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.
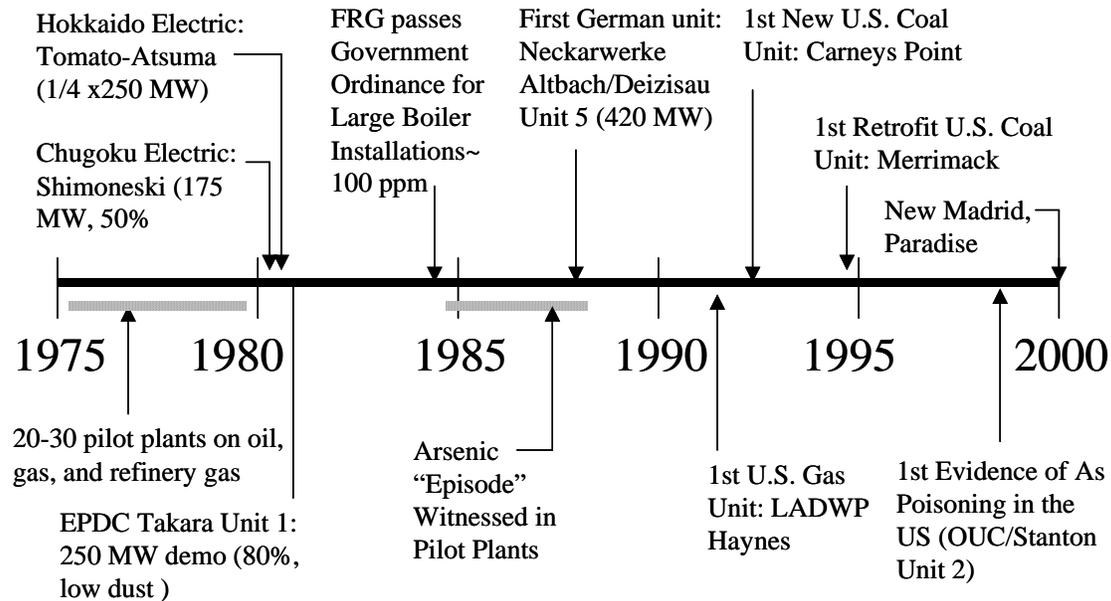
INTRODUCTION

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

Hokkaido Electric:
Tomato-Atsuma
(1/4 x250 MW)

Chugoku Electric:
Shimoneski (175
MW, 50%

FRG passes
Government
Ordinance for
Large Boiler
Installations~
100 ppm

First German unit:
Neckarwerke
Altbach/Deizisau
Unit 5 (420 MW)

1st New U.S. Coal
Unit: Carneys Point

1st Retrofit U.S. Coal
Unit: Merrimack

New Madrid,
Paradise

1975   1980   1985   1990   1995   2000

20-30 pilot plants on oil,
gas, and refinery gas

EPDC Takara Unit 1:
250 MW demo (80%,
low dust)

Arsenic
"Episode"
Witnessed in
Pilot Plants

1st U.S. Gas
Unit: LADWP
Haynes

1st Evidence of As
Poisoning in the
US (OUC/Stanton
Unit 2)

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 NH_3 (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
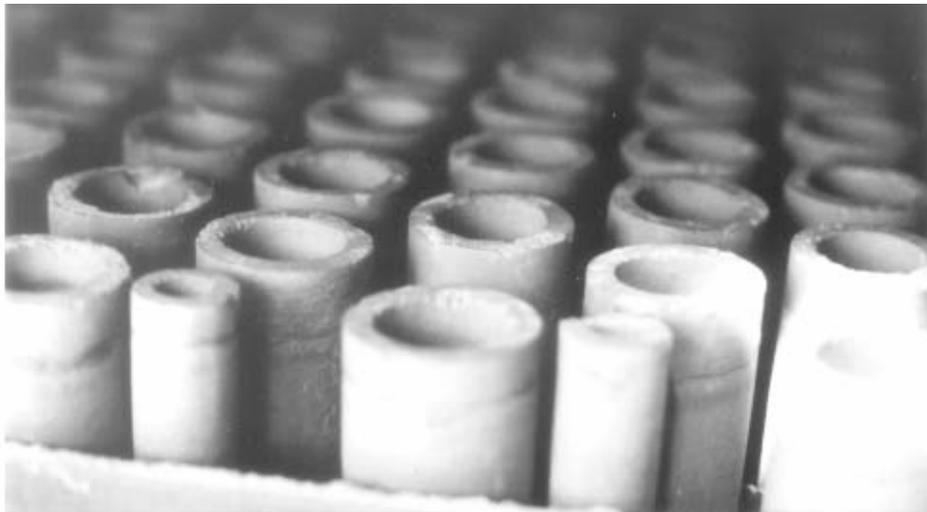
COMPARISON TO DESIGNS FOR US APPLICATION

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
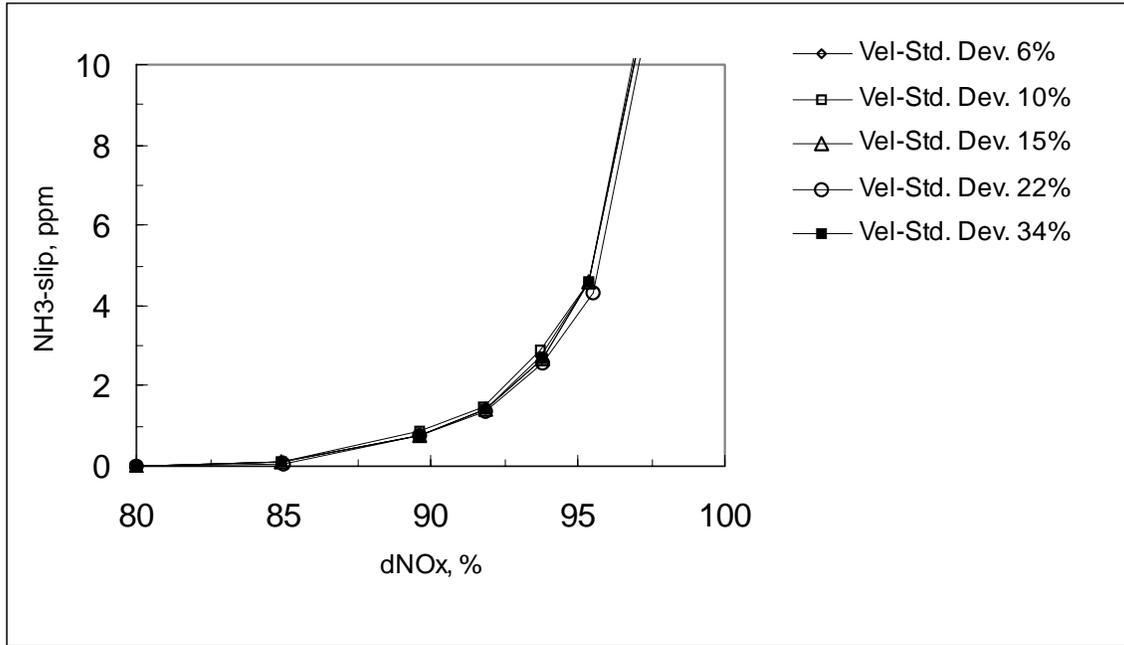
(a) Velocity Non-Uniformity Effects (NH_3/NO_x Non-Uniformity = 7%)
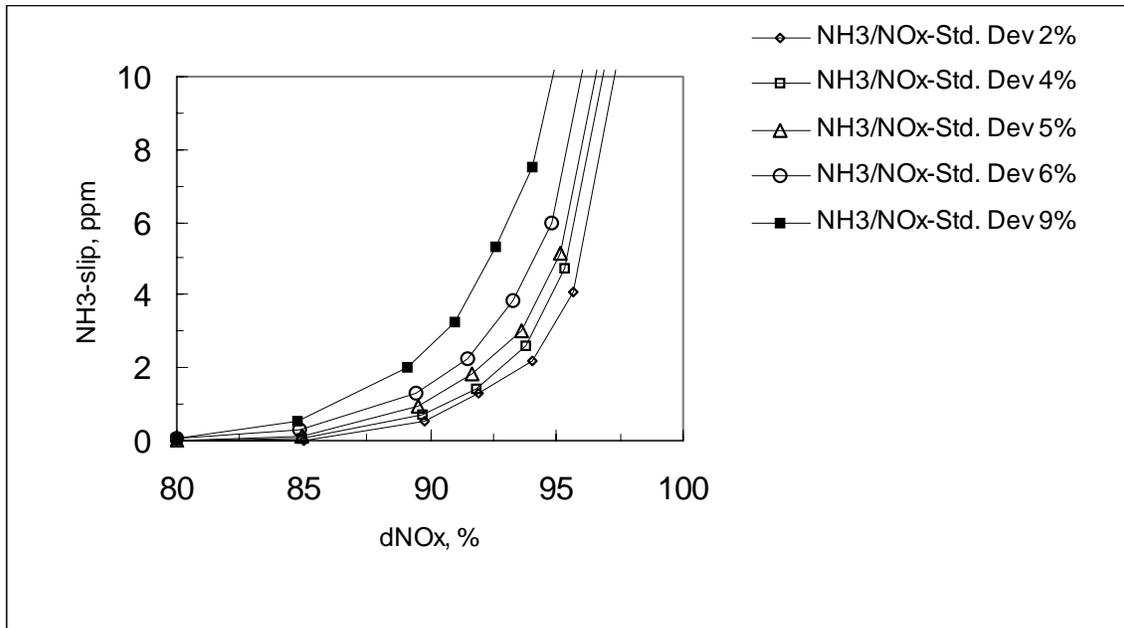
(b) NH_3/NO_x Non-Uniformity Effects (Velocity Non-Uniformity = 10%)

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
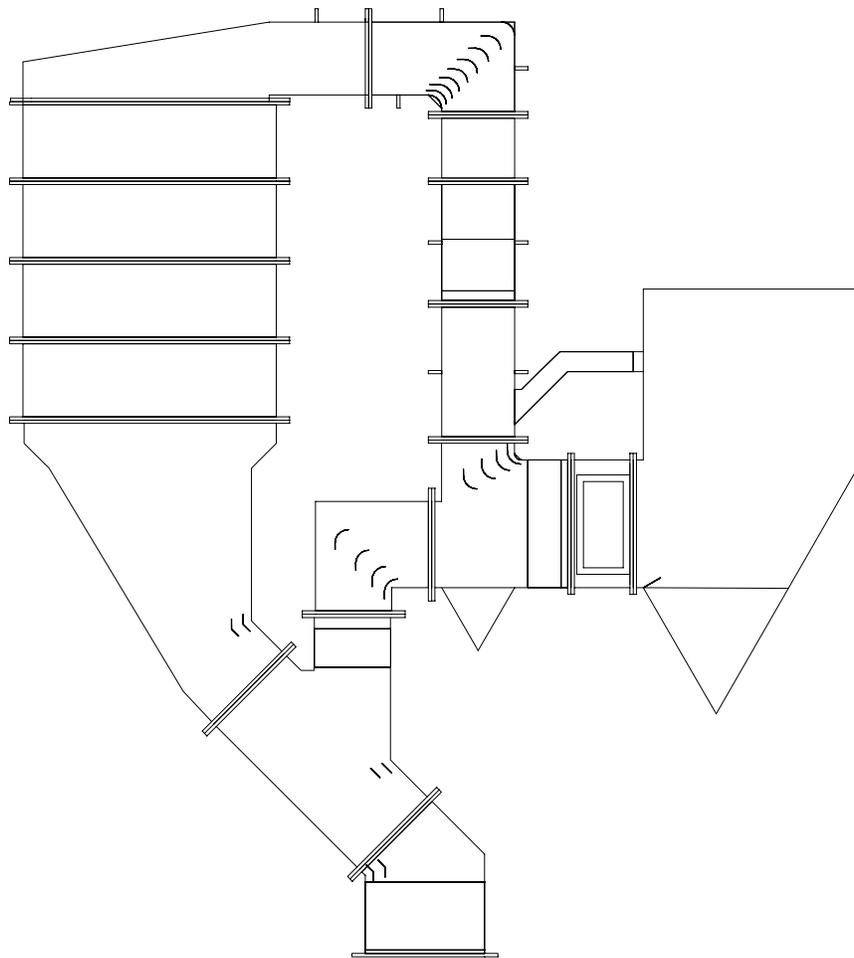
Reagent Injection Equipment

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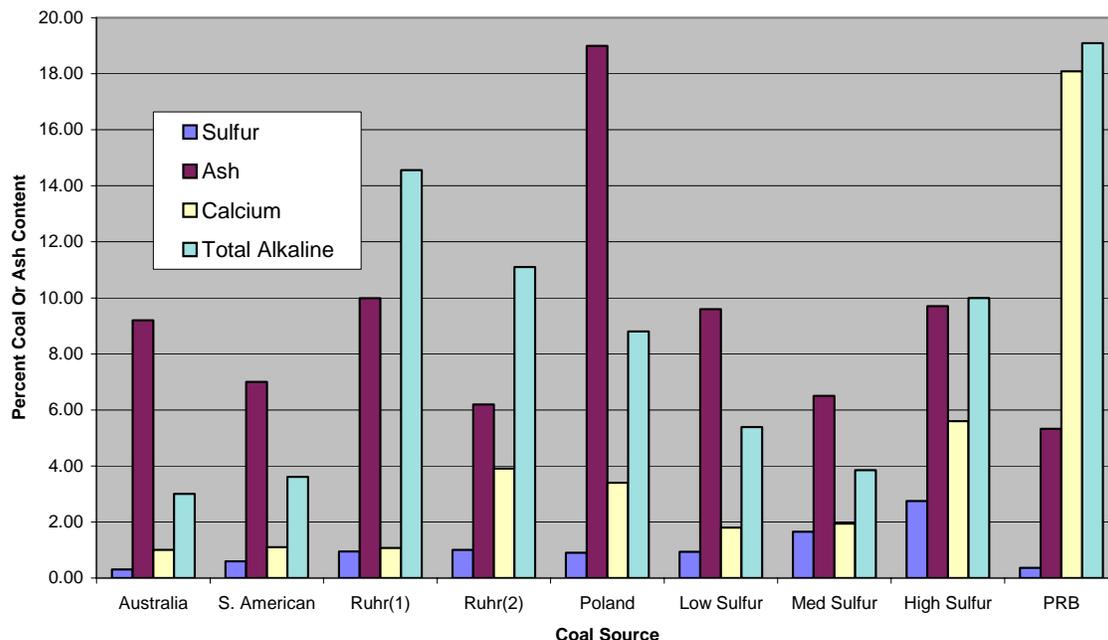
In summary, some US coals are not described by the existing experience database, and despite the best efforts of catalyst suppliers, some risk to deactivation or balance-of-plant problems exists.

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.

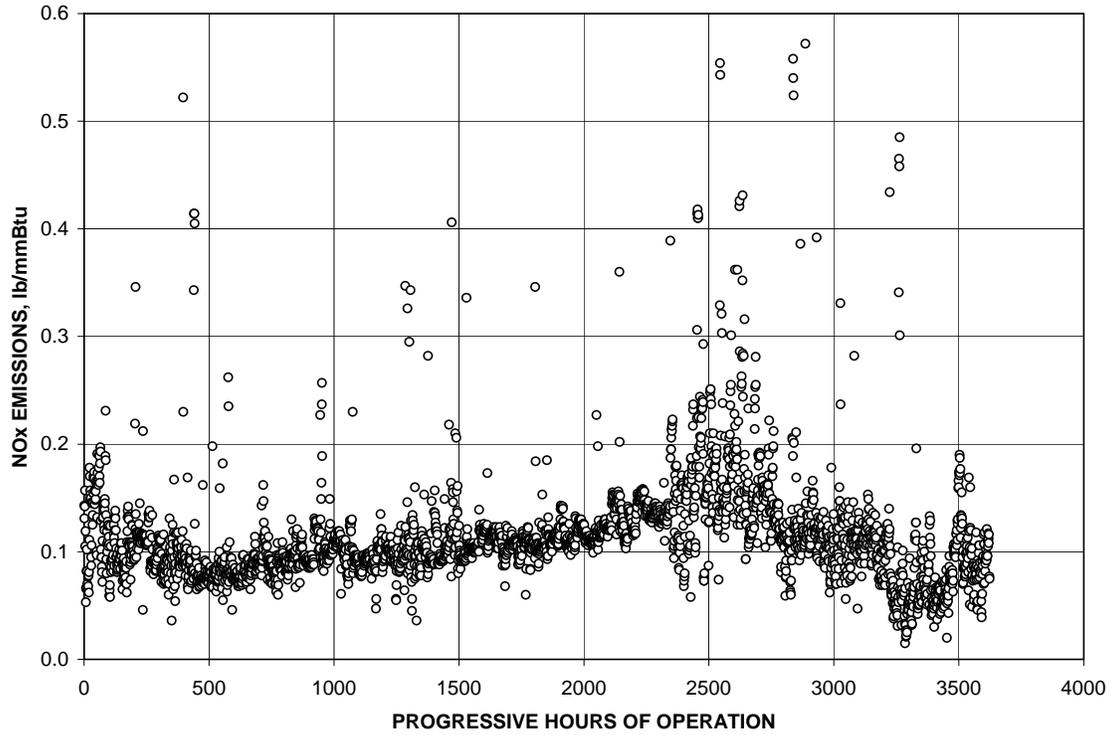**Figure 6:** SCR Outlet Emissions Data Scatter For 90% Removal System

Figure 7: Comparison of 30 Day, 24 hour, and 8 Hour NO_x Outlet Data for Selected SCR-Equipped Units
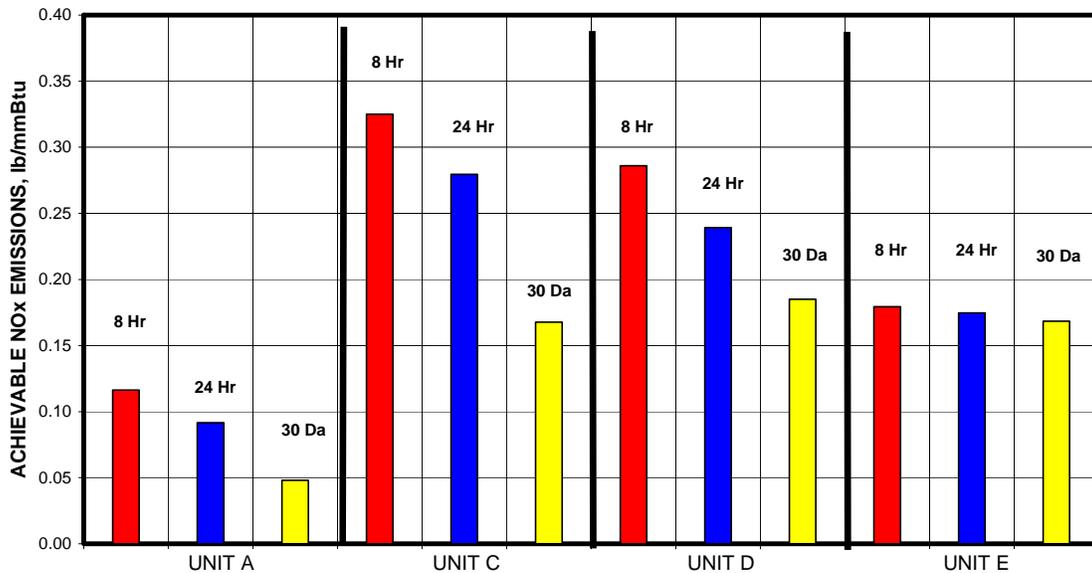
Figure 8 compares this "margin" for the four units cited, in addition to a second cyclone unit (Unit E) and a second new unit with 50% NO_x capability. This figure again depicts the wide variability in SCR outlet NO_x from Unit A; however, as the subject unit has operated with SCR for less than one year, 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
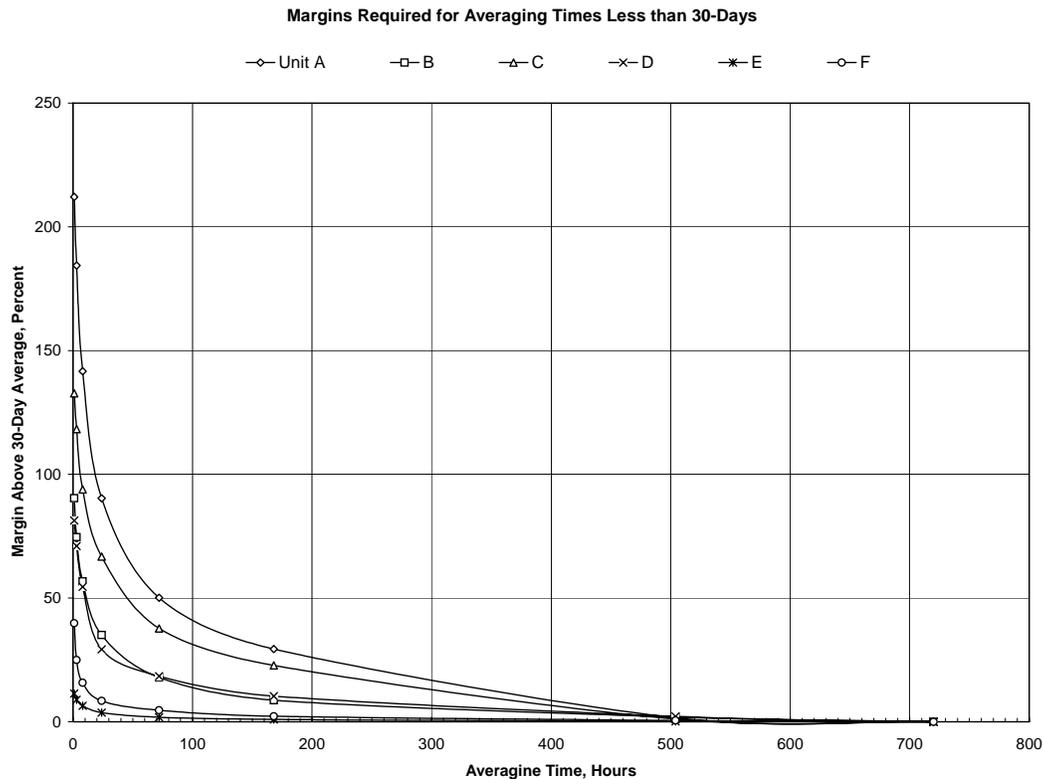
IMPLICATIONS FOR US O&M ACTIVITIES

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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