An Examination of Nitric Oxide Emissions and Potential Control Techniques for Industrial and Institutional Steam Generators

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ABSTRACT

States with areas in nonattainment for the ozone ambient air quality standard or in the Ozone Transport Region (OTR) under Title I of the Clean Air Act Amendment of 1990, were to have promulgated various regulations for the control of nitric oxide emissions from existing sources. The impact of these Nitric Oxide Reasonably Available Control Technology, NOx RACT, regulations on industrial and institutional steam generation equipment is examined for equipment sized from 50 million to 250 million Btu per hour heat input. Issues concerning fuel bound nitrogen content in heavy residual oils and their relationship to NOx formation are reviewed. The impact of oxygen levels in excess of stoichiometric combustion requirements for various fuels is analyzed relative to control techniques possible with existing equipment and with new technology "low NOx burners." The use of steam or water as a diluent for NOx control is discussed with presentations on fuel costs and boiler performance. Test data from field experiments using steam injection technology in boilers is presented which shows it as an effective control technology. The technical and economic feasibility of various commercial NOx control techniques are also reviewed.

INTRODUCTION

For purposes of this paper it is necessary to define what is considered to be an industrial or institutional boiler. These boilers are in a class that is distinct from the much larger steam generators which are employed for the production of electrical power. This segregation is accomplished by a technological and size classification. From a design aspect, industrial-institutional boilers are typically constructed with a boiler bank and lacking a reheat cycle. They can be either field erected or shop assembled as "package boilers." The primary duty for these boilers is to provide low pressure steam for process applications or building heating systems. Although some boilers in this set are employed by organizations whose primary purpose is the production of electrical power, this overlap is not considered to be significant. Furthermore, the authors wish to consider only steam generation equipment in the size range from 50 MMBtu/hr to 250 MMBtu/hr of fuel heat input. Excluding boilers above and below these heat inputs was strictly arbitrary for the purposes a placing a bound around the study group.

NOx RACT REGULATIONS

Under Title I of the Clean Air Act Amendments (CAAA) of 1990, states with areas in nonattainment for ozone were to have promulgated emissions regulations by November 15, 1992. Phase I implementation is required by May 31, 1995 for major sources of NOx emissions. Industrial and institutional boilers are in a category of equipment affected by these rules. As part of the CAAA, individual states were allowed to define the NOx emissions standards for plants within their political boundaries. The resulting product of the various state NOx RACT rules has been a patchwork quilt of inconsistent regulations.

Within a twelve state region, known as the Ozone Transport Region (OTR) as defined by Congress in the CAAA, an attempt was made at promulgating consistent regulations. An ad hoc coordinating group, under the name of Northeast States Coordinated Air Use Management (NESCAUM), recommended NOx RACT standards. Although some attempt was made to follow the recommendations of this organization, local politics intervened to provide a significant alteration to the proposed standards. The result was a wide range of NOx RACT regulations. For example, Pennsylvania developed an open policy known as "write your own RACT" while other states have promulgated varying regulations shown in Table #1.

ANTICIPATED NOx EMISSIONS

Of interest to the industrial boiler owner are the actual emission rates of operating equipment. Accordingly, emission characteristics for various fuels based upon actual testing is presented herein.

Table #1: Examples of Phase I NOx RACT Emission Rates from Various Northeastern States

Classification	Heat Input Capacity (mmBtu / hr)	Fuel & Firing Arrangement	NOx RACT (lbs / mmBtu) Low	NOx RACT (lbs / mmBtu) High
Very Large & Large Boilers	> = 250 & > = 100 & < 250	Coal - T Fired (dry)	0.38	0.50
		Coal - Wall Fired (dry)	0.20	0.50
		Coal - Stoker T Grate	0.33	
		Coal - Stoker S Grate	0.25	
		Coal - T Fired (wet)	1.00	
		Coal - Wall Fired (wet)	1.00	
		Coal - CFB	0.29	
		Coal - Cyclone	0.55	0.60
		Gas Only - T Fired	0.10	0.20
		Gas Only - Wall Fired	0.10	0.20
		Gas / Oil - T Fired	0.20	0.40
		Gas / Oil - Wall Fired	0.20	0.40
		Gas / Oil - Cyclone	0.43	
		Oil Only	0.25	0.40
		Distillate Oil Only	0.12	0.20
		Kraft Recover Boilers		
		Other Fuels (Biomass)	0.33	
Medium Boiler	>= 30 & < 100	Coal - T Fired (dry)	0.38	
		Coal - Wall Fired (dry)	0.50	
		Coal - Stoker T Grate	0.30	0.43
		Coal - Stoker S Grate	0.25	0.43
		Gas Only - T Fired	0.10	
		Gas Only - Wall Fired	0.10	
		Gas / Resid - T Fired	0.25	0.40
		Gas / Resid - Wall Fired	0.25	0.40
		Gas / Distil - T Fired	0.12	
		Gas / Distil - Wall Fired	0.12	
		Other Fuels (Biomass)	0.33	0.43

RESIDUAL OIL

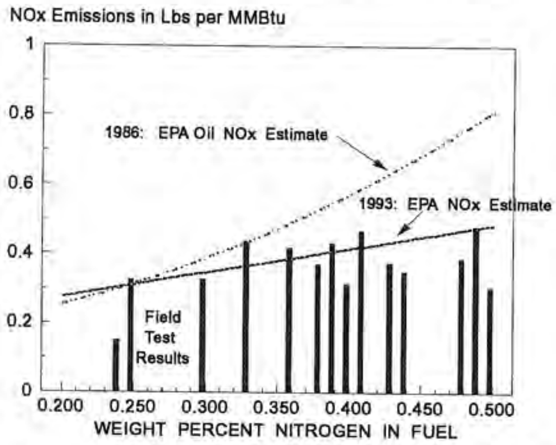
Residual fuels, designated by the API classification grades of No. 4, No. 5 and No. 6, are a significant industrial boiler fuel in regions not serviced by a natural gas pipeline. Even when gas is available, residual oils are used as a backup fuel during supply disruption periods or as a economic alternative. In the literature the EPA provides formulas for anticipated NOx emissions rates.

For industrial boilers these rates are a function of the fuel based nitrogen content. Figure 1 provides a graphical presentation of the potential NOx emissions rates based upon the EPA emissions factors. Note should be made of the fact that the EPA has reduced its original 1986 estimates of potential emissions to lower projections in 1993. The bars in the graph are averages from a sampling of boilers tested with varying fuel bound nitrogen rates. The field data appears to agree with the most recent EPA estimates.

NATURAL GAS

In spite of legislation aimed at reducing the combustion of natural gas as a boiler fuel, such as the Fuel Use Act (repealed in 1987), gas remains the dominant fuel in regions with access to pipeline service. NOx regulations appear to support the use of natural gas. This is particularly true in the case of seasonal averaging options, which favor the use of natural gas during the high ozone months of May through September.

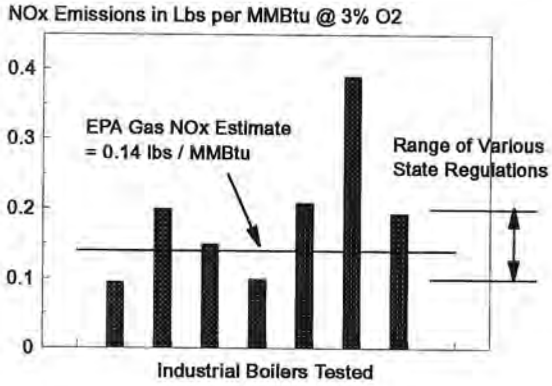
Figure 1. EPA NOx Emissions Estimates For Residual Oil and Field Results (Industrial Boilers)



Gas NOx RACT regulations for industrial boilers range from 0.1 to 0.2 lbs NOx per MMBtu depending upon boiler design heat input capacity. This band of emissions rates approximates the results obtainable from "old" technology burners as is demonstrated in Figure 2. The EPA considers 0.14 lbs NOx per MMBtu to be an average NOx rate for gas fired boilers. However, it should be noted that some natural gas fired boilers do exhibit high NOx readings. These steam generators are generally equipped with air preheaters, which are used as heat recovery devices.

Figure 2. EPA NOx Emissions Estimates for Natural Gas and Field Results (Industrial Boilers)

NOx Generation from Oil Fuels



Based upon actual test results, the NOx emissions rate from a residual oil fired boiler is influenced by four controlling factors. These are:

1. Excess oxygen supplied to the burner
2. Furnace heat release rate
3. Fuel bound nitrogen
4. Combustion air temperature

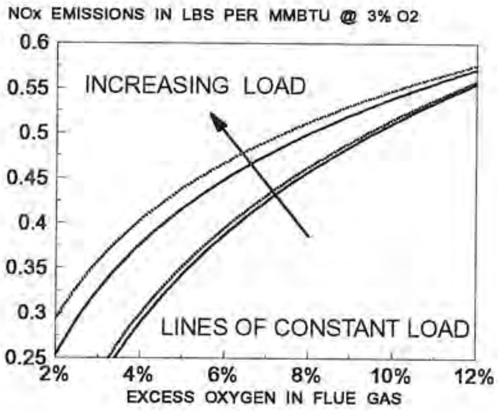
Excess Oxygen & NOx

The primary variable influencing the rate of NOx formation in an industrial boiler is the stoichiometry of the burner as measured by the quantity of excess oxygen in the flue gas. This fact is demonstrated by the excess oxygen vs. NOx curves in Figure 3.

For boilers equipped with old register burner technology a change of 1% in excess oxygen, as measured in the flue gas, can produce a corresponding NOx emissions rate change of 0.05 lbs NOx per MMBtu of fuel oil input. The exact relationship of excess oxygen to NOx produced will vary from installation to installation. However, most oil fired boilers will exhibit the same characteristic steep sloping curve while approaching stoichiometric conditions and an asymptotically flattening of the curve at high excess air levels.

Operating with excess oxygen below 3% produces less efficient combustion, as is demonstrated by increasing amounts of CO in the flue gas. For most register type burners, the knee in the CO curve is in the 2.5% to 3.0% excess oxygen range. This is also evidenced by increasing opacity readings. Since this low excess air NOx reduction phenomenon has become evident to state environmental agencies, compliance testing regulations have been modified to place a cap of allowable CO in the flue gas at 200 ppm, corrected to 3% O_2.

Figure 3. EPA NOx Emissions from Residual Oil at Various Loads and Excess Oxygen



Furnace Heat Release Rates and NOx

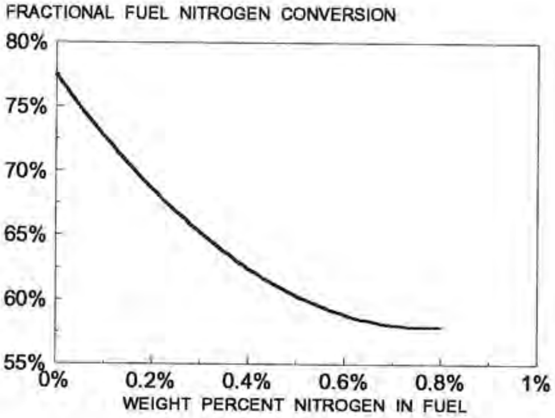
The importance of furnace heat release rates, as measured by fuel energy burned per unit volume, is also a significant contributing factor to the rate of NOx formation. This is particularly true for fuel oils, which are highly radiant. Consequently, regulators have factored the influence of furnace volume into the NOx rules. Many states will consider boilers with furnace volumes of greater than 70,000 ft^3 to be in a "high" heat release category and have assigned corresponding higher NOx emissions regulations.

Many older industrial boilers which were originally brought on line as coal fired units have since been converted to oil-gas steam generators. Boilers, which were originally constructed as stoker units, are often found to have large furnaces and low net heat input to plan area ratios. The authors found that this class of steam generators had emissions rates below 0.3 lbs NOx per MMBtu.

Fuel Bound Nitrogen Contributions to NOx

The quantity of fuel bound nitrogen, based upon research on utility class boilers, has been found to a significant contributor to NOx formation. Figure 4 is a graph frequently used to estimate the conversion ratio of fuel bound nitrogen. The curve in Figure 4 is based upon an average of the data. Assuming that the average curve is an adequate estimate, then a 0.4% nitrogen fuel would generate 0.289 lbs NOx per MMBtu with fuel bound nitrogen as a source. The total NOx rate would be 0.415 lbs NOx per MMBtu based upon EPA estimates.

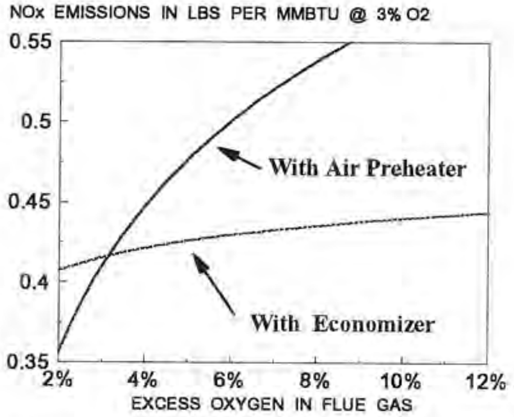
Figure 4. Percentage of Fuel Bound Nitrogen Converted to NOx as a Function of Weight of Nitrogen in the Fuel (Source: EPRI)



Influence of Combustion Air Temperature on NOx

Another factor influencing NOx formation is combustion air temperature. Higher NOx emission rates are evident on steam generators equipped with an air preheater. Figure 5 is the result of residual oil NOx emissions data taken from two nearly identical package boilers produced by the same manufacturer. From this graph it can be seen that the lower NOx generator was equipped with an economizer for heat recovery equipment, whereas the high emitter used a rotating air preheater. Forced air to the burner from an economizer-boiler arrangement is at ambient temperature plus the rise associated with the forced draft fan. The corresponding windbox air on the air preheater unit was in the range of 550 deg F.

Figure 5. NOx Emissions Rates from Similar Boilers Equipped With Different Forms of Heat Recovery Firing Residual Oil



NOx GENERATION FROM NATURAL GAS

Based upon actual test results, the NOx emissions rate from a natural gas fired boiler is influenced by three controlling factors. These are:

1. Excess oxygen supplied to the burner
2. Furnace heat release rate
3. Combustion air temperature

The above listing is identical to that for residual oil with the exception of fuel bound nitrogen factor. Although pipeline gas actual contains as much as 1% nitrogen, this nitrogen is found in the stable state as gaseous N_2.

Figure 6. Natural Gas Fired Boiler NOx Emissions

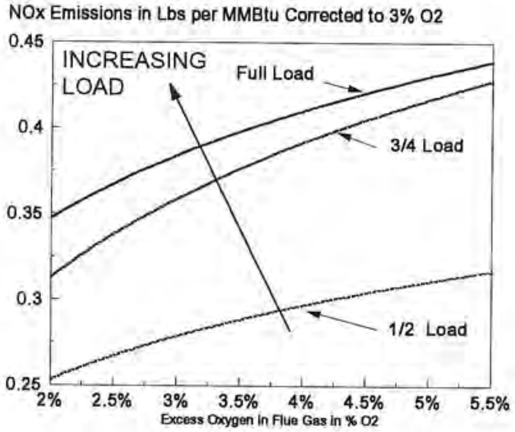


Figure 6 demonstrates the impact of both furnace heat release, presented as boiler loading, and the influence of excess oxygen on the formation of NOx from a natural gas fueled flame.

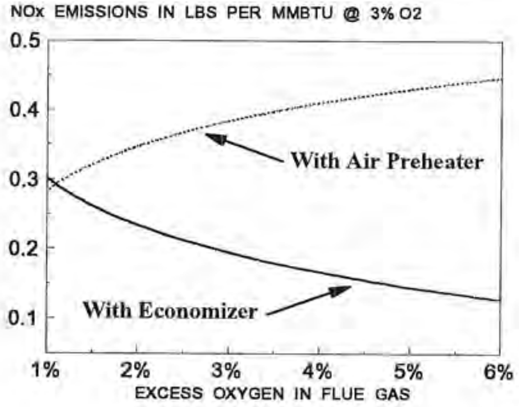
Since the NOx generated by the combustion of natural gas is primarily thermal NOx, factors impacting flame temperature have a significant influence on the rate of NOx formation. The high temperatures generated by preheat from air preheaters is the primary cause of elevated NOx readings in industrial boilers. Figure 7 depicts the influence of preheated air on NOx by comparison to a similar unit equipped with an economizer for heat recovery.

NOx CONTROL OPTIONS

Having determined factors influencing the formation of NOx in the flame of industrial boilers, NOx control options are presented for units categorized under the regulations as a major source. Possible NOx control techniques include:

1. Application of combustion control systems capable maintaining low levels of excess air with safe limits for CO.
2. Upgrading of air flow distribution systems for stoker fired boilers.
3. Reduction of fuel bound nitrogen in residual fuels by blending a distillate oil.
4. Use of modified oil gun nozzle tips for residual oil combustion
5. Application of diluents for gaseous fuel combustion, including air, steam and flue gas.
6. Reduction in the boiler's maximum continuous rating (MCR) for the purpose of lowering the furnace heat release rate.
7. Replacement of an air preheater with an economizer
8. Installation of burners designed to combust fuels at low NOx generation rates.
9. Use of seasonal or other forms of emissions averaging to trade the advantage of cleaner fuels against fuels not easily controlled.

Figure 7. Impact of Preheated Air on NOx Production Rates for Natural Gas Fired Boilers.



Combustion Air Control

As can be seen from Figures 3 and 6 the rate of formation of NOx is highly dependent the level of excess air. Therefore the maintenance of flame stoichiometry is of primary importance in the control of NOx emissions. Regardless of any other NOx control technique planned for compliance, the first focus should be on developing a plan to effectively manage combustion air. Such a plan would include:

1. Reviewing forced and induced draft fans to insure that they are operating properly.
2. Examining air flow control drives.
3. Repairing refractory, casing and ductwork where leakage is evident.
4. Considering upgrading air flow measurement devices if accuracy is in doubt.
5. Evaluating economics of variable speed fan drives for low load efficiency and control.
6. Adding an oxygen trim control loop to the air circuit of the combustion control system.

7. Instead of reliance on opacity monitors, considering installation of a CO recorder.
8. Considering replacement of the entire combustion control system with digital technology.

These steps need to be considered even if the installation of "Low NOx" burner technology is planned. "Low NOx" burners cannot compensate for flow management deficiencies which might be found in the boiler system. For the boilers surveyed by the authors, approximately 50% of the group had some form of an air flow control problem and few had modern controls. Furthermore, it should be pointed out that in addition to NOx emissions control, following these steps will improve boiler efficiency.

The difficulty in the management of boiler combustion air is increased in cases where multiple fuels or combustion processes are involved. An example of this are stoker fired units, fueled by wood or coal which are combined with burners for natural gas or oil. In addition to the undergrate air plenum and the windbox, these boilers are also often equipped with an overfire air system. For steam generators of this type the air flow control issues are:

1. Maintaining the proper stoichiometry for each fuel
2. Providing adequate undergrate air distribution

Failure to control fuel specific stoichiometry will result in imbalances and increased emissions. Poor undergrate air distribution will result in "hot and cold" spots on the grate. "Cold" spots can often be detected by scanning the backpass and monitoring for high CO concentrations. Eliminating "hot" spots reduces potential NOx generation sources.

Addressing stoker air flow management can be accomplished in two ways. The first should be to attempt to tune the boiler on line using the proper test equipment. Further refinements can be made after an analysis of the system using air flow modeling techniques such as computational fluid dynamics.

Control of Fuel Bound Nitrogen

The impact of fuel bound nitrogen and the formation of NOx for residual oils has been demonstrated. A means of controlling the fuel nitrogen content would be to dilute a No. 6 fuel oil with a distillate to produce a No. 5 or No. 4 residual product. This technique may prove economically effective, particularly for those boilers which are operating near their statutory limit. Figure 9 demonstrates the range of possible NOx emissions by using alternate fuels.

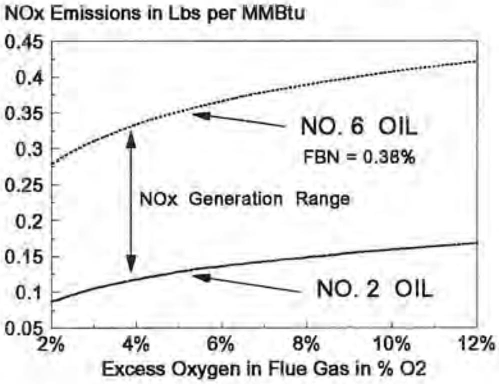
Low NOx Oil Gun Nozzle Tips

A unique method of NOx reduction for oil combustion has been through the application of oil gun nozzle tips which have been modified for the purpose of reducing NOx. The installation of these tips require some trial and error adjustments. Manufacturers will design several variants for trial and error adjustments during a test period. These tips concentrate on:

1. Spray angle changes
2. Fuel atomization characteristics
3. Increasing atomization steam flow

NOx reductions in the range of 10 to 20% are feasible with this application.

Figure 9. NOx Generation Rates Using Oils with Different Fuel Bound Nitrogen Contents

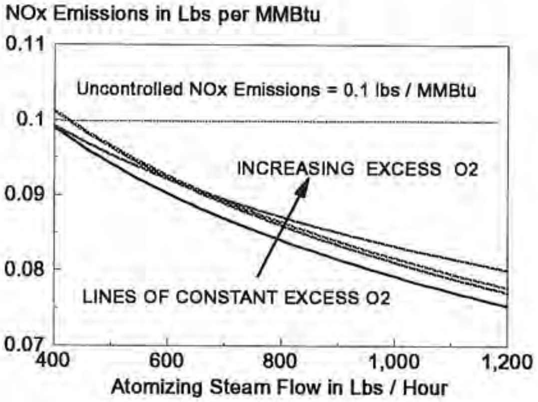


Using Diluents for NOx Control

The application of diluents for the management of thermal generated NOx has been investigated on utility applications and rejected. However, the use of diluents may prove to be successful on industrial applications and particularly with gaseous fuels.

Steam injection as a diluent is a feature commonly available to most industrial boiler owners provided the burner is designed to combust oil. By introducing steam through the atomizing circuit of the oil gun, NOx reductions of up to 25% are feasible as shown in Figure 10.

Figure 10. Steam Injection for NOx Control



A second diluent method discovered by the authors is the use of air. For natural gas burners equipped gas emission points located around the periphery of the burner throat, such as rings or spuds, increasing amounts of air produced decreasing amounts of NOx. In one case, shown in Figure 11, NOx varied linearly with excess oxygen and the slope of the curve varied as a function of heat input. It is believed that some burners of this type have the characteristic of a premixed flame, which can be cooled by higher stoichimetry.

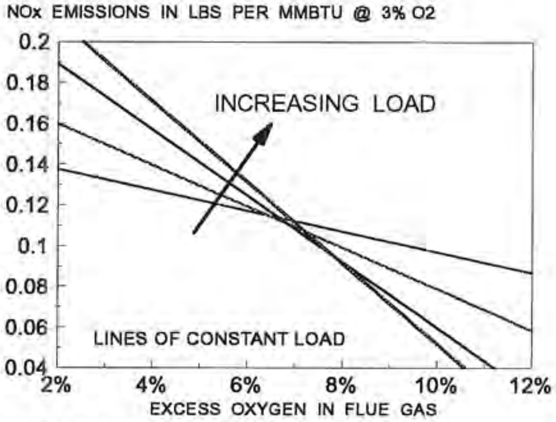
Reducing Boiler Rating for NOx Control

As has been demonstrated, NOx generation is also function of furnace net heat release rate. Therefore operation at reduced boiler loads will yield a lower emissions rate. This form of control may be effective in cases where the plant steam load has been reduced substantially below the design capability of the existing equipment. Furnace load reductions techniques may prove more effective with field erected units as opposed to package boilers. Figure 12 is an example of a boiler which would meet NOx criteria of 0.3 lbs per MMBtu based upon low load operation. However it should be noted that most regulatory agencies would require some form of a guarantee that the boiler's steam production limit could be exceeded.

Replacement of Air Preheaters

Although the removal of an air preheater and the replacement with an economizer is a costly project, it may be the only alternative in some cases even when "low NOx" burners are installed. Figures 5 and 7 demonstrate the impact on NOx emissions by using preheated air for combustion.

Figure 11. Using Air as a Diluent



Low NOx Burners and Averaging

Commercially available burners are capable of low NOx emissions in the range of 35 ppm for natural gas. Guarantees of 0.08 lbs NOx per MMBtu are generally considered to be the norm in regions where 0.1 lbs is the standard. However, guarantees for oils are tied to the fuel bound nitrogen content, which suppliers of No. 6 oil will not accept specifications on. Therefore it may prove advantageous to consider one of the various forms of averaging allowed under local regulations. By over correcting NOx emissions on natural gas, credits are generated for use with fuel oils.

Figure 12. NOx Generation With Residual Oil and the Impact of Furnace Heat Release Rate