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High SO₂ Removal Efficiency Testing

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1.0

INTRODUCTION

This document provides a discussion of the technical progress on DOE/PETC project number DE-AC22-92PC91338, "High Efficiency SO₂ Removal Testing", for the time period 1 October through 31 December 1994. The project involves testing at six full-scale utility flue gas desulfurization (FGD) systems, to evaluate low-capital cost upgrades that may allow these systems to achieve up to 98% SO₂ removal efficiency. The upgrades to be evaluated primarily involve using additives in the FGD systems. The "base" project involved testing at the Tampa Electric Company Big Bend station. All five potential options to the base program have been exercised by DOE, involving testing at the Hoosier Energy Merom Station (Option I), the Southwestern Electric Power Company Pirkey Station (Option II), the PSI Energy Gibson Station (Option III), the Duquesne Light Elrama Station (Option IV), and the New York State Electric and Gas Corporation (NYSEG) Kintigh Station (Option V). By the beginning of the fourth quarter of 1994, testing had been completed for the base project and for all options.

The remainder of this document is divided into four sections. Section 2, Project Summary, provides a brief overview of the status of technical efforts on this project. Section 3, Results, summarizes the outcome from these technical efforts during the quarter. In Section 4, Plans for the Next Reporting Period, an overview is provided of the technical efforts that are anticipated for the first quarter of calendar year 1995. Section 5 contains a brief acknowledgment.

2.0 PROJECT SUMMARY

On the base program, testing was completed at the Tampa Electric Big Bend Station in November 1992. The upgrade option tested was DBA additive. Base project efforts during the fourth quarter of calendar year 1994 consisted only of project management activities.

For Option I, at the Hoosier Energy Merom Station, results from another program co-funded by the Electric Power Research Institute (EPRI) and the National Rural Electric Cooperative Association have been combined with results from DOE-funded testing. Three upgrade options have been tested: DBA additive, sodium formate additive, and high pH set point operation. All testing was completed by November 1992. There were no significant efforts for this option during the current quarter.

Option II involved testing at the Southwestern Electric Power Company Pirkey Station. Baseline testing was conducted in February of 1993. Both sodium formate and DBA additives were tested as potential upgrade options. Parametric testing was conducted with DBA additive in March 1993, and with sodium formate in April 1993. Based on results from these tests, DBA appeared to be the more attractive upgrade option for this site, and a DBA additive consumption test was conducted in May 1993. There were only reporting activities for this site during the current quarter.

On Option III, for testing at the PSI Energy Gibson Station, baseline testing was conducted in May of 1993. Parametric testing with sodium formate additive began in September 1993, and was completed with a sodium formate consumption test in early October 1993. A DBA additive performance and consumption test was conducted in late February through mid-March of 1994. Efforts for this site during the current quarter included only data reduction and reporting.

Option IV is for testing at the Duquesne Light Elrama Station. The FGD system employs magnesium-enhanced lime reagent and venturi absorber modules. Baseline testing was

completed in July 1993. An EPRI-funded model evaluation of potential upgrade options for this FGD system, along with a preliminary economic evaluation, determined that the most attractive upgrade options for this site were to increase thiosulfate ion concentrations in the FGD system liquor to lower oxidation percentages and increase liquid-phase sulfite alkalinity, and to increase the venturi absorber pressure drop to improve gas/liquid contacting. Parametric testing of these upgrade options was conducted in late March of 1994. As for Option III above, efforts during the current quarter included only data reduction and reporting. An overview of the results of recent economic evaluations for this site is provided in Section 3 of this report.

Option V is for testing at the NYSEG Kintigh Station. Baseline testing was conducted in July 1994. Parametric testing at this site was conducted in late August, and a sodium formate additive consumption test was conducted in September 1994. Results from this parametric and additive consumption testing are included in Section 3 of this Technical Progress Report. Also during the quarter, an FGDPRIISM calibration for the Kintigh FGD system was completed, and the economics of high-efficiency SO₂ removal operation were evaluated. Results of the modeling and economic evaluation for this site will be included with the next quarterly Technical Progress Report, after NYSEG has had an opportunity to review those results.

3.0 RESULTS

Results from the base program (at the Tampa Electric Big Bend Station) and the first optional site (Hoosier Energy Merom Station) were presented in detail in the April 1993 quarterly Technical Progress Report. Updates were included in the July 1993 and October 1993 reports. For the second optional site (the Southwestern Electric Power Company Pirkey Station), results were presented in the July 1993 quarterly Technical Progress Report and updated in the October 1993 report. There are no plans to discuss these three sites any further in this or future quarterly reports.

For the third optional site (the PSI Energy Gibson Station), baseline testing was conducted in May 1993, and those results were presented in the July 1993 quarterly report. Parametric testing at this site was completed in early October of 1993, and these results were discussed in the January 1994 Technical Progress Report. A DBA performance and consumption test was conducted in February and March of 1994. Preliminary results from this test were discussed in the April 1994 Technical Progress Report. An update of the results from this site will be presented when the revised draft Technical Note for this site is submitted, in the first quarter of calendar year 1995.

Baseline testing at the fourth optional site (Duquesne Light's Elrama Station) was completed in July 1993. Those results were discussed in the October 1993 quarterly report. The results of EPRI-funded FGDPRISM modeling and preliminary economic evaluations of potential upgrades for this FGD system were discussed in the January 1994 Technical Progress Report. In March of 1994, parametric testing of the most promising upgrade options was conducted. The preliminary results of these tests were discussed in the April 1994 Technical Progress Report. A draft of the Technical Note for this site was submitted to DOE on January 4, 1995. An overview of the new results presented in this draft technical note is included below.

For the fifth optional site (the New York State Electric and Gas Corporation's Kintigh Station), baseline, parametric, and additive consumption efforts were completed during

the third quarter of 1994. Results from the baseline testing at this site, which was conducted in July 1994, were discussed in the Technical Progress Report for the third quarter of calendar year 1994. This report was dated December 1994. The parametric and additive consumption tests at this site were also completed late in the third quarter. At the time the Technical Progress Report for the third quarter of 1994 was prepared, these parametric and additive consumption test results had not been adequately reviewed by the host utility, so these results were not included in that report. Instead, they are discussed below.

Late in the fourth quarter, FGDPRISM modeling of the Kintigh FGD system was completed, as were the economic evaluations of potential upgrade options for this site. These results will be included in the next quarterly Technical Progress Report, after NYSEG has had an opportunity to review and comment on those draft results.

3.1 Results of Economic Evaluations of FGD System Upgrades at Duquesne Light's Elrama Station

3.1.1 Overview of the Approach for this Site

The first step in identifying low-cost upgrades for the Elrama FGD system was to measure the performance of the magnesium-lime reagent venturi scrubbers as they were operating at the start of the program. This information was collected through a series of baseline tests. These tests provided a benchmark against which later improvements could be measured, and also provided the information needed for modeling scrubber performance with EPRI's FGDPRISM model. The model was calibrated to the Elrama scrubber performance using data collected from the baseline tests, then used to make predictions of how the scrubber would perform with a variety of different potential upgrade options. Once the modeling of the candidate upgrade options was complete, a cursory economic evaluation of each option was performed. The options that appeared most promising based on the cursory economic evaluation were selected for further testing during the next series of tests, called parametric tests. The parametric tests were performed to evaluate at full scale the effectiveness of selected upgrade options. These full-scale

results were then used to conduct a second round of economic evaluations which were based on measured rather than modeled performance.

The results of the baseline tests, FGDPRISM modeling, cursory economics, and parametric tests have been reported in previous Technical Progress Reports, as described in the introduction to this section. The following provides a discussion of the second round of upgrade economic evaluations, which were based on full-scale test results.

3.1.2 Economic Evaluation Results

The primary options selected for testing during the parametric tests were operating at elevated thiosulfate concentrations and at increased venturi pressure drop. During the parametric testing, thiosulfate concentrations ranged from the normal level of 170 ppm as sodium thiosulfate, as measured during the baseline test series, to as high as 2800 ppm. Tests were performed at two venturi throat pressure drops: the normal value of 10 inwc and an elevated value of 12 inwc, and at two pH values: the normal value of 7.2 and a lower value of 6.5.

With elevated thiosulfate levels, improved SO₂ removals were obtained for three of the scenarios: pH 6.5 and 12 inwc venturi pressure drop, pH 7.2 and 10 inwc venturi pressure drop, and pH 7.2 and 12 inwc venturi pressure drop, as summarized in Table 1. The highest SO₂ removal efficiencies were measured at the pH 7.2 and 12 inwc venturi pressure drop conditions; an SO₂ removal of 93.2% was obtained when the thiosulfate concentration was increased to 2700 ppm during parametric Test 16.

The costs associated with operating at each test condition are also summarized in Table 1. At the highest SO₂ removal conditions of pH 7.2 and 12 inwc venturi pressure drop, the costs were estimated to range from \$105 to \$149/additional ton of SO₂ removed, depending on the thiosulfate concentration. Assuming an SO₂ credit value of \$150/ton, the overall net value of operating at the elevated venturi pressure drop ranges from \$3,000 per year to \$65,000 per year, depending on the thiosulfate concentration. The costs or savings associated with improved SO₂ removal are compared to the base case parametric test, where 89.1% SO₂ removal efficiency was

Table 1

Economic Evaluation of Options to Increase SO₂ Removal Efficiency

	Measured SO ₂ Removal %	Net Increase in SO ₂ Removal ton/hour	Thiosulfate Concen- tration ppm	Sulfur Consump- tion lb/hour	Lime Utiliza- tion %	Waste Solids wt%	Net Sulfur Cost \$1000/ year	Net Lime Cost \$1000/ year	Net Waste Dispos- al Cost \$1000/ year	Total Cost \$/ton SO ₂	Net Annual Value @ \$0/ton \$1000/ year	Net Annual Value @ \$150/ton \$1000/ year	Net Annual Value @ \$250/ton \$1000/ year
Base Case	89.10		170	10.0	89.30	40							
Case 1 - pH 7.2, 10 inwc													
Test 3	90.1	509	454	26.7	89.3	40	10	31	23	125		13	64
Test 7	91.1	993	1021	60.5	89.3	40	30	60	44	135		15	114
Test 11	91.5	1197	1579	93.7	89.3	40	50	72	53	147		4	124
Test 15	90.9	891	2705	160.0	89.3	40	89	54	40	205		(49)	40
Case 2 - pH 7.2, 12 inwc													
Test 2	92.0	1451	170	10.1	89.3	40	0	87	65	105		65	210
Test 4	92.2	1578	454	27.0	89.3	40	10	95	70	111		61	219
Test 8	92.5	1731	1021	60.9	89.3	40	30	104	77	122		48	221
Test 12	93.0	1986	1579	94.5	89.3	40	50	120	89	130		39	238
Test 16	93.2	2062	2705	161.9	89.3	40	90	124	92	149		3	209
Case 3 - pH 6.5, 12 inwc													
Test 6	87.3	(916)	437	25.4	96.5	40	9	(255)	(168)	453	-	277	186
Test 10	90.7	815	1135	67.1	96.5	40	34	(159)	(96)	(272)	222	344	426
Test 14	92.0	1477	1667	99.2	96.5	40	52	(122)	(68)	(94)	139	360	508
Test 18	91.8	1375	2836	168.6	96.5	40	93	(127)	(73)	(79)	109	315	452

achieved at a pH of 7.2, a venturi pressure drop of 10 inwc, and a thiosulfate concentration of 170 ppm.

The lowest cost operating scenario was for the pH 6.5, 12 inwc venturi pressure drop conditions. The test results showed that for these operating conditions, it is possible to improve the SO₂ removal efficiency while achieving an overall savings in operating costs, as shown by the results in Table 1 for parametric Tests 10, 14, and 18. The savings come from the improved lime utilization achieved at the lower operating pHs. Assuming an SO₂ credit value of \$150/ton, the overall value of operating at the pH 6.5, 12 inwc venturi pressure drop conditions (compared to the base case conditions) can be as much as \$360,000 per year, depending on the thiosulfate concentration.

3.1.3 Other Impacts of High-Efficiency Operation

The SO₂ removal measured at normal operation conditions during the baseline tests was 86.1%, while during the parametric tests the measured removal at similar conditions was 89.1%. This represents a substantial improvement in removal at what were meant to be identical operating conditions. Some of the improvement in removal can be explained by the fact that the dissolved sulfite concentrations were higher during the parametric tests than during the baseline tests. However, much of the improvement can only be explained by the fact that the tower used for the parametric tests appeared to be in better mechanical condition than the tower used during the baseline tests. "Better mechanical condition" includes items such as improved operation of the throat dampers, cleaner tower internals, etc. This measurable improvement in SO₂ removal efficiency highlights the benefits that could be achieved simply by improving the maintenance of the towers.

Many of the parametric tests were performed at venturi pressure drops of 12 inwc. The amount of improvement in SO₂ removal efficiency compared to operating at 10 inwc varies depending on operating conditions, but is typically on the order of two percentage points. In the economic evaluations described above, the most attractive options involve operating at a venturi

pressure drop of 12 inwc. During the parametric tests, operating at 12 inwc pressure drop required a substantial amount of operator effort, though - operators had to break the dampers free of scale and manually move them to the desired positions. However, with improved maintenance of the throat dampers, it should be possible to operate at 12 inwc pressure drop automatically. Improved SO₂ removal performance could then be achieved merely by resetting the automatic controls. The only costs (other than the costs to get the throat dampers working better) would be for the additional lime and waste disposal associated with removing larger quantities of SO₂. Fan power requirements did not increase at the higher venturi pressure drops, since the overall FGD system pressure drop is controlled with fan inlet dampers to provide a constant suction at the boiler exit.

Operating at higher thiosulfate concentrations should also lead to reduced scaling. The gypsum relative saturations (an important indicator of the scaling tendency) dropped to roughly half their original values at the elevated thiosulfate concentrations. Operating at higher thiosulfate concentrations could, therefore, lead to significant reductions in the amount of scale that forms in the towers.

The laboratory settling tests indicated that the settling rate of the scrubber solids improved at the higher thiosulfate concentrations. This suggests that the thickeners should be able to do a better job of concentrating the scrubber liquor solids. It is, therefore, possible that the moisture content of the waste solids could be reduced through operation at high thiosulfate concentrations. This could result in substantial savings in waste disposal costs. However, since the tests were all performed on a single tower, it was not possible to determine what effect would actually occur in the full-scale system. Full-scale testing at high thiosulfate concentrations would be required to determine if Elrama could realize cost savings associated with reduced waste solids moisture.

3.2 Parametric and Additive Consumption Testing at NYSEG's Kintigh Station

The paragraphs below summarize results of the parametric SO₂ removal tests and sodium formate consumption test performed at NYSEG's Kintigh Station FGD system. The objectives of the parametric tests were to characterize FGD system performance with sodium formate additive and to obtain additional process data suitable for calibrating EPRI's FGDPRISM model to the Kintigh FGD system. The objective of the consumption test was to measure the steady-state consumption of sodium formate additive under conditions required to obtain 95%+ SO₂ removal. The test approach and chronology are described in Section 3.2.1, and results are presented in Section 3.2.2.

3.2.1 Test Approach and Conditions

The NYSEG Kintigh Station is located in Niagara County near Barker, New York. Figure 1 is a simplified flow diagram for the Kintigh FGD system. Flue gas exits the boiler and passes through ESPs for particulate control. From the ESPs, flue gas goes through ID fans and then to the FGD system. At full load, four modules (with two additional spare modules) are required to treat flue gas from 685 MW of generating capacity.

The absorber modules are Peabody open spray towers. In this configuration, flue gas enters the bottom of the vessel and flows upward. A recirculating slurry is introduced countercurrent to the gas flow through up to five levels of spray headers. Each spray header level on the absorber has its own recycle pump. The combined L/G is about 116 gal/1000 acf, with all five headers in service and four modules in service at the full-load flue gas flow rate. Only four headers each in four operating modules are typically required to achieve SO₂ emissions compliance (0.6 lb SO₂/million Btu), which is equivalent to about 85% overall SO₂ removal.

After leaving the spray section, the flue gas flows past a sieve tray to a vertical gas flow mist eliminator. From the mist eliminator, flue gas exits the absorber. The absorber exit gas then flows to the stack. The FGD system is equipped with an absorber bypass duct, but typically

Figure 1. Flow Diagram of New York State Electric and Gas Kintigh Station's FGD System

nearly all of the flue gas exiting the boiler is treated in the absorbers and the stack operates in a "wet" mode. Some flue gas bypass is used to prevent excess condensate in the absorber outlet plenum.

The reagent used in the FGD system is a slurry of finely ground limestone. The limestone is ground in ball mills, and the prepared slurry is stored in slurry feed tanks, from which it is added to the absorbers at a rate to maintain the recirculating slurry pH set point. Elemental sulfur emulsion is added to the slurry feed tank to produce thiosulfate ion in the absorber reaction tanks, to serve as an oxidation inhibitor.

The recirculating slurry falls from the absorber into a secondary reaction tank external to the tower. In the secondary reaction tank, fresh limestone slurry is added to control the recirculating slurry pH set point. Slurry from the secondary reaction tank then flows by gravity to the primary reaction tank, which is integral to the bottom of the absorber. The slurry recirculation pumps draw suction from the primary reaction tanks.

Slurry from the primary reaction tank is also recirculated to hydroclones. A portion of the low solids content overflow from the hydroclones is used to wash the underside of the sieve tray below the mist eliminators. The remainder is routed to a baffled section in the primary reaction tank in the base of the absorber, from which it overflows to a waste sump along with a portion of the slurry from the primary reaction tank. The high-solids-content underflow from the hydroclones falls into the external, secondary reaction tank.

Waste slurry is bled from the primary reaction tank of each absorber to a waste slurry sump, where it is combined with the excess hydroclone overflow, a small bleed stream from the secondary reaction tanks, and some recycled thickener overflow. This mixed waste stream is fed to one of two thickeners. Liquor overflow from the thickeners flows to a supernate tank, and the underflow is fed to vacuum filters. The filtrate from the vacuum filters is returned to the thickeners. Supernate is returned to the absorber by being used in the limestone grinding circuit

and by makeup to the secondary reaction tanks. The primary makeup of fresh water to the FGD system is via the mist eliminator wash and pump seals.

The dewatered FGD sludge is blended with lime and fly ash from the ESPs for stabilization before being landfilled on the site. The solids content of the dewatered FGD sludge is approximately 65 wt%.

The parametric tests, like the baseline tests, were conducted on a single module (Module E) of the FGD system. The four operating modules receive flue gas from a common plenum so that the flow to the test module could not be independently controlled. During the parametric tests, the unit load varied significantly. To the extent possible, NYSEG operators varied the number of operating modules and manually adjusted the inlet control dampers to the other modules to maintain a full-load equivalent flue gas velocity in the test module.

The parametric tests included three two-day tests, during which the solids composition in the test module reaction tank was expected to approach steady state, and seven shorter tests for which SO₂ removal efficiency was the primary performance indicator. Prior to each test, the formate concentration in the test module was measured by buffer capacity titration and adjusted to the desired test level. During a typical test, one or more outlet flue gas SO₂ and velocity traverses were done while slurry and filtered slurry samples were obtained. During the two-day tests, slurry settling tests were also done. Process data were either logged automatically by the plant data acquisition system or recorded from local indicators as required.

The parametric test sequence is summarized in Table 2. The test series began on August 22 with a two-day test at normal operating conditions (four modules on line, pH set point at 5.6, and four spray pumps operating per module) but with nominally 500 ppm formate additive in the test module. The actual formate concentration determined by buffer capacity titration ranged from 435 to 530 ppm during this test.

Table 2
Planned Parametric Test Conditions at Kintigh Station

Date	Test	Objective	Nominal pH	No. of Pumps	Nominal Formate conc. mg/L	Nominal Flue Gas Velocity (ft/s)
8/22 8/23	1	Characterize performance with 500 ppm formate at normal pH set point	5.6	4	500	9
8/24 8/25	2	Characterize performance with 1000 ppm formate at normal pH set point	5.6	4	1000	9
8/25 8/25	3 4	Characterize performance versus L/G with normal pH and mid-level formate	5.6	5 3	1000	9
8/26 8/26	5 6	Characterize performance versus L/G with "high" pH and mid-level formate	5.8	5 3	1000	9
8/26 8/26	7 8	Characterize performance versus L/G with "low" pH and mid-level formate	5.2	3 5	1000 1000	9
8/27 8/29	9	Characterize performance with 1500 ppm formate at normal pH set point	5.6	4	1500	9
8/30	10	Determine mass transfer limitations	5.6	4	3800	9

Early during the first test day, the SO₂ concentration in the module inlet duct was measured to evaluate the accuracy of the on-line monitor. These results were in very good agreement. Therefore, only the outlet duct was sampled during the remaining tests. One SO₂ and velocity traverse of the Module E outlet duct was completed at Test 1 conditions at the end of the first day, and six more traverses were completed during the second day of this test. The flue gas was also sampled for formic acid under Test 1 conditions. Slurry samples were collected according to the sampling plan, and three settling tests were done.

Test 2, which was also a two-day test, was completed during the third and fourth test days (8/24-25). For this test, the pH set point and number of operating pumps remained at 5.6 and four, respectively, and the formate additive concentration was increased to a nominal level of 1000 ppm. The actual formate concentration ranged from 700 to 1040 ppm during this test. Four SO₂ and velocity traverses were completed on the first day of Test 2, and two more were completed during the morning of the second day. Three flue gas samples for formic acid were also obtained. Slurry samples were again obtained concurrently with the outlet flue gas traverses and three settling tests were done during the second day of Test 2.

Tests 3 and 4, which were conducted at the same nominal formate concentration (1000 ppm) and operating pH (5.6), were completed during the afternoon of the fourth test day (8/25) by varying the number of operating pumps (five pumps for Test 3 and three pumps for Test 4). The pH set point was then adjusted overnight to obtain conditions for Tests 5 and 6 at pH 5.8.

Tests 5 (five pumps) and 6 (three pumps) at 1000 ppm formate and pH 5.8 were completed during the morning of the fifth test day (8/26). The pH set point was then lowered to 5.2, and Tests 7 (three pumps) and 8 (five pumps) were completed during the afternoon of the same day.

In addition to the SO₂ removal efficiency measurements in Tests 3 through 7, flue gas samples for formic acid concentration were also obtained so that the effects of slurry pH and L/G on formic acid vaporization could be evaluated.

The formate concentration in the test module reaction tank was increased to approximately 1500 ppm on Saturday, 8/27, and was maintained at that level over the weekend to establish steady-state conditions for Test 9. The pH set point and number of operating pumps were returned to normal levels (pH 5.6 and four pumps). Six SO₂ and velocity traverses were completed on 8/29 under Test 9 conditions, and three flue gas samples for formic acid were obtained. Three settling tests were also done during Test 9.

Test 10, the final parametric test, was conducted on Tuesday, 8/30, after the formate concentration in the test module reaction tank was increased to 3800 ppm. Two SO₂ and velocity traverses were completed, and two flue gas samples for formic acid were obtained.

The parametric tests were followed by a steady-state sodium formate consumption test. The objective of the consumption test was to measure the amount of sodium formate required to maintain high SO₂ removal efficiency with the entire FGD system. This test began on Tuesday, 9/6. Sodium formate was added to the reaction tanks of each of the four operating modules and to the B thickener to bring the entire system formate concentration to approximately 1000 ppm (as formate ion). Sodium formate was then added continuously to the waste slurry sump to maintain this system-wide concentration until the conclusion of the test on Monday, 9/12. The amount of formate added was carefully measured by gauging the tanker.

During the consumption test, slurry samples were obtained from the major system vessels to monitor the formate concentration. Formate was measured on site by buffer capacity titration. Samples were also obtained for off-site analysis by ion chromatography. Sufficient data were obtained to determine the formate consumption rate by material balance calculations.

For at least one hour during each day of the formate consumption test, the bypass damper was closed so that SO₂ removal efficiency could be determined using the inlet and stack continuous emissions monitors.

3.2.2 Test Results

SO₂ Removal Efficiency

Table 3 summarizes preliminary SO₂ removal results for the parametric tests. For each entry, the "Average Slurry pH" is that measured by the Radian engineer with a calibrated portable meter. The "Absorber Flue Gas Velocity" was calculated from the outlet duct pitot traverse, adjusted to the scrubber cross sectional area. The "Slurry Flow" is based on intermittent slurry flow rate measurements by the Radian engineer and the number of pumps operating during the test. "L/G" is the actual liquid-to-gas ratio for the test module calculated from measured slurry and flue gas flow rates. The "On-site Formate Concentration" was determined by buffer capacity titration, while the "Off-site Formate Concentration" was determined by ion chromatography.

The "On-line Inlet SO₂" column is the average of readings recorded every five minutes during outlet flue gas traverses. The "Outlet SO₂ On-site" represents the calculated concentration based on titration of the peroxide impinger from the Method 6 sample train. The "Outlet SO₂ Off-site" represents calculated concentrations based on the results of ion chromatograph analyses of both Method 6 impingers for sulfate concentration. SO₂ removal efficiency is calculated from the On-line Inlet SO₂ and Outlet SO₂ Off-site values. The number of transfer units ("NTU" in the table), which is an alternate method for expressing mass transfer performance, is calculated as $\ln (SO_{2in}/SO_{2out})$.

Although not reported in Table 3, three inlet SO₂ determinations were done by Method 6 traverse prior to Test 1. The Method 6 flue gas traverses averaged about 2% lower than the on-line analyzer. This is considered very good agreement.

Seven outlet traverses were completed during Test 1. For this test at normal operating conditions (four towers, four pumps, pH = 5.6), plus about 500 ppm formate additive,

Table 3
Actual Parametric Test Conditions and Results

Test	Run	Date	Time	Average Slurry pH	Absorber Flue Gas Velocity (ft/sec)	Operating Recycle Pumps	Slurry Flow (gpm)	L/G (gal/kacf)	On-site Formate (mg/L)	Off-site Formate (mg/L)	On-line Inlet SO ₂ (ppm)	Outlet SO ₂ (ppm) On-site	Outlet SO ₂ (ppm) Off-site	Overall Removal Efficiency	NTU
1	1	8/22/94	1640-1720	5.60	6.7	1,2,3,4	41600	113	530	-	1941	65	72	96.3	3.30
1	2	8/23/94	0950-1019	5.74	7.4	1,2,3,4	41600	102	530	570	1430	29	37	97.4	3.66
1	3	8/23/94	1150-1218	5.60	7.9	1,2,3,4	41600	96	450	570	1361	39	63	95.4	3.08
1	4	8/23/94	1351-1418	5.58	8.8	1,2,3,4	41600	86	450	510	1531	51	52	96.6	3.39
1	5	8/23/94	1451-1521	5.60	8.8	1,2,3,4	41600	86	450	510	1553	52	58	96.3	3.29
1	6	8/23/94	1555-1622	5.63	6.3	1,2,3,4	41600	121	435	520	1603	28	31	98.1	3.96
1	7	8/23/94	1647-1714	5.63	6.1	1,2,3,4	41600	124	435	520	1567	37	41	97.4	3.65
2	1	8/24/94	0938-1005	5.60	9.0	1,2,3,4	41600	84	800	880	1272	25	25	98.1	3.95
2	2	8/24/94	1026-1053	5.63	9.3	1,2,3,4	41600	82	700	880	1284	26	26	97.9	3.88
2	3	8/24/94	1445-1512	5.67	8.6	1,2,3,4	41600	88	1000	1080	1451	24	25	98.3	4.08
2	4	8/24/94	1535-1602	5.68	8.0	1,2,3,4	41600	95	1040	1080	1381	21	23	98.3	4.08
2	5	8/25/94	0911-0939	5.67	8.6	1,2,3,4	41600	87	970	1060	1328	23	25	98.1	3.98
2	6	8/25/94	1005-1032	5.64	8.7	1,2,3,4	41600	86	970	1060	1340	25	26	98.0	3.93
3	1	8/25/94	1253-1321	5.61	7.6	1,2,3,4,5	51900	123	990	1070	1809	19	19	99.0	4.57
3	2	8/25/94	1347-1415	5.64	7.2	1,2,3,4,5	51900	130	990	1070	1789	17	16	99.1	4.72
4	1	8/25/94	1522-1539	5.59	8.0	2,3,4	31900	72	990	1090	1729	57	58	96.7	3.40
4	2	8/25/94	1610-1637	5.58	8.1	2,3,4	31900	71	990	1090	1738	61	63	96.4	3.32
5	1	8/26/94	0818-0910	5.78	6.1	1,2,3,4,5	51900	154	950	1005	1587	11	11	99.3	5.01
5	2	8/26/94	0929-1021	5.85	6.0	1,2,3,4,5	51900	156	950	1005	1654	14	14	99.2	4.80
6	1	8/26/94	1045-1113	5.87	7.7	2,3,4	31900	74	990	1010	1765	49	49	97.2	3.57
6	2	8/26/94	1133-1200	5.88	8.4	2,3,4	31900	68	990	1010	1844	45	45	97.6	3.72

Table 3
(Continued)

Test	Run	Date	Time	Average Slurry pH	Absorber Flue Gas Velocity (ft/sec)	Operating Recycle Pumps	Slurry Flow (gpm)	L/G (gal/kacf)	On-site Formate (mg/L)	Off-site Formate (mg/L)	On-line Inlet SO ₂ (ppm)	Outlet SO ₂ (ppm) On-site	Outlet SO ₂ (ppm) Off-site	Overall Removal Efficiency	NTU
7	1	8/26/94	1436-1505	5.14	8.1	2,3,4	31900	71	1000	1110	1877	151	152	91.9	2.52
7	2	8/26/94	1524-1551	5.17	8.6	2,3,4	31900	67	1000	1110	1867	137	139	92.6	2.60
8	1	8/26/94	1632-1700	5.20	8.5	1,2,3,4,5	51900	110	1000	1120	1878	65	65	96.6	3.37
8	2	8/26/94	1718-1745	5.20	8.2	1,2,3,4,5	51900	114	1000	1120	1868	66	66	96.4	3.34
9	1	8/29/94	0904-0954	5.52	7.5	1,2,3,4	41600	100	1450	1520	1677	25	26	98.4	4.16
9	2	8/29/94	1016-1107	5.56	7.6	1,2,3,4	41600	98	1450	1520	1755	24	24	98.6	4.28
9	3	8/29/94	1130-1157	5.58	8.0	1,2,3,4	41600	94	1450	1510	1851	29	31	98.3	4.08
9	4	8/29/94	1219-1246	5.56	7.9	1,2,3,4	41600	95	1450	1510	1827	29	31	98.3	4.08
9	5	8/29/94	1517-1544	5.62	8.1	1,2,3,4	41600	92	1450	1520	1713	27	29	98.3	4.09
9	6	8/29/94	1604-1631	5.62	8.9	1,2,3,4	41600	84	1450	1520	1687	26	28	98.4	4.11
10	1	8/30/94	0948-1108	5.67	8.6	1,2,3,4	41600	87	3750	3810	1508	8	9	99.4	5.10
10	2	8/30/94	1133-1251	5.68	8.6	1,2,3,4	41600	87	3800	3810	1540	10	10	99.4	5.05

the SO₂ removal efficiency averaged about 97%. The results in the table show how the inlet SO₂ concentration and flue gas velocity both varied substantially during this test.

Test 2 was completed at the same operating pH and number of pumps after the formate concentration was increased to a nominal level of 1000 ppm. Operation at Test 2 conditions increased SO₂ removal to an average of 98%. This was within the range of removals seen during Test 1, but the flue gas velocities were generally higher in Test 2.

For Tests 3 and 4, the pH set point and formate concentration remained the same as for Test 2, but the number of operating pumps was changed. In Test 3, with five pumps operating, SO₂ removal efficiency increased to 99%. In Test 4, with three pumps operating, SO₂ removal decreased to 96.6%.

For Tests 5 and 6, the pH set point was increased to 5.8, and the formate concentration was maintained at about 1000 ppm. At the higher pH set point, the SO₂ removal efficiency ranged from 97.4% with three pumps operating to 99.2% with five operating.

For Tests 7 and 8, the pH set point was decreased to 5.2, and the formate concentration was maintained at about 1000 ppm. At this pH, the SO₂ removal efficiency was 92.3% with three pumps and 96.5% with five pumps operating.

In Test 9, the pH set point and number of operating pumps were returned to normal (5.6 and four, respectively), and the formate concentration was increased to about 1500 ppm. The six outlet traverses showed an average SO₂ removal efficiency of about 98.2% for this test.

For the final test, the formate concentration was increased to 3800 ppm in the test module reaction tank. With the pH set point at 5.6 and four pumps operating, SO₂ removal increased to 99.4%

Data Correlation

During the previous baseline tests, the unit load and test module flue gas velocity were relatively constant except during Test 8, when a fifth module was brought on line to deliberately reduce the flue gas velocity in the test module. During the parametric tests, however, the flue gas velocity varied significantly within each test because of unpredictable swings in unit load. For the baseline tests, reported previously, results were adjusted for flue gas velocity by assuming (based on mass transfer theory) that NTU was inversely proportional to flue gas velocity. For this assumption to be valid, the product of the total droplet surface area and overall mass transfer coefficient in the absorber must be independent of gas velocity. For the parametric tests, the velocity varied enough to check this assumption.

SO₂ removal efficiency at otherwise constant conditions is also affected by inlet SO₂ concentration. The absorber inlet SO₂ concentrations varied significantly during the parametric tests as well. A non-linear least squares curve fit routine was used with all of the baseline and parametric data to determine the relationship between NTU and these two variables for the test absorber. It was determined that NTU varied with $G^{-0.3}$, and with inlet SO₂^{-0.25}.

In Figure 2, the NTU data from Table 2 have been plotted after adjusting for the effect of inlet SO₂ concentration and gas velocity. All of the data are adjusted to the same basis of 1600 ppm inlet SO₂ (dry basis) and to a gas velocity of 9 ft/s. The figure shows the effect of formate concentration on adjusted NTU for tests at pH 5.6 with three, four, and five pumps operating. As seen in previous tests with organic acid additives at other FGD systems, most of the relative increase in mass transfer is obtained over the range from 0 to 1000 ppm formate.

Figure 2 also illustrates the relationship between NTU and recycle slurry spray rate. Comparing the three-pump and five-pump data, NTU is seen to be less than proportional to the slurry spray rate, which indicates that droplet surface area does not increase proportionately with increasing spray rate. At Kintigh, NTU was found to be proportional to $L^{0.65}$. Results from some of the other absorber types evaluated in this project showed that NTU was directly

Figure 2. Adjusted NTU vs. Formate Concentration for Tests at pH = 5.6

proportional to L. Apparently, droplet agglomeration or other effects in the Kintigh spray tower reduce the effectiveness of increasing slurry spray rate.

Figure 3 shows the effect of slurry pH on NTU for tests with 1000 ppm formate and three or five pumps operating.

Limestone Utilization

Limestone utilization for each test was calculated from slurry solids analyses. Limestone utilization results for the baseline tests, and the long-term formate consumption test are shown in Figure 4, plotted as a function of recirculating slurry pH. The results from the long-term test indicate that the sodium formate additive had no significant effect on the relationship between limestone utilization and recirculating slurry pH. The parametric test results are not plotted in Figure 4 because sampling problems appeared to invalidate the limestone utilization values measured.

Sulfite Oxidation and Gypsum Relative Saturation

As described above, Kintigh Station adds emulsified sulfur to the reagent feed tank to produce thiosulfate ion, which serves as an oxidation inhibitor. During the baseline test series, recirculating slurry solid-phase analyses indicated that sulfite oxidation percentages were very low, averaging about 3.8% with liquid-phase thiosulfate concentrations averaging about 250 mg/L. This oxidation percentage is well below the threshold of 15%, above which gypsum scaling may begin to occur. Correspondingly, the gypsum relative saturation levels in the recirculating slurry liquor were very low, averaging 0.08.

During the sodium formate parametric tests, the sulfite oxidation percentages averaged slightly higher, at 4.7% in spite of a slightly higher average thiosulfate concentration of 320 mg/L. Correspondingly, the liquor gypsum relative saturation levels were slightly higher, averaging 0.15. However, this is still well below the level where gypsum scaling could begin to

Figure 3. Adjusted NTU vs. pH for Tests with 1000 ppm Formate

occur. The reason for this observed increase in sulfite oxidation percentage and in gypsum relative saturation levels appears to be that unit loads were lower during the parametric tests than during the baseline tests. The resulting higher flue gas oxygen levels tend to promote sulfite oxidation.

In contrast, during the sodium formate consumption test, unit loads were higher, averaging about the same as during the baseline tests. The sulfite oxidation percentages measured during the consumption test averaged 2.5%, although at a higher average thiosulfate concentration of 750 mg/L. The gypsum relative saturation levels measured were also quite low, averaging 0.05. This decrease in gypsum relative saturation is consistent with the lower oxidation percentages measured during this test.

In summary, the oxidation percentages measured for solids samples from the test module's recirculating slurry during the sodium formate parametric and long-term consumption test do not indicate any impact of the sodium formate additive on sulfite oxidation. Similar, no apparent effect of sodium formate addition on recirculating slurry gypsum relative saturation levels was noted.

Settling Test Results

A total of eleven settling tests were conducted during the parametric tests: three during each of the two-day tests (Tests 1, 2, and 9) at increasing formate concentrations and two extra tests with 1000 ppm formate in the test module. Three additional settling tests were also conducted during the consumption test. The objective of the settling tests was to measure any potential changes in settling rate due to the formate additive.

The raw data have been used to calculate thickener unit areas ($\text{ft}^2/\text{ton}/\text{day}$) required to produce a 30 wt% underflow solids content. The parametric and formate consumption test results are summarized in Table 4 along with previous baseline test results. Also shown are average unit loads for a 48-hour period prior to each of the settling tests.

Table 4
Results of Settling Tests

Test No.	Condition	Date	Settling Test Time	Prior 48-Hour Avg Load (MW)	Initial Solids Content (wt%) ^a	Unit Area (ft ² /ton/day)	Final Settled Solids Content (wt%)
B-1	Baseline pH 5.6	7/18/94	1530	NA	9.0	1.9	65
		7/19/94	0800	NA	9.7	2.3	60
		7/19/94	1340	564	11.2	1.9	61
		7/19/94	1435	573	10.6	2.2	64
P-1	500 mg/L formate pH 5.6	8/22/94	1200	651	10.9	2.9	54
		8/23/94	1200	600	9.3	4.4	51
		8/23/94	1310	598	9.3	4.8	49
P-2	1000 mg/L formate pH 5.6	8/25/94	0820	410	7.8	18	39
		8/25/94	1310	412	7.8	20	38
		8/25/94	1610	424	10.4	12	40
Extra	1000 mg/L formate, pH 5.8	8/26/94	1330	533	10.4	11	43
Extra	1000 mg/L formate, pH 5.6	8/27/94	0900	632	10.9	11	43
P-9	1500 mg/L formate pH 5.6	8/29/94	0730	638	9.0	3.9	52
		8/29/94	1125	631	8.9	3.3	49
		8/29/94	1620	624	9.0	2.7	55
C-1	1040 mg/L formate, pH 5.6	9/7/94	1405	NA	7.0	2.9	46
C-2	1180 mg/L formate pH 5.6	9/9/94	1325	664 ^b	11.3	1.9	56
C-3	1250 mg/L formate, pH 5.6	9/12/94	1140	647	10.1	2.0	50

^a Initial slurry solids content estimated from NYSEG slurry density data.

^b Thirty-hour average load prior to test.

NA = Data not yet available.

The baseline settling test samples had showed unit areas of 1.9 to 2.3 ft²/ton/day. The first settling test for the parametric test series was done at the start of Test 1, shortly after 500 ppm formate had been added to the test module. At that time, the solids in the reaction tank would not be representative of steady-state operation with formate. The results of this first test showed a unit area slightly higher than the baseline results, at 2.9 ft²/ton/day. Additional settling tests during the second day of parametric Test 1 showed a further increase in unit area (decrease in settling rate) to 4.4 and 4.8 ft²/ton/day.

The settling rate decreased markedly over the next few days, and the unit area increased into the range of 12 to 20 ft²-ton/day during parametric Test 2, with 1000 ppm formate in the test module reaction tank. Over the same time period, however, the Kintigh boiler was operated at a much lower load than usual, so that the observed increase in unit area may have been a result of increased sulfite oxidation percentages. The unit returned to sustained high-load operation over the weekend prior to Test 9, and the settling rate increased (unit area decreased) to approximately the same as at the beginning of the parametric tests, and nearly as low as those during the baseline tests. Therefore, it is unlikely that formate alone affected the settling rate to any great extent.

Settling tests done during the consumption test yielded unit areas slightly lower than baseline results. The unit operated at sustained high load throughout the consumption test. These consumption test results, along with the results for parametric Test 9, suggest that sodium formate addition had no measurable effect on solids settling rates.

Recycle Pump Flow Measurements

Recycle pump flow measurements were repeated during the parametric tests using an ultrasonic Doppler flow meter. There was no significant difference in flow rates compared to those reported for the baseline tests. The additional flow measurements are shown in Table 5 along with the previous measurements.

Table 5
Results of Recycle Pump Flow Measurements

Pump No.	Individual Flow Measurements						Average Flow	Average Amps	Average Discharge Pressure (psig)
	7/18	7/19	7/20	7/21	8/23	8/25			
1	9850	9700	9650	9700	10000	9500	9700	45	NA
2	10600	10500	10600	10500	10500	10500	10500	42	36
3	11650	12000	11300	11400	10950	10950	11400	44	34
4	-	-	10500	10000	9800	9750	10000	44	38
5	10250	10200	10400	10350	-	10250	10300	42	37

Sodium Formate Consumption Test Results

During each day of the consumption test, formate concentrations were measured in each of the major system vessels. For tanks that operate with variable levels, the level of each tank was also measured. The formate inventory in each system vessel could then be calculated from these two values. The formate content of the solids in each vessel was not measured, but was estimated based on a correlation developed using EPRI ECTC data. The amount of formate in the solid phase is much less than that in the liquid phase, so that the accuracy of this estimate does not strongly affect the calculated consumption rate.

The actual liquid formate concentrations were measured each day for the reaction tanks, limestone slurry tanks, thickeners, and filtrate. The concentrations in the underflow storage tanks and supernate tank were assumed to be the same as that in the filtrate.

Also measured each day was the amount of 40% sodium formate solution in the tanker trailer which was used for on-site storage of the additive and the calculated amount added since the previous test day. These amounts were determined by gauging the tanker.

The amount of formate leaving the system with the filter cake was another input to the balance. The amount of filter cake produced since the last inventory was provided by NYSEG from weigh belt readings. The solids content of the filter cake was estimated. The formate concentration in the filter cake liquid was assumed to be the same as that of the filtrate, which was measured.

Finally, the total tons of SO_2 removed each day was estimated using the average unit load, unit heat rate, and inlet and outlet CEM data in lbs of SO_2 per million Btu heat input.

From these input values, the calculated "nonsolution loss" rate, or NSL, was determined as follows:

NSL (lb formate/ton SO₂ removed) =

(formate added-formate lost with filter cake-total formate inventory
change)/tons of SO₂ removed

A total of 13380 lbs of formate was added (20220 lb as sodium formate) to the system over a four-day period. The average formate concentration in the module reaction tanks was about 1080 mg/L. The total estimated formate ion inventory decreased by only 1420 lbs out of a total of about 40,000 lbs over this period. A total of 1700 lbs of formate, or about 11% of the total consumption of 14,800 lbs, was lost with the filter cake. By material balance, the total formate ion nonsolution loss was 13,100 lbs. The total SO₂ removal over the four-day period was 1346 tons, so that the average nonsolution loss rate was 13,100/1346 or 9.7 lbs formate/ton SO₂ removed (14.7 lbs sodium formate/ton SO₂ removed). The average solution loss was 1700/1346 or 1.3 lbs formate/ton SO₂ removed (2.0 lbs sodium formate/ton SO₂ removed). The resulting overall consumption rate was measured at 11 lb/ton, expressed as the weight of formate ion consumed (16.6 lbs sodium formate/ton of SO₂ removed).

Overall FGD system SO₂ removal efficiencies measured during the consumption test are summarized in Table 6. In order to measure overall SO₂ removal efficiency during the consumption test, it was necessary to close the system bypass damper so that the system efficiency could be calculated using the inlet and stack CEM data. The normal operating procedure at Kintigh includes sufficient flue gas bypass to maintain an outlet flue gas temperature of about 131°F so that excess condensation does not occur in the scrubber outlet plenum. The data in Table 6 represent average removal efficiencies for one-hour periods each day during which the bypass damper was closed.

With the bypass damper closed, the average SO₂ removal was nearly 97% with the unit operating at essentially full load. This was slightly lower than the value of 98% that was

Table 6
SO₂ Removal Efficiency During Consumption Test

Date	Time	Load (MW)	Average Formate Concentration (ppm)	SO₂ in (lb/10⁶ Btu)	SO₂ out (lb/10⁶ Btu)	SO₂ Removal (%)
9/8/94	1100	675	1100	4.43 ^a	0.14	96.7
9/9/94	1500	693	1120	2.88 ^a	0.08	97.2
9/10/94	1000	673	1190	4.35	0.15	96.6
9/11/94	1100	668	1110	4.51	0.17	96.2
Average	-	677	1130	-	-	96.7

^a Inlet SO₂ estimated due to CEM malfunction.

expected at these conditions based on the results of the parametric tests. However, performance differences between individual modules, or a small amount of undetected inlet flue gas leakage past the closed bypass damper could easily account for the overall efficiency being slightly lower than previously measured for Module E.

4.0

PLANS FOR THE NEXT REPORTING PERIOD

All of the testing planned for this project has been completed. Efforts during the first quarter of calendar year 1995 will only consist of data reduction and reporting. The base program (Tampa Electric Big Bend) and Options I and II (Hoosier Energy's Merom Station, SWEPCo's Pirkey, respectively) are in the final reporting phases. Draft Topical Reports for all three of these sites have previously been submitted. These drafts will be revised as needed after review comments are received from DOE and from the host utilities.

For the PSI Energy Gibson Station (Option III), a Technical Note summarizing results from the sodium formate parametric tests and additive consumption test was completed in early April 1994. Since a DBA additive performance and consumption test was completed during 1994 as well, results from the DBA tests have been incorporated into a revised Technical Note for this site, which should be distributed for review and comments in the first quarter of calendar year 1995.

Parametric testing of the most favorable upgrade options for the Duquesne Light Elrama site (Option IV) has been completed, as mentioned in the previous sections. A draft Technical Note which summarizes all test results, results of FGDPRIISM modeling, and results of economic evaluations of the upgrade options tested, was submitted to DOE and to Duquesne Light on January 4, 1995. A draft Topical Report for this site will be prepared later in the first quarter of 1995, after review comments are received on the draft Technical Note.

For Option V, testing at the New York State Electric and Gas Corporation's Kintigh Station, baseline, parametric, and sodium formate additive consumption testing were completed in third quarter. FGDPRIISM modeling of the FGD system and an economic evaluation of potential FGD system upgrade options were completed during the fourth quarter of calendar year 1994. A draft Technical Note summarizing these test results and the results of FGDPRIISM modeling and economic evaluations for this site should be submitted during in the first quarter of calendar year 1995.

Also during the quarter, two papers will be prepared for and presented at the upcoming EPRI-EPA-DOE 1995 SO₂ Control Symposium. The papers will present and discuss results from the Gibson and Kintigh sites, respectively.

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