SCR Levels of NOx Reduction with ROFA and Rotamix (SNCR) at Dynegy's Vermilion Power Station

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Abstract

NOx was reduced 83% at full load (80 MW) to 0.10 lb/MMBtu using a boosted over-fired air system (ROFA®) and an advanced SNCR system (Rotamix®). ROFA and Rotamix, two-thirds of the MobotecSystem, were installed at Dynegy Midwest Generation's Vermilion Power Station Unit 1, a 1955, bituminous coal, Combustion Engineering, tangentially fired boiler. ROFA was installed in summer 2002 and Rotamix in spring 2004.

The total installed cost over 10 ozone seasons for the MobotecSystem installed at Vermilion is under $400 per ton of NOx removed for ROFA and under $200 per ton of NOx removed for Rotamix. Recurring chemical costs (urea) are below $250 per ton of NOx removed. With NOx credits as low as $3000 per ton the payback period for the Vermilion installation is under 10 months (two ozone seasons). ROFA and Rotamix can inexpensively reduce NOx to emission levels previously only achieved with an SCR installation. ROFA and Rotamix provide additional benefits detailed in the paper.

Introduction

Utilities, under increasing federal and state regulations require more options for NOx, SOx, and mercury (Hg) reduction. The focus of this paper is NOx reduction. Many options exist for NOx control, among them: low NOx burners (LNB), over-fired air (OFA), selective non-catalytic reduction (SNCR) systems, and selective catalytic reduction (SCR) systems. These options achieve markedly different levels of NOx reduction (see Figure 1) and have widely varying installed pricing and O&M costs for differently sized boilers.

Ultimately, users must choose economically feasible options that will achieve their NOx reduction requirement. The status quo for small boilers (40 to 150 MW) has been to combine LNB with OFA systems to achieve NOx emissions in the 0.30 to 0.35 lb/MMBtu range. NOx emissions in the 0.20 to 0.25 lb/MMBtu have been possible by including SNCR systems, but until recently, these systems have not reliably reached NOx emissions below 0.15 lb/MMBtu, much less 0.10 lb/MMBtu.

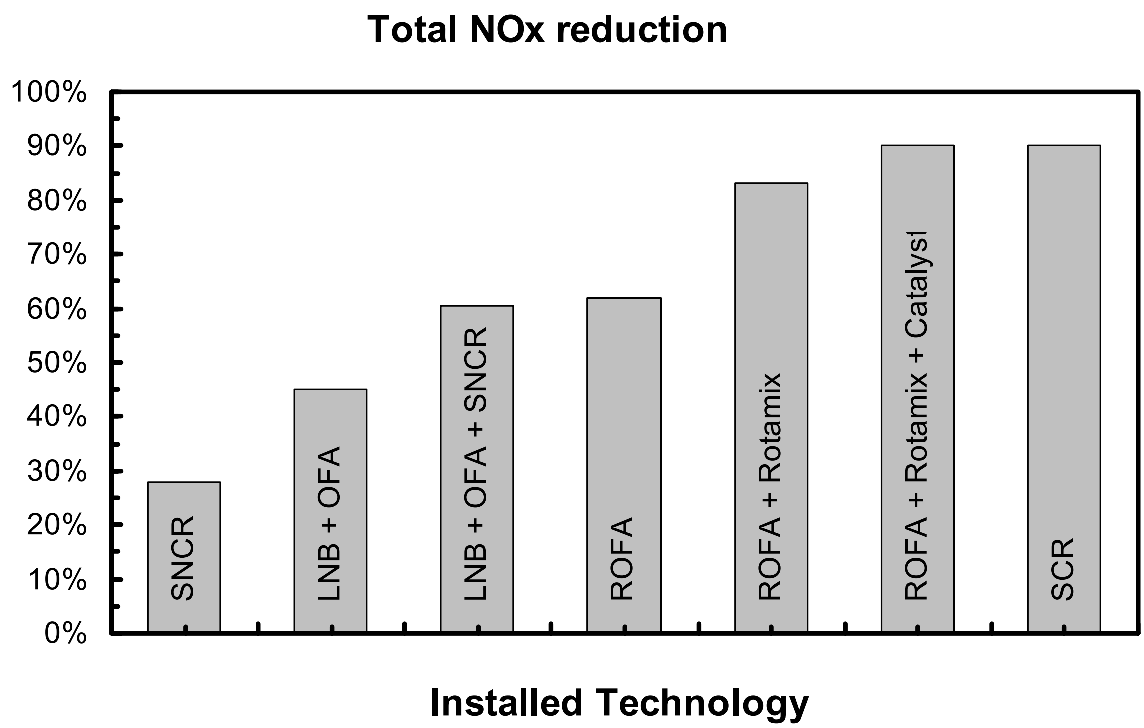

Figure 1: NOx reduction limits for commonly installed NOx reduction systems on coal fired units

To reach NOx emission regulations from 0.10 to 0.15 lb/MMBtu, utilities have been forced to install expensive catalysts (SCR) systems or buy NOx credits on the EPA trading market. SCR installations on small boilers can provide 80% to 90% NOx reduction but can have costs exceeding $100/kW.[1] A large utility can afford to install SCR systems on their largest units where the economics makes more sense (lower $/kW) and use the excess generated NOx credits to allow for lesser reductions on smaller units. As NOx regulations become tighter, this trading method will become less attractive, specifically for utilities that own a significant number of coal fired units or for small utilities that only own small units.

Addressing multi-pollutant reduction technologies, SOx credits have more than doubled in price on the EPA spot market in the previous 12 months and imminent regulations will enforce Hg reduction requirements affecting both large and small coal fired boilers. SOx reduction from FGD systems can be expected to cost between $100 and $200/kW[2] and Hg reduction systems are estimated at $50,000 to $70,000 per lb of Hg removed.[3] Mobotec's SOx and Hg reduction system is discussed at the end of the next section.

[1] Tavoulareas and Charpentier, "Clean Coal Technologies for Developing Countries," World Bank Technical Paper No. 286, Energy Series, E., July 1995

[2] *ibid*

[3] Freeley, Murphy, Hoffmann, and Renninger, "A Review of DOE/NETL's Mercury Control Technology R&D Program for Coal-Fired Power Plants", DOE/NETL Hg R&D Program Review, April 2003. http://www.fossil.energy.gov/programs/powersystems/pollutioncontrols/mercurycontrols_whitepaper.pdf

Technology Background

The MobotecSystem is a three tiered solution to multi-pollutant control. The MobotecSystem consists of ROFA, Rotamix (SNCR and FSI), and an in-duct catalyst (SCR). The MobotecSystem has been shown to economically reduce NOx, SOx, and Hg.[4]

ROFA directly affects combustion and NOx emissions by staging the furnace and by turbulently mixing the flue gas with high velocity secondary air. Rotamix is an advanced selective non-catalytic reduction (SNCR) system that makes use of the well mixed flue gas and high velocity air to evenly distribute chemicals into the flue gas. Both SNCR urea or ammonia injection (NOx control) and sorbent injection (SOx and Hg control) can be utilized in a Rotamix system. An in-duct catalyst (SCR) can be added with the MobotecSystem at reduced costs over a standard SCR due to the size reduction available by the upstream NOx reduction from ROFA and Rotamix.

ROFA

OFA systems are not uncommon in coal fired power plants. However, they have limited capabilities to reduce NOx unless boosted to high pressure. ROFA, Rotating Opposed Fired Air, is a boosted OFA system that also includes a patented rotation process which includes asymmetrically placed air nozzles.

The flue gases mix well with the added air, due to increased turbulence mixing and rotation in the entire furnace. This improves temperature and species distribution and improves particle burnout in the upper furnace.

Highly turbulent mixing and rotation prevent the formation of stratified laminar flow, which enables the entire furnace volume to be used more effectively for the combustion process. The ROFA swirl reduces the maximum temperatures of the combustion zone and increases heat transfer, which may improve boiler efficiency. Mixing the combustion air more effectively with ROFA can also reduce the need for surplus excess air. A reduction of surplus excess air decreases the mass flow through the furnace (for the same firing rate), increases the heat absorption in the furnace, and results in a heat rate decrease.

Some the documented[5] advantages of the ROFA technique include:

1) Less temperature variation in the cross-section of the furnace.
2) Even distribution of flue gas in the cross-section of the furnace (e.g., O_2, CO, and NOx).
3) Lower CO levels which allows for reduced excess air (O_2).
4) Less excess air (O_2) which means less NOx and higher overall efficiency.
5) Increased primary combustion zone staging to reduce NOx and SO_3.[6]

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[4] Haddad, Ralston, Green, and Castagnero, "Full-Scale Evaluation of a Multi-Pollutant Reduction Technology: SO_2, Hg, and NOx", MEGA Symposium #117 (2003)
[5] *ibid*
[6] Crilley, Haddad, and Higgins, "Reducing SO_3 Emissions at Coal-Fired Power Plants," MEGA Symposium #162 (2004)

ROFA consists of a boost fan, insulated ductwork, modulated dampers, air nozzles, and a control system. At Vermilion, hot air is drawn through the boost fan from downstream of the air heater and delivered to the ROFA boxes *via* insulated ducts. The flow of air to each ROFA box at Vermilion is modulated and controlled by the Moboview control software. Each of six ROFA boxes has 3 or 4 air nozzles that are angled into the furnace as determined by CFD design analysis. On site, tuners are able to change nozzle diameters and angles to further tune for lower NOx and better combustion.

Like typical OFA systems, ROFA stages the primary combustion zone to burn overall rich. Excess air is added high in the furnace to burnout incomplete combustion products (i.e., CO, H_2, and UBC). Due to the high kinetic energy of Mobotec's boosted OFA system, the ROFA boxes are located higher in the furnace than typical OFA systems. This creates a longer residence time for NOx reduction in the furnace between the burners and the ROFA ports. Further, since roughly one-third of the secondary air is directed through the ROFA ports, the mass flow through the lower furnace is reduced, thus further increasing the residence time in the reducing environment. Other OFA systems can not provide the same long reducing residence time without creating high CO or LOI problems downstream due to poor burnout (oxidation). Economizer exit concentrations of CO are below 20 ppm for ROFA installations. For units with high LOI and CO emissions, ROFA installations further increase unit efficiency by promoting more complete burnout.

Some Mobotec installations duct the boost fan inlet from the FD fan outlet (upstream of the air heater). This is called "ambient ROFA" and there is a heat rate penalty associated with this technique on the order of 1%. However, this can typically be countered by a reduced auxiliary fan load (smaller boost fan) and a reduced cost installation due to smaller ducts and a lack of insulation. In both hot and ambient ROFA, the mass flow through the boiler is typically reduced by reducing excess air. Reduced mass flow through the boiler results in 1% to 2% increase in boiler heat transfer efficiency.

Rotamix-SNCR

Rotamix is a third-generation SNCR and sorbent injection system. Upstream of Rotamix, ROFA provides high kinetic energy (mixing) and a well mixed, evenly distributed combustion product flow. The turbulent air injection and mixing provided by ROFA allows for the effective mixing of chemical reagents with the combustion products in the furnace.

As a result, reducing chemicals are injected with Rotamix directly into a well-distributed, rotating mixture. The Rotamix system is controlled to adapt to changes in load and temperature in the furnace, and only introduces reducing chemicals to the furnace where the temperature is most favorable for pollution reduction. This reduces chemical consumption and lowers chemical slippage by increasing the reaction efficiency. Relative to other SNCR systems, Rotamix can decrease recurring chemical costs.

The Rotamix system consists of a small ambient-air Rotamix fan placed on deck. On grade is the reagent delivery system, including: reagent storage tank, reagent pump skid, dilution water pump skid, and humidification water pump skid. The delivery lines supply pressurized water and urea to the Rotamix cabinet, located near the Rotamix boxes at the upper furnace. The water and urea are mixed inside the Rotamix cabinet and are delivered to individual injectors. A humidification cabinet, located beside the Rotamix cabinet, provides humidification to the Rotamix air nozzles to condition the air flow to optimize chemical utilization. The locations of the ROFA and Rotamix ports are determined from CFD modeling and field test data. At Vermilion, five SNCR injection points are used. The small number of injection points is sufficient due to the upstream ROFA kinetic energy (mixing).

Rotamix-FSI

Though not installed at Vermilion, Rotamix can be expanded to include furnace sorbent injection (FSI) at a cost less than 20% that of an FGD system. Previous Mobotec FSI installations have demonstrated SOx reduction from 64% to 90% and Hg reduction from 67% to 89%.[7]

In-Duct Catalyst (SCR)

The third tier to the MobotecSystem is the installation of an in-duct catalyst (SCR). As reported previously, each dollar spent to install ROFA and Rotamix upstream of an SCR will decrease the SCR costs by more than two dollars, primarily by reducing the required SCR catalyst volume to reach 90% NOx reduction due to upstream NOx reduction by ROFA and Rotamix.[8]

MobotecSystem Summary

NOx reduction with typical LNB and OFA systems can sometimes exceed 50%. ROFA NOx reduction routinely exceeds 60%. ROFA and Rotamix reduce NOx 75% to 85%. Figure 1 illustrates how the MobotecSystem components compare to other installed technologies.

Vermilion Unit 1

Dynegy Midwest Generation's Vermilion Power Station Unit 1 is located approximately 25 miles east of Champaign-Urbana in Oakwood, Illinois. The unit is a Combustion Engineering (CE), tangentially fired, pulverized coal fired boiler. This unit was commissioned in 1955 with 16 burners in four corners in four rows. Secondary air injection occurs above, between, and below each burner. The unit has four mills fed by CE feeders. Full load capacity is 82 MW_{gross} (77 MW_{net}) with a boiler operating pressure of 1450 psi and a design superheat temperature of 1005ºF. The unit burns a bituminous Illinois coal. Before ROFA and Rotamix were installed, there were no over-fired air or SNCR systems installed.

Mobotec performs "design-build" installation with guaranteed NOx reduction. At Vermilion, ROFA and Rotamix were installed in stages:

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[7] Haddad, Ralston, Green, and Castagnero, "Full-Scale Evaluation of a Multi-Pollutant Reduction Technology: SO_2, Hg, and NOx", MEGA Symposium #117 (2003)
[8] Haddad, Crilley, and Higgins, "The Viability and Economics of Adding a ROFA/Rotamix MobotecSystem to a Selective Catalytic Reduction (SCR) Installation," NETL/DOE 2003 Conference on SCR and SNCR for NOx Reduction, Pittsburgh, PA October 29-30, (2003)

1) Analysis, CFD, and Design 04/01 to 06/01
2) Engineering 06/01 to 12/01
3) ROFA procurement 10/01 to 05/02
4) ROFA construction 05/02 to 06/02
5) ROFA high-load tuning 07/02
6) ROFA low-load tuning 09/02
7) Rotamix procurement 12/02 to 06/03
8) Rotamix construction 09/03 to 10/03
9) Rotamix tuning 04/03

By June 2001, the CFD analysis was performed and the initial design was formulated. At this point, a contract between Dynegy and Mobotec was signed in July 2001 for 46% NOx reduction from ROFA. From July 2001 through May 2002, Mobotec provided proprietary engineering services, procurement, control systems development, and commissioning. During construction (May and June of 2002), Dynegy provided the installation labor, Power Maintenance was the service contractors for the project, and Sargent & Lundy provided the detail and balance of plant engineering.

The ROFA installation included placement of the air injection boxes, duct, supports, primary/secondary steel, ROFA fan, instrumentation and tie-in to the existing boiler secondary steel. Tuning at full load was done in July 2002. Because of capacity demands on the unit during summer, low load tuning was not completed until September 2002.

Rotamix was installed two years after successful completion of ROFA. For Rotamix, Dynegy received partial funding for the design, procurement, and installation from the State of Illinois. Components were procured during the winter of 2003 and construction was in March of 2004. Commissioning and tuning were complete in April 2004. Though ROFA and Rotamix at Vermilion were installed separately, installation time can be halved by co-installing ROFA and Rotamix.

Results

Baseline NOx emission at Vermilion fluctuates between 0.58 and 0.62 lb/MMBtu. Before Rotamix was installed, ROFA was tuned and optimized across load. Tables 1 and 2 show the results for high and low load, respectively. NOx was reduced with ROFA by 62% at high load and 50% at low load. NOx emission across load is shown in Figure 2 and the full data set is tabulated in the Appendix in Table 1A.

Table 1: Full Load (80 MW) data

Full Load 80 MW	Baseline Uncontrolled	ROFA	Rotamix
CO [ppm]	< 5	< 5	< 5
Excess O_2 [%]	2.0	2.0	2.0
NOx [lb/MMBtu]	0.58	0.22	**0.10**
Reduction from baseline		62%	**83%**
Reduction from ROFA			55%

Table 2: Low Load (40 MW) data

Low Load 40 MW	Baseline Uncontrolled	ROFA	Rotamix
CO [ppm]	< 5	< 5	< 5
Excess O_2 [%]	2.8	2.8	2.8
NOx [lb/MMBtu]	0.59	0.295	**0.18**
Reduction from baseline		50%	**69%**
Reduction from ROFA			39%

After Rotamix was installed, tuned, and optimized, NOx reduction was found to be 55% over ROFA at high load and 39% at low load. Over the baseline, ROFA and Rotamix together reduced NOx by 83% at full load and 69% at low load.

As indicated by the results NOx values are reduced significantly. Reduction occurs as soon as the ROFA and Rotamix system has been activated and the unit has stabilized.

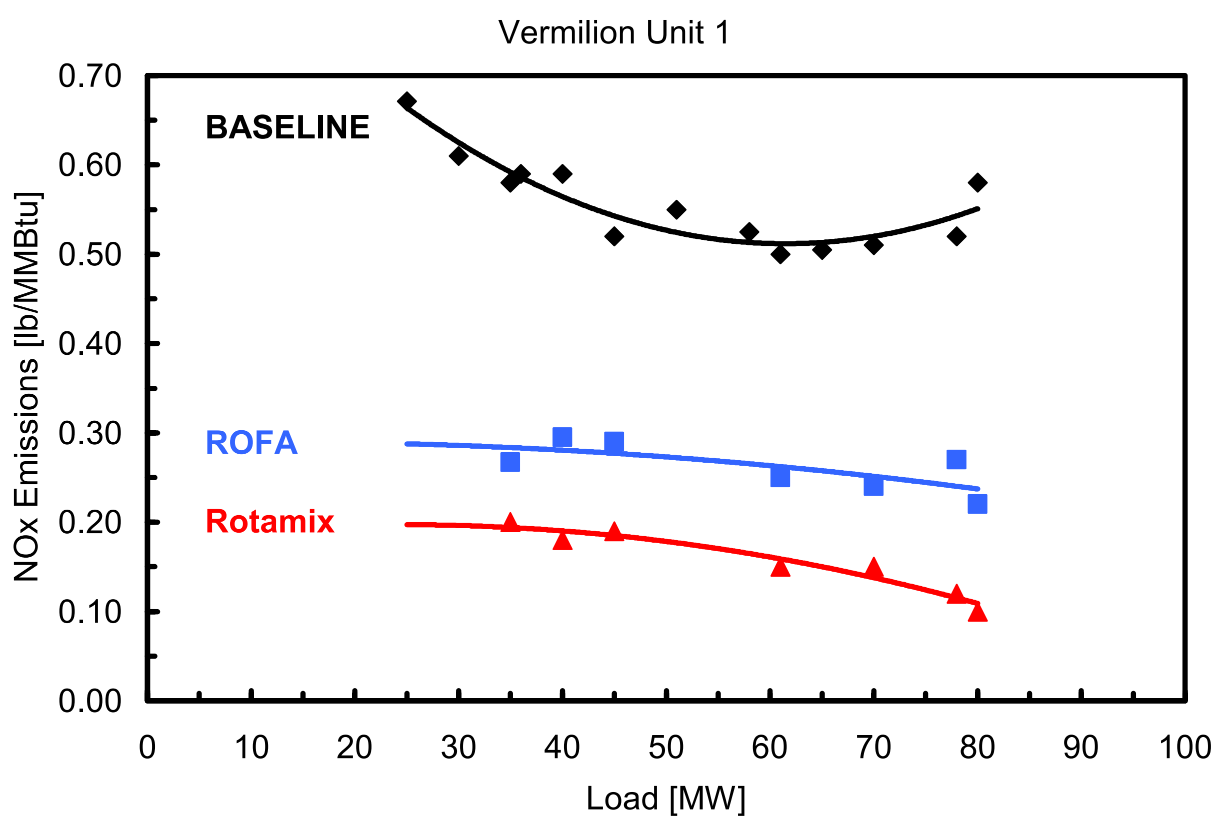

Figure 2: Baseline, ROFA, and Rotamix NOx at Vermilion Unit 1

At full load, NOx emission was reduced to 0.10 lb/MMBtu. To reduce NOx to this level, urea was injected through three Rotamix ports. Mobotec is able to use a very small number of

Rotamix ports since the ROFA swirl creates such high mixing rates between the effluent and the reagent. With NOx concentrations, urea flow, and installed capital and labor costs, an analysis to determine the cost per ton of NOx removed can be performed. This is presented next.

Cost Analysis

ROFA:

At full load, ROFA alone reduced NOx from 0.58 lb/MMBtu to 0.22 lb/MMBtu. This amounts to a 62% reduction in NOx. There is a small power draw associated with the ROFA fan, but there is also a drop in stack temperature (discussed later). These two effects counter each other and we can assume that the efficiency does not change appreciably. Therefore, there are no significant O&M costs associated with the ROFA NOx reduction.

Rotamix:

At full load, Rotamix (urea) further reduced NOx from 0.22 lb/MMBtu to 0.10 lb/MMBtu. This is a further 55% reduction in NOx over-and-above the ROFA reduction. Since urea is injected, there are additional chemical costs. Further, there is an ambient fan installed at Vermilion for the Rotamix system. This fan draws less than 20 kW during full-load operation.

MobotecSystem:

The costs per ton of NOx removed can be calculated for the ROFA & Rotamix installation. At full load, the MobotecSystem (ROFA and Rotamix) reduced NOx from 0.58 to 0.10 lb/MMBtu. This is an 83% reduction in NOx. The capital costs and O&M costs have been calculated and are plotted in Figure 3.

Note that the cost per ton of NOx removed is significantly less for larger units. For example, on a recent 190 MW ROFA installation the cost per ton of NOx removed (ROFA only) was 30% less than for Vermilion due to the economies of scale. Due to the widely varying electrical work required at each plant, Figure 3 excludes electrical work, which is typically less than 10% of the total cost.

Payback period: For a 3600-hr ozone season with NOx credits at $3000 per ton, the total MobotecSystem ROFA and Rotamix payback period is two ozone seasons. Likewise, for a 12-month ozone season the payback period is less than 10 months. After the payback period, the only recurring cost is for O&M.

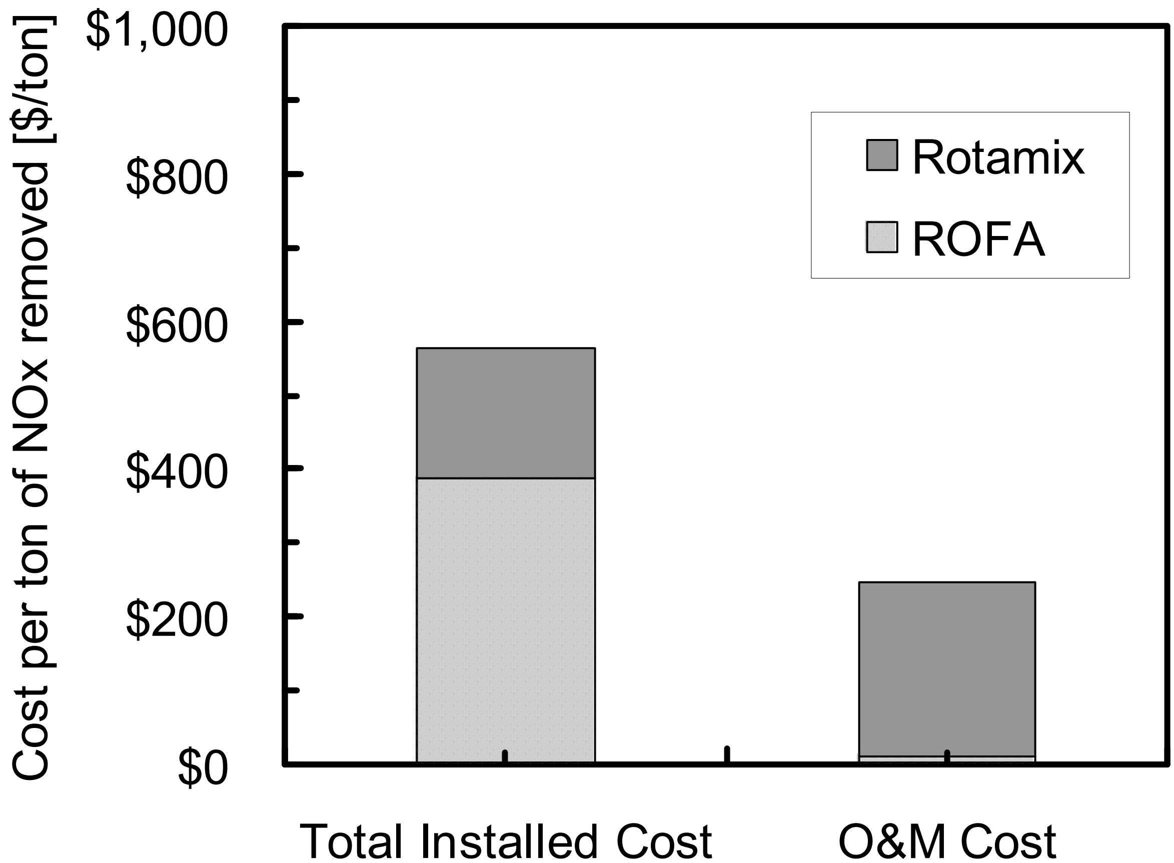

Figure 3: Total Installed Cost and O&M Cost associated with ROFA and Rotamix at Vermilion. This calculation assumes operation over ten 3600-hr ozone seasons with an 80% capacity factor.

<u>Operational Benefits</u>

Aside from significant NOx reductions, the facility has seen operational benefits. They are discussed next.

<u>Increase in Precipitator Performance:</u>

Units #1 and #2 share a common stack; thus, quantifying precipitator performance levels is challenging. Before ROFA was installed, the two units maintained an opacity level near 20%. When the ROFA system is in service this level drops to approximately 17%. Since Unit 1 (with ROFA) is a 77 MW unit and Unit 2 is a 128 MW unit, the drop in common stack opacity from 20% to 17% indicates a substantial drop in opacity from Unit 1.

The facility attributes the reduction of opacity to better precipitator performance due to a more even distribution of particulate matter (PM) entering the precipitator. The more even distribution of PM is a result of the better mixing caused by ROFA. Mobotec has also found that by reducing the total mass flow through the boiler (decreased O_2) and by further decreasing the mass flow below the ROFA ports (staging), less lift is provided to carryover bottom ash out of the furnace unburned. This both reduced UBC potential and increased bottom ash (resulting in decreased fly ash and opacity).

No impact on LOI:

Baseline LOI on this unit was low, between 1.5% and 1.8%. Any further reduction in LOI due to ROFA was indistinguishable due to the already low LOI at this plant. LOI was not observed to increase.

Continued low excess O_2:

Excess O_2 at Vermilion Unit 1 has always been low (~2% O_2 at full load) and is an indication of good boiler operation. With and without the ROFA system in service, the excess O_2 value remains at approximately 2% at full load and between 3.5% and 4% at low load.

Reduced back end/stack temperature:

The common stack flue gas temperature drops 10ºF to 15ºF when ROFA is in service. Because Unit 2 is much larger, this translates to approximately a 30ºF to 40ºF drop in stack temperature from Unit 1. This equates to about a 1% increase in efficiency due to better mixing and heat transfer in the furnace. However, after factoring for the low baseline CO, the low baseline LOI, and the boost fan power requirement, the over all heat rate is not expected to be lower.

No tube wastage presently exists:

Unit 2 (non-ROFA) has low NOx burners and a non-boosted OFA system installed. Tube wastage has been a significant problem with a very large cost associated with the problem. Dynegy was very concerned that this issue would occur in the Mobotec installation. Mobotec has nearly 20 units installed in Sweden and now nearly 20 in the USA and has experienced no tube wastage at any installation. Vermilion Unit 1 has been online since June 2002 and there is no evidence of any tube wastage.

Pockets of flue gas with high H_2S and chlorine concentrations produce water wall wastage. Since ROFA increases mixing and intensifies combustion, tube wastage is prevented by eliminating pockets of fuel rich flue gas near the walls. The Vermilion operations team has taken a full set of UT measurements at the time of installation and will have detailed results in the fall of 2005. These values will provide a good indication of tube wear in the furnace with the MobotecSystem installation.

OFA slag issues:

Similar to other OFA systems, Unit 1 has observed a buildup of slag on the air nozzles that create an "eyebrow". These can potentially break off and drop into the ash hopper causing damage. Mobotec has demonstrated that these eyebrows can be removed with water probes before they get too large to cause damage. Mobotec has since redesigned the air nozzles to minimize and possibly eliminate slag buildup.

Conclusions

The addition of a ROFA or Rotamix MobotecSystem on Vermilion Unit 1 has been shown to be an effective method of reducing NOx emissions to levels previously only found with SCR installations. The installation has yielded additional benefits such as enhanced ESP performance and has provided the Vermilion facility operational flexibility *via* significant emissions reductions.

Contact Information

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Appendix

Table A1: Raw Vermilion Data

Load [MW]	NOx Baseline [lb/MMBtu]	NOx ROFA [lb/MMBtu]	NOx Rotamix [lb/MMBtu]	ROFA Reduction [%]	Rotamix Reduction [%]	ROFA & Rotamix Reduction [%]
35	0.580	0.267	0.200	54%	25%	66%
40	0.590	0.295	0.180	50%	39%	69%
45	0.520	0.290	0.190	44%	34%	63%
61	0.500	0.250	0.150	50%	40%	70%
70	0.510	0.240	0.150	53%	38%	71%
78	0.520	0.270	0.120	48%	56%	77%
80	0.580	0.220	0.100	62%	55%	83%