Chapter 5
Oxygen Based NOx Control

Editor's Note:

Chapter 5 is written by Dr. Brian Doyle and is drawn primarily from personal knowledge and the material developed for the NOx Emissions course offered by the Rutgers Air Compliance Center from 2000 to 2008.

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5 Oxygen Based NOx Controls

Staging Concepts

When boilers fire coal or #6 oil, more than half of the total NOx comes from fuel nitrogen, so thermal approaches like flue gas recirculation are much less effective than when firing gas or #2 oil. When firing nitrogen bearing fuels, reduced oxygen concentration in the primary combustion zone is an effective way to reduce both fuel NOx and thermal NOx. The most basic approach is to reduce the combustion air flow - reduced excess air. Another approach is some form of staged combustion that limits the oxygen concentration in some region of the flame. Most staged combustion concepts fall into a category we will call *stratified combustion*, but there are others - one of which is *reburning*

1. *Reduced excess air*. This is the most basic way to reduce NOx in most combustors. With diffusion combustion (most burners) the first step to control NOx emissions is to minimize the excess air level. Here the key word is "minimize" because as soon as the excess air is reduced to near stoichiometric, all the pollutants associated with incomplete combustion begin to increase. At this point there is a trade off between NOx and products of incomplete combustion (PIC)

2. *Stratified combustion*. The general concept is to burn the fuel with an insufficient amount of air in a primary combustion zone. With insufficient oxygen available for complete combustion, most of the O_2 is consumed by carbon and hydrogen, leaving less available to form NO_x. As a result the fuel nitrogen combines to form N_2 ($N + N = N_2$) During the few hundredths of a second it takes for combustion to occur, the flame cools slightly. Once this cooling has occurred, the rest of the air is added to complete combustion. Since the fuel nitrogen radicals have disappeared, and the flame is too cool to generate a lot of thermal NOx, relatively little NO_x will be formed in this secondary combustion zone. This is the conceptual basis for low NO_x burners and for burners-out-of-service applied to a large furnace. The trick has been to get this concept to actually work consistently in real furnaces. To be successful it requires precise control of air-fuel mixing throughout the combustion zone. Stratified combustion is being used successfully on boilers as well as in combustion turbines and gas fired reciprocating engines. An inevitable side affect of staged combustion is longer less brilliant fires.

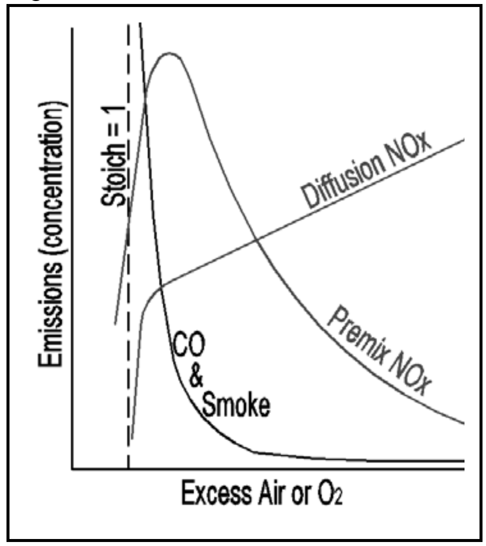
3. *Reburning* creates two separate combustion zones. Conceptually this starts with a normal boiler combustion zone operated with minimum practical NO_x emissions. Then a second combustion zone is created downstream (after the flue gases have cooled a bit) injecting additional fuel - usually natural gas - with no additional air. With insufficient oxygen, this forms a chemically reducing zone that actually consumes NOx formed in the initial combustion zone. Still further downstream additional air is injected to complete combustion. Little or no additional NOx is after the first combustion zone because the temperatures are too low. While this

approach can work (conceptually) on any furnace with sufficient space, it is most attractive on systems like stoker boilers where no other combustion NO_x control can be implemented.

With this introduction, let's discuss each of the oxygen control concepts in more detail.

Reduced Excess Air

Figure 5.1 NOx versus CO & Smoke



Varying the combustion zone excess air causes emission changes that are illustrated in Figure 5.1 - similar to Figure 3.1, but with more features. First note that CO and smoke emissions are negligible at high excess air levels. As excess air is reduced, CO and/or smoke appears abruptly and increases rapidly - this is commonly referred to as the knee in the curve. So no burner can be operated at very low excess air unless there is a back end control device to get rid of the products of incomplete combustion.

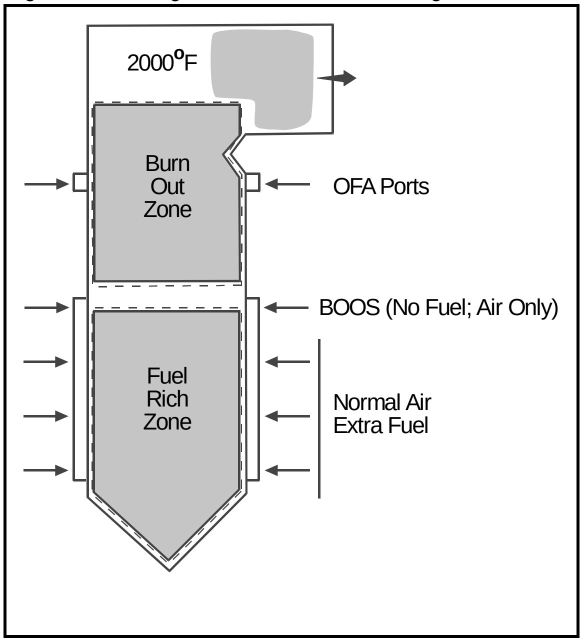
The behavior of NOx depends on the type of flame. For a diffusion flame (most traditional burners) NOx decreases almost linearly as excess air is reduced - until you get to very low excess air, where NOx drops off precipitously. So we can minimize diffusion flame NOx by reducing the excess air as far as possible without excessive CO or smoke. For a premix flame NOx behavior is more complex. With very low excess air NOx is suppressed by lack of oxygen. It peaks on the lean side of stoichometric where there is adequate oxygen and high temperature. Then as excess air is increased, it drops rapidly because the flame temperature drops. The best operating point for the premix flame appears to be on the right side (high excess air level) side of the graph. But this is impossible without some special techniques because the mixture is too lean to ignite or burn in a stable fashion. So traditional premix flames operate at fairly high NOx levels with some limited flexibility to trade NOx for smoke and CO.

This highlights the need to control air flow precisely on any combustion system that is attempting to minimize NOx. Air flow needs to be maintained near the minimum practical (not quite smoking) level. The automatic air flow control system needs to do this continuously as the boiler load changes. Precise control of excess air is the first and most important step in controlling emissions from boilers and furnaces. This can only be achieved by using an O_2 monitor tied into an intelligent (microprocessor based) control system.

Stratified Combustion in Large Furnaces

Early efforts to reduce NOx from utility boilers in Southern California paved the way for technologies still used today. Utility boilers have multiple burner levels and the fuel can be shut off from a few of the burners without affecting the boiler load. The remaining burners pick up the

Figure 4-1. Staged Combustion in a Large Boiler



slack. If fuel is shut off from a few of the top level burners without shutting the burner air dampers, the bottom of the furnace will be fuel rich. Air flow through the *burners out of service* (BOOS) will make up the air deficit without generating much additional NOx. Figure 4-1 illustrates the concept. Typically this approach can achieve a 15% to 30% NOx reduction without seriously affecting boiler performance or generating excessive smoke. This is not always as simple as it sounds and there will be one or more particular combinations of burners-out-of-service which are most effective. The BOOS approach is still used on some boilers.

Removing burners from service frequently incurs some sort of operating restriction on a large boiler. To get around this, utilities began installing over-fired air (OFA) ports above the top row of burners as shown in Figure 4-1. This leaves all the burners in service - consistent with the original design and operation. OFA ports have become a fairly standard component of a low NOx system on large utility boilers.

One consequence of staged combustion in any form is that flames are longer and generally less brilliant. In fact some low NOx fires have an alarmingly dark and dirty appearance - which is counter to the traditional operating philosophy of optimizing performance with short bright flames. Operators who try to "optimize" the combustion by getting brighter flames, will almost invariably increase the NOx emissions

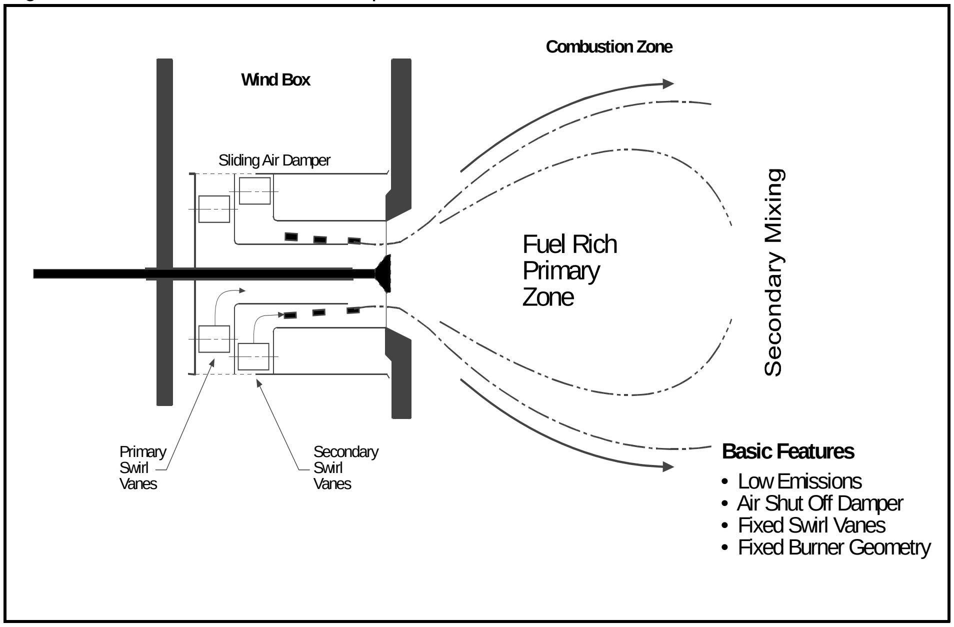
Low NOx Burners

Once the success of BOOS and OFA in large furnaces was demonstrated, it was natural to try to extend the concept to individual burners. The BOOS concept cannot be used on smaller boilers with only one or two burners and these boilers frequently lacked any location for installation of OFA ports. And if low NOx burners could be combined with OFA in large boilers, there should be additional NOx reduction. All the companies that manufacture boiler burners have developed low NOx burners - with varying degrees of success.

Figure 4-2 attempts to illustrate the low NOx burner concept. The burner creates a primary zone in which all the fuel burns without quite enough air. Then, a few feet further into the furnace, additional air is added to complete combustion. The concept is much easier to illustrate than it is to execute in practice.

The first challenge is to design a burner which will actually create two mixing zones - one following the other. A number of vendors with combustion laboratories have been able to develop and demonstrate full scale burners - a significant accomplishment. But the hardest challenge has been to get these burners to perform as well in the field as they do in the laboratory. Several problems arise in practice, particularly on multiple burner boilers. First, air flow and fuel flow may not be identical to all burners. If one burner operates with lower excess air that the rest, then the whole furnace has to be fired with enough air to keep the one rich burner from smoking. An uneven air and fuel distribution to each burner can be caused by either air or fuel system design. Another potential problem is that air velocity in the windbox upstream of the burner may cause more air to enter one side of a burner than the other. A similar problem can appear in a pulverized coal burner. The powdered coal is transported pneumatically and it may not enter the combustion zone in a circumferentially uniform pattern A critical element of combustion NOx control on large boilers is to get all the burners to behave in exactly the same manner. This has frequently taken a great deal of tuning and trouble shooting.

Figure 4.2 Low NOx Burner Concept



A question that is frequently asked is, "What is a low NOx burner?" The best answer appears to be: "**A burner with low NOx emissions**". In general low NOx burners have severaldesign features worth noting:

1. All adjustable features are configured so they are not easily altered by the boiler operators. Adjustments should be made when the system is initially tuned, and then left alone. Boiler operators are accustomed to adjusting burners to get a nice looking fire, and this kind of tinkering will defeat low NOx performance.

2. Air registers that control swirl must be separate from those than control flow. Older burners have dampers that combine swirl and air flow control. With a low NOx burner you need to be able to shut off the burner and its air flow without adjusting the swirl (flow pattern).

3. The system will have air flow controls that can maintain the air flow at the minimum level practical without generating excess CO or smoke.

Note, as discussed above, that low NOx burners will only give low NOx performance if the whole furnace installation works as intended. Simply installing low NOx burners alone won't necessarily give low NOx performance.

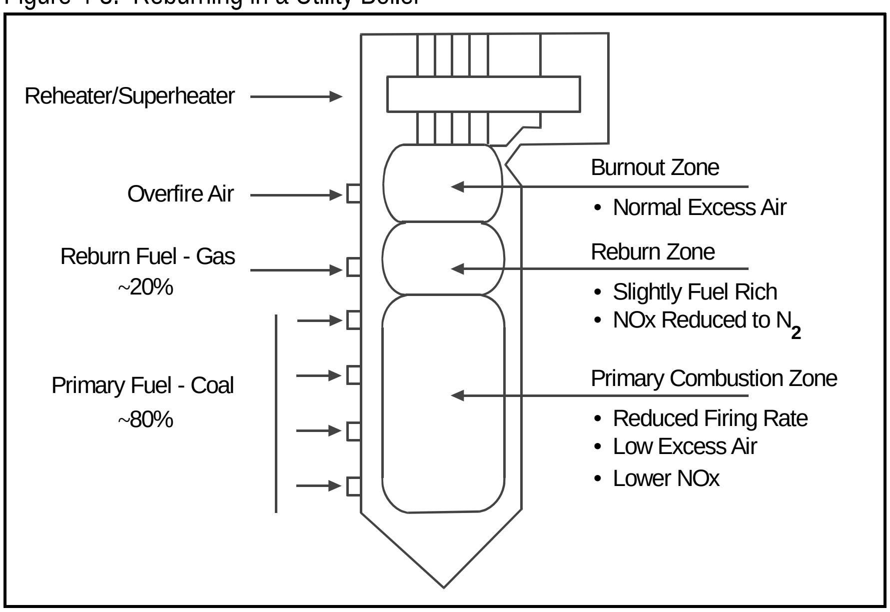
Reburning

Reburning is a NO_x reduction technique demonstrated around 1990 that can be attractive on existing boilers when traditional combustion control technologies are not applicable. It is not restricted to large utility boilers, but there are geometric limitations. Figure 4-3 is a general schematic of reburning in a large utility boiler. The reburning section is installed just downstream of the main combustion zone where the amount of NO_x present will be typical of uncontrolled emission levels. So it can be used on stoker furnaces and cyclone fired boilers.

Reburning seeks to reduce (literally and chemically) the NO_x by injecting more fuel with no accompanying air. This creates a fuel rich zone where no additional NOx will be formed because of (1) the lack of oxygen and (2) temperatures are below that required for NOx formation but are still hot enough to ignite the supplemental fuel. In this fuel rich zone, hungry fuel species take oxygen away from the NO_x, reducing it to N_2.. Of course the gases leaving this reducing zone are full of PICs, so additional air is now required to complete combustion. Over-fired air can be added without creating much NOx because the gases outside the primary flame zone have lost heat to the furnace walls and temperatures are too low generate thermal NOx.

NOx reduction levels using reburning depend on how much fuel is burned in the reburn zone. Full scale demonstration projects firing up to 25% of the total heat input have reduced NOx by about 50%. Since this scheme works by creating a fuel rich zone, the amount of reburn fuel must, in theory, be more than enough to consume all the excess air present in the original combustion zone. In practice, NO_x emissions drop as reburn fuel flow increases, but maximum reduction is limited by nonuniform excess air distribution and nonuniform mixing.

Figure 4-3. Reburning in a Utility Boiler



Typically the injected fuel is natural gas because it is relatively easy to inject and mix. At least one demonstration project has shown than “micronized” (very finely pulverized) coal will also work. Although any fuel that can be throughly mixed with the flue gases should work, reburning fuel will probably be limited to natural gas for practical reasons. There were very few operational reburn systems when natural gas was cheap, so it seems unlikely we will see wide spread application of this technology.

Review Exercises

1. In a boiler or other diffusion combustion system, how does changing the excess air level affect the emissions of NOx? and of CO?

2. Stratified combustion implies at least two combustion zones. How is NOx formation suppressed in each zone?

3. In a large furnace with multiple burners what sort of burner firing pattern would probably reduce the NOx emissions.

4. Describe a key element that defines a "low NOx" burner.

5. Would you describe the in place testing of a low NOx burner retrofit as desirable or absolutely critical? Why?

6. How does "reburning" work to reduce NOx and why is it not in common use?