO_X mass emissions (pounds), along with the summation of the gross heat input (mmBtus) and the boiler operating hours for the same rolling 12-month period corresponding to the highest NO_X pounds. Dividing the summation of the rolling 12-month NO_X pounds by heat input results in a average unit emission rates (lb/mmBtu). Likewise, the summation of the rolling 12-month gross heat input (mmBtus) divided by the boiler operating hours yields an average gross heat input rate (mmBtu/hr). This emission evaluation revealed that:

- Unit 2 at Milton R. Young Station is typically operated in a base-loaded manner;
- MRYS Unit 2's highest 12-consecutive month NO_X mass emissions summation divided by the summation of the same 12-month period's heat input averaged 0.786 lb/mmBtu at a corresponding average unit heat input rate of 4,885 mmBtu/hr and unit gross electrical output of 440 MW_g.

3.3.2 ESTIMATING CONTROL-EFFECTIVENESS OF NO_X EMISSIONS CONTROL OPTIONS

The degree of success in operation of separated overfire air alone and in combination with the other selected feasible alternatives is important to the amount of NO_X emission reduction achieved. The

[26] Ibid, NSR Manual B.37

emission control performance from the advanced version of separated overfire air (ASOFA) is highly dependent on the degree of success in admitting combustion air insufficient for complete combustion in the cyclones without causing related negative impacts. The control percentages estimated for firing North Dakota lignite in the MRY Station boilers reflect the belief that operating the existing cyclones much below an average cyclone stoichiometric ratio of approximately 0.95 (95% of the theoretical amount of combustion air required for complete combustion) will not be successful. This is due primarily to the expected "starved air" combustion causing a reduction in cyclone furnace gas temperatures, thus creating a strong potential for molten slag solidifying in the cyclone barrels, slag taps, and lower furnace floor openings. This would impose a great interruption to steam production since forced outages would be required to remove this physical obstruction before full load boiler operation could be reestablished. The EPA's draft NSR Manual states "It is not the EPA's intention to require analysis of each possible level of efficiency for a control technique, as such an analysis would result in a large number of options"[27].

The potential operational limitations for deeply air-staged cyclones associated with separated overfire air and coal reburn alternatives are expected to limit the amount of NO_X control potential possible from successful practice of the particular technique or technology. This is described in the detailed feasibility discussions included in Appendix A1.

The advanced form of separated overfire air is expected to be effective in NO_X emission reduction and can be combined with other feasible combustion-related and post-combustion control alternatives for these lignite-fired cyclone boilers. The basic form of SOFA in combination with coal reburn, gas reburn options, and SNCR, was not included in the detailed control effectiveness analysis in order to limit the number of options that were evaluated.

Using an advanced form of SOFA system, M.R. Young Station's Unit 2's boiler operating at MCR is expected to achieve a NO_X emission level of 0.49 lb/mmBtu when operating modestly air-staged cyclone furnaces with suitable combustion controls. This level of NO_X reduction from ASOFA operation, approximately thirty eight percent, is based on the expected ability to reduce emissions without incurring potential significant negative impacts of this technique. This reduction estimate includes the additional amounts of control potential available from operating with relocated lignite drying system vent ports (and FGR ports for Unit 2) associated with ASOFA operation with modestly air-staged cyclone furnaces.

[27] Ibid, NSR Manual B.37

Coal reburn with ASOFA is estimated to reduce NO_X emissions for M.R. Young Station's Unit 2's boiler operating at MCR slightly more than 54 percent from the pre-control baseline NO_X emission rate, considering similar control levels demonstrated by previous coal-reburn retrofits on cyclone-fired boilers and limitations previously discussed with ASOFA.

Conventional Gas Reburn and Fuel Lean Gas Reburn options were both assumed to be installed with ASOFA. NO_X reduction from CGR with ASOFA operation is expected to be approximately 55.4 percent. FLGR with ASOFA is expected to reduce NO_X emissions approximately forty five percent. Estimates for NO_X emissions for M.R. Young Station's Unit 2's boiler considered similar control levels demonstrated by previous gas-reburn retrofits on cyclone-fired boilers with modestly air-staged cyclone furnaces and limitations previously discussed with ASOFA.

The NO_X emission rate for Selective Non-Catalytic Reduction (SNCR) (using urea) with ASOFA is expected to be approximately 0.355 / 0.33, resulting from a reduction in NO_X emissions of approximately 58 percent from the 12-month average pre-control baseline NO_X emission rate.

Included in the feasible control option ranking of Table 3-7 are layered alternatives that were shown in Table 3-5. The highest-performing NO_X control alternatives remaining in consideration are ranked in declining order of expected emission reduction. These combined control options refer to "advanced" SOFA, which is expected to have significantly lower NO_X emissions than a typical SOFA system as applied to the Milton R. Young cyclone boilers.

TABLE 3-7 – Ranked NO_X Control Options Feasible for MRY Station Unit 2 Boiler with Expected Control Performance

Alt. Label(1)	NO_X Control Technique	Emission Rate (lb/mmBtu)	Control Percentage(2)
E	SNCR (using urea) w/ ASOFA	0.330	58.0
D	Gas Reburn with ASOFA	0.350	55.4
C	Lignite Reburn w/ ASOFA	0.360	54.2
B	Fuel Lean Gas Reburn with ASOFA	0.432	45.0
A	Advanced Separated Overfire Air (ASOFA)	0.489	37.7
-	Baseline	0.786	-

(1) - Alternative designation assigned from highest to lowest unit NOx emission rate.
(2) - Control percentages are relative to an average pre-control emission baseline of 0.786 lb/mmBtu based on annual operation at highest pre-control 12-month rolling NOx summation mass emissions divided by the 12-month heat input summation.

The annual emission levels developed for Table 3-7's ranking the feasible alternatives assume that the highest 12-month average pre-retrofit level of unit NO_X emissions for M.R. Young Station's Unit 2's boiler is a baseline of 0.786 lb/mmBtu. This was determined from the highest reported rolling 12 consecutive month period's summation of hourly NO_X emissions (lbs).

The hourly gross fuel heat input (mmBtu) was summed over that same 12-month time period, and divided by the number of boiler operating hours to yield an annual average gross fuel heat input rate (mmBtu/hr). Multiplying the 12-month average heat input rate (mmBtu/hr) by the baseline or control alternative's 12-month average unit emission rate (lb/mmBtu) equals a 12-month average hourly NO_X emissions rate (lb/hr). Annual NO_X emissions (tons) for the baseline pre-control condition were calculated by multiplying the 12-month summation for boiler operating hours during the same period as the highest NO_X emissions by the 12-month average emission rate (lb/hr). The annual tons for the control options were calculated by multiplying the alternative's average annual emission rate (lb/yr) by a reduction factor (if applicable) for heat input or running plant capacity and adjusting boiler operating hours by an annual uptime (availability) factor. Details for these adjustments are included in Appendix C3. Based on these calculations, the annual emissions for M.R. Young Station's Unit 2's boiler are shown in Table 3-8.

TABLE 3-8 – Expected Annual NO_X Control Performance for MRY Station Unit 2 Alternatives

		EMISSIONS				NOx Removal Efficiency[5]
Alt. Label[1]	NOx Control Alternative	Emission Rate lb/mmBtu	Hourly Emission[2] lbs/hr	Annual Emission[3] tons/yr	Emission Reduction[4] tons/yr	%
E	SNCR (using urea) w/ ASOFA	0.330	1,612	6,421	9,372	58.0
D	Gas Reburn w/ ASOFA	0.350	1,710	6,882	8,910	55.4
C	Lignite Reburn w/ ASOFA	0.360	1,759	6,964	8,829	54.2
B	Fuel Lean Gas Reburn w/ ASOFA	0.432	2,110	8,490	7,303	45.0
A	Advanced Separated Overfire Air (ASOFA)	0.489	2,391	9,621	6,172	37.7
-	Baseline	0.786	3,839	15,793	0	-

(1) - Alternative label has been assigned from highest to lowest unit NOx emission rate.
(2) - Hourly NO_X emission estimates (lb/hr) were calculated based upon average annual unit emission rate (lb/mmBtu) x 4,885 mmBtu/hr MCR heat input.
(3) - Estimated annual emission tons assume an annual unit availability factor specific to each alternative; 93.9% was assumed for the baseline case. See Appendix C3.
(4) - Estimated annual tons of emission reduction is the difference between annual baseline tons and each alternative's annual emissions (tons).
(5) - Estimated NO_X control level percentage reductions relative to 0.786 lb/mmBtu emission baseline at 4,885 mmBtu/hr MCR heat input.

3.4 NO_X CONTROLS ANALYSIS AND IMPACTS EVALUATION

The fourth step of a "top-down" BACT review is to evaluate the most effective emission controls. Energy, economic, and environmental impacts are to be considered in the control technology evaluation. The purpose of the evaluation is to determine if there are any energy, economic or environmental impacts that would eliminate the top control technologies from consideration.

3.4.1 NO_X CONTROL ECONOMIC IMPACTS FOR MRY STATION UNIT 2

An evaluation was performed to determine the various cost impacts of installing feasible NO_X control alternatives on Milton R. Young Unit 2. This evaluation includes estimated:

- Capital costs;
- Fixed and variable operating and maintenance costs; and
- Levelized total annual costs

to engineer, procure, construct, install, startup, test, and place into commercial operation the particular control technology. The results of this evaluation are summarized in Tables 3-9 through 3-13.

3.4.1.1 CAPITAL COST ESTIMATES FOR NO_X CONTROL ALTERNATIVES

The capital costs to implement the various NO_X control technologies were largely estimated from unit output capital cost factors ($/kW) published in technical papers discussing those control technologies. In the cases of SNCR, preliminary vendor budgetary cost information was obtained and used in place of, or to adjust, the published unit output cost factors. These cost estimates were considered to be study grade, which is + or – 30% accuracy.

The unit nameplate output capacity (gross electrical output in megawatts) assumed for the NO_X control technologies capital cost estimate basis was 477 MW_g for MRY Station Unit 2[28].

A review of the unit capital cost factor range and single point factors applicable to MRY Station Unit 2 NO_X control technologies are presented in Table 3-9. The estimated installed and levelized capital costs for the highest-performing form of the various feasible NO_X emission reduction technologies evaluated for cost-effectiveness are shown in Table 3.10. These are listed in order of control effectiveness, with the highest ranked option at the top.

[28] Ibid footnote number 23.

TABLE 3-9 – Unit Capital Cost Factors of Feasible NO_X Control Options for MRY Station Unit 2

Alt. Label(1)	NO_X Control Technique	Range(2) ($/kW)	Single Point Unit Capital Cost Factor(3), ($/kW) MRYS Unit 2
E	SNCR (using urea) w/ ASOFA	20-35)6)	35.9(4),(5)
D	Gas Reburn w/ ASOFA	15-30(6)	74.4(5),(6),(7)
C	Lignite Reburn w/ ASOFA	30-60(6)	170.2(5),(8)
B	Fuel Lean Gas Reburn w/ ASOFA	--(9)	45.7(4),(5),(9)
A	Advanced Separated Overfire Air (ASOFA)	5-10(6)	21(5)

(1) – Alternative designation has been assigned from highest to lowest unit NOx emission rate.
(2) – Unit capital cost factors ($/kW) of these individual technologies combined by simple addition. Actual installed costs may differ this due to positive or negative synergistic effects. Range based on published values or vendor proposals.
(3) – Single point cost factor is best estimate for determination of total capital cost for a particular technology or combination, assuming maximum unit capacity is based on existing nameplate rating. Single point cost figures in 2006 dollars.
(4) – Estimated capital cost for SNCR point estimate and FLGR point estimate derived from December 2004 budgetary proposal by Fuel Tech. See Appendix C2 for details.
(5) – The single point unit capital cost factor shown for the "advanced" version of SOFA derived from Burns & McDonnell internal database and cost estimate for North Dakota lignite-fired cyclone boilers.
(6) – NESCAUM 2005 Technical Paper, posted at their website. See technical references in Appendix A1 for details.
(7) – The single point unit capital cost factor shown for a conventional gas reburn system includes the estimated capital cost to install a high-pressure natural gas supply pipeline (31.4 $/kW), and that both boilers share the capital cost in proportion to their respective rated MW gross output capacities.
(8) – The single point unit capital cost factor shown for a lignite reburn system is highly site-specific, and assumes that new pulverizers and building enclosures are required. The general cost range for pulverized coal-fired boilers is included in the NESCAUM 2005 Technical Paper; for cyclone boilers is included in the 2005 WRAP Draft Report, posted at their website. The single point unit capital cost factor for this alternative for increased PM collection capacity included in lignite reburn option is 75.5 $/kW. See technical references in Appendix A1 for details.
(9) – The unit capital cost factor range for FLGR applications on boilers without an existing a high-pressure natural gas supply was not found in available technical literature. The single point unit capital cost factor shown for a fuel lean gas reburn system includes the estimated capital cost to install a high-pressure natural gas supply pipeline (15.7 $/kW), and that both boilers share the capital cost in proportion to their respective rated MW gross output capacities.

TABLE 3-10 – Estimated Capital Costs for NO_X Control Alternatives - MRY Station Unit 2

Alt. Label(1)	NOx Control Alternative	Installed Capital Cost(2) $1,000	Annualized Capital Cost(3) $1,000
E	SNCR w/ ASOFA	17,128	1,493
D	Gas Reburn w/ ASOFA[4]	35,490	3,094
C	Lignite Reburn w/ ASOFA[5]	81,167	7,077
B	Fuel Lean Gas Reburn w/ ASOFA[4]	21,817	1,902
A	Advanced SOFA (ASOFA)	10,008	873
	Baseline	0	0

(1) - Alternative label has been assigned from highest to lowest unit NOx emission rate.
(2) - Installed capital cost is estimated for determination of total capital cost for a particular technology or combination, assuming 477 MWg unit capacity rating. All cost figures in 2006 dollars.
(3) - Annualized capital cost = Installed capital cost x 0.08718 annualized capital cost factor.
(4) - Costs for gas reburn options include high-pressure natural gas supply pipeline installed capital cost of $14,988,000 for CGR and $7,494,000 for FLGR; and annualized capital cost of $1,307,000/yr for CGR and $653,000 for FLGR. See footnotes #8 and 10 under Table 3-9.
(5) - Costs for increased PM collection capacity included in lignite reburn option are $36,013,000 for installed capital cost, and $3,140,000/yr annualized capital cost.

3.4.1.2 Operating and Maintenance Cost Estimates for MRY Station NO_X Controls

The operational and maintenance costs to implement the various NO_X control technologies were largely estimated from cost factors (percentages of installed capital costs) established in the EPA's Air Pollution Control Cost Manual (OAQPS) for SNCR[29], and from published in technical papers discussing those control technologies. In the cases including various forms of SNCR, preliminary vendor quotes were obtained and used in place of, or to adjust the OAQPS cost factors. These cost estimates were considered to be study grade, which is + or – 30% accuracy.

Fixed and variable operating and maintenance costs considered and included in each NO_X control technology's annual O&M costs are estimates of:

- Auxiliary electrical power consumption for operating the additional control equipment;
- Reagent consumption, and reagent unit cost for SNCR alternatives; and
- Reagent dilution water consumption and unit cost for SNCR alternatives.

[29] EPA Office of Air Quality Planning and Standards (OAQPS) publication EPA/452/B-02-001, Section 4.2, NO_X Controls – NO_X Post-Combustion, Chapter 1 - Selective Non-Catalytic Reduction, dated October 2000, posted at their website: http://www.epa.gov/ttn/catc/dir1/cs4-2 ch1.pdf

- Increases or savings in auxiliary electrical power consumption for changes in coal preparation equipment and loading, primarily for fuel reburn cases;
- General operating labor, plus maintenance labor and materials devoted to the additional emission control equipment and its impact on existing boiler equipment.
- Reductions in revenue expected to result from loss of unit availability, i.e. outages attributable to the control option, which reduce annual net electrical generation available for sale (revenue).

For economic evaluation purposes, an annual average running plant capacity factor of 95.2 percent compared to a nominal unit output capacity of 462 MWg combined with an average annual availability (uptime) of 8,229 operating hours (93.9 percent of 8760 hours per year) resulting in an annual unit capacity factor of 89.5% were assumed for Unit 2's pre-control baseline annual operation. A heat input rate of 4,885 mmBtu/hr and a NO_X emission rate of 0.786 lb/mmBtu were assumed for calculating control and cost-effectiveness from pre-control maximum rolling 12 month summation of nitrogen oxides' mass emissions for MRY Station Unit 2.

Table 3-11 show the estimated annual operating and maintenance costs and levelized annual O&M cost values for the highest-performing form of the various feasible NO_X emission reduction technologies. These are listed in order of control effectiveness, with the highest ranked options at the top. The cost methodology summarized in Appendix C3 provides more details for the levelized annual O&M cost calculations and cost factors.

TABLE 3-11 – Estimated O&M Costs for NO_X Control Alternatives - MRY Station Unit 2

Alt. Label(1)	NOx Control Alternative	Annual O&M Cost(2) $1,000	Levelized Annual O&M Cost(3) $1,000
E	SNCR w/ ASOFA	8,108	10,125
D	Gas Reburn w/ ASOFA	48,688	60,798
C	Lignite Reburn w/ ASOFA	9,929	12,398
B	FLGR w/ ASOFA	21,954	27,411
A	Advanced SOFA (ASOFA)	2,805	3,503
	Baseline	0	0

(1) - Alternative label has been assigned from highest to lowest unit NOx emission rate.
(2) - Annual operating and maintenance cost for a particular technology or combination is compared to unit baseline operation at nominal unit capacity (462 MWg) and assumes a 93.9% average annual availability, which is highest consecutive 12-months of operation from 2001-2005. All cost figures in 2006 dollars.

(4) - Costs for increased PM collection capacity included in lignite reburn option are $3,358,000/yr for annual O&M cost, and $4,194,000/yr annualized O&M cost.

3.4.1.3 LEVELIZED TOTAL ANNUAL COST ESTIMATES FOR MRY STATION NO_X CONTROLS

In order to compare a particular NO_X emission reduction alternative during the initial engineering analysis portion of the BACT selection process, the sum of estimated annualized installed capital plus levelized annual operating and maintenance costs, which is referred to as "Levelized Total Annual Cost" (LTAC) of expected pollutant removal by implementing that alternative was calculated. The LTAC for all NO_X control alternatives was calculated based on the same economic conditions and a 20 year project life (see Appendix C1 for methodology). The unit control cost was then determined as the LTAC divided by annual tons of pollutant emissions that would be avoided by implementation of the respective alternative. The control alternatives were also compared by calculating the change in unit cost (incremental cost) per incremental ton removed for the next most stringent alternative. This identified which alternatives produced the highest increment of expected pollutant reduction for the estimated lowest average annual cost increment compared with the baseline emission rate. The expected annual number of tons of pollutant removed versus estimated LTAC for each remaining control alternative was then plotted.

The comparison of the cost-effectiveness of the remaining NO_X emission reduction technologies was made and is shown in Table 3-12 and Figures 3-1 and 3-2 for MRY Station Unit 2. These figures plot estimated annual amount of NO_X removal (emission reduction) in tons per year on the ordinate (horizontal axis) and the estimated levelized total annual cost in thousands of U.S. dollars per year on the abscissa (vertical axis), for each of the remaining NO_X control technologies. Points on the graph that are farthest to the right and closest to the horizontal axis are deemed more cost-effective, since they represent controls that achieve more NO_X removal per dollar required for total annual costs of operation, maintenance, and capital recovery (depreciation).

Although the NSR Manual repeatedly prescribes following a "top down" analysis approach for BACT determination, the development of a least cost envelope with dominant controls (as seen in NSR Manual Figure B-1, page B.42) clearly labels points with lower emissions reductions and total annual costs first, i.e. "A", "B", etc. then proceeding with labeling and connecting points plotted further away from the zero emission reduction point. This "bottom-up" approach is for plotting the least-cost (dominant) control curve. The labeling of each unit's NOx control technique alternative has followed this approach.

TABLE 3-12 – Estimated Annual Emissions and Levelized Total Annual Cost for NO_X Control Alternatives - MRY Station Unit 2

Alt. Label(1)	NOx Control Alternative	Annual NOx Emissions(2) Tons/yr	Annual NOx Emissions Reduction(3) Tons/yr	Levelized Total Annual Cost(4) $1,000	Average Control Cost(5) $/ton
E	SNCR w/ ASOFA	6,421	9,372	11,618	1,240
D	Gas Reburn w/ ASOFA	6,882	8,910	63,892(6)	7,171
C	Lignite Reburn w/ ASOFA	6,964	8,829	19,475(7)	2,206
B	FLGR w/ ASOFA	8,490	7,303	29,317(6)	4,014
A	Advanced SOFA (ASOFA)	9,621	6,172	4,376	709
	Baseline	15,793	0	0	

(1) - Alternative label has been assigned from highest to lowest unit NOx emission rate.

(2) - Estimated annual emission tons assume an annual unit availability factor specific to each alternative; 93.9% was assumed for the baseline case.

(3) - Estimated annual tons of emission reduction is the difference between annual baseline tons and each alternative's annual emissions (tons).

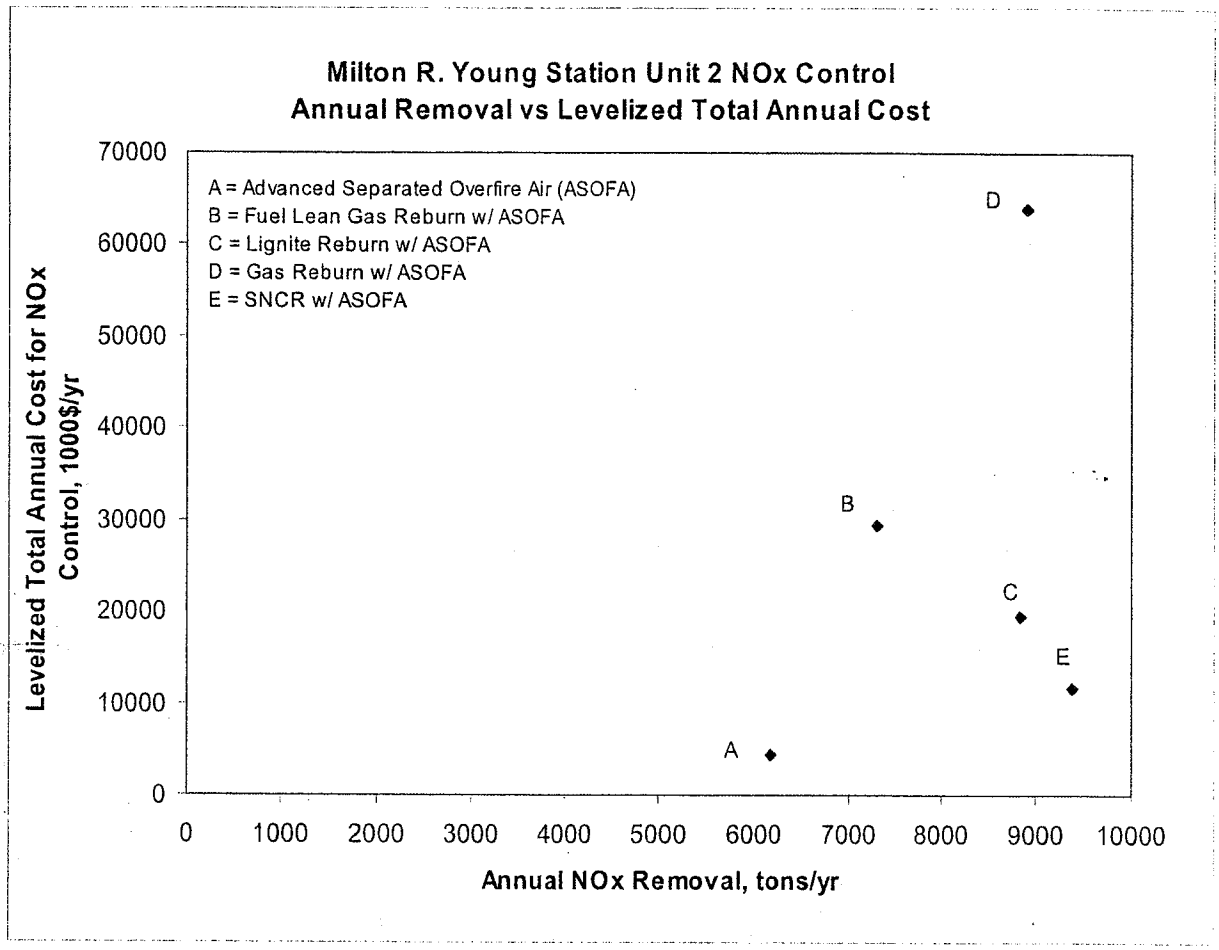
(4) - Levelized Total Annual Cost = Annualized Installed Capital Cost + Levelized Annual O&M cost. See note #3 for Tables 3-10 and 3-11 for annualized cost factors. Emissions are calculated from unit emission rates, control percentage, hourly heat input, and annual hrs/yr operation compared to pre-control baseline based on annual operation at highest allowable pre-control NOx emission rate.

(5) - Average Control Cost Effectiveness ($/ton) is the Levelized Total Annual Cost (1000$/yr) divided by Annual Emission Reduction (tons/yr). All cost figures in 2006 dollars.

(6) - LTAC for gas reburn options include high-pressure natural gas supply pipeline annualized capital cost of $1,307,000/yr for CGR and $653,000 plus for FLGR. See footnotes #8 and 10 under Table 3-9

(7) - LTAC for increased PM collection capacity included in lignite reburn option are approximately $3,140,000 for annualized capital cost plus $4,194,000/yr for annualized O&M cost, for a LTAC subtotal of $7,333,000/yr.

Figure 3-1 – NO_X Control Cost Effectiveness - MRY Station Unit 2(1)



(1) - All cost figures in 2006 dollars. Numbers are listed and qualifiers are noted in Table 3-12.

The purpose of Figure 3-1 is to show the range of control and cost for all feasible NO_X reduction alternatives evaluated. A dominant set of control alternatives were determined by generating what is called the "envelope of least-cost alternatives". The dominant controls cost curve is the best fit line through the points forming the rightmost boundary of the data zone on a scatter plot of the annual NO_X removal tonnage versus LTAC for the various remaining BACT alternatives. Following a "bottom-up" graphical comparison approach, each of the NO_X control technologies represented by a data point to the left of and above the least cost envelope are inferior control alternatives per the NSR Manual and should be excluded from further analysis on a cost efficiency basis.

Of the technically feasible NO_X control alternatives considered for MRY Station Unit 2, data points for conventional gas reburn (Point D) and fuel-lean gas reburn (Point B) with advanced separated overfire air, and lignite reburn with ASOFA (Point C), lay distinctly left and above the other points of the control cost points' scatter plot of Figure 3-1. These control options are inferior and therefore were eliminated from further control cost-effectiveness analysis.

Average and incremental annual costs and NO_X emission reductions for the dominant least-cost control alternatives remaining after the elimination of the obviously inferior options are listed in Table 3-13. The annual NO_X control tons per year, divided by the total levelized annual cost, yields an average unit cost ($/ton). Incremental cost effectiveness is a measure of the increase in marginal cost effectiveness between two specific alternatives. The additional tons per year of NO_X control relative to the previous apparent least-cost curve point, divided by the increase in levelized annual cost, yields an incremental unit cost ($/ton). Alternatively, the incremental cost effectiveness analysis identifies the rate of change of cost effectiveness with respect to removal benefits (i.e., the slope of the envelope of least-cost control alternatives, also called the dominant controls cost curve or DCCC) between successively more effective alternatives which are considered technically feasible for Milton R. Young Station boilers.

TABLE 3-13 – Dominant Controls Cost Curve Points for Feasible BACT NO_X Alternatives - MRY Station Unit 2

Alt. Label(1)	NOx Control Technique	Levelized Total Annual Cost(2),(3) ($1,000/yr)	Annual Emission Reduction(3) (tpy)	Incremental Levelized Total Annual Cost(2),(4) ($1,000/yr)	Incremental Annual Emission Reduction(4) (tpy)	Incremental Control Cost Effectiveness ($/ton)(2),(4)
E	SNCR w/ ASOFA	11,618	9,372	7,242	3,200	2,263
A	Advanced SOFA (ASOFA)	4,376	6,172	4,376	6,172	709

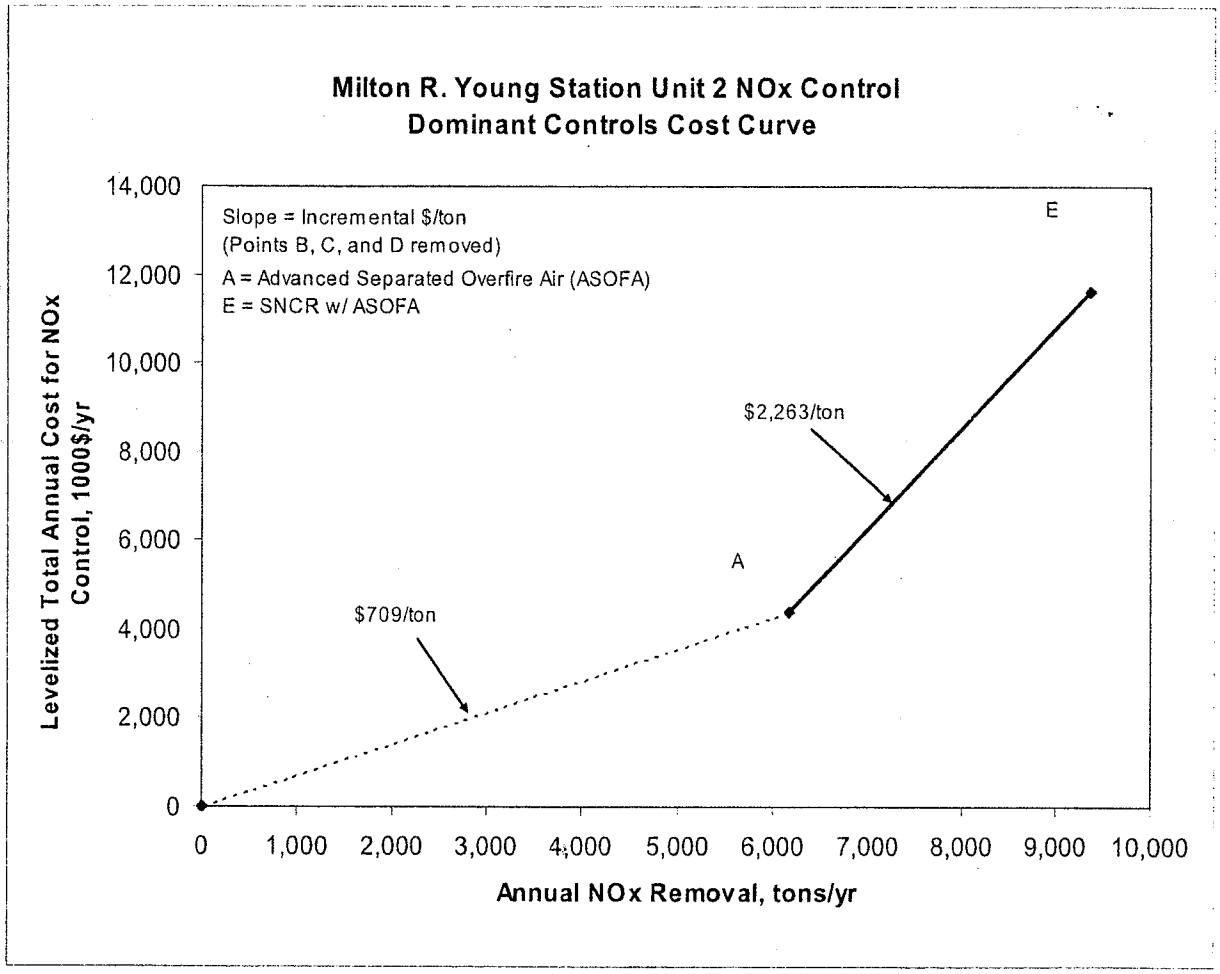
(1) – Dominant controls cost curve points from lowest (ASOFA) to highest (SNCR w/ ASOFA) are labeled the same as in Table 3-12, and on the graphs that accompany this table (Points B, C, and D were eliminated).
(2) – All cost figures in 2006 dollars.
(3) – Annual emission reduction and levelized control cost of these alternatives is relative to current costs and pre-control unit MCR baseline emission rate.
(4) – Increment based upon comparison between consecutive alternatives (points) from lowest to highest, except as noted.

The incremental cost analysis indicates that from a cost effectiveness viewpoint, the SNCR with ASOFA alternative incurs a significant annual (levelized) incremental cost compared to the ASOFA NO_X control

technique (slope from zero baseline to ASOFA, Point A was $709/ton for MRYS Unit 2; the incremental cost (slope) from ASOFA, Point A to SNCR with ASOFA, Point E was $2,263/ton for MRYS Unit 2.

Figure 3-2 contains a repetition of the levelized total annual cost and NO_X control information from Figure 3-1 for MRY Station Unit 2, with Point B (FLGR™ with ASOFA) , Point C (Lignite Reburn with ASOFA) and Point D (conventional gas reburn with ASOFA) removed. This is the dominant controls cost curve for MRY Station Unit 2 NO_X emissions alternatives.

Figure 3-2 – MRY Station Unit 2 NO_X Control Alternatives BACT Dominant Controls Cost Curve(1)



(1) - All cost figures in 2006 dollars. Numbers are listed and qualifiers are noted in Table 3-13

In the U.S. EPA's NSR Manual, the EPA does not specify acceptable or unacceptable ranges for average (unit control costs) and incremental cost effectiveness values. As can be seen from a review of Table 3-

14, the average levelized control cost effectiveness (called the unit control cost in this report) ranges from approximately $709/ton to $7,171/ton of MRYS Unit 2's NO_X emissions removed. It should be noted, however, that the highest estimated average control costs involve gas reburn technologies that were shown to be inferior options (not on the dominant controls cost curve) and thus were eliminated from further impacts analysis.

The incremental cost effectiveness is a measure of the increase in marginal cost effectiveness between two specific alternatives. Alternatively, the incremental cost effectiveness analysis identifies the rate of change of cost effectiveness with respect to removal benefits (i.e., the slope of the least-cost envelope of dominant control alternatives or dominant controls cost curve) between successively more effective alternatives. The economic impact analysis indicates that from a cost effectiveness viewpoint, the highest performing alternative is SNCR with ASOFA (Point E). This control option is considered technically feasible for Milton R. Young Station Unit 2 boiler but incurs a significant annual (levelized) incremental cost relative to the next highest feasible NO_X control technique, ASOFA (Point A) when ASOFA is compared against the pre-control baseline. The Advanced Separated Overfire Air alternative has an average unit control cost ($709/ton) approximately 58% of the highest performing feasible alternative on the dominant controls cost curve (SNCR with ASOFA, $1,240/ton). ASOFA also has a much lower incremental cost per ton relative to the pre-control baseline (slope from zero to Point A, $709/ton) compared to SNCR with ASOFA (Point E) versus ASOFA (Point A); the slope from Point A to Point E was $2,263/ton.

The other elements of the fourth step of a BACT analysis following economic impacts are to evaluate the following impacts of feasible emission controls:

- The energy impacts.
- The environmental impacts.

TABLE 3-14 – Estimated Emissions and Economic Impacts Summary for NO_X Control Alternatives - MRY Station Unit 2

Summary of Estimated Annual Emissions and Economics for NOx Control Alternatives Evaluated for Milton R. Young Station Unit 2

		EMISSIONS(2)					ECONOMIC IMPACTS			
Alt. Label(1)	NOx Control Alternative	Emission Rate lb/mmBtu	Hourly Emission lbs/hr	Annual Emission tons/yr	Emission Reduction tons/yr	NOx Removal Efficiency(2) %	Installed Capital Cost(3) $1,000	Annual O & M Cost(4) $1,000	Levelized Total Annualized Cost(5) $1,000	Average Control Cost(6) $/ton
E	SNCR w/ ASOFA	0.330	1,612	6,421	9,372	58.0	17,128	8,108	11,618	1,240
D	Gas Reburn w/ ASOFA	0.350	1,710	6,882	8,910	55.4	35,490	48,688	63,892	7,171
C	Lignite Reburn w/ ASOFA	0.360	1,759	6,964	8,829	54.2	81,167	9,929	19,475	2,206
B	FLGR w/ ASOFA	0.432	2,110	8,490	7,303	45.0	21,817	21,954	29,317	4,014
A	Advanced SOFA (ASOFA)	0.489	2,391	9,621	6,172	37.7	10,008	2,805	4,376	709
	Baseline	0.786	3,839	15,793	0	0.0	0	0	0	

(1) - Alternative label has been assigned from highest to lowest unit NOx emission rate.
(2) - Estimated NO_X control level reductions relative to average annual emission baseline of 0.786 lb/mmBtu at 4,885 mmBtu/hr MCR heat input. Emissions are calculated from unit emission rates, control percentage, hourly heat input, and annual hrs/yr operation compared to pre-control baseline based on annual operation at a gross unit electrical output of 440 MWg and assumes a 93.9% average annual availability. Values from reported emission data for the 12 month operating period during 2001-2005 with the highest rolling summation of NOx pounds.
(3) - Installed capital cost is estimated for determination of total capital cost for a particular technology or combination, assuming 477 MWg unit capacity rating. All cost figures in 2006 dollars. Costs for gas reburn options include high-pressure natural gas supply pipeline installed capital cost of $14,988,000 for CGR and $7,494,000 for FLGR; and annualized capital cost of $1,307,000/yr for CGR and $653,000 for FLGR. Costs for increased PM collection capacity included in lignite reburn option are $36,013,000 for installed capital cost.
(4) - Annual operating and maintenance cost for a particular technology or combination is compared to unit baseline operation at a gross unit electrical output of 440 MWg and assumes a 95.2% average running plant capacity factor compared to nominal unit gross electrical output capacity of 462 MWg. All cost figures in 2006 dollars. Costs for increased PM collection capacity included in lignite reburn option are $3,155,000/yr for annual O&M cost.
(5) - Levelized Total Annual Cost = Annualized Installed Capital Cost + Levelized Annual O&M cost. Annualized capital cost = Installed capital cost x 0.08718 annualized capital cost factor. Levelized annual O&M cost = Annual O&M cost x 1.24873 annualized O&M cost factor.
(6) - Average Control Cost Effectiveness ($/ton) is the Levelized Total Annual Cost (1000$) divided by Annual Emission Reduction (tons). All cost figures in 2006 dollars.
(7) - LTAC for reburn options include high-pressure natural gas supply pipeline annualized capital cost of $1,307,000/yr for CGR and $653,000 for FLGR; LTAC for increased PM collection capacity included in lignite reburn option are $3,140,000 for annualized capital cost plus $3,940,000/yr for annualized O&M cost, for a total of $7,080,000/yr.

3.4.2 ENERGY IMPACTS OF MRY STATION NO_X CONTROLS

Operation of the most cost-effective NO_X control technologies considered feasible for potential application at the Milton R. Young Station impose direct impacts on the consumption of energy required for the production of electrical power at the facility. The details of estimated energy usage and costs for the various NO_X control alternatives are summarized in Appendix C3.

Control alternatives for reduction of NO_X emissions were reviewed to determine if the use of the technique or technology will result in any significant or unusual energy penalties or benefits. There are several basic kinds of energy impacts for NO_X emissions controls:

- Potential increase or decrease in power plant energy consumption resulting from a change in thermal (heat) energy to net electrical output conversion efficiency of the unit, usually expressed as an hourly unit heat rate (Btu/kW-hr) or the inverse of pounds of pollutant per unit electrical power output (MW-hr). This may or may not change the net electrical output (MW) capacity of the EGU, depending on if there are physical or imposed limits on the total heat input to the boiler or electrical power output.
- Potential increase or decrease in net electrical output of the unit, resulting from changes in physical operational limitations imposed on the ability to sustain a fuel heat input rate (mmBtu/hr) which results in a potentially lower or higher unit net electrical output (MW) capacity. This is effectively a change in net electrical output (MW) capacity of the EGU.
- Potential increase or decrease in net electrical output of the unit, resulting from changes in auxiliary electrical power demand and usage (kW, kW-hrs). This is effectively a change in net electrical output (MW) capacity of the EGU.
- Potential increase or decrease in reliability and availability to generate electrical power. This results in a change to the number of hours of annual operation, not necessarily a change in net electrical output (MW) capacity of the EGU.

3.4.2.1 ENERGY IMPACTS OF SOFA TECHNOLOGY

There should not be a major impact on energy consumption resulting from the operation of the advanced variation of a separated overfire air system. SOFA does not significantly change the total amount of air introduced into the boiler, only the location where it is introduced. Damper resistance and supply pressure impacts of the SOFA system on fan power consumption should be insignificant. The amount of flyash emitted from the boiler is expected to be reduced (less than five percent) from the baseline level

when the SOFA system is in full operation. Slightly higher levels of unburned carbon in the flyash may occur with the operation of a SOFA system. This could have a small negative impact on the plant heat rate (higher Btu/kw-hr). These changes are expected to be within the typical range of current operation.

There is a potential reduction in reliability and availability of a lignite-fired cyclone boiler to generate steam for production of electrical power as a result of installing and operating a separated overfire air system. Typical SOFA operation on bituminous or western subbituminous coal-fired cyclone boilers does not carry a significant additional risk of causing insufficient or excessive accumulation of slag within the cyclone barrels or furnace bottom compared with non air-staged combustion. Reliable boiler operation depends on avoiding such adverse conditions in the cyclones and lower furnace, which could require a forced outage to remove the solidified slag prior to returning the boiler to generation production service.

The challenges of maintaining adequate slag layer development and flow while firing lignite in MRY Unit 2's cyclones under excess air conditions have been significant during the operating history of the powerplant. Minimizing forced outages resulting from cyclone slag issues have largely been successful through operational practices that do not affect day-to-day boiler reliability and availability. Due to the variability of combustion characteristics of lignite supplied from the Center mine, and the dependency of the slag flow on the temperature within the cyclone barrels or furnace bottom, conditions may occur during ASOFA operation that exceed the ability to adjust operational practices sufficiently to avoid forced outages to remove the solidified slag.

The potential impact on annual unit operating time due to cyclone slag issues associated with air-staged cyclones/ASOFA system operation was estimated to be approximately 2% reduction from the assumed pre-control baseline availability, i.e. 0.94-0.02=0.92. The estimated electrical generation production lost due to the reduction in MRY Unit 2's annual availability is shown in Table 3-16.

3.4.2.2 ENERGY IMPACTS OF SNCR TECHNOLOGY

For SNCR, the injection of a diluted urea solution will require some additional auxiliary power for heating and pumping the liquid and using compressed air for atomization and cooling the reagent injection nozzles/lances, on the order of 100 to 300 kW. The injection of water (used for urea dilution) into the boiler flue gas also will have a small negative impact on the plant heat rate (higher Btu/kw-hr), although the vendor of SNCR systems advises that the heat released from the oxidation of a portion of the

injected urea compensates for this impact. The impact of additional flue gas created by operation of an SNCR-related system on fan power consumption should be small.

There is a potential reduction in reliability and availability of a lignite-fired cyclone boiler to generate steam for production of electrical power as a result of installing and operating a SNCR-related system. Typical SNCR operation with low ammonia slip when firing low-sulfur western subbituminous coal in cyclone-fired boilers does not carry a significant additional risk of causing excessive fouling of the tubular air preheater compared with non-SNCR operation. Reliable boiler operation depends on avoiding adverse fouling conditions in the air preheater, which could require a forced outage to remove the ash deposits prior to returning the boiler to generation production service.

The challenges of maintaining open passages through the air preheater tubes while firing lignite in MRY Unit 2's cyclones under typical conditions have been minor during the operating history of the powerplant. Minimizing forced outages resulting from ash deposits within the air preheater have largely been successful through operational practices that do not affect day-to-day boiler reliability and availability. Due to the variability of fouling characteristics of lignite supplied from the Center mine, and the dependency of the fouling within the air preheater on sodium, sulfur, and ammonia slip emission levels, conditions may occur during SNCR operation that exceed the ability to adjust operational practices sufficiently to avoid forced outages to remove the air preheater deposits.

The potential impact on annual unit operating time due to air preheater fouling and other potential issues associated with SNCR system operation was estimated to be an incremental 1% reduction from the assumed pre-control baseline or ASOFA availability. The estimated electrical generation production lost due to the reduction in MRY Unit 2's annual availability is shown in Table 3-16.

TABLE 3-15 – Expected Auxiliary Electrical Power Impacts for NO_X Controls - MRY Station Unit 2

Alt. Label(1)	NOx Control Technique	Estimated Annual Average Auxiliary Electrical Power Demand and Consumption of NOx Control Equipment	
		Gross Demand(2) kW	Power Usage(3) kW-hrs/yr
E	SNCR w/ ASOFA	133	1,008,774
A	Advanced SOFA (ASOFA)	1	7,664

(1) – Alternative number has been previously assigned from least removal to highest removal percentage.
(2) – The APC NOx equipment gross auxiliary electrical power demand of alternatives is the sum of individual technologies combined by simple addition. Actual power demands may differ from this due to positive or negative synergistic effects.
(3) – The annual change in APC NOx equipment auxiliary electrical power demand electricity usage in kW-hrs/yr for these alternatives is the net power demand multiplied by the estimated annual operating time and running plant capacity factor which reflects the adjustment for any expected reliability and capacity impacts from the implementation of the control technique. A negative reduction in generation is an increase in annual new electrical power available for sale.

TABLE 3-16 – Expected Electrical Power Generation Availability and Capacity Impacts for NO_X Controls - MRY Station Unit 2

Alt. Label(1)	NOx Control Technique	Estimated Annual Average Availability(2)	Estimated Annual Average Operating Time Reduction, hrs/yr(3)	Estimated Annual Average Running Plant Capacity Factor(4)	Estimated Annual Average Electricity Generation Reduction kW-hrs/yr(5)
E	SNCR w/ ASOFA	0.909	263	0.951	110,176,095
A	Advanced SOFA (ASOFA)	0.919	181	0.952	75,859.855

(1) – Alternative number has been previously assigned from least removal to highest removal percentage.
(2) – Baseline availability is assumed at 93.9 percent. These values reflect estimated amounts of negative reliability impact expected from the implementation of the individual NOx control technique.
(3) – Annual lost operating time resulting from the implementation of the individual NOx control technique is the difference between the baseline and expected annual outage times.
(4) – Baseline running plant capacity factor is assumed at 95.2 percent. These values reflect estimated amounts of negative reliability impact expected from the implementation of the individual NOx control technique.
(5) – Annual electricity generation reduction is annual reduction of operating time multiplied by the annual running plant capacity factor resulting from the implementation of the individual NOx control technique multiplied by the MCR capacity rating of 462 MW (MCR gross unit electrical output capacity).

TABLE 3-17 – Expected Total Electrical Power Generation Impacts for NO_X Controls - MRY Station Unit 2

Alt. Label(1)	NOx Control Technique	Power Usage(2) kW-hrs/yr	Estimated Annual Average Electricity Generation Reduction(3) kW-hrs/yr	Est. Annual Change in Net Electrical Power Generation Available for Sale(4) kW-hrs/yr
E	SNCR w/ ASOFA	1,008,774	110,176,095	111,184,869
A	Advanced SOFA (ASOFA)	7,664	75,859.855	75,867,520

(1) – Alternative number has been previously assigned from least removal to highest removal percentage.
(2) – The annual change in APC NOx equipment auxiliary electrical power demand electricity usage in kW-hrs/yr for these alternatives is the net power demand multiplied by the estimated annual operating time and running plant capacity factor which reflects the adjustment for any expected reliability and capacity impacts from the implementation of the control technique. A negative reduction in generation is an increase in annual new electrical power available for sale.
(3) – Annual electricity generation reduction is annual reduction of operating time multiplied by the annual running plant capacity factor resulting from the implementation of the individual NOx control technique multiplied by the MCR capacity rating of 462 MW (MCR gross unit electrical output capacity).
(4) – Annual change in net electrical power generation available for sale is arithmetic sum of annual power generation reduction due to a change in the auxiliary electrical power consumed plus the annual generation reduction from a decrease in annual operating time and average annual running plant capacity factor resulting from the implementation of the individual NOx control technique, compared with baseline.

3.4.3 ENVIRONMENTAL IMPACTS OF NOx CONTROLS - MRY STATION

Nitrogen oxides react with oxygen in the atmosphere to produce elemental nitrogen and ozone (O_3). This is one of the common causes of visible pollution in the atmosphere referred to as "smog". Operation of the various NO_X control technologies considered for potential application at the Milton R. Young Station impose direct and indirect impacts on the environment. The most pronounced direct environmental impact expected from operation of any of the NO_X control options considered is the reduction of ozone and improvement in atmospheric visibility (i.e. reduced visibility impairment) downwind of the facility.

3.4.3.1 ENVIRONMENTAL IMPACTS OF SOFA TECHNOLOGY

The operation of a separated overfire air system is expected to slightly increase carbon monoxide concentrations in the stack flue gas. The advanced form of SOFA alternative is expected to slightly lower the amount of particulate matter emitted from the boiler and may raise the amount of unburned carbon in the flyash collected for land disposal and emitted to the atmosphere by small increments. Alternatives involving forms of gas reburn should experience lower particulate emissions, and a reduction in the amount of boiler bottom and flyash requiring disposal.

The environmental impact from potential reduction of annual unit operating time by approximately two percent due to cyclone slag issues associated with air-staged cyclones/ASOFA system operation will be to reduce the annual amount (tons) of nitrogen oxides emitted, and therefore the annual number of NO_X tons removed will increase, by approximately two percent.

3.4.3.2 ENVIRONMENTAL IMPACTS OF SNCR TECHNOLOGY

Operation of a conventional SNCR system is not expected to significantly impact emissions of CO or volatile organic compounds (VOCs).

Operation of an SNCR system will normally create a small amount of unreacted urea or ammonia to be emitted. The amount of ammonia slip produced by SNCR depends on the amount of reagent utilization and location of the injection points. Higher SNCR NO_X reduction performance involves greater amounts of reagent usage and ammonia slip. This is typically controlled to less than 10 ppmvd, especially when the possible formation of sulfates such as ammonium sulfate [$(NH_4)_2SO_4$] and ammonium bisulfate [NH_4HSO_4] will be more problematic at higher slip levels. Sulfur trioxide (SO_3) formed during combustion in the boiler can combine with ammonia during passage through the flue gas ductwork to form the sulfates.

Some of the unreacted ammonia from SNCR operation will be collected with the flyash in the electrostatic precipitator. Any remaining ammonia slip that is not collected or condensed in the air pollution control system will be emitted from the stack as an aerosol or condensable particulate. This has the potential to increase atmospheric visibility impairment downwind of the facility compared with a pristine condition. Although the predicted amount of such potential impact from ammonia slip emissions has not been determined, it is expected to be small in comparison with the significant anticipated reduction in far-field ozone and improvement in atmospheric visibility as a result of the overall NOx emission reduction.

Delivery of the urea reagent to the powerplant facility and storage of aqueous urea reagent on-site creates the potential for accidents, leaks, and subsequent releases to air, ground, and surface water immediately surrounding the facility. Urea is much less volatile than anhydrous or aqueous ammonia, and these risks are expected to be manageable. Emergency planning and community communications are part of the management plan requirements for such reagent usage.

The environmental impact from potential reduction of annual unit operating time by approximately one percent due to air preheater fouling issues associated with SNCR system operation will be to reduce the annual amount (tons) of nitrogen oxides emitted, and therefore the annual number of NO_X tons eliminated relative to the constant pre-control emission baseline will increase by approximately one percent.

3.4.4 SUMMARY OF ECONOMIC, ENERGY AND ENVIRONMENTAL IMPACTS OF MRY STATION NO_X CONTROLS

The economic, energy, and environmental impacts of each feasible BACT alternative evaluated for this study is summarized in this Section. Table 3-18 summarizes the various impacts discussed in Sections 3.4.1 through 3.4.3. The economic analysis examined the capital cost of each feasible BACT alternative evaluated and any other powerplant upgrade costs necessary to implement the alternative. In addition, the economic analysis examined the operating and maintenance cost associated with the highest-performing forms of each feasible BACT alternative evaluated. These costs were then combined into the levelized total annual cost for a comparative assessment of the total implementation cost of each alternative. Finally, as part of the top-down analysis, a dominant controls cost curve was plotted and the unit control cost for each alternative was evaluated. Two alternatives were on the dominant controls cost curve and thus were identified as the more cost effective alternatives. The two BACT NO_X control alternatives evaluated for incremental cost, energy, and environmental impacts applicable to Milton R. Young Station Unit 2 were:

- Selective Non-Catalytic Reduction (SNCR) combined with a special form of separated overfire air (SOFA) specifically for lignite-fired cyclone boilers (referred to as Advanced SOFA or ASOFA); and
- ASOFA alone.

3.5 BACT RECOMMENDATIONS AND CONTROL LEVELS – MRY STATION UNIT 2

This report presents the analysis of control technologies for nitrogen oxides (NO_X) for Minnkota Power Cooperative's (MPC's) Milton R. Young Station Unit 2 using the EPA's "top-down" BACT approach. BACT is an emissions limitation for each pollutant from a source determined to be achievable using control technologies(s) that provide the "maximum degree of emission reduction…taking into account energy, environmental, and economic impacts"[30]. A BACT review does not result in a percent removal efficiency requirement. The generally accepted procedures for performing a BACT analysis are outlined in the EPA's draft NSR Manual. The BACT analysis for Milton R. Young Station NO_X emissions was performed in accordance with this procedure. The EPA's draft NSR Manual outlines five basic steps that are to be followed in the "top-down" BACT evaluation. These steps were as follows:

Step 1 – Identify All Control Technologies
Step 2 – Eliminate Technically Infeasible Options
Step 3 – Rank Remaining Control Technologies by Control Effectiveness
Step 4 – Evaluate Most Effective Controls and Document Results
Step 5 – Select BACT

The final result of this analysis is a recommendation of the BACT alternative and the associated NO_X emission rate for Square Butte Electric Cooperative's Milton R. Young Station Unit 2. The emission limitations for a generation facility are expressed in a pounds per million British Thermal Units (lb/mmBtu) basis.

3.5.1 UNIT 2 NO_X BACT

In step one of the technology evaluation, three basic categories of NO_X controls for EGUs were-identified: pre-combustion, combustion, and post-combustion. Eleven basic types of NO_X control processes were identified within these three categories. Twenty four variations of these eleven processes were reviewed for availability and applicability to cyclone-fired EGUs burning North Dakota lignite. An "advanced" form of Separated Overfire Air, alone and in various combinations with Lignite Reburn, Selective Non-Catalytic Reduction (SNCR), Conventional Gas Reburn and

[30] Ibid, NSR Manual B.1

Fuel Lean Gas Reburn™, was evaluated for cost-effectiveness. The cost-effectiveness analysis indicated that ASOFA alone, and ASOFA with SNCR were cost effective alternatives for MRY Station Unit 2 NO_X control. The energy and environmental impacts analysis for MRY Station Unit 2's cost-effective NO_X control alternatives were generally insignificant.

Based upon the definition of BACT and the results of the BACT analysis, Selective Non-Catalytic Reduction (SNCR) in combination with a special form of separated overfire air (SOFA) specifically for lignite-fired cyclone boilers (referred to as Advanced SOFA or ASOFA) is recommended as the Best Available Control Technology for nitrogen oxides emissions from Square Butte Electric Cooperative's Milton R. Young Station Unit 2. The unit BACT NO_X emissions rate for MRYS Unit 2 is 0.330 lb/mmBtu , determined as a rolling 12-month average. This is shown in Table 3-19.

TABLE 3-19 – NO_X Emission Control Technology and Rate Recommended as BACT for Milton R. Young Station Unit 2

Control Technology and Emission Rate Recommended as BACT			
Unit	**Pollutant**	**BACT Control Method**	**12-Month Rolling Average BACT NOx Emission Rate (lb/mmBtu)**
2	NO_X	Selective Non-Catalytic Reduction with Advanced Separated Overfire Air (ASOFA)	0.330

3.5.2 EMISSION RATE LIMITATION RECOMMENDATION

To complete the BACT determination process, the Consent Decree (CD) requires that "specific control technologies to be installed and a specific Phase II 30-day Rolling Average NO_X Emission Rate limitation (lbs/MMBtu)"[31] (pounds per million Btu) must be established for each subject emission Unit. The CD also states that "a "30-day Rolling Average Emission Rate" shall be determined by calculating an arithmetic average of all hourly emission rates in lbs/MMBtu for the current Operating Day and the previous 29 Operating Days. A new 30-day Rolling Average Emission Rate shall be calculated for each new Operating Day. Each 30-day Rolling Average Emission Rate shall include startup, shutdown, and Malfunction periods within each Operating Day"[32].

[31] Ibid footnote number 1, Paragraph 66, page 20.
[32] Ibid footnote number 1, Paragraph 5, page 4.

The Consent Decree also states that the North Dakota Department of Health's (NDDH) NO_X "BACT Determination shall address specific emission limitations during Unit startups"[33] at Milton R. Young Station. The type and duration of firing during startups, and the limited ability of available and feasible technologies to control startup NO_X emissions, both significantly influence the 30-day rolling average BACT NO_X emission rate limit recommended for Milton R. Young Station boilers. A 24-hour rolling average NO_X emission rate limit applied to startup periods is also recommended for Milton R. Young Station boilers.

The Consent Decree and the EPA's NSR Manual do not describe the method for determining a 30-day Rolling Average NO_X Emission Rate permit limitation (CD Phase II) that reflects BACT applied to Milton R. Young Station Unit 2.

In keeping with the establishment of a specific CD Phase II 30-day Rolling Average NO_X Emission Rate limitation, a relevant precontrol baseline level of emissions and its basis must be determined. The EPA's NSR Manual states:

> "The baseline emissions rate represents a realistic scenario of upper boundary uncontrolled emissions from the source. The NSPS/NESHAP requirements or the application of controls, including other controls necessary to comply with State or local air pollution regulations, are not considered in calculating the baseline emissions. In other words, baseline emissions are essentially uncontrolled emissions, calculated using realistic upper boundary operating assumptions"[34].

Also stated in the EPA's NSR Manual:

> "Estimating realistic upper bound case scenario does not mean that the source operates in an absolute worst-case manner all the time. For example, in developing a realistic upper boundary case, baseline emissions calculations can also consider inherent physical or operational constraints on the source. Such constraints should accurately reflect the true upper boundary of the source's ability to physically operate and the applicant should submit documentation to verify these constraints"[35].

[33] Ibid footnote number 1, Paragraph 66, page 20.
[34] Ibid footnote number 2, NSR Manual page B.37
[35] Ibid footnote number 2, NSR Manual page B.37.

The BACT Analysis was conducted based upon the highest historical 12-month rolling NO_X emission summation operating conditions for Milton R. Young Station boilers during years 2001-2005. However, a baseline reflecting a realistic upper bound case scenario based upon the highest historical 30-day rolling NO_X emission operating conditions during years 2001-2005 was established prior to recommending enforceable permit conditions for BACT to be applied to each Milton R. Young Station boiler.

The approach taken in this analysis was to identify pre-control 30-day baseline operating conditions from the 30-consecutive day period with the highest historic unit NO_X mass emissions (pounds) reported for actual operation between January 1, 2001 and December 31, 2005. This reflects unit NO_X emissions that were generated during periods of high unit operations, not affected by unit shutdowns, startups, or malfunctions. MRYS Unit 2's highest reported 30-day rolling average NO_X unit emission rate during years 2001-2005 was 0.874 lb/mmBtu for the period ending April 5, 2002. The corresponding MRYS Unit 2 30-day average hourly NO_X mass emission rate was 3,726 lb/hr. The average unit heat input rate for MRYS Unit 2 was 4,264 mmBtu/hr, and the average gross unit electrical power output was 450.2 MW_g for the same 30-day period.

The operating conditions during the highest historical 30-day rolling NO_X emission for years 2001-2005 were then compared to the highest 12-month historic pre-control baseline conditions. The average unit NO_X emission rate (lb/mmBtu) from the highest historic pre-control 30-day baseline period was compared with the average NO_X emission rate (lb/mmBtu) from the 12-consecutive month period with the highest historic unit NO_X mass emissions (pounds) reported for actual operation during the same 5-year look-back period. An estimate of NO_X emission reduction for the proposed BACT NO_X alternative operating at the historic pre-control 30-day baseline average NO_X emission rate (lb/mmBtu) was made. This rate considered recognized operational factors and equipment designs applied to "steady state" conditions with sustained output close to maximum continuous capacity ratings. The potential impact of startups, recognizing operational and technical limitations on NO_X emission control performance, was then applied to the steady-state rate, to establish a recommended 30-day Rolling Average NO_X Emission Rate permit limitation (CD Phase II) that reflects BACT for Milton R. Young Station Unit 2. This is explained below.

NO_X emissions for cyclone-fired boilers are typically higher in pounds per million BTUs during start up events than during steady-state operation at maximum continuous rating (MCR) conditions. This is because hourly heat and combustion air input rates required to establish adequate molten

slag formation within the cyclone barrels and promote slag tapping are typically produced from firing conditions that create high flame temperatures. NO_X emissions are sensitive to peak furnace gas temperatures, thus uncontrolled NO_X emissions can be high during cyclone boiler startups. Furnace exit flue gas temperatures (FEGTs) during cyclone boiler startups are less than those occurring during conditions of steady state MCR firing rates due to the high heat absorption of the boiler metal and water being raised from ambient or near-ambient temperatures. Until sufficient FEGT exists for a feasible and available post-combustion technology, such as SNCR, to be effective, NO_X emissions will be basically uncontrolled. There is a practical lower limit of boiler heat input for conventional combustion-based NO_X emission control techniques, such as the advanced version of separated overfire air, to be operated beyond the amount required for cooling the SOFA injection nozzles when it can be diverted from the cyclone burners and significantly control NO_X emissions. These limitations of the effectiveness of BACT controls on Milton R. Young Station boilers during startups and other reduced-load operating periods influence the recommended 24-hour and 30-day rolling average NO_X emission rate limits.

Startup procedures for steam electric generating units (SEGUs) comprising a fossil fuel-fired boiler and steam turbine-generator are specified by the original equipment manufacturers to follow guidelines for heat and pressure increases to provide protection of boiler and turbine equipment. Initial start up duration after an outage may be dictated by the need to gradually warm up burner port/cyclone refractory materials, steam drum shell, steam headers, and other boiler metal surfaces exposed directly or indirectly to furnace gases, and the steam turbine's multiple casings and rotor shafts. This is normally accomplished with easy-to-ignite fossil fuel firing (such as natural gas, distillate fuel oil, or propane) of the boiler combined with coal to gradually increase firing until recommended boiler steam outlet temperature and pressure are reached. This is followed by supplying the steam turbine with sufficient inlet steam flow to reach conditions that allow the coupled generator to be synchronized and electricity to be generated above zero megawatts. From this point, boiler fuel firing is increased within prescribed rates until the desired operating load is achieved.

The SEGU startup operating period is usually not defined in emission permits. Startup is the period beginning with initiation of fuel ignition, and continuing until the powerplant equipment has reached operating conditions that include continuous fuel firing and sustained operating steam pressure and temperature levels within the guidelines of the designs for the boiler and turbine and their auxiliary systems for minimum sustainable levels without causing damage to the equipment.

A recent SEGU proposed PSD permit has included a definition of startup as "the period beginning with ignition and lasting until the equipment has reached a continuous operating level and operating permit limits"[36]. Similarly, a shutdown is defined as "the period beginning with the lowering of equipment from base load and lasting until fuel is no longer added to the boiler and combustion has ceased"[37]. Based on the referenced definitions of a startup period and a shutdown period, the amount of time required for a SEGU's load (boiler steam output or generator electrical output) to increase beyond such minimum sustainable operating levels can be considered part of startup events if the SEGU is typically base-loaded at full load or MCR output. This is the case with both MRY Station SEGUs.

Startups of SEGUs may be labeled as cold, warm, and hot to account for the amount of residual heat remaining in the boiler and steam turbine equipment. The various types of starts are dependent upon the amount of time the SEGU has been out-of-service (i.e. without boiler fuel firing or generator megawatt output). Cold starts have been defined as starts after the boiler has been without fuel firing for more than 72 hours, warm starts are more than 8 hours and less than 72 hours, and hot starts are less than 8 hours[38].

Although the definition of a startup event and the corresponding startup period is not required by the Consent Decree, defining start-ups is recommended. This helps to address the specific emission limitations during Unit startups at Milton R. Young Station and determine the impact of such operations on 30-day rolling average NO_X emissions. For the purpose of this NO_X BACT analysis, a Unit startup was defined as the period from initial fuel combustion to the point in time when:

- the measured Heat Input to the boiler on a 6-hour rolling average basis is greater than or equal to 4800 million BTU/hr for Unit 2; or
- the amount of time reported for the longest individual Unit 2 startup period during actual operation between January 1, 2001 and December 31, 2005 elapses, whichever occurs first; or
- fuel firing is discontinued prior to satisfying either previous criteria.

This startup definition for MRY Station Unit 2 accounts for conditions where cyclone refractory materials replaced during boiler overhauls must be cured by extended low-firing heating cycles,

[36] Desert Rock Energy Center (AZP04-01) Proposed PSD Permit Conditions, page 7. (http://www.epa.gov/region09/air/permit/desertrock/#permit)
[37] Ibid, page 7.
[38] Application for Prevention of Significant Deterioration Permit for the Desert Rock Energy Facility, Document Number 09417-360-250R1, May 2004, page 5-1.

unit controls are upgraded and must be adjusted during low-load operation, or for boiler feedwater quality to improve after boiler maintenance has been performed that affects the insides of the waterwall and superheated steam tubes. It also allows for a failed or interrupted start sequence which can require considerably less or more time to elapse than an average startup duration.

Analysis of MRY Station Unit 2 operations data from 2001 through 2005 revealed:

- There were 62 total startups in the five year period;
- Minimum startup was 14 hours for a "hot" start following a boiler master fuel interruption (Unit "trip");
- Maximum startup with an extended ramp-up period until full load was reached was 115 hours.

Unit 2 had a start-up that began on October 25, 2001 that lasted for 115 hours. This startup included initial firing in the 20th hour of 10/25 (2000 hours being the beginning of the startup period), and which ended at the end of the 14th hour (i.e. at 1500 hours) on October 30, 2001, upon reaching 451 MW (gross) output. The criteria of a 6-hour average heat input rate of more than 4800 million Btu per hour was not reached during this startup.

There are certain boiler operating conditions that need to exist before the BACT NOx control techniques and technologies can be effectively operated:

1. The furnace gas temperature in the region where a urea reagent solution is injected for SNCR-based NO_X control must be between 1700°F and 2100°F. This region is expected to be in the vicinity of the furnace exit, which is commonly defined as either the horizontal plane extending from the furnace rear wall arch ("nose") to the front wall of the boiler, or the vertical plane from the nose up to the furnace roof, upstream of the gas inlet to the superheater tube banks. The gas temperature (FEGT) range in this furnace region is dependent on boiler heat input rate and cleanliness of the firesides of the furnace walls, which affects the amount of radiant energy absorbed by the wall tubes and transferred to the water within.
2. The numbers of active cyclones and continuous coal firing rates must be enough to establish sufficient:
   a. coverage of molten slag on the actively-fired cyclone barrel surfaces and drainage of the slag from the bottom of the boiler; and

b. combustion airflow through the actively-fired cyclones to allow a portion to be diverted to the separated overfire air system above the amount required for idle cyclone cooling and SOFA nozzle cooling.

As previously discussed, furnace exit flue gas temperatures (FEGTs) will need to be measured or determined empirically during operation of the MRY Station boilers in order to be able to effectively control NO_X emissions using SNCR technology. The design and operation of the SNCR systems at MRYS for CD Phase II emissions control should include features that accommodate cyclone boiler startups and low-load operation with "clean" or "dirty" boiler heat transfer surfaces as soon as conditions occur that are technically practicable, i.e. within the SNCR system vendor's recommended operating guidelines, as well as full-load conditions in order to minimize NO_X emissions.

The amount and duration of sustained boiler heat input required to establish the operating conditions described in item 2 above is more difficult to precisely determine. Lignite heat content variability and inability to accurately determine the actual air/fuel ratio on a cyclone-by-cyclone basis in real-time, and the slagging and fouling characteristics of the lignite ash, cause (and are expected to continue to cause) difficulties with stable combustion performance. The minimum firing rates of the MRY Station boilers required to successfully initiate the effective operation of the SOFA system are specific to each individual boiler, and are not currently known. Due to such operating problems and emission control limitations, the ability to effectively limit NO_X emissions during startup periods and low-load operation following implementation of advanced SOFA (CD Phase I control) and/or an SNCR system (CD Phase II control) is uncertain.

Because there are expected to be minor short term variations in operating conditions during startups where Minnkota has not, in fact, materially changed any of their normal startup operating practices and criteria, a margin between the 30-day rolling average steady-state NO_X emission rate (which does not include the impacts of startups) and the proposed 30-day rolling average NO_X emission permit limit that includes startup emissions is recommended. This rate considered recognized operational factors and equipment designs applied to steady state conditions with sustained output close to maximum continuous capacity ratings. The recommended 30-day Rolling Average NO_X Emission Rate permit limitation excluding the impact of startups that reflects BACT for Milton R. Young Station Unit 2 is shown in the table below.

TABLE 3-20 – Recommended NO_X BACT Control Method and 30-Day Rolling Average NO_X Emission Rate Limit Without Startups

Unit	Pollutant	Control Method	30-day Rolling Average NOx Emission Rate Limit Excluding Startups (lb/million Btu)
2	NO_X	Selective Non-Catalytic Reduction with Advanced Separated Overfire Air (ASOFA)	0.350

This recommended BACT 30-day NO_X emission rate limit is based upon a historic pre-control 30-day baseline average NO_X emission rate of 0.874 lb/mmBtu for Unit 2. The baseline emission was determined from the 30-consecutive day period with the highest historic unit NO_X emissions rate reported for actual operation between January 1,2001 and December 31, 2005.

A recommended BACT 30-day NO_X emission rate limit that includes the impact of startup emissions should be suitably higher such that operation consistent with the technological limitations, manufacturer's specifications, and good engineering and maintenance practices to the extent practicable for the MRY Station boilers would not result in an exceedance (violation) of an enforceable 30-day rolling average NO_X emission permit limit.

For MRYS Unit 2, the recommended 30-day rolling average NO_X emission permit limit rate that includes the impact of startups is based upon recognized operational factors and equipment designs that influence whether the startup emissions result in higher 30-day emissions compared to normal continuous operation without or excluding such startup periods:

1. The uncontrolled emission rate (i.e. without separated OFA or SNCR in operation) and its variability during operation from a cold, warm, or hot startup up to and including maximum continuous rated output;
2. The operating conditions that are required to exist for the selected NO_X BACT control techniques to be initiated and be effective; and
3. The effectiveness of these two particular control techniques if invoked at less-than-MCR steady-state operating conditions.
4. The number of startups and their range of typical durations per 30-day period time frame.

The October 25-30, 2001 startup was chosen for additional evaluation as the start-up for MRY Station Unit 2.

An incremental adjustment to the proposed 30-day rolling average steady-state unit NO_X BACT emission rate without startups of 0.35 lb/mmBtu for Unit 2 is recommended for the 30-day rolling average NO_X emission permit limit periods as defined and applied to Milton R. Young Station. This is summarized in the table below.

TABLE 3-21 – Recommended BACT 30-Day Rolling Average NO_X Emission Rate Limit and Startup Impact

Unit	30-day Rolling Average NOx Emission Rate Limit Excluding Startups (lb/million Btu)	Impact on 30-day Rolling Average NOx Emission Rate Limit Due to Startups (lb/million Btu)
2	0.350	+0.102 per startup

This recommended adjustment to the proposed 30-day rolling average steady-state NO_X BACT emission rate limit without startups is based upon average historic pre-control NO_X emission rates of 0.959 lb/mmBtu for Unit 2 reported for the longest individual Unit 2 startup period during actual operation between January 1, 2001 and December 31, 2005. These emissions occurred during the 115-hour October 25-30, 2001 startup for Unit 2.

A 24-hour rolling average BACT NO_X emission rate limit applied to startup periods is also recommended for each of the Milton R. Young Station boilers. This is summarized in the table below.

TABLE 3-22 – Recommended 24-Hour Rolling Average NO_X Emission Rate Limit During Startups

Unit	24-hour Rolling Average NOx Emission Rate Limit During Startups (lb/million Btu)
2	1.064

These emissions occurred during the 115-hour October 25-30, 2001 startup for Unit 2.

Compliance with these emission rates would be measured at the stack of the Unit, verified with Continuous Emission Monitoring (CEM) systems in accordance with the reference methods specified in 40 C.F.R. Part 75, and would be determined on a 30 consecutive Operating Day and 24-consecutive hour rolling average basis, respectively.

A trial demonstration operating period of 18 months after the completion of Consent Decree Phase II NO_X emission reduction system installation commissioning at Milton R. Young Station is recommended. It is proposed to allow Minnkota (for Square Butte) to demonstrate the actual control system capabilities of the combined NO_X BACT emissions reduction system. Operating experience during the trial period will:

- confirm steady-state control performance of the combined NO_X BACT emissions reduction system;
- allow determination of the ability to further control Unit start-up emissions;
- allow the determination of the permitted 30-day rolling average NO_X emission limit including startups, shutdowns, and malfunctions; and
- address the specific emission limitations during Unit startups at Milton R. Young Station and their impact on the proposed 30-day rolling average emission rate limit (without startups).

Based upon the information obtained during the trail period, final emission limits can then be determined.

The means that will be employed to minimize emissions during startup will primarily be based on operating procedures, both before and after the level of upper furnace gas temperatures and/or heat input rate are considered sufficient to start the NO_X controls and operating conditions are conducive for effective emissions reduction. These could be similar to Minnkota's current MRYS practices, or could be different, depending upon the capabilities of the NO_X controls and their impacts on Unit operations.

References:

1. In the United States District Court For The District Of North Dakota, United States Of America and State Of North Dakota, Plaintiffs, v. Minnkota Power Cooperative, Inc. and Square Butte Electric Cooperative, Defendants, Civil Action No.1:06-CV-034.

2. EPA New Source Review Workshop Manual, Prevention of Significant Deterioration and Nonattainment Area Permitting, Draft October 1990 (The "NSR Manual").

3. EPA Docket OAR-2002-0076-0446 Technical Support Document for BART NOx Limits for Electric Generating Units Excel Spreadsheet 6/15/2005, posted on their website: from EDOCKET at http://docket.epa.gov/edkpub/do/EDKStaffItemDetailView?objectId=090007d48084562b; this is associated with EPA Acid Rain Program Clean Air Markets Division, Technical Support Document – Methodology For Developing BART NO_x Presumptive Limits, June 15, 2005, OAR-2002-0076-0445.

4. EPA Office of Air Quality Planning and Standards (OAQPS) publication EPA/452/B-02-001, Section 4.2, NO_X Controls – NO_X Post-Combustion, Chapter 1 - Selective Non-Catalytic Reduction, dated October 2000, posted at their website: http://www.epa.gov/ttn/catc/dir1/cs4-2 ch1.pdf

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APPENDIX A

Technical Feasibility Assessment Details for NO_X Control Technologies (A1)

U.S. Coal Cyclone NO_X Reduction Projects Summary

With Retrofit NO_X Control Projects' Technical Literature Summary (A2)

A.1 Technical Feasibility Assessment of NO_X Control Alternatives

A.1.1 Pre-Combustion Fuel Treatment/Switching

Fuel switching can be a viable method of NO_X emission reduction in certain situations. Often, coal combustion facilities are constructed to take maximum advantage of the particular combustion characteristics of a specific fuel. In the case of MRY Station, the Unit 1 and 2 boilers were designed and constructed specifically for firing North Dakota lignite, which has a fuel higher heating value (Btu/lb) approximately 20% lower than typical Powder River Basin (PRB) coal. A cyclone–fired boiler (Ottertail's Big Stone Unit 1) that is similar in geometry and steam generation design to MRY Station Unit 2 fires PRB coal. Based on a comparison of available emission data between Big Stone Unit 1 and MR Young Unit 2, there is no expected reduction in baseline (i.e. uncontrolled) NO_X emissions from switching to PRB from lignite at Milton R. Young Station.

Conversion of Milton R. Young Station Unit 2 boiler to fire PRB coal is technically possible. It is expected that major plant modifications will be required. Rail service is not presently installed at this site, so the additional operational and capital costs to bring in large quantities of PRB coal will be significant. Investigation of the specific source, distance, and costs for supplying necessary quantities of PRB coal via rail or trucks to M.R. Young station has not been performed. With zero baseline NO_X emissions reduction expected from application of fuel switching, this alternative will not be economically competitive with other NO_X control technologies that offer better results for a much lower combination of capital and operational costs. Although fuel switching is technically feasible, it has not been considered further as an effective NO_X emissions control option for MRY Station Unit 2 boiler.

A.1.2 Combustion Controls

Combustion controls comprise the most numerous category of NO_X emission reduction technologies. These techniques employ methods that reduce the amount of NO_X emissions created in the combustion zone of the boiler prior to exhausting the flue gases from the furnace (upstream of the convective heat transfer zones). These controls result in fewer emissions to atmosphere or that may require subsequent reduction from additional applicable combustion and/or post-combustion techniques.

As the boilers in question were designed for firing North Dakota lignite fuel, they were furnished with suitably-sized furnaces and limited back-end economizer heat transfer surfaces upstream of the air preheaters. This provides high temperature air to aid the evaporation of excess moisture from the crushed coal particles in the pre-combustion drying systems, and long residence times for solid and gaseous fuel

particles to burn essentially to completion prior to leaving the furnaces. The latter feature is especially advantageous for applying various forms of combustion modifications which are conducive in reducing NO_X emissions.

A.1.2.1 Basic Combustion Improvements

Combustion improvements are commonly-applied techniques which may produce modest incremental NO_X emissions reductions. In their most basic form, these typically provide improvements to combustion air flow distribution, measurement, and pressure, together with fuel flow measurement and metering, to promote consistent combustion performance by burning fuel with more accuracy in maintaining a desired fuel/air ratio.

These improvements may allow, or be combined with, the practice of several other NO_X control techniques. Separated overfire air (discussed below), with or without "low excess air" (LEA), burners out-of-service (BOOS) and biased firing (BF) operation of the cyclones, cause a decrease in the ratio of combustion air to fuel supplied to the cyclones (burners), thus reducing the amount of thermal NO_X emissions produced during combustion. The amount of potential NO_X emission reduction achievable from these basic techniques is highly-dependent on the specific type of firing, fuel, and conditions which apply to the boiler(s) being reviewed.

Making lignite drying system air adjustments and adding improvements to the boiler combustion controls and reducing combustion air inputs have already reduced uncontrolled NO_X emissions at Milton R. Young Station Unit 2 boiler approximately 27%. Further incremental improvements from additional combustion controls that allow operation with modest amounts of cyclone air staging, similar to the effect of a separated overfire air system, are possible. Incremental NO_X emissions reductions are expected from such improvements being incorporated into another feasible alternative, such as separated overfire air. This alternative was not considered as a stand-alone option for additional NO_X reduction at Milton R. Young Station for the Unit 2 boiler.

A.1.2.2 Low NO_X Burners (LNB)

Low NO_X burners (LNBs) of various designs have been commonly applied to pulverized coal-fired utility and industrial boilers for more than ten years. However, they are not installed on cyclone-fired boilers. This technology is infeasible on cyclone boilers[1], and was eliminated from consideration for additional NO_X reduction at Milton R. Young Station Unit 2's boiler.

A.1.2.3 Separated Overfire Air (SOFA)

Separated overfire air (SOFA) is a combustion-related NO_X emission reduction technology frequently-applied with and without low NO_X burners to utility and industrial boilers for more than twenty five years. Separated Overfire Air (SOFA) is an air-staging NO_X emission reduction combustion technique that is typically based on withholding 15 to 20 percent of the total combustion air conventionally supplied to the firing zone. The diverted combustion air is then injected in the upper furnace, where combustion is completed. For typical cyclone coal-fired boilers, this involves diverting approximately 20 percent of the secondary combustion air, forcing the cyclones to operate fuel-rich. Starved-air combustion causes fewer NO_X emissions to be produced.

At least thirty nine existing cyclone-fired boilers, firing eastern bituminous, midwestern bituminous, and western subbituminous ("Powder River Basin") coals in units ranging in size from 50 to 1150 MW, have been retrofitted with commercial SOFA since 1998. A summary of several of the first SOFA (and reburn) retrofits to cyclone-fired boilers is described in published technical papers[1,2]. Cyclone boiler retrofit SOFA installations are included in the EPA's BART technical support document[3] and listed later in Appendix A2.

A basic form of separated overfire air (SOFA) can be applied and installed on MRY Station Units 2. There are potential impacts and limitations unique to the firing of North Dakota lignite in cyclone-fired boilers that should be recognized as part of this emission reduction technology application.

Key aspects of successfully applying and operating a separated overfire air system on a cyclone-fired boiler are the ability to:

- Accurately measure the fuel heat input rate (BTUs) and combustion air inputs on a real-time, individual cyclone by cyclone basis, to allow the ability to determine and control the desired air/fuel ratio, especially when "starved air" (i.e. substoichiometric) combustion conditions are required.
- Maintain adequate molten coal ash (slag) formation and flow within the barrels and slag taps.

The degree to which the cyclone furnaces can be operated with less than theoretical (substoichiometric) combustion air directly contributes to less NO_X formation and further in-furnace emission reduction but also risks solidification of the molten coal ash. In the case of MRY Station Unit 2 boiler, cyclone combustion must be sufficiently air-staged to reduce NO_X emissions while releasing enough heat to continue to melt the fuel ash so that it flows effectively within and from the cyclone burners.

In the case of MRY Station boilers, there is a significant amount of variability in the combustible and ash components of North Dakota lignite supplied from the current mine near Center, ND. Analysis of several hundred coal feed samples taken simultaneously from multiple cyclones of MRY Station Unit 2's boiler revealed that the maximum differential of the lignite heating values from cyclone-to-cyclone was just over 12% of the average heating value of all the samples. Assuming an operating case occurred where the maximum cyclone-to-cyclone differential heating value was for two cyclones at the opposite ends of the fuel heat content range, there would be a plus or minus 6% variation in fuel heat content for either of the individual cyclones from the overall average. If the desired average cyclone air/fuel (stoichiometric) ratio was 0.95 when operating with air-staged cyclones associated with separated overfire air, and the amount of secondary combustion air to each cyclone was equal, there would be a stoichiometric ratio of approximately 1.01 in one cyclone and a stoichiometric ratio around 0.89 in another cyclone at the same time. The modestly air-staged cyclone would produce higher than average NOx emissions. The deeply staged cyclone would produce less than average NOx emissions and potentially insufficient amounts of heat release, and raise the risk of solidifying the fuel ash so that it accumulates within the cyclone barrel. This could result in firing auxiliary fuel oil in the deeply-staged cyclone or taking the boiler out-of-service to remove the pluggage. Neither of these conditions is desirable because they result in lower emissions removal performance and higher operating costs. Thus, due to the variability of the fuel heat content and the complex behavior of lignite ash when exposed to high temperatures, the extent of air-staging and thus the level of NO_X control in MRY Station boilers is expected to be modest while firing lignite coals.

In order to potentially achieve lower NO_X emission rates with modestly air-staged combustion for MRY Station boilers, additional combustion improvements can be installed. One potential improvement is to implement a unique form of SOFA for North Dakota-lignite–fired cyclone boilers. This includes relocated lignite drying system vent ports, and in Unit 2's case, also involves blocked or relocated lower furnace flue gas recirculation ports. This will be referred to as "Advanced SOFA" (ASOFA). There are several design challenges anticipated for implementing the advanced version (with the described port relocations) of separated OFA. These are believed to be solvable.

Both forms of separated overfire air as a combustion-related NO_X control technique are considered feasible for application to Milton R. Young Station cyclone boilers. Since the advanced SOFA is the highest-performing form of this technology, only this ASOFA version of the alternative was considered for additional NO_X reduction at Milton R. Young Station boilers.

Another form of separated overfire air being marketed commercially is "Rotating Opposed Fire Air" (ROFA). For utility applications in the United States, this has only been applied to pulverized coal-fired boilers, primarily tangentially-fired units[4]. It is different than basic SOFA in that it includes a hot air booster fan, and injects the overfire air in an offset fashion from opposite sides of the furnace at high velocities, with multi-port nozzles located at high elevations relative to the top burner row. The vendor (Mobotec USA) claims ROFA maximizes air-staged in-furnace combustion NOx reduction while minimizing negative impacts on carbon monoxide and flyash unburned carbon.

While this variation of separated overfire air could potentially be applicable to cyclone boilers, it has not been marketed to serve such applications. Because cyclone boilers do not require the addition of hot air booster fans for SOFA, this technique is not distinct enough from basic SOFA from functional and air-staged cyclone NO_X reduction performance standpoints to warrant individual consideration. ROFA technology lacks demonstrated cyclone-fired boiler experience, and thus was considered infeasible and not included in the control effectiveness and cost-effectiveness sections of the main report.

A.1.2.4 Oxygen-Enhanced Combustion

A supplier of liquid oxygen (Praxair) has developed a method of replacing some of the combustion air supplied to the burners with pure oxygen. Combustion air, which is normally input through the secondary air system ductwork downstream of the forced draft (FD) fan and air heater, is supplemented with pure oxygen directly injected into the burners. Oxygen-enhanced combustion (OEC) can reduce boiler NO_X emissions resulting from " thermal NO_X", a reaction of the nitrogen in the combustion air admitted to the burners with the available oxygen in the air in the flame or peak temperature regions of the fuel combustion process. The use of pure oxygen instead of air reduces the availability of nitrogen from the air to be oxidized in the high temperature regions, thus reducing formation of thermal NO_X. This technique has only been demonstrated in a boiler with pulverized fuel burners firing bituminous coal[5].

The lack of adequate experience on any cyclone-fired coal-burning boiler, on a temporary demonstration or permanent full-scale basis, and for a coal-fired facility of this size, precludes consideration of oxygen-enhanced combustion at MRY Station Unit 2's boiler. This is deemed to be infeasible technology at this location at the present time.

A.1.2.5 Flue Gas Recirculation

Flue gas recirculation (FGR) has been commonly applied to coal-fired boilers, primarily to inject into the lower furnace, just above the burners, supplied from the boiler's economizer flue gas outlet via a hot gas booster fan. This modifies the amount and temperature of hot furnace gas either in the lower-middle or upper furnace and convection heat transfer zones. As this flue gas typically has an oxygen content around 2-5%, it limits the availability of oxygen in a high temperature, possibly fuel-rich lower furnace zone. Flue gas recirculation for NO_X control is most commonly applied with gaseous or liquid fossil fuels to reduce the high temperatures which convert nitrogen in the combustion air to nitrogen oxides. No examples of using or installing FGR on cyclone-fired boilers strictly for NO_X emissions control were found in available technical literature.

FGR is already practiced at MRY Station in the Unit 2 boiler, primarily for furnace gas temperature and lower wall slagging reduction reasons. For this boiler, FGR could aid in potentially providing some small additional NO_X emissions control if it were modified from its current configuration, as part of an advanced form of separated overfire air. Complete elimination of the use of FGR could also slightly reduce NO_X emissions from Unit 2's boiler during air-staged cyclone combustion with separated overfire air system operation. There is uncertainty whether elimination of the use of FGR in the lower furnace of MRY Station's Unit 2 boiler could be successful in controlling lower furnace wall fireside ash deposition.

A.1.2.6 Water/Steam Injection (Combustion Tempering)

When applied to older gas-fired and oil-fired utility and industrial boilers, water and/or steam injection adds moisture into the lower furnace, concurrent with or near (to the side or slightly above) the burners, supplied from the boiler's treated feedwater or auxiliary steam systems via a metering pump or valve. There has been some limited testing of water injection for NO_X emissions control on natural gas-fired and coal-fired cyclone boilers[6,1]. For coal-fired cyclones, this technique is most effective on boilers burning bituminous coal; however, it has not been permanently installed and continuously operated in such applications. Successful long-term operation of water injection would be difficult for lignite-fired cyclone boilers, due to the high moisture levels in the coal and the need to readily ignite and sustain stable combustion and molten slag formation in the cyclone furnaces. For these reasons, water/steam injection is considered technically infeasible for NO_X control application at Milton R. Young Station.

A.1.2.7 Fuel Reburn

Another combustion technology that may be applicable to control NO_X emissions from the Milton R. Young Station units is fuel reburn. In a similar manner that overfire air diverts a portion of the combustion air input to the main firing zone, the reburning process involves supplying a portion of the fuel heat input to the boiler at a higher elevation in the furnace. This creates an upper furnace atmosphere where the reburn fuel's combustion products causes some of the NO_X formed in the main burner combustion zone and reburn zone to be converted into molecular nitrogen. Depending on the amount of reburn fuel added and the amount of oxygen available in the furnace gases to combine with the reburn fuel introduced, additional combustion air may be supplied as supplemental or overfire air. Downstream of the air injection elevation, the intention is to complete the reaction of any remaining carbon monoxide (CO) to carbon dioxide (CO_2), plus reduce the amount of combustible matter remaining in the entrained flyash.

The most common forms of reburn technology applied to utility powerplant boilers are:

- Pulverized or micronized coal reburn (PCR or MiCR); and
- Gas reburn (GR).

Pulverized coal reburning and micronized coal reburning have been applied to pulverized coal and cyclone-fired boilers. NO_X reduction efficiencies of 50 to 60 percent have been demonstrated on eastern bituminous coal and midwestern bituminous and Powder River Basin (PRB) western subbituminous coals while supplying up to approximately 20-30% of the boiler's total fuel heat input to the reburn zone[7,8].

For utility powerplant boiler applications, natural gas has been utilized as reburn fuel most often, demonstrated in two basic approaches:

- Conventional gas reburn (CGR); and
- Fuel-lean gas reburn (FLGR™).

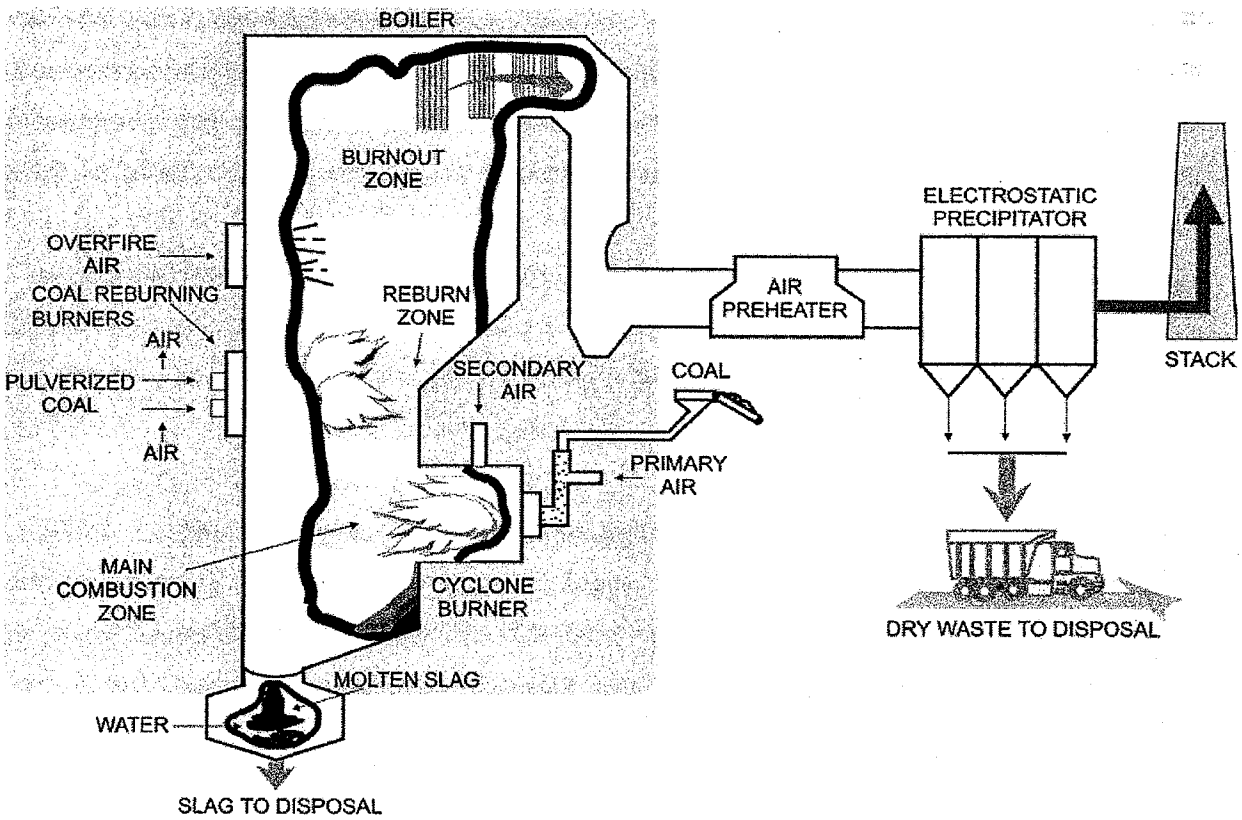
Either natural gas or pulverized coal (lignite) can be used as the reburn fuel. A sufficient quantity of natural gas is not currently available at the Milton R. Young Station plant site. Supplying enough natural gas to provide 6 to 25% of the total heat input to either or both boilers at MRY Station is expected to be technically feasible, although transport pipeline installation capital costs, and current and predicted unit natural gas costs and operating economics, are likely to be unfavorable.

Various forms of fuel reburning have been demonstrated and operated routinely on cyclone boilers for NO_X emission controls. This has been applied to units firing eastern bituminous coal, and western subbituminous or PRB/bituminous coal blends, using pulverized or micronized coal or natural gas as the most common reburn fuel. Reburning for NO_X emissions reduction has not been demonstrated on a unit firing high moisture, low heat content North Dakota lignite. Pulverized/micronized coal, along with conventional and fuel lean gas reburn technologies, are discussed below.

A.1.2.7.1 Coal Reburn

In the case of applying conventional coal reburn to cyclone boilers, the existing cyclones are supplied with the majority of the fuel, with either natural gas or pulverized coal (lignite) used as the reburn fuel such that the total heat input to the boiler is essentially the same as without fuel reburn. Separated OFA ports are located above the reburn fuel injection section of the furnace. These SOFA ports provide sufficient oxygen in a conventional fuel reburn installation to complete the combustion process that begins in the main combustion zone and is supplemented in the reburn and burnout zones. This is shown schematically for a pulverized coal reburn application on a cyclone-fired boiler with SOFA in Figure A.1-1.

Figure A.1-1 Pulverized Coal Reburn Application on Cyclone Boiler With Overfire Air[8]



In the United States, pulverized coal reburning and micronized coal reburning techniques for utility powerplant NO_X emissions reduction have been applied on a very limited full-scale, full-time basis to cyclone-fired boilers in field demonstration tests and longer-term demonstration operation, respectively. There have been only two known pulverized or micronized coal reburn installations in the United States on cyclone boilers, one on a utility boiler in Wisconsin, and one on a small industrial-size cyclone boiler in New York state[7,8,9,10,11,12,13,14]. NO_X emissions reduction efficiencies of 57 percent have been demonstrated on cyclone boilers firing eastern bituminous coal, or midwestern bituminous and Powder River Basin (PRB) western subbituminous coals while supplying up to approximately 20-30% of the boiler's total fuel heat input to the reburn zone. With the exception of the U.S. Department of Energy's (DOE) Clean Coal Technology Program demonstration projects[7,8,9], no known commercially-available coal reburn systems have been installed and are routinely operated on cyclone boilers in the United States to date. The DOE-CCTP projects for coal reburn applied to cyclone boilers are described below.

Pulverized coal reburning for NO_X emissions reduction in a cyclone-fired boiler was demonstrated on the 110 MW Nelson Dewey Unit 2 for Wisconsin Power & Light in 1991-1992. Reburn fuel preparation and handling, reburn burners with flue gas recirculation, and a separated overfire air system were added. Coal reburn tests were conducted on this unit while firing bituminous and PRB coals. NO_X emission control efficiencies of 50 to 60 percent, with reductions from 0.75-0.83 lb/mmBtu baselines to around 0.38 lb/mmBtu, but as low as 0.29 to 0.32 lb/mmBtu, with PRB coal at full load with approximately 25-30% of the total fuel heat input from reburn fuel were demonstrated[9,11,12]. The reburn system is no longer operated on Nelson Dewey Unit 2.

Micronized coal reburning has been demonstrated in 1997-1998, and continues to operate year-round on a small industrial cyclone boiler (400,000 lb/hr steam output, 50 MW gross equivalent) for Eastman Kodak Company at their Kodak Park facility in Rochester, NY. This unit (Boiler #15) achieves a NO_X reduction efficiency of approximately 57 percent on eastern bituminous coal, involving limited cyclone air-staging (cyclones believed to be slightly above 0% excess air) and a modest amount of overfire air injection downstream of the micronized reburn fuel input nozzles. Approximately 17% of the boiler's total fuel heat input is typically supplied to the reburn zone. This coal reburn system continues to operate routinely at this facility. This installation is reported to use a Fuller MicroMill to produce micronized coal with 80% passing through a 325 mesh screen[7,9,13].

If a coal reburn system was applied to MRY Station boilers, the existing cyclones would be supplied with the majority of the fuel in the form of crushed coal, and the balance of fuel would be supplied to a pair of dedicated pulverizers to feed the reburn injection ports, such that the total heat input to the boiler is essentially the same as without fuel reburn. In a conventional fuel reburn installation, OFA ports located above the reburn section of the furnace provide sufficient oxygen to complete the combustion process that begins in the main combustion zone and is supplemented in the reburn and burnout zones.

Similar to the application of separated overfire air, there are potential impacts and limitations unique to the firing of North Dakota lignite in cyclone-fired boilers that should be recognized as part of this emission reduction technology application. As a reburn fuel, lignite is expected to behave appropriately upon introduction in the lower middle furnace to help reduce NO_X emissions. The concerns are that the diversion of a significant amount of heat input from the cyclone barrels to use as a source of reburn fuel in the form of pulverized or micronized lignite may reduce cyclone temperatures enough to inhibit slag formation and flow, especially as boiler load is reduced. Air-staging the cyclones with the use of separated overfire air to further complement combustion NO_X reduction as part of this reburn technique will further risk slag "freezing" in the barrels and lower furnace. Reducing the number of active cyclones which are air- and fuel-staged to accommodate reduced firing rates while operating a coal-fired boiler with reburn and separated overfire air is the typical approach to avoid slag tapping problems.

Potential NO_X emissions reduction performance is expected to be limited on lignite-fired cyclone boilers with a basic form of separated overfire air system, since the reburn fuel injection location is expected to coincide with the existing lignite pre-drying system vent ports. The amount of oxygen introduced by the vent ports will be disruptive to any conventional reburn process in that it would require much higher reburn fuel injection rates to create a substoichiometric atmosphere in the lower secondary furnace that is conducive to promoting in-furnace NO_X reduction.

Significant additions to the fuel preparation equipment in the existing plant facilities will be required. The coal reburn system expected to be applied to MRY Station boilers may use two new fine-grind pulverizers and dynamic classifiers to achieve the level of coal particle size distribution required.

Higher unburned carbon levels in the flyash exhausted from the boiler may occur, especially when the reburn fuel is coal, and the regular burners are fired with less than theoretical amounts or combustion air commonly practiced with the use of overfire air. Lowering the reburn fuel injection elevation, decreasing

the amount of reburn fuel, and grinding the reburn coal to a greater degree of fineness can help to offset some of the increase in flyash unburned carbon content. Flue gas opacity from the stack may increase if the particulate removal equipment is an electrostatic precipitator, due primarily to reduced resistivity and smaller particle sizes of the flyash.

An issue that affects the feasibility of lignite reburning is the uptime required for the lignite reburn fuel pulverizing system, and impact of the reburn system on effectiveness in reducing NO_X emissions during load changes and lower loads. Typically, one new pulverizer is dedicated to prepare reburn fuel in existing pulverized fuel-fired boiler applications. Cyclones may be fired with less fuel or deactivated during boiler operation in order to accommodate changes in fuel combustion characteristics, boiler load, and for scheduled or unscheduled individual crusher maintenance. Milton R. Young Station Unit 2 has twelve crushers for cyclone coal grinding, each dedicated to one of the twelve cyclone furnaces. Diverting as much as 30% of the total heat input as reburn fuel could require four existing cyclones to be deactivated, and two new MPS-89 pulverizers to be dedicated to reburn fuel preparation. As each of these mills requires periodic maintenance, boiler emissions and/or load could be negatively impacted during individual reburn mill outage periods while the boiler remained in service. A high level of fineness of coal particles from the reburn mills is important to achieve and maintain in order to limit increases in flyash combustibles. A minimum of 60 percent passing through 200 mesh fineness is recommended by one of the reburn technology vendors (B&W) for pulverized lignite reburn. Micronized coal reburn requires even greater fineness: 70-80 percent passing through a 325 mesh screen.

Pulverized or micronized coal reburn with the advanced form of separated overfire air (ASOFA) can be applied and installed on MRY Station Unit 2's boiler. These combined techniques are expected to reduce NO_X emissions approximately 54% from current pre-control baseline levels (down to 0.36 lb/mmBtu) for the MRY Station Unit 2 boiler. These levels of NO_X reduction depend on the advanced form of separated overfire air technique to achieve the expected NO_X reduction percentages when applied to lignite-fired cyclone boilers, which may not be successful given the concerns expressed about the potential impacts of this technique. Using finely pulverized lignite for reburn fuel is considered technically feasible for NO_X emissions control under evaluation for application to MRY Station Unit 2's boiler.

A.1.2.7.3 Fuel Lean Gas Reburn

Another approach to gas reburning is "fuel-lean gas reburn" (FLGR™) technology, which injects limited amounts of natural gas (approximately 3-10 percent of the total fuel heat input) above the burners (or cyclones) with or without significant air-staging of the burners (cyclones) or the addition of overfire air upstream of the fuel injection elevation. FLGR's first field-test on a cyclone-fired boiler was at Commonwealth Edison's Joliet Unit 6 (327 MW), a 9-cyclone-furnace boiler[15]. NO_X emissions reduction with FLGR (without SOFA) was believed to be approximately 35-40% with 7% of the boiler's total fuel heat input supplied in the reburn zone. This test yielded 0.59 lb/mmBtu NO_X emissions from a baseline of 0.98[16]. One other cyclone boiler has been modeled using computational fluid dynamics (CFD) as part of a study looking at applying FLGR at Owensboro Municipal Utilities' Elmer Smith Station Unit 1 (150 MW single-wall, eastern bituminous coal-fired boiler). This model predicted that NO_X emissions could be reduced by 25-30% over that achievable from overfire air and SNCR[17].

More commonly, FLGR™ has been applied on medium to large pulverized coal wall-fired boilers burning eastern bituminous or western subbituminous coals. On Wisconsin Electric Power Company's (WEPCO's) Pleasant Prairie Unit 1, a 620 MWg Riley turbo-fired wet-bottom (slagging) boiler, FLGR™ alone was predicted to reduce NO_X emissions by 35-39 percent at a gas reburn rate of 7-8 percent but only achieved 20% from a baseline of 0.45 lb/mmBtu[16,18]. This is presumably without burner air-staging or SOFA. It has also been applied in combination with SNCR at this WEPCO site.

A potential advantage of FLGR™ over conventional gas reburn is that the former is generally compatible with, but does not require, the installation and operation of SOFA. The staged reburn fuel is introduced into an oxygen-rich atmosphere downstream of the burners and any OFA injection points. The amount of reburn fuel injected is typically limited by acceptable carbon monoxide levels in the boiler exit flue gas.

There are potential impacts and limitations unique to the firing of North Dakota lignite in cyclone-fired boilers that should be recognized as part of this emission reduction technology application. This is significant, especially for alternatives with FLGR™ technology when combined with basic or advanced SOFA to allow the natural gas introduced above the SOFA ports to burn completely prior to the furnace exit plane. In either case, the amount of additional potential NOx reduction possible with FLGR™ is limited, since the reburn fuel injection location is expected to coincide with the existing lignite pre-drying system vent ports. The amount of oxygen introduced by the vent ports will be disruptive to the fuel-lean

reburn process in that it would require much higher reburn fuel injection rates in the lower secondary furnace to promote in-furnace NO_X reduction. There are reduced concerns that the withholding of a modest amount of heat input from the cyclone barrels to use natural gas as a source of reburn fuel may reduce cyclone temperatures enough to inhibit slag formation and flow, especially as boiler load is reduced. Air-staging the cyclones with the use of separated overfire air to further complement combustion NO_X reduction is an optional part of this reburn technique which will further risk slag "freezing" in the barrels and lower furnace.

Fuel lean gas reburn can be applied and installed on MRY Station Unit 2's boiler with or without SOFA/ASOFA. This technique is considered technically feasible for application to MRY Station Unit 2's boiler. Expected NO_X reduction will be modest for FLGR™ without SOFA and FLGR™ with a basic form of SOFA. Unit operating and capital costs to supply large quantities of gaseous fuel not currently available at this site are economic disadvantages. Because of these factors, these variations of this technology will not be cost-effective compared to other alternatives with similar control effectiveness. FLGR™ without SOFA and FLGR™ with a basic form of SOFA were not included in the control effectiveness and cost-effectiveness sections of the main report.

Other demonstrated forms of fuel lean gas reburning in combination with post-combustion technologies, such as amine-enhanced fuel lean gas reburn (FLGR™ with SNCR), are discussed under the layered technologies section.

A.1.2.7.4 Fuel Oil Reburn

Fuel oil has been substituted for natural gas in a conventional reburn application. This is much less common in the United States than using natural gas as a reburn fuel, due to the general lack of demand and difficulties in supplying the volume of fuel oil which would be required. It has been installed commercially on three 350 MW oil-fired boilers in New Brunswick (Canada) at the Coleson Cove plant. NO_X emissions reduction with reburn and SOFA was 78% with 25% of the boiler's total fuel heat input supplied in the reburn zone. This yielded 0.22 lb/mmBtu NO_X emissions from a baseline of 1.0 lb/mmBtu[9]. No examples of conventional fuel oil reburn applied to a coal-fired cyclone boiler were found in available literature.

Fuel oil reburn could potentially be considered for application to MRY Station Unit 1 and Unit 2 boilers. Investigation of the specific source, distance, and costs for supplying significantly increased quantities of fuel oil via transport trucks hauling tanker trailers or underground pipeline to M.R. Young station has not

been performed. The unit operating and capital costs to supply large quantities of high-volume liquid fossil fuel at this site are economic disadvantages. The concerns regarding potential impacts and limitations unique to the firing of North Dakota lignite in cyclone-fired boilers that should be recognized as part of this emission reduction technology application are similar to those expressed for conventional gas reburn. It is believed that potential NO_X control with oil reburn would be slightly less than comparable conventional gas reburn systems.

Although fuel oil reburn could potentially be considered for application to MRY Station Unit 2's boiler, the lack of any distinct potential NO_X reduction advantages and demonstration on cyclone-fired boilers does not appear to support its consideration. This alternative was not included in the NO_X control and cost-effectiveness analysis.

A.1.3 Post-Combustion Controls

Post-combustion controls deal with techniques that thermally or chemically-treat the flue gases to reduce NO_X emissions after they have exited the boiler's lower furnace. In the case of Milton R. Young Station Unit 2, this primarily involves forms of selective catalytic reduction (SCR) and selective non-catalytic reduction (SCR) technologies. Another emerging technology that has recently entered the commercial market is Powerspan's Electro Catalytic Oxidation®, which treats utility boiler flue gas for removal of nitrogen oxides, sulfur oxides, and mercury. Another emerging technology that has recently entered the commercial utility air pollution control market is Powerspan's Electro Catalytic Oxidation®, which treats boiler flue gas for removal of nitrogen oxides, sulfur oxides, and mercury.

A.1.3.1 Selective Non-Catalytic Reduction (SNCR)

Selective Non-Catalytic Reduction (SNCR), and variations such as hydrocarbon-enhanced SNCR (sold under the trade name of NOxStar™), and Rich Reagent Injection (RRI), are all post-combustion types of boiler NO_X emission controls. While these technologies are insensitive to the specific fuel types whose combustion products are being treated, the large majority of boiler applications to date have been on pulverized coal-fired units burning eastern bituminous fuels. SNCR has been used to reduce NO_X emissions on numerous utility boilers burning eastern bituminous coal, midwestern bituminous coal, and, to a lesser extent, western subbituminous coal. SNCR has also been used with fuel oil and natural gas-fired units. SNCR (and hydrocarbon-enhanced SNCR) technologies can each be applied to cyclone boilers with or without the use of a SOFA system. SNCR does not appear to be dependent directly on the type of burners (wall-fired, tangentially-fired, and cyclone-fired) employed in the boilers where it has

been installed, with or without overfire air in full operation. Operation at these plants has demonstrated that SNCR can decrease NO_X emissions as much as 15-40% at full load, most typically between 25-35 percent[19].

In the conventional SNCR process, urea or ammonia is injected into the boiler in a region where the combustion gas temperature is in the 1700 to 2100 degrees F range. Under these temperature conditions, the urea reagent [$CO(NH_2)_2$] or ammonia [NH_3] reacts with the NO_X, forming N_2 and water, reducing NO_X emissions.

Long-term examples where SNCR has been used to reduce NO_X emissions on two cyclone-fired boilers are on a 138 MW unit and 160 MW unit burning eastern bituminous coal at Conectiv's B.L England Station (Units 1 and 2) since 1995 and 1996, respectively. Tests at these plants demonstrated that SNCR can decrease NO_X emissions as much as 30-36% at full load, from around 1.3-1.4 lb/mmBtu respectively to as low as 0.85 lb/mmBtu (without overfire air)[18,19,20]. These boilers, located near Atlantic City, New Jersey, continue to operate SNCR (with OFA) for annual NOx emissions around 0.55 and 0.45 lb/mmBtu, respectively.

SNCR can be applied and installed on MRY Station boilers. Estimated NO_X emission rates for using SNCR with North Dakota lignite considered published levels achieved by cyclone-fired units firing western subbituminous coal, and vendor predictions. SNCR alone is expected to reduce NO_X emissions approximately 37% from MCR baseline levels (down to around 0.5 lb/mmBtu) for the MRY Station Unit 2 boiler with ammonia slip limited to approximately 5 ppmvd. Because of the operating costs of the consumed reagent, this technology will not be cost-effective compared to other alternatives with similar control effectiveness (i.e. SOFA), SNCR alone was not included in the control effectiveness and cost-effectiveness sections of the main report.

Other demonstrated forms of SNCR-related technologies, such as Rich Reagent Injection with SNCR, and amine-enhanced fuel lean gas reburn (FLGR™ with SNCR), are discussed under the layered technologies section.

A.1.3.2 Hydrocarbon-enhanced SNCR (NOxStar™)

Hydrocarbon-enhanced SNCR technology, commercially marketed as NO_XStar™, is offered by a single vendor (Mitsui Babcock) as a post-combustion type of enhanced SNCR technology, whereby an

ammonia-based reagent is continuously injected into the superheater/reheater pass of an operating boiler with small amounts of gaseous hydrocarbon (typically either natural gas or propane) and air or steam to provide lance cooling and aid reagent dispersion. The targeted combustion gas temperature range is between 1500°F and 2000°F. The amount of gaseous hydrocarbon introduced is small enough (0.1 to 0.2% of total fuel heat input) that this is not intended to act as a form of reburn or staged fuel combustion. An array of permanently-installed injection lances are located within the boiler convection pass, divided into numerous discrete zones across the full width and height of the duct. The hydrocarbon auto-ignites, forming hydroxyl (OH) radicals which react with the NO_X and ammonia to produce elemental nitrogen (N_2) and water vapor (H_2O).

NO_XStar™ was demonstrated at Tennessee Valley Authority's Kingston Power Station Unit 9 (tangentially-fired 200 MW twin-furnace boiler firing eastern bituminous coal) in 2002[21]. This technology was subsequently permanently-installed at TVA's Colbert Station Unit 4 in late 2003 on a 192 MW wall-fired boiler burning eastern bituminous coal[22]. NO_X reduction was stated as 68-80% for these applications, which included the impact of overfire air and air-staged combustion upstream of the ammonia and propane injection locations.

An example of a hydrocarbon-enhanced SNCR installation on a wall-fired pulverized fuel boiler is shown as a sectional side elevation view of the upper furnace in Figure A.1-3.

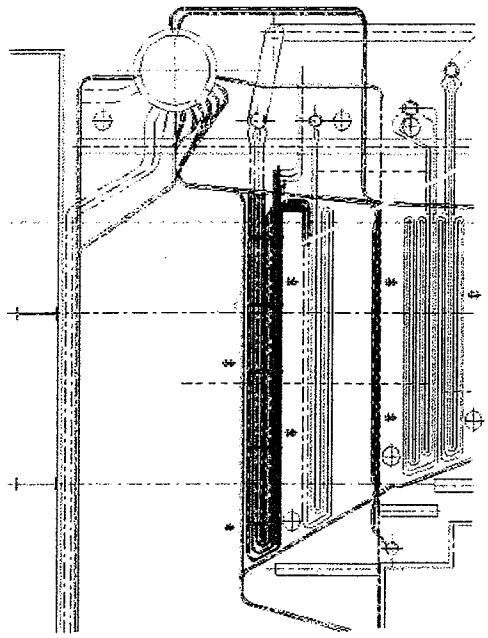


Figure A.1-3 Hydrocarbon-enhanced SNCR Application on PC-fired Boiler[22]

The supplier (Mitsui Babcock) of hydrocarbon-enhanced SNCR technology claims there is little sensitivity to the type fuel (coal) or burners this technique can be potentially applied to in order to reduce NO_X emissions. The chemical reagent injection for hydrocarbon-enhanced SNCR (NO_XStar™) NO_X control technology must be precisely located and carefully controlled to be effective. Operation outside of the required operating ranges can even result in increased NO_X emissions. Extensive computational fluid dynamic (CFD) model simulations are needed to determine the optimum injection points and spray patterns. Boiler operating conditions change with unit load and varying fuel characteristics. The NO_XStar™ process control system must be able to adjust for these changing conditions in order to be effective throughout the intended load range and firing conditions encountered. Non-retractable ammonia injection lances arranged in a parallel-series manner are permanently mounted inside the upper furnace zone, attached to convective tube elements. Different sections of the injection "grid" can be turned off or on, depending on load and firing conditions and amount of NO_X reduction required. Injection nozzles are continuously purged and cooled by extracted superheated steam from the boiler's main steam outlet, whether ammonia reagent is being introduced into the flue gas stream or not. Ammonia slip can be minimized by injecting less reagent, although NO_X control performance will be reduced.

There are a number of issues with firing North Dakota lignite that make the applicability of hydrocarbon-enhanced SNCR infeasible compared to previous experience in other coal-fired powerplants. These issues include:

- Hydrocarbon-enhanced SNCR (NOxStar™) technology has not been applied to cyclone boilers (with or without the use of a SOFA system). It has been only applied to date on pulverized coal-fired boilers burning eastern bituminous fuels.
- There is no successful demonstrated full-scale experience in continuous service of hydrocarbon-enhanced SNCR (NO_XStar™) technology on units firing high-slagging coals such as western subbituminous (PRB) and lignite. The heat transfer surfaces in the convective heat transfer zone where the reagent mixture is injected are prone to severe fouling from flyash constituents common in North Dakota lignite coals. Flyash deposit accumulation on the outside of the NO_XStar™ lances in Milton R. Young Station Unit 2 boiler's upper furnace is expected to be significant, potentially occurring within a matter of a few weeks from startup and nearly impossible to prevent or remove effectively during boiler operation. Such buildup is expected to cause maldistribution of the NO_X reduction chemical reagent from the injection nozzles. Effective on-line removal of these deposits from the injection nozzles is anticipated to be insufficient to maintain effective injection distribution and volume control. It is anticipated that this would significantly reduce the NO_X emission reduction performance consistently achieved on a sustainable basis.

The lack of experience with cyclone boilers, especially those firing coal with severe deposition characteristics such as North Dakota lignite, makes this technology technically infeasible for application on the Milton R. Young Station Unit 2 boiler.

A.1.3.3 Rich Reagent Injection (RRI)

Rich Reagent Injection (RRI) is a NO_X control process that has been developed and demonstrated specifically for use on cyclone boilers. Rich Reagent Injection is an SNCR process that involves the injection of aqueous urea into the lower furnace between the cyclones and the SOFA ports. RRI targets a high temperature, fuel-rich zone within the boiler-furnace environment immediately adjacent to the cyclone burners, and requires temperatures in the range of 2400 to 3100 degrees F.

The three zones of a Rich Reagent Injection SNCR application on a boiler with separated overfire air are shown as a sectional side elevation view of the furnace in Figure A.1-4.

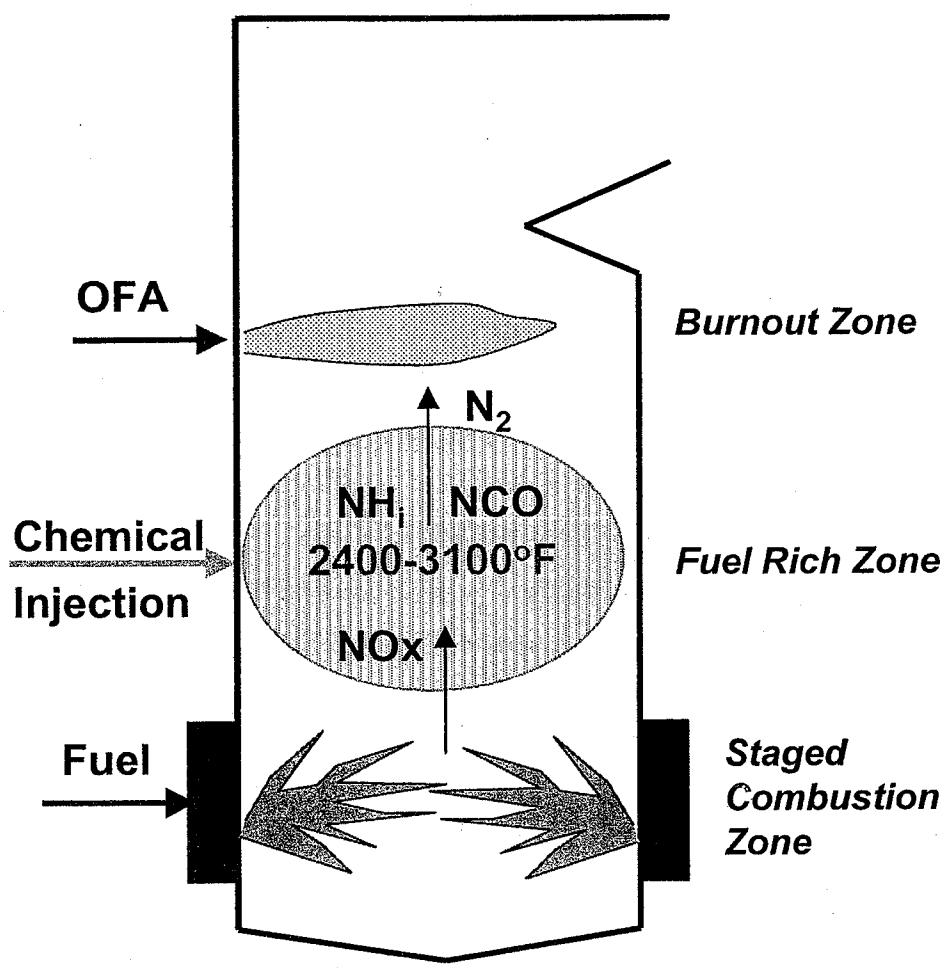


Figure A.1-4 Rich Reagent Injection Application on Boiler With Overfire Air[23]

The Rich Reagent Injection (RRI) process has been successfully demonstrated on at least two cyclone-fired boilers, with the most recent installation at Ameren's Sioux Unit 1, a 500 MW boiler firing a blend of PRB and midwestern bituminous coals. Generally, the heat content of these coals typically varies very little. Short-term testing of the RRI process has been performed alone and in combination with SNCR on B.L. England Unit 1 in 1999[24,25], and more recently at Ameren's Sioux Unit 1 in 2002[23,25], in 2004[26] (alone), and in the first half of 2005[27] (alone, and with SNCR).

The RRI process is intended to be used only with air-starved (substoichiometric staged-air) cyclone combustion, in conjunction with the installation and operation of an OFA system. The RRI process has not been demonstrated on any unit that fires North Dakota lignite. As of October 2006, no commercial installation of a permanent Rich Reagent Injection system has been made at any cyclone-fired boiler.

There is only one holder of a commercial license for modeling and conceptually designing RRI (Reaction Engineering International), with two vendors sub-licensed to design and sell RRI equipment (Fuel Tech and Combustion Components Associates). Since these license agreements are in place, and considering that successful demonstration testing has been performed at two cyclone-fired boiler powerplants, this technology is considered to be applicable and commercially available for potential application on cyclone boilers which burn coals with heat contents that are relatively constant. However, due to the variable heat content of lignite coal, RRI is considered to be technically-infeasible for application on North Dakota lignite-fired boilers. Technical feasibility and expected NO_X emissions from RRI for application on the Milton R. Young Station Unit 2 boiler are included in the "Layered NO_X Reduction Technologies" section.

A.1.3.4 Selective Catalytic Reduction (SCR)

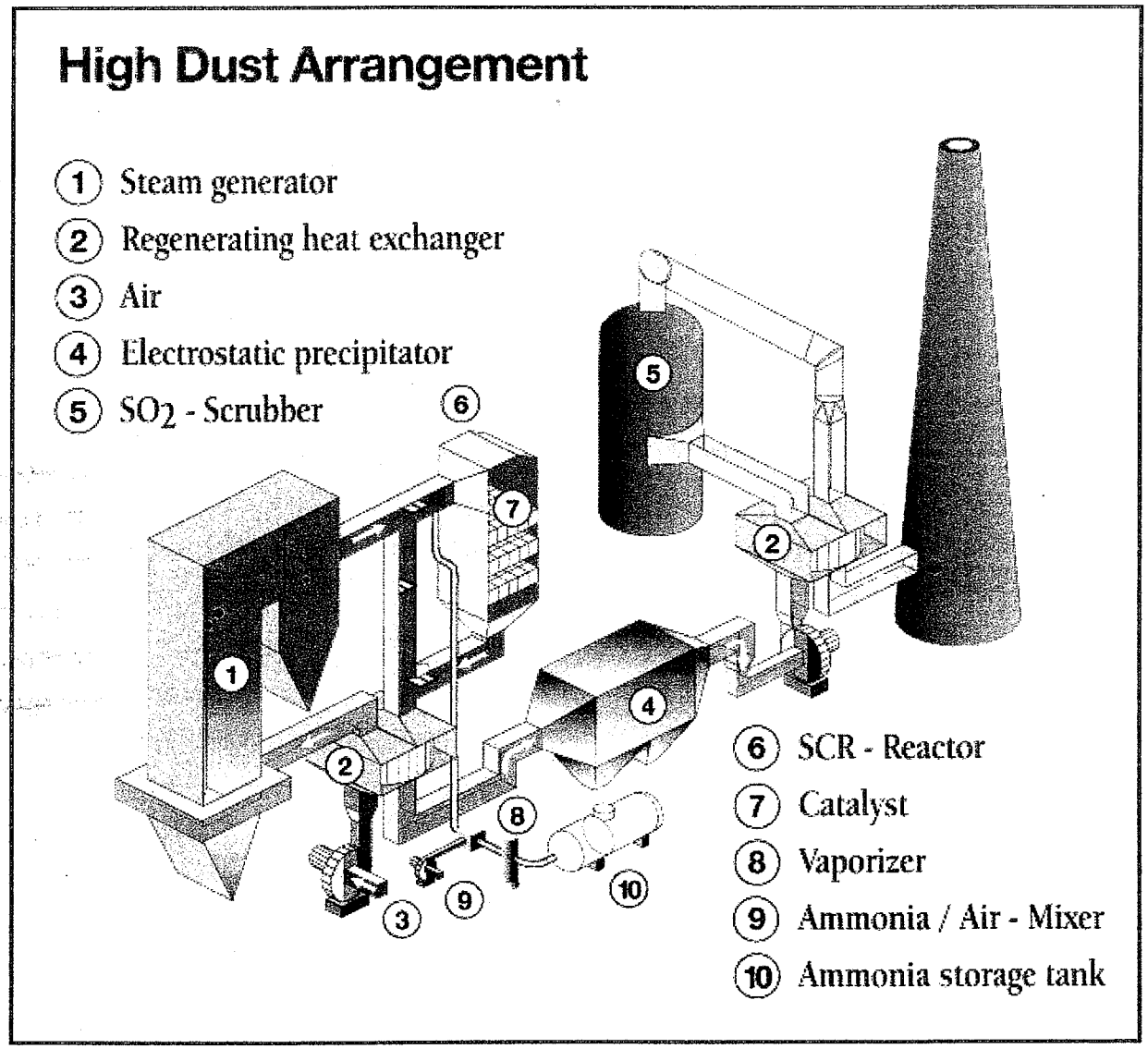
The lowest NOx emission levels from coal-fired utility boilers are typically achieved by installing and operating selective catalytic reduction (SCR) technology. In the SCR process, the gas stream is passed through a catalyst bed in the presence of ammonia to reduce NO_X to molecular nitrogen and water. The process is termed "selective" because the ammonia preferentially reacts with the NO_X rather than with the oxygen in the flue gas. A catalyst is used to enhance NO_X reduction and ammonia utilization at appropriate flue gas temperatures. SCR is usually applied to flue gas in the 600°F to 750°F temperature range. There are variations in the SCR process for coal-fired boilers that mostly involve locations in the flue gas path where the catalyst is placed in order to promote the desired NO_X emission reduction effect. These are described below.

A.1.3.4.1 High-Dust Selective Catalytic Reduction (HD-SCR)

For coal-fired boilers, a conventional SCR reactor utilizes readily-available catalyst materials and reagent in the form of ammonia. A conventional SCR reactor is commonly installed in a high-dust, hot-side arrangement, located between the economizer outlet and air heater inlet, where the flue gas temperature is within the desired operating range for the SCR catalyst. The conventional SCR reactor arrangement is preferred for most coal-fired applications in utility boilers because it avoids the added expense of reheating the flue gas if placed after the air heaters which cool the flue gas, and downstream of any flue gas treatment to remove acid gases. Conventional SCR technology uses an ammonia injection grid (AIG), which consists of multiple nozzles, for distributing the reagent into the flue gas at the boiler's economizer flue gas outlet.

A schematic graphic diagram for a conventional high-dust, hot-side SCR system on a boiler with a flue gas desulfurization system and stack gas reheat is provided in Figure A.1-5.

Figure A.1-5 Conventional High-Dust SCR Arrangement with FGD Scrubber Outlet Reheat



(figure copied from Wheelabrator Air Pollution Control literature)

Conventional high-dust, hot-side SCR technology has been installed on several pulverized coal and cyclone boilers firing bituminous and subbituminous coal in the United States. There are also a limited number of European SCR installations on steam electric generating units (SEGUs) firing lower grade (brown) coal. There are, however, no existing full-scale SCR installations on units that fire North Dakota

lignite. There are approximately 50 cyclone-fired units located in the states affected by EPA's NO_X SIP call. Over half of these units are planning to install conventional high-dust, hot-side SCR systems in response to the SIP call. The installation of conventional high-dust, hot-side SCR systems has been completed on approximately 22 of these units. Appendix A2 lists several conventional high-dust hot-side U.S. SCR installations on pulverized coal and cyclone-fired utility boilers, along with measured NO_X emissions. Initial data from these units indicate that conventional high-dust, hot-side SCR systems operated on suitable cyclone-fired units may be able to reduce NO_X emissions to as low as 0.07 lbs/mmBtu. Several SCR installations have been retrofit on existing cyclone-fired boilers burning western subbituminous coal (or PRB blended with midwestern bituminous coal). For cyclone coal-fired utility boilers retrofitted with SCR technology, all were originally designed to burn bituminous coal.

The EPA NO_X SIP call only applies to units in the eastern United States. There are no facilities firing North Dakota lignite in the EPA NO_X SIP call region. SCR system operation is currently only needed during the ozone season (June – September) for units installing control equipment solely to meet the EPA NO_X SIP call requirements. Limited annual operation is a significant factor with respect to SCR equipment reliability, maintenance, operational costs, and catalyst life. The demands on the SCR system are much more severe if the equipment is required to operate on a full-time, annual basis.

Two byproducts from the high-dust, hot-side SCR process are ammonia slip and SO_3:

- Ammonia Slip: Slip is ammonia that is unreacted in the NO_x emission reduction process. Maximum ammonia slip for a gas fired unit is usually 10 ppmvd whereas, on a coal fired unit, ammonia slip below 5 ppm is desired. For certain applications, this concentration can be problematic, therefore requiring more catalyst to reduce slip. Most new SCR applications have ammonia slip guaranteed at a 2 ppmvd maximum for an initial operating period.
- SO_3: Due to the composition of typical SCR catalysts, a small percentage of inherent SO_2 will be oxidized to SO_3. This oxidation can be controlled by catalyst selection and can be less than one percent. SO_2 to SO_3 oxidation must be carefully controlled to avoid creating SO_3 levels sufficiently high to raise the possibility of air heater fouling. A unit firing high-sulfur coal with SCR technology is especially vulnerable to SO_3 oxidation and ammonia slip-related fouling problems. The deposition and fouling is due to formation of solid ammonium sulfate ($(NH_4)_2SO_4$) and liquid ammonium bisulfate (NH_4HSO_4). The most important design variable is optimizing the catalyst selection and amount of catalyst that will reduce NO_X emissions, control ammonia slip, and minimize SO_2 oxidation.

Recent technology has allowed catalyst suppliers to make more rigorous and lengthy guarantees. A reasonable initial operating period for conventional catalysts in high-dust reactor arrangements on boilers firing eastern or midwestern bituminous coal is around 24,000 active operating hours (i.e. when ammonia reagent is being injected). Factors that need to be taken into account in design of a high-dust, hot-side SCR application that affect the need for catalyst replacement are:

- Pressure drop: The amount of restriction to flue gas flow through the SCR inlet, ammonia injection grid, SCR reactor, and downstream ductwork directly increases induced draft fan horsepower required to maintain adequate boiler draft. This is an important parameter to consider and minimize during the design stage. Pressure drop is a function of the average and maximum SCR reactor duct velocities, the amount of restriction caused by flow distribution correction devices (baffles or vanes), and the number and geometrical aspects of the catalyst layers. Many retrofit SCR installations require a booster fan or upgraded induced draft fan to overcome the added flow resistance. This increases operating cost for the increase in auxiliary power consumption and loss of saleable electric power. The type and pitch of the catalyst are factors most influential in determining the amount of pressure drop.
  - Catalyst type: The most common types or forms of catalyst material are honeycomb or plate. The former offers more surface area per volume, but can be more restrictive and prone to pluggage from ash deposits. The latter is usually less restrictive but requires more catalyst per layer or more layers to achieve the active surface needed to achieve the intended NO_X emission reduction.
  - Catalyst pitch: The pitch of the catalyst, a term used to describe the size of the gas path openings through the catalyst, varies depending on the manufacturer and design dust loading. Pitch is generally on the order of 5 to 7 millimeters. Potential pluggage of flow channels within the catalysts layers is therefore an issue that must be dealt with during design.
- Catalyst performance: The amount of NO_X emission reduction expected is a function of the specific activity level of the catalyst material and the amount of catalyst installed, over a given period of time. Catalyst formulation selection and features of construction have a significant impact on long-term NO_X emission reduction and subsequent costs for reagent and catalysts replacement. The frequency of catalyst replacement is influenced strongly by:
  - Catalyst erosion: Erosion of the catalyst material in coal fired units from entrained flyash or sootblowing action reduces the amount of active surface available for reacting with the reagent and flue gas, and can cause distortions in gas distribution ("channeling") through the

SCR reactor. Catalyst material is fragile and can be easily damaged. Some catalyst is provided with erosion-resistant top edges to mitigate this tendency.

- Moisture absorption: Many types of catalyst are damaged by absorption of moisture. The reactor must be kept above ambient dewpoint temperatures or protected from freezing during outages in order to protect the catalyst from moisture damage. Spare catalyst must be carefully packaged to keep it dry and must be handled delicately to prevent damage.
- Thermal degradation: The specific active elements of the catalyst surface, or the matrix structure itself upon which the catalyst material is applied, can degrade when exposed to flue gas temperatures greater than the intended design of the formulation. High flue gas temperatures within the reactor causes sintering, leading to a permanent loss of catalyst activity due to a change in the pore structure of the catalyst. Proper selection and manufacturing control of the catalyst structure and formulation can minimize thermal degradation.
- Catalyst poisoning: The loss of performance or activity of the catalyst over time can be due to chemical damage or poisoning. Two elements especially detrimental to the life of common titanium-supported vanadium pentoxide SCR catalyst are arsenic and zinc. Vanadia/tungsten-based catalysts are particularly susceptible to rapid deactivation due to gaseous arsenic poisoning. In some German SCR installations, a 50% loss of activity has been reported within 10,000-15,000 operating hours. Addition of molybdenum to a vanadia-titanium SCR catalyst on similar applications shows relative activity reductions of 20-25%. Progressive loss of SCR NO_X reduction performance from catalyst deactivation due to poisoning is not possible to restore without effective cleaning to remove the deposits, or eventual replacement.
- Catalyst fouling: The surface area potentially exposed to the reagent (ammonia) and nitrogen oxides in the flue gas can become fouled with flyash or sulfur-related compounds. The presence of excess calcium oxide in the presence of sulfur in the flue gas can form a calcium sulfate surface coating that can be extremely dense, masking the pores of the catalyst. Progressive loss of SCR NO_X reduction performance from catalyst deactivation due to fouling is difficult to restore without effective cleaning to remove the deposits, or eventual replacement.

SCR technology has been installed on numerous coal-fired utility boiler facilities around the world and there are a large number of manufacturers that market the catalysts. The question is whether SCR is a

feasible technology for a unit firing North Dakota lignite. There are serious concerns whether installation of SCR technology on a North Dakota lignite-fired unit can be successful, especially in a conventional "hot-side, high-dust" configuration. The effectiveness of the SCR process is highly dependent upon the ability of the nitrogen oxides in the flue gas being able to contact the active sites within microscopic pores of the catalyst in the presence of ammonia reagent with minimal interference from contaminants.

A recent technical paper "Ash and Mercury Behavior in SCR Catalysts When Firing Subbituminous and Lignite Coals" by the Energy & Environmental Research Center (EERC) of the University of North Dakota was published in the February 2005 issue of Fuel Processing Technology magazine[28]. This paper summarized the results of SCR slipstream testing at two PRB-fired plants and one North Dakota lignite-fired powerplant. The evaluation included determination of impacts of ash on SCR plugging and blinding. Flue gas was isokinetically extracted from the convective pass of the boiler upstream of the air heater. Pressure drop across the catalyst was measured during the initial two-month test period, and the two consecutive two-month test periods following the initial trial, while holding flue gas flow and temperatures constant. Ammonia was injected downstream of a screen, upstream of a flow straightener and air pulse section. Compressed air was injected ahead of the reactor, and was periodically pulsed to simulate sootblowing to minimize ash deposit accumulation.

This slipstream SCR testing examined the significance of ash accumulations on SCR catalyst on both the macroscopic and microscopic levels. Very small flyash particles were found bonded together by a matrix of sodium-, calcium-, and sulfur-rich materials, likely in the form of calcium sulfate. North Dakota lignite coal contains many alkali and alkaline-earth elements, and sulfur. The firing of lignite coal which produces fine (less than 5-μm diameter) flyash particles creates conditions that enter the pores of the catalyst, react with SO_3 in the flue gas, and form sulfates which bind other ash particles into the matrix.

As posted on Electric Power Research Institute Inc.'s (EPRI's) website regarding the impact of coal type on SCR catalyst life and performance, a recent EPRI study[29] produced field data analyzed from an "In-Situ Mini SCR Reactor" system installed in a typical "high-dust" location at seven different test sites, including four firing PRB coal, one firing Texas lignite, one firing high-sulfur eastern bituminous coal, and one firing a PRB/eastern bituminous coal blend. The PRB/bituminous coal blend test was performed at AmerenUE's Sioux Station, on one of the two 500 MW cyclone-fired boilers. This study found that the cyclone unit firing the PRB/bituminous coal blend exhibited the fastest rate of catalyst activity degradation. Also, the higher deactivation rates seen at this site were due to economizer exit flue gas

temperatures being significantly higher than at the other sites. A comparison of the Texas lignite and one of the PRB-fired sites with two different catalysts, deactivation was more a function of trace elements in the flue gas and flyash than the specific catalyst type or formulation.

North Dakota lignite produces an ash that is very sticky and creates severe ash deposition problems. There have been no installations of SCR systems (full-scale) on units that fire North Dakota lignite. A technical assessment was conducted for the installation of SCR technology on a North Dakota lignite unit. In order to further evaluate the feasibility of installing a conventional SCR system on a North Dakota lignite fired unit, the Energy & Environmental Research Center (EERC) at the University of North Dakota was consulted. EERC has extensive experience investigating the deposition characteristics of North Dakota lignite ash.

Technical difficulties and anticipated operating problems that are unresolved with respect to installing conventional SCR technology at Milton R. Young Station include the impacts of erosion, severe ash deposition, and "popcorn ash" on the catalyst. According the EERC's study (see Appendix B), "the most significant problems that prohibit the successful operation of SCR catalysts to lignite coal is the formation of low-temperature sodium-calcium-magnesium sulfates and phosphates that will form on the surfaces of catalysts and the carryover of deposits that will plug the catalyst openings, resulting in increased pressure drop and decreased efficiency". For these reasons, application of available conventional high-dust SCR technology is considered technically infeasible for Milton R. Young Station Unit 1 and Unit 2 boilers. These concerns can be divided into four categories. Each category is addressed below. An explanation of the factors that make conventional SCR technology infeasible for these boilers follows:

1. Ash Deposition: North Dakota lignite contains a variable and complex variety of inorganic compounds that contribute to ash deposition. This fuel produces ash with severe deposition characteristics that are not typical with other coals. When exposed to the heat of the combustion process inside the cyclone burners, the majority of the fuel ash becomes molten and flows into the bottom of the furnace. A significant portion of the fuel ash is entrained into the flue gas exiting the cyclone barrels at high velocity, where it comes into contact with the lower furnace waterwalls. The portion that is carried with the rising flue gas cools and some is deposited on heat transfer surfaces in the upper furnace and boiler convection pass. Ash deposition on heat transfer surfaces is a substantial problem for units that fire North Dakota lignite. The problem is so severe at Milton R. Young that the Unit 2 boiler must be shut down at 80 to 90-day intervals to

allow for cleaning of ash deposits from the boiler heat transfer surfaces in order to restore reasonable furnace exit gas velocities and temperatures.

Sodium is a significant contributor to the "stickiness" of the ash produced from firing North Dakota lignite. Sodium content of the lignite ash averages approximately 4.4%, and can nearly double this value for some of the lignite produced from the Center mine. PRB coal typically averages around 1.5% sodium content. Boilers firing North Dakota lignite typically have a 2.5% higher heat rate (million Btu per kilowatt of electric generation) than a typical boiler firing PRB coal, thus requiring more heat input and firing more fuel per megawatt of electricity output. A cyclone boiler firing North Dakota lignite also converts approximately 50% of the fuel ash to flyash, compared with a 35% conversion rate for PRB coal-fired cyclone boilers. Overall, this results in an amount of sodium emitted from a cyclone boiler firing North Dakota lignite of approximately 7.3 lbs/MW-hr compared with 0.9 lbs/MW-hr for a PRB-fired cyclone boiler.

The catalysts in coal-fired boiler SCR reactors are highly susceptible to ash deposition. In a typical conventional high-dust SCR reactor, the flue gas typically passes through two to four layers of catalyst modules. The catalyst modules have numerous narrow passages to provide intimate contact between the flue gas, ammonia and catalyst. The clearance (pitch) in these passages is typically 6-10 millimeters. A typical catalyst layer is approximately 1 to 1.5 meters deep. The catalysts in coal-fired boiler SCR reactors must be cleaned frequently using soot blowers and/or sonic horns. This is true even on units firing fuels that do not produce a sticky ash that contributes to ash deposition. Ash deposition on the catalyst in a high-dust SCR application would be severe for a unit firing North Dakota lignite.

Sulfur in the coal is oxidized during excess air combustion to form sulfur dioxide (SO_2), and a small amount of sulfur trioxide (SO_3). Some of the ammonia-based reagent injected upstream of the SCR reactor will combine with SO_3 to form ammonium bisulfate. The catalyst in the SCR reactor will also oxidize a portion of the SO_2 to SO_3. Excess unreacted ammonia reagent carryover ("ammonia slip") from the SCR reactor will also react with these sulfuric acid compounds in a similar fashion. The deposition characteristics for a unit burning North Dakota lignite will create difficult-to-remove ash deposits and pluggage of a conventional high-dust catalyst, and increase the probability that the air preheater downstream and flue gas ductwork will be prone to accumulations which could be severe. High-dust SCR performance and catalyst life

will be severely impacted. It is anticipated that a high-dust SCR's catalyst life will be shortened from 3-6 years (typical) to as little as 2-12 months, requiring extended, frequent outages for replacement.

Hot-side air preheaters are susceptible to fouling. Tubular air pre heaters originally supplied with all cyclone boilers also tolerate moderate dust loadings, since their height and size make them difficult to maintain cleanliness. Leak tightness of the air preheater is important on cyclone-fired boilers with relatively high forced draft fan discharge (combustion air supply) pressures. A high-dust SCR installation will be prone to air preheater tube fouling and pluggage, requiring extended, frequent outages for cleaning.

2. "Popcorn Ash": A second consideration in the application of conventional high-dust SCR technology on a lignite-fired unit is the potential of the SCR reactor catalyst pluggage resulting from carry over of "popcorn ash" from the boiler. Boilers firing North Dakota lignite have severe problems with ash deposition on boiler surfaces. North Dakota lignite has a high propensity to form deposits on the boiler's furnace and convection pass fireside surfaces. For lignite-fired units, the boiler's heat transfer surfaces must be cleaned by sootblowing and other methods (e.g. water lances) frequently to maintain satisfactory boiler operation. Some of the removed deposits released by the cleaning action within the boiler and convection passes form "popcorn ash", which will be entrained in the flue gas. Carry over of boiler ash deposits will contribute to pluggage of the "popcorn ash" screen ahead of the top layer of SCR reactor catalyst. This can cause distortions in gas distribution ("channeling") through the SCR reactor, which will aggravate erosion in the high velocity areas and ineffective performance of the catalyst.

3. Temperature: A third issue that impacts the feasibility of installing high-dust SCR technology on the North Dakota lignite-fired units is catalyst operating temperature. The performance of any SCR catalyst is highly dependent on the temperature of the flue gas passing through the reactor. Typically, a temperature of 600 – 750 degrees F is required to obtain satisfactory operation of an SCR reactor. Operation of commonly supplied catalyst suitable for a high-dust SCR reactor at temperatures above 750 degrees results in severe and rapid deterioration of the catalyst and SCR reactor's NO_X emission reduction performance. For bituminous and sub-bituminous coal-fired units, boiler flue gas passing between the economizer outlet and air heater inlet is generally

within a temperature range acceptable for conventional SCR catalysts without additional heating or cooling of the flow stream.

North Dakota lignite-fired cyclone boilers, including those at Milton R. Young Station, have high temperatures at the economizer's flue gas outlet by design. The highest gas temperatures downstream of the convection pass economizer sections and upstream of the air heater inlets in Milton R. Young Unit 2's boiler are much higher than 750 degrees.

High gas temperatures at the air heater inlet are required to produce the high air temperatures (700°F) needed for the pre-combustion lignite drying system, along with primary and secondary combustion air supplied to the cyclones. Such air preheater arrangements and capabilities have been taken into account in the design of the North Dakota lignite-fired cyclone boilers. Reducing this high gas temperature to accommodate conventional catalysts for a conventional high-dust SCR reactor would result in pre-combustion air temperatures that are too low to provide satisfactory drying and rapid ignition of the high-moisture fuel. This will seriously impact reliable combustion, slag formation and tapping in the cyclone burners. Consequently, it is not feasible to modify the Milton R. Young Unit 2's boiler to operate with the lower economizer outlet flue gas temperature.

Catalysts for a conventional high-dust, hot-side SCR system have not been installed nor successfully demonstrated in a full-scale installation of an operating solid fuel-fired unit that are designed to continuously operate at the high temperatures (above 750 degrees F) that exist between the convection pass economizer and air heater on the Milton R. Young Unit 2's boiler.

4. Erosion: A final consideration on whether hot-side, high-dust SCR technology can be successful on a North Dakota lignite-fired unit is the potential for erosion of the SCR catalyst. North Dakota lignite supplied from the Center mine has an average fuel ash content of 10.5%, and can have an ash content up to 25.5 percent. PRB coal fuel ash content typically averages approximately 5 percent. As previously stated, a cyclone boiler firing North Dakota lignite converts a significantly greater amount of flyash than a PRB-fired cyclone boiler. Overall, this results in a flyash output rate from a cyclone boiler firing North Dakota lignite of approximately 83 lbs/MW-hr compared with 21 lbs/MW-hr for a PRB-fired cyclone boiler. High ash contents in the flue gas stream can result in physical erosion of the catalyst. In addition, effective on-line cleaning of the

high-dust catalyst will likely require steam or compressed air sootblowing. Cleaning cycles of the catalyst will be required much more frequently than a typical conventional SCR installation due to the ash deposition characteristics of the North Dakota lignite and the expected buildup and pluggage resulting from the carry over of "popcorn ash". Frequent sootblowing of the catalyst to remove fouling deposits and ash accumulations will contribute to erosion and decreased catalyst life. There is some European experience with high ash brown coals that catalyst manufacturers will be able to draw upon. This experience, however, will not be directly applicable to these United States units because of the severe deposition characteristics of the North Dakota lignite ash compared to brown coal.

The EPA's NSR Manual states that for a technology to be feasible it must "available and applicable". SCR technology is an available technology which has been installed on numerous powerplant facilities around the world and there are a large number of manufacturers that market the technology. The question is whether SCR technology is "applicable" for a unit firing North Dakota lignite.

In accordance with EPA's NSR Manual, a technology is "applicable" if it has been installed on a "similar unit". Hot-side, high-dust SCR technology has been retrofit on coal-fired units featuring cyclone boilers. However, there are no SCR installations in operation or planned on units that include cyclone burners firing North Dakota lignite with severe slagging and fouling tendencies combined with such high boiler economizer outlet gas temperatures (over 750°F) required for high-moisture fuel pre-drying systems and tubular air preheaters.

The EPA's NSR Manual also states a technology may be determined to be not applicable if "a technical assessment considering physical, chemical and engineering principles and/or empirical data showing the technology would not work on the emissions unit under review or that unsolvable technical difficulties would preclude the successful deployment of the technique." In this SCR technology application, it appears that a facility utility powerplant firing North Dakota lignite would experience extended time delays or be required to devote significant internal resources and engage outside research, followed by extended field trials to learn how to apply a conventional high-dust, hot-side SCR technology on a such a fuel source.

Based upon this technical assessment that looked at the various design and operational issues associated with the installation of hot-side, high-dust SCR technology on a North Dakota lignite-fired steam-electric

generating unit, this control option is considered technically infeasible for Unit 2's boiler at Milton R. Young Station.

A.1.3.4.2 Low-Dust Selective Catalytic Reduction (LD-SCR)

Low-dust SCR (LD SCR) technology could potentially be applicable to North Dakota lignite-fired boilers for NOx emission control. Low-dust SCR refers to the location of the SCR system downstream of a particulate collection system, such as an electrostatic precipitator or a fabric filter. If the low-dust SCR is downstream of a hot-side electrostatic precipitator and prior to the air preheater, flue gas reheating is unnecessary. This has been the prevalent form of alternative retrofit SCRs in the United States for coal-fired utility boilers. There are ten known hot-side low-dust SCR installations (without flue gas reheat) operating in the United States as of July 2005. These are listed in Appendix A2. If applied to MRY Station Unit 2's boiler, the low-dust SCR equipment would be downstream of a cold-side electrostatic precipitator; flue gas reheat prior to the LD SCR reactor inlet would be required for proper NO_X emission reduction performance.

For a cold-side LD SCR, the ESP outlet flue gas passes through a low-dust gas-to-gas heat exchanger (LD GTG-HE), prior to passing to the low-dust SCR reactor. After the LD GTG-HE, the flue gas will travel through the new duct, receiving hot flue gases from a direct-fired gas burner or set of high-pressure steam coils, leading to an ammonia injection grid, turning vanes and then into the LD SCR reactor. The flue gas entering the inlet to the LD GTG HE is expected to be near the air heater outlet temperature (330-340°F) in a cold-side LD SCR application. The supplemental heat added downstream of the LD GTG-HE can be supplied from high temperature steam coils (indirect heat exchange) or directly from natural gas-fired duct burners. The flue gas must be heated to a minimum of approximately 600°F for the LD SCR NO_X–ammonia reaction to be effective. The LD gas-to-gas heat exchanger is used to recover part of that supplied heat, prior to exhausting to the FGD system (if applicable) and stack. The use of rotary regenerative-type heat exchangers has been applied in European LD SCRs. With this design, there will be leakage between the untreated and treated gas streams such that the exit flue gas has higher NO_X concentrations than the LD SCR outlet gas. The direct-fired flue gas reheat duct burners will also create NO_X emissions, which will add to the amount emitted from the boiler and input into the LD SCR reactor. The LD SCR reactor, GTG HE, and connecting ductwork will increase the pressure drop through the flue gas system. This normally requires an induced draft fan upgrade or a booster fan addition.

The factors that make low-dust SCR technology infeasible for the Milton R. Young Station Unit 2's boiler with existing particulate collection via electrostatic precipitators are as follows:

- Catalyst Fouling and Deactivation: An existing electrostatic precipitator upstream of a low dust SCR reactor will still expose the catalyst to the acid gas content and fine particulate containing trace metals and the high alkali mineral content of the entrained lignite flyash not removed by the ESP upstream. Although the total amount of flyash carryover into the LD-SCR reactor is greatly reduced compared with a high-dust design, it is anticipated that the low-dust SCR catalyst life will still be unacceptably short. The small particle flyash passing into the reactor will be sufficient to cause pluggage of the catalyst pores, resulting in deactivation of the catalyst. The firing of lignite coal produces fine (less than 5-μm diameter) flyash particles, which are also least likely to be removed by the existing particulate collection equipment (e.g. ESP) upstream of a low-dust SCR. This creates conditions that allow these small flyash particles to enter the pores of the catalyst, react with SO_3 in the flue gas, and form sulfates which bind other ash particles into a matrix of sodium-, calcium-, and sulfur-rich materials (likely in a form of calcium sulfate). Once such a matrix forms within the catalyst, it can be extremely tenacious and difficult to remove. One catalyst vendor's has stated it is their "experience that low-dust catalyst is more difficult to clean than that from high-dust"[30]. Low-dust SCR performance and catalyst life could be severely negatively impacted. Shortened lifespans of the LD SCR catalyst will require premature, extended, frequent outages for replacement.
- Site Space Constraints: The installation of a low-dust SCR system with flue gas reheat requires a substantial amount of space for installation and operation. A low-dust SCR system will likely use a regenerative gas-to-gas heat exchanger (reheater) to raise the temperature of the flue gas at the SCR inlet. A GTG HE will transfer heat from the flue gas at the SCR reactor outlet to the flue gas entering the SCR reactor in order to minimize the supplemental SCR energy usage. The gas-to-gas heat exchanger dictates the footprint of the cold-side low-dust SCR system. Space is required for the GTG HE and for ductwork in and out of the reheater. Sufficient free space around the reheater and SCR is also required for maintenance.

  The area around Units 1 and 2 at the M.R. Young station is extremely congested in the areas where low-dust SCR systems must be located. The situation is particularly severe for Unit No. 2. Equipment that impacts the feasibility of installing a low-dust SCR system on Units 1 and 2 includes the Unit 2 absorbers, Unit 2 flue gas desulfurization (FGD) dewatering equipment, fly ash handling equipment, fuel storage and transfer equipment, stacks, fans and ductwork. It would be extremely

disruptive to the continued economic operation of both boilers to relocate all the mentioned equipment to create space for the low-dust SCR systems at the M.R. Young Station. Stacks, fans and ductwork and the Unit 2 FGD system cannot be readily relocated due to adjacent structures and the need to continue operation while constructing the retrofit installations. The fuel handling equipment includes a coal storage barn and the main conveyors supplying lignite to the units. Relocating the coal handling equipment currently occupying space needed for the low dust SCR systems would be quite difficult given the site configuration. It is conceivable that the fly ash equipment located west of Unit 1 could be relocated to provide some of the space needed for the low-dust SCR. However, the availability of this space is doubtful, since avoiding the likelihood of severe SCR catalyst sulfate fouling will require a new Unit 1 FGD system to be installed. If a new FGD system is installed for Unit 1, the FGD system would need to occupy the space that can be made available by relocating ash handling equipment. This space subsequently would not be available for a low-dust SCR system.

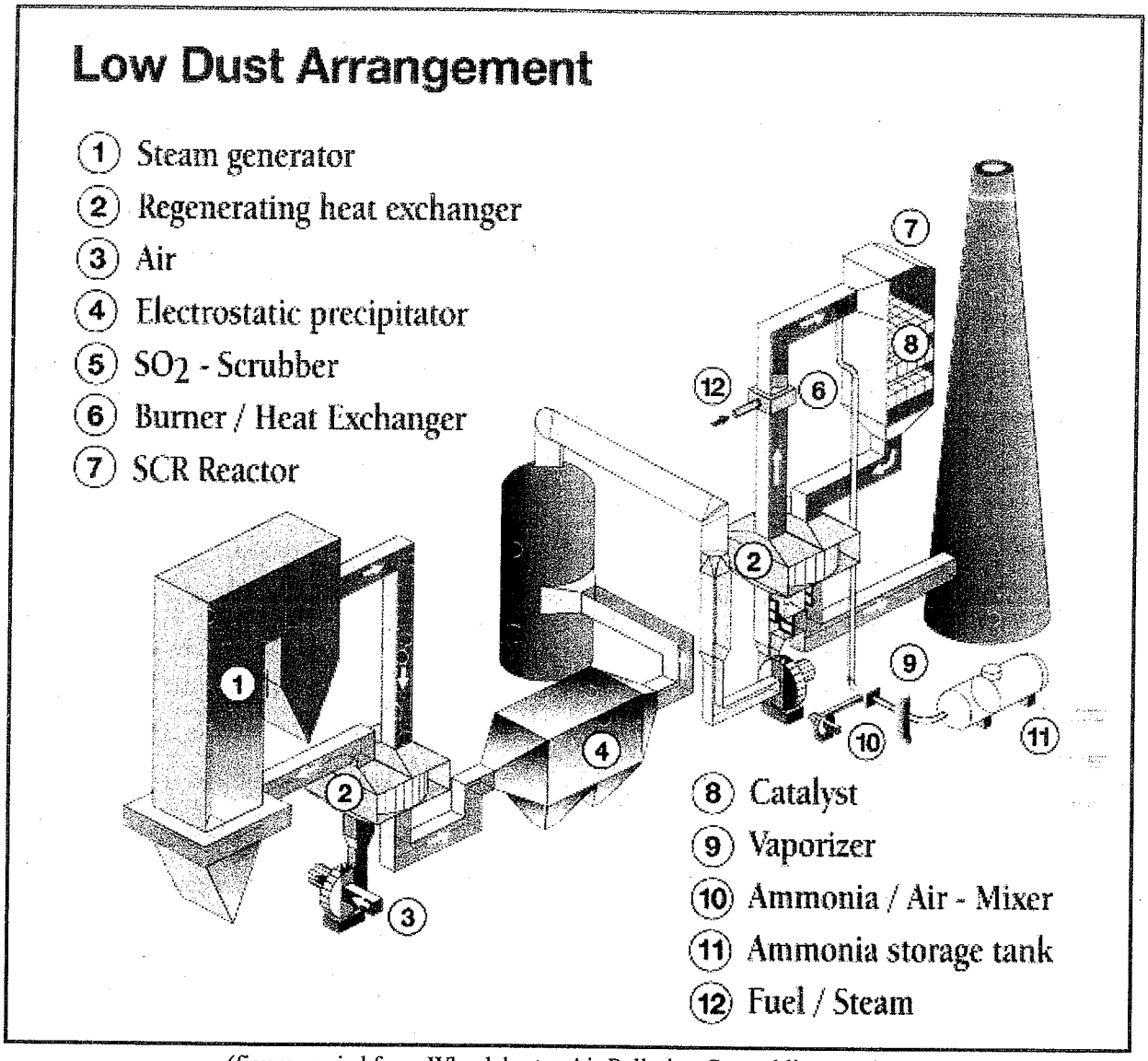
Based upon a technical assessment that looked at the various design and operational issues associated with the installation of low-dust SCR technology on a North Dakota lignite-fired steam-electric generating unit, this control option is considered technically infeasible for the Milton R. Young Station Unit 2's boiler.

A.1.3.4.3 Tail-Gas Selective Catalytic Reduction (LD-SCR)

A tail-gas (TG) SCR is a low-dust SCR system where the LD SCR reactor is installed downstream of a FGD scrubber. The FGD outlet flue gas passes through a gas-to-gas heat exchanger (GTG-HE), prior to passing to the tail-gas SCR reactor. The flue gas will travel through new or modified ductwork leading to an ammonia injection grid, turning vanes and then into the TG SCR reactor. The TG SCR reactor, GTG HE, and connecting ductwork will increase the pressure drop through the flue gas system. This normally requires an induced draft fan upgrade or a booster fan addition.

A schematic graphic diagram for a low dust arrangement is shown in Figure A.1-6.

Figure A.1-6 Tail-Gas SCR Arrangement



(figure copied from Wheelabrator Air Pollution Control literature)

The flue gas from a wet FGD scrubber outlet entering the inlet to the gas-to-gas heat exchanger is expected to be near the saturation temperature (140°F) in a cold-side TG SCR application. The supplemental heat added downstream of the TG GTG-HE can be supplied from high temperature steam coils (indirect heat exchange) or directly from natural gas-fired duct burners. The flue gas must be heated to a minimum of approximately 600°F for the TG SCR NO_X– ammonia reaction to be effective. The TG gas-to-gas heat exchanger is used to recover part of that supplied heat, prior to exhausting to the stack. With a rotary regenerative-type gas-to-gas heat exchanger, there will be internal leakage between the untreated and treated gas streams such that the stack exit flue gas has higher NO_X concentrations than the

TG SCR reactor outlet gas. Using direct-fired flue gas reheat duct burners will also create NO_X emissions, which will add to the amount emitted from the boiler and input into the TG SCR reactor.

There is limited technical information published in English for coal-fired steam-electric generating units (SEGU) with low-dust/tail-gas SCR technology in applications requiring full flue gas reheat prior to the reactor inlet. There is no experience with TG SCR on eastern bituminous, western subbituminous coal or lignite-fired SEGUs in the United States. As of 1997, there was one low-dust/tail-gas SCR on a 220 MWe German cyclone-fired boiler with a 1988 retrofit installation. This boiler was reported to be operating without combustion controls or FGD, burning low sulfur, low ash, moderate moisture bituminous coal with an average pre-SCR NO_X emission rate of approximately 1.07 lb/mmBtu, and was meeting a 30-day rolling average emission limit of approximately 0.16 lb/mmBtu (85% reduction)[31].

Milton R. Young Station Unit 1 does not currently incorporate any flue gas desulfurization equipment, which would place the reactor catalyst in a low-dust SCR configuration, which is considered infeasible when burning North Dakota lignite. A new FGD system for Unit 1 would be required in order to avoid or significantly reduce expected sulfate formation within the catalyst and gas-to-gas heat exchanger when combined with ammonia required for the TG SCR. Unit 2 currently employs a wet scrubber which currently treats approximately 83% of the total flue gas flow from the boiler. Flue gas reheat is currently provided by the FGD bypass (i.e. warm, untreated flue gas is mixed with the cool scrubbed gas).

The factors that make tail-gas SCR technology infeasible for both Milton R. Young Station boilers with existing particulate collection via electrostatic precipitators are as follows:

- Catalyst Fouling and Deactivation: The TG SCR reactor downstream of a flue gas desulfurization (FGD) scrubber will still be susceptible to fouling, contamination, pluggage, and catalyst deactivation.
    - An existing electrostatic precipitator (ESP) upstream of a tail-gas SCR reactor will still expose the catalyst to fine particulate containing trace metals and the high alkali mineral content of the entrained lignite flyash not removed by the ESP upstream. Although the total amount of flyash carryover into the TG-SCR reactor is greatly reduced compared with a high-dust design, it is anticipated that the tail-gas SCR catalyst life will still be unacceptably short.
    - The firing of lignite coal produces fine (less than 5-μm diameter) flyash particles, which are also least likely to be removed by the existing particulate collection equipment (e.g. ESP) upstream of

a TG-SCR. Flue gas with entrained fine particulate matter, including some involving sodium and sulfur-containing compounds, will pass through and be carried-over from a wet FGD scrubber. This treated gas stream will carry sodium sulfate particles, formed by homogenous condensation after exiting the boiler and not removed by the FGD system, into the catalyst layers of the TG-SCR reactor. A dry FGD system followed by a fabric filter upstream of the TG-SCR will still allow sulfur-bearing flue gas and fine particles to enter the catalyst. There is serious concern that fine particles passing into the reactor will accumulate within the catalyst, and be resistant to removal by conventional sootblowers and other cleaning technologies. This creates conditions that allow these small flyash particles to enter the pores of the catalyst, react with SO_2 and/or SO_3 in the flue gas, and form sulfates which bind other ash particles into a matrix of sodium-, calcium-, and sulfur-rich materials (likely in a form of calcium sulfate). Once such a matrix forms within the catalyst, it can be extremely tenacious and difficult to remove. Catalyst that is exposed to such conditions will be ineffective at maintaining adequate activity upon which the performance of the TG-SCR's NO_X removal is based.

- These entrained particles will also deposit on the gas-to-gas heat exchanger ahead of the tail gas SCR reactor. This deposition will decrease heat transfer between the incoming (cool) flue gas and the outgoing (warm) flue gas. Sootblowers could be used to remove the accumulated deposits from the GTG HE, but the SCR reactor could still suffer catalyst fouling from the deposits dislodged from the GTG HE cleaning cycle becoming reentrained in the reheated flue gas. Tail-gas SCR performance and catalyst life could be severely negatively impacted. Shortened lifespans of the TG SCR catalyst will require premature, extended, frequent outages for replacement.

- Site Space Constraints: The installation of a tail-gas SCR system with flue gas reheat requires a substantial amount of space for installation and operation. A tail-gas SCR system will likely use a regenerative gas-to-gas heat exchanger (reheater) to raise the temperature of the flue gas at the SCR inlet. A GTG HE will transfer heat from the flue gas at the TG SCR reactor outlet to the scrubbed flue gas entering the SCR reactor in order to minimize the supplemental SCR energy usage. The gas-to-gas heat exchanger dictates the footprint of the TG SCR system. Space is required for the GTG HE and for ductwork in and out of the reheater. Sufficient free space around the reheater and SCR system is also required for maintenance.

  The area around Units 1 and 2 at the M.R. Young station is extremely congested in the areas where TG SCR systems must be located. A flue gas desulfurization system will be needed for Unit 1 in the

near future to comply with the Consent Decree. When a new FGD system is installed for Unit 1, the FGD system would need to occupy the space that can be made available by relocating ash handling equipment. This space subsequently would not be available for a tail-gas SCR system. Thus, the availability of adequate space for all the new FGD and TG-SCR system equipment and structures while accommodating existing coal storage and handling needs for both existing boilers at Milton R. Young Station is doubtful.

The challenges for installation of new ductwork, SCR reactors, and flue gas reheating equipment and the lack of pertinent experience with all aspects of design, construction, operation and maintenance of tail-gas SCRs on such high-fouling coals as North Dakota lignite are significant. The flue gas conditions that the TG-SCR catalyst will be exposed to will create unresolvable fouling and blinding that makes successful application of this technology difficult, expensive, and uncertain.

The risk of failure and uncertainty of successfully applying low-dust, tail-gas SCR technology to a cyclone-fired utility powerplant firing North Dakota lignite appear substantial.

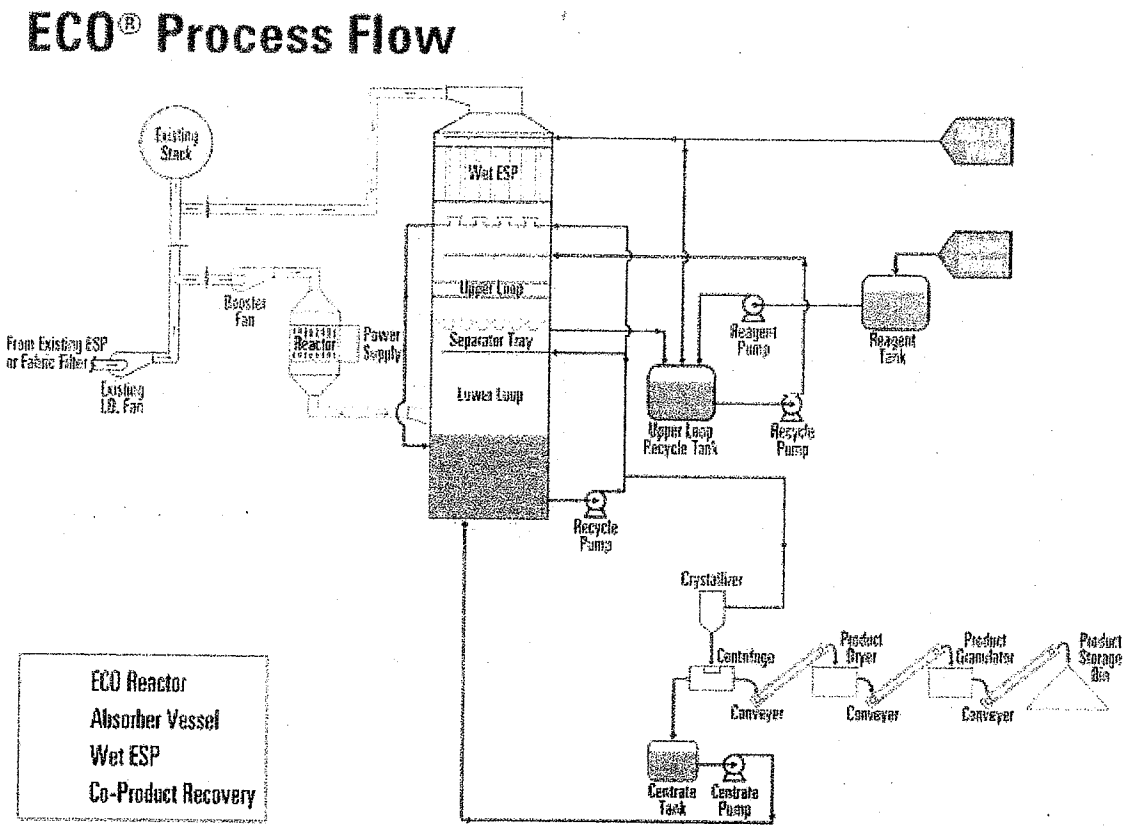
Based upon a technical assessment that looked at the various design and operational issues associated with the installation of tail-gas SCR technology on a North Dakota lignite-fired steam-electric generating unit including a cyclone boiler, this control option is considered technically infeasible for the Milton R. Young Station Unit 2's boiler.

A.1.3.5 Electro-Catalytic Oxidation (ECO®)

Powerspan's Electro-Catalytic Oxidation (ECO®) system is a multi-pollutant technology designed to control emissions of NO_X, SO_2, fine particulate, mercury and certain Hazardous Air Pollutants (HAPs). The ECO® process has two main process vessels, a barrier discharge reactor, and a multi-level wet scrubber. The barrier discharge reactor utilizes an electrical discharge to create oxygen and hydroxide radicals which then react with NO_X, and other constituents in the flue gas stream. The flue gas stream then enters the bottom of the ECO® scrubber where the lower loop cools the flue gas and removes a portion of the acid gasses [sulfur trioxide (SO_3), sulfuric acid (H_2SO_4), nitric acid (HNO_3)] produced in the barrier reactor and oxidized metals such as mercury, with a low pH aqueous ammonia reagent. A second scrubbing loop is then entered where additional SO_2, NO_2, acid gases and oxidized metals are removed with an aqueous ammonia reagent, though at a higher pH. Above the second scrubber loop is an absorber section for absorbing fugitive ammonia from the first and second scrubbing loops. The final

step in the ECO® process is a wet electrostatic precipitator (WESP) which collects fine particulate matter, aerosols generated in the scrubber and additional mercury. An updated schematic process flow diagram for the basic ECO® process is shown in Figure A.1-7.

Figure A.1-7 – Electro-Catalytic Oxidation (ECO®) Process Flow Diagram
(copied from http://www.epa.gov/appcdwww/aptb/EPA600R03110.pdf)



Powerspan has been involved in an extended ECO® process demonstration using a 28 MW Commercial Demonstration Unit (CDU) at R.E. Burger Station Units 4&5. The ECO® CDU project treated a slipstream and demonstrated performance, reliability and economics for approximately one year. The demonstration program started in January, 2004. NO_X removal is stated to be up to 90% with a claimed 0.05 lb NO_X/mmBtu outlet condition achievable for the front-end of the ECO® process. Further sustained operational tests of the ECO® CDU are underway during the second and third quarters of 2005.

As this is a post-combustion multi-pollutant control technology, it is claimed that there is little sensitivity to the type boiler or burners that Powerspan's Electro-Catalytic Oxidation (ECO®) process can be

potentially applied to in order to reduce NO_X emissions. The effectiveness of this ECO® process for NO_X control has been demonstrated on a slip-stream commercial demonstration unit (CDU) associated with pulverized fuel boilers firing midwestern or eastern bituminous coal.

Powerspan's published data from the commercial demonstration unit's performance of up to 90% when treating flue gas with an inlet NO_X concentration around 0.5 lb/mmBtu. This would result in a stack NO_X emission around 0.05 lb/mmBtu.

The ECO® process has not been demonstrated in a full-scale configuration on any unit, nor tested in a slipstream configuration on any boiler that fires western subbituminous coals or North Dakota lignite. It has also not been applied to emissions from a cyclone-fired boiler. According the EPA's Draft NSR Manual, "Technologies which have not been applied to (or permitted for) full scale operations need not be considered available: an applicant should be able to purchase or construct a process or control device that has already been demonstrated in practice".

There are a number of issues with firing North Dakota lignite that make the applicability of the ECO® process technically infeasible for MRY Station boilers. These issues include:

- Deposits and Pluggage: The flyash deposition characteristics of the North Dakota lignite are extremely severe. Anything that contributes to flyash deposition and pluggage within the barrier reactor is expected to have a detrimental impact on the multi-pollutant control performance of the ECO® process, and thus could have a serious impact on MRY Station operations. The lack of demonstrated operation on treating the emissions from a boiler firing coal with a high slagging index precludes the use of the ECO® process as technically feasible for BACT as applied to a boiler firing North Dakota lignite.
- Reliability and Availability: Milton R. Young Station's major planned outages for each unit are scheduled to occur once every three years. Any NO_X control technology selected as BACT will need to operate year-round, year in and year out, on a routine basis, while performing at high levels of pollutant reduction. The Powerspan ECO® system is a new technology and is not as highly developed as other more common NO_X and SO_2 control technologies such as SCR or SNCR plus wet or semi-dry flue gas desulfurization (FGD). It is expected to require a full-time, full-scale application with sustained continuous operation to confirm levels of currently demonstrated reliability and availability from the ECO® CDU are acceptable to meet the

expectation of infrequent major outages over long time periods while maintaining high levels of control.

There are additional factors that make the application of the ECO® process potentially more difficult than other established emission control technologies available for coal-fired powerplants:

- There is a lack of experience with the ECO® downstream ammonia scrubber's coproduct crystallization and granulization equipment design, operation, and maintenance, which was not included with the initial commercial demonstration unit. The coproduct stream that would normally feed into the crystallization and granulation processes was collected and transported offsite for this process step during CDU operation. Because crystallization and granulation of ammonium sulfate from an ammonia scrubber solution is not a new technological process, this was not considered a technical feasibility deficiency. For instance, the Dakota Gasification Company (DGC) in Beulah, ND currently operates an SO_2 scrubber utilizing ammonia as a reagent. Following the generation of ammonium sulfate, DGC crystallizes and granulates a fertilizer product on site. However, at MRY Station, considerable costs would be incurred for interim storage and shipment of the ECO® process scrubber's liquid bleedstream until sufficient experience has identified and eliminated potential failures and repairs for the crystallization and granulation equipment should it prove to be unreliable.

- Size of the barrier reactor: Powerspan recently indicated that they would scale the reactor for optimum cost and space arrangement based upon lessons learned from the CDU plant operation. The number of individual passages within a barrier reactor sized for either of MRY Station boilers' maximum flue gas flow and gas stream constituents is expected to require a cross-sectional area comparable to half of a large electrostatic precipitator. Although this has not been closely examined for all aspects of design, construction, operation and maintenance, the amount of physical space required to hold the barrier reactor and inlet and outlet ductwork is believed to not be available for potential retrofit to MRY Station units. Site space constraints are considered to be a barrier to technical feasibility for potential application of the ECO® process at Milton R. Young Station for Unit 1 and Unit 2's boilers.

- Additional station auxiliary power consumption: The barrier reactor, plus the ammonia scrubber and wet electrostatic precipitator additions by an ECO™ system, require an increase in station

auxiliary power consumption. For NO_X control, this includes more horsepower required by the booster fan needed to compensate for the flue gas pressure drop created across the barrier reactor. It also includes the power consumed by the electrodes of the barrier reactor itself.

Because of the technical feasibility issues and lack of commercial availability and full-scale experience, especially on such high fouling coals, the ECO® system was considered technically infeasible as a BACT alternative for Milton R. Young Station for Unit 2's boiler.

A.1.4 "Layered" NOx Reduction Technologies

Many of the NO_X emission reduction technologies which involve furnace or convection pass areas for their introduction into the flue gas stream have been, or can potentially be, applied in combinations so as to result in an overall higher level of removal. Separated overfire air, various types of fuel reburn, and various forms of SNCR could potentially be combined in series to reduce NO_X emissions prior to boiler's flue gas exit. However, all the possible NO_X control technology combinations have not been installed on coal-fired powerplants, so actual feasibility of some combinations have not been demonstrated as viable, particularly in consideration of the special challenges posed by cyclone boilers firing lignite coal.

A.1.4.1 SOFA Combined With Other NO_X Reduction Technologies

Separated Overfire Air can be favorably combined with every other method in order to reduce the amount of reagent or reburn fuel required to achieve the resulting level of NO_X emission reduction. Some control technologies, especially conventional fuel reburn systems, require overfire air to complete the combustion of the staged fuel admitted to the upper furnace. Fuel lean gas reburn can be applied with or without SOFA, as this limited amount of staged fuel is introduced into an oxygen-rich atmosphere downstream of the cyclone burners and any overfire air injection points.

A.1.4.1.1 SOFA with SNCR

Selective non catalytic reduction technologies are post-combustion, in-furnace NO_X control alternatives that have been installed in numerous boilers of various designs, fuel types, with and without overfire air. It is usually advantageous to apply overfire air so that the amount of chemical reagent consumption can be minimized in order to achieve the targeted NO_X emission rate from the boiler outlet.

Tests at Conectiv's B.L England Station (Units 1 and 2) demonstrated that SNCR can decrease NO_X emissions as much as 31% at full load, from 0.55 to 0.38 lb/mmBtu, over and above the reduction possible from overfire air alone (approximately 60% drop, from 1.3 to 1.4 down to 0.55) in full operation. This is an overall NO_X emission reduction of 72% from pre-retrofit baseline[24].

SNCR can be applied alone or combined with either the basic or the advanced forms of separated overfire air (ASOFA) on MRY Station boilers. Air-staging the cyclones with the use of separated overfire air to further complement combustion NO_X reduction is an optional part of this technique. However, as previously explained in the discussion of SOFA alternatives, this will risk slag "freezing" in the barrels and lower furnace. Estimated NO_X emission rates for using SNCR techniques with North Dakota lignite considered published levels achieved by cyclone-fired units firing western subbituminous coal, and vendor estimates. SNCR with ASOFA is expected to reduce NO_X emissions approximately 32.6% below NO_X levels predicted for ASOFA operation, and potentially 58% overall from current baseline level for the MRY Station Unit 2 boiler with ammonia slip limited to approximately 5 ppmvd. This highest performing basic SNCR system is potentially able to achieve a NO_X emission rate of 0.330 lb/mmBtu, when combined with the advanced form of SOFA on MRY Station Units 2 boiler during operation at the pre-control baseline (near MCR load). These levels of NO_X reduction depend on the advanced form of separated overfire air technique to achieve the expected NO_X reduction percentages when applied to lignite-fired cyclone boilers.

Another form of SNCR is combined with separated overfire air. This is currently being marketed commercially as "Rotating Mixing" (Rotamix). In the United States' utilities industry, this has only been applied to pulverized coal-fired boilers. It is different than basic SNCR in that it includes a hot air booster fan and a small ambient air fan, and injects the ammonia (or urea) reagent into the high-pressure overfire air flow stream ahead of the ROFA nozzles' outlets. This mixture is imparted into the boiler in an offset fashion from opposite sides of the furnace at high velocities, with multi-port nozzles located at high elevations relative to the top burner row. This vendor (Mobotec USA) claims that Rotamix (rotating opposed fire air or ROFA + SNCR) helps to distribute the reagent across the furnace cross section, which maximizes in-furnace NOx reduction while minimizing negative impacts on carbon monoxide and flyash unburned carbon. Three tangentially-fired utility boilers burning eastern bituminous coal or Illinois bituminous coal were retrofitted with Rotamix, each achieving a NO_X reduction of approximately zero to 55 percent beyond the levels produced by ROFA alone, from pre-SNCR baselines of 0.22 to 0.28 lb/mmBtu down to 0.10 to 0.23 lb/mmBtu without low-NO_X burners[4,32,33,34].

While this variation of SNCR combined with separated overfire air could potentially be applicable to cyclone boilers, it has not been marketed to serve such applications. Since cyclone boilers do not require the addition of hot air booster fans for SOFA, and optimum injection locations for both SOFA and SNCR reagent may not coincide, Rotamix may not perform as well as, or significantly better than, a well-designed combination of conventional SOFA and SNCR. This technique is not distinct enough from basic SNCR from functional and air-staged cyclone NO_X reduction performance standpoints to warrant individual consideration for Milton R. Young Station boilers. Because of a lack of cyclone-fired boiler experience with ROFA and Rotamix, the latter was considered infeasible and thus was not included in the control effectiveness and cost-effectiveness sections of the main report.

A.1.4.1.2 SOFA with RRI

Rich Reagent Injection must be used in an oxygen-deprived atmosphere in order to effectively reduce nitrogen oxide emissions. This requires air-staged cyclones and separated overfire air operation. The NO_X emission reduction reagent injection for RRI processes must be precisely located and carefully controlled to be effective. Operation outside of the required operating ranges can even result in increased NO_X emissions. Extensive computational fluid dynamic (CFD) simulations are needed to determine the optimum injection points. Boiler operating conditions will change with unit load and varying fuel characteristics. The RRI process control systems must be able to adjust for these changing conditions.

RRI has the potential to provide a moderate degree of NO_X reduction on coal-fired boilers. Data from B.L. England and Sioux plants show this technology can reduce NO_X emissions between zero and 39 percent beyond the amount attributable to overfire air system operation[23,24,25,26,27]. During initial demonstration testing of RRI at Ameren's Sioux Unit 1 boiler, a 500 MW unit firing a blend of PRB and midwestern bituminous coals (without SNCR), with SOFA in August 2001 at a lower furnace SR of approximately 0.99, NO_X emissions were reduced approximately 55% to 0.55 lb/mmBtu w/ SOFA only, with zero to 15% additional NO_X reduction from RRI (down to 0.47 lb/mmBtu) with zero ammonia slip[25]. Results of this initial RRI testing at Sioux plant were poor at cyclone stoichiometric ratios close to 0.99 because inconsistent, sporadic, and non-repeatable NO_X emissions reductions between zero and 15% were measured. Subsequent RRI testing at Sioux Unit 1 in March 2002 with SOFA at an average cyclone stoichiometric ratio around 0.95 showed NO_X emissions reduction of 29 percent (down to 0.27 lb/mmBtu) beyond those achieved with a modest amount of cyclone air-staging with SOFA (68% drop down to 0.38 lb/mmBtu from SOFA alone), for an 80% overall decrease from uncontrolled baseline; RRI CFD model

predictions for these conditions were NO_X emissions reduction of 31% with FGR and 37% without FGR operation. Tested NO_X emissions with RRI+SOFA in 2002 were with a reagent normalized stoichiometric ratio (NSR) of 3 (lbs NH_3 per lb NO_X)[25].

Parametric testing at Sioux Unit 1 in May 2005 reduced NO_X emissions between 15-38% with RRI, down to 0.15 to 0.20 lb/mmBtu. Reagent NSR between 1.0 and 4.0 and low ammonia slip levels less than 2 ppm from an established baseline condition of 0.20 to 0.285 lb/mmBtu level achieved NO_X emissions as low as 0.12 lb/mmBtu with deep cyclone air-staging and SOFA operation firing an 80:20 PRB/Illinois coal blend at 480 MWg unit output[27].

The intent of the RRI process for NO_X reduction is that it must be used in conjunction with air-starved (substoichiometric staged-air) cyclone combustion resulting from the installation and operation of an OFA system, with or without SNCR. The cyclones' air/fuel stoichiometry must be carefully controlled to maintain fuel-rich conditions for the RRI process to be effective. The combustion gases in the vicinity of the RRI urea injection ports must be essentially devoid of free oxygen, in order to avoid oxidizing the nitrogen contained in the injected reagent, which will increase NO_X emissions. For lignite-fired cyclone boilers, the basic form of separated overfire air (without relocated lignite drying system vent ports) is incompatible with RRI. Reagent injection will be near the elevation of the existing lignite drying system vent ports in the lower front and rear walls of a lignite-fired cyclone boiler located immediately above the top rows of cyclones. These vent ports are located concurrently with the existing flue gas recirculation (FGR) ports on Unit 2's boiler. The oxygen introduced with the lignite drying system's vented moisture-laden airstreams will cause the urea to be oxidized, creating NO_X emissions.

The advanced form of SOFA relocates these lignite drying system vent ports from the lower to the middle furnace, enhancing the desired in-furnace nitrogen oxides reduction process. Therefore, in order for RRI to be even moderately effective in reducing NO_X emissions from a lignite-fired cyclone boiler, this technology must be combined with an advanced form of separated overfire air, whether installed with or without SNCR.

As mentioned in the feasibility discussion of applying separated overfire air to lignite-fired cyclone boilers, the degree to which each and every individual cyclone furnace can be successfully operated with less than theoretical (substoichiometric) combustion air directly impacts potential NO_X formation and further in-furnace emission reduction. Because the heat content of lignite from the Center mine is not

consistent from hour to hour, there can be substantial deviations in air/fuel ratios for individual cyclones from the overall average.

In the case of MRY Station boilers, Minnkota has simultaneously sampled the unprepared lignite feed to several cyclones' lignite drying systems in order to determine the variability in the combustible and ash components of North Dakota lignite. This investigation found that fuel quality variations can result in individual samples' heating values to have a maximum differential of over 12% of the lignite samples' average.

TABLE A1-1 – Lignite Heating Values and Variations for Milton R. Young Station Unit 2

M.R. Young Station Individual Cyclone Lignite Samples		Differences Between Individual Cyclone Lignite Samples	
Higher Heating Values, Btu/lb	Percentage of Average HHV	HHV Differential, Btu/lb	Percentage of Average HHV
Minimum HHV: 5,852	88.9%	Minimum : 4	0.06%
Maximum HHV: 7,101	1.08%	Maximum : 797	12.1%
Average HHV: 6,584	100%	Average: 165	2.51%

When operating with air-staged conditions associated with separated overfire air, any individual cyclone with lignite heat input lower than average can allow significant amounts of oxygen to oxidize the urea reagent at high temperatures, thus increasing NOx emissions in that zone at that time. Cyclones with lignite heat inputs higher than average would produce lower stoichiometric air/fuel ratios and less NOx emissions. Less complete combustion in the deeply staged cyclones may release insufficient amounts of heat, thus raising the risk of solidifying the fuel ash so that it accumulates within the cyclone barrel. This could result in firing auxiliary fuel oil or taking the boiler out-of-service to remove the pluggage. Neither of these conditions is desirable because they result in increased emissions, lower performance, and higher operating costs.

The MRY Station Unit 2 boiler's cyclone air/fuel ratios vary in real-time based on significant changes in combustible content on an individual cyclone by cyclone basis. Adjustment of individual cyclone combustion air inputs to compensate for the variability in individual cyclone lignite heat input rates for Unit 2's boiler would be necessary to maintain consistent substoichiometric operation of every cyclone during air-staged combustion. This places great emphasis on achieving tight control over the air/fuel

ratios on each cyclone during air-staged combustion operation in order for ASOFA to be successful in producing significant additional NOx emissions reduction on lignite-fired cyclone boilers.

There is no equipment available for coal-fired boilers that can measure the fuel heat input at the prepared feed injection point on such a variable fuel to allow the determination of reasonably accurate air/fuel ratios on individual cyclones in real time. Without being able to measure the cyclone air and heat inputs to allow for control of air/fuel proportions and emissions, the stoichiometric ratios of individual cyclones can not be established accurately to produce combustion products essentially devoid of free oxygen. This requirement is especially necessary when employing RRI to avoid increasing, rather than reducing, NO_X emissions on the Milton R. Young Station Unit 2 boiler.

Flue gas recirculation in MRY Station Unit 2 boiler's lower furnace could increase NO_X emissions by admitting oxygen-bearing flue gas in the vicinity of the injected urea if RRI were applied with basic or advanced forms of SOFA. To avoid this negative impact, FGR in the lower furnace would need to be discontinued. There is uncertainty whether modification or elimination of the use of FGR in the lower furnace of MRY Station's Unit 2 boiler could be successful in controlling lower furnace wall fireside ash deposition and gas temperatures.

Because of the significant insurmountable problems discussed above which would increase NO_X emission rates, RRI is considered technically infeasible for application on the Unit 2 cyclone boiler at the Milton R. Young Station.

A.1.4.1.3 SOFA with RRI and SNCR

When RRI is combined with separated overfire air and SNCR, it has demonstrated very high NO_X emissions reduction at Conectiv's B.L. England Unit 1 boiler during short-term testing firing eastern bituminous coal, on the order of 80% from an uncontrolled baseline around 1.2 lb/mmBtu[24]. In May 2005, testing RRI+SNCR+SOFA at Ameren's Sioux Unit 1 boiler firing a high PRB-blend coal demonstrated NO_X emissions as low as 0.12 lb/mmBtu. This was from an established baseline condition of 0.20 lb/mmBtu level achieved with deep cyclone air-staging and SOFA operation. These testing results when firing an 80%:20% PRB/Illinois coal blend at 480 MWg unit output with a reagent NSR of 4 and ammonia slip limited to less than 5 ppmvd, showed an overall 90% reduction with no apparent adverse short-term impacts of deeper air-staged combustion together with overfire air, RRI and SNCR applications[27].

Because of the significant insurmountable problems regarding RRI as mentioned above, RRI with SNCR and ASOFA is considered technically infeasible for application on the Unit 2 cyclone boiler at the Milton R. Young Station due to the variable heat content of the lignite fuel which allows the creation of oxygen-rich conditions in the boiler.

A.1.4.2 SNCR and Reburn

SNCR could potentially be installed downstream of separated overfire air and various types of fuel reburn, to reduce NO_X emissions prior to a boiler's flue gas exit. Several of these examples were already described[7,8,9,10,11,1213,14]. Conventional gas (CGR) or coal reburn systems, by and large, have not been combined with forms of SNCR, although at least one vendor (GE Energy) has promoted a combination of conventional gas reburn with SNCR and overfire air systems as "advanced" gas reburn. Only one example of permanent installation of SNCR with conventional gas reburn (and overfire air) on a tangentially-fired boiler was found in available technical literature[10] and vendor experience lists[14]. The vendor (GE Energy) that provided the advanced gas reburn system at 120 MW NRG Somerset Station claimed NO_X emissions were reduced by 44% from a baseline of 0.45 down to 0.25 lb/mmBtu with overfire air alone; an additional reduction of 20% resulting from conventional gas reburn with overfire air, down to 0.20 lb/mmBtu; and further decrease of 45% down to 0.11 lb/mmBtu using gas reburn with SNCR with an unstated amount of ammonia slip, for an overall reduction of 75% from uncontrolled baseline[14].

No examples of actual demonstration or permanent installation of SNCR with conventional gas or coal reburn (and overfire air) on cyclone-fired boilers were found in a search of published and proprietary technical literature. The lack of experience with these combinations on a cyclone-fired boiler, especially for lignite-firing, makes the application for MRY Station's boilers infeasible.

FLGR™ has been installed with SNCR for NO_X emission reduction on several pulverized coal boilers, as discussed in the following subsection. A potential advantage of FLGR™ over conventional coal or gas reburn techniques is that the former is generally compatible with, but does not require, the installation and operation of SOFA.

Rich Reagent Injection would appear to be less capable of being combined with fuel reburn, especially conventional fuel reburn alternatives with high amounts of reburn fuel injection. This is due to the

expected need to idle (e.g. not fire) up to four of the twelve cyclones when operating the reburn system at full boiler load. In this case, the cooling air introduced into the idle cyclones, and any conveying air injected with pulverized reburn coal (or if natural gas is injected with recirculated flue gas), are expected to counteract the fuel-rich conditions of the air-and fuel-staged cyclones operating substoichiometrically. This will cause a portion of the amine reagent to be oxidized in the lower furnace, creating NO_X emissions instead of converting them to nitrogen and water. No example of actual demonstration or permanent installation of RRI with reburn (and overfire air) on cyclone-fired boilers was found in available technical literature or vendor experience lists. This combination is considered infeasible due to the location of injection and variable heat content of the lignite reburn fuel which allows the creation of oxygen-rich conditions in vicinity of RRI injectors in the lower furnace of Unit 2's boiler.

Hydrocarbon-enhanced SNCR (e.g. NO_XStar™) may potentially be combined with all types and forms of reburn previously discussed, since the location of the enhanced ammonia injection nozzles will be above (beyond) the elevation in the middle furnace where any reburn fuel should be reacted. No example of actual demonstration or permanent installation of HE-SNCR with reburn (and overfire air) on any coal-fired utility boilers, especially cyclone-fired units, was found in available technical literature or vendor experience lists. The advantage that HE-SNCR presents is the potential for greater-than-SNCR-levels of NOx reduction without significant amounts of gaseous hydrocarbon being required. Because of a lack of experience with HE SNCR applied to cyclone boilers, and none with significant amounts of fuel reburn, this combination has not been investigated further, and was not included in the control and cost-effectiveness analysis for NO_X controls.

A.1.4.2.1 Amine-Enhanced FLGR™ (AEFLGR™) or FLGR™ + SNCR

Fuel-lean gas reburn has been combined with SNCR as a hybrid form of amine reagent technologies on at least five pulverized coal-fired utility powerplants retrofit installations within the United States. This combination of technologies allows the boiler to be operated with FLGR™ alone, FLGR™ and SNCR simultaneously, or SNCR only (without SOFA) for the specific level of control desired or required.

No examples of actual demonstration or permanent installation of FLGR™ + SNCR (with or without overfire air) applied to a cyclone-fired boiler were found in available technical literature or vendor experience lists. The vendor (Fuel Tech) that provided the AEFLGR™ system at Mercer Station claimed NO_X emissions were reduced by 60% (from a baseline of 1.4 down to 0.56 lb/mmBtu) with 5 ppm ammonia slip without overfire air. A technical paper provides more details[18]. Another technical paper

stated that FLGR™ alone only reduced NO_X emissions approximately 27% from the 1.4 lb/mmBtu baseline, down to 1.03 lb/mmBtu[35].

An AEFLGR™ system (with or without SOFA or ASOFA) may be potentially applied to a cyclone-fired boiler. The high capital and operating costs associated with applying fuel lean gas reburn is expected to make this economically unattractive, and the existing lignite pre-drying vent ports will likely limit the NO_X emission reduction potential of the FLGR™ component if installed without the advanced form of SOFA. The lack of experience with this combination on any cyclone-fired boiler, especially for lignite-firing, makes this combination infeasible for MRY Station Unit 2 boiler.

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A.2.1 - U.S. Cyclone NOx Reduction Projects Summary

SELECTIVE NON-CATALYTIC REDUCTION/ RICH REAGENT INJECTION

Cyclone-Fired Boilers

Conectiv (formerly Atlantic Electric)

BL England Unit 1	Crushed Coal, single-wall cyclone-fired	1962 vintage
138 MW B&W boiler	aqueous urea SNCR, 1995 startup	eastern bituminous coal

Boiler has only 3 cyclone burners, arranged "1 over 2" style.
RJM implemented commercial Fuel Tech urea-based SNCR system installation in 1995 after short-term (3-month demonstration test) in 1993-1994. 31 % NOx reduction claimed, from 1.31 lb/mmBtu NOx baseline[(1)] for SNCR only; RJM claimed 35% reduction from 1.31 lb/mmBtu down to 0.85 lb/mmBtu (without overfire air) with urea-to-NOx NSR = 0.85 (RJM experience list).

Added eight temporary RRI ports (three nozzles on each lower sidewall, and two nozzles on the upper rear wall, and performed one month demonstration parametric testing of overfire air only (without SNCR or RRI), at 120 MW nominal boiler load and cyclone S.R. = 0.90 in 1999. REI claimed 55% NOx reduction from a 1.2 lb/mmBtu uncontrolled NOx baseline to 0.55 lb/mmBtu with OFA only, with stack CO emissions below 50 ppm. For Rich Reagent Injection; REI claimed 25-30% NOx reduction for RRI down to 0.38 lb/mmBtu from controlled baseline w/ OFA alone of 0.55 lb/mmBtu NOx and a RRI urea-to-NOx NSR = 2; also showed RRI+SNCR w/ OFA reduced NOx 55% to 0.25 lb/mmBtu (34% beyond RRI w/ OFA), for an overall 79% NOx reduction with a SNCR urea-to-NOx NSR = 1. Measured less than 1 ppm ammonia slip during RRI testing, < 5 ppm slip for RRI + SNCR. No significant increase in CO emissions during RRI testing[(2)].
Source: [(1)] ICAC White Paper; RJM experience list; [(2)] REI 2001 Technical Paper.

Conectiv (formerly Atlantic Electric)

BL England Unit 2	Crushed Coal, cyclone-fired, single-wall-fired	1964 vintage
160 MW B&W boiler	SNCR, 1996 startup	eastern bituminous coal

RJM implemented commercial Fuel Tech urea-based SNCR system in 1996, claimed 36% reduction from 1.36 lb/mmBtu down to 0.85 lb/mmBtu, urea-to-NOx NSR = 0.85 (without overfire air) [(1)].
An OFA system was added in 1998, resulting in NOx emissions of 0.33 lb/mmBtu, for an overall NOx reduction of 76%.
Source: RJM experience list. (Also listed in [(1)] ICAC White Paper).

AmerenUE (formerly Union Electric Co.)

Sioux Unit 1	Crushed Coal, opposed-wall cyclone-fired	1969 vintage
500 MW B&W boiler	Rich Reagent Injection demonstration testing in 2001	

Boiler has 10 cyclone burners, arranged "2 over 3" style, on opposite walls, and fires a blend of 85% to 50% western subbituminous (PRB) coal, with Illinois bituminous coal, petroleum coke, and tire-derived fuel.

Installed twenty temporary RRI ports (six nozzles on each lower sidewall, and four nozzles on each front and rear wall), and performed one month demonstration parametric testing of overfire air only and initial testing with RRI in August 2001, followed by additional testing in March 2002, and the second quarter of 2004. Added 8 RRI ports (1 in each sidewall, 4 in each front and rear wall) and 14 SNCR ports (5 on upper front wall, 9 on upper rear wall) to the furnace in early 2005, followed by three weeks of parametric testing and 3 days of continuous testing of RRI with SNCR and deeper-staged OFA.
Tested in August 2001 at lower furnace SR approx.=1.0, 0.55 lb/mmBtu w/ OFA only, only 15% NOx reduction w/ RRI, zero ammonia slip.

Tested in March 2002 at lower furnace SR approx.=0.95, from 0.38 lb/mmBtu baseline w/ OFA only, achieved 29% NOx reduction w/ RRI down to 0.27 lb/mmBtu, NSR=3, zero ammonia slip[3].
(assume blend of PRB and Illinois bituminous coal w/ tire-derived fuel and petroleum coke)[3].
Operation in the second quarter 2004 showed actual stack NOx averaged around of 0.30 lb/mmBtu with OFA only and lower furnace at a cyclone SR around 0.88 burning a 85% PRB, 15% Illinois #6 bituminous coal blend, presumably at 440 MW. This is a 75% NOx reduction from a 1.19 lb/mmBtu pre-control baseline. REI using CFD modeling predicted NOx down to 0.18 lb/mmBtu with RRI+OFA, and below 0.15 with RRI+SNCR under similar deep cyclone air-staging (1.19 to 0.28 lb/mmBtu is 76% reduction, 0.18 vs 0.28 is an additional 36% reduction w/ RRI, and 0.14 vs 0.28 is a 50% reduction w/ RRI+SNCR, for an overall reduction of 88%)[4].
Tested in May 2005 at 480 MWg with lower furnace SR approx. = 0.85-0.88, 76-83% reduction from 1.2 lb/mmBtu baseline down to as low as 0.20 lb/mmBtu w/ SOFA only firing 80% PRB, 20% Illinois #6 bituminous coal blend; additional 15-39% NOx reduction w/ RRI, to as low as 0.15 lb/mmBtu from 0.20-0.28 lb/mmBtu baseline w/ SOFA only at urea NSR varied between 1 and 4, with one ppm ammonia slip; achieved additional NOx reduction w/ RRI +SNCR down to 0.12 lb/mmBtu, NSR=4, ammonia slip10 ppm or less. RRI+SNCR w/ SOFA NOx reduction percentage varied from 15% to 50% below SOFA-only levels, with NSRs between 1 and 4.5. SNCR alone had 13% (NSR=1) to 32% (NSR=1) NOx reduction with ammonia slip around 1-2 ppm*.
Source: [3] REI 2002 and 2003 Technical Papers; [4] REI 2004 Technical paper;* REI 2005 Technical paper.

REBURN – GAS, CONVENTIONAL
Cyclone-Fired Boilers
Constellation Energy (formerly Baltimore Gas & Electric)
C.P. Crane Station, Units 1 & 2 (MD) Crushed Coal, cyclone-fired, eastern bituminous coal
2 x 200 MW B&W boilers (four cyclones each) 1961, 1963 vintage
GE-EER Conventional Gas Reburn, 1999 startup
Added gas supply piping, metering, hangers, supports; reburn injectors and cooling air ductwork, OFA ductwork, injection nozzles and wall ports, field (assume eastern bituminous coal)
GE-EER claimed Gas Reburn with OFA lowered NOx between 60% and 65% from baselines of 1.50 lb/mmBtu to between 0.60 and 0.52 lb/mmBtu, at full load with reburn operation. No claims of percent reburn fuel or percent OFA included in GE-EER's experience list.
Another technical paper showed this installation of CGR operated with 25 percent reburn fuel[5].
Source: Sept. 2005 GE-EER experience list; [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

City Water, Light & Power
Lakeside Unit 7 Crushed Coal, front-wall cyclone-fired, midwestern bituminous coal
300,000 lb/hr steam B&W boiler (approx. 33 MWe equivalent, two cyclones) 1961 vintage
Springfield, IL DOE Clean Coal demonstration project (included sorbent injection)
GE-EER conventional gas reburn w/ OFA 1992 startup (CGR not currently operating)
Vendor claimed to lower NOx by 66% from 0.95 lb/mmBtu baseline to 0.32 lb/mmBtu. A GE-EER 2004 technical paper showed 25% reburn fuel yielded minimum NOx emissions[6].
A DOE NETL technical paper showed this demonstration of CGR from 5/93-10/94 (assume with OFA) with 23 percent reburn fuel reduced NOx 60% from 0.97 to 0.39 lb/mmBtu [5].
Source: Sept. 2005 GE-EER experience list; [6] GE-EER 2004 Technical paper; [5] DOE-NETL 2004 Reburn Conference Technical paper.

Eastman Kodak Company
Kodak Park Boilers 41 & 42 Crushed Coal, front-wall cyclone-fired, 1964 & 1966 vintage

400,000 lb/hr steam B&W boilers (approx. 50 MWe equivalent, two 8-ft dia. cyclones)
Rochester, NY eastern bituminous coal
B&W conventional gas reburn w/ OFA December 1998, July 1998 startups (still operating)
Commercial installation of CGR, with (1) gas burner added to each sidewall + (2) large and (2) small OFA ports added to front wall above cyclones, utilizing higher reburn gas pressure (vs. Boiler #43) requires no flue gas recirculation; {Very small furnace w/ cyclone SR not <1.0}.
B&W claimed reburn with OFA lowered NOx by 50% from 1.20 lb/mmBtu baseline to 0.6 lb/mmBtu. B&W graph shows 10-12% percent reburn fuel to achieve 0.6 lb/mmBtu and 23-24% reburn gas input to reach 0.33 lb/mmBtu NOx (73% reduction)[7].
Another technical paper showed NOx lowered by 52% from 1.25 lb/mmBtu baseline to 0.60 lb/mmBtu with 18 percent reburn fuel[5].
Source: [7] B&W Technical Paper; [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

REBURN – GAS, CONVENTIONAL
Cyclone-Fired Boilers, continued
Eastman Kodak Company
Kodak Park Boiler 43 Crushed Coal, front-wall cyclone-fired 1968 vintage
600,000 lb/hr steam B&W boiler (approx. 60 MWe equivalent, two cyclones)
Rochester, NY eastern bituminous coal
B&W conventional gas reburn 1995 startup (still operating)
Commercial installation of CGR, with flue gas recirculation (FGR) for injection mass momentum w/ (1) FGR fan; (1) gas burner added to each sidewall + (2) OFA ports added front wall above cyclones. {Very small furnace/low residence time w/ cyclone SR not <1.0}
B&W claimed reburn with OFA & FGR lowered NOx by 50% from 1.20 lb/mmBtu baseline to 0.6 lb/mmBtu. B&W graph shows 18% percent reburn fuel to achieve 0.6 lb/mmBtu and 29% reburn gas input to reach 0.36 lb/mmBtu NOx (70% reduction)[7].
Another technical paper showed NOx lowered by 56% from 1.35 lb/mmBtu baseline to 0.60 lb/mmBtu with 18 percent reburn fuel[5].
Source: [7] B&W Technical Paper; [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

Tennessee Valley Authority (TVA)
Allen Station Unit 1 (TN) Crushed Coal, cyclone-fired (seven cyclones) 1959 vintage
300 MW B&W boiler PRB &western bituminous coal blend fired
GE-EER Conventional Gas Reburn, 1998 startup
Commercial installation added gas supply piping, metering, hangers, supports; reburn injectors and cooling air piping, OFA ductwork, injection nozzles and wall ports, field I&C devices.
Reburn with OFA claimed to lower NOx 65% from baseline 1.20 lb/mmBtu to 0.42 lb/mmBtu) at full load with reburn operation. No claims of percent reburn fuel included. (TVA also installed duplicate OFA systems on Allen Units 2 & 3 boilers).
Another technical paper showed NOx lowered by 65% from 0.86 lb/mmBtu baseline (to 0.30 lb/mmBtu) with 7 percent reburn fuel[5].
Source: Sept. 2005 GE-EER experience list; [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

REBURN – COAL, CONVENTIONAL
Cyclone-Fired Boilers
Alliant Energy (formerly Wisconsin Power & Light)
Nelson Dewey Station Unit 2 Crushed Coal, cyclone-fired, PRB coal 1962 vintage

110 MW B&W boiler 3-cyclones across front wall, 4 reburn burners + 4 OFA ports across rear wall, aligned vertically in columns.
US DOE Clean Coal Demonstration project of B&W's Conventional Coal Reburn, 1991 startup (since discontinued) added coal supply piping, reburn burners with flue gas recirculation, OFA ductwork + dual zone ports; coal feeder, pulverizer & PA fan, tested with PRB and bituminous coals. (western subbituminous coal)
B&W claimed reburn operation lowered NOx by 57% from baseline of 0.83 mmBtu to 0.38 lb/mmBtu at full load[7]. Approx. 30% percent of total fuel input supplied as reburn fuel. Increased unit output by 10 MW, increased flyash unburned carbon by 4% (13-22% vs 9-18%), decreased furnace exit gas temperature (FEGT). OFA ports listed in B&W experience list.
B&W shows full load NOx w/o reburn was 0.75 lb/mmBtu, and 0.29-0.32 lb/mmBtu w/ PRB fuel during reburn operation (57% decrease). At 75% load, 0.64 vs 0.29-0.32 lb/mmBtu. At 55% load, 0.62 vs 0.29-0.31 lb/mmBtu without and with reburn activated[8].
Another technical paper showed NOx lowered by 52-55% from 0.82 lb/mmBtu baseline (to 0.39-0.34 lb/mmBtu) with 25-30 percent reburn fuel[5].
Source: [7] 2004 B&W Technical Paper; [5] DOE-NETL 2004 Reburn Conference Technical paper; [8] B&W case history (from website, dated 1997).

REBURN – COAL, MICRONIZED, CONVENTIONAL
Cyclone-Fired Boilers
Eastman Kodak Company
Kodak Park #15 Boiler Crushed Coal, front-wall cyclone-fired, 1956 vintage
400,000 lb/hr steam B&W boiler (approx. 50 MWe equivalent, two cyclones)
Rochester, NY eastern bituminous coal
GE-EER micronized coal reburn1996 initial startup (operating since 1997)
Demonstration project performed with Dept. of Energy's US Clean Coal Technology Program. Project added flue gas recirculation for injection mass momentum, FGR fan and two micronized coal pulverizers; (6) reburn coal injectors added to rear wall + (1) reburn coal injector on each of the sidewalls, with (4) OFA ports added across front wall above cyclones[9]. GE-EER designed and fabricated the coal injectors and OFA ports. {Extremely small furnace and low residence time}.
GE-EER claimed reburn + OFA w/ FGR reduced NOx by 50% from 1.20 lb/mmBtu baseline to 0.6 lb/mmBtu. No claims of percent reburn fuel included.
Another technical paper showed this demonstration of micronized coal reburn from 4/97-10/98 lowered NOx by 57% from 1.36 lb/mmBtu baseline (to 0.59 lb/mmBtu) with 17 percent reburn fuel[5].
Source: [9] DOE Topical Report Number 14 (May 1999); GE-EER experience list; [5] DOE-NETL 2004 Reburn Conference Technical paper.

REBURN – FUEL LEAN GAS REBURN
Cyclone-Fired Boilers
Midwest Generation (formerly Commonwealth Edison)
Joliet Station 9, Unit 6 Crushed Coal, opposed-wall cyclone-fired (nine cyclones)
340 MW B&W boiler 1959 vintage, 1997 startup (FLGR has since been decommissioned)
Energy Systems Associates demonstrated 25-30% NOx reduction using 5-10% of total heat input as reburn natural gas injected (without OFA)[5].
Another technical paper showed this demonstration in collaboration with Gas Research Institute of FLGR lowered NOx by 28-43% from 1.36 lb/mmBtu baseline (to 0.59 lb/mmBtu) with 7 percent reburn fuel[10].
Source: [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference); [10] NGB Technologies Technical Paper.

REBURN – FUEL LEAN GAS REBURN w/ SNCR continued

Cyclone-Fired Boilers

Owensboro Municipal Utilities (KY) Crushed Coal, front-wall cyclone-fired
Elmer Smith Unit 1 (three cyclones) 1965 vintage
150 MW B&W boiler
CFD model study only predicted NOx reductions from 1.59 to 0.39 lb/mmBtu with OFA only (75% reduction, 0.90 SR); 25-30% NOx reduction using 6% of total heat input as reburn natural gas injected above OFA; 40-45% NOx reduction from SNCR with <5 ppm ammonia slip[11].
Source: [11] REI Technical paper.

Separated OVERFIRE AIR

Cyclone-Fired Boilers

Tennessee Valley Authority (TVA) Crushed Coal, cyclone-fired, 1959 vintage
Allen Station Units 2 & 3 (TN) (seven cyclones)
300 MW B&W boilers PRB &western bituminous coal blend
GE-EER Overfire air (duplicate of Allen 1), 1999 startup
GE-EER claimed to lower NOx with OFA alone up to 29% from baseline 1.20 lb/mmBtu to 0.85 lb/mmBtu on Units #2 and 3 at full load.
Source: Sept. 2005 GE-EER experience list.

AmerenUE (formerly Union Electric Co.)
Sioux Unit 1 Crushed Coal, opposed-wall cyclone-fired 1969 vintage
500 MW B&W boiler PRB/Illinois Coal blend
Boiler has 10 cyclone burners, arranged "2 over 3" style, on opposite walls, and fires a blend of 85% to 50% western subbituminous (PRB) coal, with Illinois bituminous coal, petroleum coke, and tire-derived fuel.
A ten-port OFA system (five ports on each front and rear wall) began operation in mid-2001, which reduced NOx emissions approx. 40-50% reduction from 1.1-1.3 (assume average of 1.19) down to 0.7 lb/mmBtu with moderate cyclone air-staging (cyclone SR from 1.19 to 1.0).[3] Subsequent testing and full load operation at deeper cyclone air-staging (SRs ≤0.90) has dropped NO_X with SOFA alone to around 0.3 lb/mmBtu in 2004[4].
Source: [3] REI 2002 and 2003 Technical Papers; [4] REI 2004 Technical paper;* REI 2005 Technical paper

Coal burning cyclone-fired utility boilers in the United States that have been retrofitted with Separated Overfire Air CR technology are listed in Table A.2-1. A large majority of the cyclone-fired boilers listed burn western subbituminous coal (or PRB blended with midwestern bituminous coal).

TABLE A.2-1 – Cyclone-Fired Boiler Overfire Air Retrofit Installations[12]

Facility Name	Installation Date	Comments
Allen Station Units 1	Installed 1998*	OFA w/ CGR retrofit; has SCR
Allen Station Unit 2	Installed 1999*	(Similar to Unit 1, w/o CGR) have SCR
Allen Station Unit 3	Installed 1999*	(Similar to Unit 1, w/o CGR) have SCR
Asbury Unit 1	Installed 5/10/1999	Empire District, BART-eligible
Bailly Unit 7	Installed 2003[13]	SCR to be installed in 2006-7
Bailly Unit 8	Installed 5/31/2000	SCR retrofit 5/11/2004
Baldwin Unit 1	Installed 12/31/1999	SCR retrofit 4/28/2003
Baldwin Unit 2	Installed 5/8/2000	SCR retrofit 4/12/2002
Big Stone Unit 1	Installed 10/22/1997	part of conversion to PRB
BL England Unit 2	Installed 1998*	previous SNCR retrofit in 1996
CP Crane Unit 2	Installed 2/1/1999	OFA w/ CGR retrofit
Coffeen Unit 1	Installed 2/1/2001	SCR retrofit 4/21/2003
Coffeen Unit 2	Installed 2/9/2000	SCR retrofit 4/09/2002
Edgewater Unit 3	Installed 11/2001[13]	
Edgewater Unit 4	Installed 6/19/2001	
Joliet 9 Unit 6	Installed 2000[13]	
Kincaid Unit 1	Installed 4/28/2000	SCR retrofit 12/17/2002
Kincaid Unit 2	Installed 5/24/2000	SCR retrofit 6/07/2002
Allen S. King Unit 1	Installed 11/30/1999	
LaCygne Unit 1	Installed 2/28/2000	
Lake Road Unit 6	Installed 6/01/2002	
Michigan City Unit 12	Installed 4/1998[13]	SCR retrofit 5/01/2003
Nelson Dewey Unit 1	Installed 2002[13]	
Nelson Dewey Unit 2	Installed 2002[13]	
Paradise Unit 1	Installed 11/14/1998	SCR retrofit 5/01/2001
Paradise Unit 2	Installed 12/8/1999	SCR retrofit 5/01/2000
Paradise Unit 3	Installed 5/4/2000	SCR retrofit 3/10/2004
Powerton Unit 5-1	Installed 6/1/2003	
Powerton Unit 5-2	Installed 6/1/2003	
Powerton Unit 6-1	Installed 6/1/2002	
Powerton Unit 6-2	Installed 5/4/1999	
Schahfer Unit 14	Installed early 2000[13]	SCR retrofit 5/11/2004
Sibley Unit 2	Installed 5/24/2002	
Sibley Unit 3	Installed 5/4/1999	
Sioux Unit 1	Installed 4/30/2001	SNCR demo May 2005
Sioux Unit 2	Installed 4/30/1997	
State Line Unit 4	Installed 11/2001[13]	Similar to Joliet 9 Unit 6
Tanners Creek Unit 4	Installed 5/12/2002	
Thomas Hill Unit 1	Installed June 2004[13]	
Thomas Hill Unit 2	Installed November 2000[13]	

Note: This table does not include every installed U.S. coal-fired cyclone boiler OFA retrofit project.
Source: [12] US EPA Docket OAR-2002-0076-0446 Technical Support Document for BART NOx Limits for Electric Generating Units Excel Spreadsheet 6/15/2005 (except as noted below)
* Vendor experience list (GE Energy for Allen Station Units 1-3; RJM for BL England Unit 2)
[13] Burns & McDonnell internal database.

Coal burning cyclone-fired utility boilers in the United States that have been retrofitted with SCR technology are listed in Table A.2-2. This list includes at least eighteen cyclone-fired boilers burning western subbituminous coal (or PRB blended with midwestern bituminous coal). The highest emission

reductions listed in Table A.2-2 for SCR systems are for clean reactor catalyst and ideal operating conditions.

TABLE A.2-2 – Cyclone-Fired Boiler High-Dust SCR Installations

Facility[1]	Unit Size[2],MW	Tested Control Efficiency[3]	Tested Outlet NO_X Emission Rate (lb/mmBtu)[3]	2003 Ozone Season Average NO_X Emission Rate[4] (lb/mmBtu)
Allen 1, 2, & 3[5,6]	330 ea.	91.1/NAD[7]/88.7	0.070/NAD[7]/0.088	0.088/0.077/0.086
Baldwin 1[5,6]	600[3]	82.9	0.072	0.238
Baldwin 2[5,6]	605[3]	83.5	0.067	0.286
Bailly 8[5,6]	422	NAD[7]	NAD[7]	0.84
Coffeen 1[5,6]	389	NAD[7]	NAD[7]	0.114
Coffeen 2[5,6]	617	NAD[7]	NAD[7]	0.120
Dallman 31 & 32	207	NAD[6]	NAD[6]	0.149/0.146
Kincaid 1 & 2[5,6]	660[3] ea.	89/89	0.079/0.079	0.181/1.198
Marion 4	173	94.3	0.067	0.252
Merrimack 1[5,8]	114	50.5[9]	0.148	0.158
Merrimack 2	346	51.3[9]	0.155	0.171
Michigan City 12[5,10]	540	84.2	0.109	0.418
New Madrid 1 & 2[8,10]	600 ea.	87.4/88.1	0.149/0.147	0.319/1.172
Paradise 1 & 2[5,6]	704 ea.	87.7/87.7	0.102/0.101	0.124/0.113
Paradise 3[5,6]	1150	89.1	0.088	0.658
Schahfer 14[5,10]	540	83.5	0.106	0.478

[1] – original design fuel for all listed cyclone boilers was bituminous coal
[2] – Generator nameplate rating, March 2002 Energy Information Administration report DOE/EIA-0095(2000). Actual unit MW output rating may be higher or lower than nameplate.
[3] – Burns & McDonnell internal database.
[4] – as reported to US EPA, available from their website at http://cfpub.epa.gov/gdm/index.cfm
[5] – includes application of separated overfire air for combustion NO_X control
[6] – current fuel believed to be a blend of subbituminous and bituminous coals
[7] – NAD = no published data from SCR emission testing found on these units.
[8] – original air preheaters were tubular-type; changed to rotary-type during SCR retrofit
[9] – Design NO_X removal efficiency is higher, approx. 90%.
[10] – current fuel believed to be subbituminous coal

For Merrimack Unit 1's SCR, inlet (i.e. uncontrolled) NO_X was 1.34 lb/mmBtu, for a blend of high sulfur bituminous and medium or low sulfur bituminous coals, and requires year-round SCR operation for compliance. The catalyst was designed for 88.9% NO_X removal efficiency

and 5 ppm ammonia slip. SCR commercial service date July 20, 1999. [(14) Babcock Borsig Power 2000 technical paper on SCRs].

For Merrimack Unit 2's SCR, inlet (i.e. uncontrolled) NO_X was 2.66 lb/mmBtu, for a blend of high sulfur bituminous and medium or low sulfur bituminous coals, and requires year-round SCR operation for compliance. Initial testing demonstrated 70% removal(15), which exceeded the 65% requirement to achieve a 0.92 lb/mmBtu permit limit. The catalyst was designed for 85-95% NO_X removal efficiency and 5 ppm ammonia slip(16).

(15)NETL-DOE Clean Coal Technology 1997 technical paper on SCRs; (16) 1997 ICAC White Paper on SCRs.

Northern Indiana Public Service Company (NIPSCO)
Bailly Unit 8 Crushed Coal, cyclone-fired, opposed-wall-fired 1968 vintage
360 MW B&W boiler Urea/ammonia conversion for high-dust SCR, 2004 startup
Boiler fires a blend of 85% western subbituminous (PRB) coal, with Illinois bituminous coal.
Commercial Fuel Tech urea-based system installed in 2004 to convert urea to ammonia for injecting reagent ahead of boiler economizer outlet and high-dust SCR. An OFA system was retrofitted in 2000(13).
Source: Fuel Tech experience list dated 1/28/2005; (13)Burns & McDonnell internal database.

Northern Indiana Public Service Company (NIPSCO)
Michigan City Unit 12 Crushed Coal, cyclone-fired, opposed-wall-fired 1974 vintage
520 MW B&W boiler Urea/ammonia conversion for high-dust SCR, 2003 startup
Boiler fires western subbituminous (PRB) coal.
Commercial Fuel Tech urea-based system installed in 2003 to convert urea to ammonia for injecting reagent ahead of boiler economizer outlet and high-dust SCR. An OFA system was retrofitted in 1998(13).
Source: Fuel Tech experience list dated 1/28/2005; (13)Burns & McDonnell internal database.

Northern Indiana Public Service Company (NIPSCO)
Schahfer Unit 14 Crushed Coal, cyclone-fired, opposed-wall-fired 1975 vintage
520 MW B&W boiler Urea/ammonia conversion for high-dust SCR, 2004 startup
Boiler fires western subbituminous (PRB) coal.
Commercial Fuel Tech urea-based system installed in 2004 to convert urea to ammonia for injecting reagent ahead of boiler economizer outlet and high-dust SCR. An OFA system was retrofitted in 2000(13).
Source: Fuel Tech experience list dated 1/28/2005; (13)Burns & McDonnell internal database.

TABLE A-3 – Low-Dust Pulverized Coal-Fired Boiler SCR Installations

Operator/Facility[1,2]	SCR Startup Date[3]	Average NO_X Emission Rates[4] (lb/mmBtu)	Unit Size[5], MW
AEP/Cardinal Unit 3[6]	5/01/03	0.74 / 0.34 / 0.135	650
Carolina P&L/Mayo Unit 1[7]		- / (0.36) / N/A	368 x 2
Carolina P&L/Roxboro Unit 4[7,8]	5/07/01	0.57 / 0.26 / 0.081	372 x 2
Cinergy/East Bend Unit 1	4/01/02	- / (0.28) / 0.067	648
Constellation/Brandon Shores Unit 1[8]	(2001)	0.47 /0.33 / 0.126	685
Constellation/Brandon Shores Unit 2[8]	(2000)	0.45 / 0.31 / 0.094	685
Dayton P&L/Killen Station Unit 2	11/01/03	- / (0.48) / 0.06[9]	666
Dynegy Midwest Gen/Havana Unit 6[10]	(2000)	0.46 /0.20 / 0.102[9]	488
PSEG Power LLC / Mercer Unit 1[11]	(2005)	- / (0.63) / N/A	320
PSEG Power LLC / Mercer Unit 2[11]	(2004)	- / (0.76) / N/A	320

[1] – Burns & McDonnell internal database.
[2] – Current fuel is eastern or midwestern bituminous coal, except Havana
[3] – US EPA Docket OAR-2002-0076-0446 Technical Support Document for BART NOx Limits for Electric Generating Units Excel Spreadsheet 6/15/2005, except where noted. Dates in () are believed to be accurate but have not been confirmed.
[4] – The three values are "Pre-control average", "2004 annual average", and "2003 ozone season average" NO_X emission rates, as reported to US EPA. Pre-control and year 2004 annual average data as shown in US EPA Docket OAR-2002-0076-0446 Technical Support Document for BART NOx Limits for Electric Generating Units Excel Spreadsheet 6/15/2005, posted on their website: http://docket.epa.gov/edkpub/do/EDKStaffItemDetailView?objectId=090007d48084562b. Values shown in parentheses are year 2003 annual average where 2004 data is not available. Year 2003 and 2003 ozone season data is available from the EPA's website at http://cfpub.epa.gov/gdm/index.cfm, includes application of separated overfire air for combustion NO_X control where applicable.
[5] – Generator nameplate rating, March 2002 Energy Information Administration report DOE/EIA-0095(2000). Actual unit MW output rating may be higher or lower than nameplate.
[6] – This boiler has low-NOx burners for combustion controls.
[7] – Carolina Power & Light plants listed here have two boilers per unit, total nameplate for Mayo is 736 MW, Roxboro is 745 MW; emission numbers are the average of both boilers.
[8] – This boiler has low-NOx burners and overfire air for combustion controls.
[9] – This is preliminary data reported to the US EPA for 2004 ozone season average emission rate.
[10] – This boiler's current fuel is believed to be subbituminous coal.
[11] – Mercer boilers listed have low-dust SCR with flue gas reheat. Unit size is approximate, not nameplate.
N/A = complete 2004 ozone season data is not available, and 2003 ozone season data is not representative of the post-SCR installation emission rate.

SELECTIVE NON-CATALYTIC REDUCTION

Pulverized coal-fired boilers

American Electric Power (AEP) Pulverized Coal, cell-burner, opposed wall-fired B&W boiler
Cardinal Unit 1 1967 vintage; Low NO_x burners installed in October 1998
600 MW (nominal) Brilliant, Ohio
Fuel Tech urea-based SNCR installed in October 1998.
Fuel Tech, DOE, EPRI-member utilities SNCR demonstration project. Tested in March-April 1999, claimed 65% reduction with LNBs + SNCR w/ 5 ppm NH_3 slip, (from pre-LNB retrofit baseline of 1.20 lb/mmBtu*) down to 0.52 lb/mmBtu at 620 MW (100% MCR). SNCR reduced NO_X 31% below LNBs alone (0.75 lb/mmBtu baseline), at 620 MWg (100% MCR), 34% reduction at 75% MCR (450 MWg), and 42% reduction at minimum load (340 MWg, 55% MCR) ≤5% ammonia slip[17], burning eastern bituminous coal. Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005; [1]ICAC White Paper, [17] 2000 Fuel Tech technical paper, *Riley Power (Babcock Power Inc.) experience list 8/16/04.

Carolina Power & Light (Progress Energy)
Asheville Unit 1 Pulverized Coal, front wall fired
200 MWe DB Riley boiler 1964 vintage, eastern bituminous coal, June 2000 SNCR startup
Fuel Tech commercial SNCR installation claimed 25% NOx reduction from low-NO_X burner w/o OFA baseline of 0.58 lb/mmBtu (down to 0.44 lb/mmBtu on SNCR alone). Urea-to-NOx NSR not stated. (Also see FLGR + SNCR installation summaries for pulverized coal boilers).
Source: Fuel Tech experience list dated 1/28/2005.

Carolina Power & Light (Progress Energy) Pulverized Coal, Tangentially-fired
Cape Fear Unit 5 1956 vintage; eastern bituminous coal
154 MW CE boiler SNCR startup in 2002
Mobotec USA "Rotamix" ammonia-based SNCR system injects aqueous ammonia liquid into a high velocity boosted separated overfire air (ROFA) system at the boiler.
CP&L technical paper claimed to lower NO_X from 0.28 lb/mmBtu baseline by 43% to 0.16 lb/mmBtu in 2002 with 5 ppm NH_3 slip following the installation of ROFA in 2000.
Overall reduction 73% from full-load pre-ROFA baseline 0.60 lb/mmBtu to 0.16 lb/mmBtu[18].
Mobotec claimed further NO_X reduction was possible by injecting urea in place of ammonia, achieving 0.13 lb/mmBtu instead of 0.18 lb/mmBtu, which would be 54% decrease from 0.28 lb/mmBtu with ROFA alone, or 78% overall decrease[19]. Ammonia-to-NOx NSR not stated.
Source: [18] CP&L 2002 Technical paper; [19] Mobotec 2003 technical paper.

Carolina Power & Light (Progress Energy) Pulverized Coal, Tangentially-fired
Cape Fear Unit 6 twin-furnace (eight corner), 1958 vintage; eastern bituminous coal
175 MW CE boiler SNCR startup in 2001
Mobotec USA "Rotamix" ammonia-based SNCR system, injects aqueous ammonia liquid into a high velocity boosted separated overfire air ("ROFA") system at the boiler.
CP&L technical paper claimed to lower NO_X from 0.23 lb/mmBtu baseline by 22% to 0.18 lb/mmBtu with 5 ppm NH_3 slip following the installation of ROFA+SNCR in 2001[18]. Presentation slide graph shows no reduction for Rotamix beyond ROFA alone at full load NO_X emission rate of 0.23 lb/mmBtu. Ammonia-to-NOx NSR not stated.
Overall reduction 67% from full-load pre-ROFA baseline 0.54 lb/mmBtu to 0.18 lb/mmBtu.
Mobotec claimed further NO_X reduction was possible by injecting urea in place of ammonia, achieving 0.10 lb/mmBtu instead of 0.18 lb/mmBtu, which would be 56% decrease from 0.23 lb/mmBtu with ROFA alone, or 81% overall decrease[19]. Urea-to-NOx NSR not stated.
Source: [18] CP&L 2002 Technical paper; [19] Mobotec 2003 technical paper.

SELECTIVE NON-CATALYTIC REDUCTION continued

Pulverized coal-fired boilers

Cinergy (formerly Cincinnati G&E) — Pulverized Coal, Tangentially-fired,
Miami Fort Unit 6 (Ohio) — 1960 vintage; startup prior to 2000
163 MW CE boiler
Fuel Tech urea-based SNCR system, claimed to lower NOx by 35% from 0.55 lb/mmBtu baseline[(1)].(assume eastern bituminous coal). Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005, [(1)] ICAC White Paper.

Conectiv (formerly Delmarva Power & Light)
Edgemoor Unit 3 — Pulverized Coal, Tangentially-fired, 1954 vintage
84 MW CE boiler — mid-March 1996 startup; (assume eastern bituminous coal)
Hamon Research-Cottrell supplied a urea-based SNCR system. HRC claimed 35% NOx reduction with less than 10 ppm ammonia slip. Urea-to-NOx NSR not stated.
Another source shows a 30% reduction from 0.54 lb/mmBtu baseline[(1)].
Source: Hamon experience list (not listed by Fuel Tech); [(1)] ICAC White Paper.

Conectiv (formerly Delmarva Power & Light) — Pulverized Coal
Indian River Units 3 & 4 (Millsboro, DE) — Unit 3 is front wall-fired, 1974 vintage
178MW and 440 MW — Unit 4 is turbo-fired opposed-wall, 1980 vintage
B&W, DB Riley boilers — Spring 2000 startup (eastern bituminous coal)
Hamon Research-Cottrell supplied a urea-based SNCR system (not listed by Fuel Tech) on both units. HRC claimed 35% NO_X reduction with less than 5 ppm ammonia slip. Urea-to-NOx NSR not stated.
An REI 1999 technical paper shows a pre-SNCR baseline of 0.37 and 0.44 lb/mmBtu, respectively. [(20)]
Another source listed these units as having a pre-control NO_X baseline of 0.97 and 0.57 lb/mmBtu, and 2004 post-SNCR startup average of 0.32 and 0.33 lb/mmBtu, respectively. [(12)]
Source: Hamon experience list (not listed by Fuel Tech); [(20)] REI 1999 technical paper;
[(12)] US EPA Docket OAR-2002-0076-0446 Excel Spreadsheet 6/15/2005.

Dominion Generation (Virginia E&P Co.) — Pulverized Coal, Tangentially-fired
Clover Station, Units 1 & 2 (VA) — ABB/CE boilers, 1995, 1996 vintage
2 x 465 MW — (eastern bituminous coal)
Urea-based SNCR (Fuel Tech system) — 1995, 1996 startup (initial commercial)
Fuel Tech claimed NOx reduced by 25% from 0.32 lb/mmBtu baseline (to 0.24 lb/mmBtu).
Source: Fuel Tech experience list dated 1/28/2005. Urea-to-NOx NSR not stated.

Dynegy Midwest Generation (formerly Illinois Power) — Pulverized Coal, Tangentially-fired
Vermillion Station, Unit 1 — 1955 vintage
82 MW — CE boiler, bituminous Illinois coal
Mobotec USA "Rotamix" urea-based SNCR system with rotating opposed fired air (ROFA).
Mobotec 2004 technical paper claimed to lower NO_X by 55% from 0.22 lb/mmBtu baseline to 0.10 lb/mmBtu in April 2004 with urea-based Rotamix SNCR and < 5 ppm CO. NH_3 slip not mentioned.
Overall reduction 83% from full-load pre-ROFA baseline 0.58 lb/mmBtu to 0.10 lb/mmBtu [(21)]. Urea-to-NOx NSR not stated.
Source: [(21)] Mobotec 2004 technical paper.

SELECTIVE NON-CATALYTIC REDUCTION continued

Pulverized coal-fired boilers

Eastern Utilities Associates, Pulverized Coal, Tangentially-fired
Montaup Electric Company 1959 vintage
Somerset Unit 8 (Massachusetts) Summer 1995 startup
112 MW CE boiler (eastern bituminous coal)
Hamon Research-Cottrell supplied a urea-based SNCR (Fuel Tech system), claimed to lower NOx below 0.38 lb/mmBtu (Mass. RACT). Urea-to-NOx NSR not stated.
Another source listed 28-60% NOx reduction from a 0.49-0.89 lb/mmBtu baseline[(1)].
Source: Hamon experience list, Fuel Tech experience list dated 1/28/2005, [(1)]ICAC White Paper.

First Energy Pulverized Coal, Tangentially-fired,
Eastlake Unit 3 (Ohio) 1954 vintage
130 MW CE boiler (w/ division wall) (eastern bituminous coal)
Urea-based SNCR (Fuel Tech system) SNCR startup prior to 2000
Fuel Tech claimed to lower NOx from 20-32.5% from 0.34-0.40 lb/mmBtu baseline[(1)]. Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005, [(1)] ICAC White Paper.

First Energy Pulverized Coal, wall-fired,
Sammis Unit 2 (Ohio) 1960 vintage
180 MW Foster Wheeler boiler SNCR startup Fall 1999
Urea-based SNCR (Fuel Tech system) (eastern bituminous coal)
Fuel Tech claimed to lower NOx from 25-30% from 0.45 lb/mmBtu baseline [(1)]. Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005, [(1)] ICAC White Paper.

First Energy Pulverized Coal, wall-fired,
Sammis Units 6 & 7 (Ohio) 1969 & 1971 vintage
680 MW B&W Universal Pressure boilers (eastern bituminous coal)
Urea-based SNCR (Fuel Tech system) SNCR startup after 1999
Fuel Tech claimed to lower NOx from 25% from 0.38 lb/mmBtu baseline. Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005.

New England Power Company (NEPCO)
Salem Harbor Station Pulverized Coal, front wall-fired,
Units 1, 2 & 3 1952, 1952, 1958 vintage (eastern bit. coal)
84 MWe x 2, & 156 MWe B&W boilers SNCR startup prior to 2000
Urea-based SNCR (Fuel Tech system)
Fuel Tech claimed 66% (50-75%) NOx reduction from baseline of 1.0 ± 0.1 (range 0.85-1.12) lb/mmBtu, (which would lower NOx to around 0.34±0.07 lb/mmBtu). Urea-to-NOx NSR not stated. {These NOx reduction percentages may include impact of low-NOx burners}.
Source: Fuel Tech experience list dated 1/28/2005, [(1)]ICAC White Paper.
(Also see LNB installation summaries for pulverized coal boilers).

Northeast Utilities (formerly Public Service of New Hampshire)
Schiller Units 4, 5, & 6 Pulverized Coal/#6 Fuel oil, front-wall-fired
50 MWe x 3Foster Wheeler boilers 1952, 1955, 1957 vintage
Urea-based SNCR (Fuel Tech system) Colombian bituminous coal
August 1999 startup
RJM implemented Fuel Tech urea-based commercial SNCR installation on all three boilers.

RJM claimed 50% reduction from 0.50 lb/mmBtu pre-SNCR baseline to 0.25 lb/mmBtu for SNCR coal-firing operation; NO_X baseline 0.82 lb/mmBtu prior to RJM's LNB modifications installed in 1994, 1992, & 1994 (39% reduction); Urea-to-NOx NSR not stated.
Fuel Tech claimed 30% NO_X reduction for SNCR from baseline of 153 ppm firing #6 fuel oil on Units 4 & 6 only.
Source: RJM experience list, Fuel Tech experience list dated 1/28/2005.

SELECTIVE NON-CATALYTIC REDUCTION continued

Pulverized coal-fired boilers

Owensboro Municipal Utilities (KY) Pulverized Coal, Tangentially-fired,
Elmer Smith Unit 2 1974 vintage
300 MW CE boiler eastern bituminous coal
Hamon Research-Cottrell supplied an ammonia-based SNCR system but stated no claims for NOx reduction; (this project is not listed in ICAC White Paper[(1)]). Ammonia-to-NOx NSR not stated.
Source: Hamon experience list.

PECO Energy (formerly Philadelphia Electric Company)
Cromby Unit 1 Pulverized Coal, front wall-fired divided furnace
160 MWe B&W boiler 1954 vintage eastern bituminous coal
RJM installed Fuel Tech urea-based SNCR with low NO_X burner modifications & OFA in 1999, June 1999 startup.
RJM claimed 29% SNCR NO_X reduction from baseline of 0.35 lb/mmBtu, down to 0.25 lb/mmBtu with urea NSR = 0.8; RJM provided burner modifications of B&W XCL low-NOx burners installed in 1994 + OFA; this reduced NO_X from 0.50 to 0.35 lb/mmBtu (30% reduction) without SNCR. Urea-to-NOx NSR not stated.
Source: RJM experience list; [(1)]ICAC White Paper.

Exelon (formerly PECO Energy/ Pennsylvania Electric Company)
Eddystone Units 1 & 2 Pulverized Coal Tangentially-fired, 1954 vintage
318, 333 MW each CE boilers 1999 SNCR startup, eastern bituminous coal
Fuel Tech claimed 30% NOx reduction from baseline of 0.26 lb/mmBtu.
Source: Fuel Tech experience list dated 1/28/2005.

Public Service Enterprise Group (PSEG) Power LLC [formerly Public Service Electric & Gas of New Jersey (PSE&G)]
Hudson Station, Unit 2 Pulverized Coal, opposed-wall-fired, 1968 vintage
660 MWe Foster Wheeler boiler eastern bituminous coal March 1999 startup
Fuel Tech urea-based commercial SNCR installation claimed 25% (initial) NOx reduction for SNCR alone from baseline of 0.65 lb/mmBtu (down to 0.49 lb/mmBtu). Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005, also listed in [(1)]ICAC White Paper. (Also see FLGR+SNCR installation summaries for pulverized coal boilers).

Public Service Enterprise Group (PSEG) Power LLC [formerly Public Service Electric & Gas of New Jersey (PSE&G)]
Mercer Station (2) twin-furnace boilers, 320 MWe each, DB Riley turbo-fired
Unit 1 and Unit 2 front wall PC, wet-bottom (slagging ash) eastern bituminous coal
Furnace #11 & #12 1960 vintage April 1999 startup
Furnace #21 & 22 1961 vintage May 1999 startup
Fuel Tech urea-based commercial SNCR installation claimed 30-35% NOx reduction from baseline of 2.0 lb/mmBtu on SNCR alone, down to 1.4 lb/mmBtu. Urea-to-NOx NSR not stated.

Source: Fuel Tech experience list dated 1/28/2005; also listed in [1]ICAC White Paper. (Also see FLGR+SNCR installation summaries for pulverized coal boilers)

SELECTIVE NON-CATALYTIC REDUCTION continued

Pulverized coal-fired boilers

Reliant Energy (formerly GPU Genco) — Pulverized Coal
(formerly Sithe, formerly Penelec) — Tangentially-fired
Seward # 15 (PA) — mid-1990's SNCR startup
Units 4 & 5 — eastern bituminous coal
62 & 156 MW CE boilers — 1950 & 1957 vintage
Urea-based SNCR (Fuel Tech system), later installed an in-duct SCR to reduce NH_3 slip.
Fuel Tech claimed to lower NOx 35% for SNCR only (55% for combined SNCR/SCR from 0.78 lb/mmBtu baseline). Boilers have since been demolished and replaced with CFBs. Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005, [1]ICAC White Paper.

Rochester Gas & Electric — Pulverized Coal, Tangentially-fired
Russell Station, Units 1-4 (NY) 1948, 1950, 1953, 1957 vintage
1 x 50 MW, 2 x 65 MW, 1 x 85 MW CE boilers — eastern bituminous coal
Urea-based SNCR (Fuel Tech system) — SNCR startup prior to 2000
Vendor claimed to lower NOx by 15-27.5% from 0.28 – 0.42 lb/mmBtu baselines. Urea-to-NOx NSR not stated.
Source: Fuel Tech experience list dated 1/28/2005.

HYDROCARBON-ENHANCED AMMONIA SNCR (NOxStar™)

Pulverized coal-fired boilers

Tennessee Valley Authority (TVA) — Pulverized Coal twin-furnace, tangentially-fired,
Kingston Power Station (TN) — 1955 vintage eastern bituminous coal
Unit 9, 200 MWe CE boiler — NOxStar™ startup January 2002
Demonstration of NOxStar™ hydrocarbon-enhanced ammonia-based SNCR installation.
Mitsui Babcock claimed 68% NOx reduction from baseline of 0.55 lb/mmBtu down to 0.17 lb/mmBtu with boosted OFA and NOxStar™ with < 5 ppm ammonia slip; NOxStar™ alone reduced NOx by 53%[22]; boosted OFA only reduced NOx from 0.55 to 0.45 lb/mmBtu (18% reduction). Ammonia-to-NOx NSR not stated.
TVA's website reported that "an earlier version of NOxStar was installed at Kingston Fossil Plant Unit 9 in 2002 with mixed results. NOx reductions were achieved, but the boiler was damaged" (http://www.tva.gov/environment/repotrs/envreports/aer/2003/env_compliance.htm)
Source: [22] Mitsui Babcock Technical paper, October 2003.

Tennessee Valley Authority (TVA) — Pulverized Coal, wall-fired
Colbert Station (AL) — 1955 vintage
Unit 4, 192 MWe twin-furnace B&W boiler w/ FGR eastern bituminous coal
First commercial installation of NOxStar™ hydrocarbon-enhanced ammonia-based SNCR technology.
Mitsui Babcock showed 80% NOx reduction from baseline of 0.50 to 0.10 lb/mmBtu; using < 0.1% of total boiler heat input for propane input and 1% of total steam flow generated in the boiler for lance cooling[23]; 2004 SNCR system startup. Ammonia-to-NOx NSR not stated.
Source: [23] Mitsui Babcock 2004 Technical paper.

REBURN – GAS, CONVENTIONAL

Pulverized coal-fired boilers

Allegheny Power (formerly West Pennsylvania Power)
Hatfield's Ferry Station
Units 2 & 3, 600 MW (nominal) each (B&W boilers)
GE-EER Gas Reburn; 1999 startup (Unit 2) & 2003 (Unit 3)

Pulverized Coal, opposed wall-fired
cell-burner, 1969 & 1972 vintage
eastern bituminous coal

GE-EER Low NOx burners, boosted OFA, gas reburn system.
GE-EER claimed to lower NOx up to 67% from baseline of 0.60 lb/mmBtu to 0.20 lb/mmBtu at full load with reburn operation on Unit 2, 68% from 0.62 lb/mmBtu to 0.20 lb/mmBtu on Unit 3. No claims of percent reburn fuel included.
GE-EER technical paper shows approx. 35% NOx reduction at 600 MW load with LNB + OFA w/o reburn fuel, and an additional 50% reduction to 0.20 lb/mmBtu with reburn fuel[24].
B&W added 20 OFA ports in 1994 per B&W's experience list. No NOx reduction claims. Source: Sept. 2005 GE-EER experience list; [24] GE-EER 2004 Technical paper. Unit 2 and Unit 3 listed in [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

REBURN – GAS, CONVENTIONAL continued

Pulverized coal-fired boilers)

Conectiv (formerly Delmarva Power & Light)
Edgemoor Unit 4
160 MW CE boiler

Pulverized Coal, Tangentially-fired
1966 vintage, eastern bituminous coal
1999 startup

GE-EER Gas Reburn project added gas supply piping, metering, hangers, supports, reburn injectors and cooling air piping; OFA ductwork, injection nozzles and wall ports, field instrumentation. No FGR or OFA booster fans.
Vendor claimed to lower NOx up to 48% from baseline of 0.32 lb/mmBtu to 0.16 lb/mmBtu) at full load with reburn operation. No claims of percent reburn fuel included.
GE-EER technical paper shows approx. 32% NOx reduction for gas reburn with 4-mill operation at 160 MW load from 0.31 lb/mmBtu LNB + OFA baseline w/o reburn fuel (down to 0.21 lb/mmBtu), and 48% NOx reduction for gas reburn with 3-mill operation, to 0.16 lb/mmBtu [24].
Source: Sept. 2005 GE-EER experience list; [24] GE-EER 2004 Technical paper. Listed in [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference)

Dynegy (formerly Illinois Power)
Hennepin Unit 1
71 MW CE boiler

Pulverized Coal, Tangentially-fired
1966 vintage
eastern bituminous coal

GE-EER Gas Reburn, 1990 startup (not currently operating); GE-EER Orimulsion Reburn, 1997.
DOE Clean Coal demonstration project (included sorbent injection).
Vendor claimed gas reburn w/ OFA lowered NOx up to 67% from baseline of 0.75 lb/mmBtu to 0.25 lb/mmBtu) at full load; 65% reduction from baseline of 0.75 lb/mmBtu down to 0.26 lb/mmBtu with subsequent Orimulsion reburn operation.
GE-EER 2004 technical paper shows 18% gas reburn fuel yielded minimum NOx emissions[6].
Another technical paper showed this 80 MW US DOE Clean Coal demonstration project in January 1991-January 1993 lowered NOx by 67% from 0.75 lb/mmBtu baseline (to 0.25 lb/mmBtu) with 18 percent reburn fuel[5].
Source: Sept. 2005 GE-EER experience list; [6] GE-EER 2004 Technical paper; [5] DOE-NETL 2004 Reburn Conference technical paper, and DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference). (Also see Conventional Oil reburn installation summaries for pulverized coal boilers).

REBURN – GAS, CONVENTIONAL continued

Pulverized coal-fired boilers)

AES (formerly New York State Gas & Electric (NYSEG)

Greenidge #6 (NY)	Pulverized Coal, Tangentially-fired,	1953 vintage
100 MW CE boiler	GE-EER Conventional Gas Reburn, 1996 startup	

Vendor claimed to lower NOx 55% from 0.63 lb/mmBtu baseline to 0.28 lb/mmBtu at full load with reburn operation burning eastern bituminous coal. Gas Research Institute predicted would achieve 76% (down to 0.15 lb/mmBtu) w/ advanced gas reburn.
GE-EER 2004 technical paper shows 23% reburn fuel yielded minimum NOx emissions around 0.23 lb/mmBtu[(6)].
EPA's "Scorecard on Reburning 6/1/2004" shows a 109 MW t-fired boiler (listed as Greenidge Unit 4) lowered NOx by 50% from 0.50 lb/mmBtu baseline (to 0.25 lb/mmBtu) with 10 percent reburn fuel (no longer operating) [(5)].
Source: Sept. 2005 GE-EER experience list; [(6)] GE-EER 2004 Technical paper; [(5)] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

Potomac Electric Power (formerly West Pennsylvania Power)

Chalk Point Station	Pulverized Coal	opposed wall-fired B&W boilers
Units 1 & 2	1964, 1965 vintage	eastern bituminous coal
360 MW (nominal)	GE-EER Gas Reburn, 2000 startup	

Vendor claimed to lower NOx up to 43% and 45% from 0.60 lb/mmBtu baseline to 0.34 and 0.33 lb/mmBtu) at full load with reburn operation, respectively. No claims of percent reburn fuel included.
Source: 2002 GE-EER experience list. Listed in [(5)] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

Xcel Energy (formerly Public Service Company of Colorado)

Cherokee Unit 3	Pulverized coal, wall-fired, 1962 vintage
175 MW B&W boiler	western bituminous coal
DOE Clean Coal demonstration project	November 1992-January 1995

Gas reburn demonstration performed with Dept. of Energy and Gas Research Institute 1992-1995.
Existing boiler with 16 burners was retrofitted with low NO_X burners and GE-EER gas reburn OFA, FGR, and reburn injectors. Added OFA booster fan, 800 hp flue gas recirculation fan for injection mass momentum, for increased gas injection mass momentum (which was subsequently removed). The CGR installation portion has since been decommissioned.
Vendor claimed to lower NOx up to 64% from baseline of 0.73 lb/mmBtu to 0.26 lb/mmBtu) at full load with reburn operation.
GE-EER 2004 technical paper shows 15-20% reburn fuel yielded minimum NOx emissions[(6)].
A 2004 DOE-NETL technical paper showed this project achieved 0.46 lb/mmBtu NO_X emissions with low NO_X burners alone (37% reduction), further reduced NO_X by 44% with 12.5 percent reburn fuel[(5)].
A 2001 DOE-NETL technical paper claimed a NOx reduction of 65% at an average reburn gas heat input of 18% of total boiler fuel input, with and without FGR. Demonstrated 70% NOx reduction at higher reburn input rates. Referred to technology as GR-LNB. FGR was added for gas injection momentum but was subsequently removed to reduce fuel input. [(25)]
Source: Sept. 2005 GE-EER experience list; [(6)] GE-EER 2004 Technical paper; [(5)] DOE-NETL 2004 Reburn Conference technical paper and DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference); [(25)] DOE-NETL 2001 Technical paper; also in [(9)] DOE 1999 Topical Report Number 14.

REBURN – OIL, CONVENTIONAL

Pulverized coal-fired boilers

Dynegy (formerly Illinois Power) Pulverized Coal, Tangentially-fired
Hennepin Unit 1 1966 vintage, eastern bituminous coal
71 MW CE boiler 1997 startup
GE-EER Orimulsion Reburn system w/ OFA, claimed orimulsion reburn lowered NOx up to 65% from baseline of 0.75 lb/mmBtu to 0.26 lb/mmBtu at full load with Orimulsion reburn operation (installed after gas reburn was demonstrated in early 1990's). No claims for percent reburn fuel included.
GE-EER 2004 technical paper shows 60% reduction with subsequent Orimulsion reburn [6].
Source: GE-EER experience list; [6] GE-EER 2004 Technical paper. Orimulsion not mentioned in [5] DOE-NETL 2004 Reburn Conference technical paper or DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference). (Also see Conventional Gas Reburn installation summaries for pulverized coal boilers).

New Brunswick Power
Coleson Cove, Bunker C/Orimulsion–fired, opposed-wall
St. John, New Brunswick, Canada
3x 350 MW B&W Boilers
Sixteen new low-NO_X oil/Orimulsion burners, eight reburn burners, nine SOFA ports, two combustion air booster fans, reburn and OFA wall penetration openings, OFA windboxes, ductwork, dampers, and accessories were added[7].
Another technical paper showed this reburn system lowered NOx by 78% from 1.0 lb/mmBtu baseline to 0.22 lb/mmBtu at 25 percent reburn fuel input[5].
Source: [7] B&W 2004 Technical Paper;[5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

Georgia Power Pulverized Coal, Tangentially-fired
Scherer Unit 1 1982 vintage
887 MW CE boiler 2000 oil reburn startup
GE-EER Oil Reburn system, claimed to lower NOx from baseline of 0.36 lb/mmBtu.
GE-EER 2004 Technical paper shows reduction up to 48% (to 0.19 lb/mmBtu) at 800 MW load with oil reburn operation. No claims of percent reburn fuel included[24].
Source: Sept. 2005 GE-EER experience list shows this as a coal reburn project with eastern bituminous coal, reducing NO_X emissions 33% from 0.36 to 0.24 lb/mmBtu;
[24] GE-EER 2004 Technical paper. Not listed in [5] DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

REBURN – COAL, MICRONIZED, CONVENTIONAL

Pulverized coal-fired boilers

AES (formerly New York State Electric and Gas Milliken Station Unit 1)
Cayuga tangentially-fired, pulverized coal, 1956 vintage
148 MWe, CE boiler eastern bituminous coal
GE-EER micronized coal reburn system 1996 startup (still operating)
US DOE Clean Coal demonstration project from March 1997-April 1999 lowered NOx with this reburn system by 29% from 0.35 lb/mmBtu baseline to 0.25 lb/mmBtu at 14 percent reburn fuel input[5]. Not listed in GE-EER's experience list nor in their 2004 technical paper.
Source: [5] DOE-NETL 2004 Reburn Conference technical paper and DOE-NETL Scorecard on Reburning 6/1/2004 (from 2004 Reburn Conference).

LOW NO_x BURNERS (Replacement or modifications) w/ and w/o OVERFIRE AIR continued

Pulverized coal-fired boilers

Dynegy Midwest Generation (formerly Illinois Power) Pulverized Coal, wall-fired
Havana Station, Unit 6 1978 vintage
460 MW B&W boiler, bituminous Illinois coal
GE-EER provided modifications to the original B&W dual-register burners, and an OFA system in 2000.
Vendor claimed full load NO_X was unchanged from 0.38 lb/mmBtu baseline.
Source: GE-EER Experience list 2/1/02. (Also see low-dust SCR installation list for pulverized coal boilers)

Dynegy Midwest Generation (formerly Illinois Power) Pulverized Coal, Tangentially-fired
Vermillion Station, Unit 1 1955 vintage
82 MW CE boiler, bituminous Illinois coal
This rotating opposed fire air (Mobotec USA ROFA) system was installed in July 2002, as part of a "Rotamix" SNCR + ROFA system, without low-NOx burners.
Mobotec 2004 technical paper claimed to lower full load NO_X by 62% from 0.58 lb/mmBtu baseline to 0.22 lb/mmBtu in July 2002 (without LNB or SNCR).[21]
Source: [21] Mobotec 2004 technical paper. (Also see SNCR installation summaries for pulverized coal boilers).

Georgia Power Pulverized coal, opposed wall-fired,
Harlee Branch Unit 1 250 MW B&W boiler, 1965 vintage 2003 startup
Harlee Branch Unit 2 359 MW Riley boiler, 1967 vintage 1998 startup
B&W provided 24 DRB-4Z low NOx burners for Unit 1 B&W boiler, 24 DRB-XCL low NOx burners for Unit 2 Riley boiler (believe southeast coast lignite is primary fuel).
Source: B&W's experience list. No NOx reduction claims.

Kansas City Power & Light Pulverized coal, opposed wall-fired, 600 MW B&W boiler
Hawthorn Unit 5 30 burners, 2001 vintage, (Powder River Basin coal)
B&W provided 30 DRB-4Z low NOx burners and 11 OFA ports with the new boiler.
Source: B&W's experience list. No NOx reduction claims.

- New England Power Company (NEPCO)
Salem Harbor Station Pulverized Coal, front wall-fired,
Units 1, 2 & 3 1952, 1952, 1958 vintage (eastern bit. coal)
84 MWe x 2, & 156 MWe B&W boilers LNBs startup in 1995, 1995, and 1993
Riley claimed Unit 1 LNBs reduced NOx emissions by 57% from baseline of 1.10 lb/mmBtu down to 0.42 lb/mmBtu; Unit 2's LNBs achieved 42% NOx reduction from a baseline of 0.95 lb/mmBtu down to 0.55 lb/mmBtu; Unit 3's LNBs achieved 60% NOx reduction from a baseline of 1.05 lb/mmBtu down to 0.42 lb/mmBtu.
Source: Riley Power (Babcock Power Inc.) 8/16/04 experience list.
(Also see SNCR installation summaries for pulverized coal boilers).

Northeast Utilities (formerly Public Service of New Hampshire)
Shiller Station Pulverized Coal/#6 Fuel oil, front-wall-fired
Units 4, 5, & 6 1952, 1955, 1957 vintage
50 MWe x 3 Foster Wheeler boilers
RJM provided (6) Low NO_x burner modifications per boiler in 1994, 1992, & 1994 respectively;
LNBs reduced NOx 43% from 0.85 to 0.48, 50% from 1.0 to 0.50, and 51% from 0.82 to 0.40 lb/mmBtu.
Source: RJM experience list

LOW NO_x BURNERS (Replacement or modifications) w/ and w/o OVERFIRE AIR continued

Pulverized coal-fired boilers

Potomac Electric Power (formerly West Pennsylvania Power)

Chalk Point Station	Pulverized Coal	opposed wall-fired
Units 1 & 2	1964, 1965 vintage	eastern bituminous coal
360 MW (nominal)	B&W boilers	

DB Riley (now Babcock Power) CCV type low NOx burners retrofitted in 1993 and 1994, respectively. Vendor claimed to lower NOx up to 52% and 50% from 1.35 and 1.40 lb/mmBtu baselines (to 0.65 and 0.70 lb/mmBtu, assumed at full load).
Source: Riley Power (Babcock Power Inc.) 8/16/04 experience list. (Also see Conventional Gas Reburn installation summaries for pulverized coal boilers).

Xcel Energy (formerly Public Service Company of Colorado)

Cherokee Unit 3	Pulverized coal, wall-fired, B&W boiler, 16 burners, 1962 vintage
175 MW	October 1992 baseline testing started (western bituminous coal)

Installed (16) Foster Wheeler Controlled Flow/Split Flame low NO_x replacement burners as part of a DOE Clean Coal Technology gas reburn demonstration performed with Gas Research Institute 1992-1995.
Uncontrolled NOx w/ original B&W flare-type burners was 0.73 lb/mmBtu. Replacement LNBs (assuming OFA included) reduced NO_X 37% to 0.46 lb/mmBtu[25].
Source: [25] DOE NETL 2001 Technical paper.

A.2.2 Technical Literature References for U.S. NOx Control Retrofit Projects:

[1] SNCR White Paper, Institute of Clean Air Companies, Inc. (ICAC), SNCR Committee, May 2000, Fuel Tech website http://www.fueltechnv.com/pdf/TPP-534.pdf

[2] REI 2001 Technical Paper "Design and Demonstration of Rich Reagent Injections (RRI) Performance For NOx Reduction at Connectiv's B.L. England Station" by Marc A. Cremer and Bradley R. Adams, Reaction Engineering International, David C. O'Connor, Electric Power Research Institute, Venkata Bhamidipati, Conectiv B.L. England Station, and R. Gifford Broderick, RJM Corporation, presented at the 2001 US EPA/DOE/EPRI MEGA Symposium on SCR and SNCRs, Chicago, IL, August 20-23, 2001. (REI website http://www.reaction-eng.com/donwloads/rri_mega.pdf)

[3] REI 2002 Technical Paper "Demonstration of Rich Reagent Injection for NOx Control in AmerenUE's Sioux Unit 1" by Marc A. Cremer and Bradley R. Adams, Reaction Engineering International, David E. Boll, AmerenUE, and David C. O'Connor, Electric Power Research Institute, presented at the US DOE Conference on SCR/SNCR for NOx Control, Pittsburgh, PA, May 15-16, 2002; and
REI 2003 Technical Paper "Improved Rich Reagent Injection (RRI) Performance For NOx Control In Coal Fired Utility Boilers" by Marc A. Cremer and Huafeng D. Wang, Reaction Engineering International, David E. Boll, AmerenUE, Edmund Schindler, RJM Corporation, and Edmundo Vasquez, RMT, Inc., Alliant Energy Corp., presented at 2003 U.S. DOE Conference on SCR and SNCR for NOx Control, Pittsburgh, PA, October 29-30, 2003.

[4] REI 2004 Technical paper, "Evaluation of Cost Effective Non-SCR Options for NOx Control in PRB Fired Cyclone Boilers" by Marc A. Cremer and David H. Wang, and Bradley R. Adams, Reaction Engineering International, David E. Boll and Kenneth B. Stuckmeyer, AmerenUE, presented at the Western Fuels Symposium, 19th International Conference on Lignite, Brown, and Subbituminous Coals (formerly Low-Rank Fuels), October 12-14, 2004, Billings, MT.

* REI 2005 Technical paper "NOx Emissions Below 0.15 lb/Mbtu Achieved in a Cyclone-Fired Boiler Using In-Furnace Control" by M. Cremer, B. Adams, and A Chiodo, Reaction Engineering International; C. Giesmann, K. Stuckmeyer, and J. Boyle, AmerenUE, presented at the PowerGen International 2005 conference, December 6-8, 2005, Las Vegas, Nevada.

(5) DOE-NETL 2004Technical Paper "Reburning Projects in the Department of Energy's Clean Coal Technology Demonstration Program", by Al Mann and Tom Ruppel, Parsons Corporation, and Tom Sarkus, National Energy Technical Laboratory, presented at the 2004 DOE-NETL Conference on Reburning for NOx Control, Morgantown, WV, May 18, 2004. A reburn-related document (an updated version of a poster from the May 18 Conference) is titled "Scorecard on Reburning 6/1/2004" by Al Mann and Tom Ruppel, Parsons Corporation, available on-line at: http://www.netl.doe.gov/publications/proceedings/04/NOx/posters/Reburning%20Scorecard.pdf

(6) GE Energy 2004 Technical paper "Reburn Technology Application Guidelines", by David Moyeda, GE Energy, presented at the 2004 DOE-NETL Conference on Reburning for NOx Control", Morgantown, WV, May 18, 2004.

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APPENDIX B

EERC REPORT

Ash Impacts on SCR Catalyst Performance

ASH IMPACTS ON SCR CATALYST PERFORMANCE

Prepared by:

Steven A. Benson, Ph.D.

Energy & Environmental Research Center
University of North Dakota
PO Box 9018
Grand Forks, ND 58202-9018

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ASH IMPACTS ON SCR CATALYST PERFORMANCE

EXECUTIVE SUMMARY

The ash deposition behavior of the lignites from North Dakota is the most complex and severe of any coals in the world, and installation of catalysts for NO_x reduction is going to be plagued with problems. The Center lignite fired at the Milton R. Young (MRY) Power Station is highly variable in abundance of various types of ash/slag-forming components. Ash-forming components consist of inorganic elements (sodium, magnesium, calcium, and potassium) associated with oxygen functional in the organic matrix and mineral grains (quartz, clays, carbonates, sulfates, and sulfides). Upon combustion, the inorganic components undergo chemical and physical transformations that produce intermediate inorganic species in the form of inorganic gases, liquids, and solids. The alkali and alkaline-earth elements combine with minerals during combustion, resulting in low-melting-point phases that cause a wide range of fireside deposition problems. In addition, the alkali and alkaline-earth elements also form very small particles that are carried into the backpasses of the combustion system and react with flue gas to form sulfates that can cause deposition, blinding, and plugging problems in selective catalytic reduction (SCR) systems. This report analyzes these problems, and concludes that SCR is not a feasible option to control NOx emissions at MRY Power Station because of the high sodium levels present in the coal.

Following is a list of the key problems that are associated with Center lignite which have not been overcome and, in our opinion, make the installation of SCR at the MRY plant technically infeasible for NO_x control.

- Blinding of Catalyst Pores by High Sodium Compounds

  X High levels of alkali and alkaline-earth elements present in the coal fired at the MRY plant produce small particles that react to form sulfates that blind the catalyst pores. The high levels of sodium in the coals combined with calcium will produce low-melting-point eutectic sulfate compounds that will form and melt inside the pores of the catalyst.

  - Alkali and alkaline earth sulfates are enhanced by cyclone fired system. The cyclone firing results in partitioning of the ash between bottom slag and the body of the boiler. The sulfate forming materials are more concentrated in the ash as a a result of cyclone firing.

  - Sulfate formation is enhanced by the presence of an SCR catalyst; this accelerates the sulfation reactions, causing blinding of the catalyst.

  - The sulfate reactions are more severe at MRY because of the high temperature where an SCR would be installed. The higher temperature increases the rate of formation of sulfates and rate of pore plugging.

  - The testing conducted by the Germans found catalyst deactivation and blinding occurs when firing coals with lignite or brown coals that have ashes that are rich in alkali and alkaline-earth elements. .

- The findings by the Germans were confirmed by recent SCR catalyst slipstream testing that showed significant evidence of sodium and calcium-rich sulfate formation that fill and plug the catalyst at both lignite- and subbituminous-coal-fired power plants. The results of this recent testing showed that the presence of sodium significantly enhanced the formation of bonding of particles and more rapid sulfation, filling of pores, and rapid increase in pressure drop across the catalyst.

- Deposit carryover, or "popcorn ash," plugging the top of the SCR catalyst is a significant problem because of the extremely high deposition rates of the Center coal. When firing Center coal, deposits form on various parts of the boiler requiring continuous sootblowing. The sootblowing of upstream heat-exchange equipment will cause deposit fragments to be carried back to the SCR catalyst, resulting in plugging. In addition, during sootblowing of the SCR catalyst, the entrainment of deposit fragments along with the sootblowing media will result in significant erosion of the catalyst surfaces.

- Recent testing with subbituminous and lignitic coals indicated a significantly higher level of pore filling and plugging in the catalyst exposed to lignite ash as compare to subbituminous coal ash. The catalyst pores as well as the catalyst surface in the lignite tests were completely coated with a sodium calcium sulfate material, while only pore filling was found in the subbituminous coal testing. The pressure drop across the catalyst exhibited for lignite was 4 to 5 times greater than that found for a catalyst exposed to subbituminous coal ash. The plugging occurred over a 1000 hour test period.

➢ Cold Side SCR Installation

- High-sodium lignite coal from the Center Mine Hagel A and B seam coal produces significant levels of homogeneously condensed sodium sulfate that pass through the ESP and wet scrubber.

- These small particles have been shown to pass through a wet scrubber and will accumulate on surfaces of tail-end SCR systems. The accumulated materials require sootblowing to remove the particulate and will result in increased opacity.

- Liquid pyrosulfate materials at temperatures as low as 535°F from sodium sulfate materials occurs in coal-fired power systems and is well documented. Pyrosulfates will form and cause blinding of tail-end SCR devices. In addition, SCR systems are known to catalyze the formation of SO_3 from SO_2. The presence of SO_3 significantly enhances the formation of the pyrosulfates.

ASH IMPACTS ON SCR CATALYST PERFORMANCE

INTRODUCTION

Ash produced during combustion of coal in conventional power systems is a major problem that results in decreased efficiency, unscheduled outages, equipment failures, and increased cleaning. The many ways in which the detrimental effects of ash manifest themselves in a boiler system include fireside ash deposition on heat-transfer surfaces, corrosion and erosion of boiler parts, poor slag flow, and production of fine particulates that are difficult to collect. Decades of research have been conducted to develop a better understanding of the chemical and physical processes of ash formation and deposition in combustion systems. Overviews of ash-related issues and compilations of work by many investigators can be found by referring to the work of Mehta and Benson (1), Schobert (2), Baxter and DeSollar (3), Couch (4), Williamson and Wigley (5), Benson and others (6), Benson (7), Bryers and Vorres (8), Raask (9, 10), and Benson (11). This work has led to a detailed understanding of ash formation and behavior in combustion systems as well as the development of predictive methods (12, 13).

The chemical composition and physical characteristics of ash-forming or inorganic components (mineral and organically associated elements) of the fuel(s) fired have an influence on the following processes in the combustion systems:

- Firing conditions such as cyclone, pulverized coal, and low-NO_x burners
- Transformations of coal inorganic components to ash particulate and vapor-phase species
- Boiler design characteristics, including number of burners, radiant section area, tube bank spacing, access for cleaning, and number of sootblowers
- Ash transport to heat-transfer surfaces in utility boilers
- Erosion wear and sticking
- Ash deposit growth and impact on heat transfer
- Ash blinding and plugging of selective catalytic reduction (SCR) catalysts
- Ash deposit removability

The ash deposition in North Dakota lignite-fired power plants is a major problem that impacts all fireside surfaces of the power plant. The ash problems are due to the variable and complex nature of inorganic components associated with lignite coals (2). Upon combustion, the inorganic components undergo chemical and physical transformations that produce intermediate inorganic species in the form of inorganic gases, liquids, and solids. During the gas-cooling processes in the boiler, the gas-phase species condense and the liquid-phase materials solidify. The abundance of these gas-phase and liquid materials entrained in the bulk gas flow is highly dependent upon coal composition and system operating conditions. The inorganic materials are transported to heat-transfer and catalyst surfaces by diffusion, electrophoresis, thermophoresis,

and inertial impaction. The particle sticking and accumulation rates are dependent upon the quantity of ash and the abundance and viscosity of the liquid-phase components. In high-temperature regions of the boiler, high-temperature sodium–calcium–aluminosilicate liquid phases act as the sticky material, causing deposit initiation, growth, and development of deposit strength. As the temperature of the flue gases decreases, the condensation and reaction of flame-volatilized species play a more significant role in the formation of deposits from lignite coals. The formation of sodium and/or calcium magnesium sulfates dominates the deposit accumulation mechanisms at lower temperatures. The aluminosilicate phases are dominant above about 1800°F. Below about 1800°F, the sulfate phases become stable, with an optimum temperature of formation of about 1400°F, and can form at temperatures as low as 300°F.

The most significant problems that prohibit the successful operation of SCR catalysts to lignite coal is the formation of low-temperature sodium–calcium–magnesium sulfates and phosphates that will form on the surfaces of catalysts and the carryover of deposits that will plug the catalyst openings, resulting in increased pressure drop and decreased efficiency (14–16).

INORGANIC COMPOSITION OF LOW-RANK COALS

Inorganic elements in coal occur as discrete minerals, organically associated cations, and cations dissolved in pore water. The fraction of inorganic components that are organically associated varies with coal rank. Lower-ranked subbituminous and lignitic coals have high levels of oxygen, which act as bonding sites for cations such as sodium, magnesium, calcium, potassium, strontium, and barium (other minor and trace elements may also be present in this form). In higher-ranked coals, bituminous and anthracite, inorganic components consist mainly of minerals. Mineral grains are usually the most abundant inorganic component in coal. The major mineral groups found in coals include silicates, aluminosilicates, carbonates, sulfides, sulfates, phosphates, and some oxides.

The behavior of ash produced during coal combustion is related to the abundance, size, and association of mineral grains in the coal. In addition, the association of the mineral grain with the coal matrix influences the temperature and gaseous environment the mineral is exposed to during combustion. A mineral associated with the organic part of a coal particle is said to be included. A mineral that is not associated with organic material is referred to as excluded. The behavior of the organically associated elements, those elements that are atomically dispersed in the coal matrix, must also be measured as to their abundance in the coal. The organically associated elements will react and interact with the other ash-forming constituents during combustion.

The Center lignite is highly variable in abundance of various types of ash/slag-forming constituents. Ash-forming components in the Center lignite are of two types. The first form may constitute up to 50% of the ash and is derived from inorganic elements (sodium, magnesium, calcium, and potassium) associated with oxygen functional in the organic matrix of the coal. The second type consists of mineral grains (sand, clay, limestone, and pyrite). The minerals are discrete particles of ash-forming species and the sources of silicon, aluminum, iron, titanium, and minor amounts of the calcium and potassium. The Center lignite fired at the Milton R. Young (MRY) plant has been examined extensively because of its problem with ash behavior. Analyses

of as-fired and drill core samples have been conducted. The mean and the range of selected components are shown in Figure 1. The results indicate that both the abundance of ash and the abundance of major oxides in the ash vary significantly. In addition, the abundance of alkali and alkaline-earth elements (Na and Ca) varied dramatically. Variations in Si were found to be the most significant. High levels of Ca and/or Na were found for lower-ash coals as compared to high levels of Al and Si associated with higher-ash coals (17, 18).

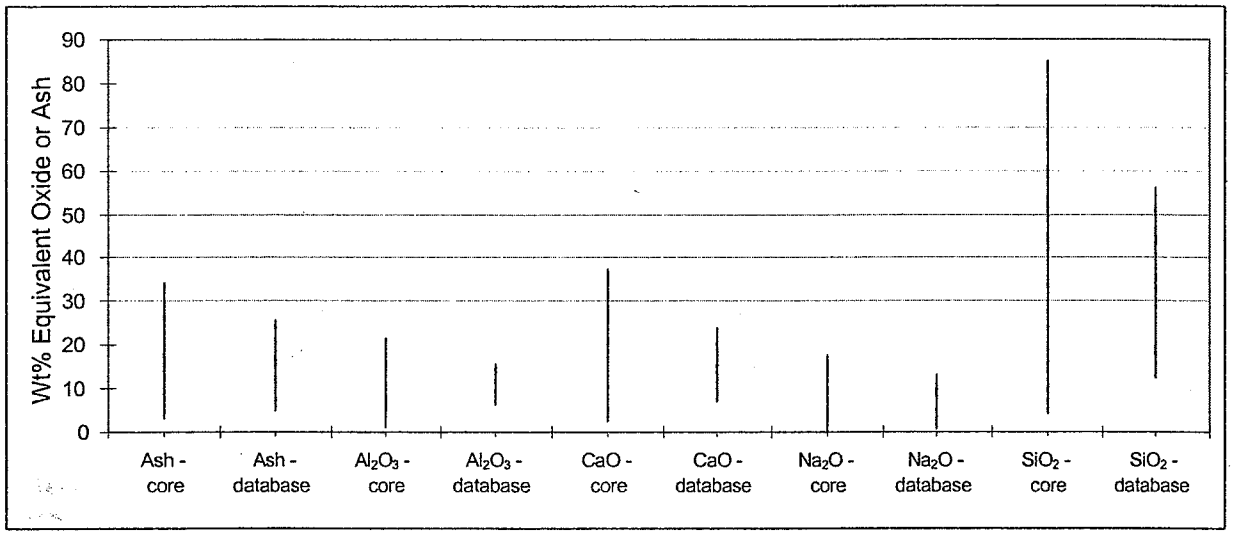

Figure 1. Variability of ash and selected constituents in core analysis database provided by BNI Coal, Ltd. and Minnkota as fired coal analysis database.

The variability of the ash-forming components has been examined for the approximately 5000 samples characterized to date. Wide variations in ash contents and the major ash-forming constituents are observed. During the mining processes, the inorganic components are mixed, and some of the extreme characteristics are diluted (17).

INORGANIC TRANSFORMATIONS AND ASH FORMATION

The inorganic coal components undergo complex chemical and physical transformations during combustion to produce intermediate ash species. The inorganic species consist of vapors, liquids, and solids. The partitioning of the inorganic components during combustion to form ash intermediates depends upon the association and chemical characteristics of the inorganic components, the physical characteristics of the coal particles, the physical characteristics of the coal minerals, and the combustion conditions.

The physical transformation of inorganic constituents depends on the inorganic composition of the coal and combustion conditions. The inorganic components can consist of organically associated cations, mineral grains that are included in coal particles, and excluded mineral grains. There is a wide range of combinations of mineral–mineral, mineral–coal,

mineral–cation–coal, and mineral–mineral–cation–coal associations in coal. These associations are unique to each coal sample.

The physical transformations involved in fly ash formation include 1) coalescence of individual mineral grains within a char particle, 2) shedding of the ash particles from the surface of the chars, 3) incomplete coalescence due to disintegration of the char, 4) convective transport of ash from the char surface during devolatilization, 5) fragmentation of the inorganic mineral particles, 6) formation of cenospheres, and 7) vaporization and subsequent condensation of the inorganic components upon gas cooling. As a result of these interactions, the ash has a bimodal size distribution. The submicron component is largely a result of the condensation of flame-volatilized inorganic components. The mass mean diameter of the larger particles is approximately 12 to 15 μm, depending upon the coal and combustion conditions. The larger-size particles have been called the residual ash by some investigators (19) because these ash particles resemble, to a limited degree, the original minerals in the coal. Processes such as ash mineral coalescence, partial coalescence, ash shedding, and char fragmentation during char combustion and mineral fragmentation, all play an important role in the size and composition of the final fly ash. Loehden and others (20) and Zygarlicke and others (21) indicate that three potential modes for fly ash generation can be used to describe fly ash particle-size and composition evolution. The first, "fine limit," assumes that each mineral grain forms a fly ash particle and that the organically associated elements form fly ash particles of less than 2 μm. The second, "total coalescence," assumes one fly ash particle forms per coal particle. The third, "partial coalescence," suggests that the fly ash composition and particle size evolve because of partial coalescence.

The transformations of excluded minerals are dependent upon the physical characteristics of the mineral. Excluded minerals such as quartz (SiO_2) can be carried through the combustion system with its angular structure still intact. Excluded clay minerals can fragment during dehydration, melt, and form cenospheres. The behavior of excluded pyrite depends upon its morphology. Some of the pyrite may be present as framboids. Framboidal pyrite may fragment more easily than massive pyrite particles. In addition, the decomposition of pyrite is very exothermic, and it transforms to pyrrhotite and oxidizes to FeO, Fe_3O_4, and Fe_2O_3 during combustion.

ASH DEPOSITION ON HEAT-TRANSFER AND OTHER SURFACES EXPOSED TO ASH AND FLUE GAS

The characteristics of a deposit depend upon the chemical and physical characteristics of the intermediate ash species, geometry of the system (gas flow patterns), gas temperature, gas composition, and gas velocity. Figure 2 illustrates the ash deposition phenomena in utility boilers. Ash particle accumulations occur via transport of particles to the fireside surfaces (heat transfer, ceramic materials, support materials, SCR catalysts, baghouse materials, and ESP wires and plates) and sticking of the particles. The transport mechanisms important for ash deposition include small-particle mechanisms for particles less than 10 μm that involve thermophoresis, electrophoresis, and vapor-phase and small-particle diffusion; and large-particle mechanisms for particles greater than 10 μm that involve inertial impaction. The ability of larger particles to stick depends upon the quantity and viscosity of the liquid phase on the particle surface.

Thermophoresis is a phenomenon that involves the transport of very small particles as a result of a thermal gradient from hot gases to cooler surfaces. Electrophoresis is the transport of particles because of a difference in charge. Vapor-phase and small-particle diffusion occurs in the boundary layer next to the surface and results in transport of ash to the surface. Inertial impaction is a larger-particle phenomenon where the particles are of a sufficient size and density to leave airflow patterns around the tube and impinge upon the surface of a tube or deposit. Deposits that form in high-temperature regions of the boiler, such as the radiant section, are called slag deposits. Deposits that form in lower-temperature regions of the boiler, such as in the convective pass on steam tubes and lower-temperature surfaces such as SCR catalysts, are called fouling deposits. Slag deposits are usually associated with a high level of liquid-phase components and are exposed to radiation from the flame. This is a description that many researchers use to aid in classification of deposits since some engineers call any type of deposit "slag". Slag deposits are typically dominated by silicate liquid phases, but may also contain moderate to high levels of reduced iron phases such as FeO and FeS. The liquid characteristics of the silicates are highly dependent upon the quantities of Na, Mg, Ca, K, and Fe ash on the silicates. In addition, the initiating layers of slag deposits may consist of very fine particulate and can produce a reflective ash layer. This phenomenon is especially evident when high organically associated calcium subbituminous coal is fired. These coals produce small CaO particles that usually form the initiating layers.

Fouling deposits form in the lower-temperature regions of the boilers and, in most cases, do not contain the high levels of liquid phases that are usually associated with slagging-type deposits. Fouling deposits contain lower levels of liquid phases as compared to slag deposits. The fouling deposit liquid phases usually consist mainly of sulfates that bind the particles together. Fouling deposits typically form as a result of the reaction of gas-phase sulfur oxide species with particles rich in alkali and alkaline-earth elements.

Alkaline Earth
barium strontium calcium

Alkali Metals
sodium potassium magnesium lithium rubidium cesium francium

ASH-RELATED EXPERIENCES AT MRY FACILITY

The MRY is a minemouth electrical generating plant located near Center, North Dakota. The station consists of two units: Unit 1, rated at 276 MWg, began production in 1970; Unit 2, rated at 506 MWg, began production in 1977. Both Units 1 and 2 are equipped with B&W cyclone-fired boilers; the Unit 1 boiler has seven cyclones, and the Unit 2 boiler has twelve cyclones. Annual station gross generation is approximately 5.5 million MWh.

BNI Coal Ltd. is the sole coal supplier for the MRY Station. Coal is mined from the nearby Center mine, which consists of three distinct seams varying from 2½–9 feet thick. Coal is strip-mined using two draglines and is loaded with front-end loaders and delivered to the plant with bottom-dump haul trucks. Annual coal production is 4.3 million tons per year.

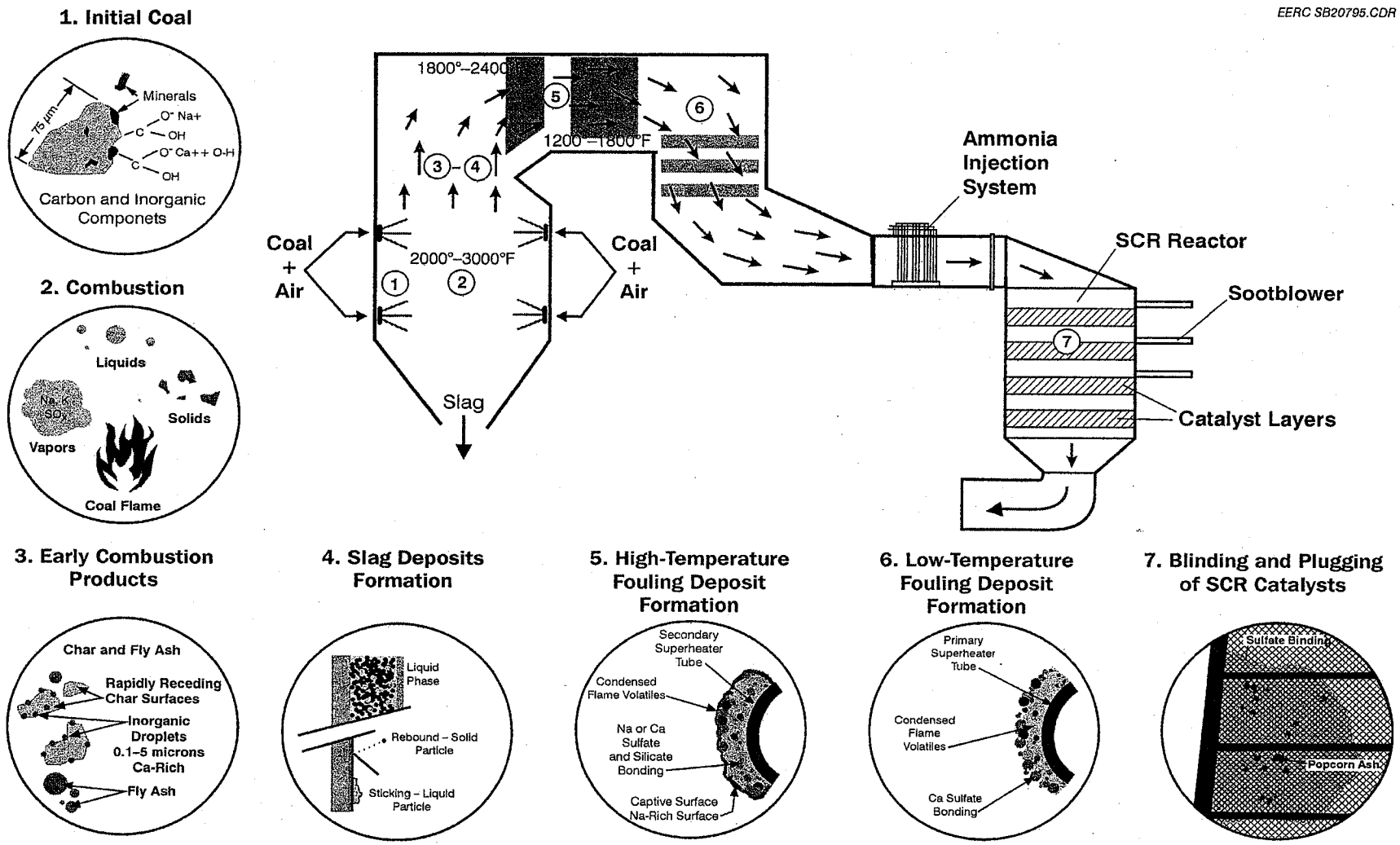

Figure 2. Overall processes of ash deposition typical of a lignite- or subbituminous-fired boiler.

History of Furnace Slagging/Fouling

Prior to 1991, besides annual maintenance outages, load reductions and forced outages due to furnace slagging/fouling were the largest cause of production loss. In 1985, operating guidelines were established that reduced furnace slagging/fouling, including deslagging outages scheduled every six months.

In 1991, a 3-month boiler cleaning cycle was proposed and initiated. The goal of this program was to increase annual generation by running the units at higher sustained loads and scheduling boiler-cleaning outages at 3-month intervals. However, furnace slagging/fouling continued to have a significant impact on plant operations. Success was measured in the number of production days between boiler-cleaning outages.

During the mid-1990s, a major outage every third year was scheduled for each unit. In addition, Unit 1 cleaning outages were scheduled for 80–90-day runs (four cleaning outages per year), and Unit 2 cleaning outages were scheduled for 65–75-day runs (five cleaning outages per year). The problem was that furnace and convection-pass surfaces gradually become coated with ash deposits, which, over time, sootblowers cannot remove. Some of the contributors to the ash deposits were as follows:

- Organically associated sodium is a primary contributor to deposition problems. Sodium is vaporized in the cyclones and condenses on other ash particles, causing them to become sticky and deposit at the furnace exit. The problem is associated with sulfate formation and occurs in the convective pass, including the economizer. Samples show that sodium in the ash varies from 0.6%–13.0%.

- Organically associated calcium is another component that causes deposition problems. Unlike sodium, calcium does not produce a vapor-phase component. Calcium does react with silicate (derived from clays) to cause low-melting-point phases that produce wall deposits and deposits in the high-temperature regions of the convective pass. Calcium also produces very small particles that will be transported to heat-transfer surfaces, resulting in the formation of thin, light-colored layers called reflective ash. These small particles of ash are carried through to the back passes where they are sulfated and can combine with sodium to cause the formation of strongly bonded sulfate-based deposits. Samples show that calcium in the ash varies from 6.8%–24.0%.

- Clay minerals and quartz – Center lignite can contain high levels of illite, which has a 1:3 Al:Si ratio and high levels of potassium, both of which cause wall slagging and high-temperature fouling. Quartz and other clays can significantly contribute to the mass of the deposits. Samples show that ash content varies from 5.0%–25.5%.

Advanced Boiler Performance Indices

Advanced indices are used to relate the coal characteristics as determined by computer-controlled scanning electron microscopy (CCSEM) and chemical fractionation to ash behavior in a coal-fired utility boiler (12). Fuel performance is estimated in terms of slag flow behavior,

abrasion and erosion wear, wall slagging, high-temperature silicate-based convective pass fouling, and low-temperature sulfate-based convective pass fouling. The following indices are used to assess the effects of ash behavior on utility boiler performance:

- Convective-Pass Fouling Indices

Sulfation Index: Indicates the propensity of deposit to form in the convective pass of the utility boiler in the temperature range from 1000°–1750°F. This index is based on the availability of alkali (Na and K) and alkaline-earth (Ca and Mg) elements to react with SO_2 and SO_3 to form sulfates. The sulfates are the primary materials that cause particle-to-particle bonding in high-calcium coals. The sulfates are thermodynamically stable at temperatures below about 1650°F. Index values range from 1 (low) to 10 (severe).

Silicate Index: Indicates the propensity of deposits to form from 1600°–2400°F. This index is related to the formation of deposits in which the silicate material is the primary component that bonds the deposits together. The information used to derive the index includes the size of the minerals such as quartz and clay minerals, availability of alkali and alkaline-earth elements, and viscosity of the silicate liquid phase. Index values range from 1 (low) to 200 (severe).

- Waterwall Slagging

Slagging Index: Indicates the propensity of a deposit to form on the radiant walls from 2000°–3000°F. The basis of the slagging index is the size of the minerals (especially the illite, quartz, and pyrite), association of the calcium (calcite can contribute to slagging), and viscosity of the silicate-based liquid phase. Index values range from 1 (low) to 20 (severe).

- Wear Indices

Abrasion Index: This index indicates the potential for wear of fuel preparation and handling equipment. The wear is related to the hardness of minerals in the coal. The primary minerals of concern include quartz and pyrite. The index values range from 0.1 (low) to 10 (severe).

Erosion Index: This index indicates the potential for wear of boiler parts due to the impaction of fly ash particles. The erosion index is dependent upon the size of the ash/mineral particle, size of the particle, and velocity of the particle. The index values range from 0.1 (low) to 1.0 (severe).

- Cyclone Slagging Index: This index provides information on the slag flow behavior in cyclones. The factors that are included in this index include the partitioning of the ash in the cyclone based on size and association of the ash-forming components in the coal. The partitioning of the ash between the slag and entrained ash can significantly influence the flow behavior of the slag. Standard partitioning criteria have been developed to provide the composition of the slag. The composition is used to estimate the viscosity of the slag as a function of temperature. The index values have several ranges as follows: 1 (low viscosity), 1.5–2.5 (optimum viscosity), >3.0 (slag freezing).

- Strength Development Index: The strength index is based on the ability of the deposited material to develop strength. Strength development is primarily dependent upon the abundance and viscosity of the liquid-phase components in the deposits. Index values less than 0.25 indicate that the material will produce weak deposits; index values of 0.25–0.34 indicate weak-to-moderate-strength deposits; index values of 0.34–0.41 indicate high-strength deposits; and index values >0.41 indicate flowing slag.

Indices were calculated for a range of coals from the Center mine, and the propensity for ash deposition in various portions of the boiler indicates wide variations, as shown in Table 1. The BNI numbers indicate the location in the seams where the coal originated: Kinneman Creek seam (KC), Hagel A (HA), and Hagel (HB). Each seam has a different distribution of minerals and organically associated elements that can have a significant impact on the formation of deposits in the system. Comparison of Center lignite to subbituminous and bituminous coals from other regions of the United States, shown in Table 2, indicates significant differences in the potential to form deposits in the boilers. In all cases, the lignite (not the worst coal from Center mine) from the Center mine has a high propensity to produce deposits as compared to the other coals.

Another indication of the variability of lignites can be illustrated based on the calculation of the temperature where the slag flow would occur. This is defined as the T250 temperature, where the slag viscosity is 250 poise. Frequency distributions of the T250 values for all the data for coals analyzed are illustrated in Figure 3. Calculations of T250 values for 1212 samples obtained from the Center mine database (17) were made using empirical relations derived from CCSEM and chemical fractionation data and knowledge of how ash partitions in the cyclone. Figure 3 shows a bimodal distribution in the T250 based on the Urbain equation calculations. The primary mode was at a value of 2000°F. The secondary mode was at about 2700°F. The results indicate that many of the coals have a sufficiently low T250 for good slag flow. However, coals with T250 at 2700°F are not suitable for maintaining good slag flow.

Figures 4 through 6 illustrate the variations in T250 for the various seams of coals characterized. The HA and HB seam coals appear to have large numbers of samples, with T250 values at or near 2000°F. The KC seam coal, as illustrated in Figure 6, has extremely high T250 values. Based on these data, the KC coals are not favored relative to the slag flow behavior of the ash.

Frequency distributions of cyclone slagging index values indicated significant variations in slagging potentials of coals mined from the three seams, KC, HA, and HB. This information proved particularly useful in planning the mining and firing of coal from the KC seam.

During a July 1999 test burn, the composition of the cores was used to examine and illustrate the variability of the delivered coal quality based on base-to-acid ratio calculated from the ash composition. Figure 7 shows the variation in the base-to-acid-ratio and the seam where the coal was loaded. The base-to-acid ratios were calculated from core data that corresponded to the location in the seam where the coal was mined. There is a significant variation in the base-to-acid ratio for the coals. The coals that have the highest base-to-acid ratio are typically from the HA seam. HB seam coals generally have an intermediate base-to-acid ratio. KC or top-seam coal has the lowest base-to-acid ratio. Lower base-to-acid-ratio coals typically produce slag with high viscosities.

Table 1. Characteristics and Indices Calculated for Selected Center Lignite Samples

BNI No.	41-132HB	41-44KC	41-144HA	41-144HB	41-168KC	41-168HA	41-168HB	41-180KC	41-180HA	41-180HB	41-192KC	41-192HA
Mineral wt%, mineral basis												
Total Quartz Content			18.8	9.8	30.3	8.7	8.8	11.4	20.0	3.9	15.0	17.4
Quartz <10 microns		10.8		6.4	24.6	4.4	4.0	6.8	3.3	2.6	9.7	12.7
Total Kaolinite Content		10.6		10.8	7.7	6.4	1.7	9.5	4.4	2.4	14.3	28.0
Kaolinite Content <10 microns		5.1		6.3	4.5	2.6	0.9	4.8	1.1	0.9	10.2	20.8
Total Montmorillonite		10.7		2.7	6.5	1.7	6.1	7.0	2.3	2.4	7.6	5.1
Total Illite		14.1		9.3	6.6	0.2	28.0	19.1	10.2	1.6	6.8	1.9
Total Pyrite		8.0		26.7	18.9	67.1	19.7	9.1	10.9	57.2	22.6	32.3
Pyrite Content <10 microns		4.5		10.5	2.8	9.8	4.7	2.5	2.5	17.0	6.6	7.0
Gypsum Content		6.5		0.0	1.6	2.7	0.8	5.4	0.0	16.1	2.2	0.0
Proximate (wt% as received)												
Moisture		30.95		41.66	36.24	38.23	37.50	37.90	37.99	38.21	37.85	39.52
Volatile Matter		27.26		25.74	26.32	25.90	24.55	25.11	24.42	25.88	26.13	24.27
Fixed Carbon		26.56		27.97	28.18	29.65	30.37	27.94	29.53	31.54	29.15	30.30
Ash		10.30		4.63	9.26	6.22	7.58	9.05	8.1	4.37	6.88	5.91
Total Sulfur (% as received)		0.94		0.55	1.49	1.08	0.75	0.99	0.64	0.86	0.90	0.85
Btu/lb		6597		6593	6791	6957	6806	6584	6653	7194	6881	6835
% Ash (dry basis)	11.64	10.30		7.94	14.52	10.07	12.13	14.57	13.00	7.07	11.07	9.77
Ash Comp. (wt% equiv. Oxide)												
Na_2O		0.50		10.65	0.82	9.25	8.02	0.46	8.15	11.99	1.48	9.69
MgO		3.30		5.74	3.72	4.90	4.45	3.90	5.00	4.59	6.13	5.10
Al_2O_3		11.90		10.37	9.34	5.64	11.81	12.12	10.19	5.23	10.59	7.46
SiO_2		30.60		14.70	33.71	8.47	30.74	35.57	36.25	5.31	25.80	13.06
P_2O_5		0.20		0.06	0.15	0.42	0.25	0.07	0.26	0.23	0.25	0.24
SO_3		23.00		25.50	21.28	35.25	21.05	18.32	15.93	35.75	24.15	32.75
K_2O		1.20		0.96	0.47	0.62	1.52	1.03	1.22	0.47	0.55	0.60
CaO		16.80		21.00	15.31	18.94	12.10	17.15	14.87	15.43	20.01	18.98
TiO_2		1.30		0.39	0.72	0.29	0.40	0.51	0.29	0.16	0.48	0.28

Continued . .

MnO	0.20	0.03	0.07	0.05	0.04	0.10	0.07	0.04	0.07	0.12
Fe_2O_3	10.30	8.43	14.87	15.95	10.44	7.80	6.84	18.88	10.12	13.29
Cyclone Slagging Index	2.77	1.28	2.5	1.1	2.6	3.3	2.9	0.4	2.2	1.3
Silicate	10.71	102.43	29.47	108.33	109.93	16.29	176.22	137.49	14.19	149.54
Sulfate	9.43	3.57	2.2	5.01	3.46	1.75	3.98	4.4	2.21	3.24
Wall Slagging Index	1.18	11	2.67	10.68	9.27	1.79	8.83	12.63	2.2	10.53
Erosion Index	0.19	0.15	0.17	0.19	0.22	0.21	0.27	0.17	0.17	0.17
Abrasion Index	2.14	0.71	6.46	1.55	1.41	2.25	1.93	0.83	1.75	1.68
Strength Index	0.32	0.66	0.35	1.11	0.35	0.3	0.33	1.32	0.43	0.63

Table 2. Advanced Index Values for Other Coals (12)

Advanced Indices	Lignite North Dakota	Powder River Basin	Bituminous Illinois	Bituminous Appalachian
Cyclone Slagging Index	1.6	2.1	3.5	3.2
Convective Pass Fouling				
Silicate	61.8	23.99	10.36	14.21
Sulfate	4.09	2.88	0	0
Wall Slagging Index	9.28	1.85	1.53	1.66
Erosion Index	0.15	0.17	0.14	0.17
Abrasion Index	0.71	1.96	3.94	1.96

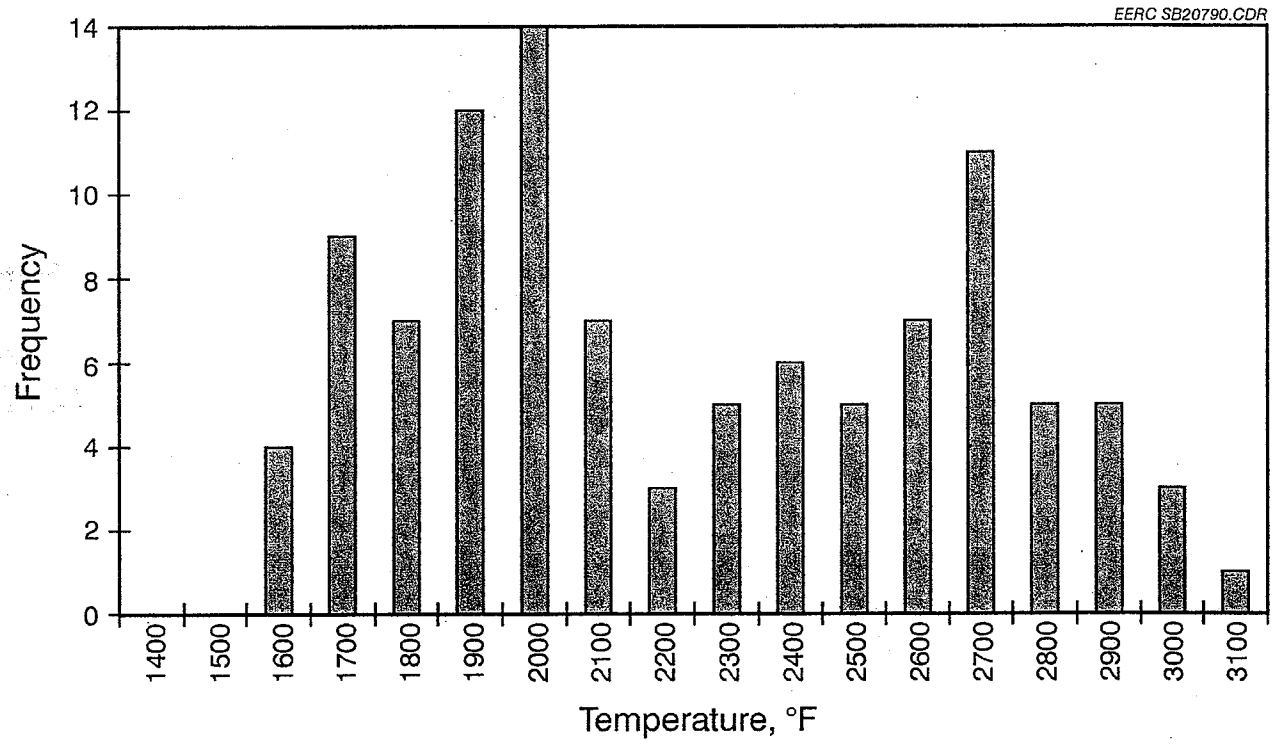

Figure 3. T_{250} frequency distribution for all Coal Quality Management System (CQMS) data, °F.

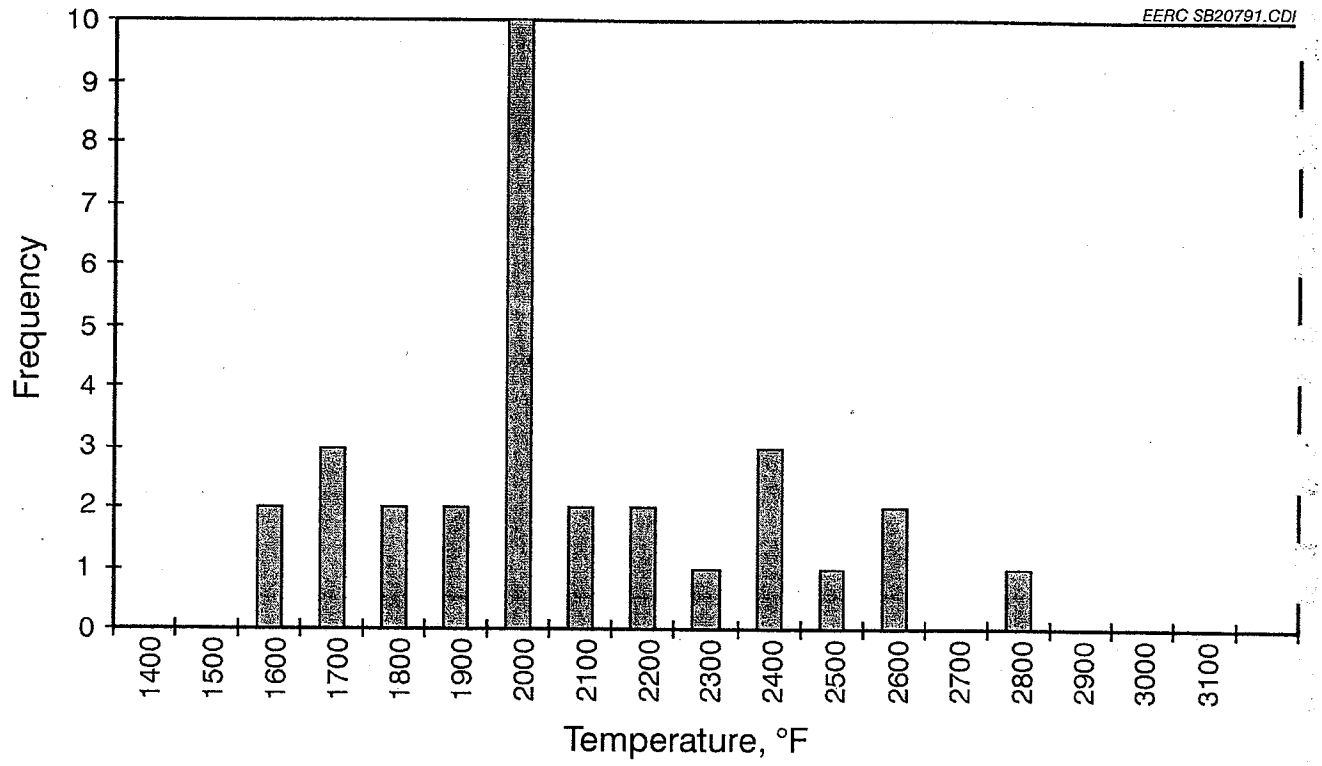

Figure 4. T_{250} distribution for HA seam coal.

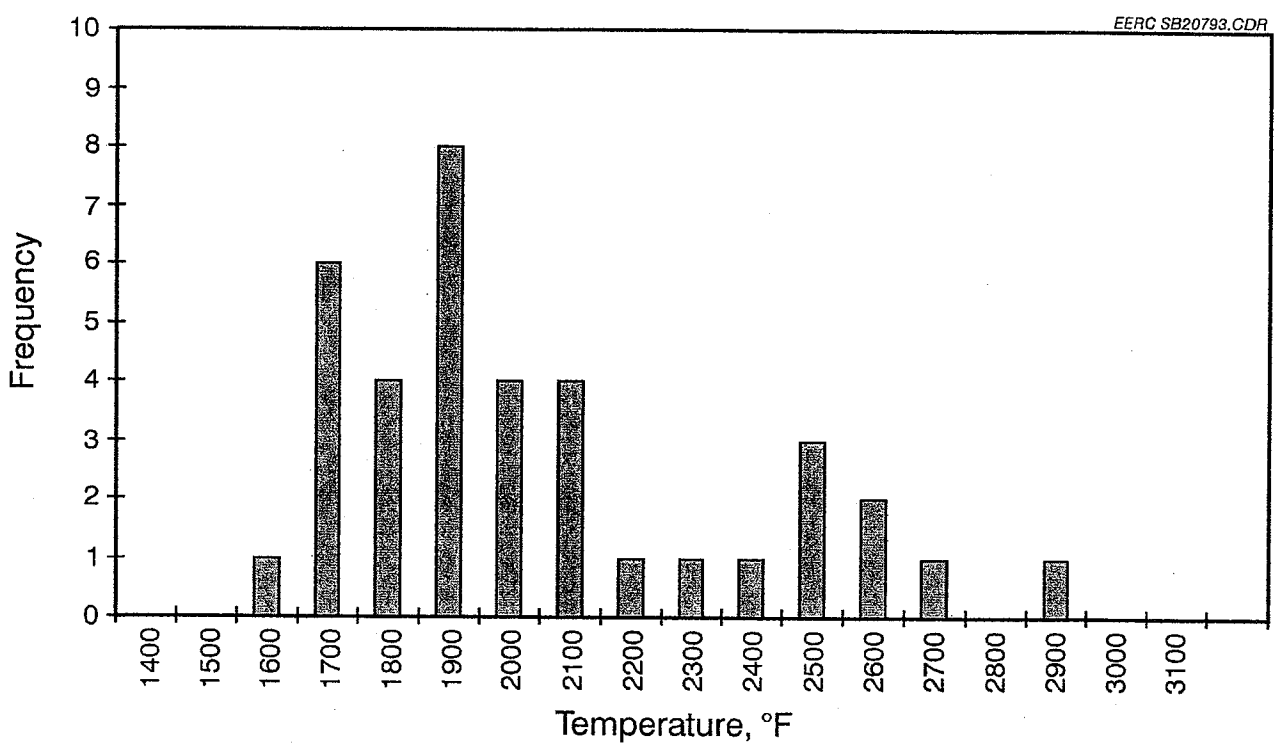

Figure 5. T_{250} distribution for HB seam coal.

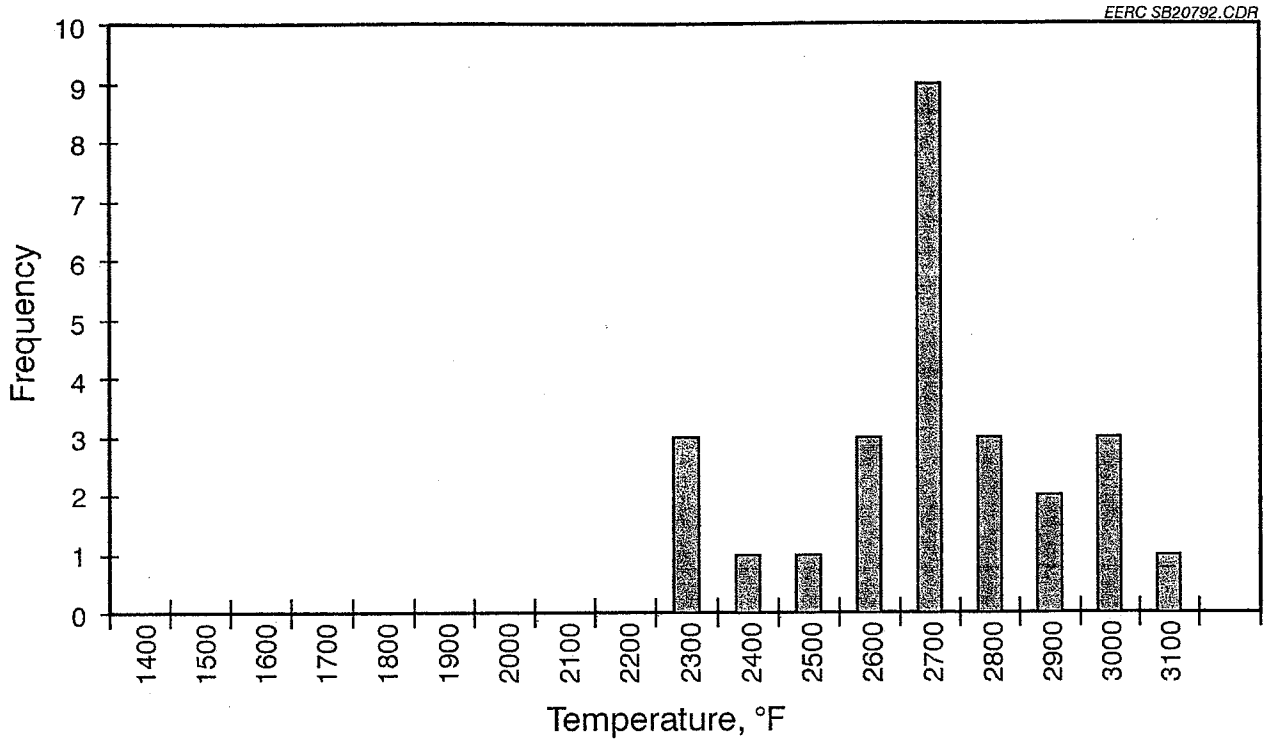

Figure 6. T_{250} distribution for KC seam coal.

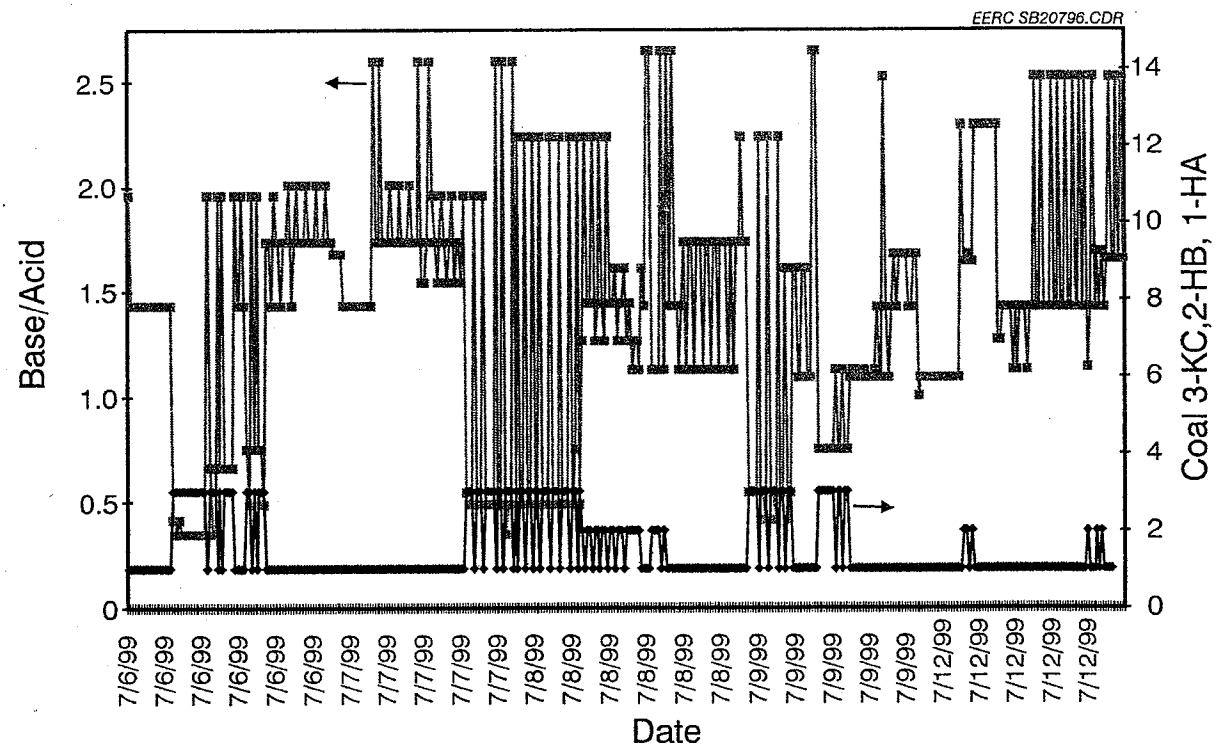

Figure 7. Variations in the delivered coal quality during a test burn period.

Figure 7 shows the sequence of deliveries beginning on July 6 and ending on July 12, 2004. During this period, the majority of the coal delivered was from the HA seam, followed by KC, and HB. Most of the deliveries alternated between KC and HA. Figure 6 shows several instances where significant quantities of KC coal were delivered, on July 6 through July 9. The quantity of KC coal delivered will have the potential to increase the viscosity of the slag and result in poor slag flow from the cyclones.

ASH-RELATED IMPACTS ON SCR CATALYST PERFORMANCE

Ash-related impacts on SCR catalyst performance will depend upon the composition of the coal, the type of firing systems, flue gas temperature, and catalyst design (14–16, 22). The problems currently being experienced on SCR catalysts include the following:

- Formation of sulfate- and phosphate-based blinding materials on the surface of catalysts.

- Carrying of deposit fragments, or popcorn ash, from other parts of the boiler and depositing on top of the SCR catalysts.

Licata and others (14) conducted tests on a South African and German Ruhr coal and found that the German Ruhr coal significantly increased the pressure drop across the catalyst because of the accumulation of ash. They found that the German coal produced a highly adhesive ash consisting of alkali (K and Na) sulfates. In addition, they reported that the alkali elements are in a water-soluble form and highly mobile and will migrate throughout the catalyst material, reducing active sites. The water-soluble form is typical of organically associated alkali elements in coals. The German Ruhr Valley coal has about 9.5% ash and 0.9 % S on an as-received basis, and the ash consists mainly of Si (38.9%), Al (23.2%), Fe (11.6%), and Ca (9.7%), with lower levels of K (1.85%) and Na (0.85%) (15). Cichanosicz and Muzio (16) summarized the experience in Japan and Germany and indicated that the alkali elements (K and Na) reduced the acidity of the catalyst sites for total alkali content (K+Na+Ca+Mg) of 8%–15% of the ash in European power plants. They also found that alkaline-earth elements such as calcium react with SO_3 on the catalyst, resulting in plugging of pores and a decrease in the ability of NH_3 to bond to catalyst sites. The levels of calcium in the coals that caused blinding ranged from 3%–5% of the ash.

The mechanisms for this type of low-temperature deposition have been examined and modeled in detail at the Energy & Environmental Research Center (EERC) in work termed Project Sodium and Project Calcium in the early 1990s; however, the focus of those projects was specific to primary superheater and economizer regions of boilers and not SCR systems (22, 23). Deposit buildup of this type can effectively blind or mask the catalyst, diminishing its reactivity for converting NO_2 to N_2 and water and potentially creating increased ammonia slip (14). Arsenic and phosphates, which are not uncommon in low-rank coals, may also play a role in catalyst degeneration. Arsenic is a known catalyst poison (14) in applications such as catalytic oxidation for pollution control. Phosphates can occur in low-temperature ash deposits to create blinding effects, and they also occur with arsenic and can cause catalyst poisoning (23).

Lignite and subbituminous coals produce ash that plugs and blinds catalysts (25–28). The problems currently experienced with SCR catalysts include the formation of sulfate- and phosphate-based blinding materials on the surface of catalysts and the carrying of deposit fragments, or popcorn ash, from other parts of the boiler and depositing them on top of the SCR catalysts (14). The most significant problem that limits the successful application of SCR catalysts to lignite coal is the formation of low-temperature sodium–calcium–magnesium sulfates, phosphates, and possibly carbonates that will form on the surfaces of catalysts and the carryover of deposits that will plug the catalyst openings, resulting in increased pressure drop and decreased efficiency (14–16, 27–28). The degree of the ash-related impacts on SCR catalyst performance depends upon the composition of the coal, the type of firing systems, flue gas temperature, and catalyst design (15–16, 24, 27–28).

In studies (7) the impacts of temperature and the presence of catalyst on the ability of ash to sulfate were examined. The tests were conducted using a thermogravimetric analyzer (TGA). TGA testing was conducted using a <5-μm-size fraction of ash produced from Powder River Basin (PRB) coals and lignites and exposing them to vapor-phase sulfur dioxide with and without catalyst at several temperatures. The aim of the testing was to determine the potential of the formation of sulfates to cause particle-to-particle bonding that leads to the formation of deposits in the temperature range where SCR catalysts are used. The TGA testing is focused on determining the reactivity of the <5-μm ash produced from selected PRB and blends to sulfur dioxide and gas-phase phosphorus species as a function of temperature. Testing was conducted to determine the weight gain with flue gas containing ammonia. The impact temperature on the weight gain due to the formation of sulfates for a PRB blend is shown in Figure 8. The rates of sulfation were found to increase with increased temperature. The results show an increase in the weight gains when ammonia and phosphorus were added. Ground catalyst was mixed with PRB and placed in the TGA. Increases in weight gain were observed when catalyst was added as compared to baseline cases for 100% PRB, as shown in Figures 8 and 9, respectively. The presence of catalyst enhances the formation of sulfates.

Full-Scale Slipstream Testing

More recently (8), the behavior of ash and mercury in flue gas produced from the combustion of lignite and subbituminous coals from the United States of America in selective catalytic reduction (SCR) systems for nitrogen oxide removal has been examined. Typically, these coals contain ash-forming components that consist of inorganic elements (sodium, magnesium, calcium, and potassium) associated with the organic matrix and mineral grains (quartz, clays, carbonates, sulfates, and sulfides). Upon combustion, these coals produce ash that has an abundance of alkali and alkaline-earth-rich oxide particles (<5 μm) that are carried into the backpasses of the combustion system and react with flue gas to form sulfates and possibly carbonates. The forms of mercury in the flue gas produced from the lignite and subbituminous coals are dominated by the elemental form. Slipstream testing was conducted at two subbituminous-fired power plants and one lignite-fired power plant to determine the impacts of ash on SCR plugging, blinding, and mercury oxidation.

The SCR slipstream system consists of two primary components: the control room and the SCR reactor. The reactor section consists of a catalyst section, an ammonia injection system, and sampling ports for NO_x at the inlet and exit of the catalyst section. The control room houses a computer system that logs data and controls the gas flow rates, temperatures, pressure drop across the catalyst, and sootblowing cycles. The computer is programmed to maintain constant temperature of the catalyst, gas flow rates, sootblowing cycles, and ammonia injection. The computer is equipped with a modem that allows for downloading of data and modification of the operation of the reactor from a remote computer located at the EERC.

Flue gas is isokinetically extracted from the convective pass of the boiler upstream of the air heater. The temperature is typically about 790°F. The flue gases pass through a 4-inch pipe equipped with sampling, thermocouple, and pressure ports. Ammonia is injected into the piping upstream of the reactor section. The reactor consists of a steel housing that is approximately 8.5 inches square and 8 feet long. The reactor section has three components, including a flow straightener, a pulse section or sootblower, and a catalyst test section. A metal honeycomb is used as a flow straightener upstream of the catalyst section and is about 6 inches long. A purge section was installed ahead of the catalyst test section to remove accumulated dust and deposits. The catalyst test section is located downstream of the purge section. The entire catalyst section is insulated and equipped with strip heaters for temperature control. The catalyst test section is 3.28 ft (1 m) in length and houses three catalyst sections. Thermocouple and pressure taps are located in the purge sections for measurements before and after each section.

The induced-draft fan is used to extract approximately 400 acfm (200 scfm) of flue gas from the convective pass of the utility boiler to achieve an approach velocity of 5.2 m/s (17.0 ft/s). The gas velocity is similar to that found in full-scale applications. The total gas flow through the reactor represents a thermal load of approximately 300 kW.

The range of operating conditions for the reactor is listed below:

- X Gas temperature: ~700°–800°F
- X Gas flow rate: 400–500 acfm
- X Approach velocity range: 5.0–5.5 m/sec
- X Ammonia injection rate: 0.5:1 with NO_x level
- X Tempering air for fan: ~ 50–200 scfm
- X Catalyst dP: 0.5–1.0 inches water column
- X Fan sized for up to 30 inches water column

The catalyst installed at the Baldwin and Coyote Stations was the Haldor Topsoe catalyst. Topsoe's DNX-series of catalysts comprises SCR DENOX catalysts tailored to suit a comprehensive range of process requirements. DNX-series catalysts are based on a corrugated, fiber-reinforced titanium dioxide (TiO_2) carrier impregnated with the active components vanadium pentoxide (V_2O_5) and tungsten trioxide (WO_3). The catalyst is shaped to a monolithic structure with a large number of parallel channels. The unique catalyst design provides a highly porous structure with a large surface area and an ensuing large number of active sites. The pitch of the catalyst was approximately 6 mm.

The catalyst installed at the Columbia Station was a Babcock Hitachi plate-type catalyst. This catalyst is a TiO_2-based plate catalyst, developed and manufactured by Hitachi. The pitch of the catalyst was approximately 10 mm.

The coals produced ash that had significant accumulations of ash on the catalyst on both macroscopic and microscopic levels. On a macroscopic level, there were significant observable accumulations that plugged the entrance as well as the exit of the catalyst sections. On a microscopic level, the ash materials filled pores in the catalyst and, in many cases, completely masked the pores within 4 months of operation.

The deposits on the surfaces and within the pores of the catalyst consisted of mainly alkali and alkaline-earth element-rich phases that have been sulfated. The results of this testing found that the <5-μm ash rich in alkali and alkaline-earth elements is captured on the surface and within the catalyst pores. These materials react with SO_2/SO_3 in the flue gas, resulting in the formation of a continuous phase that blinds the catalyst. The ability of elemental mercury to be oxidized across the SCR catalyst was investigated at a North Dakota lignite-fired plant. These results showed no oxidation of mercury across the SCR catalyst.

The reactor was installed at the Baldwin Station and operated for a 6-month time period on the Haldor Topsoe catalyst. The information obtained from testing included pressure drop, sootblowing cycles, and reactor temperatures. Figure 10 show the pressure drop across the catalyst test periods from 0 to 2 months. During the first two months of operation, the pressure was about 0.5 inches of water; at the end of two months, the pressure drop was about 0.8 inches of water, indicating plugging had occurred. The air was pulsed a minimum of every 8 hours in an attempt to maintain cleanliness. The reactor was monitored on a daily basis, and adjustments in pulsing cycles were made in order to minimize deposit accumulation. However, for the first two months, the pressure drop steadily increased. There are several periods where the unit was taken off-line; during those times, the temperature of the catalyst was maintained. At 2-month intervals, a section of catalyst was removed and replaced with a new one.

For Months 2 through 4, the pressure drop was highly variable initially but was about 0.8 inches of water. From Months 4 through 6, the pressure drop was maintained between 0.6 and 0.8 inches of water. This is due to the installation of a fresh catalyst section and leaving two thirds of the catalysts in place that were partially plugged. The gas velocity in the single section of new, clean catalyst was high because of channeling, and the result of the high gas flow was less deposition and accumulation. Gas velocity has a significant impact on the potential for deposits to form. However, at high gas velocity, low NO_x conversion is likely.

The reactor was installed at the Columbia Station and operated for a 6-month period of time with the Babcock Hitachi catalyst. The information obtained from the testing included pressure drop information, sootblowing cycles, and reactor temperature. Figure 11 shows the test periods from 0 to 2 months. The pressure drop across the SCR upon installation was about 0.4 inches of water and increased to an average of about 0.5 inches of water, but ranged from less than 0.4 to greater than 0.8 inches of water. The pressure drop for Months 2 to 4 increased from about 0.5 to 0.7 inches of water because of accumulation of ash. After cleaning the reactor and replacing one catalyst section, the pressure drop was about 0.3 but increased to over

0.6 inches of water up to about 4100 hours. There was an outage at the plant, and aggressive pulsing of the reactor was conducted; the pressure drop was brought back down to 0.3 but rapidly increased to over 0.5 inches of water within 500 hours.

The same reactor that was installed at the Baldwin Station was moved and installed at the Coyote Station. In addition, the same Haldor Topsoe catalyst type was used in the reactor. The reactor was operated for a 6-month period of time. Figure 12 shows the test periods from 0 to 2 months. As this paper is being prepared, the reactor is still operating on-site. The pressure drop across the catalyst upon installation was about 0.4 inches of water. After only 750 hours, the pressure drop was 1.5 inches of water, indicating significant plugging and blinding. Very aggressive air pulsing was conducted, with little success in removing the deposits. The pressure drop for the catalyst was over two times greater than the pressure drop observed for the Baldwin Station utilizing the same reactor and same catalyst. At about 1700 hours, the reactor was cleaned, and a section of catalyst was removed for characterization. The pressure drop after cleaning was about 0.8 to 1.0 inches of water. The pressure drop did not increase as rapidly because of the higher velocities through the clean section of the catalyst.

The tops of the catalysts were photographed during inspection and sampling of the catalyst sections. Figure 13 shows the ash materials that accumulated on the catalyst inlet after 2 months of operation. The most significant accumulation was noted for the Coyote Station, followed by Columbia and Baldwin. The Coyote Station had some larger pieces of ash deposit material on the surface as well as plugging of the catalyst passages. The Baldwin Station showed some obvious deposition along the walls of the reactor and some accumulation on the inlet sections. The Columbia Station showed more significant accumulation and plugging than the Baldwin Station.

After 4 months, the tops of the catalysts were photographed during inspection and sampling of the catalyst sections, as shown in Figure 14. The most significant accumulation was noted for the Coyote Station and some accumulation for the Baldwin Station.

SCR Ash Deposit Characterization

The characteristics of the ash materials that collected on the catalyst surfaces and pores were characterized by SEM and x-ray microanalysis and, in selected cases, XRD was used to determine the crystalline phases present. The catalysts were sampled after 2, 4, and 6 months. The sections were sampled, and approximately 2.5-cm squares were mounted for SEM analysis on double-stick tape and in epoxy resin. The double-stick tape samples allowed for characterization of the external morphology of the particles and catalyst surface. The samples mounted in resin were cross-sectioned and polished, which allowed for more detailed and quantitative analysis of the bonding materials and materials that accumulated in the pores of the catalyst. Detailed information on all the samples can be found elsewhere (add FPT reference). Examples of two deposit and catalyst analysis are presented here.

The 6-month sample from the Baldwin Station showed extensive sulfation of the alkaline-earth elements present in the deposits. Figures 15a and 15b show regions of the catalyst where all the pores were blocked and a minimal amount of deposit on the surface of the catalyst. Figure

15c shows a higher-magnification view of the deposit that is filling the catalyst pore. The deposit consists of particles of fly ash bonded together by a matrix of calcium- and sulfur-rich material, likely in the form of calcium sulfate. The chemical compositions of selected points that indicate the presence of high levels of calcium and sulfur are listed in Table 3. There is much more extensive bonding of the materials with the sulfate matrix as compared to the 2-month sample. In addition, there are some regions of high levels of calcium, aluminum, and sulfur present. The calcium aluminum materials are likely derived from the calcium aluminum phosphate minerals found in the coal fired at this plant.

The 4-month sample from the Coyote Station showed particles adhering to the surface and filling pores in the catalyst. Figure 16 shows the 4-month sample from the Coyote Station. The catalyst showed particles adhering to the surface and completely filling and masking the pores in the catalyst. The external morphology of the catalyst surface shows the masking of the catalyst surface. Chemical compositions of selected points are shown in Table 4. The 4-month sample shows more sulfation than the two months of exposure samples. Figures 16b and 16c shows a higher-magnification view of the deposit that is filling the catalyst pore. The deposit consists of particles of fly ash bonded together by a matrix of sodium-, calcium-, and sulfur-rich material, likely in the form of calcium sulfate. Significant sodium was found in the deposits, as shown in Table 4. The sample shows significant evidence of sulfation after 4 months of exposure and was much more pronounced than the samples for the Baldwin and Columbia Stations that are fired on PRB coals. The presence of sodium enhances the bonding and sulfation of the particles to form a strongly bonded matrix (22).

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SCR Deposit Formation Mechanisms

The mechanism for the formation of deposits that blind SCR catalysts involves the transport of very small particles rich in alkali and alkaline-earth elements, the surface of the catalyst, and reactions with SO_2/SO_3 to form sulfates. The formation of SO_3 from SO_2 is catalyzed by the SCR; this, in turn, increases the reaction rate of SO_3 to form sulfates. In some cases, the alkali and alkaline-earth elements will also react with CO_2 to form carbonates. XRD analysis identified $CaSO_4$ as a major phase and $Ca_3Mg(SiO_4)_2$ and $CaCO_3$ as minor phases.

Lignite and subbituminous coals contain high levels of organically associated alkali and alkaline-earth elements including sodium, magnesium, calcium, and potassium, in addition to mineral phases. The primary minerals present in these coals include quartz, clay minerals, carbonates, sulfates, sulfides, and phosphorus-containing minerals (6).

During combustion, the inorganic components in the coal are partitioned into various size fractions based on the type of inorganic component, their association in the coal, and combustion system design and operating conditions. Significant research has been conducted on ash formation mechanisms and relationships to impacts on power plant performance (1–6, 9–13, 19–21, 29). During combustion, the inorganic components associated with western subbituminous and lignite coal typically are distributed into various size fractions of ash. The smaller size fractions of ash are dominated by partially sulfated alkali and alkaline-earth elements. These ash particles are largely derived from the organically associated cations in the coal. The larger size

fraction has higher levels of aluminum and silicon derived from the mineral fraction of the ash-forming component of the coal. Entrained ash was extracted from the Columbia Station at the point of the inlet to the SCR reactor and was aerodynamically classified and analyzed. The composition of the size fractions was compared to the chemical composition of the ash deposited on and in the catalyst, as shown in Figure 17. The comparison shows that the composition of the particle captured in the SCR catalyst is very similar to the <5-μm size fraction. The deposited material shows significantly more sulfation than the entrained-ash size fraction, indicating that the sulfation process occurs after the particles are deposited in the catalyst.

The mechanism of SCR catalyst blinding when firing lignite or subbituminous coals is shown in Figure 18 (30). The requirements for the formation of deposits that blind SCR catalyst include firing a coal that produces significant levels of <5-μm-sized particles. The particles are transported into the pores of the catalyst and subsequently react with SO_3 to form sulfates. The sulfate forms a matrix that bonds other ash particles. The SCR catalyzes the formation of SO_3 and thereby increases the rate of sulfation (24, 25). The sulfation of CaO increases the molar volume, resulting in the filling of the pore. For coals that have high sodium contents, formation of low-melting-point phases such as pyrosulfates is possible (31). Pyrosulfate materials can melt at temperatures as low as 535°F in coal-fired power systems.

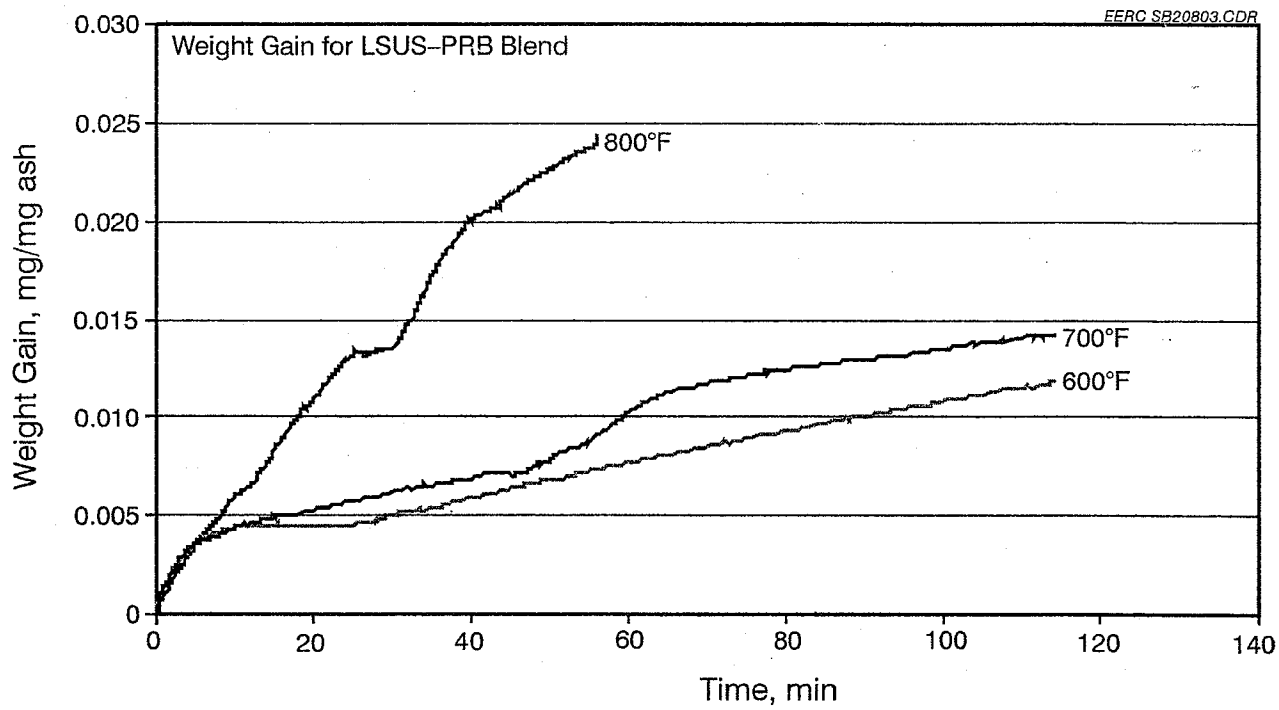

Figure 8. Weight changes for PRB-blend coal ash exposed to flue gases and ammonia at three temperatures.

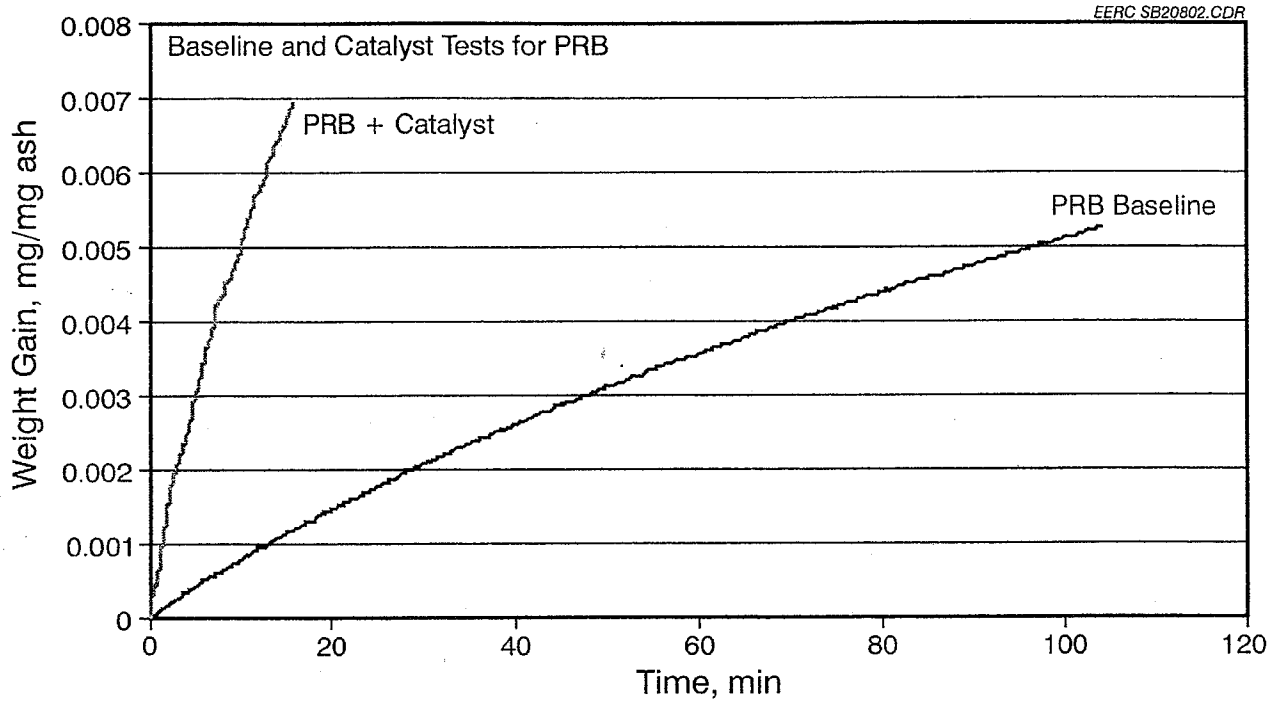

Figure 9. Weight changes for PRB-blend coal ash exposed to flue gases and ammonia with and without SCR catalyst present.

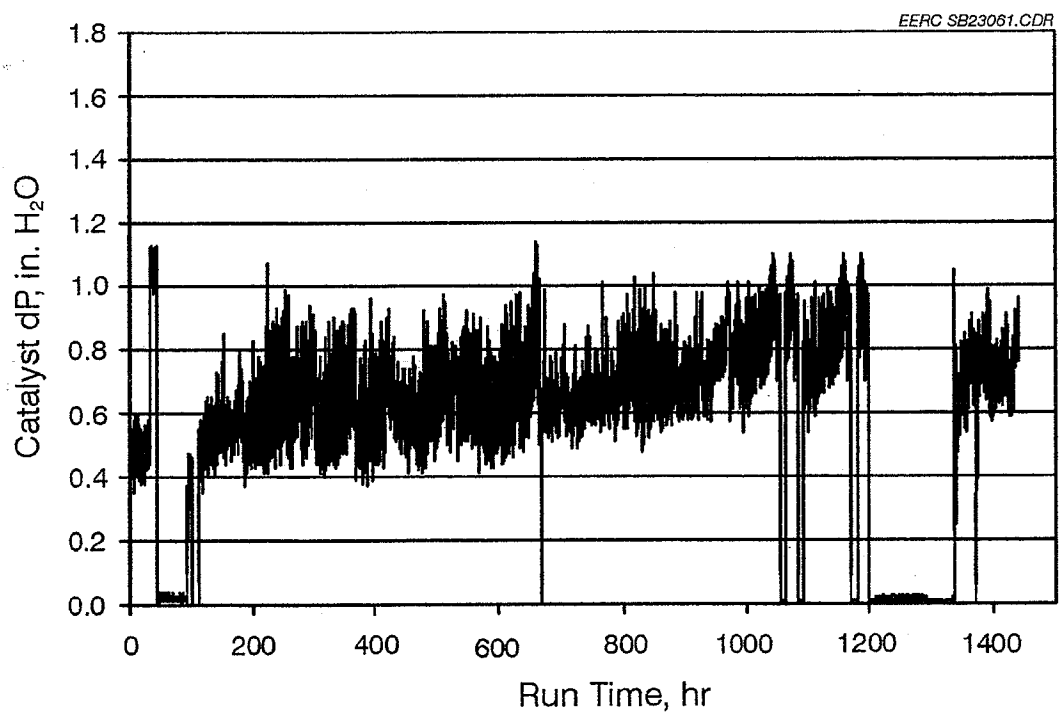

Figure 10. Catalyst pressure drop at Baldwin Station at 0 to 2 months of operation.

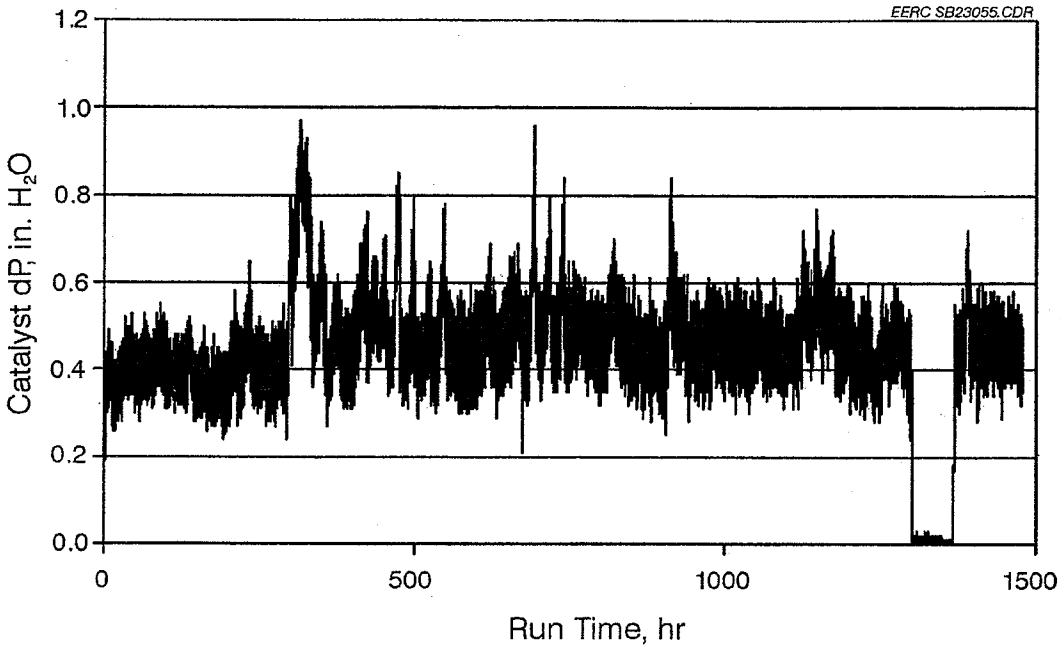

Figure 11. Catalyst pressure drop at Columbia Station at 0 to 2 months of operation.

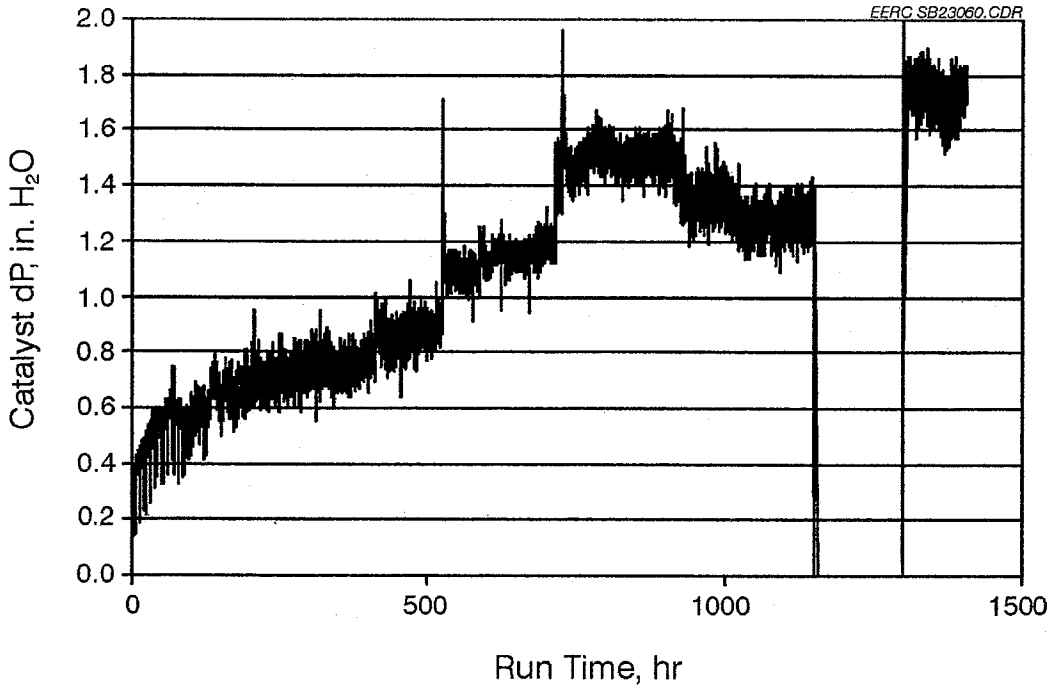

Figure 12. Catalyst pressure drop at Coyote Station at 0 to 2 months of operation.

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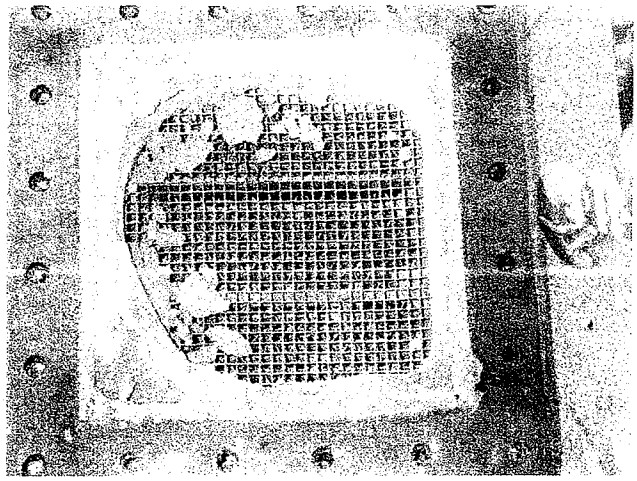
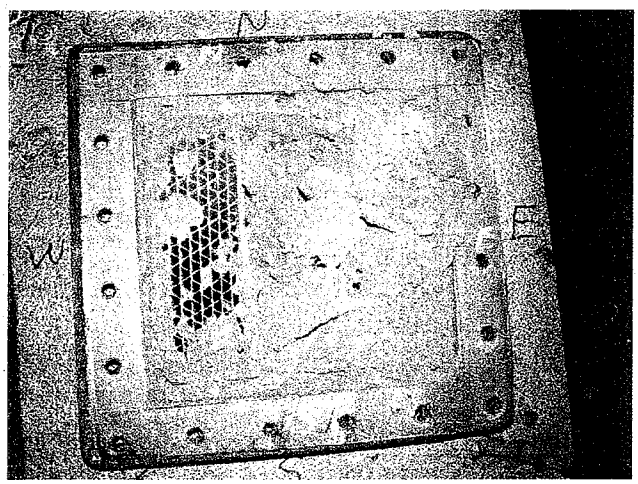
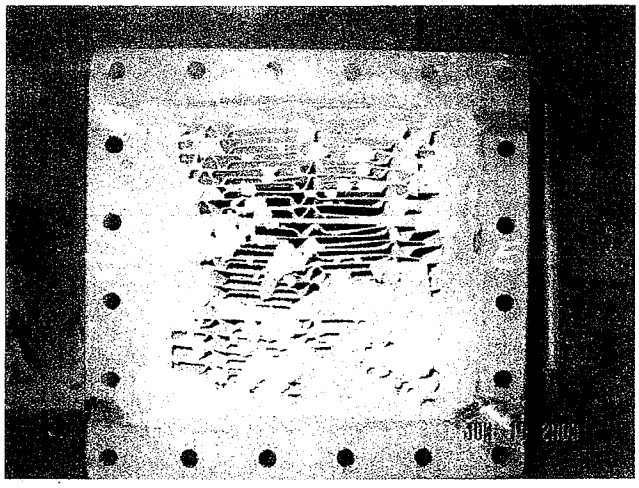


Baldwin Station after 2 months

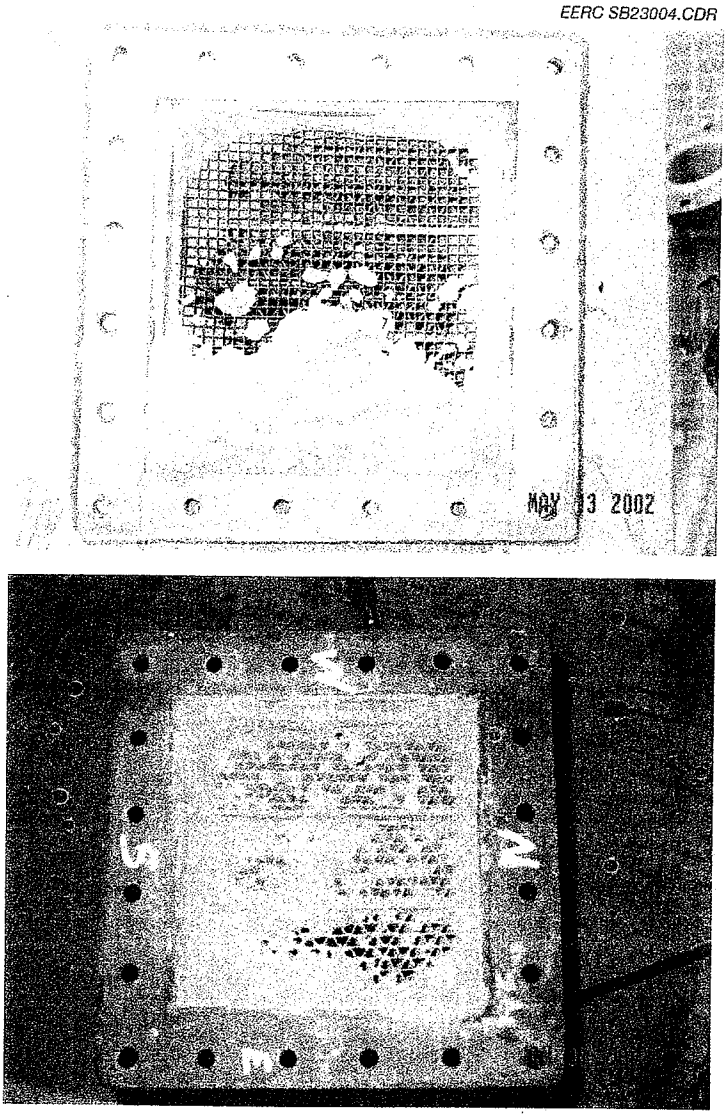


Coyote Station after 2 months



Columbia Station after 2 months

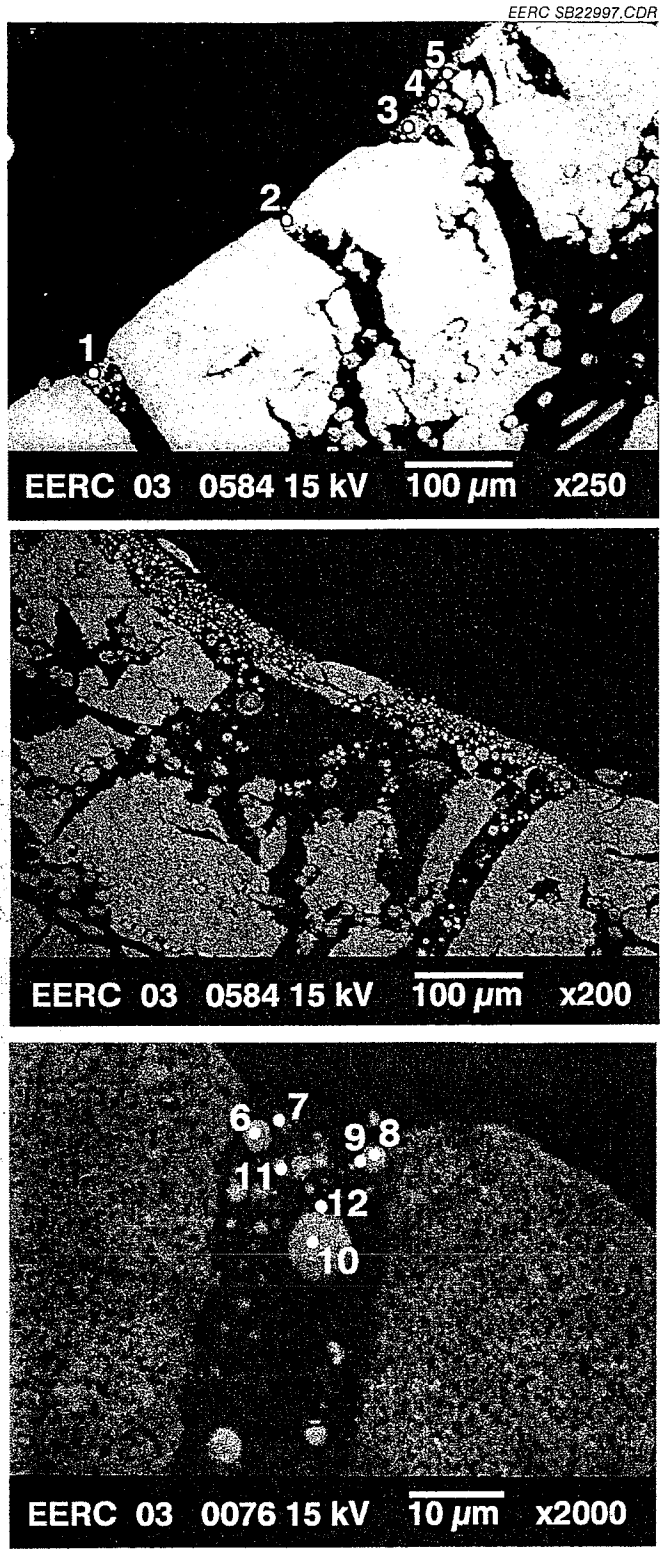
Figure 13. Pictures of catalyst inlet after about 2 months of testing at each plant.



Baldwin Station after 4 months

Coyote Station after 4 months

Figure 14. Pictures of catalyst inlet after about 4 months of exposure to flue gas and particulate.



A

B

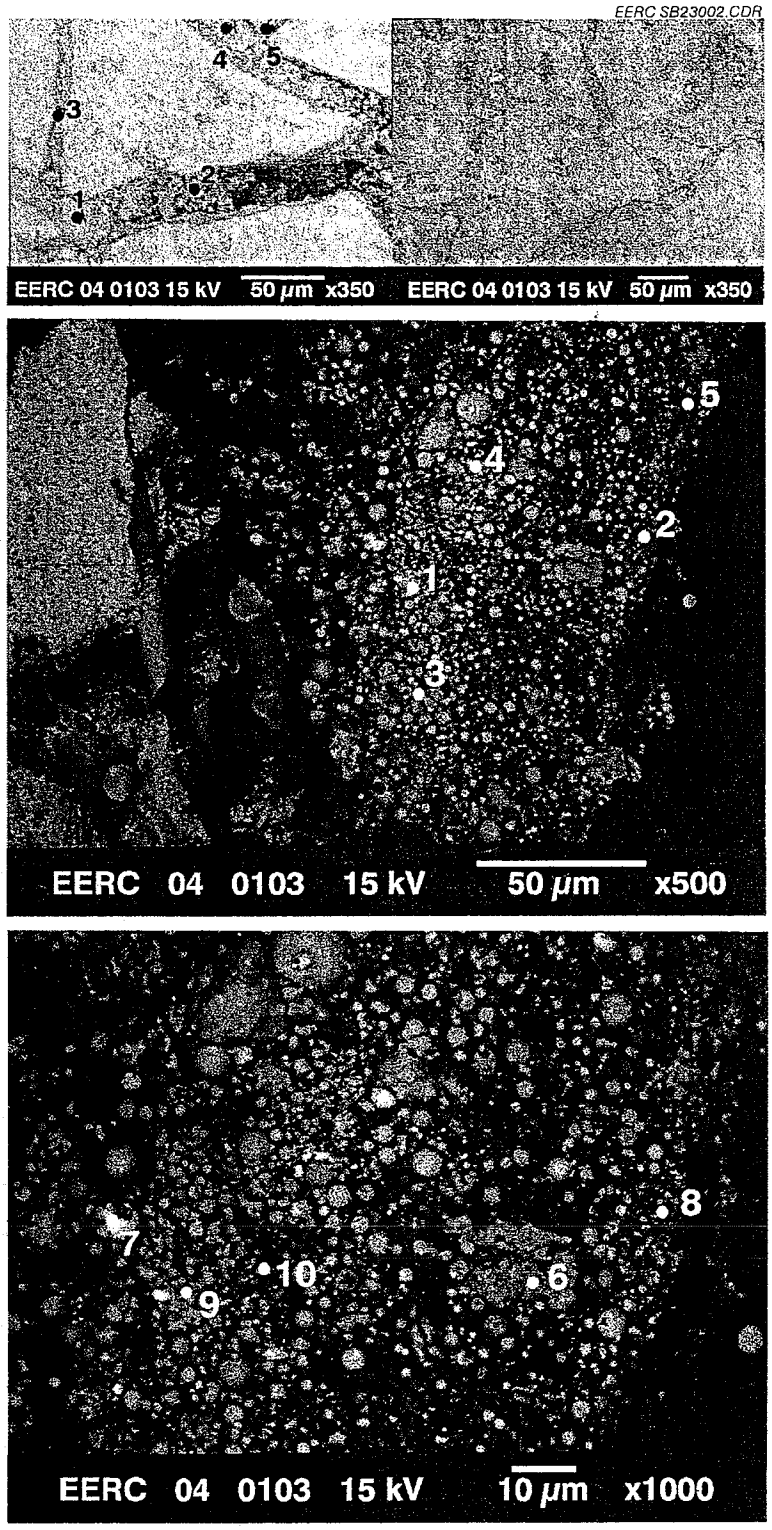
C

Figure 15. SEM images of ash collected on catalyst surface at the Baldwin Station after 6 months of exposure. A) and B) low-magnification images of ash deposit on catalyst surface

and C) high-magnification image of polished cross section showing particles in a matrix of calcium- and sulfur-rich materials.

Table 3. Chemical Composition of Selected Points and Areas in Figure 15

	Chemical composition (normalized wt% equivalent oxide)					
Oxide	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
1.1.1						
	0.6	1.0	2.1	0.3	0.5	2.7
Na_2O	4.3	2.5	6.3	0.7	1.6	7.6
MgO	14.8	16.0	15.6	15.5	14.7	0.9
Al_2O_3	3.3	7.8	18.8	57.7	7.7	47.3
SiO_2	2.3	2.1	0.5	0.6	1.8	0.0
P_2O_5	30.7	20.4	17.7	0.0	29.0	0.8
SO_3	0.7	0.0	1.0	0.4	0.9	0.9
K_2O	28.8	28.7	28.1	22.5	34.9	28.4
CaO	2.0	7.2	2.2	0.3	1.3	1.1
TiO_2	11.4	12.9	6.2	0.0	7.6	7.9
Fe_2O_3	1.1	1.4	1.4	2.0	0.0	2.5
BaO						
Total	100	100	100	100	100	100
Oxide	Point 7	Point 8	Point 9	Point 10	Point 11	Point 12
1.1.2						
	1.7	0.4	0.5	2.2	1.3	1.7
Na_2O	4.5	6.4	5.9	5.0	3.4	6.4
MgO	5.0	2.4	3.0	19.2	10.8	3.8
Al_2O_3	8.4	18.4	18.5	31.0	17.9	16.7
SiO_2	1.8	0.9	1.0	0.0	1.7	1.2
P_2O_5	37.9	1.7	5.3	0.0	22.5	13.9
SO_3	0.4	0.0	0.0	0.9	0.8	0.0
K_2O	31.4	52.6	49.0	28.9	30.6	45.4
CaO	1.9	6.9	7.4	2.4	2.0	1.1
TiO_2	7.1	5.7	6.0	6.3	6.1	6.5
Fe_2O_3	0.0	4.6	3.5	4.2	2.9	3.3
BaO						
Total	100	100	100	100	100	100



A

B

C

Figure 16. SEM images of ash collected on catalyst surface at the Coyote Station after 4 months of exposure. A) low-magnification image of ash deposit on catalyst surface, B) low-

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magnification image of polished cross section showing particles in a matrix of calcium- and sulfur-rich materials, and C) higher-magnification image of bonding.

1.1.2.1 Table 4. Chemical Composition of Selected Points and Areas in Figure 16

	Chemical composition (normalized wt% equivalent oxide)				
Oxide	Point 1	Point 2	Point 3	Point 4	Point 5
1.1.3					
	6.7	1.9	7.1	6.2	3.1
Na_2O	1.1	1.7	1.1	2.6	3.2
MgO	2.6	8.8	4.0	4.8	10.5
Al_2O_3	7.0	21.1	11.3	5.6	32.2
SiO_2	0.2	2.4	0.0	0.2	0.9
P_2O_5	54.7	38.5	56.4	57.5	30.4
SO_3	2.0	2.8	0.7	2.8	2.4
K_2O	18.0	3.4	15.8	9.3	2.3
CaO	0.6	0.8	1.1	1.3	1.5
TiO_2	5.8	5.1	2.1	6.5	9.8
Fe_2O_3	1.4	13.5	0.5	3.4	3.6
BaO					
Total	100	100	100	100	100
Oxide	Point 6	Point 7	Point 8	Point 9	Point 10
1.1.4					
	9.5	2.6	10.4	8.9	4.4
Na_2O	1.2	1.9	1.3	3.0	3.7
MgO	2.6	8.6	4.2	4.9	10.6
Al_2O_3	6.3	18.2	10.5	5.0	28.9
SiO_2	0.1	1.9	0.0	0.1	0.7
P_2O_5	41.8	28.4	44.9	44.5	23.4
SO_3	3.2	4.3	1.2	4.4	3.8
K_2O	24.5	4.4	22.5	12.8	3.1
CaO	0.6	0.8	1.3	1.5	1.8
TiO_2	7.7	6.6	2.9	8.9	13.2
Fe_2O_3	2.4	22.3	0.9	5.9	6.3
BaO					
Total	100	100	100	100	100

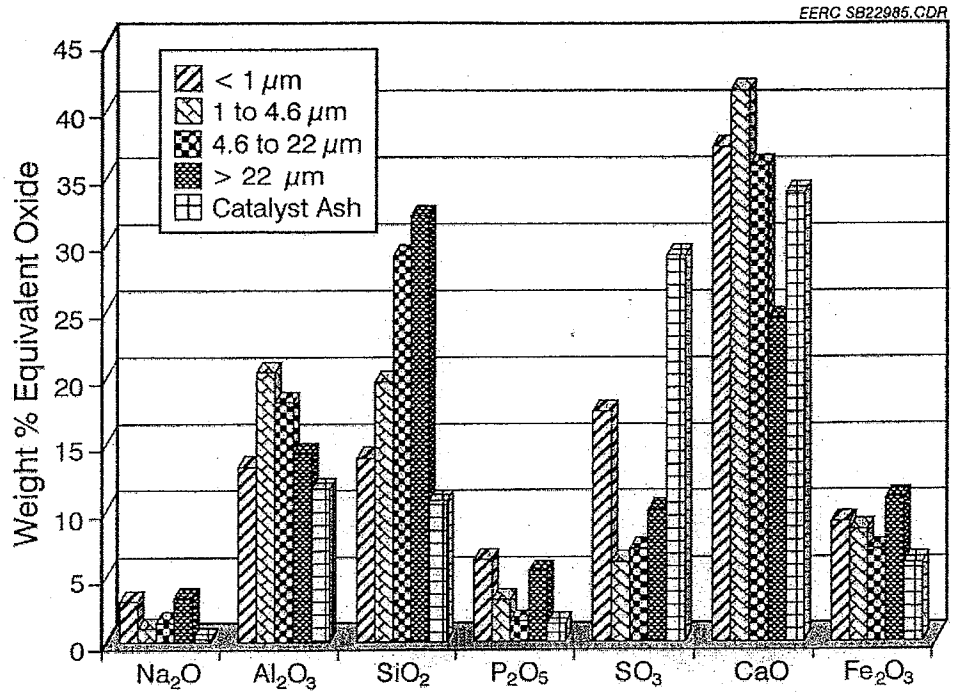

Figure 17. Comparison of entrained ash and deposited ash on catalyst for Columbia Station.

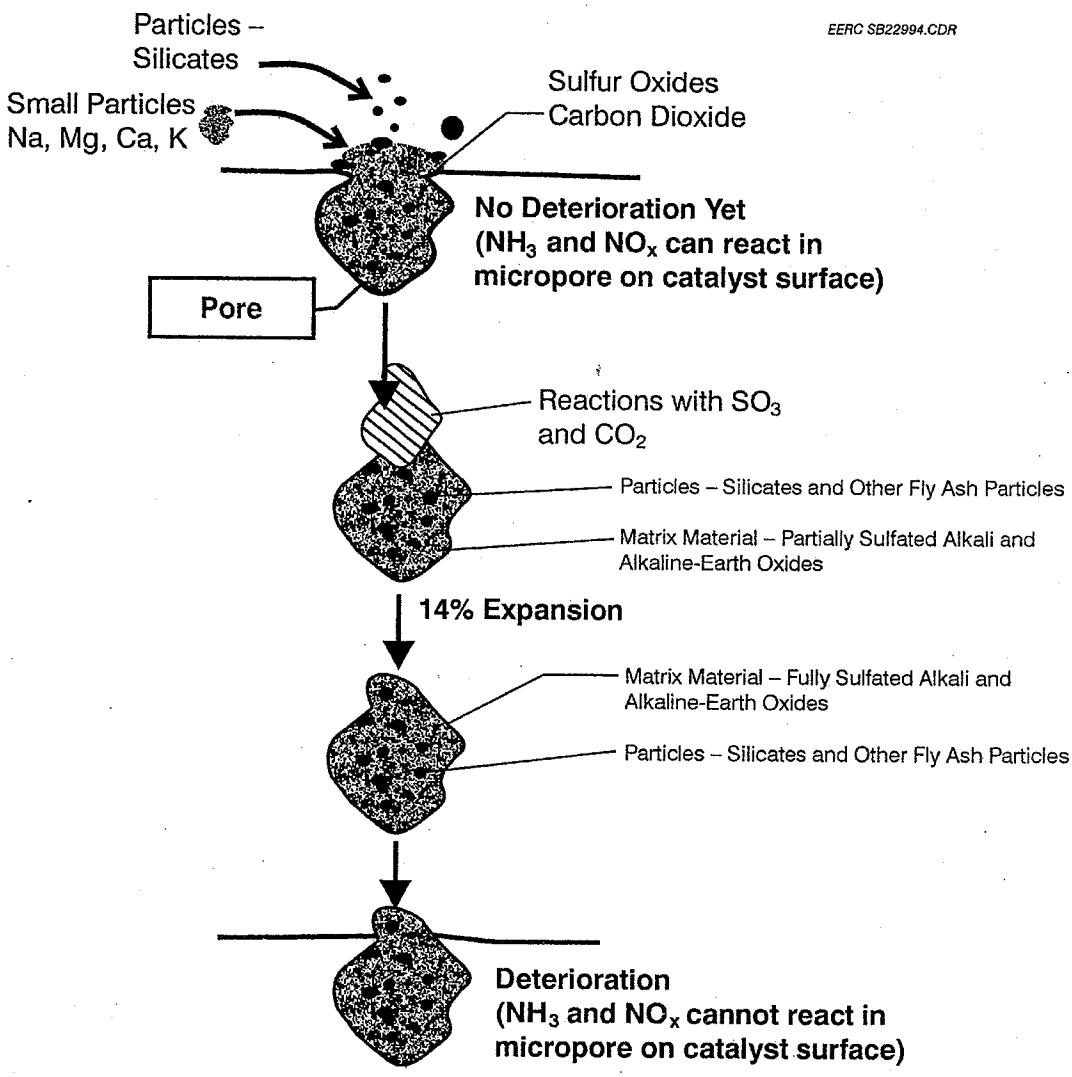

Figure 18. Mechanism of SCR catalyst blinding via the formation of sulfates and carbonates (modified after Pritchard and others [30]).

Low-Temperature Pyrosulfates

The presence of sodium sulfate in the flue gas exiting a scrubber will cause problems to low-dust and tail-end devices such as selective catalytic reduction (SCR) systems for NO_x reduction. There are two problems associated with the fine particulate rich in sodium sulfate on downstream devices. These include accumulation of fine particles on the SCR that, when sootblown, will cause opacity problems, and that the fine particles on the SCR will form pyrosulfates such as $(K_{1.5}Na_{0.5})S_2O_7$ that have melting points as low as 535°F (31) that will blind the catalyst. The presence of these compounds in low-temperature corrosion deposits is well known (32). In addition, the presence of SO_3 enhances the formation of the low-melting-point pyrosulfates (31). The sodium sulfate materials will cause opacity and SCR catalyst

blinding problems that limit the feasibility of the low-dust or tail-end SCR technology for use with high-sodium lignite coals.

The sodium sulfate materials will be transported to the catalyst surfaces by diffusion, electrophoresis, and, possibly, inertial impaction. The particles are held in place by weak electrostatic and van der Waals forces. Once accumulation takes place, the sodium sulfate particles will react with flue gas components, resulting in the formation of pyrosulfates. The formation of pyrosulfates involves the following processes (31):

1. Formation of sulfates such as Na_2SO_4 and K_2SO_4

2. Conversion of SO_2 to SO_3 in the bulk gas phase – catalytically active surface such as an SCR catalyst – $SO_2 + \frac{1}{2} O_2 \rightarrow SO_3$

3. Pyrosulfate formation – $Na_2SO_4 + SO_3 \rightarrow Na_2S_2O_7$

The melting points of selected pyrosulfate phases are shown in Table 5.

Table 5. Melting Points of Selected Pyrosulfate Compounds

Compound	Temperature, °C	Temperature, °F
$K_3Fe(SO_4)_3$	618	1144
$K_3Al(SO_4)_3$	654	1209
$KFe(SO_4)_2$	694	1281
$Na_3Fe(SO_4)_3$	624	1155
$Na_3Al(SO_4)_3$	646	1195
$NaFe(SO_4)_2$	690	1274
$Na_2S_2O_7$	401	754
$K_2S_2O_7$	300	572
$(K_{1.5}Na_{0.5})S_2O_7$	279	535

Melting points for pyrosulfates between 535° and 770°F have been reported in the literature. Much of the past work has focused on the formation of these phases on tube surfaces. These species contribute to the corrosion of heat-transfer surfaces in coal-fired power plants. The exact melting point depends on the relative amounts of sodium and/or potassium.

There is significant evidence for the formation of sodium-rich fine particulate in full-scale power plants when firing high-sodium-containing coals. For example, Minnesota Power's Boswell Energy Station found that when it fired high-sodium, lower-ash subbituminous coal, it experienced increases in opacity. Hurley and Katrinak (33) conducted a field-testing project on Unit No. 4, a pulverized coal-fired boiler equipped with an electrostatic precipitator and a wet scrubber, to better understand the reasons for the opacity problems. During the field testing, sampling of the coals, flue gases, and scrubber materials was conducted. The particulate in flue gases downstream of the scrubber was aerodynamically classified using an impactor and

multicyclone. The sized fractions were analyzed to determine the composition of the submicron-sized fraction.

The results of the study indicated that the particulate collected downstream of the scrubber was coal-related and caused by the high sodium content of one of the coals. Vapor-phase sodium condenses in the convective pass to form fine sodium sulfate particles or other Na species that later react with ash particles. Pure Na_2SO_4 particles are too small to be removed by scrubbing.

CONCLUSION: SCR IS NOT FEASIBLE FOR NO_X REDUCTION AT MILTON R. YOUNG

The ash deposition behavior of the lignites from North Dakota is the most complex and severe of any coals in the world, and installation of catalysts for NO_x reduction is going to be impossible because of the formation of sodium calcium sulfates in the pores of the catalyst. Following is a list of the key roadblocks associated with lignites which have not been overcome and, in our opinion, make the installation of SCR catalyst at the MRY plant technically infeasible for NO_x control.

- High alkali and alkaline-earth elements present in the coal fired at the MRY plant form sulfates that blind the catalyst.
    - Cyclone-firing partitions the ash during combustion. As a result the level of sodium and calcium in the fly ash is enhanced and will increase the SCR catalyst blinding.
    - Sulfate reactions increase with increasing temperature, and the suggested temperature of installation at the MRY facility is higher than typical installations; therefore, sulfation problems are enhanced.
    - Sulfate formation is also enhanced by the presence of an SCR catalyst; this accelerates the sulfation reactions, causing blinding of the catalyst.
    - The high levels of sodium in the coals combined with calcium produces low-melting-point eutectic compounds that will melt on the surface.
    - Sulfates form on the surfaces of catalysts firing PRB coals. Lignites will be several orders of magnitude worse because of the higher levels of sodium.

- The ash components to impact SCR performance in Japan and Europe (14–16) include alkali and alkaline-earth elements that result in sulfate formation. The total calcium content and the sum of the calcium, magnesium, potassium, and sodium provide an indication of the problems that occur. For the coals fired at the MRY power plant, the CaO content ranges from 6.8%–19.99%, and the sum of the alkali and alkaline-earth elements range from 9.33%–29.87% of the ash. The levels of calcium in Center lignite are 2 to 4 times higher than the problematic coals in Japan and Europe.

- The finding or work conducted in Germany and Japan were confirmed by recent SCR catalyst slipstream testing that showed significant evidence of sodium and calcium-

rich sulfate formation that fill and plug the catalyst at both lignite (North Dakota)- and subbituminous-coal-fired power plants. The results of this recent testing showed that the presence of sodium significantly enhanced the formation of bonding of particles and more rapid sulfation, filling of pores, and rapid increase in pressure drop across the catalyst.

- Deposit carryover, or popcorn ash, plugging the top of the SCR catalyst with deposit fragments, is a significant problem because of the extremely high deposition potential of the coal. The formation of deposits in various parts of the boiler requires continuous sootblowing. The deposit fragments are likely going to be carried with the bulk gas flow to the SCR catalyst, resulting in plugging.

- The variability of the lignite is a problem of unique concern at MRY. The deposition potential of the coal is always changing rapidly, resulting in rapid growth and formation of deposits in various sections of the boiler. Aggressive sootblowing of all fireside surfaces is already required to maintain full-load operation. The sootblowing of upstream heat exchange equipment will cause deposit fragments to be carried back to the SCR catalyst, and during sootblowing of the SCR catalyst, the entrainment of deposit fragments along with the sootblowing media will result in significant erosion of the catalyst surfaces.

The ash-related impacts of the lignites from North Dakota are the most complex and severe of any coals in the world, and installation of tail-end SCR systems for NO_x reduction will not be possible. The key problems associated with lignites that have not been overcome and, in our opinion, make the installation of tail-end SCR systems at the MRY plant technically infeasible for NO_x control at MRY's Units 1 and 2 are listed below:

X High-sodium lignite coal from the Center Mine Hagel A and B seam coal produces extreme levels of homogeneously condensed sodium sulfate that pass through the wet scrubber. In addition, the cyclone-firing system captures much of the ash as slag, resulting in a decrease in ash that is available for providing condensation sites for vapor-phase sodium compounds upon gas cooling. This results in an increased homogeneous condensation of sodium sulfate.

X These small particles pass through a wet scrubber and will accumulate on surfaces of tail-end SCR systems. The accumulated materials cannot feasibly be resolved through conventional sootblowing and cleaning technologies to remove the particulate.

X Recent testing with subbituminous and lignitic coals indicated a significantly higher level of pore filling and plugging in the catalyst exposed to lignite ash as compare to subbituminous coal ash. The catalyst pores as well as the catalyst surface in the lignite tests were completely coated with a sodium calcium sulfate material, while only pore filling was found in the subbituminous coal testing. The pressure drop across the catalyst exhibited for lignite was 4 to 5 times greater than that found for a catalyst exposed to subbituminous coal ash. The plugging occurred over a 1000 hour test period.

The formation of liquid pyrosulfate materials at temperatures as low as 535°F from sodium sulfate materials occurs in coal-fired power systems and is well documented. Pyrosulfates will form and cause blinding of tail-end SCR devices. In addition, SCR systems catalyze the formation of SO_3 from SO_2. The presence of SO_3 significantly enhances the formation of the pyrosulfates at MRY to an extreme level that cannot be dealt with effectively using cleaning technologies that exist today.

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APPENDIX C

COST METHODOLOGY

CAPITAL COST ESTIMATE DETAILS FOR NO_X CONTROLS

O&M COST ESTIMATE DETAILS FOR NO_X CONTROLS

C.1 METHODOLOGY FOR ESTIMATED COSTS

The summary economic evaluations of each alternative are presented in the cost impact sections of the main report. Capital and O&M cost estimates for each alternative are presented individually. The Levelized Total Annual Cost (LTAC) for all the alternatives for control of a single pollutant (i.e. NO_X) from a single unit is then presented together with Unit Control Costs. The Levelized Total Annual Cost (LTAC) represents the levelized annual cost of procurement, construction and operation over a 20 year design life, again in current (2006) dollars. As a minimum, the design life for any alternative was taken to be that recommended by "The EPA Air Pollution Control Cost Manual", Sixth Edition, January 2002, EPA/452/B-02-001[i].

The LTAC is also used to calculate the average annual and incremental cost effectiveness of each alternative. The LTAC represents an annual payment in current day dollars sufficient to finance the project over its entire life.

In determining the LTAC a Capital Recovery Factor and an O&M Levelization Factor were calculated from the project economic conditions and then applied separately to the estimated capital and O&M costs. The equation used is shown below.

$$LACC / NPV = \left(\frac{i(1+i)^n}{(1+i)^n - 1} \right) = CRF$$

Where,
LACC = Levelized Annual Capital Cost
NPV = Net Present Value of the capital investments required.
i = discount rate
n = design life in years
CRF = Capital Recovery Factor

Therefore:

$$LACC = CRF \times NPV$$

For the economic conditions described in Table C.1-1 the Capital Recovery Factor was calculated to be 0.08718.

In determining the levelized annual O&M cost the estimated annual O&M cost, the inflation rate, the discount rate, and the equipment life are taken into account. The O&M Levelization Factor (OMLF) was calculated as follows.

$$LAOMC / A_1 = \left(\frac{1+i_d}{1+i_i} - 1\right)\left(\frac{i_d(1+i_d)^n}{(1+i_d)^n - 1}\right) = OMLF$$

Where,
A = Levelized Annual O&M Cost (LAOMC)
A_1 = Total annual O&M cost in current dollars
i_d = discount rate
i_i = inflation rate
n = design life in years

Therefore:

$$LAOMC = OMLF \times A_1$$

For the economic conditions described in Table C.1-1 the Operating and Maintenance Levelization Factor was calculated to be 1.24873.

The Levelized Total Annual Cost, or LTAC is the sum of the levelized capital cost and the levelized O&M cost. Therefore:

$$LTAC = LACC + LAOMC = (CRF \times P) + (OMLF \times A_1) = 0.08718 \times P + 1.24873 \times A_1$$

The differences between alternatives are also presented graphically in the form of a plot of the annual emissions reduction (tpy) versus the LTAC for each alternative. This form of plot graphically depicts the cost effectiveness or Unit Control Cost (in $/ton of pollutant reduction) of each alternative relative to all of the others. The cost effectiveness is also referred to as the Unit Control Cost and defined as the LTAC divided by the annual emissions reduction (ton/yr). The area on the plot indicated by the various data points represents the cost effectiveness envelope for the alternatives under consideration. A smooth line is drawn on this plot connecting the rightmost points (those with the lowest cost for a given level of emissions reduction). This line is referred to as the Dominant Control Curve (DCC). The DCC defines the right hand boundary of the envelope encompassing all of the alternatives considered. The DCC is used as a screening tool between considered alternatives. Those alternatives whose plotted position is above and/or to the left of the DCC are not as cost effective as those forming the line and thus can be eliminated from further analysis if desired.

In order to compare various pollutant control alternatives, the Unit Control Cost and the incremental Unit Control Cost of each alternative were also calculated and tabulated for comparison purposes. The Unit

Control Cost compares control technologies on a basis of dollars expended per ton of pollutant reduced ($/ton). This relationship is graphically depicted in the DCC chart.

To more accurately compare between alternatives with different costs and control efficiencies, the incremental cost effectiveness is also determined for those alternatives on the DCC. The incremental cost effectiveness is defined as the LTAC of a given control option minus the LTAC of an alternative, divided by the difference between the annual emissions reduction (tpy) of the given control option and the alternative being evaluated. The combination of these two economic analyses can be used as an argument for the elimination of control technologies with significantly greater marginal control costs than the given case. The equation used for the incremental cost effectiveness is shown below.

$$ICF = \frac{(LTAC_1 - LTAC_2)}{(AE_1 - AE_2)}$$

Where,

ICF = Incremental cost effectiveness ($/incremental ton removed)
$LTAC_1$ = Levelized Total Annual Cost of control alternative No. 1 ($/yr)
$LTAC_2$ = Levelized Total Annual Cost of control alternative No. 2 ($/yr)
AE_1 = Control option No. 1 Annual Emissions Reduction (ton/yr)
AE_2 = Control option No. 2 Annual Emissions Reduction (ton/yr)
(The higher cost, more effective control option is subscript 1 in this equation.)

The economic analyses presented in this report not only include the estimated capital and O&M costs for each alternative, but also the LTAC for economic comparison of the various alternatives. In addition, the Unit Control Cost or cost effectiveness is presented for each alternative. Finally, a comparison between alternatives, in the form of the marginal cost effectiveness, is presented in both numerical and graphical form. Thus a comprehensive comparison of the economic impacts of each alternative, as well as the differences in economic impact between alternatives is clearly presented.

Table C.1-1 – Economic Factors(1),(2)

Total Possible Operating Hours per Year	8,760
Amortization Life, Years	20
Cost of Money	6%
Property Taxes, Insurance, %	NA
Conversion Tax (in lieu of property tax)	NA
Amortization Rate for APC Capital Costs	6%
Interest During Construction (IDC)	6%
Discount Rate (used to calculate NPV)	6%
Construction Cost Escalation	3%
Non-Fuel O&M Escalation	2.5%
Fuel (coal and natural gas) Escalation	2.5%
Auxiliary Electric Power Cost, $/MW-hr	$35.00
Urea Cost, ($/ton delivered, 50% aqueous solution)	$380.00
Natural Gas ($/mmBtu)	$7.98

(1) - All financial percentages and unit auxiliary electric power cost were provided by MPC.
(2) - All costs are in 2006 dollars unless noted otherwise.

C.2 NOx CONTROLS - CAPITAL COST ESTIMATES

The capital costs to implement the various NO_X control technologies were largely estimated from unit output capital cost factors ($/kW) published in technical papers discussing those control technologies. In the cases of SNCR and FLGR, preliminary vendor budgetary cost information was obtained and used in place of, or to adjust, the published unit output cost factors. These cost estimates were considered to be study grade, which is + or – 30% accuracy, or better.

The limitations of these capital cost estimates developed from unit capital cost factors multiplied by unit output are:

- Scope basis uncertainty – inability to precisely determine what scope of supply, including such things as balance-of-plant (BOP) systems and equipment improvements were required, assumed, or accounted for when developing the unit cost factors. Some alternatives may have higher indirect or BOP capital costs than others. Similarly, the inclusion of general facilities, preproduction and inventory costs, and other indirect costs is not known. It is likely that the utility owner's final total expenditure for the implementation of the alternatives, especially options that are most capital cost-intensive, will be greater than the calculated cost estimates.
- Location-specific influences – most NO_X control techniques have been applied primarily to eastern bituminous coal-fired plants located near large metropolitan areas, not in largely rural, upper midwestern United States locales. The amount of space available is dependent on the existing powerplant equipment and building layout and property plot area, versus what is expected to be required for implementing various control technologies. Transportation and local/regional labor costs are also variables.
- Size influences – some technologies' capital costs are more sensitive to "economies of scale" than others.
- Capacity margins – some technologies' may require higher capacity margins to allow sustained operation at high throughput rates over extended periods of time.
- Reliability concerns – some technologies' have been refined to a higher degree, and others may require more component redundancy than others in order to avoid performance reductions and potential outages for failures and repairs or replacements.
- Inflationary influences – the significant increases in 2004-2005 for raw material costs, especially steel and alloys for fabrication of structural and mechanical components, has occurred after many of these technologies were installed in projects upon which the referenced unit capital cost factors were based.

- Market conditions – as demand increases for emission controls, some alternatives become more cost-competitive, while others do not. This can be influenced by the relative supply and demand for the technology and number of suppliers who can furnish it. The demand for some alternatives can also be strongly influenced by the stringency of the local, state, and national regulatory requirements. Schedule for implementation and availability of local/regional labor for installation contractors are also market-driven factors.

The estimated NO_X control costs are in addition to capital costs to provide normal replacements of the existing Milton R. Young Station's major power generating equipment.

C.2.1 Separated Overfire Air Capital Cost Estimates

Installation of separated overfire air systems typically includes windbox and/or secondary combustion air supply duct modifications, boiler waterwall tube openings, airflow distribution devices (dampers/registers), airflow controls and measurement instrumentation, and related structural and electrical tie-ins to the existing plant facilities. A basic separated overfire air retrofit system installed on a lignite-fired cyclone boiler includes ports across the front and rear walls of the upper furnace. The unit capital cost factor is expected to be above the high end of the typical published cost range of $5-10/kW[ii] ($11.5/kW or $5.500,000[3] for MRYS Unit 2), due to the large ducts, relatively tall furnace (compared to typical bituminous coal-fired cyclone boilers), and the need to avoid existing obstructions within the boiler house.

An advanced form of SOFA unique to North Dakota lignite-fired boilers will include relocation of the existing lignite drying system vent port openings from the lower primary furnace to the upper furnace, to be placed at the same elevation as the new SOFA ports. This requires extension of the existing cyclones' lignite drying systems' vent piping to supply the new boiler furnace ports. This retrofit will also close-off the existing FGR ports in the lower front and rear furnace walls of Unit 2, currently coinciding with the existing pre-dry vent ports. These FGR ports may be blocked, or relocated to the lower portion of the upper (secondary) furnace, across the front and rear walls. This is expected to cost in the area of +$9.5/kW or $4,500,000 for Unit 2's additional capital cost over and above the basic SOFA system. Overall, the advanced version of separated overfire air technology is estimated to have an installed capital cost of approximately $10.0 Million ($21.0/kW) for MRYS Unit 2.

C.2.2 Reburn Capital Cost Estimates

C.2.2.1 Coal Reburn Capital Cost Estimates

There is one alternative that includes a new coal reburn system. Capital cost estimates for coal reburn systems are highly dependent on the requirements for reburn fuel preparation and feeding to the boiler. For the purposes of this analysis, the application of a pulverized coal reburn system assumed the need to make extensive additions to the existing fuel preparation equipment in the existing plant facilities and feeding to new furnace injectors. At least two new fine-grind pulverizers, or MPS-89 standard pulverizers followed by dynamic classifiers are expected to supply the amount of finely ground reburn coal for this method.

Addition of new electrical loads for the pulverized coal preparation equipment to the existing plant facilities will be required. For the purposes of this preliminary study, it is assumed that additional plant auxiliary electrical power will be available for powering the new pulverizers/micro-mills and related new coal reburn equipment, but this has not been confirmed.

The existing crusher bays do not have floor space available to allow the new milling equipment for reburn fuel preparation to be located adjacent to the existing coal crushers. This will require a separate building or addition to the existing powerhouse to be built to provide sufficient space to enclose the new milling and coal silo/handling equipment. Separate modified pulverized coal-style burners or coal injectors will be installed through new openings in the upper furnace front and rear waterwalls at or above the elevation of the existing lignite drying system vent ports, along with new overfire air ports located at a higher elevation, above the reburn fuel injectors. This would have the capacity to supply approximately up to thirty percent of the total full load fuel heat input to the boiler through the coal reburn injectors. This coal reburn system design was not expected to change the existing cyclone silo/feeder arrangement, such that all cyclones would remain operational. To achieve maximum NO_X emission control, only the advanced form of SOFA for pulverized coal reburn was included. Confirmation of these concepts and cost estimates requires more detailed equipment design and plant layout than has been performed for the purposes of this BACT analysis.

The installed capital cost of pulverized coal reburn for the cyclone boilers at Milton R. Young Station used in this cost effectiveness analysis was estimated based upon a Clean Air Markets Division [CAMD] of the US EPA dollar per kilowatt unit capital cost factor for cyclones. The installed capital cost estimate of $40.65 Million for MRYS Unit 2's pulverized coal reburn alternative used in this cost effectiveness analysis was estimated based upon applying a 3.5% assumed inflation cost adjustment to the CAMD unit

capital cost factor for cyclones of $82.33/kW (x 1.035 = $85.2/kW) included in a WRAP (Western Regional Air Partnership) draft report[iv] published on their website, dated April 26, 2005. The cost to relocate the lignite drying system vent ports and FGR ports was added to the inflation-adjusted CAMD number ($85.2 + $9.5/kW = $94.7/kW), since coal reburn is expected to include separated overfire air but not the extra costs for the special improvements identified for air-staged lignite-firing in cyclone boilers. This increased the installed capital cost by $4.M for MRY Station Unit 2's coal reburn system to a total of $45,154,000. This does not include the additional particulate matter collection capacity considered necessary to limit the expected negative impact on opacity from this option.

To control particulate matter (PM) emissions that would be expected to increase from installation and operation of pulverized or micronized coal reburn, additional PM collection capacity will be required. A hybrid form of PM collection that supplements the existing electrostatic precipitator's performance, referred to as COHPAC (COmpact Hybrid PArticulate Collector). This was estimated in 2002 dollars at $30,200,000 for MRYS Unit 2's COHPAC[3]. Adjusted by an escalation factor of 1.2623, the installed capital cost of the COHPAC addition was estimated to be $36,013,000 for MRYS Unit 2 in 2006 dollars. When the COHPAC addition was combined with the Lignite Reburn and ASOFA alternatives, the resulting total estimated capital costs were $81,167,000 for MRYS Unit 2 ($94.7 + $75.5 = $170.2/kW).

C.2.2.1 Gas Reburn Capital Cost Estimates

Conventional gas reburn options assume that seventeen percent of the total fuel heat input to the boiler is through the new gas reburn injectors to be located in the lower secondary furnace above the top rows of cyclones. Eight to twelve gas reburn injectors would be expected to be required in this case. Seven percent of the total fuel heat input to the boiler through the gas reburn injectors is assumed to be supplied for the fuel lean gas reburn alternatives. Four to eight gas reburn injectors could be assumed in FLGR™ cases. Gas reburn options assume that a new high-pressure gas pipeline would be brought from near Bismarck, ND approximately twenty six miles. The pipeline diameter is proportional to the amount of fuel required for the specific alternative, ranging from 24 inches for conventional gas reburn to 12 inches for fuel lean gas reburn cases. A station gas main, with new gas trains, consisting of valves, metering, and safety shutoff valves for the front and rear boiler for the gas injectors' supply, would be furnished and installed.

The capital costs for conventional gas reburn alternatives were estimated considering unit capital costs published in published technical literature. One vendor that has supplied numerous domestic utility boiler

gas reburn systems (GE Energy, formerly GE-EER) published $10/kW for gas reburn in a 2001 technical paper[v]. Another source published a 2005 technical paper[vi] that provided a unit capital cost range for gas reburn of $15/kW to $30/kW. Neither source included a detailed scope description nor cost breakdown for engineering, equipment, materials, and labor to install a gas reburn system.

Site-specific needs and challenges identified for applying conventional gas reburn to Milton R. Young Station, and lack of detailed gas reburn project scope and equipment descriptions available in published technical literature leads to a much greater degree of uncertainty with regards to an accurate capital cost estimate for this alternative. For the purposes of this study, the estimated installed capital cost for a conventional gas reburn system with advanced SOFA on MRYS Unit 2 is expected to be approximately $20.5M ($43/kW), which is above the top end of the previously stated range, before adding the new underground gas pipeline capital costs. This study assumed an average unit capacity capital cost factor of $22/kW for conventional gas reburn, plus the additional costs for the advanced form of SOFA over basic SOFA +$4.5M ($9.5/kW), and the new high-pressure gas pipeline. This results in a an estimated installed capital cost for conventional gas reburn system with advanced SOFA on MRYS Unit 2 of $20.5M ($43/kW) plus the new high-pressure gas pipeline costs. Confirmation of these concepts and cost estimates requires more detailed equipment design and plant layout than has been performed for the purposes of this BACT analysis.

Fuel lean gas reburn (without SOFA) capital cost estimates were based upon a late 2004 budgetary proposal[vii] by a vendor (Fuel Tech) with experience in supplying FLGR™ equipment, typically combined with an SNCR system. Estimated capital costs of $3M include budgetary numbers for the equipment installation, including installation management, material and labor, with a +6.0% price adjustment assumed for 477 vs 450 MW for a fuel lean gas reburn system without SOFA on MRY Unit 2, not including the capital cost for the gas supply pipeline. Costs for work outside the vendor's scope, such as balance-of-plant additions plus other indirect costs were estimated to add approximately $1.1M (25% plus 10% contingency) to the adjusted vendor's estimated installed cost of $3.2M for their scope of supply. These adjustments result in a total installed capital cost for FLGR (without SOFA) estimated to be $4.3M plus the capital cost for the gas supply pipeline. Adding the incremental costs for the advanced from of SOFA over no SOFA (+$10M ($21/kW) results in an estimated installed capital cost for a fuel gas reburn system with advanced SOFA on MRYS Unit 2 of $14.3M ($30.0/kW) plus the new high-pressure gas pipeline costs.

The capital cost estimates for the new high-pressure underground gas supply pipeline assumed $7 per inch of diameter per foot of length. This was calculated to be approximately $23M for conventional gas reburning and $11.5M for FLGR™. The cost analysis for each NO_X control alternative involving a particular form of gas reburn assumed that both boilers at Milton R. Young Station select the same alternative that burns natural gas. Therefore, the estimated capital costs for gas reburn alternatives reflect a capacity-based proportional share of the gas pipeline capital costs, avoiding double-counting. This results in an estimated installed capital cost for MRYS Unit 2's share of the gas pipeline to be $15M for the conventional gas reburn alternative and $7.5M for fuel-lean gas reburn alternatives.

The total installed capital costs for conventional gas reburn (with ASOFA) with MRYS Unit 2's share of the total capital cost for the gas supply pipeline estimated to be $35.5M ($74.4/kW). The total installed capital costs for FLGR™ (with ASOFA) with MRYS Unit 2's share of the total capital cost for the gas supply pipeline were estimated to be $21.8M ($45.7/kW). Confirmation of these concepts and cost estimates requires more detailed equipment design and plant layout than has been performed for the purposes of this BACT analysis.

C.2.3 SNCR Capital Cost Estimate

The alternatives that include selective non-catalytic reduction systems assume the use of urea unless noted otherwise. The SNCR systems' preliminary design and estimated capital costs were based upon a 450 MW lignite-fired cyclone boiler in a late 2004 budgetary proposal[7] by a vendor (Fuel Tech) with experience in supplying SNCR equipment. Circulation, metering, dilution, control, and injection equipment is included. A 180,000 gallon field-erected stainless steel storage tank will hold the 50% urea solution (as delivered by truck). Individual and multiple nozzle lances with multiple levels of urea reagent injection will be designed and located to optimize distribution and accommodate various boiler load conditions. Estimated capital costs of $4.9 Million include budgetary numbers for equipment installation, including installation management, material and labor assumed for a SNCR system applied to a 450 MW boiler. Costs for work outside the vendor's scope, such as outdoor reagent storage tank and building enclosure/equipment foundations and containment, and balance-of-plant additions plus other indirect costs were estimated to add approximately $1.9 Million (25% plus 10% contingency) to the vendor's estimated installed cost for their scope of supply. This results in an estimated total capital cost for SNCR (without SOFA) of $6.8M for a 450 MW lignite-fired cyclone boiler.

Applying these adjustments to a 477 MW boiler results in an estimated total installed capital cost for SNCR of $7,120,000 for MRY Station Unit 2 ($14.9/kW).

C2.5 Layered Technology Capital Cost Estimates

Capital costs were generally estimated based upon simple arithmetic addition of individual unit output capital cost factors for combinations of available NO_X reduction technologies, such as SNCR with ASOFA. An advanced form of separated overfire air system included the lignite-fired cyclone boiler equipment changes within the estimated unit capital cost factors.

Adding the advanced SOFA capital cost of $10.0 Million to the previous estimated installed capital cost of $7.12 Million yields a total estimated installed capital cost of $17.128 Million ($35.9/kW) for the SNCR with ASOFA alternative for MRYS Unit 2.

As previously discussed, Lignite (coal) reburn (CR) was assumed to be combined with advanced SOFA and a COHPAC addition considered necessary to limit the expected negative impact on opacity from this option. The installed capital cost of the COHPAC addition was estimated to be $36,013,000 for MRYS Unit 2. When the COHPAC addition was combined with the Lignite Reburn and ASOFA alternatives, the resulting total estimated capital costs were $81,167,000 for MRYS Unit 2 ($94.7 + $75.5 = $170.2/kW).

C.3 Operating and Maintenance Cost Estimates for MRY Station NO_X Control

An evaluation was performed to determine the estimated operating and maintenance cost impacts of installing and continuously operating various feasible NO_X control technologies on Milton R. Young Station Unit 2. These were estimated to be in addition to existing O&M costs to operate and maintain the MRY Station equipment.

The expected loss of electrical power sales from the operation of the specific NO_X control alternative was included as an annualized cost, assuming $35 per megawatt-hour. This was determined to include estimates for:

- Reduction in annual unit output due to an expected negative reliability (i.e. uptime availability) impact for each alternative. This generation reduction was calculated by multiplying the estimated additional numbers of outage hours per year by the average running plant capacity factor for that specific alternative, multiplied by the historic 12-month average unit gross electrical power output (MW_g) determined during the same period as the highest 12-month rolling summation NO_X pounds.
- Net additional auxiliary electric power demand for the added control equipment for each specific alternative based on assumptions for gross horsepower, plus additional power demand for existing fans caused by flue gas pressure drop (COHPAC for additional PM collection capacity), with adjustment for expected reductions in power demand (such as a decrease in existing coal crusher and feeder electric demand for the pulverized coal reburn case).
- The average running plant capacity factor for each alternative, which may also include an expected negative impact on the unit capacity from operation of the technology. This assumes that the control technique limits the gross electrical power output of the Unit (such as causing an increase in flue gas flow) such that the firing rate of the boiler cannot be maintained or raised to compensate for the load impact. Examples are lower boiler thermal efficiency (higher unit heat rate) when firing natural gas (due to higher moisture content of the flue gas).

For the SNCR alternative that involves a chemical reagent injected for NOx control, such as urea, the annual reagent consumption based on an assumed actual stoichiometric ratio (ASR) of moles of equivalent NH_3 injected per mole of uncontrolled NO_X emission estimated at the point of injection, converted to a mass rate (lbs/hr) by multiplying by the estimated annual number of hours of operation and the estimated NOx reduction fraction, and then multiplied by unit reagent cost (for a specific inlet NO_X concentration, emission reduction percentage and ammonia slip level).

General annual maintenance costs were assumed to be 1.5 percent of the estimated installed capital cost for each alternative, except for the coal conveying and grinding equipment portion of the coal reburn alternative, which was assumed to be 3 percent. The periodic bag replacement costs and other COHPAC system maintenance costs were estimated to be approximately 5.3% of the installed capital cost of the additional particulate matter collection equipment.

Additional operating labor costs directly attributable to each alternative were assumed to be zero for all alternatives.

Other operating costs include:

- Reagent dilution water for those alternatives that involve a chemical reagent injected for NOx control, typically four times the amount of urea consumption (assumes urea is a 50% solution as delivered and is injected as a 10% solution); this follows EPA OAQPS convention[1].
- Heat required for urea reagent storage, for those alternatives that involve a chemical reagent injected for NOx control; the source of heat is assumed to be auxiliary electrical power, but could be auxiliary steam (depending on heat source availability and plant preference).
- Additional coal consumption for those alternatives that involve a chemical reagent injected for NOx control to compensate for the heat of vaporization of the reagent dilution water; This follows EPA OAQPS convention[1], but is not accepted practice by an experienced SNCR vendor (Fuel Tech) who claims that the heat produced from the exothermic reaction of urea and NO_X is approximately equal to the heat required to evaporate the dilution water. For the purposes of this study, this additional coal consumption has been included in the annual O&M costs.

The sum of the estimated annual O&M costs was multiplied by the O&M levelization factor (1.24873) for each alternative to yield levelized total annual O&M costs.

C.3.1 Separated Overfire Air O&M Cost Estimate

Operation of SOFA is expected to add a small amount of O&M cost, primarily electricity consumed by the conventional SOFA damper electric drive actuator and airflow measuring system transmitter on each port. Using the existing forced draft, induced draft, and flue gas recirculation fans is not expected to change the overall amount of fan horsepower demand to be supplied by those fans' electric motors. Maintenance of the new overfire air ports and relocated lignite drying system vent ports (and FGR ports

for Unit 2) is included, assumed to be 1.5 percent of the installed capital cost. This is included in every control alternative's estimated O&M cost.

SOFA is not expected to significantly reduce unit reliability and availability to generate electrical power, assuming consistent combustion and continuous slag tapping under substoichiometric air/fuel operating conditions for MRYS boilers can be routinely established. A Unit availability reduction of 2.2% (181 hours per year), for M.R. Young Station Unit 2 was assumed, which allows for forced or extended scheduled boiler outages that may result from problematic cyclone slag tapping operational conditions encountered during substoichiometric cyclone operation with SOFA. The expected loss of electrical power sales from the reduction in annual electrical power output due to a decrease in expected Unit availability from ASOFA operation is included in every control alternative's estimated O&M cost.

Boiler furnace waterwall tube maintenance may increase slightly as a result of more fireside corrosion due to substoichiometric cyclone operation with SOFA. There may be some changes in the degradation rate of the boiler's furnace waterwall tubes resulting from exposure of more area of the furnace walls to slightly air-starved conditions during SOFA operation. Such conditions can promote corrosion from sulfur compounds in the furnace gases being created above the cyclones and below the SOFA injection ports. Due to the relatively moderate amounts of sulfur content in the lignite, modest amount of air-staging of the existing cyclones during SOFA operation, and the potential use of recirculated flue gas along the lower furnace walls, the expected change in corrosion rate of the boiler tubes should be minor. This degradation is expected to occur over many years of operation, and normally requires periodic replacement of the deteriorated sections of boiler furnace waterwall tubes to avoid forced outages to repair tube leaks or failed sections. The additional costs associated with potential change in the frequency of furnace wall tube failures and changeouts are difficult to estimate, and have not been quantified.

C.3.2 Reburn O&M Cost Estimates

The alternatives that include a new coal reburn system assume the use of new equipment for preparing the reburn fuel to replace 25% of the MRY Station Unit 2 boiler's total fuel heat input. Two additional lignite silos, with coal feeders and fine-grind pulverizers followed by dynamic classifier(s), are assumed to be located in a new separate building or powerhouse enclosure. Booster fan(s) addition was included because the existing forced draft fans were assumed to be incapable supplying the additional amount of primary air to the fine-grind pulverizers and dynamic classifier(s) for processing and conveying the reburn fuel. Using the existing forced draft, induced draft, and flue gas recirculation fans is not expected

to significantly change the overall amount of fan horsepower demand to be supplied by those fans' electric motors. The expected loss of electrical power sales from the additional auxiliary electric power demand for the reburn milling equipment from an estimated 0.5% (2.5 MW) reduction in net output was included as a cost, assuming $35 per megawatt-hour for MRY Station Unit 2. Electrical power consumed by the increased load on boiler fans to overcome the higher flue gas system pressure drop, plus the COHPAC particulate collection system support equipment was estimated to be a 1.2% (5.8 MW) reduction in net output for Unit 2.

Maintenance of the separate reburn coal injectors, fuel and primary air piping, and reburn fuel milling equipment is expected to be similar to the expenses associated with typical pulverized coal burners. The estimated additional annual maintenance costs for a new micronized coal reburn system was assumed to be 3.0 percent of the installed capital cost, or roughly $1,355,000 per year, for MRY Station Unit 2. The estimated additional annual maintenance costs (inflation adjusted from 2002 to 2006 $) for the COHPAC system was approximately $1,938,000 per year for MRYS Unit 2. Boiler furnace waterwall tube and superheater/reheater tube maintenance may increase slightly as a result of more erosion due to increased particulate emissions or fouling by flyash deposits resulting from coal reburn operation with ASOFA. The additional costs associated with potential change in the frequency of boiler tube failures and changeouts are difficult to estimate, and have not been quantified.

The estimated impacts on operation and maintenance costs for the coal reburn alternative that include a new pulverized or micronized coal reburn system are approximate. The twelve (Unit 2) existing coal crushers for preparing the main (cyclone) fuel fraction will have slightly lower electrical demand. This was estimated as -0.45 MW (-0.09%) for MRYS Unit 2. Addition of new electrical loads for the micronized coal preparation equipment to the existing plant facilities will be required. For the purposes of this preliminary study, it is assumed that additional plant auxiliary electrical power will be available for powering the new pulverizers/classifiers and related new coal reburn equipment, but this has not been confirmed.

Coal Reburn with ASOFA is not expected to significantly reduce unit reliability and availability to generate electrical power, assuming consistent combustion and continuous slag tapping under substoichiometric air/fuel operating conditions for MRYS boilers can be routinely established. A Unit availability reduction of 3.7% (3.8% (313 hours per year), for M.R. Young Station Unit 2 was assumed, which allows for forced or extended scheduled boiler outages that may result from problematic operational conditions encountered during coal reburn operation with ASOFA. This reduction in annual

electrical power output due to a decrease in expected Unit availability is included in the coal reburn control alternative's estimated O&M cost.

A Running Plant Capacity Factor reduction of 0.5% of annual gross electrical output was assumed for the coal reburn alternative. This would result in an estimated 2.2 MW average load decrease for M.R. Young Station Unit 2. This expected loss of electrical power sales from the reduction in net output due to this plant capacity impact was included in the estimated annual O&M costs.

Conventional and fuel-lean gas reburn options will involve higher operating costs compared with the existing operation of M.R. Young Station. Natural gas supply was assumed to be available near Bismarck, ND, but this has not been confirmed. The estimated unit cost of this natural gas was assumed to average $7.98/million Btu on a levelized annual cost basis, with a "credit" of $0.71 per mmBtu for avoided cost of consumption of lignite coal reduced by the natural gas heat input. The estimated annual cost of natural gas for the conventional gas reburning alternative applied to MRYS Unit 2 is approximately $50.3M per year. The estimated annual cost of natural gas for the FLGR™ alternative applied to MRYS Unit 2 is approximately $20.8M per year.

The new gas reburn injectors, station gas main and injector gas trains would add a minor amount of expense to current maintenance requirements, assumed to be 1.5 percent of the installed capital cost. Maintenance of separated overfire air nozzles is expected to be similar to the expenses associated with Unit 2's existing flue gas recirculation ports.

C.3.3 SNCR O&M Cost Estimate

The alternatives that include selective non-catalytic reduction systems will involve higher operating costs compared with the existing operation of MRY Station Unit 2. Urea reagent supply was confirmed to be available regionally. The estimated unit cost of this 50% aqueous urea solution was assumed to average approximately $379/ton delivered (2006$). Consumption of urea reagent for SNCR with ASOFA was based upon preliminary numbers allowing for a boiler flue gas exit ammonia slip of 5 ppmvd. These were estimated as approximately 286 gph for SNCR when applied to MRY Station Unit 2 with ASOFA.

New electrical loads are required for high flow urea circulation, in-line and storage tank heating, water dilution, and reagent metering equipment. These auxiliary electrical demands and reagent dilution water usage were calculated based upon equations published in EPA Office of Air Quality Planning and

Standards (OAQPS) publication EPA/452/B-02-001, Section 4.2, NOx Controls – NOx Post-Combustion, Chapter 1 - Selective Non-Catalytic Oxidation[1]. Compressed air for reagent atomization and lance purging and cooling, as well as multiple nozzle lance water cooling are additional demands on the existing plant facilities. These powerhouse building service supplies were assumed to be available, but this has not been confirmed. The new urea reagent injection nozzle lances, reagent pumps, dilution water pumps, and distribution piping/valve trains would add a minor amount of expense to current maintenance requirements, assumed to be 1.5 percent of the installed capital cost.

SNCR with ASOFA is not expected to significantly reduce unit reliability and availability to generate electrical power, assuming urea injection does not impact the ability to maintain consistent combustion and continuous slag tapping under substoichiometric air/fuel operating conditions for MRYS boilers. A Unit availability reduction of 3.2% (263 hours per year), for M.R. Young Station Unit 2 was assumed, which allows for forced or extended scheduled boiler outages that may result from problematic operational conditions encountered during SNCR-related operation with ASOFA. This reduction in annual electrical power output due to a decrease in expected Unit availability is included in the these control alternatives' estimated O&M costs.

A Running Plant Capacity Factor reduction of 0.15% of annual gross electrical output was assumed for the SNCR with ASOFA alternative. This would result in an estimated 0.66 MW average load decrease for M.R. Young Station Unit 2. This expected loss of electrical power sales from the reduction in net output due to this plant capacity impact was included in the estimated annual O&M costs.

C.3.4 Layered Technology O&M Cost Estimates

Operating and maintenance costs for combinations of available NO_X reduction technologies were estimated based upon simple arithmetic addition of individual cost estimates. SNCR was combined with advanced SOFA, as previously shown. Pulverized coal reburn was assumed to be combined with advanced SOFA (and a COHPAC addition for PM control). The auxiliary electrical demands and reagent dilution water usage for SNCR with ASOFA were calculated based upon equations published in EPA Office of Air Quality Planning and Standards (OAQPS) publication EPA/452/B-02-001, Section 4.2, NOx Controls – NOx Post-Combustion, Chapter 1 - Selective Non-Catalytic Oxidation[1].

C.3.5 Summary of O&M Costs Estimates for MRY Station NOx Control

The results of this evaluation for estimated variable operating and maintenance costs for the individual NOx control alternatives are summarized in this section. The expected reductions in Unit availability (uptime) and capacity are included in Tables C.3-1 through C.3-7 for MRYS Unit 2. Tables C.3-5 and C.3-6 for MRYS Unit 2 include the estimated urea reagent and dilution water usage rates and costs for the alternatives that involve SNCR with ASOFA NO_X control technologies.

TABLE C.3-1 – Expected Availability Reductions for MRY Unit 2 NO_X Controls

Alt. Label(1)	NOx Control Technique	Estimated Annual Average Unit Operating Time			
		Unit Availability(2)	Unit Operating Time(3), hrs/yr	Unit Outage Time(4), hrs/yr	Unit Operating Time Reduction(5), hrs/yr
E	SNCR w/ ASOFA	0.909	7965	795	263
D	Gas Reburn w/ ASOFA	0.919	8048	712	181
C	Coal Reburn w/ ASOFA	0.904	7916	844	313
B	FLGR w/ ASOFA	0.919	8048	712	181
A	Advanced SOFA (ASOFA)	0.919	8048	712	181
	Baseline	0.939	8229	531	0

(1) – Alternative number has been previously assigned from least removal to highest removal percentage.
(2) – 12-month baseline availability is assumed at 93.9 percent. These values reflect estimated amounts of negative reliability impact expected from the implementation of the individual NOx control technique.
(3) – Annual operating time is annual average availability multiplied by 8760 hrs/yr of possible uptime.
(4) – Annual outage time is 8760 hrs/yr possible operating time minus estimated annual operating time.
(5) – Annual operating time reduction resulting from the implementation of the individual NOx control technique is the difference between the baseline and expected annual outage times.

TABLE C.3-2 – Expected Capacity Reductions for MRY Unit 2 NO_X Controls

Alt. Label[1]	NOx Control Technique	Estimated Annual Average Unit Electrical Power Generation Reduction from Operating Time Reduction		
		Unit Running Plant[2] Capacity Factor	Unit Generation Reduction[3] kW-hrs/yr	Unit Generation Reduction Cost[4], 1000$/yr
E	SNCR w/ ASOFA	0.951	110,176.095	3,856
D	Gas Reburn w/ ASOFA	0.943	81,416,590	2,850
C	Coal Reburn w/ ASOFA	0.948	130,375.506	4,563
B	FLGR w/ ASOFA	0.949	81,910,024	2,867
A	Advanced SOFA (ASOFA)	0.952	75,859.855	2,655
	Baseline	0.952	0	0

(1) – Alternative designation has been previously assigned from least removal to highest removal percentage.
(2) – 12-month baseline running plant capacity factor is assumed at 95.2 percent. These values reflect estimated amounts of negative reliability impact expected from the implementation of the individual NOx control technique.
(3) – Annual electricity generation reduction is annual operating time reduction multiplied by the annual running plant capacity factor resulting from the implementation of the individual NOx control technique multiplied by the 12-month average gross output of 440 MW.
(4) – Annual electricity generation reduction cost is the annual electricity generation reduction (kW-hrs/yr) resulting from the implementation of the individual NOx control technique multiplied by the incremental value of electricity generation, assumed to be $35.00/MW-hr. All cost figures in 2006 dollars.

TABLE C.3-3 – Expected Auxiliary Electrical Power Demand Changes for MRY Unit 2 NO_X Controls

Alt. Label(1)	NOx Control Technique	Estimated Annual Average APC NOx Equipment Auxiliary Electrical Power Demand and Usage				
		Gross Demand (2) kW	Credit(3) kW	Total Net Demand(4) kW	Power Usage(5) kW-hrs/yr	Power Usage Cost(6), 1000$/yr
E	SNCR w/ ASOFA	133.2	0	133.2	1,008,774	35
D	Gas Reburn w/ ASOFA	1	(228)	(227)	(1,724,428)	(60)
C	Coal Reburn w/ ASOFA	8,342	(448)	7,894	59,217,554	2,073
B	FLGR w/ ASOFA	1	(125)	(124)	(949,051)	(33)
A	Advanced SOFA (ASOFA)	1	0	1	7,664	0.3

(1) – Alternative designation has been previously assigned from least removal to highest removal percentage.
(2) – The APC NOx equipment gross auxiliary electrical power demand of alternatives is the sum of individual technologies combined by simple addition. Actual power demands may differ from this due to positive or negative synergistic effects. Coal reburn includes 2,484 kW for feed preparation and conveying equipment demand plus 5,857 kW for the COHPAC system addition for PM control.
(3) – The APC NOx equipment auxiliary electrical power demand credit of coal reburn alternatives is the estimated result of lower cyclone coal preparation and feeder power demand due to lower boiler cyclone coal equipment loading. Actual power demands may differ from this due to accuracy of estimates for assumed amount of operating horsepower reduction.
(4) – The total net auxiliary electrical power demand is the sum of the gross demand and credit.
(5) – The annual change in APC NOx equipment auxiliary electrical power demand electricity usage in kW-hrs/yr for these alternatives is the net power demand multiplied by the estimated annual operating time and running plant capacity factor which reflects the adjustment for any expected reliability and capacity impacts from the implementation of the control technique.
(6) – The annual change in APC NOx equipment auxiliary electrical power demand electricity cost is the annual change in kW-hrs/yr for these alternatives resulting from the implementation of the individual NOx control technique multiplied by the incremental value of auxiliary electricity generation, assumed to be $35.00/MW-hr. All cost figures in 2006 dollars.

TABLE C.3-4 – Expected Auxiliary Electrical Power Demand and Generation Reduction Cost Changes for MRY Unit 2 NO_X Controls

Alt. Label[1]	NOx Control Technique	Estimated Annual Change in Unit Generation Due to APC NOx Equipment Auxiliary Power Electricity Demand and Generation Reduction			
		APC Electrical Power Usage[2] kW-hrs/yr	Unit Generation Reduction[3] kW-hrs/yr	Total Unit Electrical Power Generation Change[4] kW-hrs/yr	Total Unit Electrical Power Generation Change Cost[5] 1000$/yr
E	SNCR w/ ASOFA	1,008,774	110,176.095	111,184,869	3,891
D	Gas Reburn w/ ASOFA	(1,724,428)	81,416,590	79,692,162	2,789
C	Coal Reburn w/ ASOFA	59,217,554	130,375.506	189,593,059	6,636
B	FLGR w/ ASOFA	(949,051)	81,910,024	80,960,972	2,834
A	Advanced SOFA (ASOFA)	7,664	75,859.855	75,867,520	2,655

(1) – Alternative designation has been previously assigned from least removal to highest removal percentage.
(2) – The annual change in APC NOx equipment auxiliary electrical power demand electricity usage in kW-hrs/yr for these alternatives is the net power demand multiplied by the estimated annual operating time and running plant capacity factor which reflects the adjustment for any expected reliability and capacity impacts from the implementation of the control technique.
(3) – Annual electricity generation reduction is annual operating time reduction multiplied by the annual running plant capacity factor resulting from the implementation of the individual NOx control technique multiplied by the 12-month average gross output of 440 MW.
(4) – The total unit electrical power generation change is the sum of the annual change in APC NOx equipment auxiliary electrical power demand electricity usage plus the annual electricity generation reduction resulting from the implementation of the individual NOx control technique.
(5) – The total unit electrical power generation change cost is the total generation change (kw-hrs/yr) multiplied by the incremental value of electricity generation, assumed to be $35.00/MW-hr. All cost figures in 2006 dollars.

TABLE C.3-5 – Expected NOx Reagent Usage and Cost Estimates for MRY Unit 2 NO_X Controls

Alt. Label[1]	NOx Control Technique	NOx Reduction Reagent Urea Usage[2]			NOx Reduction Reagent Dilution Water Usage[3]	
		lbs/hr	tons/yr	1000$/yr	1000 gal/yr	1000$/yr
E	SNCR w/ ASOFA	2,713	10,276	3,898	9,851	10

(1) – Alternative designation has been previously assigned from least removal to highest removal percentage.
(2) – All cost figures in 2006 dollars.
(3) – Reagent dilution water usage assumes potable water is added to create a 10% urea concentration (4 parts water to 1 part urea solution at 50% concentration) prior to injection. Dilution water unit cost assumed to be $1.00 per thousand gallons.

TABLE C.3-6 – Expected Heat Input and Equivalent Coal Cost to Evaporate Aqueous Urea for MRY Unit 2 NO_X Controls

Alt. Label[1]	NOx Control Technique	Estimated Annual Average Unit Equivalent Coal Consumption Cost for Aqueous Urea Evaporation		
		Heat Required to Evaporate Aqueous Urea[2], mmBtu/yr	Equivalent Coal Consumption for Heat Input[2], Tons/yr	Coal Consumption Cost[2], 1000$/yr
E	SNCR w/ ASOFA	73,986	5,553	52

(1) – Alternative designation has been previously assigned from least removal to highest removal percentage.
(2) – Heat required to evaporate urea reagent dilution water assumes 900 Btu/lb required based on a 10% urea concentration (4 parts water to 1 part urea solution at 50% concentration) injected for the estimated amount of urea usage. Coal heat content of 6,662 Btu/lb, unit cost of $0.71/mmBtu.

Appendix C References:

[i] EPA Office of Air Quality Planning and Standards (OAQPS) publication EPA/452/B-02-001, Section 4.2, NOx Controls – NOx Post-Combustion, Chapter 1 - Selective Non-Catalytic Reduction, dated October 2000, posted at their website: http://www.epa.gov/ttn/catc/dir1/cs4-2 ch1.pdf, Chapter 2 - Selective Catalytic Reduction, dated October 2000, posted at their website: http://www.epa.gov/ttn/catc/dir1/cs4-2 ch2.pdf.

[ii] "Stationary Source NOx and PM Emissions in the WRAP Region: An Initial Assessment of Emissions, Controls, and Air Quality Impacts", October 1, 2003 Western Regional Air Partnership Final Report of the WRAP Market Trading Forum, Section VI: Summary of Emission Controls Available for Large Stationary Sources of NOx and PM (by Reaction Engineering International), available at http://www.wrapair.org/forums/mtf/nox-pm.html

[iv] "Analysis of Combustion Controls for Reducing NO_X Emissions From Coal-fired EGU's in the WRAP Region" WRAP Draft Report EGR Contract Number 30204-101, prepared by Eastern Research Group, Inc., dated April 26, 2005, posted at their website: http://www.wrapair.org/forums/ssjf/documents/eictts/NOxEGU/050426Coal-fired%20EGUs_in_WRAP_Region-draft.pdf

[v] "Combustion Modification – An Economic Alternative for Boiler NO_X Control" GER-4192 (04/01), Folsom, Blair A, Tyson, Thomas J. GE Power Systems, Schenectady, NY, (2001) posted at their website: http://www.gepower.com/prod_serv/products/tech_docs/en/downloads/ger4192.pdf

[vi] "Assessment of Control Technology Options for BART-Eligible Sources, Steam Electric Boilers, Industrial Boilers, Cement Plants and Paper and Pulp Facilities", dated March 2005, posted at their website: http://bronze.nescaum.org/committees/haze/BART_Control_Assessment.pdf

[vii] Budgetary Proposal, Fuel Tech, Inc. NOxOUT® SNCR and SNCR/FLGR® Systems, for one 450 MW cyclone-fired unit, dated December 9, 2004.