TECHNICAL PUBLICATION

Selective Catalytic Reduction System Performance and Reliability Review

by

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ABSTRACT

Using the 2005, 2005, 2006 and 2007 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 particular 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 and that overall Ozone season average NO_x emissions rates of less than 0.05 lb/MMBtu were consistently achievable by SCR systems. The analysis also examined the effects of annual versus seasonal control, as this may become more important in the future. Last, the ability of plants to improve their operation over periods of time is also assessed.

This review is an update of a review first presented at the 2006 Mega Symposium that only examined through 2005.[i] An additional two years of data will provide important insight to the ability of facilities to improve operation over time. The review concludes that low NO_x 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.

This is an update of previous work that examined the performance of 120 SCRs on coal-fired utility boilers using 2005 and earlier data. This earlier work concluded that:

* Ninety percent (90%) removal efficiency was being achieved by a significant portion of the coal-fired SCR fleet. And, performance measured in terms of NO_x 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 NO_x reduction (over 90%) with low variability.

* The units with the highest absolute variability in NO_x emissions rate were not the units with the lowest outlet NO_x emissions rate. In fact, the data showed some units with very low outlet NO_x emissions rate (below 0.05 lb/MMBtu) and very low variability. This showed that low emissions rates can be achieved with high reliability.

* A significant amount of variability, although not all, was associated with changes in load. So, some significant amount of variability in outlet NO_x was associated with operating practices.

* Bituminous units with SCR were achieving similar NO_x emissions as PRB units with SCR, although the PRB units have a lower combustion NO_x level, This, along with the low variability of PRB emissions, suggested that lower NO_x emission rates (higher NO_x removal rates) are possible from PRB units.

* Catalyst type did not appear to have a significant impact on reduction or variability.

* The choice of anhydrous ammonia or urea as the ammonia source did not appear to impact reduction rate or variability. There was limited data on aqueous ammonia.

* There appeared to be a learning curve that benefits both NO_x removal and variability in controlled NO_x emission rates. This learning resulted in significant improvements in NO_x removal performance across the fleet of SCRs. Reductions in variability appeared 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 NO_x removal rates.

This effort has the benefit of two more years of operation of coal-fired SCRs, and can examine trends in data that may provide insights to SCR operation. Furthermore, additional units are operating on an annual basis, which will give insight to possible future annual operation.

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 that calendar year.

Reliability is more difficult to measure. In our previous effort, we developed measures intended to provide 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% = (standard deviation of hourly NO_x rate)*100 / (average hourly NO_x 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% = (((average of hourly NO_x rate over ozone season)/ (overall ozone season NO_x 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 can be 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:

- 2005, 2006 and 2007 hourly ozone season and first quarter emissions data for units equipped with SCR and operating during the ozone season. After filtering for units with missing data to determine variability, this group was reduced to 125 units.

- 2005, 2006 and 2007 year round emissions data on 25 annually controlled units equipped with SCR.

- 2002 thru 2007 hourly Ozone season and first quarter 2002 thru 2005 emissions data for three selected units equipped with SCR on similar size units and known SCR designs.

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.

Comparison of 2005 through 2007

Recalling from Erickson and Staudt i, NO_x reduction overall improved during the period from 2004 to 2005 for most SCRs monitored in that study. We perform here a similar evaluation for the period from 2004 to 2005. Figure 1 shows the trends for 2005 to 2007 for NO_x reduction versus the percent of units that provided that NO_x reduction or less. In general, NO_x reduction was still generally good, with 50% of the units evaluated achieving 85% or higher NO_x reduction in all years and at least 20% of the units at or above 90% removal. However there was a trend toward slightly lower fleet-wide levels of NO_x removal. Except for some units achieving over 95% in 2007, the curves are very similar above 90% removal for each year. On the other hand, below 90% removal there tends to be a slightly smaller percentage of units achieving any given emissions capture rate in 2007 than in the previous years. Figure 2 shows that the baselines for the most part did not change a substantially over the period. Figure 3 is a plot of controlled emissions during the ozone period versus percent of units, and it shows that for the units controlled to very low levels, there was very little change over the period in the controlled level of emissions. However, over the 2005 to 2007 period, the emissions for the units controlled to higher levels generally went up. The reason for this is unknown. But, clearly, the units controlled to low levels, in the range of 0.05 lb/MMBtu for the most part continued to control to low levels.

Figures 4, 5, and 6 each show several things for each unit and each year with the units sorted from lowest overall ozone season rate to the highest overall ozone season rate:

- The average NO_x emission achieved over the ozone season for all 125 units evaluated in this study (plotted in a blue line and designated “oz_noxem”) determined by the total mass emissions and the total heat input.

- The average of the hourly averages of the NO_x emission rates (plotted on the red line and designated “Average Hourly Oz”, which is generally close to the overall ozone season rate; but, often deviates from it significantly.

- A range shown that indicates plus or minus the standard deviation in hourly averages from the average of the hourly averages. This is an indication of CV. Of course, negative NO_x emissions do not occur. So, this is only an indicator of the standard deviation.

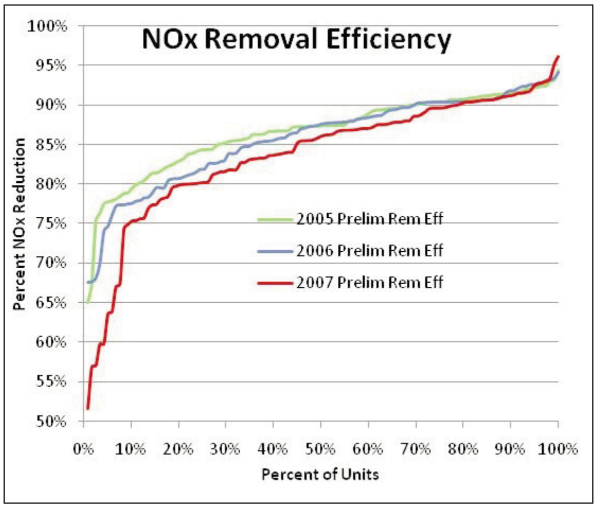

Figure 1. NO_X Removal Efficiency versus percent of units at or below that removal efficiency

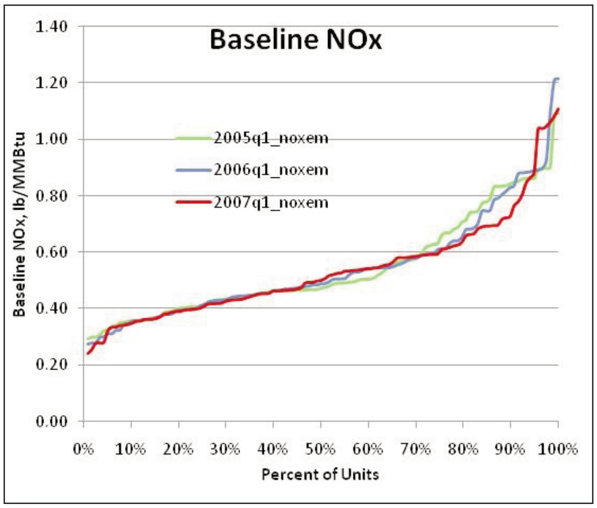

Figure 2. Baseline NO_X versus percent of units at or below that baseline NO_X level

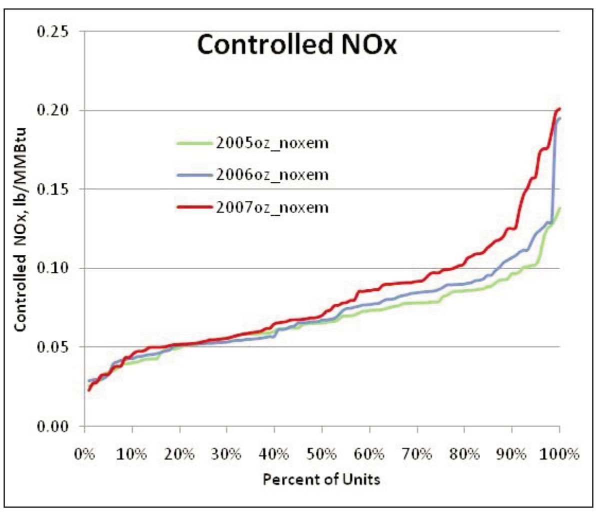

Figure 3. Controlled NO_X versus percent of units at or below that controlled NO_X level

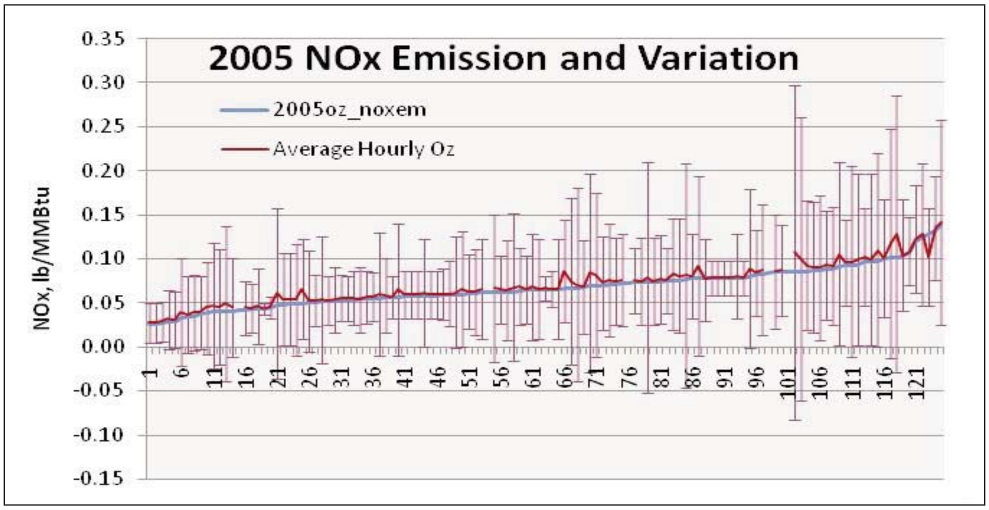

Figure 4. 2005 controlled NO_X, average of hourly averages, and ± standard deviation of hourly averages

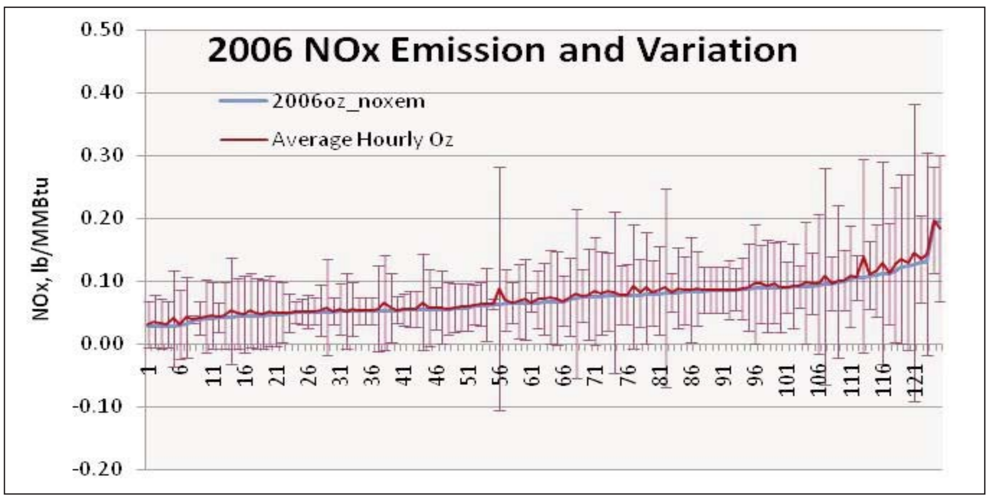

Figure 5. 2006 controlled NO_X, average of hourly averages, and ± standard deviation of hourly averages

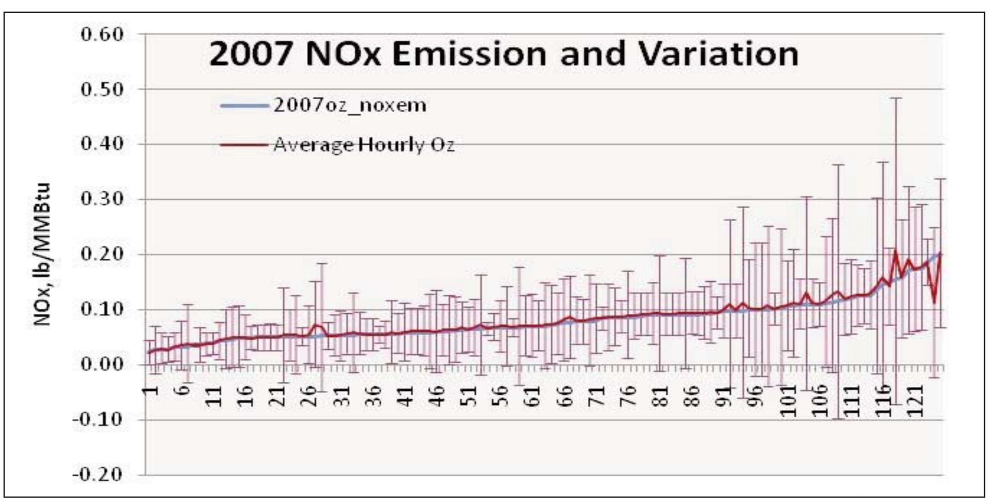

Figure 6. 2007 controlled NO_X, average of hourly averages, and ± standard deviation of hourly averages

What can be observed from Figures 4-6 are that:

- * There was significant variation in the hourly NO_x emission rate across the full range of controlled NO_x emission levels.

- * In some cases the average of the hourly NO_x emission rates deviated significantly from the overall ozone season emission rate.

- * In most cases where there was a significant difference between the average of the hourly rates and the overall ozone season rate, the average of the hourly rates exceeded the overall ozone season rate. This indicates that for these units the emissions rate at part load is typically higher than at full load. This might be a result of securing SCR operation at part load due to a lack of temperature control.

- * In most cases where there was a significant difference between the average of the hourly rates and the overall ozone season rate, there was also a greater standard deviation in the hourly NO_x emission rates.

- * The variation in hourly emission rates for units controlled to low levels in 2007 seemed to be significantly lower than in prior years.

With regard to this final point, as shown in Figure 7, both the median and average CV dropped significantly over the period from 2005 to 2007, confirming what is visually observed in Figures 4-6 that variation in hourly emissions has dropped overall for the population of boilers. Essentially, controllability, as measured by CV, appeared to improve over the period.

It was also found, when sorting the 125 units for lowest emissions over the ozone period, that of the 25 units with the lowest emissions in 2005, 20 of them were in the lowest 25 in 2006 and 16 of the original 25 were in the lowest 25 in 2007. Low emitting units tend to stay low emitting units.

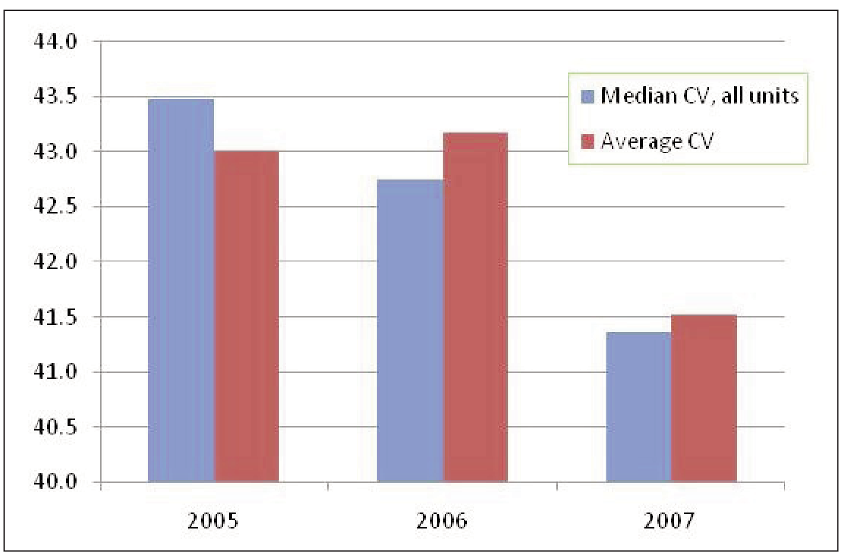

Figure 7. Median and Average CV for 125 Units

Relationship Between CV and LE Over the Period

In previous work Erickson and Staudt found a relationship between CV and the absolute value of LE.i This relationship showed that CV, or variability in hourly emission rates had a relationship between LE, or the difference between the overall seasonal rate and the average of the hourly rates. As shown in Figure 8, this trend has generally continued. The trend can be characterized as follows:

* When LE is high, CV is always high
* If LE is low, there is no trend in CV — it may be low or high
* When CV is low, LE is always low

The conclusion that can be drawn from this is the following:

In order to have a low CV (variability in hourly NO_x emissions), it is necessary to have an SCR control system that can control to a prescribed emissions level over a wide load range (which will result in a low LE). However, while this is a necessary condition for a low CV, it is not alone a sufficient condition to result in a low CV. As a result, even if one has an SCR control system that is capable of controlling to an emission rate over a wide load range, other factors can potentially result in having large variation in hourly emissions rates. These other factors would have to be unrelated to load, or they would likely show up as an increase in LE.

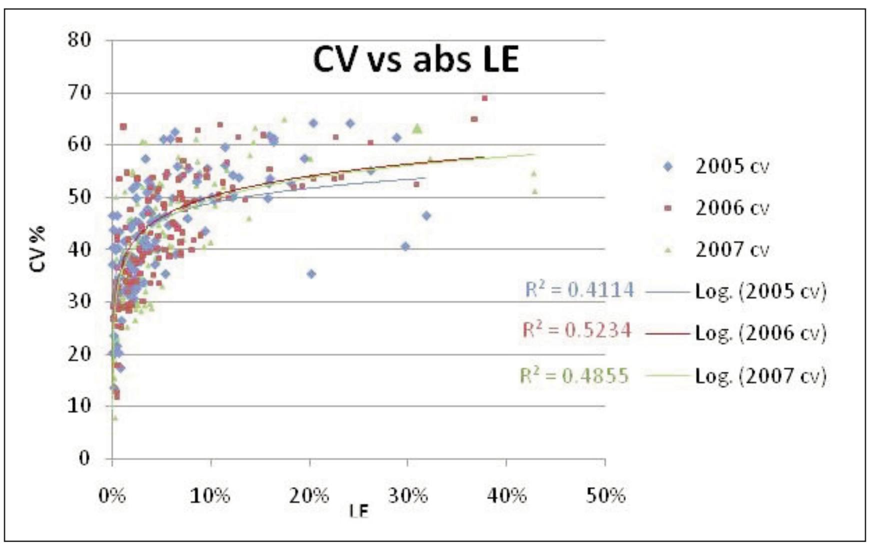

Figure 8. CV versus absolute value of LE for 2005 through 2007

Annually Controlled Versus Seasonal Units

Of the 125 units in this data set, at least 25 were operated annually by 2007. In years 2005 and 2006, at least 13 of those 25 were operated on an annual basis, with most of the remainder starting annual controls in 2007 as a result of state requirements that took effect in 2007. Because annual operation is of concern in the future for a greater number of facilities, we examined how the performance of these units compared to those of the remainder of the population of SCRs.

As shown in Figure 9, the average ozone season NO_x emissions are somewhat higher for the annually controlled units than for the rest of the population. Generally, emissions over the ozone season increased, but slightly less so for the annual units. Keep in mind that 2007 represents the average for 25 units rather than 13 for the preceding years. As shown in Figure 10, the CV of the annually controlled units was generally above the CV of the population in general.

It should also be born in mind that, due to the much smaller population size for the annual units shown in Figures 9 and 10, the standard deviation in ozone season NO_x emissions or CV for the small population of annually controlled units is relatively high, making the difference with the rest of the population well below one standard deviation in all cases. As a result, the differences with the rest of the population are statistically of little significance.

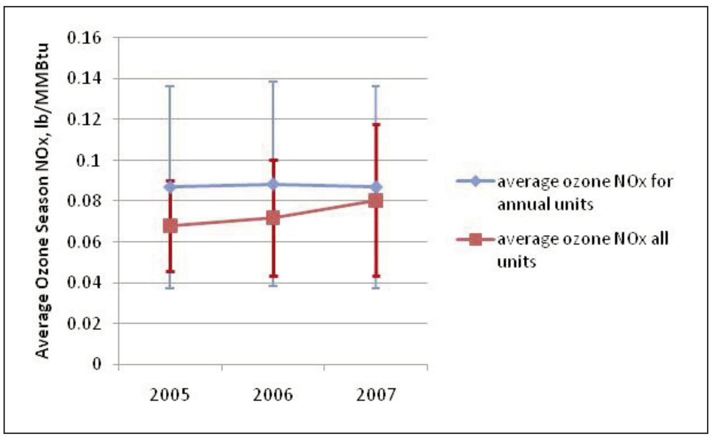

Figure 9. Average Ozone Season NO_x Emissions (lb/MMBtu) for All Units and for Annually Controlled Units with error bars showing plus and minus one standard deviation

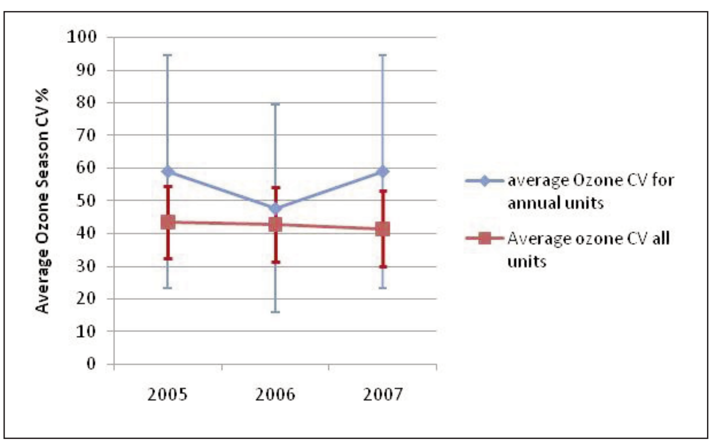

Figure 10. Average Ozone Season CV for All Units and for Annually Controlled Units with error bars showing plus and minus one standard deviation

Analysis of Year Round SCR System Operation

Figure 11 shows the 2007 annual emissions rates and ozone season emission rates for 25 year round operating SCR systems. As shown, for these systems there was fairly good consistency between the emission rates for the two periods. Figure 12 shows the standard deviation in hourly emission rates for these units in 2007 for both annual and ozone season. As shown, the standard deviation in hourly emission rates for both annual and ozone season remain fairly consistent for these units, suggesting little difference in controllability. As expected from Figure 12, the CVs of the hourly emission rates, shown in Figure 13, are also fairly consistent between ozone season and annual emission rates. This confirms that while controllability may differ from plant to plant, for any plant we should expect controllability to be the same between ozone season and annual control.

SCRs 1 through 5 represent early US SCR retrofit plants, plants 6 through 9 are units with the SCR designed as original equipment and the remaining units are units originally designed for Ozone operation that now operate year round. Units 14-25 only came into annual service in 2007. The graph shows considerable variation between plants regardless of above category. As a result, there must be factors that are unit specific, whether operational or design, that attribute to the differences in the units.

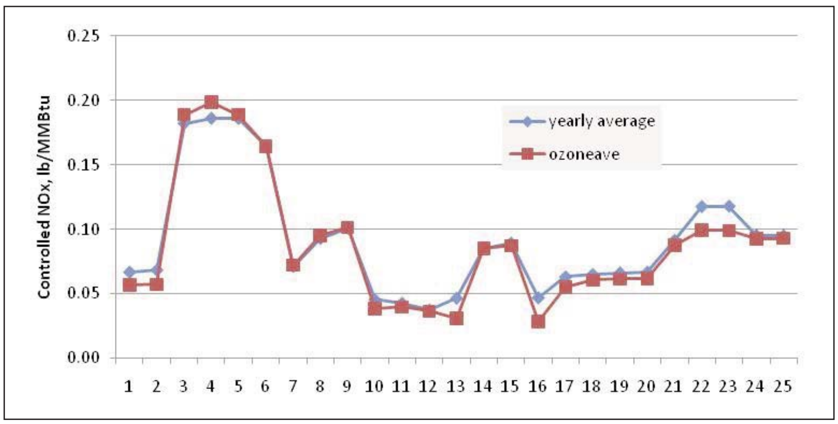

Figure 11. 2007 Controlled NO_X emission rate for 26 annually controlled plants

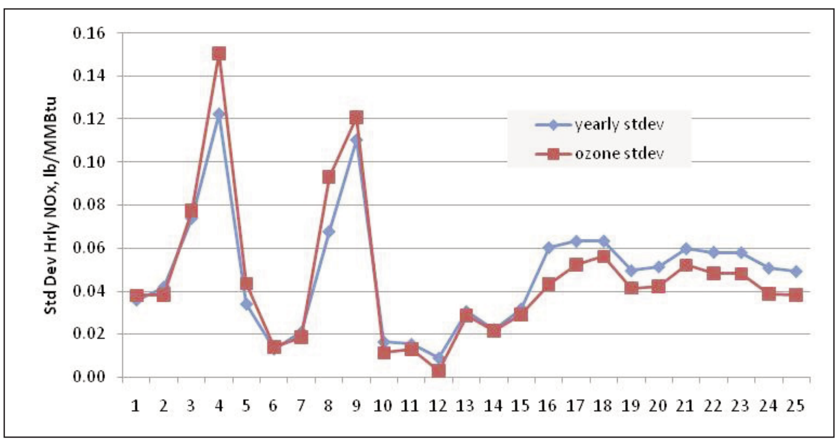

Figure 12. 2007 Standard Deviation in Controlled NO_X Emission rate for 26 annually controlled plants

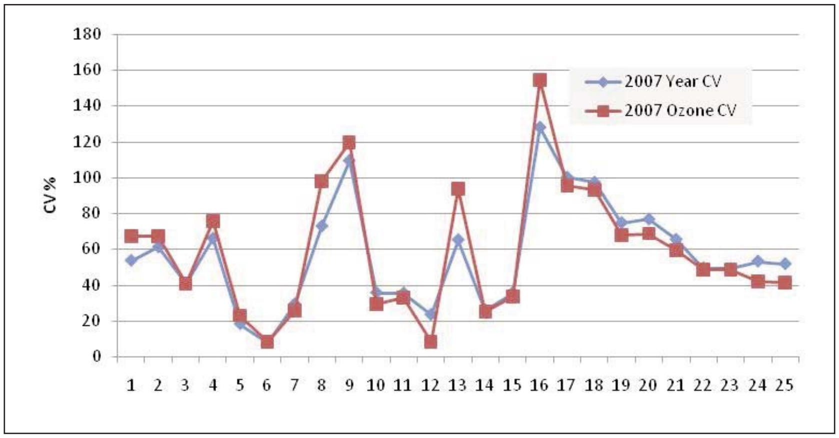

Figure 13. 2007 CV in Hourly NO_X Emission rate for 26 annually controlled plants

Figure 14 shows CV of annual hourly NO_x emissions for the 21 units for years 2005, 2006 and 2007. As shown, CV by and large remains in the same range for each unit, suggesting that CV is characteristic of the unit's design or operation.

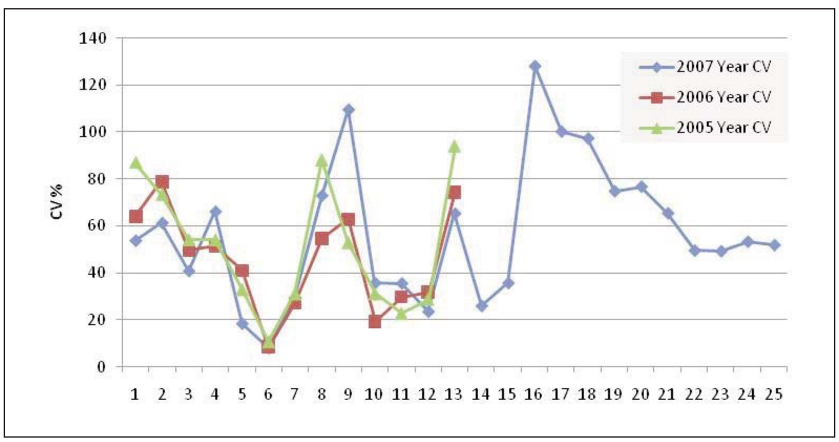

Figure 14. 2007 CV in Hourly NO_X Emission rate for 26 annually controlled plants

Figure 15 shows annual CV plotted against ozone season CV for each year for each unit. As shown, there is a strong correlation between them. Slope of the trendlines also show that, while in 2005 ozone season CV was generally slightly higher than Annual CV, the difference narrowed slightly in 2006 and 2007.

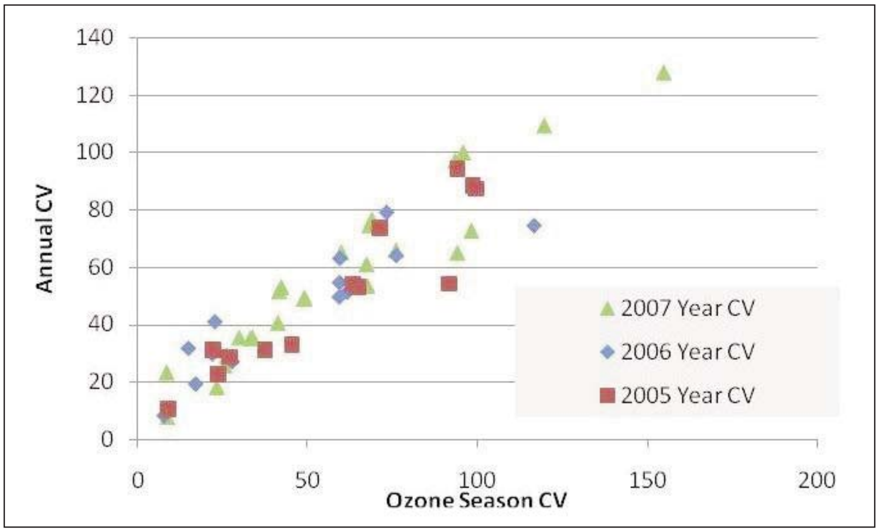

Figure 15. 2007 CV in Hourly NO_X Emission rate for 26 annually controlled plants

Analysis of Operational Improvement and Stability Over Time

Figures 16, 17 and 18 show average NO_x, CV of hourly NO_x and LE, respectively, 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.

Figure 16 shows steady reduction in controlled emission for Plant 3, while Plants 1 and 2 have less consistent emissions performance. Figure 17 shows plant 1 with the lowest CV (and lowest controlled NO_x) over the period. However, CV increases in the last two years, approaching that of Plant 2. This illustrates variability of both controlled NO_x and CV and LE over time and between plants of similar design. It also shows, in the case of Plant 3, a steady decrease in controlled NO_x and CV for the first few years; but, in years 5 and 6 continued reduction in controlled NO_x with an increase in CV and absolute value of LE. As a result, it is clear that performance can change over time, and CV will increase if LE increases.

Because Plant 1 does not have temperature control, it would seem reasonable to expect LE for Plant 1 to be the highest. But, that is not the case. Figure 18 shows that a plant without temperature controls (Plant 1) can have similar load effect (LE) as a plant with temperature controls (Plant 2). As a result, operational characteristics of the plant clearly have an impact on these performance metrics.

Figure 19 shows CV plotted against LE and is consistent with what is indicated in Figure 8, that a low CV does not occur without a low LE.

The conclusions related to CV and LE as a function of years of operation are based on six years of 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 system performance.

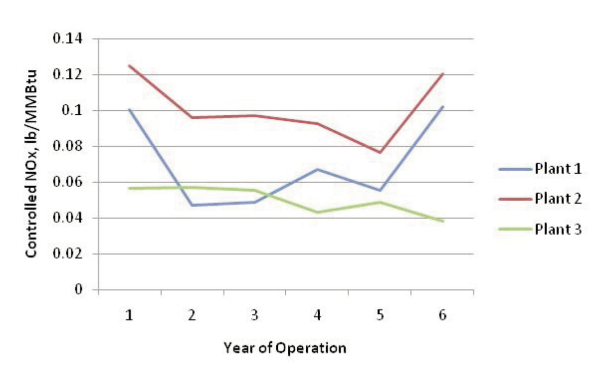

Figure 16. Controlled NO_X versus year of operation

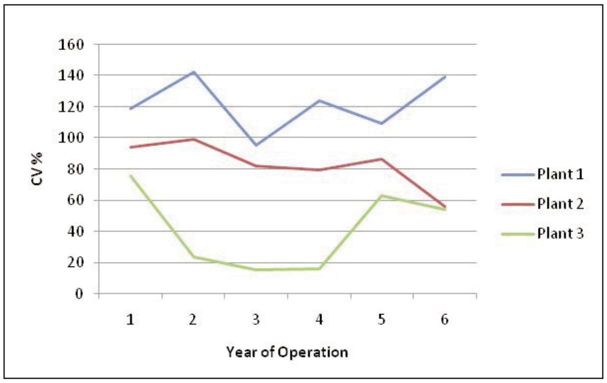

Figure 17. CV versus year of operation

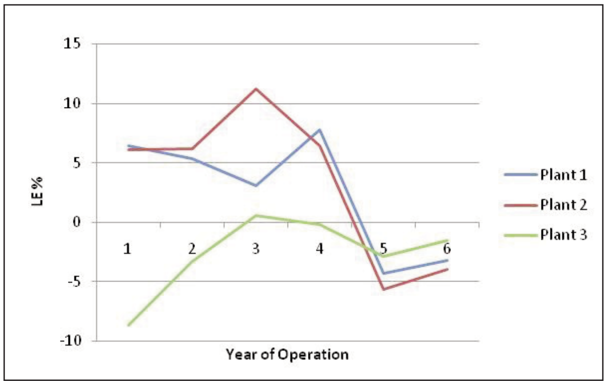

Figure 18. LE versus year of operation

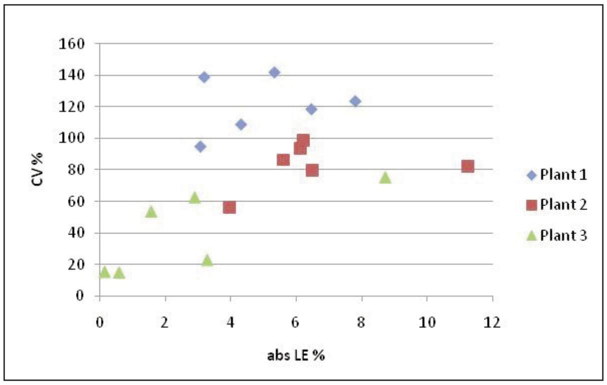

Figure 19. CV versus absolute value of LE

CONCLUSIONS

In this work we examined the performance and reliability of SCRs on US coal-fired utility boilers during the period from 2005 to 2007. Performance was measured in terms of NO_x removal and in terms of outlet NO_x levels. Reliability is more difficult to measure. However, we used measures of variability of outlet NO_x as an indicator of the SCR's reliability in providing NO_x control. One of the two measures of variability was used to determine the significance of load in the variability of outlet NO_x level. We have reached the following conclusions from this work.

* Ninety percent (90%) removal efficiency continues to be achieved by a significant portion of the coal-fired SCR fleet.

* Performance in terms of NO_x removal efficiency, and in terms of outlet emissions rates have remained consistent for the best controlled units. However, for the less well controlled units, performance has fallen off somewhat. The reason for this is unknown.

* Variability in outlet emissions rate has been reduced over the period, indicating a trend toward improving controllability.

* Over the period there was a consistent relationship between Load Effect (LE) and variability (CV). This relationship suggests that having an SCR that can maintain a constant NO_x emissions rate over the full load range is a necessary, but not a sufficient, condition for having low variability in emissions rate. Units with low CV consistently had low LE. But, units with low LE did not necessarily have low CV.

* Analysis of annually controlled versus seasonally controlled units over three ozone seasons showed that there is little or no statistical difference between performance during the ozone season.

* Analysis of units with known design characteristics over a period of several years shows significant differences in performance from year to year and between units that is not explained by design characteristics. As a result, operational differences likely have a significant impact on the observed performance.

* Analysis also showed that units can improve operation over time, in terms of both outlet emissions and variability. However, variability, measured by CV will increase if LE increases, even as controlled NO_x is reduced.

ACKNOWLEDGEMENTS

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REFERENCES

1. Erickson, C., Staudt, J., “Selective Catalytic Reduction System Performance and Reliability Review”, The 2006 Power Plant Air Pollution Control “MEGA” Symposium, Paper # 121, August 28-31, 2006, Baltimore, MD