Chapter 8

NOx Removal Technology

Editor's Note:
Chapter 8 – Back End NOx Controls – This section was written by Chuck Solt, edited by Brian Doyle and is updated from material in the NOx Emissions course presented by Rutgers University from 2001 to 2007.

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Introduction to NOx Removal Technologies

If NOx formation cannot be suppressed sufficiently in the combustion process, the only alternative is to remove it from the exhaust stream. NOx removal technologies were developed as early as the mid-1950s, and have been in common use since the mid 1980s. Some of these technologies have gained wide acceptance, while others are just emerging.

The Existing Technologies include:

- SNCR - Selective Non-catalytic Reduction
- NSCR - Non-selective Catalytic Reduction
- SCR - Selective Catalytic Reduction

Emerging Technologies (some of which may never emerge) Include:

- RAPER-NOx
- SCONOX
- LoTOx
- Activated Carbon Absorption

We will look at each of these technologies individually, first at the technologies that have wide usage and then at the emerging technologies.

Selective Non-catalytic Reduction (SNCR)

As noted in Chapter 1, NOx emissions consist of both NO and NO_2. Accordingly, the NOx control technology must address the NOx compound emitted by the source, or if (as in most cases), the source emits both, it must either reduce both compounds or convert one into the other before reducing it to N_2 and water. Several of the existing technologies we will discuss are based on using ammonia or urea:

For NO removal: $4\ NO + 4\ NH_3 + O_2 \rightarrow 4\ N_2 + 6\ H_2O$

For NO_2 removal: $4\ NO_2 + 8\ NH_3 + 2\ O_2 \rightarrow 6\ N_2 + 12\ H_2O$

This reaction is called “selective reduction” because it uses a reagent (ammonia) to react with the NOx.

In the SNCR process, a reagent is sprayed into the exhaust stream. Under the right temperature conditions, the NOx will react with it, eliminating the NOx without producing other pollutants. The first application of this technology was *Thermal DeNOx.* – developed by Exxon in about 1956. In this technology, ammonia is sprayed into the post-combustion area of a boiler or furnace when the temperature is 1650°F – 1700°F. At this temperature, a 50% reduction of

NOx can be achieved. The reaction is temperature sensitive, and the window is small. If the temperature is to high, ammonia will convert to NOx, increasing emissions. If the temperature is to low, the reaction with the NOx is too slow, resulting in emissions of both NOx and ammonia. The application of Thermal DeNOx is limited to new boilers because the space required to completely mix ammonia with exhaust gas needs to be part of the boiler design. So the main application has been new waste-to-energy boilers where there are limited options to significantly reduce NOx formation and further back end cleanup is problematic.

In a different version of SNCR Fuel Tech Inc. of Stamford CT did development work on the basic concept through part of the 1970s and 1980s and commercialized a technology they called *NOxOUT*. While this technology is similar to *Thermal DeNOx*, it uses urea as a reagent instead of ammonia. Urea gives the technology a broader and slightly lower temperature window. A significant advantage is that urea can be handled either as a solid or dissolved in water – a non toxic liquid.

The biggest advantage of *NOxOUT* is that it doesn't require injection/mixing hardware installed in a large physical space in the middle of the convective section of the boiler. Instead a water solution of urea is sprayed in key locations around the top of the firebox. As the spray is carried with the exhaust gases, the water evaporates leaving just the urea. With proper planning evaporation is completed just as the gas cools to the right temperature, allowing the urea to react with the NOx. Thus *NOxOUT* can be retrofitted to existing boilers., *NOxOUT* still has some of the same application limitations, as *Thermal DeNOx* but as result of the RACT requirements in the Clean Air Act Amendments of 1990, many existing boilers were retrofitted with *NOxOUT*. It is still the technology of choice for some boilers where NOx formation cannot be controlled.

Selective Catalytic Reduction (SCR)

Principle

Catalysts can be used to change the temperature range in which a chemical reaction occurs. With a SCR system the reaction between ammonia and NOx occurs at much lower temperatures than with SNCR. As a result, SCR can be applied to many (or most) types of combustion source.

The first applications of SCR were in coal fired generating plants in Germany, followed shortly thereafter by Gas turbines in Japan. In the mid 1980s, the South Coast AQMD (LA Basin) made a BACT determination that SCR performance should be the permit basis for several gas turbine permits. This determination was based primarily on the Japanese experience. At that time, the permitted levels were based on water injected turbines operating at 42 ppm and SCR at a guaranteed effectivity of 80% -- yeilding a permit level of 9 ppm corrected to 15% O_2 (turbine emissions are regulated and reported at a dilution level of 15% O_2). By the late 1990s, permits for gas turbines were based on lean-premix combustion at 25 ppm and SCR effectivity of 90% yielding a permit level of 2.5 ppmvd.

Alternative Catalysts

The chemical reactions are the same as SNCR, but the reactions are enabled by a catalyt. The temperature range depends on the type of catalyst used. There are three commonly used types of SCR catalyst.

- Conventional SCR, called base metal systems, usually use a *vanadium pentoxide* (V_2O_5) catalyst, but tungsten (W) and titanium dioxide are also used. The best performance is in the range of 650° to 750°F – a temperature range accessible in most boilers.
- For low temperature applications, a precious metal is used – usually *platinum* (Pt). These systems can be used at temperatures as low as 350°F, and as high as 550°F.
- High Temperature applications usually use a *zeolite* catalysts and have been used successfully at temperatures as high as 1050°F – typical of simple cycle gas turbines.

Figure 8-1 is a general illustration of catalyst reactivity versus temperature.

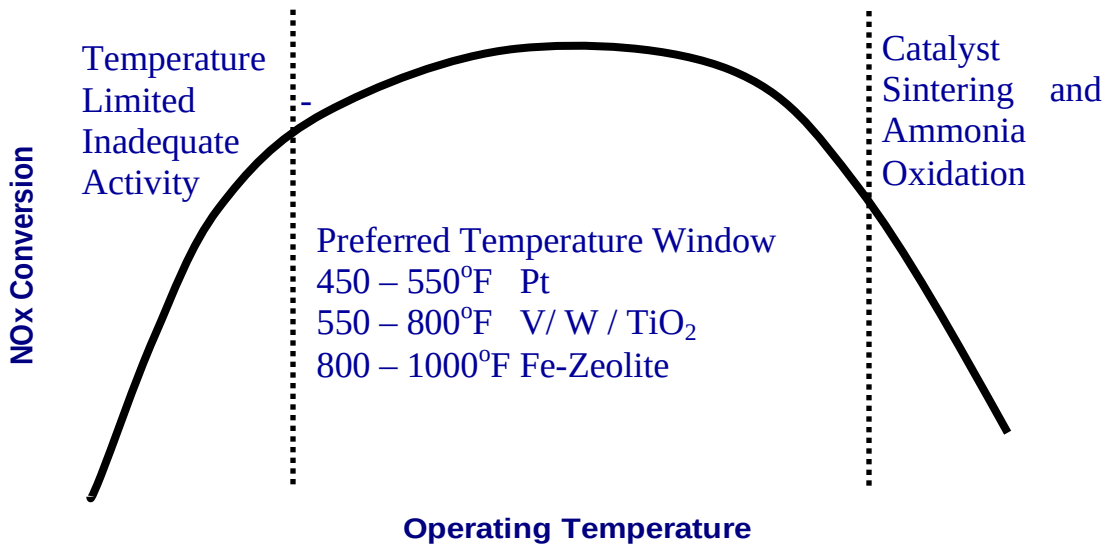

Figure 8- 1. SCR Temperature versus Catalyst Activity

NOx Reduction vs. Ammonia Slip

As can be seen in the chemical reactions shown above, in a system emitting primarily NO, the reaction ratio of NOx to ammonia will be nearly 1:1. If less ammonia is injected, some of the NOx will pass into the atmosphere. If a higher ratio is used, some of the ammonia will go unreacted and pass into the atmosphere. It's impossible to completely destroy all of both species – typically there will be some amount of both NOx and ammonia (*ammonia slip*) in the exhaust. By increasing the ammonia/NOx ratio beyond stoichiometric (the theoretically perfect ratio to balance the amounts of NOx and ammonia), NOx emissions can be reduced. So there is a tradeoff between NOx reduction and ammonia slip.

There is also an economic tradeoff – the longer the catalyst path, the more NOx molecules will find ammonia and react on the catalyst surface. So, the larger (and more expensive) the catalyst, the better the NOx reduction. Figure 8-2 plots the tradeoffs of NOx reduction versus catalyst size and relative amounts of ammonia.

Most permits today require NOx in the range of 2 to 3.5 ppm (at 15% O2, dry) and ammonia slip of 6 to 10 ppm. Even at 10 ppm, catalyst life factors into the cost of NOx reduction, Ammonia has been recognized by the US EPA as an adverse environmental impact that should be considered in a BACT determination. Unfortunately, the EPA stopped short of recommending a means of making the determination, so the permitting agency usually selects the lower NOx level and determines the ammonia slip on an economic basis.

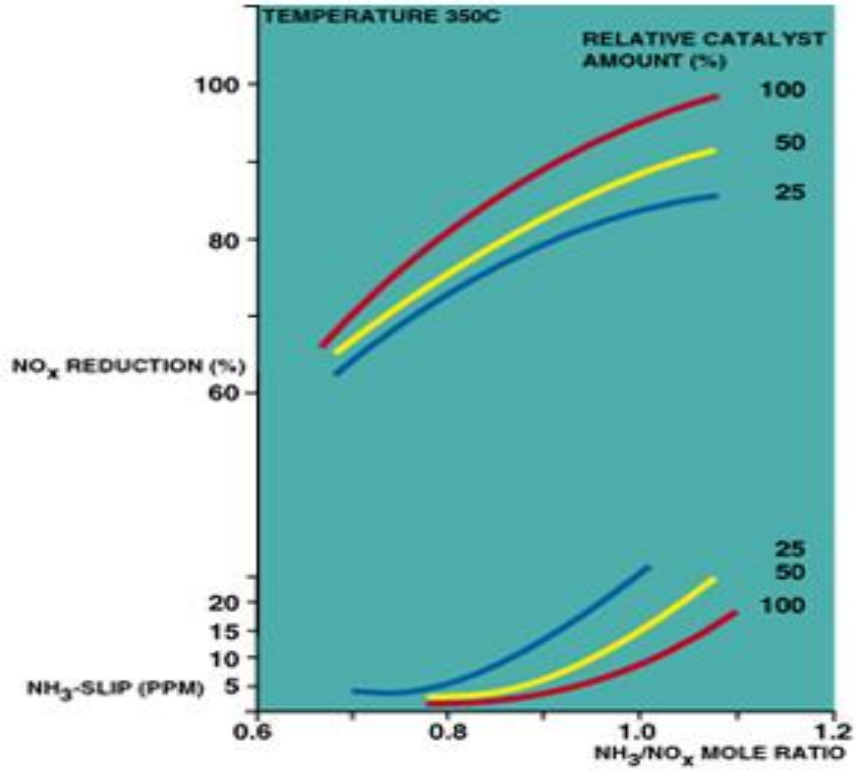

Figure 8-2. Ammonia Feed Effects on Emissions

Catalyst Performance Over Time

Catalyst performance deteriorates with time due to a number of operating factors, including:

- Sintering: Pores are blocked and fused at high temperatures
- Poisoning: Foreign molecules bind to the catalyst
- Pore blockage: fine particles become imbedded in the pores
-

Most SCR systems install the catalyst in 2 or more beds or layers. These can be replaced individually. Figure 8-3 is an example of a catalyst replacement scenario. In the system depicted, the system was initially installed with two catalyst beds, but with space to add a third bed. If initial performance did not meet permit requirements, the third bed could have been installed immediately to improve performance. If the system met initial performance, the plan calls for addition of the third bed at the end of the second year operation, when NOx and ammonia levels were both projected to reach the permitted level. In subsequent years, the catalyst beds would be replaced one at a time as either the NOx or ammonia level reached the permit level.

Reagent Alternatives

So far, we have been limiting our discussion of reagents to ammonia, but in fact, ammonia can be used in different forms, and there are other chemical reagents that will also reduce NOx into nitrogen and water. We mentioned urea in the discussion of NOxOut, but urea can also be used in SCR, in different forms. Each of these reagents has its own advantages and disadvantages. The most commonly used reagents are anhydrous ammonia, aqueous ammonia and urea.

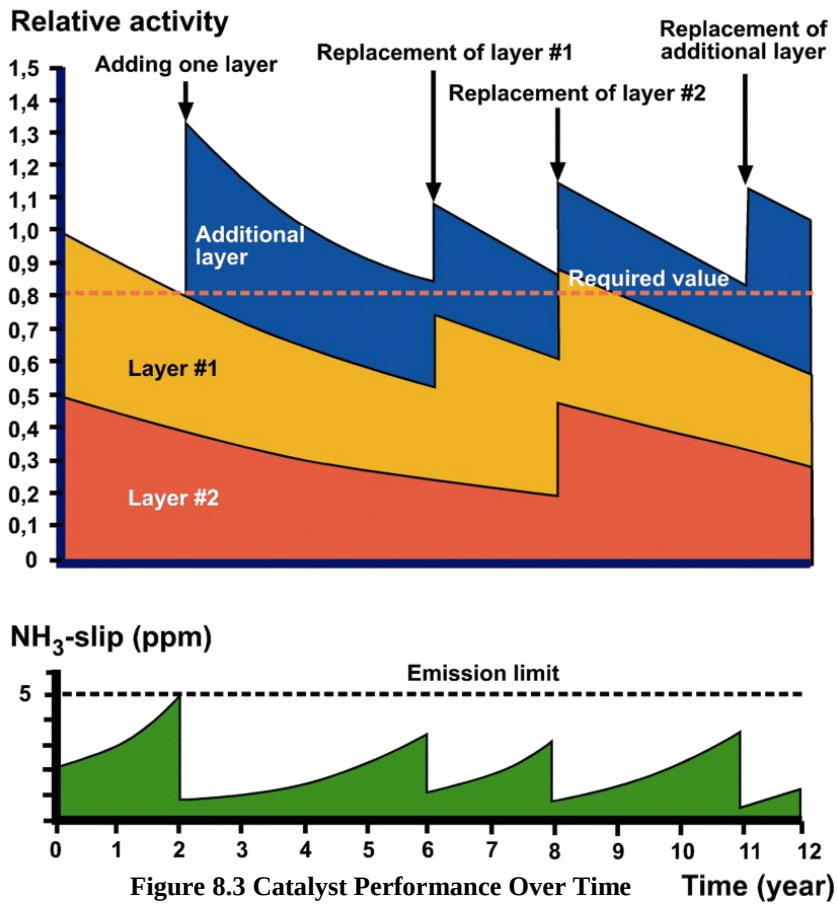

Figure 8.3 Catalyst Performance Over Time

Anhydrous Ammonia (liquefied ammonia without water)

<u>Advantages:</u>

- The cost of the ammonia and the ammonia storage and handling system make this the most economic alternative.
- The volume of the reagent is small, saving on transport, storage and handling.
- It is easy to vaporize, reducing the complexity, cost and maintenance of the reagent handling system.

<u>Disadvantages</u>

- Ammonia is regulated as a toxic substance 36 states.

- Storage of the quantities of ammonia required for SCR triggers the requirement for a Risk Management Plan (RMP).
- Ammonia slip is a precursor to PM2.5.

In the anhydrous ammonia system shown in figure 8-4, the ammonia is delivered by rail car, and transferred to an on-site storage tank. It is then sent to an evaporator where process heat is used to vaporize the liquid before it is mixed with dilution air and injected into the exhaust stream.

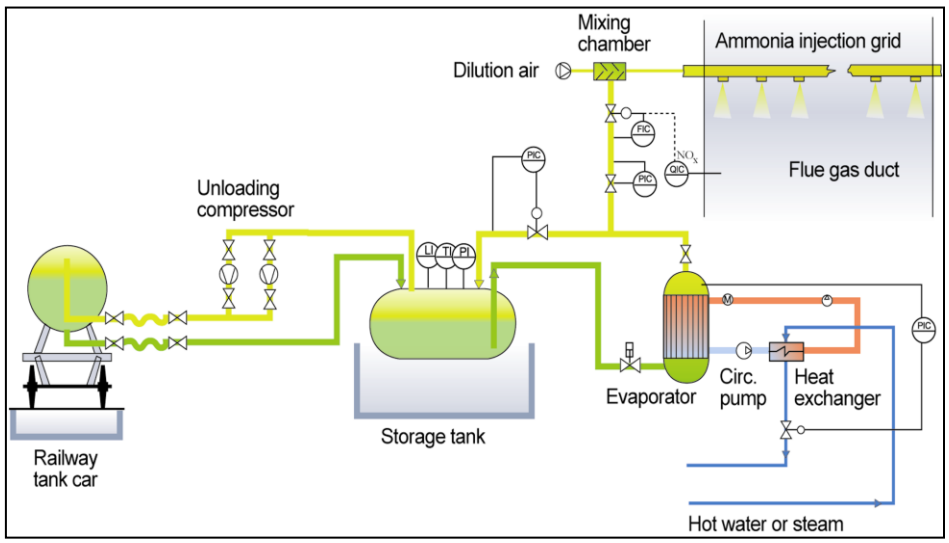

Figure 8-4. Anhydrous Ammonia Flow Diagram

Aqueous Ammonia – ammonia absorbed into water, as compared to anhydrous ammonia.

Advantages:

- It's perceived as low toxic risk

Disadvantages:

- The mass and volume of reagent to be transported, stored and handled is far greater.
- The capital and operating costs are both higher.
- Far more process heat is required to vaporize the water/ammonia solution.

Urea In most systems, the urea is converted on site to ammonia at the required rate with little or no ammonia storage.

Advantages:

- Urea can be shipped and stored as a solid.
- The toxic and hazard risk is much lower since ammonia is not transported or stored in significant quantities.

Disadvantages:

- This is the most costly system on both a first cost and operating cost basis.

- The handling system for the solid urea is far more complex and requires more maintenance.
- The Urea-to-ammonia processing facility is costly, complex and requires more energy.

The urea to ammonia system shown in figure 8-5 dissolves the solid urea into water. The solution is evaporated and passed through a decomposition catalyst where the urea is converted into ammonia.

$$H_2NCONH_2 + H_2O \rightarrow 2NH_3 + CO_2$$

There are no pressure vessels to pose a risk of hazardous or toxic release.

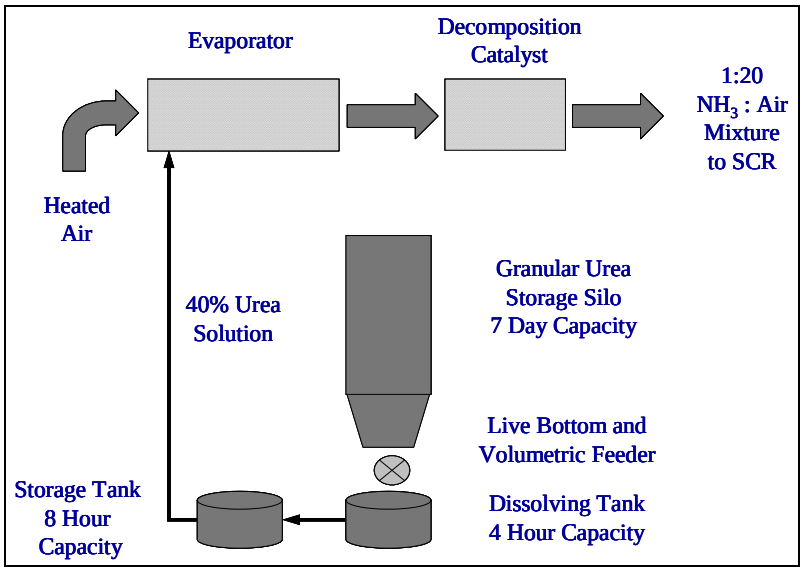

Figure 8-5. Urea to Ammonia "On Demand" System

Ammonium Bisulfate Formation

In any system where ammonia and sulfur trioxide is present there is the potential formation of ammonium bisulfate. This substance is a liquid or sticky solid at typical exhaust temperatures, causing fouling or plugging of a catalyst, air heater or other hardware.. Some of the catalysts used in SCR will oxidize SO_2 into SO_3. A CO oxidizing catalyst will do the same. If there is excess ammonia, it will react with the SO3 to form ammonium bisulfate.

$$NH_{3(g)} + SO_{3(g)} + H_2O_{(g)} \rightarrow NH_4HSO_{4(l)}$$

The bisulfate will deposit in the cold end of the boiler and economizer and plug the spaces between the heat exchanger fins. This chokes off the air flow and reduces the effectiveness of the heat recovery. There are several design consideration that will minimize the risk, including:

- What is the maximum permitted ammonia slip (emissions),
- Designing the catalyst for low SO2 to SO3 oxidatioin
- Installing an economizer bypass system to raise exhaust temperature and/or

- Installing an air heater to assure that the temperature in the cold end does not drop to the point were the bisulfate will precipitate.

Gas Turbine Applications

Because of the temperature windows associated with SCR, the system is usually installed in the heat recovery steam generator (HRSG). The system selected depends on the design of the HRSG. A turbine exhaust is typically 900°F or above, while the HRSG exhaust can be 300°F. Both high and low temperature catalysts are expensive, so the optimum configuration puts the catalyst somewhere in the middle of the HRSG. Here are three common scenarios.

- New HRSG – If the application is a new cogeneration system, the HRSG will be designed to accommodate the SCR. Usually the evaporator section will be split, and the SCR will be located between evaporator sections where the temperature range will allow the use of a base metal catalyst system. These systems are commonly permitted at 3.5 ppm or less.

- Retrofit Existing Cogeneration – In an existing system, it is usually impossible to split the evaporator section of the HRSG. In this case, a base metal system can not be used because the temperature before the evaporator is too high, and after is too low. The most common option is to locate the SCR between the evaporator and the economizer. The temperature range in this area will accommodate a precious metal SCR system. These systems can also achieve 3.5 ppm or less.

- Peaking Generator – In a peaking generation application or any other application where there is no heat recovery, the only alternative is usually a zeolite catalyst system. Experience on these systems is more limited. The first system was a demonstration project with limited success. The second system, consisting of 4 gas turbine 5000 HP natural gas compression units, was permitted at 8 ppm for operation in California. The initial SCR system failed in that it had numerous exceedences. At the insistence of EPA Region IX, the operator installed a second SCR system from a different supplier. That system has been operating successfully at less than 8 ppm for about 4,000 hours per year each since installation (about 2000). Several other units have been installed on 25 MW peaking turbines in California, permitted at 5 ppm. These have not had consistent results, and, since they are peaking units, they do not accumulate many hours of operation. In making a BACT/LAER determination, at the time this was written, 8 ppm can clearly be justified, but 5 ppm is marginal and although suppliers may guarantee as low as 2.5 ppm, there is not operating experience to support a permit at this level.

Considerations

When applying SCR to a gas turbine application there are several design constraints that must be considered:

- Turndown – As the load on the gas turbine decreases, the exhaust temperature will also decrease. The decreasing temperature in the SCR will affect its performance. It is important to assure that the temperature will support the effectivity necessary to meet NOx limits throughout the design load range.

- Duct Burners – Gas turbine exhaust still contains about 13% to 16% oxygen, enough to support the combustion of a lot more fuel. In many cogeneration applications, a “duct

burner" will be inserted into the exhaust between the turbine and the HRSG. This can be used to increase the temperature of the exhaust from 900°F to as much as 2300°F. The temperature variation in the SCR resulting from the duct burner must also be considered to assure compliant operation over the duct burner range as well as the gas turbine turndown.

Boiler and Heater Applications

When an SCR system is installed on a utility boiler, it will likely be one of several pollution control devices. There can be a scrubber for acid gases and, on a coal fired boiler, there will be a dust collector. The design of an SCR system is greatly influenced by whether it is placed upstream or downstream of other pollution control equipment. Here are some of the considerations in designing the configuration for boiler or heater applications.

- The SCR catalyst must be located at a point where it will see the necessary temperature range. The temperature range for the least expensive catalyst is usually upstream of other equipment where dust and other pollutants are present.
- Catalyst life will be longer the other pollutants have been removed
- On coal fired boilers, ash is a major consideration in the system design. If the SCR system is upstream of the dust collector, the catalyst must have very large passages to avoid plugging. This makes the catalyst extremely large.

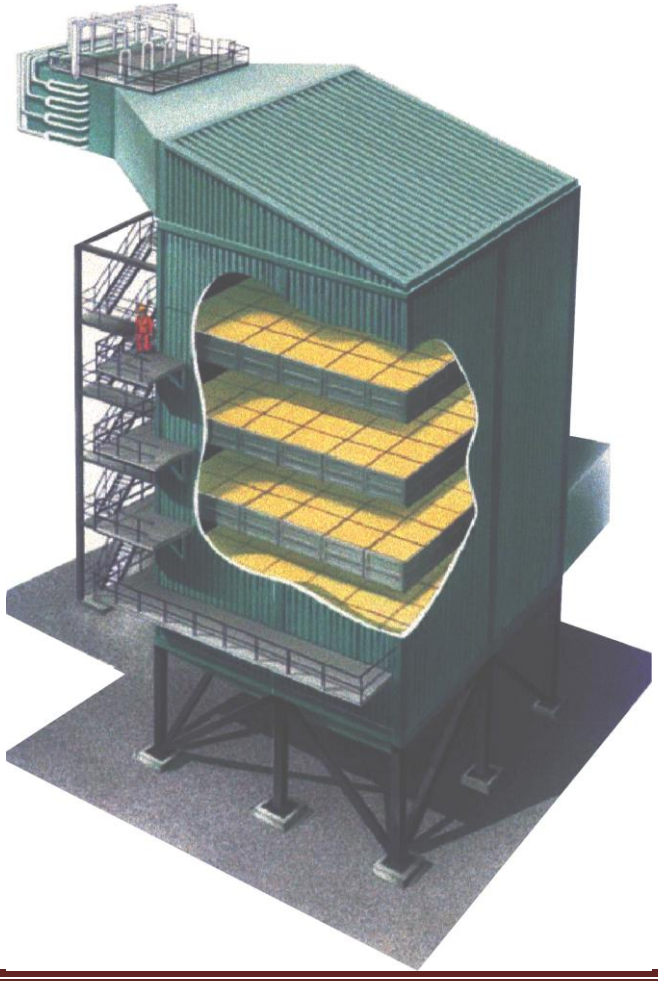

Figure 1.6 Typical SCR Configuration for a Large Boiler

- If the catalyst is after the dust collector, where there is very little ash, it can have very small passages, which keeps the size and cost of the system down. But in most applications the temperature after the dust collector is too low and the exhaust will need to be reheated to be viable for the SCR. Reheating the exhaust is expensive.
- SO2 to SO3 oxidation is a concern because of the ammonium bisulfate formation, but the low temperature will incur a heavy cost to reheat the exhaust gas.
- Turndown can be a consideration for boiler applications, although the turndown temperature range doesn't usually fall outside the catalyst operating range.

Reciprocating Internal Combustion Engine (RICE) Applications

There are several limiting characteristics in applying exhaust clean-up systems to reciprocating engines. If the engine is compression ignition (diesel fuel), NOx control technology has been developing slowly. The reason is that diesel engines are usually used for emergency service or portable equipment and have not been required to limit NOx emissions. Back end diesel engine NOx technology has been developing for mobile sources and this technology will likely be applied to stationary sources as the need arises. The preferred technology appears to be SCR with a system to convert urea to ammonia.

Most of the stationary RICE are spark ignition burning natural gas. There has been considerable progress in reducing NOx formation in these engines. (as noted in Chapter 6) and back end control, when needed, is usually SCR. This technology is well established and 90% (or greater) emission reduction is possible.

While NSCR is used on all gasoline automobiles in this country, it is not clear whether the technology will spread to other types of combustion sources. It is not immediately applicable to diesel engines, because diesel exhaust oxygen levels vary widely depending on engine load. NSCR might be applicable to boilers, but implementation will depend on how it compares with other NOx control technologies available to stationary sources.

SCR Summary

Process Design Issues

- Required NOx removal efficiency (impacts costs and ammonia slip)
- Permitted ammonia emissions (tradeoff of catalyst life vs. ammonia slip)
- SO_2 Oxidation to SO_3 (problems with acid corrosion or ammonium bisulfate)
- System Draft Loss (imposing backpressure on the combustion device)
- Catalyst Life Expectancy
- Ammonium Bisulfate Formation
- Application Specific Issues (physical space, existing hardware, etc)

Factors to Consider

- SCR has little impact on the existing process
- Proven technology, well supported
- Permitting impacts
- Risk management planning required by ammonia storage
- Real-estate available
- Visibility & community impacts

SCR Experience

- 80 to 90% reduction has been achieved with up to 20 years of operation.
- Catalyst lifetimes generally good, but are traded against ammonia slip limits
- Widely applicable to many types of sources
- Low technical and economic risk – SCR is a mature technology
- Often, some real cost factors are not identified and considered when permitting and budgeting.

Non Selective Catalytic Reduction (NSCR)

This technology uses a catalyst without the need for a reagent. The catalyst causes the NOx to give up its oxygen to products of incomplete combustion (PICs) – CO and hydrocarbons. The general form of the chemical equations are:

$$CO + NO \rightarrow CO_2 + N_2$$

$$HC + NO \rightarrow CO_2 + H_2O + N_2$$

In effect the two types of pollutants destroy each other. Aside from the catalyst, the key to this reaction is the absence of oxygen. Any oxygen present will allow the PICs to burn up without destroying the NOx. So the combustion system must be operated with zero excess air. Note that operating the combustor with zero excess air assures there will be some PICs present as well as somewhat suppressing NOx formation – see Figure 3-4.

To date the main application of this technology has been gasoline fueled automobiles. Probably the key piece of technology is the control device that keeps the excess air at exactly zero. It uses an oxygen sensor, but that device alone only gives a reading when the oxygen concentration is above zero. When there insufficient air flow, the oxygen sensor reads zero regardless of whether the excess air level is zero or negative. The solution is a fuel flow oscillator that causes the fuel flow to fluctuate very slightly but very rapidly (60 cycles per second). When the average excess air is zero, the oxygen sensor picks up a small reading half the time. The control system operates to maintain the oxygen sensor reading at this level.

Emerging Technologies

Since the mid 1990's, a number of new technologies have been shown to have potential. This section reviews several of them. It is not necessarily a complete list, and some of these technologies have achieved more commercialization than others. The technologies that are included are:

- SCONOX
- Raper-NOx
- LoTOx
- Activated Carbon Adsorption

SCONOx

In this document, the technology is referred to by the name most commonly used. In fact, both the name of the company and the technology were changed recently. The name of the company was Goal Line Environmental Technologies, and is now EmeraChem. The technology which was SCONOX is now EM_X^{GT} where the GT stands for the application of the product, in this case, gas turbines.

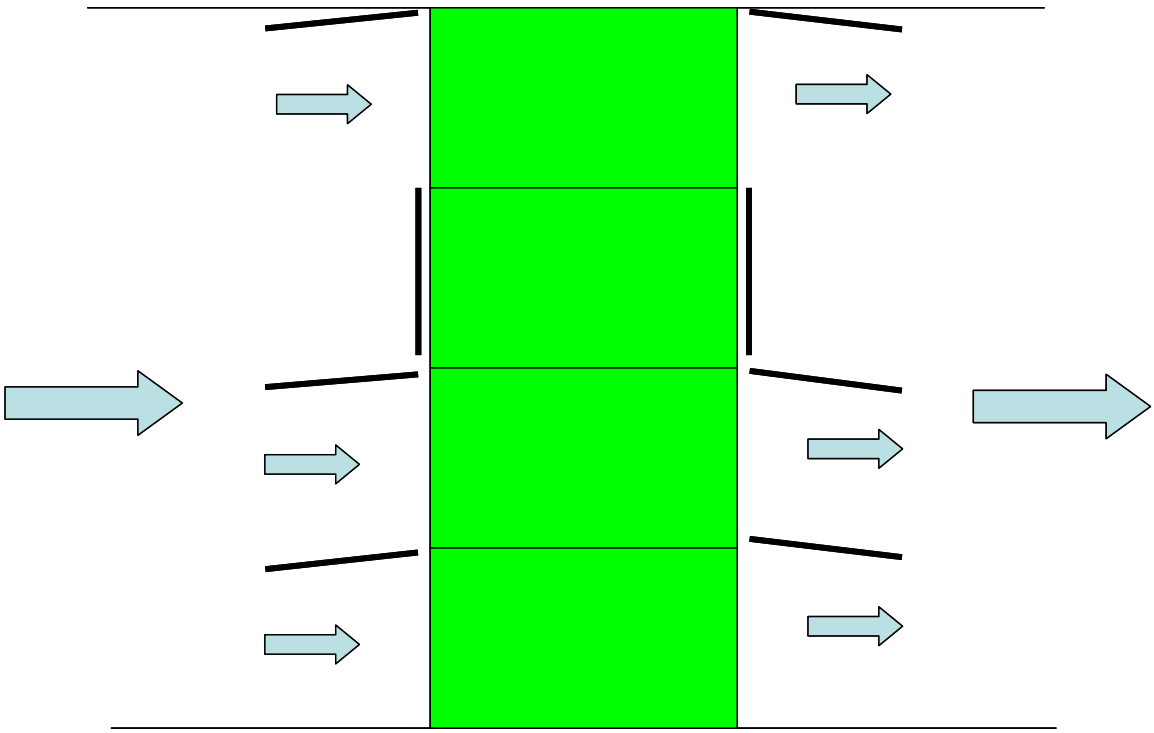

Fig. 8-7 SCONOX Chamber Configuration for Regeneration

In application, SCONOX has some similarities to SCR with four significant exceptions:

- It does not require a reducing agent
- It reduces the emissions of CO as well as NOx
- It is usually significantly more expensive, both first and operating cost.

SCR becomes less effective as exhaust concentrations get very low, but Sconox will still perform effectively with very low inlet NOx concentrations.

Like SCR, SCONOX is an exhaust gas cleanup technology using a catalytic reactor. Accordingly, it also has little impact on the process, is applicable to almost any combustion source, and is commercially available. However, SCONOX has significant limitations and limited field experience.

SCONOX uses a regenerated catalytic system. They catalytic bed has 2 materials together. A precious metal oxidizing catalyst (usually platinum) and potassium carbonate. The platinum oxidizes the NO into NO_2. The NO_2 can then be adsorbed onto the potassium carbonate. Once the potassium carbonate is saturated with NO_2, it mst be regenerated with a high hydrogen gas. The hydrogen react with the NO_2 to form water and N_2. The oxidizing catalyst, in addition to oxidizing NO into NO_2, also oxidizes CO into CO2. The system can reduce both NOx and CO by up to 90%.

The regeneration is part of the operation cycle. The catalyst is contained in separate chambers, usually 4 or groups of 4. Each of these chambers or groups of chambers will be exposed to the exhaust stream for about 15 minutes. At that time, the potassium carbonate becomes saturated with NOx. That chamber or group of chambers is them isolated from the exhaust stream by air tight doors, and the high hydrogen regeneration gas is circulated through the chamber (s). The regeneration usually takes about 5 minutes. The first chamber or group is then opened to the ehaust stream, and the second chamber or group of chambers begins regeneration. When the 4th chamber or group has completed regeneration, the process is repeated.

The high hydrogen regeneration gas is manufactured at the unit from natural gas using a steam reformer or a natural gas fired reformer.

SCONOX has been demonstrated to reduce NOx to less than 2.5 ppmvd (15% O_2). To achieve these levels, the NOx in the engine exhaust cannot be to high, typically less than 25 ppm. It has been successfully applied to:

- Gas Turbines
- Boilers
- Reciprocating Engines

There are several limitations to the application of SCONOX. These include:

- The technology is so intolerant of sulfur that it's impractical on oil fired sources. A typical installation on natural gas will include a sulfur removal section before the NOx catalyst section. The sulfur removal bed is regenerated at the same time and in the same way as the NOx section, with the liberated SO_2 being returned to the exhaust. There is no net change in the SO_2 in the stack.
- The temperature range for this technology is 450 to 700°F.
- As discussed above, the exhaust NOx concentration must be low for the unit to achieve 2.5 ppm.

SCONOX Summary

Advantages:

- Does not use reactant (e.g. ammonia or urea)
- Effectivity does not tail off at low NOx levels
- Demonstrated at less than 2.5 ppm NOx
- Scalable to any size

Disadvantages:

- First cost is higher than SCR
- Operating Cost is higher than SCR
- Catalyst wash every 90 days
- Distillate fuels still a problem
- Can't be used without heat recovery

Operating Experience:

- LM2500 gas turbine – 25 MW over 30,000 Hours
  - Confirmed by EPA and SCAQMD at less than 2.5 ppm on 1 hour rolling average basis
  - Now out of service, not due to SCONOX problems.
- Taurus 60 – 5 MW over 20,000 Hours
  - Liquid fuel operating problems
- 2 – Titans – 13 MW each over 5,000 Hours
  - Operating satisfactorily

Raper-NOx

In the mid-eighties, the US DOE's Sandia Labs in Livermore CA patented a new back-end NOx control technology. It was purported to not be catalytic. The process consisted of passing the hot exhaust through crystals of cyanic acid, an inexpensive chemical commonly used to treat swimming pools. In the hot exhaust, the cyanic acid crystals break down to form iso-cyanic acid (C_2H_5NCO) which reacts with the NOx to form CO_2, N_2 and water.

The technology has had several owners over the last 20 years, but has never been offered commercially. In this discussion the process would be classified as SNCR, but at one time, there was a question whether the stainless steel tubing used in the initial development was acting as a catalyst to bring about the reaction. In that case, this technology would have been another form of SCR .

LoTOx (Ozone Injection)

In looking at this technology, it is interesting to note that NOx is now attainment in almost all areas of the country, so the primary reason for controlling NOx is that it is a precursor to ozone. This technology starts by injecting ozone into the exhaust stream!

The principle is to further oxidize NO and NO_2 into NO_3 which is very soluble in water. The exhaust is then scrubbed to remove the NO_3 and the remaining ozone. Some other benefits are the oxidation of Carbon Monoxide hydrocarbons and organic toxics. The scrubbing process also removed SO_2 and particulate emissions. When it was first introduced, the combustion group of the US EPA was very excited. Here was a technology that removes all of the combustion pollutants at once.

The primary problem associated with the technology is the costs (both initial and operating costs) associated with the scrubbing operation. The only other costs are the ozone generator and controls & monitoring. But, in many applications, the scrubbing process is not cost effective when compared to other NOx control technologies.

The technology has found application in processes that require wet scrubbing for reasons other than NOx control. In those cases, the incremental cost of adding LoTOx is often cost effective in those applications.

This process was developed by several suppliers, but is currently marketed under the LoTOx name by BOC, a supplier of industrial gasses including span gasses.

Activated Carbon Absorption with Microwave Regeneration

Chang Y. Cha of the University of Wyoming has completed several demonstration projects using this technology. It appears to be successful in reducing NOx form a diesel engine, but it has not been progressing toward commercialization.

It consists of alternating beds of activated carbon. The exhaust flows through one while the other is regenerated with microwaves.

Summary of Significant Back End and Emerging Controls

SNCR Selective Non-Catalytic Reduction: Inject ammonia or urea into a hot (1650°F) gas stream to react/destroy NOx. Thermal DeNOx uses ammonia and is only feasible on new boilers. NOxOut uses urea dissolved in water which is sprayed into the gas stream -- it's been retrofitted on existing boilers. 50% to 70% effective.

SCR Selective Catalytic Reduction: Same chemistry as SNCR, but at temperatures of 550°F to 1050°F depending on catalyst. Applicable to most combustion sources. It can be over 90% effective depending on catalyst size & ammonia injection rate.

NSCR Non-Selective Catalytic Reduction: A catalyst causes NOx and CO to react – destroying both species. Reaction requires the absence of oxygen – hence precise combustion air control is required. It's the basis of automobile emission control.

SCONOX (EM_X^{GT}) This technology absorbs NOx on coated panels that must be regenerated with hydrogen every 15 minutes. Applicable to low NOx sources fired with natural gas. Proven technology, but it's expensive and it's only been applied a few times.

XONON (NoNOx) Catalytic combustion reduces NOx formation gas fired turbines. It's simple, has very low emissions, has been demonstrated on a few turbines, but is not widely adopted.

Review Exercises

1. What is SNCR?

2. SCR requires: (select all that apply)
    a. catalyst selected to match the gas temperature.
    b. ammonia reagent
    c. low oxygen content in the exhaust
    d. a system (usually CEM) to match the reagent flow to the NOx emissions.
    e. low sulfur fuel

3. Describe the relationship(s) between catalyst size and life expectancy, permitted NOx emissions and permitted ammonia slip.

4. Which statements regarding SNCR systems are true?
    a. Thermal DeNOx using ammonia can be retorfitted to many existing boilers.
    b. NOxOut sprays an aqueous solution of urea into the boiler.
    c. SNCR systems can achieve up to 90% NOx removal.
    d. SNCR works in relatively narrow temperature windows above 1500°F

5. Which statement is true regarding SCONOX (EMXGT)
    a. The panels absorb a fixed quantity of NOx before it saturates and needs to be recycled
    b. It requires a reagent to destroy the NOx
    c. It will work in the exhaust of an oil fired boiler or engine
    d. It controls SO2 emissions as well as NOx and CO.

6. What is NSCR?

Review Exercises – Answer Key

1. *Selective Non Catalytic Reduction injects ammonia or urea into the gas stream to destroy NOx. The applicable temperature windows are about 100°F wide above 1500°F, so the main application is in boilers.*

2. **a. catalyst selected to match the gas temperature.**
   b. ammonia reagent
   d. a system (usually CEM) to match the reagent flow to the NOx emissions.

3. *Increasing catalyst size will increase NOx destruction efficiency. Since catalyst effectiveness deteriorates with time, a system with extra capacity will last longer. Increasing ammonia flow will increase both effectiveness and ammonia slip – so there is a trade off between NOx and ammonia emissions. The tighter the NOx and ammonia emissions, the larger the catalyst and the shorter its life.*

4. **b. NOxOut sprays an aqueous solution of urea into the boiler.**
   d. SNCR works in relatively narrow temperature windows above 1500°F

5. **a. The panels absorb a fixed quantity of NOx before they saturate and needs to be regenerated**

6. *Non-Selective Catalytic Reduction uses a catalyst to make CO and NOx mutually self destruct – CO steals oxygen from the NOx. It only works if the exhaust oxygen level is essentially zero. It's very effective and is the basic concept for automobiles catalytic emission controls..*