# TECHNICAL PUBLICATION

## State of the Art Low $NO_x$ Burners to Reduce SCR Operating Costs

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## ABSTRACT

*Since the late 1990's, Selective Catalytic Reduction (SCR) systems have been installed on many large utility boilers to reduce the release of Nitrogen Oxide ($NO_x$) emissions into the atmosphere. Now with more than 10 years of operating experience in the United States, utilities are searching for new innovative ways to reduce the costs associated with operating an SCR. Many of these utilities have installed the SCR equipment while retaining the existing first generation low $NO_x$ burners. Riley Power Inc. has conducted a series of economic studies to determine how much reagent (ammonia or urea) consumption can be reduced and the amount of catalyst layers that can be removed from the SCR along with its associated cost savings by installing the latest state of the art Low $NO_x$ combustion technology. Although there is a relatively high upfront capital cost associated with the purchase and installation of new Low $NO_x$ burner technology or burner component modifications, reducing operating cost can generate a favorable Return on Investment (ROI) after a period of operation. This technical paper will detail Riley Power's approach to determining the ROI for two different types of Low $NO_x$ Burner installations on boilers already equipped with SCR systems.*

## INTRODUCTION

As many more coal-fired utilities begin to install new Selective Catalytic Reduction (SCR) systems to meet the more stringent $NO_x$ emissions requirements as mandated by governing bodies such as the EPA, utilities are finding that with the ultra-low $NO_x$ stack emissions comes the associated high cost with respect to operation and maintenance. Until recently, the majority of utilities considering installation of an SCR, disregarded the importance of also maintaining/upgrading older generation firing equipment (i.e. coal burners and overfire air systems) to further reduce inlet $NO_x$ to the SCR. The installation of upgraded firing equipment can potentially reduce overall annual ammonia consumption and further extend the life of the SCR catalyst. Instead it was understood industry-wide that lower $NO_x$ could be achieved by simply injecting more reagent (ammonia/urea) into the SCR, regardless of the level of $NO_x$ emissions coming from the furnace. However, because the price of ammonia used in SCR's tends to fluctuate with each year, plants have begun to modify normal unit operation by shedding load to reduce cost, or pass on this added expense to the end user, resulting in higher energy prices. As a solution, utilities already equipped with SCR's began to explore low $NO_x$ combustion upgrades that may help to lower the unit $NO_x$ emissions on the furnace side of the boiler.

Riley Power Inc., a subsidiary of Babcock Power Inc., is an OEM that has produced low-$NO_x$ combustion equipment capable of $NO_x$ reductions from other 1st and 2nd generation low $NO_x$ burners by greater than 50%. $NO_x$ reductions of this magnitude to the inlet of the SCR could lead to substantial savings in annual SCR operating costs. This paper summarizes the methodology and results of an economic analysis conducted to determine the cost-benefit of installing new low $NO_x$ burner systems on two utility boilers in Riley Power's experience list that are currently equipped with Riley Power SCR's. One is an opposed wall-fired furnace configuration and other a Riley Power TURBO® configuration. From this study a potential return-on-investment (ROI) was calculated assuming that the following equipment is installed on each respective unit:

Unit A, (Figure 1) Recommended Low $NO_x$ Scope of Supply for Opposed Wall Fired unit:

* Forty (40) Low $NO_x$ VS III™ Burners (see Figure 1)
* Fourteen (14) Riley Power Divided Over-fire Air System

Unit B, (Figure 2) Recommended Low $NO_x$ Scope of Supply for Riley TURBO® unit:

* Sixteen (16) Tilting Directional Flame Burners (TDF) with New Divided Wind boxes, Dampers, and Drives (see Figure 2)
* Over-fire Air System Modifications
* New Boundary Air System
* New Under-fire air System

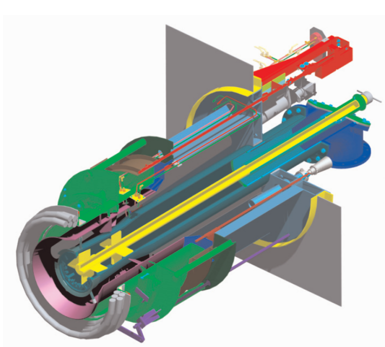

*Figure 1. RPI VS III™ Low $NO_x$ Coal Burner*

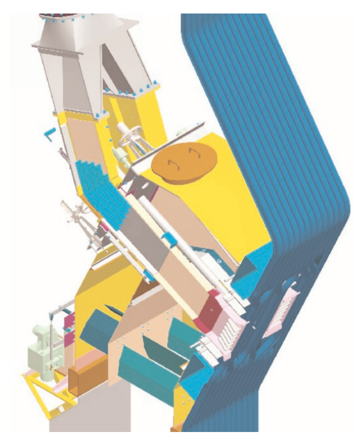

*Figure 2. RPI TDF® Low $NO_x$ Coal Burner*

## BACKGROUND

For this study, two types of coal-fired units were considered: a B&W Opposed Wall Fired Unit and a Riley Power TURBO® unit. Each boiler is still equipped with the 1st or 2nd generation low $NO_x$ combustion equipment but has recently installed a new Riley Power SCR system in the last 10 years (see respective SCR's in Figures 3 and 4.) The general configuration and annual $NO_x$ performance for each unit is provided as follows:

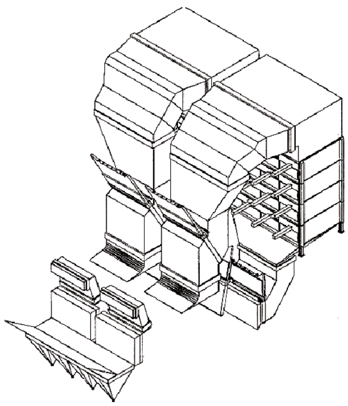

*Figure 3. SCR For Opposed Wall Fired Unit*

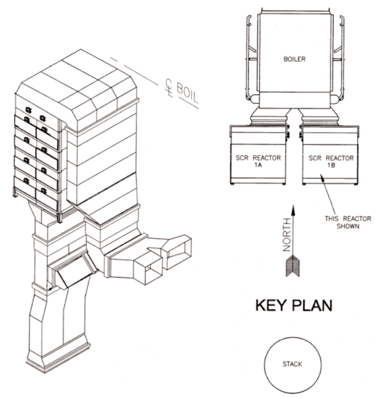


*Figure 4. SCR For TURBO Unit*

### Unit A — Opposed Wall-fired Unit

Unit "A" is an opposed-fired Babcock and Wilcox (B&W) boiler equipped with forty (40) B&W DRB-4Z burners. The boiler was designed for 3,660,000 lb/hr main steam flow at 2,600 psig and 1,005°F at 100% Maximum Continuous Rating (MCR) while burning bituminous coal. Each burner is supplied by one of four (4) MPS-89 coal pulverizers. The high dust SCR was designed to remove 90% of the inlet $NO_x$ with 9,000 hours of initial operating time without exceeding 2-ppm ammonia slip. This was accomplished with two reactors (see Figure 1) and an initial catalyst charge of two layers. Two additional spare layers were included in the reactor design for the installation of additional catalyst as part of a normal catalyst management plan. The $NO_x$ performance at full load for this unit (see Figure 5) before and after the SCR was installed is 0.45 and 0.045 lb/mmBtu, respectively. Riley Power predicts that $NO_x$ emissions can be reduced at the inlet of the SCR to 0.26 lb/mmBtu (42% reduction) by installing VS III™ Ultra Low $NO_x$ burner and separated OFA system.

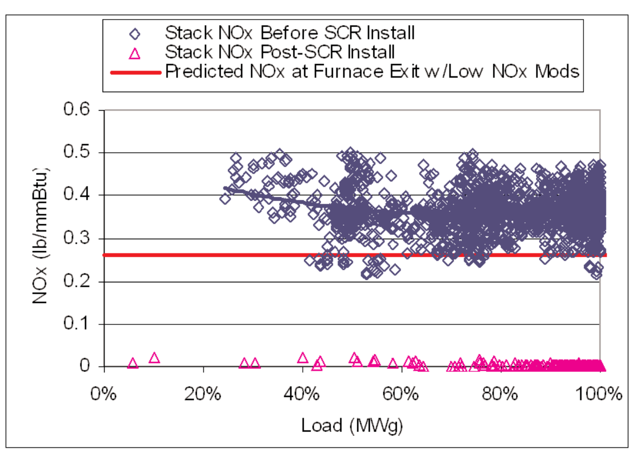


*Figure 5. $NO_x$ Emissions for an Opposed Wall Fired Unit (UNIT A)*

Unit "B" is a Riley Power (RPI), formerly Riley Stoker, coal-fired TURBO® furnace that was originally commissioned in 1981. The boiler was designed for 2,000,000 lb/hr of main steam flow at 2,475 psig and 1005 °F at 100% Maximum Continuous Rating (MCR) while burning bituminous coal. The boiler was originally supplied with sixteen (16) directional flame (DF) burners that are supplied by eight (8) #554 Duplex Riley Atrita® Pulverizers. The boiler is also equipped with two (2) Ljungstrom 27-VI-70 Air Heaters. The high dust SCR was designed to remove 90% of the inlet $NO_x$ with 18,500 hours of initial operating time without exceeding 2-ppm ammonia slip. This was accomplished with two reactors (see Figure 2) and an initial catalyst charge of two layers. Two additional spare layers were included in the reactor design for future installation of additional catalyst as part of a normal catalyst management plan. The $NO_x$ performance at full load for this unit (see Figure 6) before and after the SCR was installed is 0.65 and 0.11 lb/mmBtu, respectively without the recommended combustion modifications. The prediction is that the boiler outlet $NO_x$ emissions for this unit are to be reduced by 46% to approximately 0.35 lb/mmBtu with the recommended combustion system modifications.

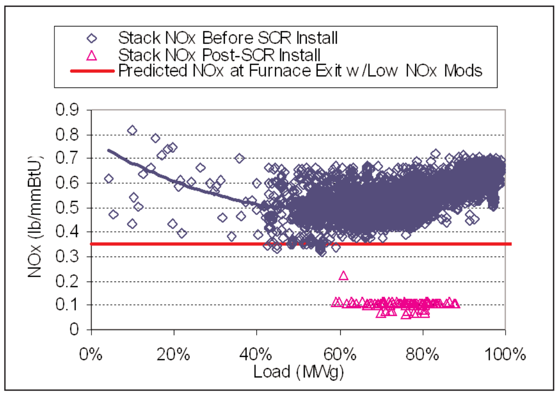


*Figure 6. $NO_x$ Emissions for a TURBO Unit (Unit B)*

## Anhydrous Ammonia Consumption

For this evaluation, it is important to consider the annual ammonia consumption as it relates to the general operation and maintenance of the unit. This can be broken down into two areas: ammonia consumption per annum, and catalyst life. In terms of ammonia consumption, the two major factors to consider are the desired percent reduction of $NO_x$ from the inlet to the SCR, which is a function of the unit load, and the average price of ammonia. These factors will help determine the cost savings that a low $NO_x$ combustion system would yield and the potential "pay back period."

For the first factor (desired $NO_x$ reduction), it is important to understand what the estimated $NO_x$ level as a function of unit load is for the unit (see Figures 5 and 6). These figures show the daily average $NO_x$ for each unit over the course of one year that was reported to the EPA. Using least-squares regression analysis techniques, the following equations for average $NO_x$ was derived:

$$\text{Unit A} - NOx\left[\frac{lb}{mmBtu}\right] = 2\times10^{-6}(Load[MWg])^2 - 0.0009(Load[MWg]) + 0.4932 \quad \text{(eq. 1)}$$

$$\text{Unit B} - NOx\left[\frac{lb}{mmBtu}\right] = 9\times10^{-6}(Load[MWg])^2 - 0.0032(Load[MWg]) + 0.7725 \quad \text{(eq. 2)}$$

Note that the stack $NO_x$ before the SCR was installed on each unit as shown in Figures 5 and 6 (blue curves) varies in load, while the stack $NO_x$ after the SCR system was installed is constant for each unit throughout the load range (pink data points). Therefore, the amount of $NO_x$ reduction achieved by the SCR is subject to change with respect to load and thus the ammonia flow rate will also vary with unit load. To calculate the amount of ammonia consumption of an SCR over the course of a year, there must be an understanding of the amount of time spent at each load. Again, using the EPA database, the approximate number of days spent at a particular load range over the course of a year was determined for each unit and is shown in Figures 7 and 8.

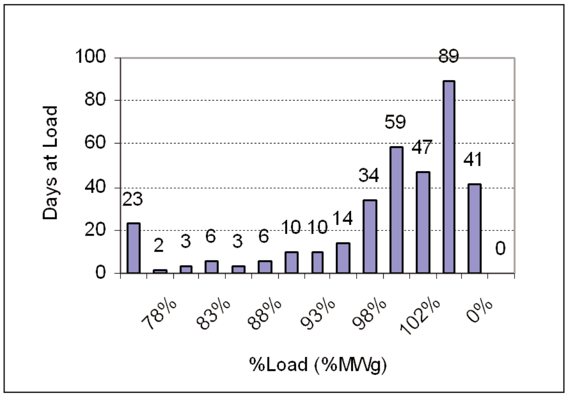


Figure 7. Days at Load
(Opposed-Wall Fired Unit- Unit A)

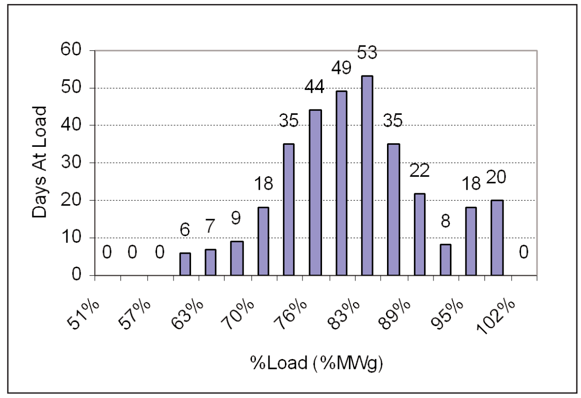


Figure 8. Days at Load (TURBO Unit - Unit B)

The molecular weights for $NO_x$ (NO and $NO_2$) are 46 and 30 lb/mol, respectively. Also, anhydrous ammonia ($NH_3$) has a molecular weight of 17 lb/mol. Using equations 1 and 2, with the known number of days spent at each average load condition as shown in Figures 7 and 8, calculate the anhydrous ammonia consumption in lbs/hr can be determined using the equation:

$$NH_3[\frac{lb}{hr}] = MW_{NH_3}[\frac{lb}{mol}] \times \left[ \frac{DesiredNOx_{removal}[\frac{lb}{hr}] \times \%NO_2}{MW_{NO_2}[\frac{lb}{mol}]} + 2 \times \frac{DesiredNOx_{removal}[\frac{lb}{hr}] \times \%NO}{MW_{NO}[\frac{lb}{mol}]} \right] \quad \text{(eq. 3)}$$

The second factor, the cost of ammonia, can be estimated based on past and future pricing of natural gas. Because ammonia is a derivative of natural gas, the prices of the two trend very closely as shown in Figure 9. In the last decade, in particular, the price for anhydrous ammonia has shown a steady increase to as much as $450/ton by the end of 2010 (see Figure 10) and is estimated to reach above $500/ton by the end of 2011. With prices increasing steadily, utilities will eventually find it difficult to continue to operate SCR's at maximum capacity from a cost standpoint for extended periods of time. For this study, a future 2012 predicted value of $650 dollars per ton of anhydrous ammonia was used.

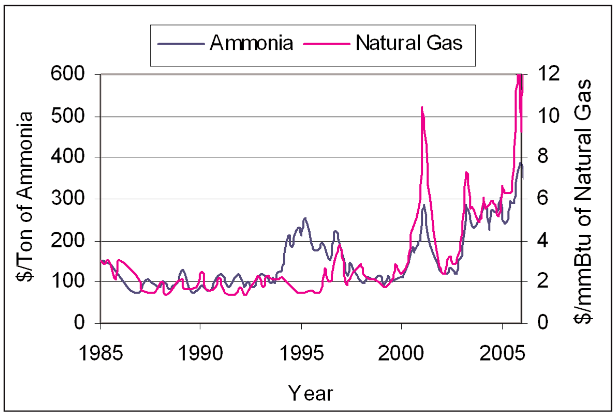


*Figure 9. Price of Anhydrous Ammonia Compared to Natural Gas*

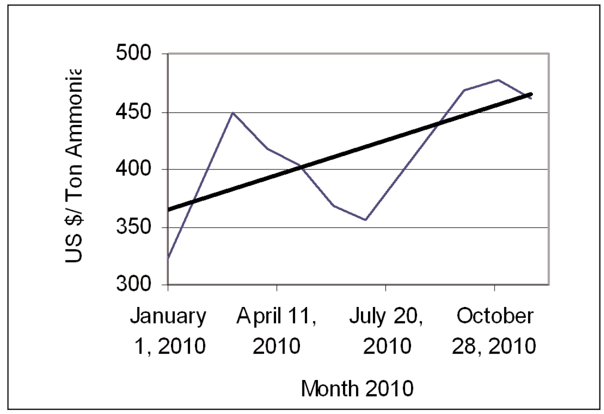


*Figure 10. Price of Anhydrous Ammonia (FY2010)*

## Catalyst Life

Another aspect of operation and maintenance of the SCR is the effect that a reduced inlet $NO_x$ entering the SCR may have on overall catalyst life. A lower $NO_x$ removal rate will require less catalyst activity and result in the original catalyst design lasting longer before meeting its end of life ammonia slip. The initial design catalyst life expectancy for Unit A and B are 9,000 hours and 18,500 hours, respectively (see Figures 11 and 12.)

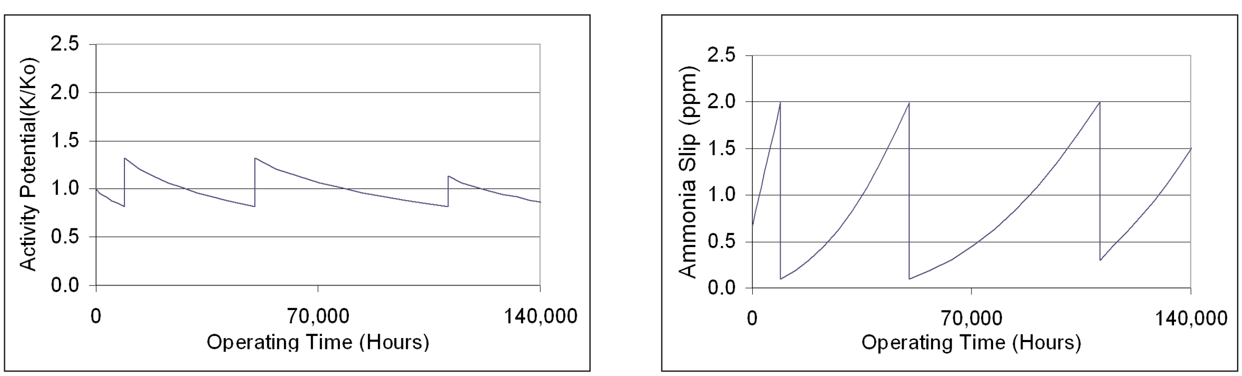


*Figure 11. Original Design Catalyst Management Plan — Unit A*

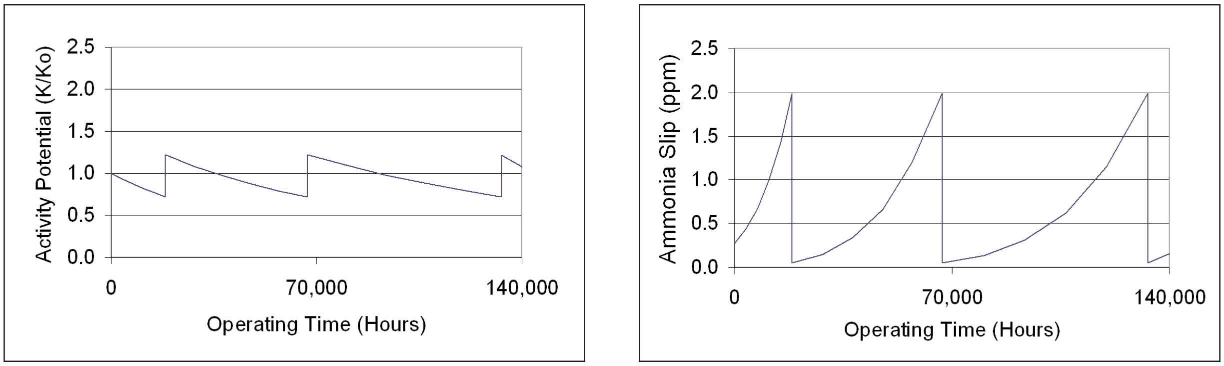


*Figure 12. Original Design Catalyst Management Plan — Unit B*

# FINDINGS

## Ammonia Savings — Opposed Wall Fired versus TURBO®

To determine the total annual consumption of anhydrous ammonia for an SCR, it is important to first consider how much $NO_x$ is actually entering the SCR at any given time over the course of the year. Unit A for example, (see Figure 7) shows that for a majority of the year the boiler is operating at 95.1% of the rated MCR, compared to Unit B (see Figure 8) the majority of boiler load was spent at 82.6% of the rated MCR. This is especially important when determining the level of $NO_x$ reduction provided by the SCR, because lower loads for both units often result in lower $NO_x$ emissions at the SCR inlet.

Using the equations 1, 2, and 3 and the known number of days spent at each %MW load given by Figures 7 and 8, the predicted total $NO_x$ emissions and thus the total amount of anhydrous ammonia required to achieve each desired $NO_x$ level at the SCR outlet, was calculated. Applying the future 2012 value of anhydrous ammonia of $650 per ton, the cost of ammonia at each load was determined and is shown in Figures 13 and 14. The total ammonia cost with and without a low $NO_x$ combustion system, was calculated for each unit. By summation across the load range, Unit A's total estimated annual ammonia cost with and without a low $NO_x$ combustion system, was determined to be approximately $1.1 million and $2.0 million dollars for a total savings of greater than 45% per year. Similarly, Unit B's savings of approximately 45% was based on a total estimated ammonia costs with and without the recommended low $NO_x$ combustion system modifications was approximately $670,000 and $1.2 million per year.

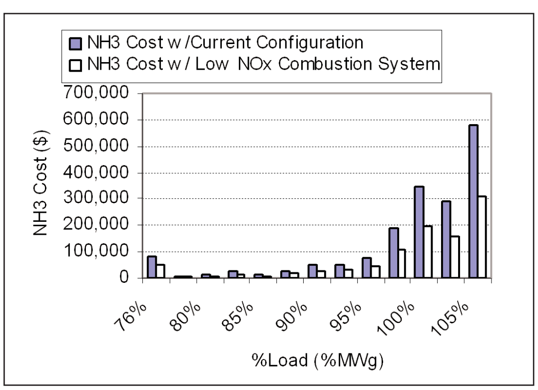


*Figure 13. Cost of NH3 per Load — Unit A*

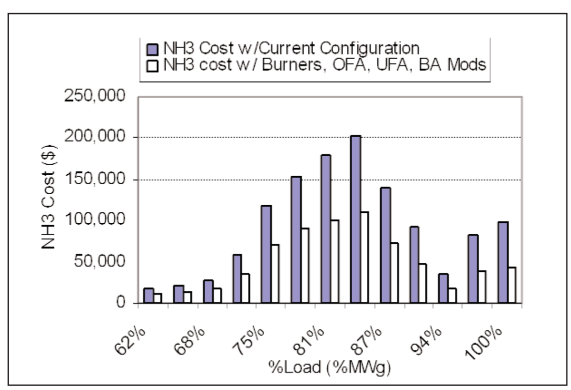


*Figure 14. Cost of NH3 per Load — Unit B*

Using Riley Power proprietary estimates for the cost of engineering, fabrication, and construction for the proposed combustion system modifications outlined for each unit, a total cost was determined on a "per MW" basis, so that budgetary estimates can be applied to other comparable units requiring similar scope of supply. The cost per MW was determined to be $11,047 and $13,920 (21% difference), for units A and B respectively. The large difference in price per megawatt between Units A and B is due to the difference in total scope needed to achieve a similar level of % $NO_x$ reduction with a new ultra low-$NO_x$ combustion system modification. Recall that Unit A requires new ultra low $NO_x$ VS III™ burners and an overfire air system to achieve a $NO_x$ reduction of 42% (see Table 1), whereas Unit B, which has a much different furnace geometry than a opposed-wall fired unit, would require new low $NO_x$ burners, overfire air system, underfire air system, and boundary air system to achieve a maximum reduction of 45%. Accounting for the savings due to reduced ammonia consumption for each unit, the total payback period on the proposed low $NO_x$ combustion system modifications for each unit was calculated to be 4 years and 10 years for units A and B, respectively.

The large difference in pay back period is due to how each unit is generally operated. As previously discussed, Unit A spends more of the year at full load (100%MCR) than Unit B, resulting in a higher annual consumption of ammonia each year. Therefore, a 42% to 45% reduction in ammonia consumption would be more substantial in terms of total annual savings for Unit A than for Unit B. As shown in Table 1, the total ammonia savings on a "per megawatt" basis was calculated to be $2,886 and $1,335 per MW. Based on these ammonia savings, in combination with the lower cost of the low $NO_x$ combustion system for Unit A, it was determined that the installation of a low $NO_x$ combustion system modifications was potentially more cost effective for an opposed wall-fired unit than for a TURBO® unit.

Table 1

**Estimated Cost of Combustion Systems**

| | | **Unit A** | **Unit B** |
|---|---|---|---|
| Unit Type | | Opposed Wall Fired | TURBO |
| Total Cost (including Engineering, Materials, Constructions | $/MW | $11,047 | $13,920 |
| % Reduction By SCR without Low $NO_x$ Combustion System | % | 90% | 83% |
| % Reduction By SCR with Low $NO_x$ Combustion System | % | 83% | 69% |
| % Reduction of SCR inlet NOx with Low $NO_x$ Combustion System | % | 42% | 45% |
| Baseline NOx at 100% MCR | lb/mmBtu | 0.45 | 0.65 |
| $NO_x$ at SCR Inlet with Low $NO_x$ Combustion System (lb/mmBtu) | lb/mmBtu | 0.26 | 0.35 |
| $NO_x$ at SCR outlet (measured) (lb/mmBtu) | lb/mmBtu | 0.045 | 0.11 |
| Average Ammonia Cost Per Ton | $ per ton | $650 | $650 |
| Annual Ammonia Cost Per MW with Current Configuration | $/MW | $6,441 | $2,994 |
| Annual Ammonia Cost Per MW with Low $NO_x$ Combustion System | $/MW | $3,554 | $1,639 |
| Ammonia Savings Per Annum with Low $NO_x$ Combustion System | $/MW | $2,886 | $1,355 |
| Annual Ammonia Savings | % | 45% | 45% |
| Pay Back Period based on Reduced Ammonia Consumption | years | **4** | **10** |

### Catalyst Life — Unit A

It was estimated that the initial catalyst life would be increased by approximately 22,500 hours from 9,000 hours to 31,500 hours. A new catalyst management plan was generated based on the lower inlet $NO_x$ and displayed in Figure 15. Note that this results in only two catalyst replacements in fifteen years of operation, compared to three replacements under the original management plan, assuming the unit runs continually with a two-week outage every year.

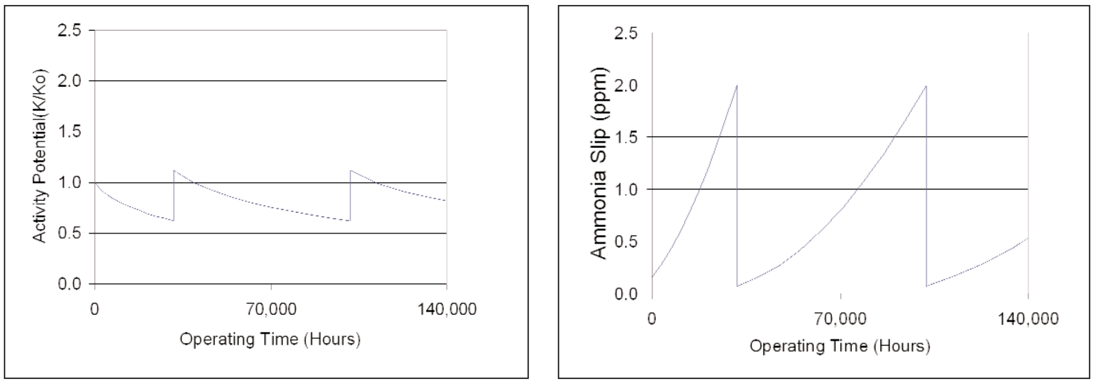


*Figure 15. New Catalyst Management Plan with Combustion Modifications — Unit A*

### Catalyst Life — Unit B

The original design catalyst management plan, as shown in Figure 12, demonstrates that two layers of catalyst will have to be added after fifteen years of operation assuming the unit runs continually with a two week outage every year. As previously discussed, the addition of the proposed low $NO_x$ combustion system for this unit will result in a $NO_x$ level of 0.35 lb/mmBtu at the SCR inlet. This lower $NO_x$ removal rate will require less catalyst activity at the end of the catalyst life, resulting in the original catalyst design lasting longer before meeting its end of life ammonia slip. Based on a simple calculation and consultation with the original catalyst suppler, it was estimated that the initial catalyst life would be increased by 8000 hours from 18,500 hours to 26,500 hours. A new catalyst management plan was then generated based on this lower inlet $NO_x$ displayed in Figure 16.

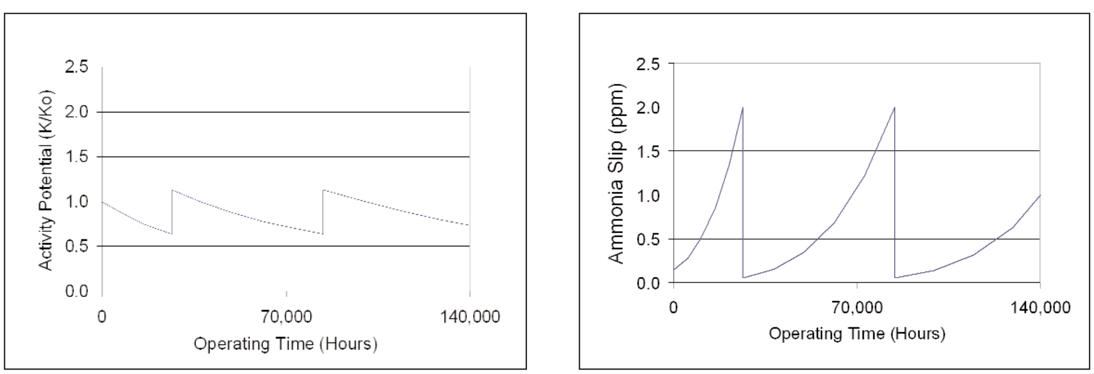


*Figure 16. New Catalyst Management Plan with Combustion Modifications — Unit B*

A simple net present value analysis was performed to determine the decrease in catalyst cost over a fifteen-year evaluation period for each unit. This analysis was based on the following criteria:

* Inflation rate of 2.5%
* Discount rate of 8.8%
* Catalyst replacement layers have the volume and activity as the initial catalyst layers
* This analysis only includes the replacement cost of the catalyst and it doesn't include lost generation, labor cost, or any other costs associated with replacing the catalyst

As shown in Table 2, the expected savings on the catalyst is approximately $2,850/MWg and $360/MWg for Units A and B, respectively. It should be stated that the results of any changes in catalyst life due to reducing the $NO_x$ removal requirements, have to take into account a number of factors that are beyond the scope of this analysis. This includes changes to the outage schedule, changes in deactivation rates from fuel changes, reduced cost by using regenerated catalyst and future emission control requirements. It should be also noted that there could be additional advantages to reducing the amount of $NO_x$ reduction in the SCR that are not included in this paper. This includes reduced ammonia slip to mitigate the air heater plugging or allowing the selling of fly ash. In addition to this, today's low $NO_x$ combustion systems are far more sophisticated and mechanically reliable than the 1st and 2nd generation low $NO_x$ combustion systems, resulting in reduced maintenance costs due to longer periods between plant outages.

Table 2

**Catalyst Cost Savings**

| | **Original Design** | |
|---|---|---|
| Unit | A | B |
| Original SCR Inlet $NO_x$ (lbs/mmBtu) | 0.45 | 0.65 |
| Original Catalyst Design $NO_x$ Removal | 90.0% | 90.0% |
| Outlet $NO_x$ (lb/mmBtu) | 0.045 | 0.065 |
| Initial Catalyst Life (hours) | 9000 | 18500 |
| | **With Combustion Modifications** | |
| Decrease from combustion modifications | 42.2% | 46.2% |
| SCR Inlet $NO_x$ (lbs/mmBtu) | 0.26 | 0.35 |
| SCR NOx removal | 82.7% | 81.4% |
| Initial catalyst Life (hours) | 31,500 | 26,500 |
| Decrease in Present Value Cost from Original Design, ($/MWg) | $2850 | $360 |

## CONCLUSIONS

In terms of ammonia consumption alone, installation of a low $NO_x$ combustion system seems to be a good investment towards the general operation of the unit, depending on what the desired payback period on the unit is. Based on this analysis, it seems that an opposed-wall fired unit has a greater potential for a faster return on investment than a TURBO® because of the lower cost of the combustion equipment, compared to the level of $NO_x$ reduction, especially if the unit operates close to 100% of the MCR unit rating for the majority of the year. With ammonia prices continually increasing for the foreseeable future and the required emissions level steadily decreasing, operating and maintaining an SCR will become more and more expensive. Installation of front-end low-$NO_x$ combustion systems or upgrades can essentially reduce total ammonia consumption by as much as 45% and is a viable, cost-effective option to lowering plant cost over the long term.

The ability to maintain or modify SCR systems to reduce operating cost is a key element of an overall $NO_x$ compliance plan. Extending catalyst life or reducing the volume of purchased replacement catalyst by the installation of a low $NO_x$ combustion system,  is one tool  in achieving optimal performance while simultaneously lowering cost. The catalyst replacement cost associated by reducing SCR inlet $NO_x$, is highly variable based on the number of reactor spare layers, actual catalyst deactivation rates, and outage schedule flexibility. Still, savings can be substantial and can only be addressed on case-by-case basis.