Selective Catalytic Reduction System Performance and Reliability Review

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ABSTRACT

Using the 2005 U.S. Environmental Protection Agency's Electronic Data Reporting (EDR) site (www.epa.gov/airmarkets/emissions/raw/index.html) database of utility stack emissions, a review of installed SCR system NO_x removal performance and reliability has been undertaken. The NO_x emissions for all plants have been determined based upon hourly emissions and gross heat input to determine the plants overall NO_x removal efficiency and average outlet NO_x for the 2005 Ozone season. The data analysis was performed for all operating hours, including low load and startup conditions. Analysis of the data showed that removal efficiencies of 90% and greater were obtained by greater than 30 units and that overall Ozone season average NOx emissions rates of less than 0.05 lb/MMBtu were consistently achievable by SCR systems. The data also looks at the type of fuel and ammonia systems and their effect on the SCR system's ability to meet high levels of reliability. Last the ability for plant with long term (greater than 3 years) of operating to improve their process is review for three selected plants.

The review concludes that low NOx emissions rates can be achieved with very low hourly standard deviations. Further the data suggests that not all units with low emissions rate can obtain low standard deviations. The reason for this are investigated as related to boiler and SCR characteristics and system operation.

BACKGROUND

US SCR installations are unique from those of other countries in that the removal efficiencies of the systems are generally higher than in Europe or Japan. US installations also have been installed with full SCR bypass system allowing for the isolation of the system during non-Ozone season operation. These differences are largely due to the US regulatory system of trading NO_x emissions that makes it economically preferable to achieve higher removal efficiencies and operate only during the Ozone season. Unit emission rate caps as practiced in Europe, on the other hand, do not create the same incentive for higher NO_x removal efficiencies.

Previous work examined the reliability of SCR systems on US coal-fired electric utility plants in achieving high NO_x removal efficiencies, however a limit number of operational units were available. As more units have come on line and more data has become available, it is now possible to look at a fairly large population of units and find what trends are apparent and what lessons can be learned. For some units, multiple years of data available allowing for an investigation of a plant ability to improve and maintain SCR performance.

For example, in Cichanowicz[1] and others examined data on twelve units that raised some questions regarding SCR reliability and ability to achieve 90% removal. In 2004, Staudt[2] and others reported on the results of surveys taken of users regarding their views on the reliability of SCR and FGD systems for high removal efficiency. In this effort, all of those companies operating SCR's installed in response to the NOx SIP Call that did respond indicated that overall reliability met or exceeded expectations. They also indicated that full load removal efficiencies were, on average 88%-89%, close to the guarantee levels of roughly 90%. However, the survey showed that the user's estimate of the best removal rate they thought the SCR system could achieve on a regular basis if they had a reason to operate it at higher removal rates was generally greater than 90% - and in every case greater than the guaranteed NO_x removal from the supplier. One of the conclusions of Reference 2 was that operational choices result in some SCRs not being operated at their highest attainable removal efficiencies.

In 2005, Erickson[3] surveyed a larger population of units for the 2004 Ozone season and examined the effects of catalyst type, ammonia source, technology supplier, and learning over time. Erickson examined the removal efficiency as determined by the average emission rate over the ozone season versus the first quarter NO_x emission rate. Some conclusions reached by Erickson include:

- Catalyst type does not appear to impact the removal efficiency of the SCR.
- Ammonia source may have some impact on removal efficiency of the SCR, data set to small for conclusion.
- 19 units achieved over 90% removal NO_x removal.
- Some units improved their SCR outlet NO_x level over the period as well as the variability in the outlet NO_x emissions.

None of the previous efforts explicitly examined the ability of the SCR to provide consistent NO_x emissions. This effort expands on the previous work by Erickson in that it updates the analysis with 2005 data and also explicitly examines variability in outlet NO_x emissions.

CURRENT EFFORT

In this effort we have evaluated the population of coal SCRs and examined performance and reliability using EPA reported emissions data. Performance is measured on the basis of outlet NO_x emissions and NO_x reduction. NO_x reduction for seasonally controlled units was evaluated by comparing ozone season emissions to first quarter emissions for 2005.

Reliability is more difficult to measure. In this effort we sought indications of reliability to maintain an emission rate. To this end, reliability was analyzed using two measures:

Equation 1. Coefficient of Variation (CV) of the hourly outlet NO_x during the ozone season, where

$$CV\% = (\text{standard deviation of hourly } NO_x \text{ rate})*100/(\text{average hourly } NO_x \text{ rate})$$

The coefficient of variation is a dimensionless number that allows comparison of the variation of data that have significantly different mean values. If CV is greater than 100%, that means that the standard deviation of the values exceed the average, in such a case the NO_x emissions rates would be greater than the average.

Equation 2. Load Effect (for lack of a better term), Load Effect (LE) was calculated, where

$$LE\% = (((\text{average of hourly NOx rate over ozone season})/(\text{overall ozone season NOx rate}))*100) - 100$$

LE is another dimensionless parameter that indicates how much higher (or lower) the average of hourly NO_x emission rates is compared to the overall rate for the period. Because the reported hourly NO_x rate for any hour is treated equally when taking the average of these values, regardless of the heat input during the particular hour, the average of the hourly NO_x emission rates will normally differ somewhat from the overall NO_x emission rate for the entire season. Therefore, LE is an indication of how the average hourly NO_x rate differs from the overall NO_x emission rate for the period as a result of changes in NO_x emission when unit load changes. If the average of hourly NO_x emission rates over the period exactly equals the overall NO_x, then load changes do not have an effect on NO_x emissions rates and LE will equal zero. For an SCR, LE is an important indicator. Because ammonia to an SCR may be secured at part load or during shutdown, the NO_x emission rate during those periods will increase and LE will be a positive number. On the other hand, if NO_x at part load is lower than at high load (for example, if the SCR and ammonia are left on at the same rate at low load), then LE will be negative. LE gives us a way to measure how important this effect was when analyzing the data for the period in question. As will be shown, some units will show high variability in terms of CV. LE provides a way to determine to what extent the variability is associated with changes in load. In calculating both CV and LE, NO_x rate is measured in lb/MMBtu.

Unfortunately, CV and LE do not fully capture reliability. High variability by either measure can result from normal operating practices, as a result of equipment choices the owner made that limit the load-following ability of the equipment, from other operating choices not associated with varying load, or from equipment problems that impact performance. So, theses measurement provide some insight, but not a complete picture of system reliability.

Analysis Data Set

In this current work, we looked at the following emissions data sets:

1. 2005 hourly ozone season and first quarter 2005 emissions data for all units (including units that do not use SCR) with less than 0.15 lb/MMBtu average NO_x emissions rate for the 2005 Ozone season. After filtering for common stacks and missing data, this group included 219 units.
2. 2005 hourly ozone season and first quarter 2005 emissions data for units equipped with SCR for the 2005 Ozone season where SCR characteristics were known. This included 130 units. However, after filtering for units with missing data to determine variability, this group was reduced to 120 units.
3. 2005 year round emissions data on selected units equipped with SCR.
4. 2002 thru 2005 hourly Ozone season and first quarter 2002 thru 2005 emissions data for three selected units equipped with SCR.

The collection of units that provide the first data set include units that do not have SCR and use other technologies to achieve under 0.15 lb/MMBtu. The collection of units that provide the second data set are combined with our database of SCR installation information to enable us to evaluate if some SCR characteristics impact the performance of the SCR. This gave us a database of 120 units with SCR's and their associated vendor, catalyst type, ammonia source and other unit-specific information. For each of the data sets, the average of the hourly Ozone season NO_x emission rates were calculated, as was the standard deviation. These are used in calculating CV and LE as described earlier.

Analysis of Units With NO_x Emissions Below 0.15 lb/MMBtu During 2005 Ozone Season

Figure 1 shows CV and LE during the 2005 Ozone Season versus 2005 Ozone Season NO_x Reduction (versus 2005 Q1) for the population of boilers with 2005 Ozone Season NO_x emissions below 0.15 lb/MMBtu. Each data point shows the data for one unit. Most of the boilers that have relatively low NO_x reductions are PRB-fired units with combustion controls that are not equipped with SCR. On the other hand, some of the low reduction units are annually operated SCRs. The units with high NO_x removals can be presumed to be equipped with SCR. As shown, there is significant variability across the spectrum. However, there seems to be somewhat more variability – in general - at the higher removal rates. This suggests that there is greater variability with SCR than with combustion NO_x controls. This probably is not surprising because SCR may be secured at times due to system design or operation desires. It is also noteworthy that some units nevertheless achieve high removal efficiencies with low variability. This demonstrates that SCR as a technology is capable of maintaining emissions levels very closely to a particular rate at high removal rates.

Figure 2 shows average hourly Ozone season NO_x emission rate plus/minus the standard deviation in hourly Ozone season NO_x emission rate for these 219 units with 2005 ozone season NO_x below 0.15 lb/MMBtu. Like Figure 1, this Figure shows data from some units that are equipped with SCR and some units that are not equipped with SCR. Also shown on this graph is the overall 2005 Ozone season emission rate – determined by the total emissions divided by the heat input. Each data point and its associated range represent one unit. As shown, some units are achieving very low NO_x emissions rates with very low variability. However, some are not. Notably, the units with the highest variability are not the units with the lowest emissions. As shown on the graph, the average of the hourly NO_x emissions rates does not always match the emissions rate for the season. This is due to low load operations having different NO_x emissions rates than high load operation. In most cases where there is a significant difference, the average of the hourly emission rates is higher than the overall ozone season rate. This difference is what accounts for the LE as described above. In most cases, a larger difference between the average of the Ozone season hourly emission rates and the overall Ozone season rate corresponds with a high standard deviation in the hourly emission rate. This is not surprising because large variations in load that impact NO_x emissions would invariably impact variability in NO_x emission rate. This is illustrated further by Figure 3, which shows the relationship between CV (which is always positive by definition) and the absolute value LE. As shown, CV and the absolute value of LE show a significant degree of correlation, although they are not perfectly correlated. This correlation persists at the same level even if only units with SCR are screened or if CV is compared to LE. So, load changes that impact NO_x emission rates are a significant part of the explanation in NO_x emission rate variability during the Ozone season for all units with low NOx emission rates. But, load changes do not fully explain relationships shown.

Figure 1. CV and LE versus 2005 Ozone Season NO_x Reduction

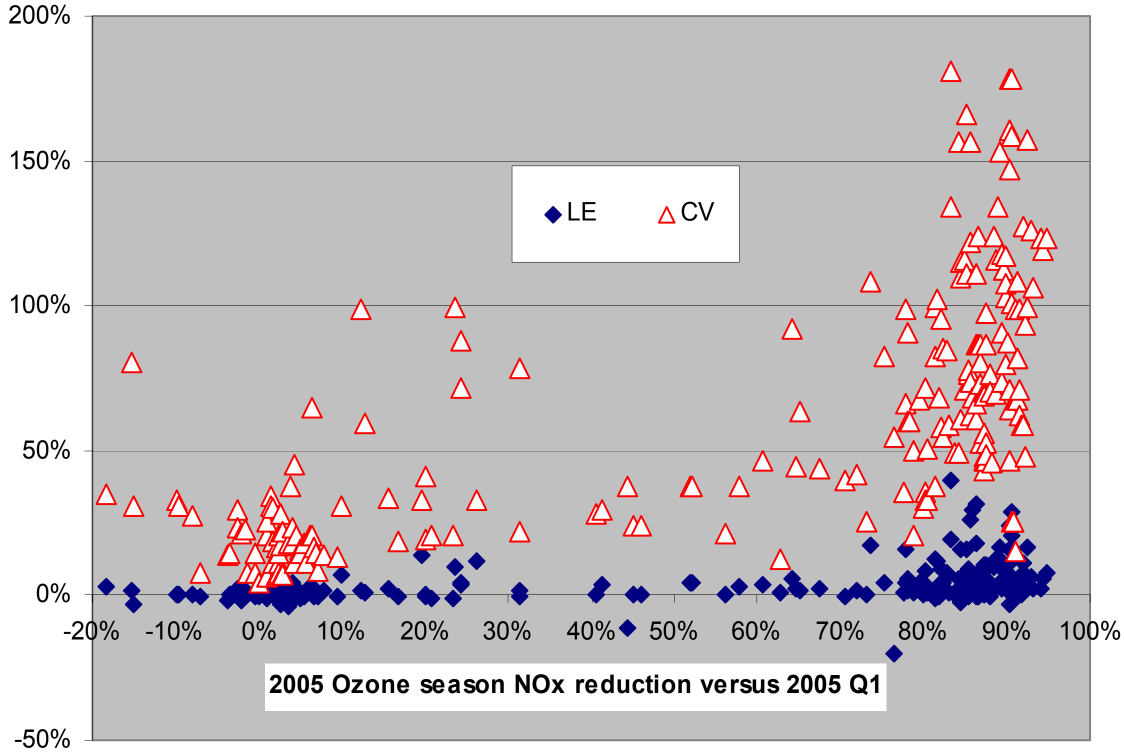
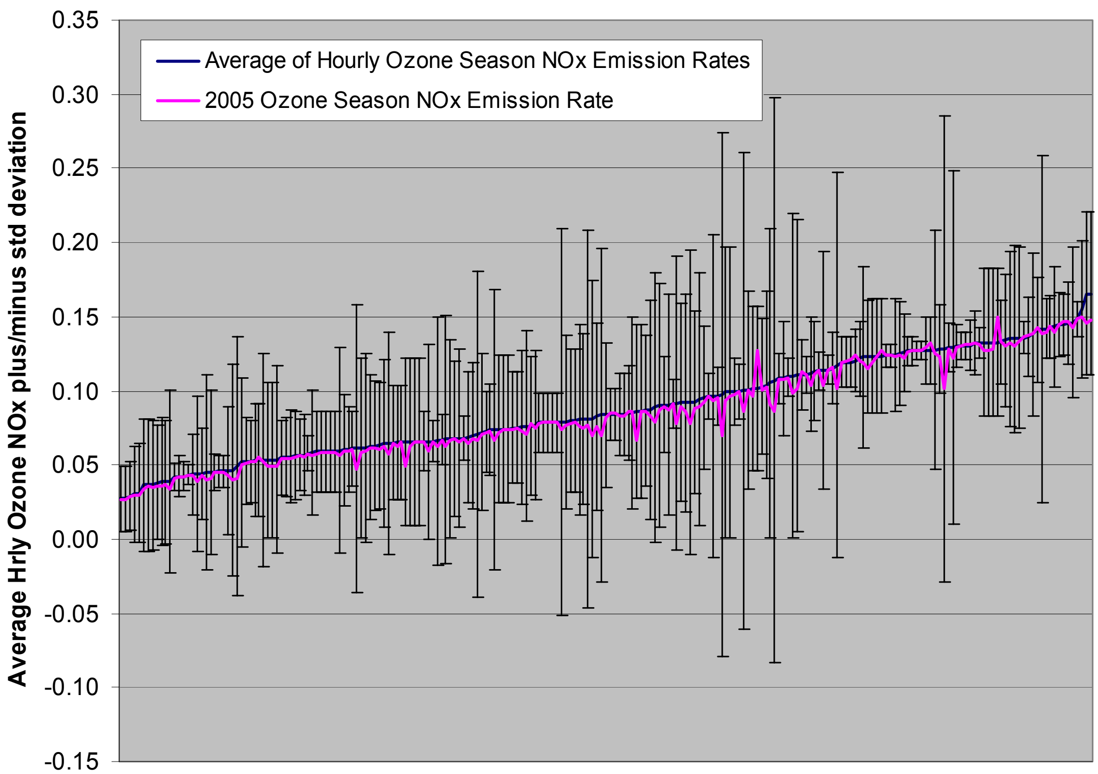


Figure 2. Average Hourly Ozone Season NO_x Emission Rate Plus/Minus Standard Deviation

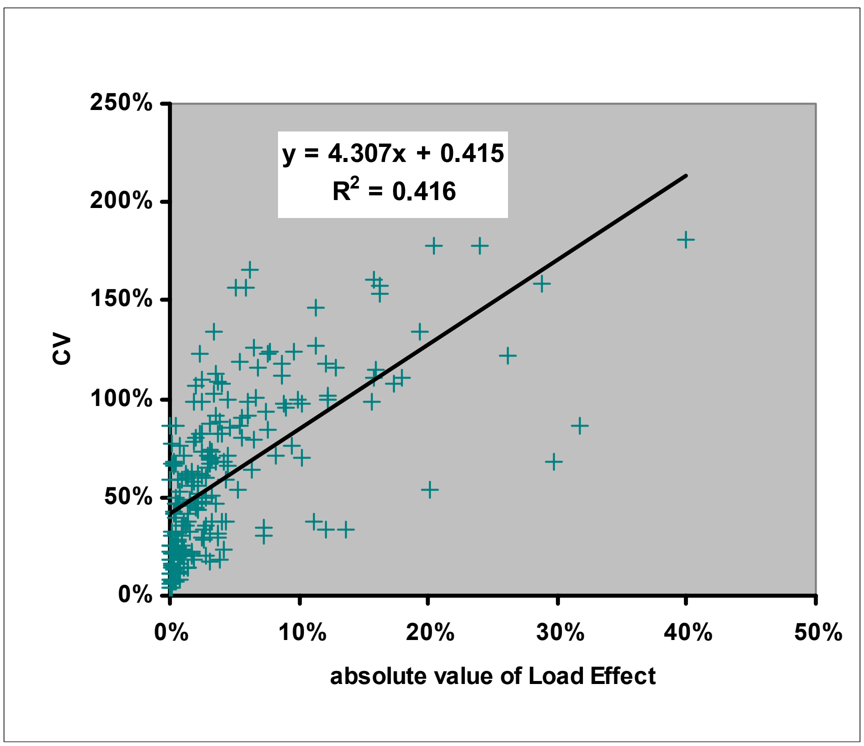


In short, there are two points to be made regarding variation in hourly NO_x emissions during the ozone season.

- The correlation between CV and LE indicates that some significant portion (but not all) of the variation in hourly NO_x emission rates is attributable to changes in NO_x associated with load changes, and may not be indicative of the reliability of the SCR, but simply how the unit is operated.
- Since not all of the variability in outlet NO_x emissions during the ozone season is associated with load changes, there are other factors that affect variability.

Variability in NO_x emission rates during the Ozone season that are not due to load changes may result from operating choices other than load changes, or they may result from other factors that may be associated with reliability. In the following sections we will attempt to isolate some of these specifically as they relate to SCR.

Figure 3. CV versus absolute value of LE for Units with Emissions Under 0.15 lb/MMBtu For 2005 Ozone Season



Analysis of SCR Operation with Different Coal Types

Figure 4 shows CV of hourly NO_x during the 2005 Ozone season versus Bituminous and Powder River Basin (PRB) coals. Nines units of each coal type were selected from the data set described above. Although some units operate on a year round basis, only the Ozone season data was considered. From the selected units the PRB units have an average CV of 48% while the nine bituminous units used for comparison have an average of 93%. The average CV for all 120 units in data set 2 is 43% - slightly below that of PRB units only. While the fuel comparison analysis does not have the large population of units to provide a high degree of statistical certainty it does suggest that SCR applications on PRB units offer no greater control or reliability issues than Bituminous coal. The Bituminous unit with the lowest CV of all units analyzed was included in the comparison, several PRB units compare within 50% of the lowest CV value and over half of the PRB units shown are within 25% of the lowest overall CV.

Figure 4. CV of Hourly NO_x During the 2005 Ozone Season versus Different Coal Types

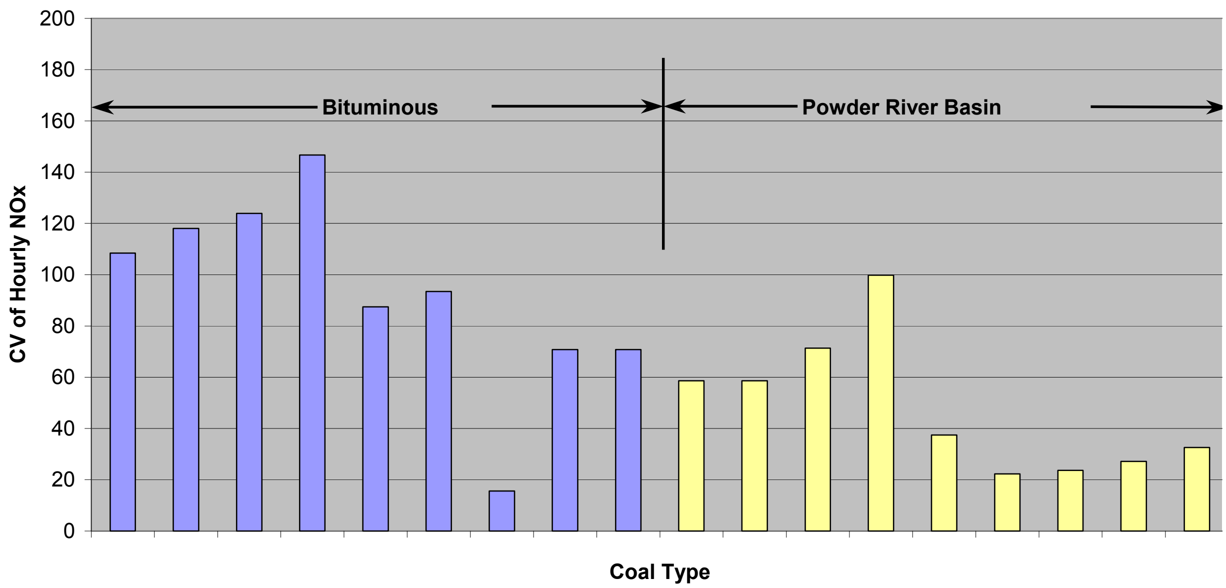


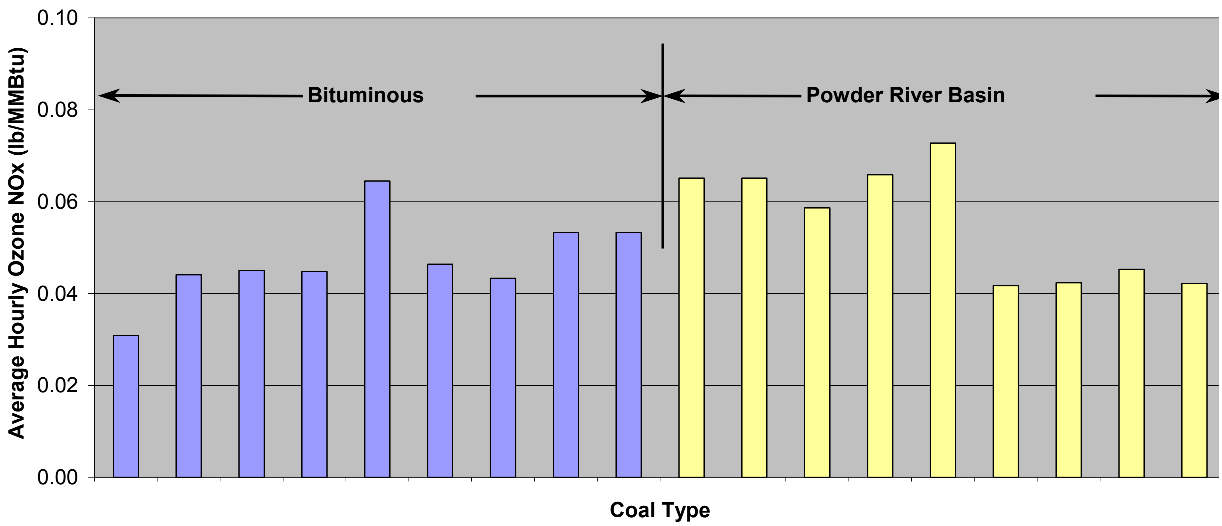
Figure 5 shows Outlet NO_x during the 2005 Ozone season versus Bituminous and Powder River Basin (PRB) coals. The same nine units of each coal type selected for Figure 4 were used in the same order. From the selected units, those fired with PRB have an average outlet NO_x of 0.0554 lb/MMBtu while the nine bituminous units used for comparison have any average of 0.0473 lb/MMBtu. This comparison illustrates that both fuels are very similar in their attainable outlet NO_x values. Some of the PRB units benefit from combustion NO_x controls providing furnace outlet NO_x emission rates significantly lower than those of bituminous units therefore requiring lower removal efficiencies for the same outlet rate. However, higher NO_x removal rates with SCR are being practiced on bituminous units resulting in bituminous outlet NO_x emission rates equal to those of PRB. The LE versus coal type was analyzed; the data indicates no clear trends and considering the small population and the large effect of plant design this data is not presented herein.

The review of bituminous versus PRB SCR systems indicates two general conclusions:

- SCR systems on PRB fired unit have no greater control or reliability issues compared to bituminous.
- SCR systems on bituminous fired units can attain, with high removal efficiencies, outlet NO_x emission limits in the same range or better than PRB units with combustion NO_x control systems.

The above conclusions on the effect of fuel type are based on a significantly smaller population of data than other analyses present herein. Even with the smaller population these conclusions appear consistent with the basic theory of SCR removal and have been an industry wide concern. One interesting question raised by this analysis is: Why are PRB units employing combustion NO_x control not operating at high removal rates resulting in even lower outlet NO_x emission rates? The CV of several PRB units appears low enough to support higher removal efficiencies. The low CV, combined with the lower sensitivity of PRB units to ammonia slip, leads the authors to believe that lower emission rates, and higher NO_x removal rates, are attainable with high reliability on PRB units than are currently being practiced.

Figure 5. Average Hourly Ozone NO_x versus Different Coal Types



Analysis of SCR Operation by Catalyst Type, Ammonia Source, Year Commissioned and 2004 versus 2005 Ozone Season Emission

In the work by Erickson[3] using 2004 Ozone season data, it was determined that catalyst type does not appear to significantly impact the removal efficiency of the SCR and that ammonia source may have some impact on removal efficiency of the SCR. In this effort we examined removal efficiency as well as variability in NO_x emissions rates using 2005 data. Also, to see if there were trends indicating operational improvement, we examined reduction efficiency as well as variability in NO_x emission rates based on the year the unit was commissioned. For this analysis we used a population of 120 units equipped with SCR where the characteristics of the SCR – catalyst supplier, system supplier, ammonia source, and year commissioned – were known.

Catalyst Type

Figures 6, 7, and 8 show the results of a sort by removal efficiency, CV and LE, respectively, to illustrate the effects of catalyst type. Consistent with the previous findings of Erickson[3] using 2004 data, catalyst type does not appear to impact removal efficiency. Figures 7 and 8 also show that there does not appear to be an impact on variability in controlled NO_x emission rates. Keep in mind that the data includes some annually controlled units that, because we are comparing Ozone season NO_x emission rates to first quarter NO_x emissions rates, will indicate low removal for these units. The conclusion that catalyst type does not affect removal efficiency, control variability and reliability implies that system design and operation have a greater effect than the type (plate, honeycomb, corrugated, etc.) of catalyst installed.

Figure 6. NO_x Removal Efficiency versus Catalyst Type

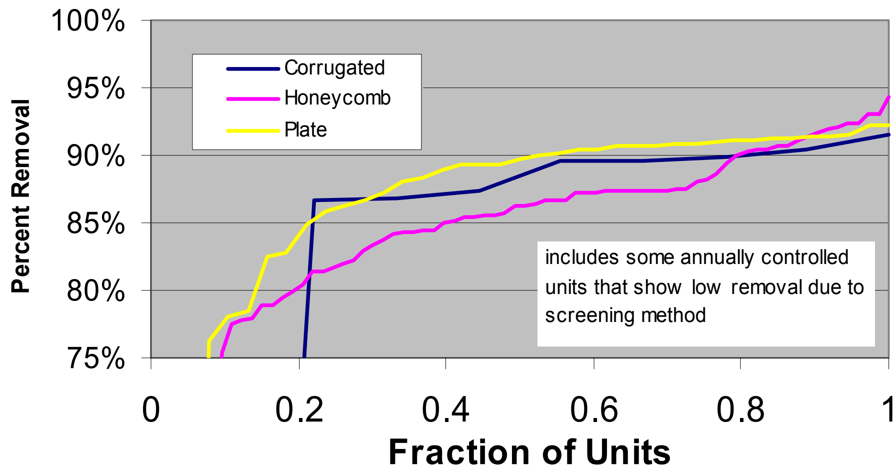
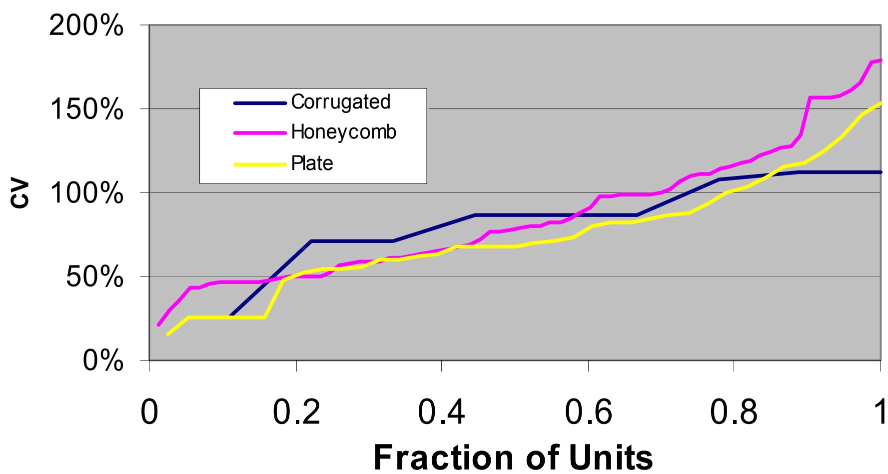


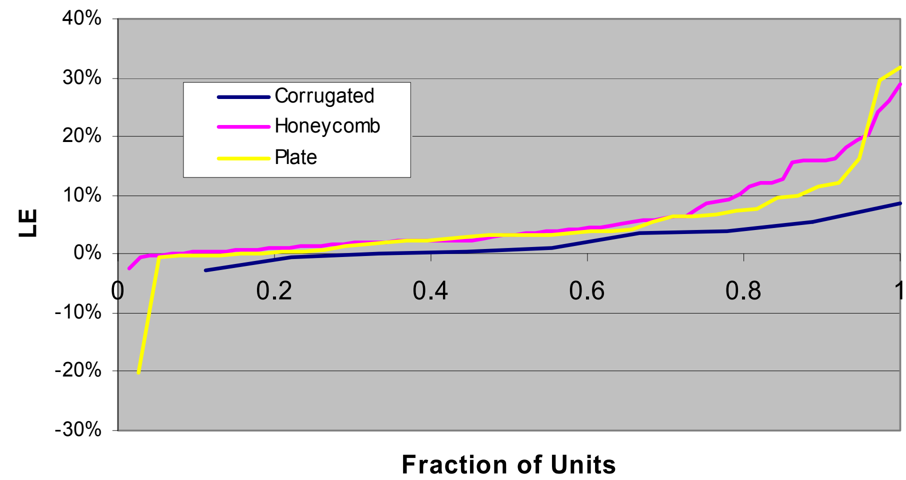
Figure 7. CV versus Catalyst Type



Ammonia Source

Figures 9, 10 and 11 show the results of a sort by NO_x removal efficiency, CV and LE, respectively, to investigate the effects of ammonia source. Consistent with the previous findings of Erickson[3] using 2004 data, the units with aqueous ammonia tend to have lower removal efficiencies than for anhydrous ammonia or urea. The units with aqueous ammonia may show slightly less variability than for the other ammonia sources, but with similar load effect. Due to the small number of aqueous ammonia units relative to anhydrous and urea units, we cannot say that these results are statistically meaningful. Moreover, even if statistically meaningful, this does not mean that aqueous ammonia is the cause of lower NO_x reduction rates on these units – it maybe coincidental that aqueous was used on units with lower NO_x reduction rates by design and we don't know the reason. Again, keep in mind that the data includes some annually controlled units that, because we are comparing Ozone season NO_x emission rates to first quarter NO_x emissions rates, will indicate low removal for these units.

Figure 8. LE versus Catalyst Type



Year Commissioned

Figures 12, 13 and 14 show the results of a sort by removal efficiency, CV and LE, respectively, to see the effects of start up date. Disregarding the data of 2000 and 2005 because there were relatively few units in these dates (3 and 2, respectively), we see that there is little difference in removal efficiency except for possibly 2002, which seems a bit lower at the low end. This effect for 2002 may be due to annually controlled units. Again, focusing on 2001 through 2004, 2004 seems to have higher variability (in both CV and LE) than 2001, 2002 and 2003. This may be indicative of a learning effect where operators take a year or more to develop operating practices at the plant that make the most of the SCR. Since the variability of the NO_x emissions, measured in CV and LE, for years 2001, 2002, and 2003 are close, this may indicate that most of the benefits of learning are achieved in the first year.

Figure 9. NO_x Removal Efficiency versus Ammonia Source

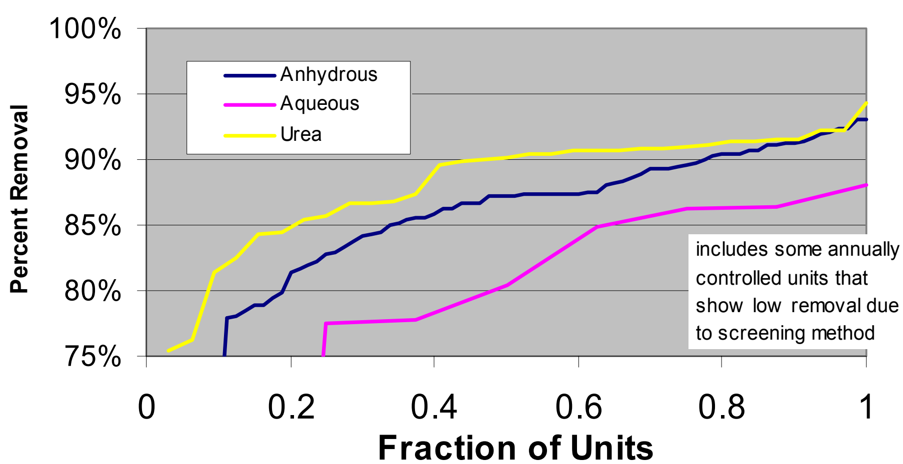


Figure 10. CV versus Ammonia Source

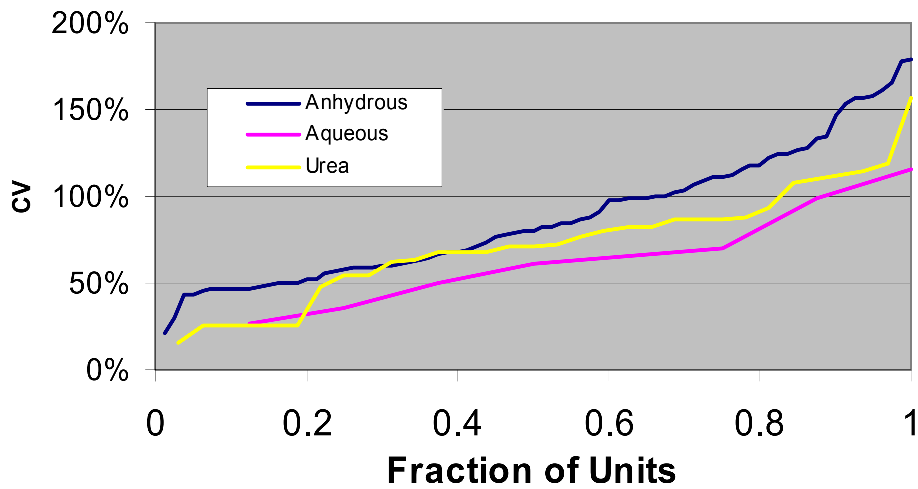
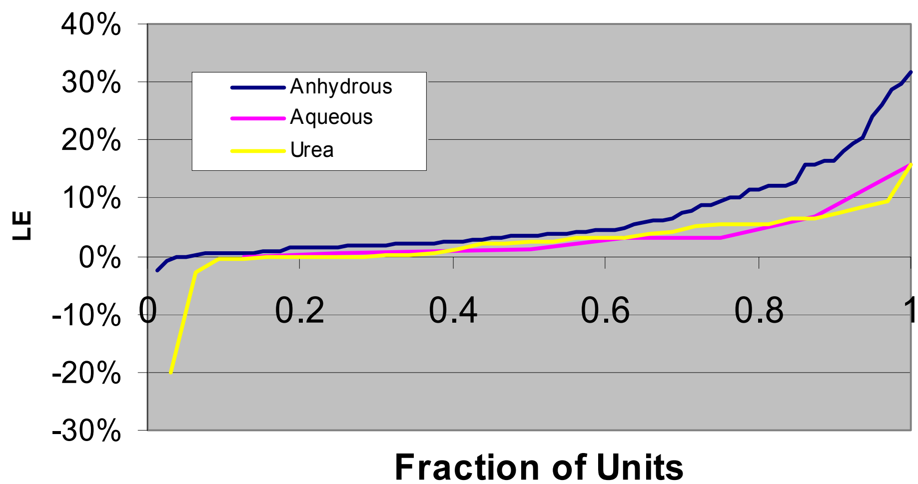


Figure 11. LE versus Ammonia Source



Comparison of 2004 to 2005

Comparison of the units analyzed by Erickson[3] for NO_x removal efficiency in 2004 showed that between 2004 and 2005 71% (or 92 of 130) of the 130 units examined improved their NO_x reduction percentage. Of these units 6% (or 8 of 130) went to annual controls (thus comparison of Q1 to ozone season NOx emission rate to estimate reduction is meaningless) and only 23% (30 of 130) had lower removal efficiency in 2005 than they did in 2004. Figure 15 compares the distribution of removal efficiency for these units in 2004 and in 2005 – sorted from highest to lowest removal efficiency for each year. In Figure 15 it is assumed that the 8 units that controlled annually in 2005 had similar removal efficiencies as in 2004. As shown, nearly 30% of the units achieved 90% or more removal in 2005 while that number was slightly over 10% in 2004. Roughly 70% of the units in 2005 achieved 85% or better removal while in 2004 the percent that achieved 85% or better removal was about 50%. This shows a clear trend toward improved performance between 2004 and 2005 for these units.

Figure 12. NO_x Removal Efficiency versus Year Commissioned

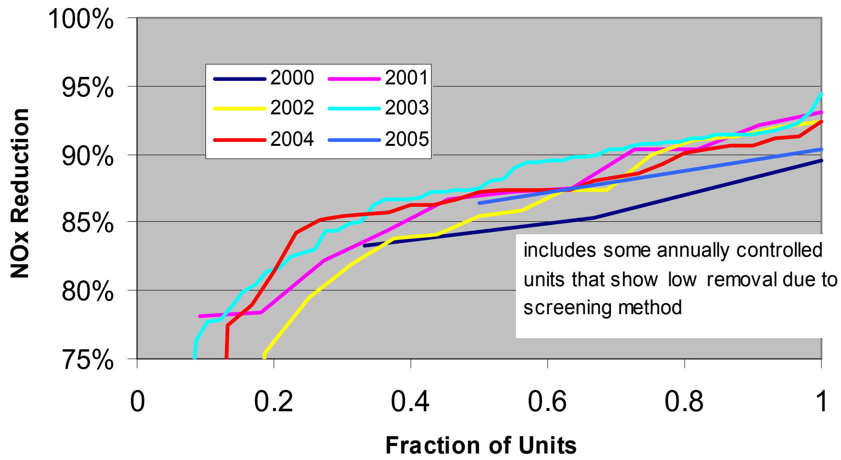


Figure 13. CV versus Year Commissioned

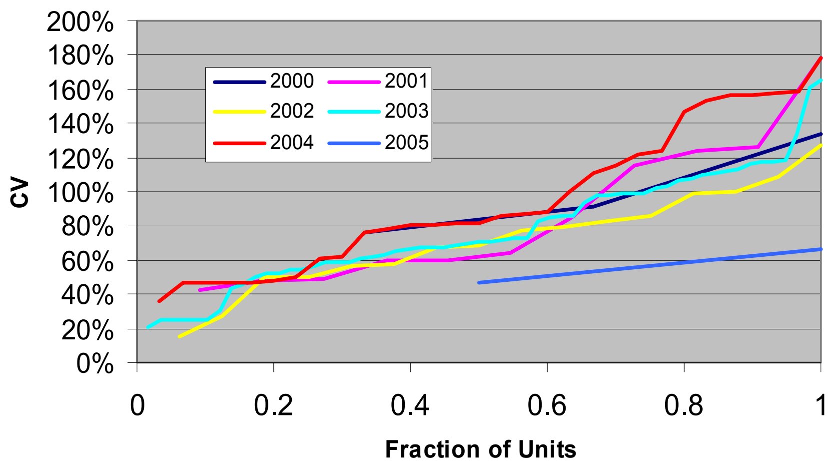


Figure 14. LE versus Ammonia Source

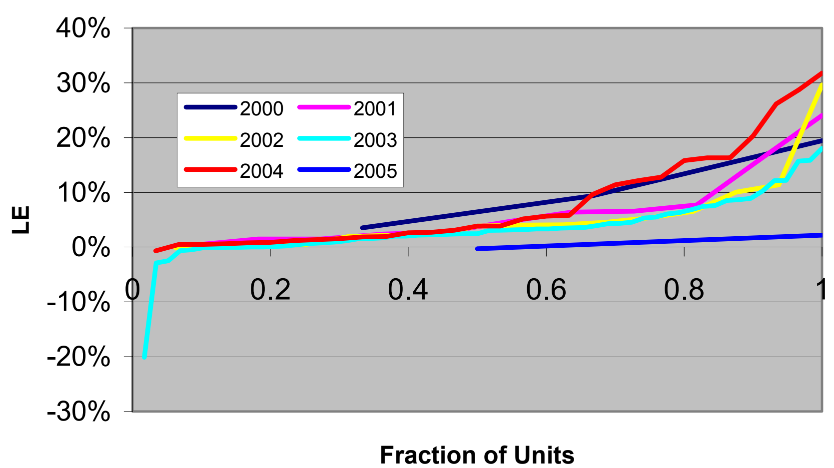
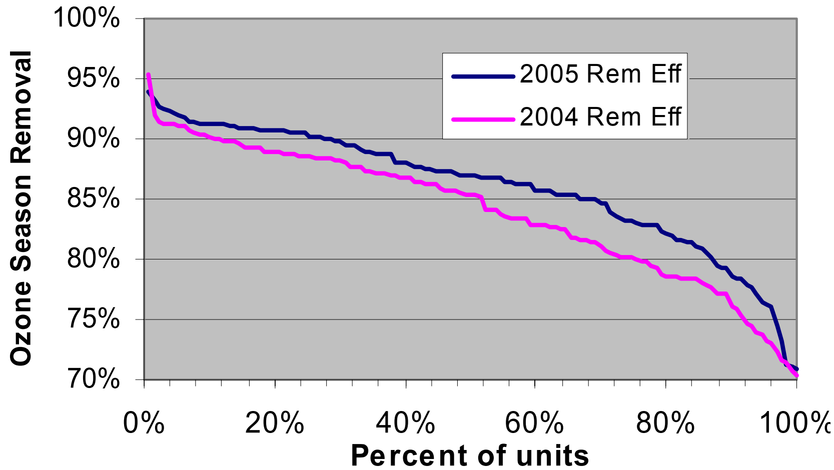


Figure 15. Ozone Season Removal 2004 versus 2005



Analysis of Operational Improvement and Stability Over Time

Figure 16 shows CV of hourly NO_x for three plants versus years of operation. All three plants fire bituminous coal and are greater than 600 MW in size. Plant one was the first SCR plant for the utility and has no SCR inlet temperature controls. Plants 2 and 3 are owned by the same utility, are the same size, and are not the first SCR systems for utility and employ steam side SCR inlet temperature control. Plant 1 uses anhydrous ammonia while plants 2 and 3 uses urea based ammonia. This illustrates variability of CV over time and between plants of similar design. This finding is in contradiction to the single plant analysis by Erickson[3], which concluded that once stable a plant remains stable. Figure 17 shows LE for the same plant over the same time period. This figure suggests that similar plants with the same design and SCR temperature control system can operate differently with respect to NO_x removal as a function of load. The analysis of operational years suggest that operational characteristic of SCR are plant dependent. The cause of this dependence is unknown and has not been investigated at this time.

The conclusions related to CV and LE as a function of years of operation are based on limited data and have not included a detailed investigation of each plant to determine the underlying reasons for the differences. This analysis does indicate that plant operation, even with similar plant and owners, has an effect on the SCR systems operation.

Analysis of Year Round SCR System Operation

Figure 18 shows the CV for 12 year round operating SCR systems; the CV is plotted for both the year and only the Ozone season. Plants 1 through 6 represent early US SCR retrofit plants, plants 7 and 8 are units with the SCR designed as original equipment and the last four (4) plants (9-12) are units designed for Ozone operation that now operate year round. The graph shows considerable variation between plants regardless of above category. Plants with low variability during the ozone season showed low variability year round. The plot also shows increased CV during the Ozone season for most units. This was not expected since it was anticipated that better operation might be found during the Ozone season due to the value of NOx allowances. The increase in CV is most likely due to plants operating at higher removal efficiencies during the Ozone season resulting in lower outlet NO_x emissions.

Figure 16. CV versus Years of Operation

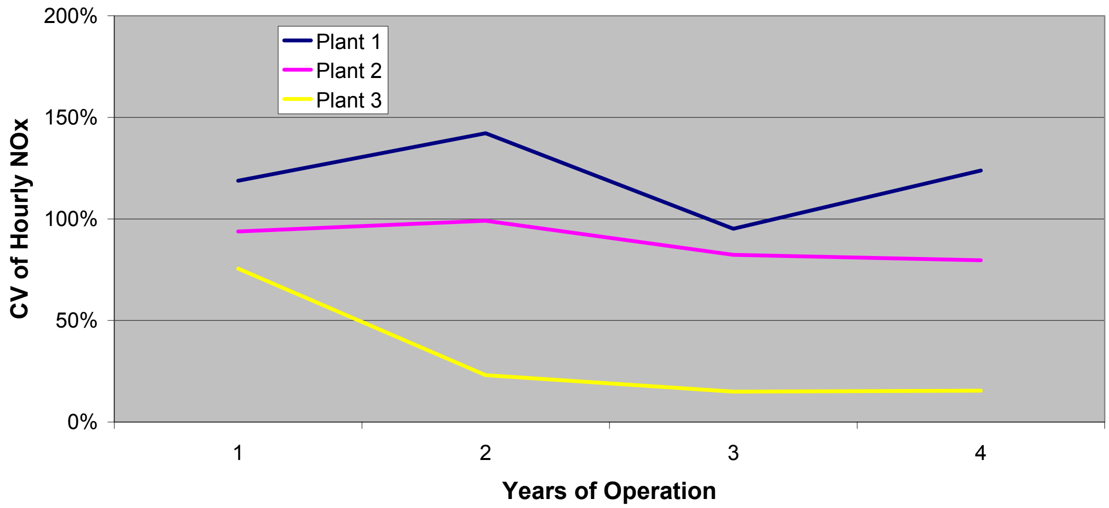


Figure 17. LE versus Years of Operation

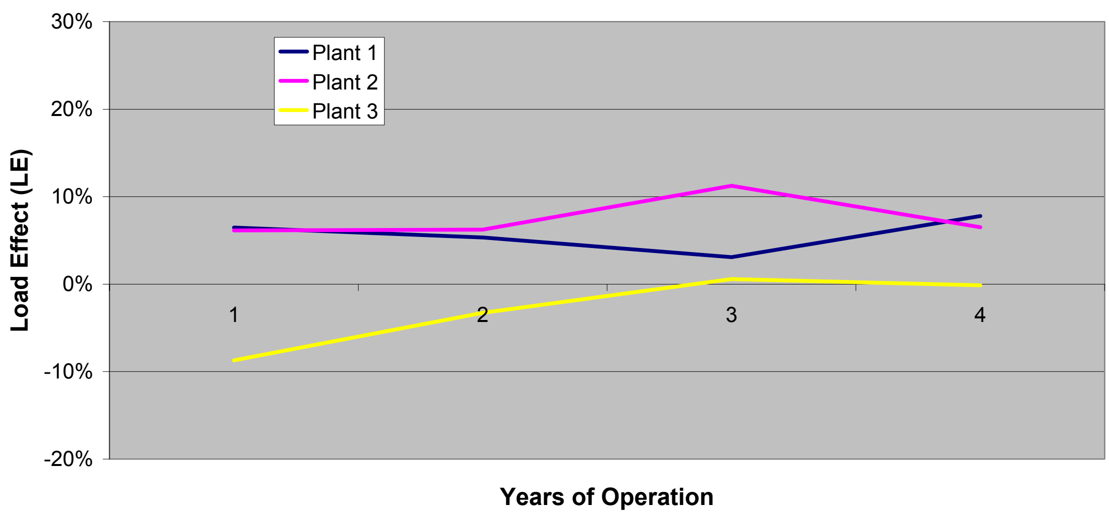
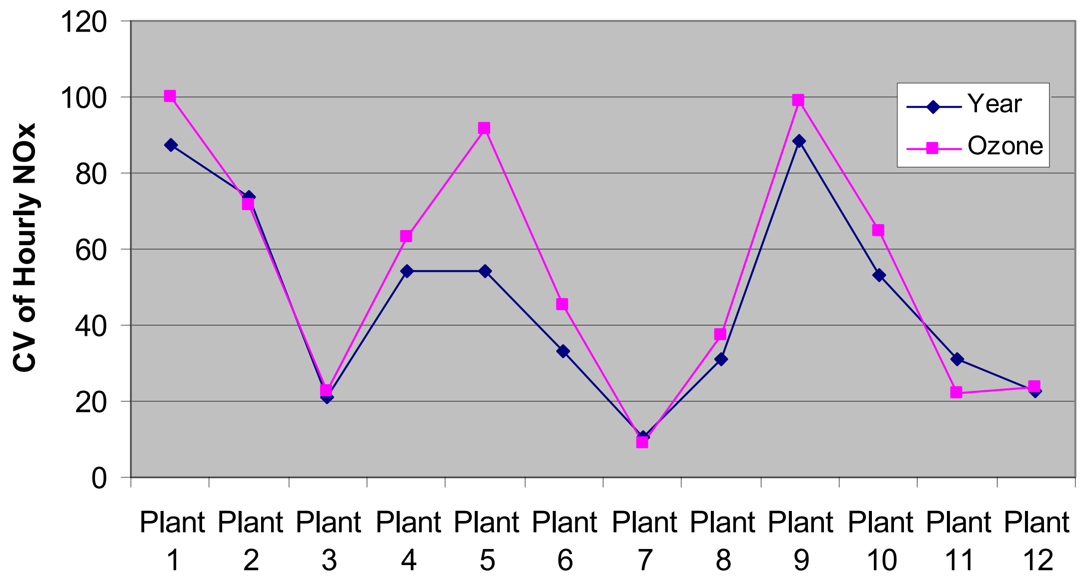


Figure 18. CV versus Year Round SCR Operation



CONCLUSIONS

In this work we examined the performance and reliability of SCRs on US coal-fired utility boilers. Performance was measured in terms of NOx removal and in terms of outlet NOx levels. Reliability is more difficult to measure. However, we used measures of variability of outlet NOx as an indicator of the SCR's reliability in providing NOx control. One of the twos measures of variability was used to determine the significance of load in the variability of outlet NOx level. We have reached the following conclusions from this work.

- Ninety percent (90%) removal efficiency is currently being achieved by a significant portion of the coal-fired SCR fleet. And, performance measured in terms of NOx removal efficiency appears to be improving for the majority of units.
- High levels of variability were demonstrated for units equipped with only combustion controls and for units equipped with SCR controls, although the highest variability was for units equipped with SCR. However, some of the units with SCR achieved high NOx reduction (over 90%) with low variability.
- The units with the highest absolute variability in NOx emissions rate were not the units with the lowest outlet NOx emissions rate. In fact, the data showed some units with very low outlet NOx emissions rate (below 0.05 lb/MMBtu) and very low variability. This shows that low emissions rates can be achieved with high reliability.
- A significant amount of variability, although not all, is associated with changes in load. So, some significant amount of variability in outlet NOx is associated with operating practices.
- Bituminous units with SCR are achieving similar NOx emissions as PRB units with SCR, although the PRB units have a lower combustion NOx level, This, along with the low variability of PRB emissions, suggests that lower NOx emission rates (higher NOx removal rates) are possible from PRB units.
- Catalyst type does not appear to have a significant impact on reduction or variability.

- The choice of anhydrous ammonia or urea as the ammonia source does not appear to impact reduction rate or variability. Aqueous ammonia may show different behavior, but it is difficult to determine since few units in this study used aqueous ammonia.
- There does appear to be a learning curve that benefits both NOx removal and variability in controlled NOx emission rates. This learning has resulted in significant improvements in NOx removal performance across the fleet of SCRs. Reductions in variability appear to be occurring as well.
- Annually controlled units that showed low variability, appeared to do so year round. Variability was usually higher in the ozone season, possibly due to higher NOx removal rates.

FUTURE AREAS OF INTEREST/QUESTIONS

This study examined reliability from the perspective of variability of NOx emissions rate. This may not be the best indicator of reliability. Future work may examine other measures of reliability.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Cichanowicz, J. Edward, and Smith, Lowell, L., "SCR Performance Analysis Hints at Difficulty in Achieving High NO_x Removal Targets", Power Engineering, November 2002, pp 82-90

[2] Staudt, J., Khan, S., and Oliva, M., "Reliability of Selective Catalytic Reduction (SCR) and Flue Gas Desulfurization (FGD) Systems for High Pollutant Removal Efficiencies on Coal Fired Utility Boilers", 2004 Combined Power Plant Air Pollution Control Mega Symposium, August 30-September 2, 2004, Washington, DC.

[3] Erickson, C., "Availability of the US SCR Fleet", EPRI SCR Workshop, November, 2005, Louisville, KY.