



## Advanced SNCR NO<sub>x</sub> Reduction Experience on Multiple Large Utility Boilers

Authors: John M. Boyle, PhD., Penelope Stamatakis, PhD., Piers de Havilland, Fuel Tech, Inc.

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### Abstract

Fuel Tech has recently completed full-scale demonstrations of Advanced Selective Non-Catalytic Reduction systems on a number of large utility boilers (>600MW) firing a variety of fuel types. The systems use the latest flexible injection technology and are controlled with a balanced algorithm utilizing unit load, a full grid of continuous furnace temperatures and the plant continuous emissions monitoring system (CEMS).

Fuel Tech has more installed SNCR applications than any other technology supplier, with more than 590 units firing all types of fossil, biomass, and industrial fuels. These systems are currently installed and operating on units ranging in size from small industrial furnaces to some of the largest utility boilers in the world.

Over the last 15 years, Fuel Tech has completed nearly 50 installations on units larger than 400MW, where the majority of these units are larger than 600MW. Large units pose a particularly difficult challenge to SNCR emission control systems, as these modern units generally have higher furnace exit gas temperatures, incorporate low- NO<sub>x</sub> burners (LNB), over-fired air (OFA) and have very low baseline NO<sub>x</sub> emissions. Each of these factors potentially limits the effectiveness of SNCR.

Fuel Tech uses the most advanced computational fluid dynamics (CFD) and chemical kinetics modeling to design sophisticated injection strategies that anticipate varying load and fuel conditions in the furnace. The analysis is translated into engineering systems that incorporate numerous injector types to deliver the reagent as effectively as possible. The target injection zone varies based on temperature, NO<sub>x</sub> baseline, CO concentration and furnace residence time.

Furnace temperature has traditionally been an important control signal for the Fuel Tech SNCR system, and recent installations have included full contour mapping of the furnace temperatures using either laser-based or acoustic pyrometers to control the system operation, while limiting ammonia slip.

Recent systems have achieved more than 35% NO<sub>x</sub> reduction from low baseline furnaces that already utilize primary control measures such as LNB and OFA. This has been accomplished while controlling ammonia slip below environmental requirements and limiting the impact on balance of plant. Furthermore, this is achieved without the use of excess dilution water, which would reduce boiler efficiency.

Specific recent examples will be discussed including the use of on-line temperature mapping, multiple nozzle lances and CFD modeling to provide effective control on large utility furnaces.



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### **Introduction**

#### **Control of Nitrogen Oxide Emissions**

The emission of nitrogen oxides (NO<sub>x</sub>) is a well-known problem for air quality, leading to the formation of tropospheric ozone and acid rain as well as adversely affecting visibility. Nitrogen oxides are formed in combustion with air at high temperature and are a particular regulatory concern for many power producers burning fossil fuels. The regulation of NO<sub>x</sub> emissions varies significantly across the globe and the required degree of control is often dependent on the source of the emissions, including the manner of combustion and the specific fuel utilized. Significant reductions are required for most utility furnaces in developed countries.

NO<sub>x</sub> control strategies include efforts to inhibit NO<sub>x</sub> formation such as fuel switching, combustion modifications, low-NO<sub>x</sub> burners (LNB) and combustion staging with over-fired air (OFA). Post-combustion NO<sub>x</sub> control technologies are also utilized, such as selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) of the nitrogen oxides through reaction with amines such as ammonia and urea. Although not all of these technologies are applicable to each utility furnace, it is often possible to create useful and efficient combinations to enhance performance and provide the most cost-effective regulatory compliance.

Fuel Tech Inc. has 30 years of experience applying each of these NO<sub>x</sub> control technologies to industrial and utility furnaces. This experience is important and relevant to commercial applications as each custom NO<sub>x</sub> control strategy requires interaction with any existing strategies in place at the site. For example, it is very common to install post-combustion NO<sub>x</sub> control to furnaces that have previously been equipped with some level of combustion control. The first-hand experience that exists within the Fuel Tech groups responsible for LNB and OFA design reinforce the strengths of the post-combustion control design effort. It is often useful, in fact, to suggest operational enhancements to the current controls that work synergistically with post-combustion processes.

Staged-combustion NO<sub>x</sub> control technologies, like LNB and OFA, reduce the formation of NO<sub>x</sub> by limiting the availability of excess oxygen in the high-temperature combustion zone where nitrogen oxidation occurs. Complete fuel oxidation is accomplished with burner swirl of additional combustion air and through the introduction of over-fired air. Combustion staging is limited by an increase in the unburned carbon in the ash (for solid fuels), increased carbon monoxide (CO) concentrations, higher furnace exit gas temperature and a decrease in furnace efficiency.



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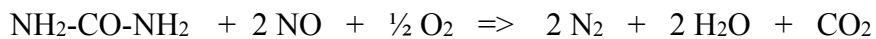
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### Post-Combustion NO<sub>x</sub> Control

Post-combustion NO<sub>x</sub> control is generally utilized when combustion staging is not sufficient to provide the required emission target. Selective catalytic reduction (SCR) utilizes a catalyst bed to promote the reduction of NO<sub>x</sub> by reaction with an amine, such as ammonia or urea. The catalyst bed is very effective at providing NO<sub>x</sub> reduction and is used routinely on large units where the gas temperature and fuel compatibility metrics have been satisfied.

SCR requires the construction of a reactor vessel, which is often very expensive. This capital expense needs to be spread over the remaining years of unit operation, however, this cannot be justified in many cases. The high utilization of the chemical reagent in an SCR, and often-higher NO<sub>x</sub> reduction capability, provides some payback for this expense. SCR reactors, especially full-scale reactors capable of NO<sub>x</sub> reductions beyond 60%, are not always a feasible solution. This is particularly true in the retrofit market.

Selective Non-Catalytic Reduction (SNCR) of NO<sub>x</sub> occurs in the furnace, utilizing the hot gas environment of the furnace to drive the desired reduction chemistry. An aqueous solution of urea is the most common reagent, especially for large furnaces. Urea (NH<sub>2</sub>-CO-NH<sub>2</sub>) reacts with NO<sub>x</sub> in the hot post-combustion gases to produce nitrogen gas (N<sub>2</sub>), carbon dioxide (CO<sub>2</sub>) and water (H<sub>2</sub>O), all typical combustion byproducts.



SNCR generally operates at a chemical utilization of about 30%, on a molar basis, although this is highly dependent on the furnaces conditions. Most of the unutilized urea is simply combusted to form nitrogen gas, water and carbon dioxide. At very high temperatures, some of the urea-bound nitrogen may be oxidized to form NO and so there is an upper temperature limit for effective control. In addition, at relatively low flue gas temperatures, the urea may be converted to ammonia gas and some portion may remain unreacted as ammonia slip at the boiler exit. This sets a lower temperature limit.

The resulting temperature window for effective SNCR injection is a key process design parameter for injection design and performance predictions. Successful applications of SNCR injection require a thorough understanding of the temperature, residence time and gas concentrations in the furnace. In addition, it is vitally important that this injection strategy be flexible to provide NO<sub>x</sub> control over a wide variety of load conditions, mill configurations, and fuel selections.

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Fuel Tech uses advanced proprietary models to study each furnace for SNCR applications. Computational fluid dynamics (CFD) modeling is used in conjunction with field measurements of furnace temperatures and gas species to provide the best possible understanding of the furnace gas conditions, Figure 1. Chemical kinetics modeling is used to determine the effective temperature window for a variety of baseline and load conditions. Detailed injection modeling is then performed to determine the most suitable injection locations, the ideal injector types, the expected chemical coverage and the resulting performance metrics required to provide guarantees for performance.

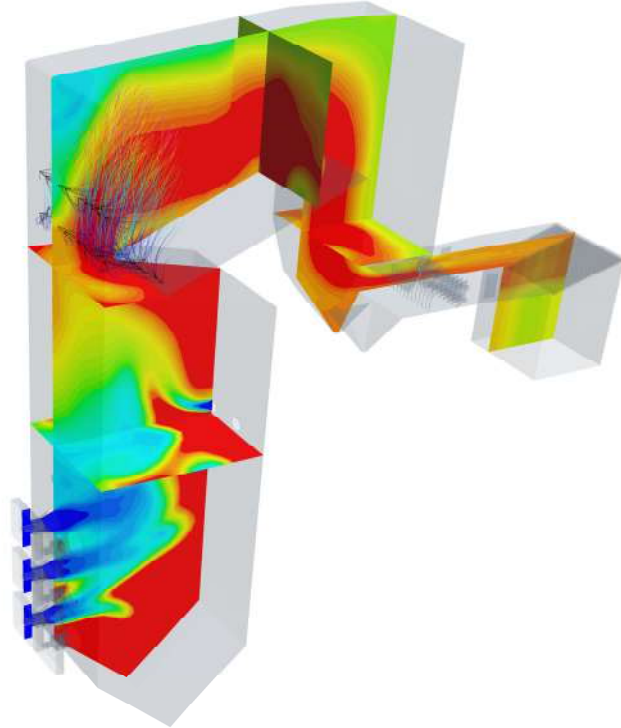


Figure 1 CFD simulation of combustion and SNCR injection

A Fuel Tech SNCR system can be relatively simple or more complex, depending on the needs of the furnace and the customer. Fuel Tech has provided more than 590 systems ranging in complexity from simple single-level industrial units with manual control to large utility applications utilizing state-of-the-art automatic controls based on temperature and CO measurements, infrared cameras, ammonia analyzers, and predictive furnace logic.

These systems have been designed with a wide variety of injection options, custom selected for each application. Fuel Tech utilizes air-atomized injectors, mechanical-atomized injectors, retractable multi-nozzle lances, and water-cooled lances. Injectors have been placed from the burner zone through the convective pass, as process conditions and design targets dictate.

The most sophisticated applications have recently been designated as Advanced-SNCR systems, utilizing acoustic or laser-based means of producing near real-time maps of furnace conditions that are then used to control the location and manner of injection for NO<sub>x</sub> control. The advanced SNCR system also contains logic to respond to ammonia CEMS and to predict future furnace behavior by monitoring current furnace transients.

Fuel Tech also provides I-NO<sub>x</sub><sup>™</sup>, an Integrated NO<sub>x</sub> Reduction System that utilizes combustion control through LNB and OFA, combined synergistically with SNCR and a small or in-duct SCR reactor where appropriate. This custom solution often involves only two or three of the



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mentioned technologies, combined using field experience with each, to satisfy the process, regulatory and financial goals of the user.

### **Scale-up of SNCR to Large Furnaces (>400MWg)**

Fuel Tech has been responding to the unique SNCR needs of very large utility furnaces for more than 20 years, since our first large-furnace application in 1993. Regulations in the United States drove application of SNCR on large units in the late 1990s, including a showcase demonstration utilizing six multiple nozzle lances in 1999 at the 620MW Cardinal Station Unit #1. This wall-fired large furnace was equipped with low- NO<sub>x</sub> burners and had recently been optimized to control CO and NO<sub>x</sub> while burning high sulfur coal.

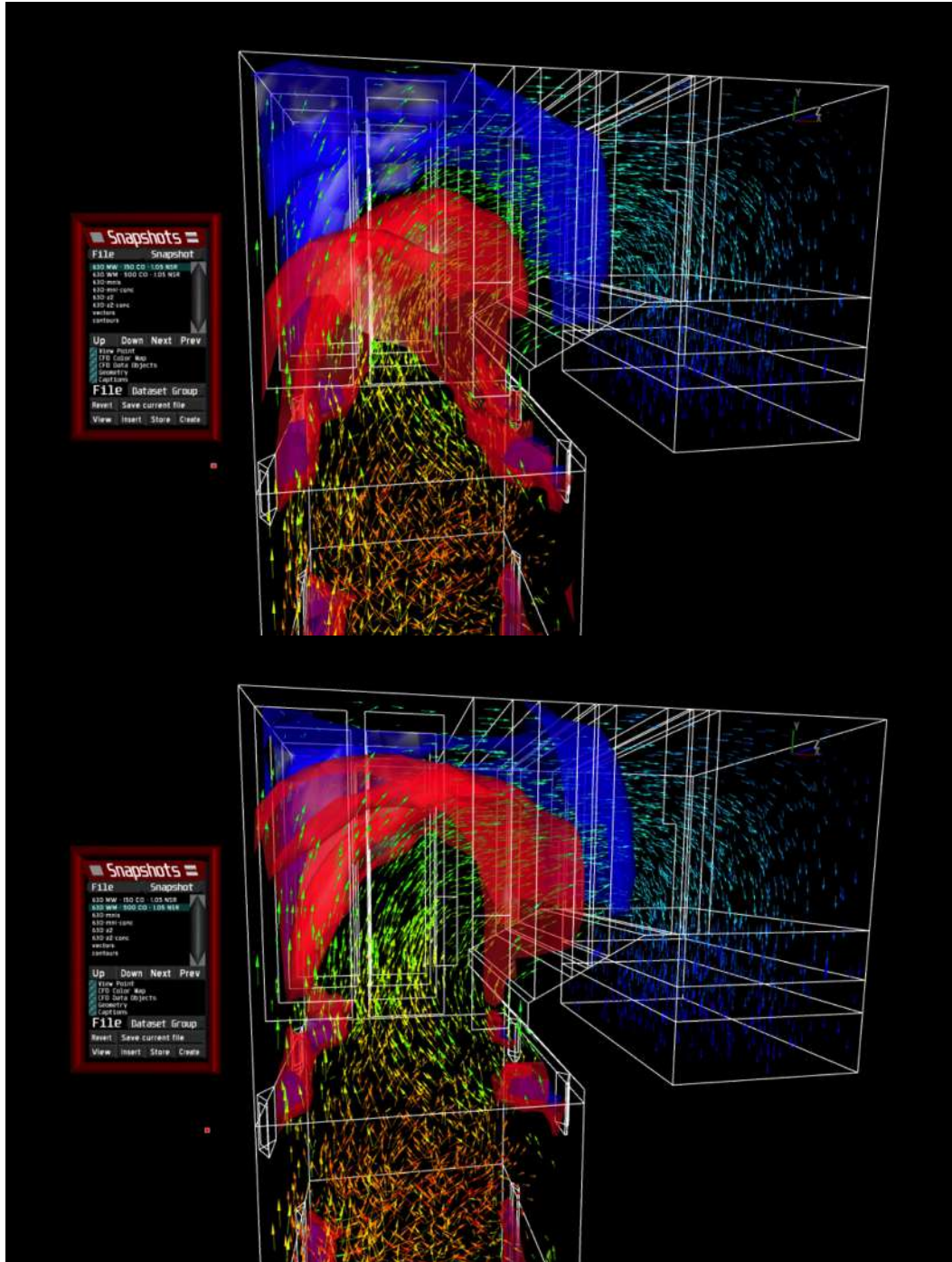
The particular challenges of SNCR scale-up to very large furnaces are not new. As compared to the earlier work on units smaller than 400MW, these larger furnaces often have lower NO<sub>x</sub> baselines, higher furnace exit gas temperature (FEGT), and increased convective pass concentrations of carbon monoxide. Each of these attributes affects the design of an effective SNCR system.

The applicable temperature window for SNCR injection is defined by the chemical kinetics of the reduction reactions and by the conditions in the furnace. Low NO<sub>x</sub> baselines effectively push the temperature window to cooler regions near the convective pass. In addition, an increased CO concentration also shifts the temperature window in the same direction, toward cooler gas conditions. Finally, these larger modern units are designed for higher steam temperatures, and so require a higher FEGT. These characteristics of large furnaces do not prohibit effective SNCR treatment, but they do require a more sophisticated approach to control and injection.

For example, Figure 2 illustrates the difference in the target temperature window for an application completed at 620MW. The CO concentration in the convective pass varies between 150ppm and 500ppm. These are both reasonable concentrations to expect at this location for a furnace with combustion staging. The target temperature window shifts dramatically between the two cases, and an effective SNCR system must be equipped to sense this difference and respond appropriately.

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**Figure 2 Temperature windows at 150ppm (higher) and 500ppm CO (lower)**

The shifting temperature window is not the result of changing temperatures in the upper furnace, but is due only to the change in CO concentration. The front-wall injectors in the upper furnace



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are particularly affected by this shift in treatment zone. Utilizing wall injectors specifically designed for large furnaces is critical for success. For this particular application, it was also effective to install retractable water-cooled multiple nozzle lances in the convective pass, although this is not always required.

**Experience on Large Utility Furnaces**

Although Fuel Tech has been implementing large-furnace SNCR systems for more than twenty years, most of the commercial activity has taken place since the year 2000. In the last 15 years, primary NO<sub>x</sub> control measures have produced lower post-combustion NO<sub>x</sub> baselines. At the same time, the regulations governing NO<sub>x</sub> emissions have forced these units to be in compliance with gradually decreasing limits and to consider post-combustion NO<sub>x</sub> control methods. Although some of these units have invested in full-scale SCR reactors, many others have opted to pursue SNCR as an addition to existing primary measures to achieve compliance at a significantly lower capital expense (CAPEX) than full-scale SCR.

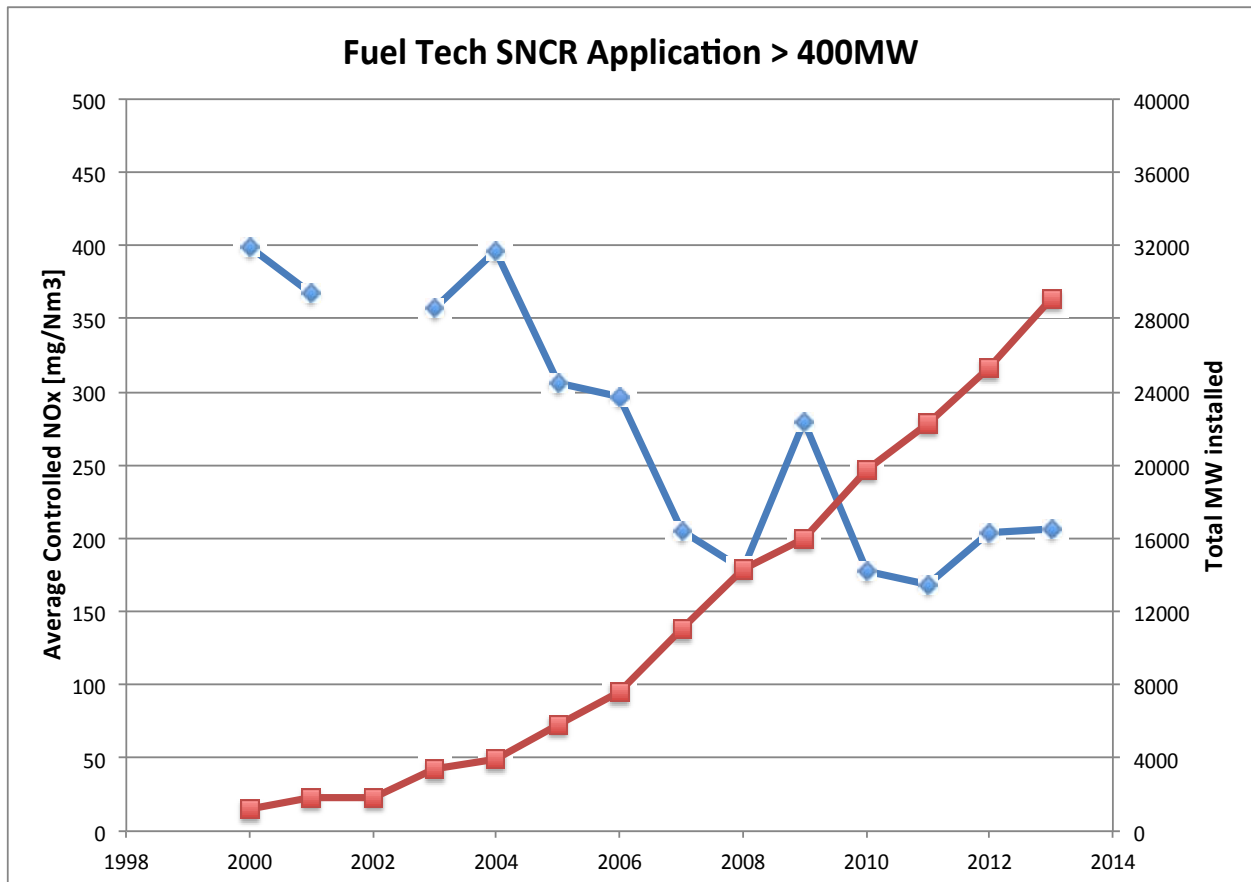


Figure 3 Timeline of large-furnace SNCR activity at Fuel Tech



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Fuel Tech has completed approximately fifty large unit SNCR systems, totaling close to 30GW, Figure 3. Most of these units were larger than 600MWg and the largest was 850MWg. These applications have primarily fired coal, but also fuel oil and biomass. SNCR performance is not dependent on the fuel source, but only on the availability of appropriate injection locations in the furnace and residence time for the reactions.

Over the past 15 years, Fuel Tech has advanced the state-of-the-art to maintain an average NO<sub>x</sub> reduction of 30% on large units, even as the baselines have decreased with combustion staging. These large units make up about 10% of Fuel Tech's installed base.

The most effective manner in which to illustrate the effectiveness of SNCR on large utility furnaces is through example. In particular, there are three useful units to discuss that were completed in 2014 using a simple SNCR design with limited front wall injection. Each of these furnaces was subsequently enhanced for commercial production utilizing optimal injection strategies and more sophisticated controls.

### **Recent Installation #1**

The first installation was on two identical 620MWg Riley turbo-furnace units burning Powder River Basin subbituminous coal (PRB). The baseline for both units averaged 320mg/Nm<sup>3</sup>, at 6% O<sub>2</sub>. Both furnaces were equipped with a single level of wall injection, but the resulting performance was dramatically different on each. On the first unit, it was possible to achieve 25% reduction in NO<sub>x</sub>, but only 13% reduction was possible on the second unit. These results were achieved while maintaining ammonia slip limits.

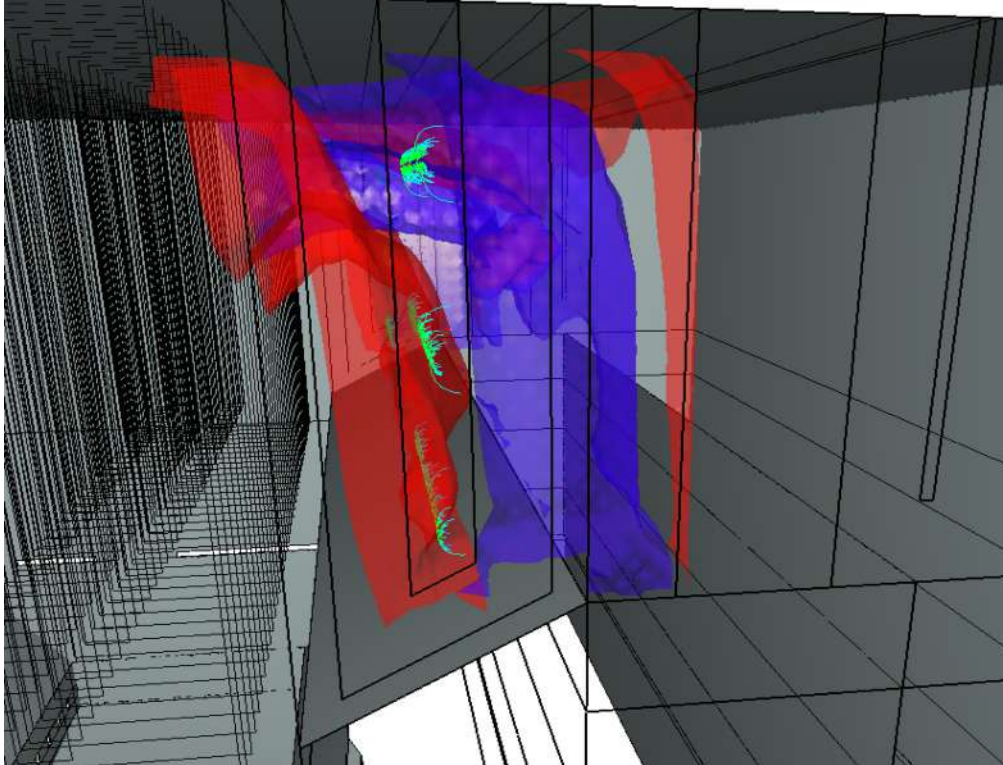
The second unit had been in service longer than the first, and so the unit was experiencing a higher level of slag on the furnace and convective pass tubes. This led to higher furnace temperatures and an increased CO concentration. The higher CO may also have been due to non-uniform gas flow patterns that occur when a furnace is partially occluded with deposits. The target temperature window on the second furnace was not ideal for treatment from the wall injectors.

Additional CFD modeling was performed to determine the ideal injection strategy for this flexible process condition. The ideal temperature window for chemical injection in the hotter situation was found to be directly within the tubes of the convective pass, just above the arch of the furnace. Injection in this section, Figure 4, is easy to model but more difficult to execute.

The Fuel Tech multiple nozzle lance (MNL), Figure 5, has been used for many years for this delicate injection solution. The lance is water-cooled and manipulated with a "rack and pinion" retract mechanism similar to what is commonly used for soot blowing lances. The resulting spray patterns can be controlled to carefully provide extremely effective chemical injection while minimizing any risk to the convective pass tubes.

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**Figure 4** CFD Injection modeling shows effective injection in the convective pass





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**Figure 5 Multiple Nozzle Lance (MNL) injector is used for convective pass SNCR injection**

Although the MNLs are more expensive to fabricate and install than typical wall injectors, they are sometimes the most effective solution for NO<sub>x</sub> control on large furnaces and help to keep dilution water flow rates as low as possible.

An additional level of front-wall injectors was modeled and installed to create a robust system for all furnace slag conditions and to provide effective coverage at 50% load (50% MCR). The additional wall-injector level and MNLs were optimized on both units and the resulting performance increased to 36% reduction on both units (205mg/Nm<sup>3</sup>, c6%), while maintaining ammonia slip limits. The SNCR treatment varies between the wall injectors and MNLs in a manner consistent with furnace conditions and the unit load.

### Recent Installation #2

The second installation was also completed in 2014 as a commercial SNCR system. This unit was a 620MWg B&W opposed-wall fired unit burning PRB coal. The NO<sub>x</sub> baseline was significantly lower, at 260mg/Nm<sup>3</sup>, at 6% O<sub>2</sub>. The target NO<sub>x</sub> for control was 195mg/Nm<sup>3</sup>, or about 25% reduction with controlled ammonia slip.

A demonstration was completed using a single level of wall-injectors in convenient locations on the furnace wall. It was possible to achieve the 25% reduction target to below 195mg/Nm<sup>3</sup> with controlled ammonia slip. Subsequent CFD, chemical kinetics and injection modeling revealed that these injectors were not ideally located.

A commercial installation was completed using two levels of wall injection to maximize performance and enhance low-load operation. The ideal injector strategy did not require MNL injectors. In this case, performance was measured with a reduction in the required chemical injected, and hence the operating cost of the installation. The commercial NO<sub>x</sub> control performance was identical to the demonstration performance but with a 35% reduction in the required chemical.

### High-Performance Advanced SNCR

Fuel Tech's most sophisticated SNCR suite of technologies is the Advanced-SNCR system. Advanced-SNCR utilizes acoustic or laser-based means of producing near real-time maps of furnace conditions that are then used to control the location and manner of injection for NO<sub>x</sub> control. In some cases the temperature mapping is the primary control signal. In other cases, the temperature mapping is used to select injectors within an injection zone for special operations.



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Standard Fuel Tech SNCR systems have logic designed to control operations based on unit load, NO<sub>x</sub> CEMS, upper furnace temperature and ammonia slip data. The Advanced system provides additional flexibility, utilizing our proprietary CFD and CKM model technology in concert with near real-time furnace contour maps to modify individual injection selection or treatment rates.

SNCR “performance” can be measured in many ways, and all are important to varying degrees. Certainly the achievable NO<sub>x</sub> reduction and ammonia slip are the foremost measures of performance. The chemical utilization is also critical to the operating cost of the system, as are the dilution water and injection air. Finally the ability of the system to operate dynamically and effectively over a wide load range is certainly significant.

Fuel Tech’s first application and development of these systems was based on the needs of much smaller grate-fired incinerators, where temperatures and gas species can change quite rapidly and can vary dramatically across the grate, Figure 6. Unsteady combustion conditions lead to wide variability in not only temperature, but also CO, NO<sub>x</sub>, and O<sub>2</sub> concentrations that affect SNCR performance.

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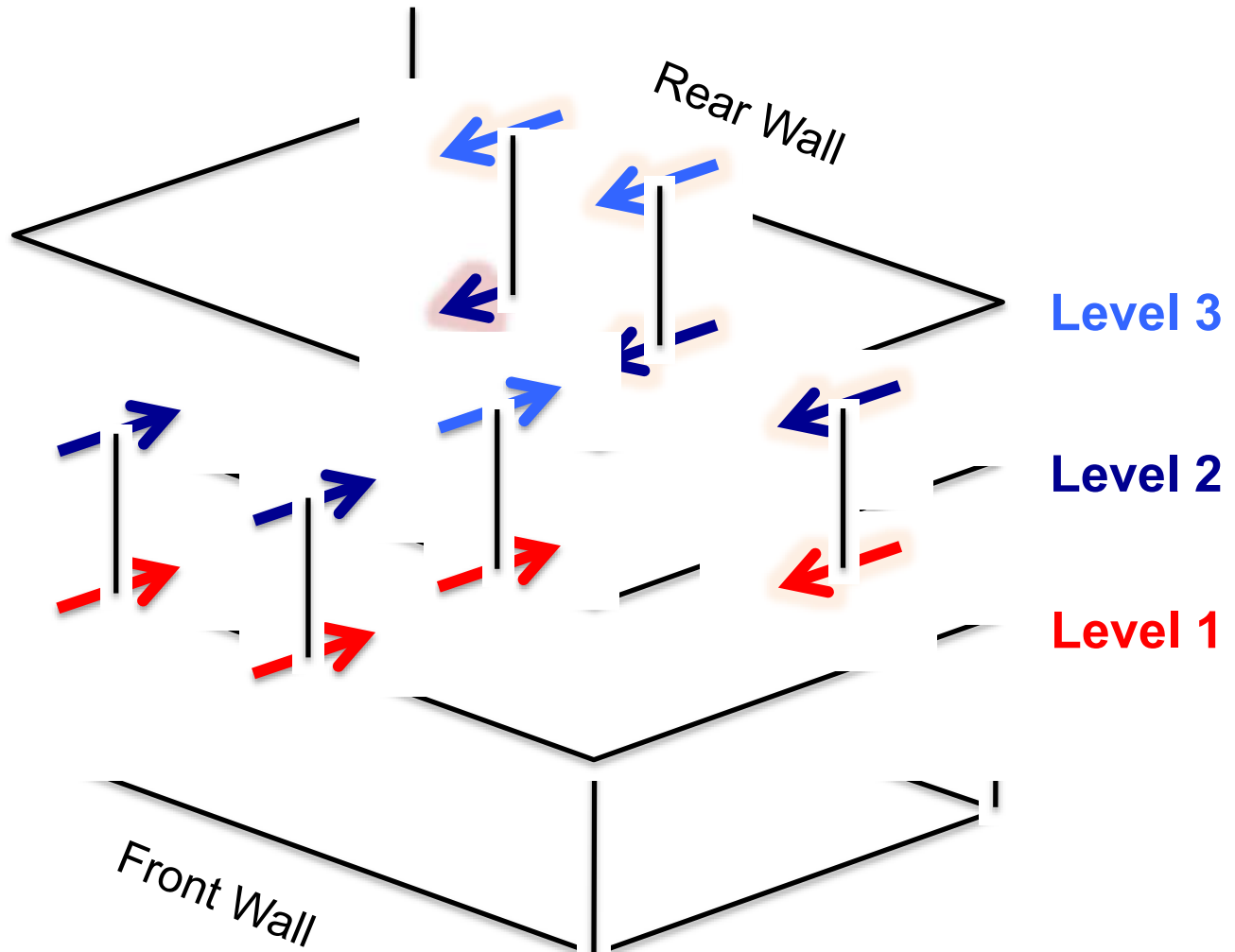


**Figure 6** Image of the highly non-uniform combustion on an incinerator grate

In simplified terms, the temperature profile can be mapped over an existing control scheme to activate only the injectors that are expected to provide the best performance, Figure 7. This can be managed in the short-term by responding to apparent conditions in the furnace. It has also been possible to measure variations in the furnace and develop algorithms to predict expected conditions in the near future. These algorithms include predictions of furnace gas concentrations and temperature changes that can be anticipated to improve chemical use and minimize balance of plant impacts.

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**Figure 7 Simple schematic showing temperature-based injector selection**

The optimized injection strategy is determined by reference to Fuel Tech’s vast SNCR experience database, CFD and CKM models, and field evaluation. Each of these three components is critical to a successful commercial project.

The approach to designing a highly flexible system is to recognize that the furnace has many different operational modes. There are large changes that occur with load variation and fuel switching, but there are also many other more subtle changes due to fuel moisture, mill behavior, and combustion air imbalance. The control theory must take into account each of the expected scenarios, and then recognize the variations from the norm. The approach is similar for any size



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unit, but the application can vary dramatically for very large furnaces. Figure 8 is a contour map of temperature from a large utility furnace, showing a wide variation in temperature from the expected predicted average.

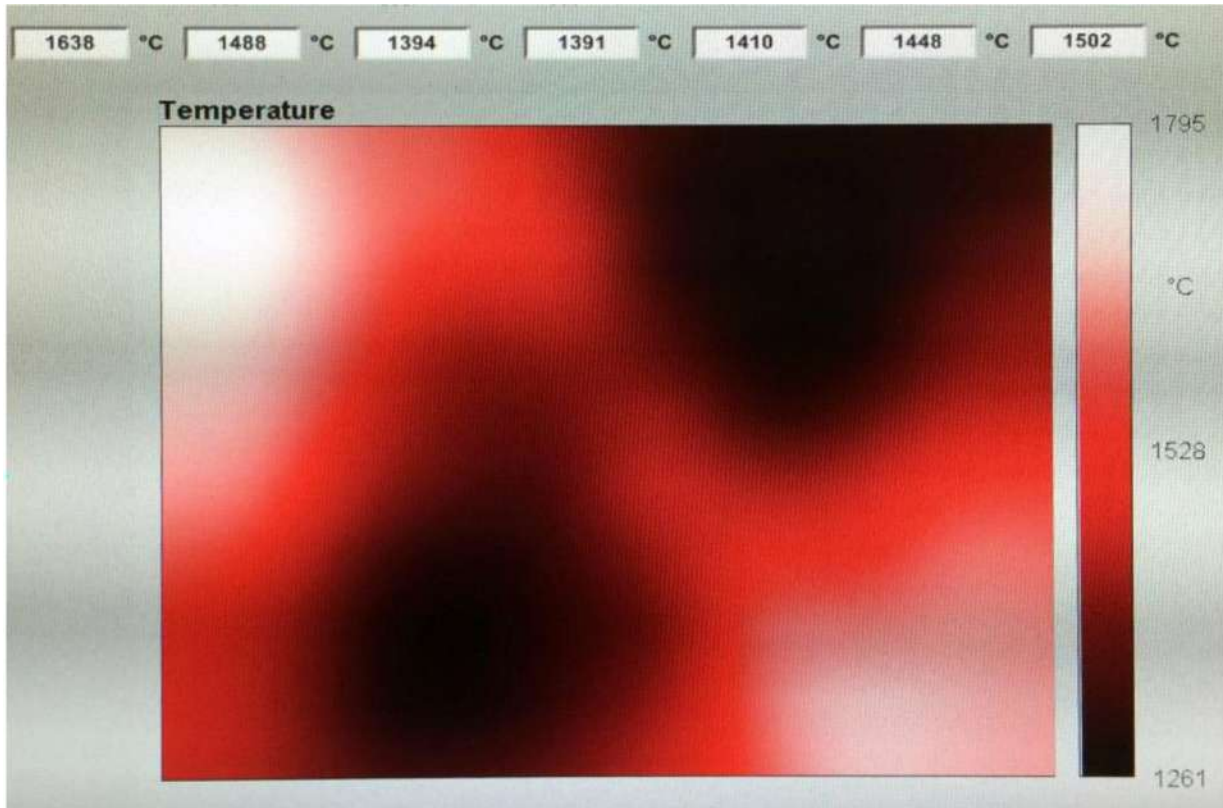


Figure 8 Temperature contour a measured in a large utility furnace

The application of Advanced SNCR to a large utility furnace incorporates many of the described features in the Advanced SNCR description with many of the unique capabilities developed by Fuel Tech to treat very large furnaces. These include both mechanically and air atomized injectors as well as water-cooled multiple nozzle lances were appropriate. The specific design solution is custom-fit to the subject furnace as well as the unique customer requirements for the project.

### Recent Large-Furnace Demonstrations

Two demonstrations of the Advanced SNCR process were completed in 2014, in support of commercial activity. Both of these units were very large furnace applications, greater than 600MWg. The first unit burned primarily biomass and the second unit burned various coals and coal blends. Both units were equipped with in-furnace temperature mapping capability and



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individual injector control, as described above. Because these were demonstration systems only, multiple nozzle lances (MNLs) were not used.



The demonstration equipment used for each of the two deployments was from Fuel Tech's containerized mobile fleet. The large-furnace equipment is designed for systems up to 850MW with as many as 6 zones of injection.

The biomass SNCR system was controlled in automatic using the gross load signal, the NO<sub>x</sub> CEMS and the on-line furnace mapping capability. Testing was conducted for various biomass



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fuels and biomass/coal blends. The demonstration system provided automatic control for NO<sub>x</sub> across the available load range. The on-line furnace mapping capability provided the data necessary to fully utilize the most effective injection points while eliminating individual injectors predicted to cause excess residual ammonia. As a result, the biomass demonstration system met or exceeded expectations for 30% NO<sub>x</sub> reduction with controlled ammonia slip over a wide range of furnace conditions.

The second large-furnace Advanced SNCR demonstration was implemented on a coal-fired unit. This unit fired five distinctly different coals during the demonstration period. In each case the baseline and furnace conditions were greatly affected. Testing was also completed to assess the impact of the combustion staging on the SNCR performance, by manipulating the over-fired air conditions. The results of this demonstration also met or exceeded the expected reductions. In particular, the system was able to respond to the higher baseline conditions with greater reduction efficiency while still controlling the ammonia slip.



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### **Summary**

Fuel Tech SNCR systems have proven to be very effective on large furnace applications, with nearly 30GW of direct experience. Large furnace applications (>400MW) of SNCR are nearly 10% of Fuel Tech's installed base of more than 590 SNCR systems worldwide.

Modern applications of combustion staging have been implemented on many units over the past 15 years, including Low- NO<sub>x</sub> Burners and Over-Fired Air systems installed by Fuel Tech in the United States. The changes have lowered NO<sub>x</sub> baselines and pushed many furnaces to the edge of their capacity for combustion modifications.

Through all of these changes, the Fuel Tech SNCR installations have continued to maintain an average NO<sub>x</sub> reduction of 30% while controlling ammonia slip. To be certain, it is not always possible to achieve 30% reduction on all units and some clients do not require this level of control.

Fuel Tech has now successfully demonstrated the Advanced SNCR system on two large utility furnaces (>600MW). In each case, the large furnace was equipped with on-line furnace mapping capability that guided the injection strategy automatically.

The demonstration systems were applied on furnaces that had already been equipped with LNB and OFA, as is standard on most large units. Fuel Tech has routinely applied SNCR systems to units with existing primary NO<sub>x</sub> control measures in place, and SNCR is particularly suited to this type of integration. Fuel Tech SNCR systems have been applied to a wide variety of fuels including biomass, waste incineration, coal, oil and natural gas. SNCR systems support fuel diversity, especially when advanced controls can be used to tailor the system operation for best performance.

Although the described demonstration systems were evaluated without process guarantees, the expectations were met and often exceeded. Fuel Tech routinely provides performance guarantees across the load range on all commercial projects, based on the Fuel Tech experience database and extensive process capability.