DISCUSSION

Background

One of the original objectives of the program was to collect data in order to optimize and evaluate the use of ammonia injection to reduce precipitator corrosion. Ammonia injection was being considered to supplement plans to raise the FD fan air temperature (and thus the average air heater outlet temperature) above the acid dew point.

Shortly after the initial startup, Hoosier Energy removed the intermediate layer of air heater heat transfer surfaces to raise the flue gas exit temperature. This was done to avoid precipitator corrosion and ash caking problems, especially at low load conditions which were prevalent at that time. Hoosier Energy plans to reinstall these heat transfer surfaces in the fall of 1988 in order to operate in a more efficient mode. Ammonia injection was the recommended method for eliminating ash caking problems and reducing corrosion in the precipitator, based on an evaluation of several physical and chemical alternatives. A field test of ammonia injection was undertaken to determine if ammonia injection would provide the needed level of flue gas conditioning.

DISCUSSION (Continued)

During the precontract discussions, the objectives were expanded to include the short and long term effects of ammonia on the precipitator operation. If ammonia was successful in reducing the acid dew point below the average gas temperature, Hoosier Energy hoped to be able to reinstall the air heater heat transfer surface which had been removed to prevent air heater fouling.

Although it is recognized that reacting ammonia with SO_3 will minimize the formation of sulfuric acid mist in the FGD system and thus reduce plume opacity, this was not an objective of the program. The mixing of untreated gas from Unit 1 with treated gas from Unit 2 at the stack prevented a visual evaluation of plume opacity modifications resulting from the ammonia injection.

One concern relating to precipitator operation was whether the ammonia would form ammonium sulfate or ammonium bisulfate as shown by the following two equations:

$$2NH_3\ (gas) + SO_3\ (gas) + H_2O\ (vapor) \text{ ----> } (NH_4)_2SO_4\ (solid)$$

$$NH_3\ (gas) + SO_3\ (gas) + H_2O\ (vapor) \text{ ---> } NH_4HSO_4\ (solid/liquid)$$

DISCUSSION (Continued)

The effect of ammonium sulfate on precipitator operation is not well published. Ammonium bisulfate, which becomes liquid above 292(F), may cause long term ash buildup on the precipitator electrodes. Ammonia injection is known to improve precipitator collection efficiency for low resistivity ash by increasing cohesiveness and thus lowering reentrainment. It also improves the interelectrode field strength due to the space charge effect of the fine particles formed and thus improves collection efficiency provided ample SO_3 is present for this effect.

The corrosion problems associated with low temperature gases are caused by the presence of sulfuric acid which is formed by the condensation of SO_3 in the presence of water vapor.

As the gas passes through the air heater, the cold heat transfer surfaces cause the formation of sulfuric acid as the flue gas temperature is reduced below the acid dew point. Gooch[1] provides a dissertation on the formation of sulfuric acid and the condensation characteristics of sulfuric acid in flue gas.

DISCUSSION (Continued)

The condensed acid becomes associated with the fly ash thereby minimizing the benefits of SO_3 neutralization with ammonia. Only the fraction of SO_3 remaining in the gaseous phase is available for rapid reaction with the injected ammonia. The acid deposited on the fly ash in the air heater may very likely still cause precipitator corrosion.

At flue gas temperatures below the sulfuric acid dew point, any exposed metal will experience some degree of corrosion. The rate of corrosion is affected by both the quantity and by the concentration of the acid in the gas stream. Therefore, corrosion may be reduced by lowering the quantity of acid in the gas stream, even though the flue gas temperature may be below the acid dew point. Corrosion can be correlated with flue gas and fly ash composition when sulfuric acid and water concentrations of the flue gas are known and the soluble sulfate and soluble base content of the fly ash is analyzed at various temperatures.

The sulfuric acid formed by the condensation of SO_3 is concentrated and has minimum corrosivity on carbon steel. Sulfuric acid is, however, an aggressive desiccant and in the presence of free moisture the concentrated sulfuric acid becomes dilute. Dilute sulfuric acid is very corrosive.

DISCUSSION (Continued)

At low load, gas temperatures as low as 245 (F) were found in the precipitator inlet duct. To eliminate acid condensation in the precipitator for this condition, at steady load, it would be necessary to reduce acid dew point below 240(F) at low load (calculated with an assumed temperature loss of 5(F) through the precipitator). An acid dew point of 240(F) corresponds to a SO_3 concentration of approximately 1 ppm.

Although the optimal solution appears to be lowering the SO_3 concentration to less than 1 ppm, the acid deposition and thus corrosion of the precipitator internals will also be reduced by lowering the dew point even though it may not be below the full range of precipitator operating temperatures.

To determine the ammonia injection feed rates necessary to form ammonia sulfate or ammonium bisulfate, it is necessary to know the sulfur trioxide concentration in gas phase. During the test program this was done by manually sampling for SO_3 concentration. However, for long term operation, a measurable parameter would be required which could be used to calculate SO_3. Since sulfur dioxide can be measured by continuous monitor, we attempted to find a correlation for the conversion of SO_2 to SO_3. For this to be practical the SO_2 to SO_3 conversion factor must remain constant or be a function of measured boiler variables. This

DISCUSSION (Continued)

conversion happens in the 700-900 (F) range and is dependent on the availability of excess oxygen. The presence of carbon in the fly ash is believed to reduce gas phase sulfur trioxide by absorption. Very little information is published on the effects of either of these phenomena.

DETAIL DISCUSSION BY TEST DAY

November 10, 1987 - Tuesday

Megawatts were reducing from 444 MW at 7:40 AM to 384 MW at 1:00 PM and held at this level for the test period.

Precipitator readings taken at 7:40 AM, as shown in Graph 16 indicate the precipitator power density was reduced in the inlet fields due to corona quenching caused by the high dust concentration. The power then increased to approximately current limit in the 4th through 7th fields as expected with high sulfur coal. The dip at the 5th field could indicate a possible gas distribution problem with gas crossing over the catwalk at an angle causing turbulence or a consistent physical problem in each precipitator chamber at this field. This dip occurred in the 5th field even with the third field out of service, see Graph 18, which indicates that this dip is not caused by selective particle classification by resistivity.

DISCUSSION (Continued)

Preliminary SO_3 and SO_2 reading were performed which show that the conversion factor averaged 0.81% for A side and 0.63% for B side with an overall average of 0.72%.

November 11, 1987 - Wednesday

The unit was operated at approximately full load, 495 MW, for three runs then reduced to 439 MW and 389 MW for the last two runs respectively.

Temperature and velocity traverses were performed at the precipitator inlet ducts. These measurements identified a gas temperature range of 265(F) to 348(F) at full load with average temperatures of approximately 312(F).

SO_3 and SO_2 readings were performed which show that the conversion factor averaged 0.67% for A side and 0.78% for B side with an overall average of 0.73%. Runs 4,7 and 8 on the B side averaged 25.26 ppm +/- 0.27 ppm. Although runs 5 and 6 on the B side varied significantly from this value they averaged 25.73 ppm suggesting the possibility that the condenser may not have been thoroughly rinsed after run 5. The A side readings are much more scattered with the first two runs averaging 14.85 ppm and the last three runs averaging 26.4 ppm. Loss on ignition (LOI) data was supplied by Flame Refractories for fly ash particulate

DISCUSSION (Continued)

samples taken at the air heater inlet in the morning prior to our runs. These data showed A side LOI to be 2.96%-3.03% which was much higher than B side at 1.26% - 1.51% .

All of the controlled condensation samples on this day were taken at locations in the duct where the gas temperature was above the acid dew point. The gas sampled was maintained well above the dew point in the probe and pre-filter, resulting in a good characterization of the baseline sulfur trioxide concentration ahead of the air heater.

The consistency of the data suggests that the coal fired on the 11th (Wednesday) was constant and therefore probably from the unit train. On other days the variations in coal trucked from 10 mines is evident. The high LOI and the difference in SO_3 concentrations from side to side indicates an abnormal boiler operation possibly due to special conditions for the boiler tests being conducted by others.

November 12, 1987 - Thursday

On this day, the boiler was operated at the low load setting of 248 Gross MW. However, the boiler oxygen was reported to have been adjusted to very low levels for boiler test purposes. The A side SO_3 results were lower than the previous two days and averaged 16.56 ppm. The B side

DISCUSSION (Continued)

averaged 5.20 ppm indicating significant reduction due to boiler operation. LOI determined on fly ash samples taken at the air heater inlet by others did not indicate a significant operational difference between the A and B sides. However, it is believed that these samples were taken in the morning prior to the start of the SO_3 sampling. It is possible that the boiler primary air was adjusted to lower oxygen levels in the interim. We cannot confirm this with our boiler data computer printout since the boiler data was not printed after 10:10 AM on this day.

Temperature and velocity traverses were performed at the precipitator inlet ducts. These measurements identified a gas temperature range of 245(F) to 292(F) at low load with average temperatures of approximately 278(F).

November 17, 1987 - Tuesday

In the morning the unit was operated at the low loads of 252 and 287 gross MW for runs 1 and 2 and was then increased to 490 gross MW for the two afternoon runs. The efficiency was generally constant for both sides and for both loads at approximately 99.95% except for the B side at the high load which showed a deterioration to 99.91% and then to 99.85% as the unit adjusted to the increased volume and dust loading. It is expected that the A side would similarly deteriorate

DISCUSSION (Continued)

with time at the high load.

November 18, 1987 - Wednesday

On this day compliance testing was performed including particulate sampling at each precipitator outlet duct and at the stack enabling a determination of FGD particulate removal or reentrainment. One run for SO_3 and SO_2 reading was performed on the B side in the morning which found an SO_3 concentration of 24 ppm with a conversion factor of 0.79%.

Ammonia injection was initiated in the late morning with an initial setting of 15 ppm. One run was then conducted on the B side which showed a SO_3 concentration of 12 ppm.

At that time it was decided to reduce the SO_3 sampling train probe and pre-filter temperatures to the gas temperature in order to measure the gas phase SO_3 without disassociating the sulfates. Initially, a temperature of 250 - 265 (F) was selected which was below the gas temperature for some sample points. This resulted in additional SO_3 condensation in the sampling train ahead of the temperature controlled condenser.

DISCUSSION (Continued)

This problem was encountered during the last two runs of the day. One of the runs on the B side with ammonia injection at 30 ppm resulted in a sulfur trioxide concentration of 4.2 ppm. This value is higher than expected for 30 ppm ammonia injection. Possible explanations for this are:

* Ammonia was injected at a much lower rate than 30 ppm.
* Ammonia was not being distributed as expected resulting in ammonia sulfate leaving free SO_3. This is not supported by previously reported work which generally show mass balances supporting the formation of ammonia bisulfate exclusively until all the gas phase SO_3 is reacted.
* Water condensation at some point in the heated condenser which then absorbed SO_2 forming a sulfate.
* Decomposition of sulfate or sulfite compounds in the probe ahead of temperature controlled condenser.

November 19, 1987 - Thursday

The boiler was operated at the low load of 247 gross MW for the early runs and then reduced to 190 MW at 2:30 PM. The ammonia injection rate was increased from 15 ppm to 30 ppm and then to 50 ppm. Again the SO_3 concentrations at the higher injection rates were higher than expected. The probe and filter temperatures were raised from 260 (F) to 360 (F)

DISCUSSION (Continued)

after the second run to prevent condensation ahead of the controlled condenser. Immediately following this change, the SO_3 readings for both the A and B side were inexplicably high. It would appear that acid lodged in the probe from earlier runs was liberated and collected in the hot condenser.

The precipitator collection efficiency and migration velocities for both sides were similar to the earlier low load tests. Electrical readings comparing the A and B side indicated generally full power input on all sets in service with the exception of the first two field in each chamber on the B side which were 40% and 60% respectively.

November 20, 1987 - Thursday

The boiler load was increased from the low load setting of 225 gross MW prior to 8 AM and was operated at the high load of 490 gross MW through the test day. The precipitator efficiency and migration velocity with and without ammonia appear essentially identical with the exception of the A side morning run. During this run, three T-R sets tripped. This also explains the higher opacity and the opacity spike. Many times during the test program, various electrical sets would trip and eventually be reenergized. Also, several sets were out of service for repair as documented by the

DISCUSSION (Continued)

electrical readings. We did not adjust the collection area for these situations when calculating migration velocity. The T-R sets, which tripped in groups of three, were generally the inlet or middle fields of side A. Precipitator guarantee testing is normally terminated during a T-R trip due to the loading spike. We did not terminate during these trips because our testing was diagnostic. We did not have a technician assigned to the precipitator control room to continuously record these trips thus most trips were not noted.

On this day, the A side sulfur trioxide data varied from 23 ppm to 32 ppm with an average of 27.5 ppm and the conversion efficiency averaged 0.82%. The abnormal high concentration of SO_2 in Run 1, Side B was believed due to an analytical procedure error in the laboratory. The failure of proper dilution might be the cause of the error.

November 23, 1987 - Monday

On this day, the boiler was operating on medium sulfur coal (nominally 2% sulfur). The boiler load was at 245 gross MW in the morning for the low load test and was increased to 491 gross MW at 3 PM. Ammonia injection was set at 8 ppm for the low load test and 10 ppm for the high. In general the precipitator efficiency tests are in good agreement with the other low load and high load tests. The one exception is

DISCUSSION (Continued)

the B side test with ammonia injection at high load which demonstrated the best precipitator efficiency and best migration velocity of the test program. The inlet loading on the A side at low load is much lower than any other low load sample. This was the only run in which the C mill was off. On the 17th the B mill was off and on the 19th the A mill was off. The migration velocity of 5.54 ft/sec is in good agreement with the other low load test.

January 6, 1988 - Wednesday

On this day, ten sulfur trioxide controlled condensation runs were conducted at the air heater gas inlets and one at each outlet while the boiler was operating at approximately 450 gross MW. Coal samples were not available due to a malfunction of the plant's automatic sampler. The sulfur trioxide concentration varied markedly from side A to B and also varied from port to port in the same duct although this could have been due to non-simultaneous sampling. Testing at the air heater inlet verified the wide range of SO_2 to SO_3 conversion efficiency found during the November tests. The conversion on this day appears to be a reverse relationship with sulfur dioxide, but as in earlier testing no sustainable relationship could be established. On this day, the conversion measured ahead of the air heaters averaged 0.73% on the A side and 0.29% on the B side. It is

DISCUSSION (Continued)

also possible that some conversion occurs in the air heater, however we do not believe it would be sufficient to explain the side B conversion of 0.87% measured after the air heater this day. The 0.69% measured after the A side air heater outlet compares much better with the inlet conversion average.

January 7, 1988 - Thursday

Ammonia injection was set at 60 ppm on both A and B sides and the boiler load was set at 450 gross MW. Four controlled condensation runs were conducted at the air heater inlet and four at each outlet. At the inlet, the conversion averaged 0.48% on the A side and 0.30% on the B. Some difficulty was encountered on the early runs at the air heater outlet due to moisture condensation at the condenser outlet fitting cause by the adverse weather conditions. This problem was rectified on the 5th run by using a hot air blower.

DISCUSSION (Continued)

Coal Ash Mineral Catalytic Effect

As noted above, the SO_2 to SO_3 conversion factors varied significantly and generally were notably different for side A and side B. We suspected that the coal from 11 different mines could have wide variations in iron and vanadium content which are the required catalysts for SO_3 formation. We analyzed selected coal samples and precipitator inlet particulate samples for these metals with the hope of finding a correlation. These results are given in table 34. We then performed a multiple regression analysis on 5 selected sets of these data and determined a fair correlation represented by:

$$\text{conversion } \% = 0.053 \times Fe + 5.6 \times V - 0.32$$

The poor correlation between the conversion factor and the catalytic elements might be explained by the high iron content of the coal. High iron coal will coat the convection section of the boiler and economizer and then continue to catalyze the reaction with a gradually decreasing effect until the surface is totally coated by a lower iron ash. Whether this effect was occurring was difficult to determine with the constantly changing coal. The wide variation in conversion between the two sides indicates that the instantaneous coal quality is not the only factor involved. The other ash analysis for the %LOI, %carbon

DISCUSSION (Continued)

and %H_2SO_4 shown in Table 35 shows the consistency of the results with the exception of the %H_2SO_4 on November 19, 1987. The relatively higher result of this H_2SO_4 can not be explained. However, the concentration of SO_3 was also relatively high for that same run. More ash analysis data would be required for conclusive remarks.

Resistivity Discussion

Resistivity measurements were made on the B side precipitator inlet on several days during the November testing using both WAHLCO and the SoRI resistivity probes. Most of the data was within a range of 1×10^9 to 1×10^{11} ohm-cm, with no significant difference noted with or without ammonia. The four lowest readings are presumed due to increased carbon in the ash which was found to vary in the range of 1% to 3%. Excluding these four readings, all were within 1 order of magnitude which is considered a normal experimental error for field resistivity readings. The 14 WAHLCO readings averaged $4.8\text{x}10^{10}$ ohms-cm and 12 the SoRI readings averaged $3.8\text{x}10^{10}$ ohm-cm which demonstrates very good agreement.

Precipitator Inlet Duct Temperature Distribution

The temperature and velocity distributions at the inlet ducts are presented topographically and as three dimensional plots on Graphs 4 through 11. These graphs present profiles for both high and low loads. You will notice that the variation in temperature is extreme at high loads which exaggerates dew point problems at the low temperature points.

Reading the Three-Dimensional Plots

The software used in producing the three-dimensional plots has a few limitations. The points where velocity and temperature were measured in the duct began at port/point 1 not port/point 0. The software interpolates to a port/point 0, and also interpolates past the last port/point measured. Halfway between port/point 0 and port/point 1 would be the duct wall. For the inlet, halfway between port 6 and port 7 and point 4 and point 5 would be the duct wall. For the outlet, halfway between port 10 and port 11 and point 5 and point 6 would be the duct wall.

Significant Findings

One of the test objectives was to determine the effect of ammonia injection on sulfur trioxide removal. Concentrations of sulfur trioxide measured at the B side precipitator inlet plotted verses ammonia are shown in graph 12 on page 4 - 47. The general trend

DISCUSSION (Continued)

shows that ammonia is effective in removing gas phase sulfur trioxide thus lowering the acid dew point.

We determined that the sulfur trioxide formation in the boiler is a function of coal sulfur, boiler load, free oxygen availability and ash mineral analysis. Gas phase sulfur trioxide available for ammonia reaction after the air heater is a function of boiler SO_3 formed minus SO_3 condensation in the air heater and minus the SO_3 absorption on free carbon in the fly ash. We had planned to use side A as the control while injecting ammonia in side B. However, we found that the gas phase sulfur trioxide concentration varied much more than expected from side to side. In hindsight, it would have been best to simultaneously sample ahead of and after the air heater during ammonia injection to determine sulfur trioxide removal efficiency. This was done on January 6th and 7th to a limited extent.

By sampling at various locations in the duct we were able to show that the calculated dew point determined by the measured sulfur trioxide concentrations generally correlated with the gas temperature when either the gas sampled or the probe temperature was below the dew point.

Using selected data (including the medium sulfur coal data) multiple regression analysis was performed for the dependent

DISCUSSION (Continued)

variables SO_2 and NH3. Although we had insufficient data for a conclusive relationship, we have found a relationship in our data which can be generally represented by the model:

$$\text{Sulfate} = 0.00695 \times SO_2 - 0.401 \times NH3 - 0.473$$

The regression explained by the model is significant ($F_{0.01}(2,21)=5.58$). More data would be needed to model the effects of boiler load, excess air, economizer sootblowing, carbon absorption and the catalyst effects of metals in the fly ash.

Graph 14 shows a plot of the dew point calculated from measured SO^3 concentrations (data points) as one data set and the minimum temperature of either the sample filter temperature or the stack temperature as another data set (solid line). In this graph, the two data sets correlate well as the calculated dew points are all below the duct/filter temperatures.

In Graph 15, the second data set also includes a dew point temperature calculated based on SO_2 to SO_3 conversion rates. In this graph, the two data sets are closely aligned with data points above and below the conversion rate predicted temperatures. The minimum temperature in the second data set should remain higher than the calculated dew point temperatures.

DISCUSSION (Continued)

Note that to the right of the graph after sample 33 the measured dew point exceeds the theoretical minimum dew point. This correlates with the increased probe and filter temperature. The probe temperature is controlled using a single point measurement in the probe. It is possible that the eight foot probe was not evenly heated resulting in some spot in the probe having been heated above the sulfate disassociation temperature. This could introduce a source of error causing a high SO_3 reading.

Recommendations for plant operations

- Electrical sets should not trip in groups especially outlet fields.
- Correct the large temperature gradient at the precipitator inlet.
- Investigate innovative technology for reacting SO_3 ahead of the air heater or providing hotter gas above the cold section of the air heater.
- Minimize air leakage in air heater.

Recommendations for future testing

- Coal analysis should be held constant for each test day.
- Simultaneous sampling for SO_3 should be done at the air heater inlet and outlet plus a simultaneous isokinetic dust sample should be drawn at the air heater inlet.

DISCUSSION (Continued)

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