Select the Right NO_x Control Technology

Consider the degree of emission reduction needed, the type of fuel, combustion device design, and operational factors.

Stephen C. Wood,
Energy Technology Consultants, Inc.

Most major industrialized urban areas in the U.S. are unable to meet the National Ambient Air Quality Standards (NAAQS) for ozone. Atmospheric studies have shown that ozone formation is the result of a complex set of chemical reactions involving volatile organic compounds (VOCs) and nitrogen oxides (NO_x). These studies indicate that many urban areas with VOC/NO_x ratios greater than 15:1 can reduce ambient ozone levels only by reducing NO_x emissions. Many states, therefore, are implementing NO_x control regulations for combustion devices in order to achieve compliance with the NAAQS ozone standard.

This article discusses the characterization of NO_x emissions from industrial combustion devices. It then provides guidance on how to evaluate the applicable NO_x control technologies and select an appropriate control method.

Characterizing emissions

Most industrial combustion devices have not been tested to establish their baseline NO_x emission levels. Rather, the NO_x emissions from these units have been simply estimated using various factors. In light of recent regulations, however, it is mandatory that the NO_x emissions from affected units now be known with certainty. This will establish each unit's present compliance status and allow definition of the applicable control technologies for those units that will require modification to achieve compliance.

Many of the emissions inventories supplied by industry were derived from the U.S. Environmental Protection Agency's "AP-42 Emission Factors" document *(1)*. NO_x emissions from combustion devices are quite variable and depend on a number of design, operational, and fuel conditions. Thus, the AP-42 factors, which were derived from the results of a number of test programs sponsored by the EPA during the 1970s, may be inaccurate when applied to a particular combustion device.

It is, therefore, important to test each combustion device to verify its NO_x emissions characteristics. The testing process should be streamlined to provide timely and necessary information for making decisions regarding the applicability of NO_x control technologies.

The basic approach is to select one device from a class of units (that is, of same design and size) for characterization testing (NO_x, CO, and O_2). Testing is conducted at three load points that represent the normal operating range of the unit, with excess oxygen variation testing conducted at each load point. Figure 1 illustrates the typical characterization test results. The remaining units in the class are tested at only one load point, at or near full load.

The operational data obtained during testing, in conjunction with the NO_x and CO data, are used to define the compliance status of each unit, as well as the applicable NO_x control technologies for those devices that must be modified. In most instances, this approach will allow multiple units to be tested in one day and provide the necessary operational data the engineer needs to properly evaluate the potential NO_x control technologies. Table 1 lists the operational data that should be obtained during the characterization testing.

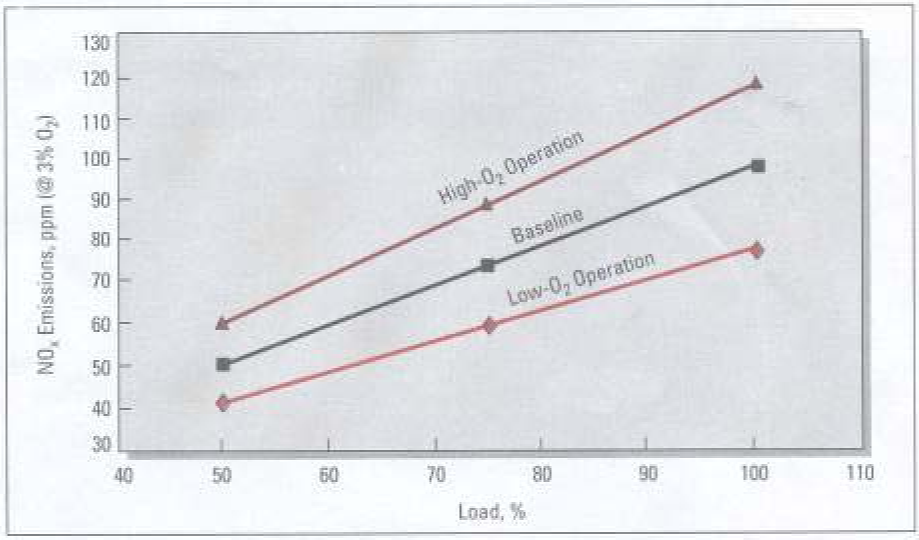


Figure 1. Characterization testing gathers NO_x emission data as a function of oxygen level and operating load.

Table 1. Collect the following operational and emissions data for each device during characterization testing.

- Flow Rates
  - Fuel, MMBtu
  - Steam, klb/h
  - Feed Water, klb/h
  - Natural Gas, kscfh
- Draft, in. H_2O
  - Forced-draft Fan
  - Windbox
  - Furnace
- Flame
  - Width, ft
  - Length, ft
- Furnace Vibration, mils
- Ultimate Fuel Analysis (specifics depend on type of fuel)
- Pressures, psig
  - Steam
  - Drum
  - Natural Gas Supply
  - Burner
- Temperatures, °F
  - Feed Water/Economizer Exit
  - Steam
  - Ambient, Wet Bulb
    - Ambient, Dry Bulb
  - Air Preheater
    - Air In
    - Air Out (combustion)
    - Gas In
    - Gas Out
  - Stack
  - Firebox
- Emissions
  - Plant Oxygen, %
  - Test Equipment
    - Oxygen, %
    - Carbon Monoxide, ppm
    - NO_x, ppm
  - NO_x Corrected to 3% O_2
    - ppm
    - lb/h
    - lb/MM Btu

Fundamental concepts

Reasonably available control technology (RACT) standards for NO_x emissions are defined in terms of an emission limit, such as 0.2 lb NO_x/MMBtu, rather than mandating specific NO_x control technologies. Depending on the fuel fired and the design of the combustion device, a myriad of control technologies may be viable options. Before selecting RACT for a particular combustion device, it is necessary to understand how NO_x emissions are formed so that the appropriate control strategy may be formulated.

NO_x emissions formed during the combustion process are a function of the fuel composition, the operating mode, and the basic design of the boiler and combustion equipment. Each of these parameters can play a significant role in the final level of NO_x emissions.

NO_x formation is attributed to three distinct mechanisms:

- thermal NO_x formation;
- prompt (*i.e.*, rapidly forming) NO formation; and
- fuel NO_x formation.

Each of these mechanisms is driven by three basic parameters — temperature of combustion, time above threshold temperatures in an oxidizing or reducing atmosphere, and turbulence during initial combustion.

Thermal NO_x formation in gas-, oil-, and coal-fired devices results from thermal fixation of atmospheric nitrogen in the combustion air. Early investigations of NO_x formation were based upon kinetic analyses for gaseous fuel combustion *(2)*. These analyses by Zeldovich yielded an Arrhenius-type equation showing the relative importance of time, temperature, and oxygen and nitrogen concentrations on NO_x formation in a premixed flame (that is, the reactants are thoroughly mixed before combustion).

While thermal NO_x formation in combustion devices cannot actually be determined using the Zeldovich relationship, it does illustrate the importance of the major factors that influence thermal NO_x formation, and that NO_x formation increases exponentially with combustion temperatures above 2,800°F.

Experimentally measured NO_x formation rates near the flame zone are higher than those predicted by the Zeldovich relationship. This rapidly forming NO is referred to as **prompt NO**. The discrepancy between the predicted and measured thermal NO_x values is attributed to the simplifying assumptions used in the derivation of the Zeldovich equation,

Table 2. Use this chart to screen potential NO_x control technologies.

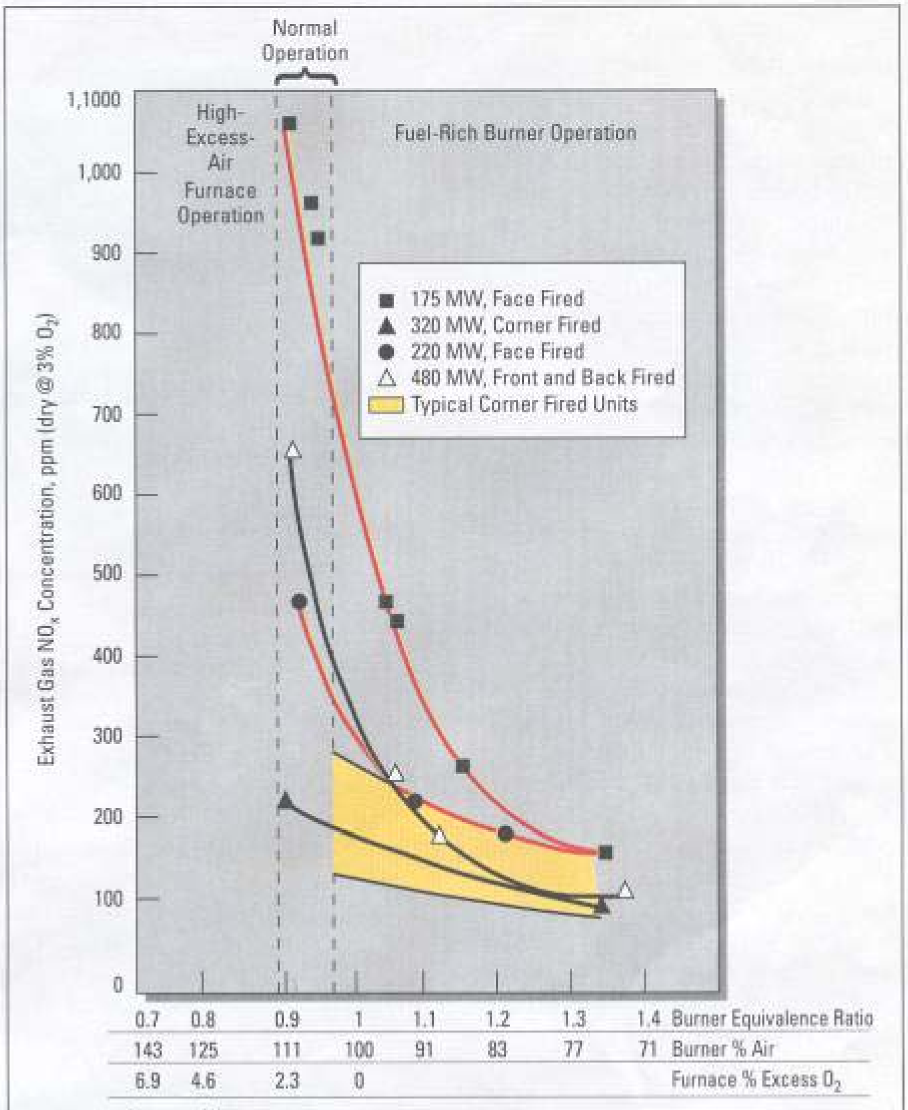
Technique	Description	Advantages	Disadvantages	Impacts To Consider	Applicability	NO_x Reduction
Low Excess Air (LEA)	Reduces oxygen availability	Easy operational modification	Low NO_x reduction potential	High carbon monoxide emissions; Flame length; Flame stability	All fuels	1–15%
Off-Stoichiometric Combustion (OS) a. Burners-out-of-service (BOOS) b. Overfire Air (OFA) c. Air Lances	Staged combustion, creating fuel-rich and fuel-lean zones	Low operating cost; No capital equipment required for BOOS	a. Typically requires higher air flow to control carbon monoxide b. Relatively high capital cost c. Moderate capital cost	Flame length; Forced-draft fan capacity; Burner header pressure	All fuels; Multiple-burner devices	30–60%
Low-NO_x Burners (LNB)	Provides internal staged combustion, thus reducing peak flame temperatures and oxygen availability	Low operating cost; Compatible with FGR as a combination technology to maximize NO_x reduction	Moderately high capital cost; Applicability depends on combustion device and fuels, design characteristics, waste streams, etc.	Forced-draft fan capacity; Flame length; Design compatibility; Turndown flame stability	All fuels	30–50%
Flue Gas Recirculation (FGR)	Up to 20–30% of the flue gas is recirculated and mixed with the combustion air, thus decreasing peak flame temperatures	High NO_x reduction potential for natural gas and low-nitrogen fuels	Moderately high capital cost; Moderately high operating cost; Affects heat transfer and system pressures	Forced-draft fan capacity; Furnace pressure; Burner pressure drop; Turndown flame stability	Gas fuels and low-nitrogen fuels	40–80%
Water/Steam Injection (WSI)	Injection of steam or water at the burner, which decreases flame temperature	Moderate capital cost; NO_x reductions similar to FGR	Efficiency penalty due to additional water vapor loss and fan power requirements for increased mass flow	Flame stability; Efficiency penalty	Gas fuels and low-nitrogen fuels	40–70%
Reduced Air Preheat (RAPH)	Air preheater modification to reduce preheat, thereby reducing flame temperature	High NO_x reduction potential	Significant efficiency loss (1% per 40°F)	Forced-draft fan capacity; Efficiency penalty	Gas fuels and low-nitorgen fuels	25–65%
Selective Catalytic Reduction (SCR)	Catalyst located in flue gas stream (usually upstream of air heater) promotes reaction of ammonia with NO_x	High NO_x removal	Very high capital cost; High operating cost; Extensive ductwork to and from reactor required; Large volume reactor must be sited; Increased pressure drop may require induced-draft fan or larger forced-draft fan; Reduced efficiency; Ammonia sulfate removal equipment for air heater required; Water treatment of air heater wash required	Space requirements; Ammonia slip; Hazardous-waste disposal	Gas fuels and low-sulfur liquid and solid fuels	70–90%
Selective Noncatalytic Reduction (SNCR) — Urea Injection	Injection of urea into furnace to react with NO_x to form nitrogen and water	Low capital cost; Relatively simple system; Moderate NO_x removal; Nontoxic chemical; Typically low energy injection sufficient	Temperature dependent; Design must consider boiler operating conditions and design; NO_x reduction may decrease at lower loads	Furnace geometry and residence time; Temperature profile	All fuels	25–50%
Selective Noncatalytic Reduction (SNCR) — Ammonia Injection (Thermal $DeNO_x$)	Injection of ammonia into furnace to react with NO_x to form nitrogen and water	Low operating cost; Moderate NO_x removal	Moderately high capital cost; Ammonia handling, storage, vaporization, and injection systems	Furnace geometry and residence time; Temperature profile	All fuels	25–50%

such as the equilibrium assumption that O = ½O_2. Near the hydrocarbon-air flame zone, the concentration of the formed radicals, such as O and OH, can exceed the equilibrium values, which enhances the rate of NO_x formation. However, the importance of prompt NO in NO_x emissions is negligible in comparison to thermal and fuel NO_x.

When nitrogen is introduced with the fuel, completely different characteristics are observed. The NO_x formed from the reaction of the fuel nitrogen with oxygen is termed **fuel NO_x**. The most common form of fuel nitrogen is organically bound nitrogen present in liquid or solid fuels where individual nitrogen atoms are bonded to carbon or other atoms. These bonds break more easily than the diatomic N_2 bonds so that fuel NO_x formation rates can be much higher than those of thermal NO_x. In addition, any nitrogen compounds (*e.g.*, ammonia) introduced into the furnace react in much the same way.

Fuel NO_x is much more sensitive to stoichiometry than to thermal conditions. For this reason, traditional thermal treatments, such as flue gas recirculation and water injection, do not effectively reduce NO_x emissions from liquid and solid fuel combustion.

NO_x emissions can be controlled either during the combustion process or after combustion is complete. Combustion control technologies rely on air or fuel staging techniques to take advantage of the kinetics of NO_x formation or introducing inerts that inhibit the formation of NO_x during combustion, or both. Post-combustion control technologies rely on introducing reactants in specified temperature regimes that destroy NO_x either with or without the use of catalyst to promote the destruction. Table 2 summarizes the commercially available NO_x control technologies, as well as their relative efficiencies, advantages and disadvantages, applicability, and impacts.



Source: *(3)*

Figure 2. Burners-out-of-service can be an effective combustion staging technique.

Combustion control

The simplest of the combustion control technologies is **low-excess-air operation** — that is, reducing the excess air level to the point of some constraint, such as carbon monoxide formation, flame length, flame stability, and so on. Unfortunately, low-excess-air operation has proven to yield only moderate NO_x reductions, if any.

Three technologies that have demonstrated their effectiveness in controlling NO_x emissions are off-stoichiometric combustion, low-NO_x burners, and combustion temperature reduction. The first two are applicable to all fuels, while the third is applicable only to natural gas and low-nitrogen-content fuel oils.

Off-stoichiometric, or staged, combustion is achieved by modifying the primary combustion zone stoichiometry — that is, the air/fuel ratio. This may be accomplished operationally or by equipment modifications.

An operational technique known as burners-out-of-service (BOOS) involves terminating the fuel flow to selected burners while leaving the air registers open. The remaining burners operate fuel-rich, thereby limiting oxygen availability, lowering peak flame temperatures, and reducing NO_x formation. The unreacted products combine with the air from the terminated-fuel burners to complete burnout before exiting the furnace. Figure 2 illustrates the effectiveness of this technique applied to electric utility boilers.

Staged combustion can also be achieved by installing air-only ports, referred to as overfire air (OFA) ports, above the burner zone, redirecting a portion of the air from the burners to the OFA ports. A variation of this concept, lance air, consists of installing air tubes around the periphery of each burner to supply staged air.

BOOS, overfire air, and lance air achieve similar results. These techniques are generally applicable only to larger, multiple-burner, combustion devices.

Low-NO_x burners are designed to achieve the staging effect internally. The air and fuel flow fields are partitioned and controlled to achieve the desired air/fuel ratio, which reduces NO_x formation and results in complete burnout within the furnace. Low-NO_x burners are applicable to practically all combustion devices with circular burner designs. [Low-NO_x burners are covered in more detail in the article by Garg, pp. 46–49. — Editor]

Combustion temperature reduction is effective at reducing thermal NO_x, but not fuel NO_x. One way to reduce the combustion temperature is to introduce a diluent. **Flue gas recirculation** (FGR) is one such technique.

FGR recirculates a portion of the flue gas leaving the combustion process back into the windbox. The recirculated flue gas, usually on the order of 10–20% of the combustion air, provides sufficient dilution to decrease NO_x emission. Figure 3 correlates the degree of emission reduction with the amount of flue gas recirculated.

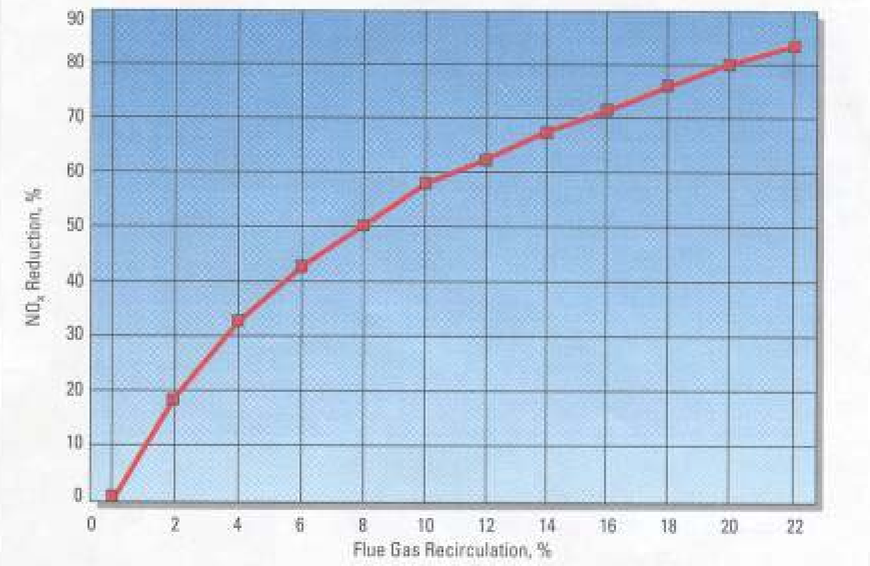


Figure 3. NO_x reduction is a function of the amount of flue gas recirculated.

On gas-fired units, emissions are reduced well beyond the levels normally achievable with staged combustion control. In fact, FGR is probably the most effective and least troublesome system for NO_x reduction for gas-fired combustors.

An advantage of FGR is that it can be used with most other combustion control methods. Many industrial low-NO_x burner systems on the market today incorporate induced FGR. In these designs, a duct is installed between the stack and forced-draft inlet (suction). Flue gas products are recirculated through the forced-draft fan, thus eliminating the need for a separate fan.

Water injection is another method that works on the principle of combustion dilution, very similar to FGR. In addition to dilution, it reduces the combustion air temperature by absorbing the latent heat of vaporiza-

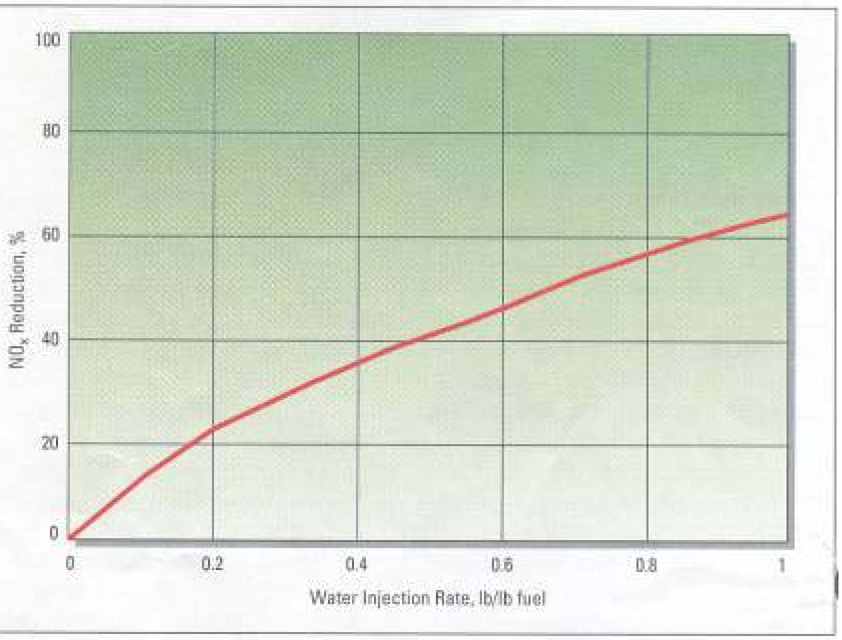


Figure 4. Water injection can reduce NO_x emissions.

tion of the water before the combustion air reaches the primary combustion zone.

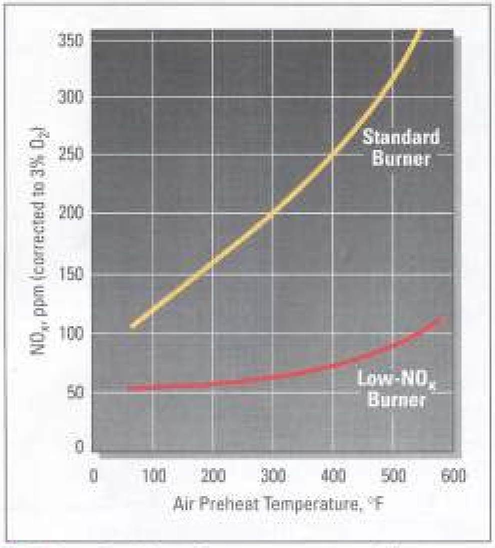
Few full-scale retrofit or test trials of water injection have been performed. What little data exist suggest that the NO_x reductions follow the relationship shown in Figure 4.

Until recently, water injection has not been used as a primary NO_x control method on any combustion devices other than gas turbines because of the efficiency penalty resulting from the absorption of usable energy to evaporate the water. In some cases, water injection represents a viable option to consider when moderate NO_x reductions are required to achieve compliance.

Reduction of the air preheat temperature is another viable technique for cutting NO_x emissions, as shown in Figure 5. This lowers peak flame temperatures, thereby reducing NO_x formation. The efficiency penalty, however, may be substantial. A rule of thumb is a 1% efficiency loss for each 40°F reduction in preheat. In some cases this may be offset by adding or enlarging the existing economizer.

Post-combustion control

There are two technologies for controlling NO_x emissions after formation in the combustion process — selective catalytic reduction (SCR) and selective noncatalytic reduction (SNCR). Both of these processes have seen very limited application in the U.S. for external combustion devices. In **selective catalytic reduction**, a gas mixture of ammonia with a carrier gas (typically compressed air) is injected upstream of a catalytic reactor operating at temperatures between 450°F and 750°F. NO_x control efficiencies are typically in the 70–90% percent range, depending on the type of catalyst, the amount of ammonia injected, the initial NO_x level, and the age of the catalyst.



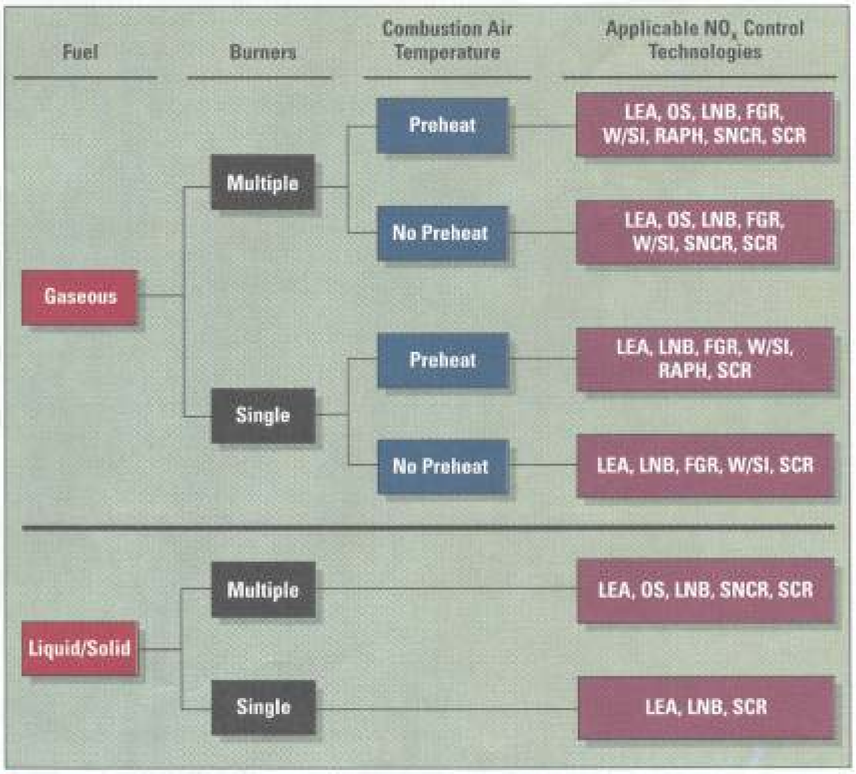
■ *Figure 5. Air preheat temperature affects boiler NO_x emissions.*

The retrofit of SCR on existing combustion devices can be complex and costly. Apart from the ammonia storage, preparation, and control monitoring requirements, significant modifications to the convective pass ducts may be necessary. [SCR is discussed by Cho in the article following this one, pp. 39–45. — Editor]

In **selective noncatalytic reduction**, ammonia- or urea-based reagents are injected into the furnace exit region, where the flue gas is in the range of 1,700–2,000°F. The efficiency of this process depends on the temperature of the gas, the reagent mixing with the gas, the residence time within the temperature window, and the amount of reagent injected relative to the concentration of NO_x present. The optimum gas temperature for the reaction is about 1,750°F; deviations from this temperature result in a lower NO_x reduction efficiency. Application of SNCR, therefore, must be carefully assessed, as its effectiveness is very dependent on combustion device design and operation.

Technology selection

As noted previously, selection of applicable NO_x control technologies depends on a number of fuel, design, and operational factors. Figure 6 sum-



■ *Figure 6. Use these guidelines to identify potential NO_x control technologies.*

Table 3. NO_x control efficiencies are multiplicative.

Control Technology	Efficiency	Final NO_x Level, ppm
Low-Excess-Air	10%	100(1–0.10) = 90
Low-NO_x Burner	40%	90(1–0.40) = 54
Flue Gas Recirculation	60%	54(1 – 0.6) = 21.6

marizes the choices for various scenarios. Figure 6 and Table 2 can be used to identify the potential control technologies for boilers and process heaters. After identifying the applicable control technologies, an economic evaluation must be conducted to rank the technologies according to their cost effectiveness. Management can then select the optimum NO_x control technology for the specific unit.

It should be noted that the efficiencies of NO_x control technologies are not additive, but rather multiplicative. Efficiencies for existing combustion devices have been demonstrated in terms of percent reduction from baseline emissions level. This must be taken into account when considering combinations of technology.

Consider, for example, the following hypothetical case. Assume a baseline NO_x emissions level of 100 ppmv and control technology efficiencies as follows: low-excess-air operation (LEA), 10%; low-NO_x burners (LNB), 40%; and flue gas recirculation (FGR), 60%. The three controls are installed in the progressive order of LEA-LNB-FGR. The stage-wise emission reductions are shown in Table 3.

It should also be noted that combining same-principle technologies (for example, two types of staged combustion) would not provide a further significant NO_x reduction than either of the combination, since they operate on the same principle.

It must be emphasized that virtually all of the available control technologies have the potential for adversely affecting the performance and/or operation of the unit. The operational data obtained during the NO_x characterization testing, therefore, must be carefully evaluated in light of such potential impacts before selecting applicable control technologies. Operational limitations such as flame envelope, furnace pressure, forced-draft fan capacity, and the like must be identified for each potential technology and their corresponding impacts quantified. (Reference *(4)*, for example, discusses these items in detail.)

As anyone familiar with combustion processes knows, one technology does not fit all. Careful consideration must be used to select the appropriate, compatible control technology or technologies to ensure compliance at least cost with minimal impact on performance, operation, and capacity. CEP

To receive a free copy of this article, send in the Reader Inquiry card in this issue with the No. 183 circled.

S. C. WOOD, southern regional manager for Energy Technology Consultants, a division of Woodward-Clyde, Inc., Houston, TX (713/690-0700; Fax: 713/744-9053), has 25 years of combustion process engineering experience. He has been responsible for analytical studies, performance, availability, and reliability optimization, as well as combustion-generated air-pollution reduction programs, on several hundred utility and industrial combustion devices throughout the U.S. and Europe. He is currently working with utility and industrial clients to achieve compliance with NO_x RACT rules. He has authored a number of technical articles on NO_x control technology and combustion process optimization. He received a BS in mathematics from the Univ. of Houston and completed graduate studies in mechanical engineering at the Univ. of Houston, and he is a member of the American Society of Mechanical Engineers and the Air and Waste Management Association.

Literature Cited

1. **U.S. Environmental Protection Agency,** "Compilation of Air Pollution Emission Factors," 4th ed., Document No. AP-42, EPA, Research Triangle Park, NC (Sept. 1985).
2. **Zeldovich, J.,** "The Oxidation of Nitrogen in Combustion and Explosion," *Acta Physiochim, U.S.S.R. (Moscow)*, **21**(4), pp. 577–628 (1946).
3. **Mormile, D., *et. al.*,** "Analysis of Minimum Cost Control Approach to Achieve Varying Levels of NO_x Emission Reduction from the Consolidated Edison Co. of NY Power Generation System," 1991 Joint Symposium on Stationary Combustion NO_x Control, sponsored by U.S. Environmental Protection Agency and Electric Power Research Institute, Washington, DC (Mar. 25–28, 1991).
4. **U.S. Environmental Protection Agency,** "Alternative Control Techniques Document — NO_x Emissions from Process Heaters," EPA-453/R-93-015, EPA, Research Triangle Park, NC (Feb. 1993).

Further Reading

American Petroleum Institute, "NO_x Emissions from Petroleum Industry Operations," Publication No. 4311, API, Washington, DC (Oct. 1979).

Bartok, W., and A. F. Sarofim, "Fossil Fuel Combustion, A Source Book," John Wiley & Sons, New York (1991).

National Research Council, "Rethinking the Ozone Problem in Urban and Regional Air Pollution," National Academy Press, Washington, DC (1991).

Smith, L. L., and S. C. Wood, "Advances in NO_x Control from Utility Power Plants," Second Conference on Air Quality Management in the Electric Power Industry, Austin, TX (Jan. 22–25, 1980).

Texas Air Control Board, "Proposed NO_x RACT Rules," *Texas Register*, **17**(87), pp. 8136–8160 (Nov. 20, 1992).

U.S. Environmental Protection Agency, "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers — Phase II," EPA-600/2-76-086a, EPA, Research Triangle Park, NC (Apr. 1976).

Vatavuk, W. M., "Estimating Costs of Air Pollution Control," Lewis Publishers, Chelsea, MI (1990).