ELECTRIC POWER RESEARCH INSTITUTE

Memorandum

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TO: 2008 Post-Combustion NOx Control Program

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SUBJECT: **REVIEW OF ACT'S HERT POST COMBUSTION NOx CONTROL TECHNOLOGY**

Process Description

Advanced Combustion Technology, Inc (ACT) has developed and patented High Energy Reagent Technology (HERT), a process that couples Overfire Air (OFA) with Selective Non-Catalytic Reduction (SNCR). ACT claims HERT can achieve up to 65% NO_x reductions while maintaining NH_3 slip below 5 ppm on boilers without existing OFA systems.

The HERT system is comprised of multi-level SNCR injection where urea is injected both through wall injectors in the upper furnace, as well as into the OFA system. The basis of the HERT system is that injecting into the OFA stream allows for improved mixing and urea distribution in the upper furnace, thereby reducing the number of injectors as compared to traditional SNCR systems. The HERT reagent injectors utilize mechanical atomizers to create droplets that range between 1 and 40 microns in diameter, resulting in vaporization times of about 0.01 seconds. ACT claims that the instantaneous vaporization of reagent in the OFA streams contributes to enhanced reagent mixing, resulting in less urea usage. Furthermore, ACT also claims that the technology can function in a temperature window beyond typical SNCR to eliminate NH_3 slip. ACT claims that HERT has the following potentials for NO_x reduction (e.g. OFA + SNCR):

- Wall Fired: 40-60%
- Cyclones: 55-65%
- T-Fired: 45-65%

ACT predetermines injector designs and locations prior to fabrication and installation through the use of Computational Fluid Dynamics (CFD) modeling and actual boiler test data, such as temperature and emissions profiles.

ACT holds the following patent: *Method and Apparatus for Adding Reducing Agent to Secondary Overfire Air Stream*, Marx, et al – U.S. Patents 6,988,454 B2, January 24, 2006. The process is somewhat similar to two other OFA-reagent injection systems: one developed and patented by GE Energy & Environmental Research Corp. (GE EER) (US Patent No 6,280,695 and No 6,865,994), and the other by Nalco Mobotec for the ROTAMIX® system.

The original GE EER patent (US Patent No 6,280,695) was for the injection of reagent in the form of large droplets (50 to 1000 microns) into the OFA, such that the droplets' lifetime was greater than the OFA mixing time with the combustion flue gas (0.1 to 5 seconds). The purpose of these larger droplets was to prevent the reagent from reacting with CO in the combustion zone, and allow the reagent to react with NOx in the upper furnace in the appropriate temperature window. The technology focused on the perceived need for the ability to install SNCR in boilers where it was difficult or impossible to install an injection system in the upper furnace. The technology required more reagent than a standard SNCR system, and the design of the large droplets to achieve the necessary residence times was difficult and often resulted in increased NH_3 slip and conversion of NH_3 to additional NOx.

The second GE EER patent (US Patent No 6,865,994) still emphasized the large-scale mixing created by injecting reagent into the OFA system, but also enhanced the small-scale mixing at the OFA jet. The technology used a step-diffuser at the injector outlet to induce vigorous air/flue gas mixing near the injector outlet which was claimed to decrease CO and improve overall OFA performance. As the CO is reduced in the reagent injection zone, smaller droplets could be used for SNCR, which decreased the overall reagent usage.

The Nalco Mobotec ROTAMIX™ system uses their ROFA™ system to inject SNCR reagent into the upper furnace. The ROFA™ (Rotating Overfire Air) system works to decrease furnace exit gas temperatures through increased mixing between the OFA and flue gas. The increased mixing is achieved through incorporation of a booster fan (e.g. 600 hp – 1200 hp for 150 MW boiler) to increase the OFA velocity introduced into the boiler. Unlike conventional OFA systems which rely upon windbox air pressures of 4 – 6 inches water column (iwc), the ROFA system generates boosted pressures in excess of 30 iwc. Mobotec claims that injection of SNCR reagent into the boosted pressure ROFA flow creates a greater degree of mixing and the potential for increased chemical utilization.

Principles of Operation

The HERT system is comprised of two common methods for NOx control: Overfire Air (OFA) and SNCR. Each mechanism is described separately below.

Overfire Air

Overfire air (OFA) is a method of staged combustion, where a portion of the burner air is removed to reduce oxygen availability during the initial combustion process, and re-introduced later in the combustion process to allow for complete burn-out. NOx emission reductions with OFA are a direct function of the burner zone stoichiometric ratio (e.g. actual air to coal ratio relative to the theoretical air to coal ratio required to achieve complete burnout). Introduction of combustion air into the upper furnace reduces the oxygen partial pressure within the burner zone, as well as the level of fuel nitrogen conversion to NOx. In addition, the delay in coal combustion suppresses peak flame temperatures and the formation of thermal NOx. OFA is especially effective in tangentially-fired boilers, with typical NOx reductions ranging up to 50%, depending upon achievable lower furnace stoichiometry, coal sulfur content, and fly ash unburned carbon levels.

Selective Non-Catalytic Reduction

Selective Non-Catalytic Reduction (SNCR) is a post-combustion method for NOx reduction, utilizing the injection of urea reagent into the upper furnace. For urea-based SNCR, it is postulated that the urea compound [$CO(NH_2)_2$] decomposes as shown below:

$$NH_2CONH_2 \Rightarrow NH_3 + HNCO \qquad \text{Equation 1}$$

The NOx reduction reactions then proceed as follows:

$$NH_3 + OH \Rightarrow NH_2 + H_2O \qquad \text{Equation 2}$$
$$HNCO + H \Rightarrow NH_2 + CO \qquad \text{Equation 3}$$
$$HNCO + OH \Rightarrow NCO + H_2O \qquad \text{Equation 4}$$
$$NH_2 + NO \Rightarrow N_2 + H_2O \qquad \text{Equation 5}$$
$$NCO + NO \Rightarrow N_2O + CO \qquad \text{Equation 6}$$
$$N_2O + M \Rightarrow N_2 + \ldots. \qquad \text{Equation 7}$$

The above set of chemical reactions determines the temperature sensitivity of the SNCR process. Equations 2 to 4 represent the initial decomposition of urea due to reaction with H or OH radical species that are short-lived and only present in sufficient concentrations at flue gas temperatures in excess of 1700 F (927 C). Without these radical species, NH_2 is not formed and NH_3 and HNCO can pass though the boiler and convective pass unreacted.

On the high temperature side of the SNCR process temperature window (i.e. > 2000 F (1093 C)), radical species concentrations can become too great, resulting in continued oxidation of nitrogen intermediates to form additional NO. As can also be seen in the sequence above, Equation 6 provides a path for the formation of N_2O and CO.

There are a number of factors which determine the amount of NOx reduction achievable with SNCR, chiefly the effectiveness of the injectors to adequately mix the reagent in the flue gas, adequate residence time for the reduction reactions to occur, and a proper temperature window as indicated above (1700 to 2000°F (927 to 1093°C)). Under ideal conditions, NOx reductions in full scale utility boilers of up to 40% are achievable; however, 25-35% reductions are more typical. Reagent distribution becomes more difficult in large coal-fire boilers because of the large distances required to cover the cross section of the boiler. Conventional SNCR systems use multiple levels of reagent injectors to follow temperature changes caused by boiler load changes. It should be noted, however, that EPRI has successfully demonstrated the SNCR Trim concept where a single level of injectors can be used to reduce NOx over the entire load range by tailoring the reagent drop size distribution to the furnace exit gas temperature and quench rate.

Low energy injection systems can be used to delay the release of urea when injected at high flue gas temperatures though the use of dilute urea solutions (e.g. 5% - 10% by weight) and large drop size distributions. Table 1 presents calculated water droplet evaporation times as a function of temperature and drop size. This characteristic typically allows the use of a lower capital cost, low-energy injection system that relies on droplet momentum and bulk furnace turbulence for reagent mixing.

Table 1
Calculated Water Droplet Evaporation Time

Temperature (^oF)	Drop Size 400 micron	Drop Size 500 microns	Drop Size 600 micron
2000	0.72 s	1.13 s	1.58 s
2200	0.65 s	1.02 s	1.46 s
2400	0.59 s	0.92 s	1.33 s

HERT

The HERT systems combine SNCR with OFA by installing wall injectors in the upper furnace and high momentum OFA injectors in the OFA ports. ACT uses Computational Fluid Dynamics (CFD) in conjunction with test data to design the OFA system and predict flue gas conditions. A multi-level injection scheme is designed to inject urea in a mixed flue gas and overfire air temperature window that is between 1600 ^oF and 2100 ^oF. The HERT system OFA injectors mechanically atomize the reagent into droplets ranging from 1 to 40 microns in diameter, which ACT claims will result in instantaneous vaporization (about 0.01 seconds), allowing for improved distribution and mixing over conventional SNCR systems. They also claim that this immediate vaporization allows for better utilization of reagent compared to other SNCR installations. ACT claims that other commercial systems which inject reagent into the OFA tend to create larger droplets, which don't evaporate until after the combustion gases have finished mixing with the OFA gas, leading to the need for higher reagent injection rates. However, in making this claim, ACT appears to be referring to the original GE EER patent which did use larger reagent droplets, but was focused on making SNCR available for boilers that were unable to install upper furnace wall injectors.

Performance and Experience Base

Table 2 lists the HERT systems installed and their performance, as reported by ACT. HERT has been installed in boilers with different firing configurations and range between 40 MW to 255 MW in size. In addition to the 14 installations listed, HERT demonstrations were conducted at Gulf Power's Plant Smith Units 1 and 2, in October, 2007.

Additional details available on select installations are discussed below.

Blue Ridge Paper Unit 4

Blue Ridge Paper Products Boiler 4 is a 40 MW, Tangentially-fired, CE boiler that burns eastern bituminous coal. ACT designed and implemented a layered NOx control strategy that consisted of low NOx burners (LNBs), separated overfire air (SOFA) and HERT. The original uncontrolled NOx was 0.70 lb/MBtu. LNB's reduced the NOx to 0.48 lb/MBtu; SOFA reduced it

Table 2. HERT Installations

Station Utility	Boiler Mfg	Firing	# of Burners	Fuel	MW	Steam Flow, klb/hr	Baseline NOx, lb/Mbtu	Urea Flow, gph	HERT NOx, lb/Mbtu	dNOx, %
Blue Ridge Paper Unit 4 Blue Ridge Paper Company	CE	Tang	12	Coal	40	400	0.3	28	0.15	50%
Clinch River Unit 3 AEP	B&W	Roof	14	Coal	255	2200	0.3	66	0.2	33%
James River Unit 1 City Utilities of Springfield	CE	Tang	8	Coal	25	200	0.35	12	0.2	43%
James River Unit 2 City Utilities of Springfield	CE	Tang	8	Coal	25	200	0.35	12	0.2	43%
James River Unit 3 City Utilities of Springfield	Riley	Wall	6	Coal	46	450	0.18	15	0.1	44%
James River Unit 4 City Utilities of Springfield	Riley	Wall	6	Coal	60	550	0.2	20	0.12	40%
James River Unit 5 City Utilities of Springfield	Riley	Wall	8	Coal	105	890	0.22	25	0.15	32%
John Sevier Unit 2 TVA	CE	Tang	16	Coal	180	1500	0.35	60	0.19	46%
Johnsonville Unit 4 TVA	CE	Tang	16	Coal	135	100	0.39	50	0.15	62%
Middletown Unit 2 NRG	Riley	Wall	12	Oil/Gas	123	960	0.23	27	0.15	35%
Philip Sporn Unit 3 AEP	B&W	Roof	10	Coal	155	1450	0.32	52	0.2	38%
Schiller Unit 4 Northeast Utilities	FW	Front	6	Coal	50	400	0.35	15	0.25	29%
Schiller Unit 6 Northeast Utilities	FW	Front	6	Coal	50	400	0.35	15	0.25	29%
Tanner Creek Unit 3 AEP	B&W	Roof	10	Coal	155	1450	0.28	49	0.18	36%

further to 0.28 lb/MBtu, and HERT system brought it down to 0.15 lb/MBtu. All three systems were supplied and installed for $25 per kW.

The LNBs and SOFA system were installed first, in 2001, to meet the initial goal of 0.34 lb/MBtu, and were able to achieve reductions down to 0.28 lb/MBtu. However, a future goal of 0.15 lb/MBtu was desired, but studies determined that traditional SNCR would only reduce NOx to 0.22 lb/MBtu. As a result, ACT determined that by maximizing the interaction of the three technologies, NOx could be reduced to 0.15 lb/MBtu.

Prior to installation, ACT performed CFD modeling to simulate the performance of each system. Additionally, a field demonstration was performed with ACT's portable HERT skid, shown in Figure 1, prior to completing the final design. The final HERT system utilized only four reagent injectors, one in each of the SOFA ports, and was able to achieve a 50% reduction in NOx over the load ranges of 50% to 100%, while maintaining less than 2 ppm ammonia slip at the air heater inlet.

Figure 1: ACT's Portable HERT Test Skid (presented at 2006 Environmental Controls Conference)

Data from the US EPA EDR database does confirm that Blue Ridge Paper Boiler 4 was able to achieve reductions in NOx levels from 0.3 lb/MBtu to 0.16 lb/MBtu in third quarter, 2005, as shown in Figure 2 versus time and Figure 3 versus load. In 2006, shown in Figure 4 versus load, second quarter NOx averaged 0.18 lb/MBtu, and third quarter averaged 0.17 lb/MBtu (first and fourth quarter data are unavailable). However, in 2007, the second and third quarter NOx averages rose to 0.27 lb/MBtu and 0.28 lb/MBtu, respectively (Figure 5). It appears as though Blue Ridge did not utilize the HERT system for at least those two quarters in 2007, which may be attributable to NOx allowance prices less than the operating cost of urea during this time period.

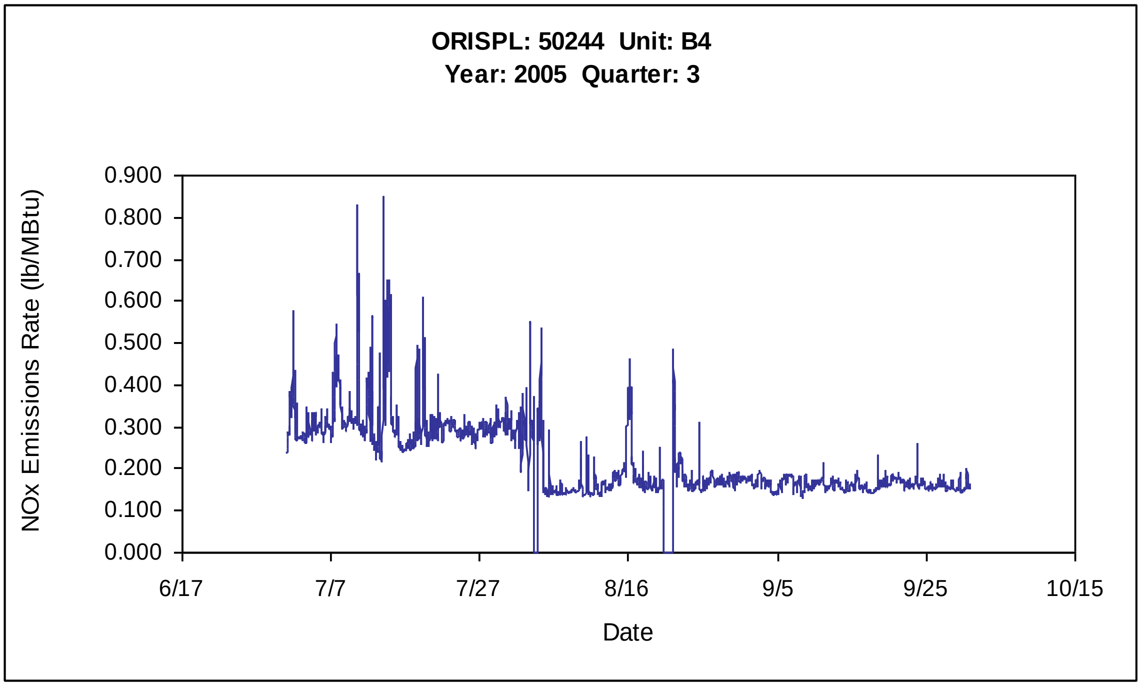


Figure 2: Blue Ridge Paper Boiler 4: NOx EDR Data, Third Quarter, 2005

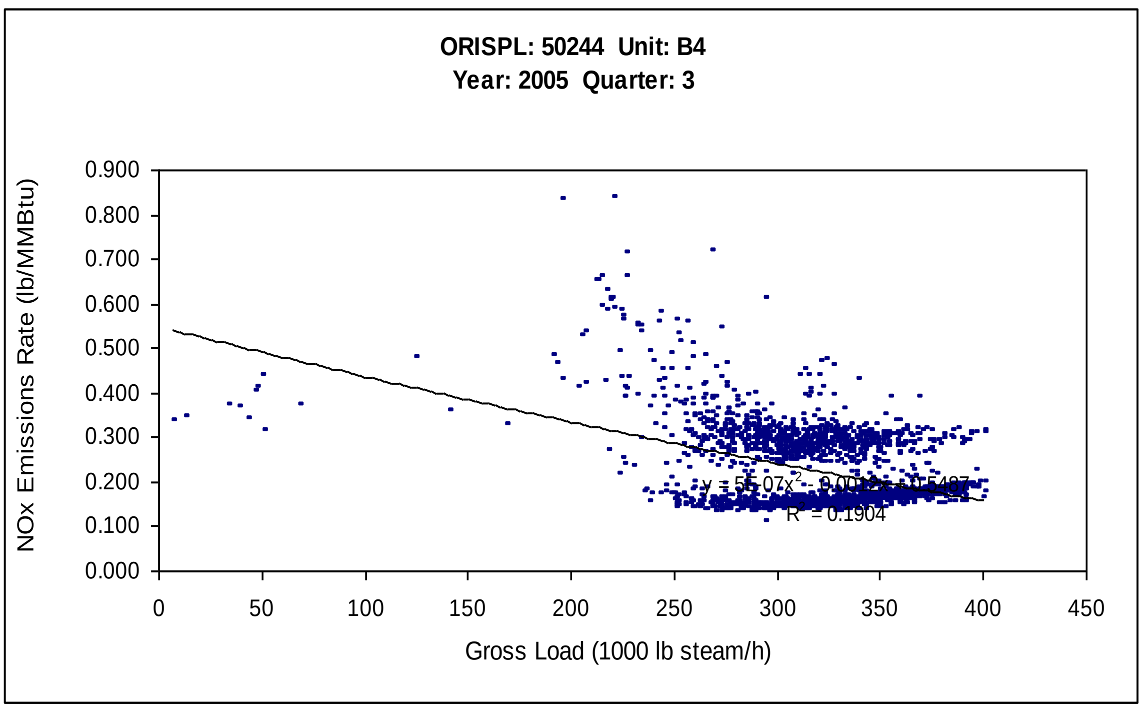
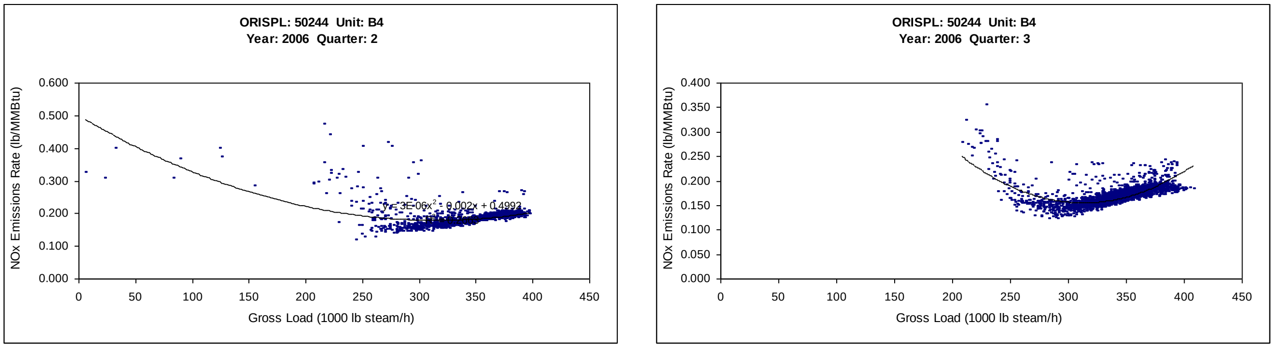
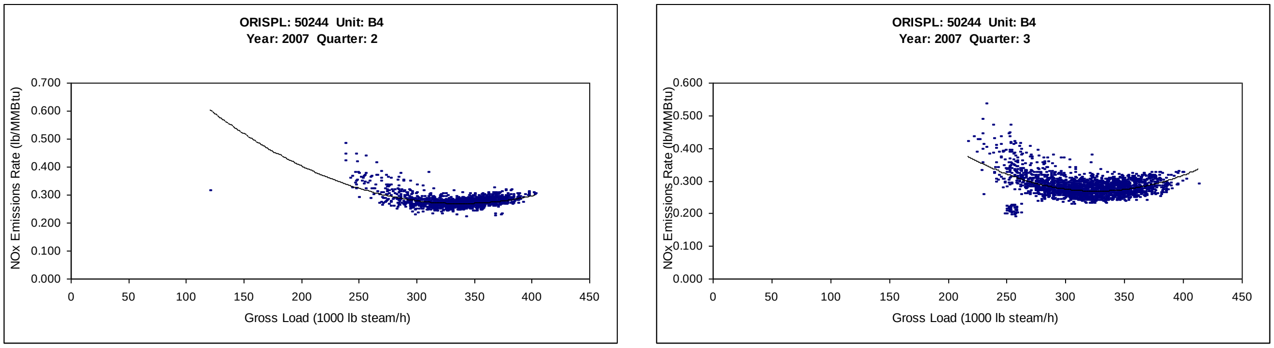


Figure 3: Blue Ridge Paper Boiler 4: NOx versus Load EDR Data, Third Quarter, 2005



a) NOx EDR Data, Second Quarter, 2006 b) NOx EDR Data, Third Quarter, 2006

Figure 4: Blue Ridge Paper Boiler 4, NOx versus Load EDR Data, Second and Third Quarters, 2006



a) NOx EDR Data, Second Quarter, 2007 b) NOx EDR Data, Third Quarter, 2007

Figure 5: Blue Ridge Paper Boiler 4, NOx versus Load EDR Data, Second and Third Quarters, 2007

NRG Middletown Unit 2

NRG Middletown Power, LLC Unit 2 is a 125MW, wall-fired, Riley boiler that burns #6 oil and natural gas. Similar to the Blue Ridge Paper installation, ACT designed and implemented a layered technology strategy that was comprised of LNBs, SOFA and HERT.

The uncontrolled baseline NO_x, when oil-fired, was 0.39 lb/MBtu. With ACT's LNBs and optimized SOFA, the NO_x was reduced to 0.19 to 0.22 lb/MBtu, with opacity below 7%. Initial HERT testing reduced NO_x further to less than 0.12 lb/MBtu, while maintaining ammonia slip less than 6.5 ppm. The HERT system utilized only two SOFA reagent injectors.

It is estimated that the installed capital cost of all three technologies at Middletown was $7 to $10 per kW.

US EPA EDR data for fourth quarter, 2007, reports that the average NO_x was 0.12 lb/MBtu, as shown in Figure 6 versus load.

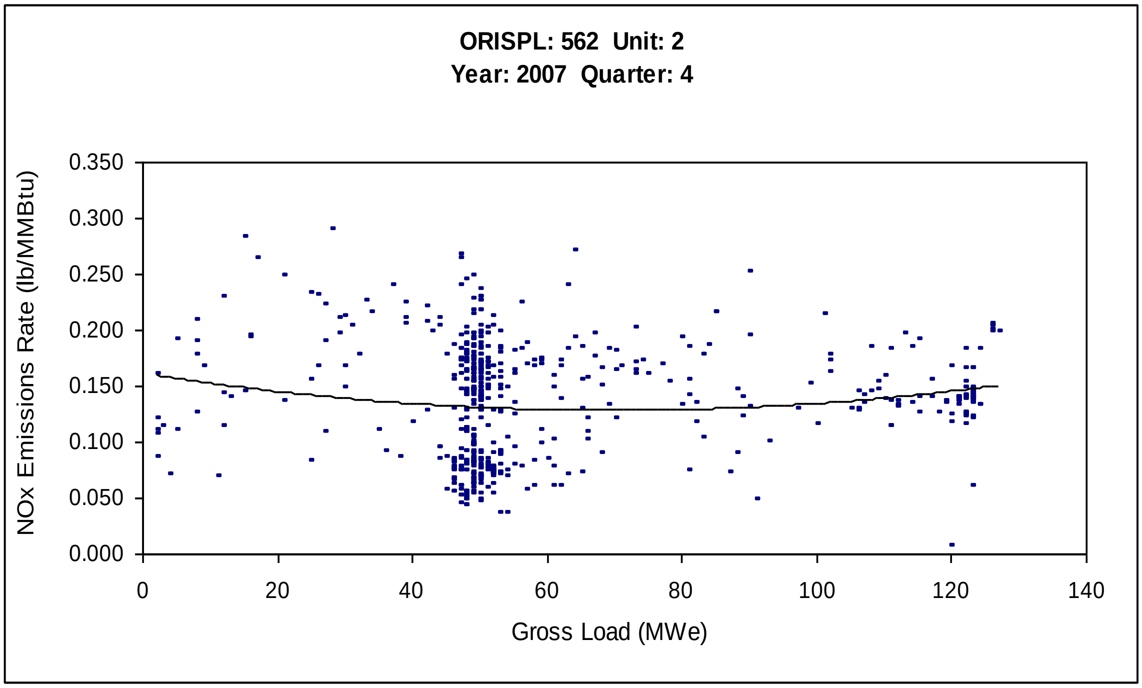


Figure 6: NRG Middletown Unit 2, NOx versus Load EDR Data, Fourth Quarter, 2007

TVA John Sevier Unit 1

TVA John Sevier Unit 1 is a 180 MW, tangentially-fired, CE boiler that burns Central Appalachian Coal. Unit 1 is a twin furnace design, with a superheat and reheat furnace. Prior to the HERT installation in spring of 2007, Unit 1 was already equipped with LNBs and OFA.

The HERT system utilizes a total of 10 SNCR injectors per furnace (20 total). Figures 7 and 8 depict installed injectors at the furnace wall and OFA system. Eight of the injectors are distributed over two upper furnace elevations, while the remaining two injectors are at the OFA level, as shown in Figure 9. The placement of these injectors was based on the results of the CFD modeling that ACT performed in 2006.

The dilution water and metering skid, the individual injector isolation valves, and the injector blower skid were all installed on the second floor of the powerhouse. The dilution water skid supplies water to both the superheat and reheat lances; the blower skid supplies air only to the upper furnace injectors, not the OFA injectors. The urea recirculation building, including the 25,000 gallon, double-walled, unheated storage tank, was installed in the yard near the loading dock. Feedforward control of the HERT system was accomplished with the installation of NOx CEMS units on both superheat and reheat ducts.

Based on the 2006 CFD modeling, ACT guaranteed 35.4% NOx removal, averaged from tests at three loads, while maintaining ammonia slip of 5 ppm or less. The three loads tested during the performance testing were 180 MW, 140 MW, and 100 MW.

Table 3 summarizes the results of the performance tests.

Table 3: John Sevier Unit 1, HERT Performance Test Results

Load MW	Baseline NO_x lb/MBtu	NO_x Removal %	NSR	NH_3 Slip ppm, dry	Urea Utilization %
180	0.33-0.35	40-46%	0.8-1.0	1.4	45-49%
140	0.33-0.40	38-42%	0.9-1.0	1.7-2.5	41-42%
100	0.34-0.36	33-36%	1.1-1.3	0.16-0.13	27-30%

As seen in Table 3, the HERT system achieved the predicted design goals. Plant personnel have reported that periodic checks on the system while in Automatic Generation Control indicate NO_x removal in the mid 30% to low 40% range.

US EPA EDR data is unavailable for John Sevier Unit 1, as it is a combined stack.

Figure 7: HERT Wall Injector
Presented at EPRI SNCR Interest Group Meeting

Figure 8: **HERT OFA injector**
Presented at EPRI SNCR Interest Group Meeting

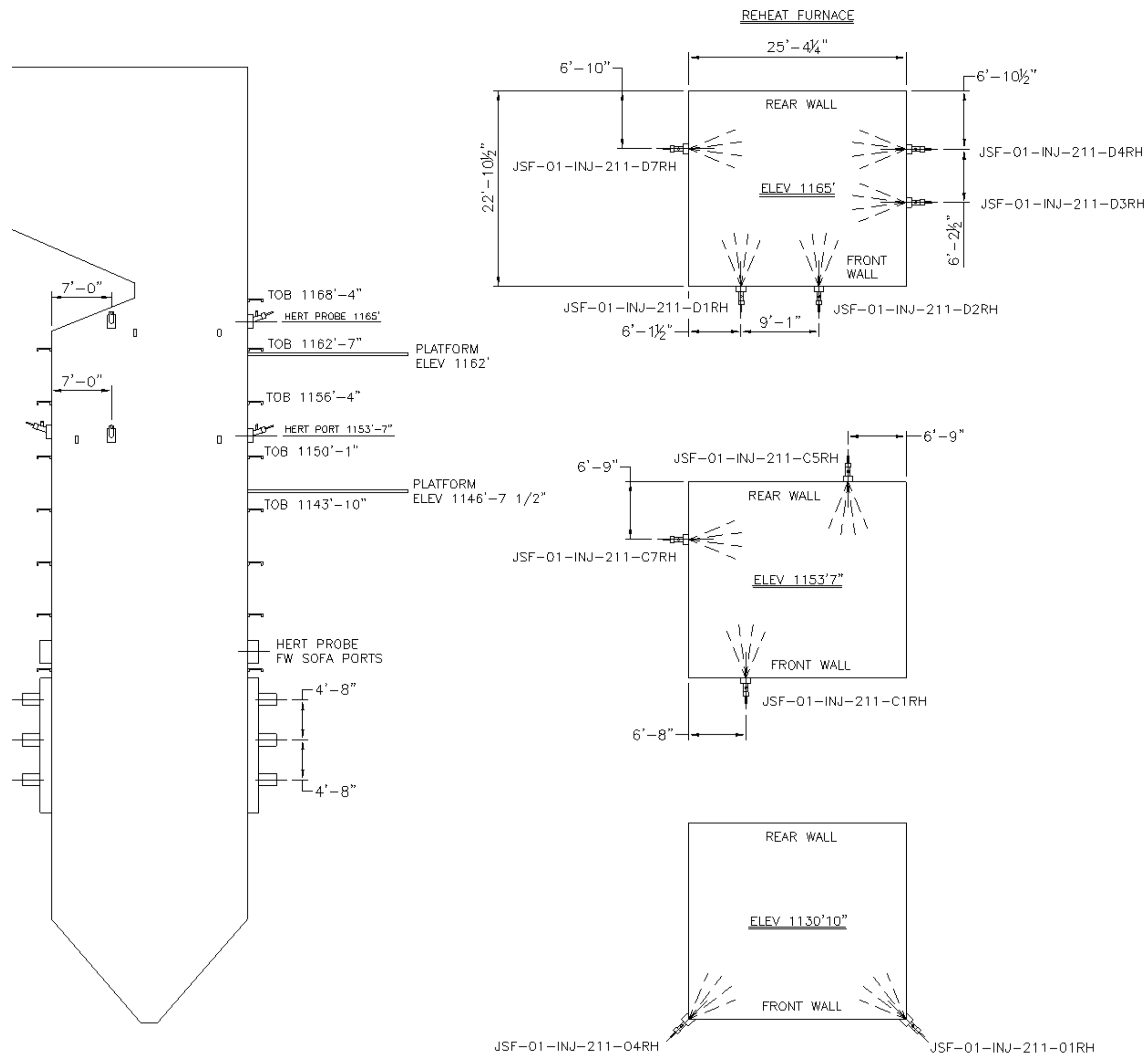


Figure 9: TVA John Sevier Unit 1, HERT Injector Locations

TVA Johnsonville Unit 4

TVA Johnsonville Unit 4 is a 120 MW, tangentially-fired, CE boiler that burns various blends of Colorado, PRB, and Illinois Basin coal. The ACT installation included both an OFA system and the SNCR HERT system. The OFA system reduced the NO_x from 0.32-0.40 lb/MBtu to 0.20-0.24 lb/MBtu. The unit does not have LNBs.

The installation at Johnsonville Unit 4 is similar to the John Sevier Unit 1 system, with some exceptions. The Johnsonville HERT system has a total of 9 SNCR injectors; five injectors were installed at a single upper furnace elevation, while the remaining four were at the OFA level (Figure 10). The placement of the injectors was based on the results of CFD modeling performed by ACT in 2006. Furthermore, the Johnsonville system does not have individual injector isolation valves, as each level is operated at the water dilution skid. An existing Fuel Tech urea recirculation skid in the yard was used for the ACT system.

ACT's performance guarantee specified 54% NO_x removal, averaged from tests at three loads, while maintaining ammonia slip of 5 ppm or less. The NO_x removal was to be calculated for both the OFA and HERT systems combined. The three loads tested during the performance testing were 120 MW, 100 MW, and 85 MW.

Table 4 summarizes the results of the performance tests

Table 4: Johnsonville Unit 4, Performance Test Results

Load MW	Baseline NO_x lb/MBtu	NO_x Removal %	NSR	NH_3 Slip ppm, dry	Urea Utilization %
120	0.37	55-61%	1.3-1.6	1.5-2.9	14-23%
100	0.33	57-59%	1.2	1.6-2.1	25-27%
85	0.36	60%	1.1	3.2	28%

As seen in Table 4 the OFA and HERT system achieved the predicted design goals. Plant personnel have reported that periodic checks on the system while in Automatic Generation Control indicate combined OFA + SNCR NO_x removals in the 51-56% range, using 0.34 lb/MBtu as the uncontrolled baseline value. US EPA EDR data is unavailable for Johnsonville Unit 4, as it is a combined stack.

The Johnsonville HERT installation provided a chance to compare HERT to a typical Fuel Tech SNCR system installed on Unit 1. The HERT system had fewer injectors (i.e. 9 injectors on Unit 4) than the Fuel Tech system (i.e. 19 injectors on Unit 1). Additionally, the HERT system used approximately 25-30% less urea than the Fuel Tech SNCR. The HERT system used 100 scfm of blower air at 3-4 iwc from a newly installed blower, while the Fuel Tech system used 370 scfm of 130 psig compressed air from the plant supply. The HERT control system was reported to be simpler than the Fuel Tech system, with only feedforward control; however TVA has indicated that the ability to control trim with feedback on the Fuel Tech system does offer some advantages. Finally, the overall HERT installed cost was reported to be less than that associated with the Fuel Tech system.

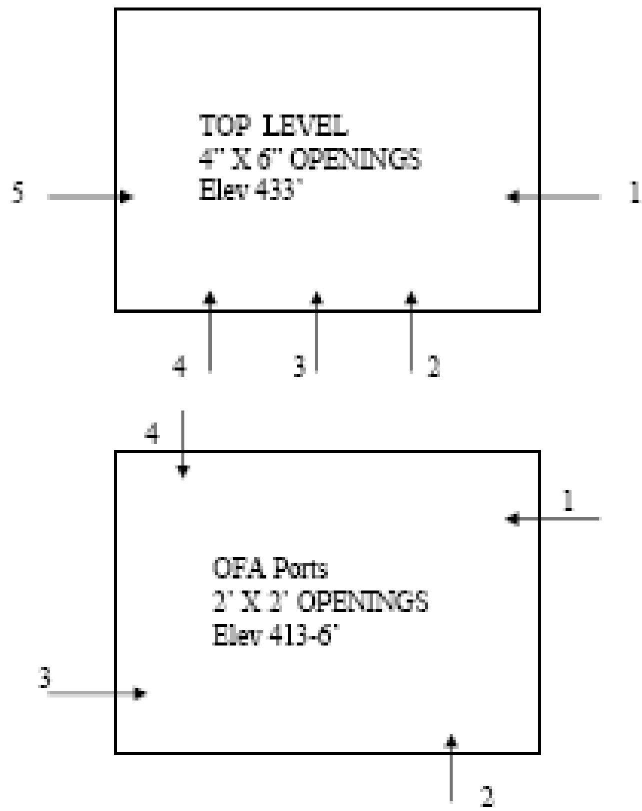


Figure 10: TVA Johnsonville Unit 4, HERT Injector Locations

Gulf Power Company Plant Smith Units 1 and 2

Gulf Power Plant Smith Unit 1 is a 180 MW, tangentially-fired, CE boiler, with baseline NO_x of approximately 0.45 – 0.50 lb/MBtu. Unit 2 is a 210 MW, tangentially-fired CE boiler, with baseline NO_x of approximately 0.35 - 0.45 lb/MBtu. The main objective of the Phase I testing was to demonstrate that the HERT system was capable of reducing NO_x by 30% over the load range, and to gather data which would be used to validate the CFD model for determining the optimal injection locations.

The Phase I work was performed with the ACT portable HERT skid in October, 2007. Injectors were inserted through existing observation doors on the 7th and 8th floors. The load ranges tested were as follows:

- Unit 1 – 173 MW, 125 MW, and 73 MW
- Unit 2 – 205 MW, 135 MW, and 73 MW

Unit 1 averaged 40% NO_x reduction over the three loads tested, while Unit 2 averaged 30% NO_x over the three loads tested. Both units utilized six injectors. NO_x reductions at full load averaged in the 20% to 25% range, while reductions at lower loads approached 50% to 60%.

Estimated Capital and O&M Cost

ACT reports that a typical cost for a HERT installation, including engineering design, ranges from $600,000 to $850,000. This cost takes into account the installation of wall injectors and OFA injectors, a reagent skid and transport and control system, and reagent storage tank. The difference in cost is due to differences in reagent storage tank size. The cost also assumes that the boiler already has an OFA system in place. The average unit size of the current installations listed in Table2 is 100 MW, which translates to a cost of $6 to $8.5 per kW. In addition to the capital costs, the HERT systems have an ongoing operating cost for the reagent.

By comparison, the capital cost for a Mobotec ROFA® installation has been reported to range between $25/kW - $50/kW, with the ROTAMIX® system costing an additional $5/kW- $10/kW, depending upon unit size. A typical SNCR system can be expected to cost between $2,000,000 to $4,000,000, or $7 - $13 per kW for a 300 MW unit. Adjusted for a 100 MW unit, this translates to approximately $15 to $20 per kW.

Potential Operational Issues

The HERT technology combines SNCR technology with OFA. As ACT, in the majority of installations, is retrofitting the SNCR HERT system to a boiler with an existing OFA system, the potential operating issues associated with OFA are not discussed here.

SNCR systems typically suffer from equipment issues, which include heating the urea solution to prevent precipitation and keeping the injectors clean. In terms of the actual SNCR chemistry, the combustion gas temperature is a key parameter, as at lower flue gas temperatures excess unreacted reagent in the form of ammonia slip can combine with SO_3 to form ammonium bisulfates, which can foul air heaters. Additionally, excess ammonia slip can combine with acidic fly ash, thereby affecting its salability. For situations where injected urea is released at high flue gas temperatures (e.g. 2000 F (1093 C)), the reagent can actually react with O_2 to form NOx.

Actual operation of the HERT system at TVA's John Sevier Unit 1 revealed problems with using filtered river water to create dilute urea solution. The solution formed a calcium precipitate that plugged the system after two weeks of operation. The short term solution was to use gland seal water instead of the river water. Additionally, use of the HERT system resulted in a drop in steam temperatures in the reheat furnace to below acceptable levels, creating the potential for condensation of water vapor to result in particle erosion in the reheat turbine. Their current solution is to shut down the reheat portion of the HERT system when the load drops below 130 MW. Finally, an ammonia smell was reported when the fly ash was mixed with water for dry stacking.

The HERT system at TVA's Johnsonville Unit 4 also suffered from system pluggage from calcium precipitate resulting from the use of filtered river water and unstabilized urea. The short term solution was to use stabilized urea, but the long term solution is likely to be the use of demineralized water.

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Advanced Combustion Technology, Inc (ACT)
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