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High SO_2 Removal Efficiency Testing

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[redacted] Topical Report
Results of Sodium Formate Additive Tests at New York State Electric & Gas Corporation's Kintigh Station

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SUMMARY

Tests were conducted at New York State Gas & Electric's (NYSEG's) Kintigh Station to evaluate options for achieving high sulfur dioxide (SO_2) removal efficiency in the wet limestone flue gas desulfurization (FGD) system. This test program was one of six conducted by the U.S. Department of Energy to evaluate low-capital-cost upgrades to existing FGD systems as a means for utilities to comply with the requirements of the 1990 Clean Air Act Amendments. The upgrade option tested at Kintigh was sodium formate additive.

Results from the tests were used to calibrate the Electric Power Research Institute's (EPRI) FGD PRocess Integration and Simulation Model (FGDPRISM) to the Kintigh scrubber configuration. FGDPRISM was then used to predict system performance for evaluating conditions other than those tested. An economic evaluation was then done to determine the cost effectiveness of various high-efficiency upgrade options. These costs can be compared with the estimated market value of SO_2 allowances or the expected costs of allowances generated by other means, such as fuel switching or new scrubbers, to arrive at the most cost-effective strategy for Clean Air Act compliance. Results from the test program at Kintigh are summarized below.

SO_2 Removal Performance. Baseline tests on one module of NYSEG's Kintigh Station wet limestone FGD system showed that the SO_2 removal efficiency at normal full-load operating conditions (pH 5.6, flue gas velocity = 9 ft/s, four recycle pumps operating) was about 86%. Tests with sodium formate additive showed that the SO_2 removal efficiency could be increased to as high as 99.4% with a formate ion concentration of 3800 mg/L in the recycle slurry. The sodium formate additive had no significant effect on process chemistry or on the dewatering properties of the calcium sulfite byproduct solids.

Sodium Formate Additive Consumption. In a long-term sodium formate consumption test with sodium formate added to the entire FGD system, an average additive

feed rate of 168 lb/hr (as sodium formate) was required to maintain an average concentration of 1080 mg/L formate ion in the recycle slurry at full-load operation. At this formate concentration, SO_2 removal efficiency averaged about 97%. The total sodium formate additive consumption rate was 16.6 lb/ton of SO_2 removed. Of the total formate consumed, 12% was lost with the filter cake liquid, about 32% was lost by precipitation with the filter cake solids, about 6% was lost by vaporization into the flue gas, and the remaining 50% was attributed (by difference) to oxidative degradation.

SO_2 Removal Upgrade Economics. The economics of sodium formate addition were evaluated based on a capital cost of $300,000 for a 100 lb/hr additive storage and delivery system, and using operating cost data provided by NYSEG. Using sodium formate additive at 1000 mg/L in the recycle slurry, more than 10,000 additional tons per year of SO_2 could be removed by the Kintigh FGD system at an average additional cost of only $76/ton. Depending on the assumed value of SO_2 allowances ($150 to $250/ton), the estimated net annual value of additional SO_2 removal at Kintigh ranged from $0.8 to $1.8 million.

Further analysis, based on performance predictions using FGDPRISM, suggested that sodium formate additive could be used to maintain the current 85% average SO_2 removal (with partial bypass) while operating fewer recycle pumps, resulting in a net annual savings of about $100,000. FGDPRISM also predicted that a significant performance improvement could be obtained by operating with a finer limestone grind. This might be done by operating the reagent preparation equipment at a lower throughput for two shifts per day instead of one shift per day. Some modifications to the ball mill classifier would also be required.

1.0 INTRODUCTION

This report describes the results of tests conducted at New York State Gas & Electric's (NYSEG's) Kintigh Station to evaluate options for upgrading the flue gas desulfurization (FGD) system's SO_2 removal efficiency using sodium formate additive. The objective of these tests was to obtain performance data needed to evaluate the cost effectiveness of upgrading an existing FGD system as part of a strategy for meeting requirements of the 1990 Clean Air Act Amendments.

1.1 Background

Provisions of the Clean Air Act Amendments of 1990 call for a ten-million ton per year reduction in U.S. SO_2 emissions (from a 1980 baseline) in two phases. Phase I calls for a five-million ton per year reduction by 1995, and the remainder of the reductions are to be completed by the year 2000 for Phase II. Affected utilities have a number of options for achieving these reductions, such as switching to lower sulfur-content coals, installing new FGD systems, and improving the SO_2 removal performance of existing FGD systems. Some utilities may employ a combination of these and other options as part of an overall compliance strategy.

The Flue Gas Cleanup (FGC) Program at the U.S. Department of Energy Pittsburgh Energy Technology Center (DOE PETC) helps to maintain and foster the widespread use of coal by developing technologies that will mitigate the environmental impacts of coal utilization. The program focuses on post-combustion technologies for the control of SO_2, oxides of nitrogen, particulate matter, and air toxics generated from coal combustion. A portion of the FGC Program, including this project, involves enhancing the SO_2 removal efficiencies of existing wet FGD systems. The results from this project will allow utilities to better consider enhanced performance of existing FGD systems as an option for achieving compliance with Phase I and/or Phase II of the Clean Air Act Amendments.

In this project, Radian Corporation is conducting tests at six full-scale FGD systems to evaluate options for achieving high SO_2 removal efficiencies (95 to 98% removal). Each system is being characterized under baseline operation and then with additives or with other modifications to enhance SO_2 removal performance.

The systems being evaluated are at Tampa Electric Company's Big Bend Station, Hoosier Energy's Merom Station, Southwestern Electric Power Company's Pirkey Station, PSI Energy's Gibson Station, Duquesne Light Company's Elrama Station, and the New York State Electric and Gas Corporation's (NYSEG) Kintigh Station. A wide variety of FGD system vendors and designs are represented in the program. Most of these systems were designed to achieve 85 to 90% SO_2 removal.

This Topical Report covers only results from the sixth site, at NYSEG's Kintigh Station. Separate Topical Reports have been issued for each of the other sites.

1.2 Project Description

Three types of performance tests were completed at Kintigh. First, "baseline" tests were done to obtain performance data without the sodium formate additive. Then, "parametric" tests were done to evaluate performance using the additive at various concentrations. The baseline and parametric tests were done using only one of the four operating absorber modules. Following the parametric tests, a steady-state sodium formate consumption test was done by adding sodium formate to the entire FGD system.

Under a separate project funded by the Electric Power Research Institute, their FGD PRocess Integration and Simulation Model (FGDPRISM) was calibrated to the Kintigh FGD system configuration. The calibrated FGDPRISM model was then used to predict system performance for evaluating conditions other than those tested.

Actual performance results, along with the steady-state sodium formate consumption data and pertinent cost information provided by NYSEG, were used as the basis for an economic evaluation. In this evaluation, the net cost of additional tons of SO_2 removal was estimated for different operating conditions and formate concentrations. These costs can be compared with the estimated market value of SO_2 allowances or the expected costs of allowances generated by other means, such as fuel switching or new scrubbers, to arrive at the most cost-effective strategy for Clean Air Act compliance.

1.3 Report Organization

The performance tests are described and results are presented in Section 2 of this topical report. The FGDPRISM calibration and performance predictions are discussed in Section 3, and the economic evaluation is addressed in Section 4. Detailed results and calculations are included as Appendices A through E.

2.0 TEST CONDITIONS AND RESULTS

This section describes the full-scale FGD system tests conducted at the NYSEG Kintigh Station and provides an overview of the results. The tests evaluated methods for achieving high SO_2 removal efficiency with the Kintigh FGD system and followed a methodology used for the other sites included in this DOE-PETC program.

This section presents and discusses results from each of these three phases of testing at Kintigh. In Section 2.1, the FGD system is briefly described. The test approach and measurement methods are outlined in Sections 2.2 and 2.3. Results of the short-term baseline and sodium formate parametric tests are presented in Sections 2.4 and 2.5. Results of the system-wide sodium formate consumption test are described in Section 2.6. Following this, the effects of sodium formate additive on FGD byproduct solids is discussed in Section 2.7, and other process measurements are summarized in Section 2.8.

2.1 FGD System Description

The NYSEG Kintigh Station is located in Niagara County near Barker, New York. Figure 2-1 is a simplified flow diagram for the Kintigh FGD system showing the arrangement of a single absorber module. Flue gas exits the boiler and passes through electrostatic precipitators (ESPs) for particulate control. From the ESPs, flue gas goes through three parallel ID fans and then to the FGD system. At full load, four modules are required to treat flue gas from 700 MW of generating capacity. There are two additional spare modules.

The absorber modules are Peabody open spray towers. In this configuration, flue gas enters the side of the vessel near the bottom and flows upward. A recirculating slurry is sprayed downward, 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 liquid-to-gas ratio (L/G) is about 116 gal/1000 acf, with all five headers in service on each of four operating modules at the full-load flue gas flow rate. However, only four headers per absorber module are

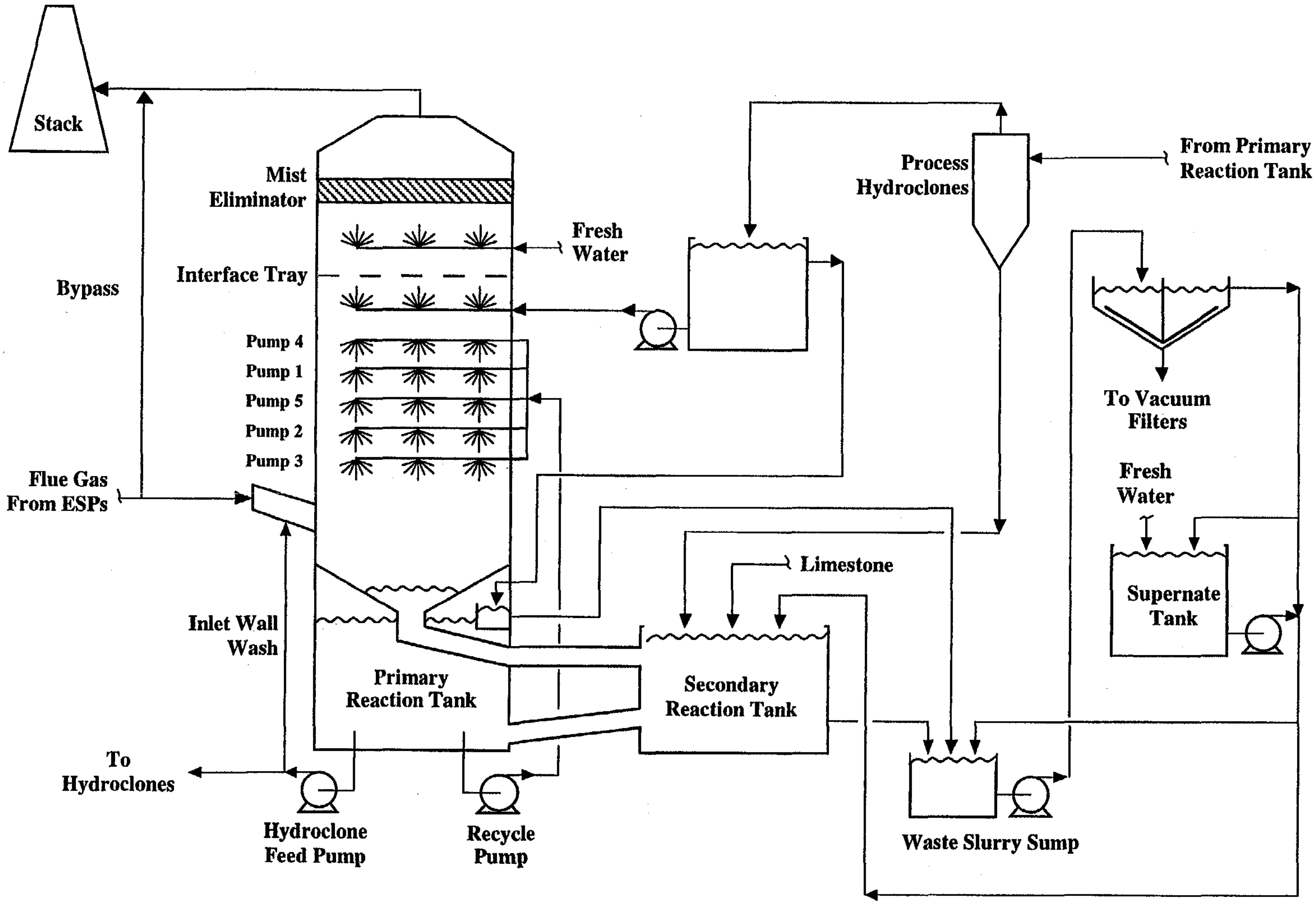

Figure 2-1. Flow Diagram of New York State Electric and Gas Kintigh Station's FGD System

typically required to achieve SO_2 emissions compliance (0.6 lb SO_2/million Btu), which is equivalent to about 85% overall SO_2 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 top of the absorber module. The combined absorber exit gases then flow to the stack through a common outlet duct. The FGD system is equipped with an absorber bypass duct. However, nearly all of the flue gas from the boiler is typically treated in the absorbers, and the stack operates in a "wet" mode. A small amount of flue gas is bypassed to prevent excess condensation in the absorber outlet plenum.

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

The recirculating slurry drains 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. 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 overflows from the primary reaction tank on each absorber to a waste slurry sump, where it is combined with a small bleed stream from the secondary reaction tanks and some recycled thickener overflow. This mixed waste stream is fed to two thickeners. Liquor overflow from the thickeners flows to a supernate tank, and the underflow is pumped to slurry storage tanks and then to vacuum filters. The filtrate from the vacuum filters is returned to the thickeners. Supernate is returned to the absorbers by being used in the limestone grinding circuit and by makeup to the secondary reaction tanks. The slurry density in the modules is controlled by adjusting the rate of supernate return. The primary makeup of fresh water to the FGD system is via the mist eliminator wash and pump seals. Additional makeup is added to the supernate tank to maintain system liquid level.

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 75 weight percent.

2.2 Test Approach

The baseline and parametric tests were conducted on a single module (Module E) of the FGD system. Module performance was measured by sampling the flue gas at the inlet and outlet. Slurry samples from the reaction tank were obtained concurrently with the flue gas samples. Sampling locations are indicated on Figure 2-1.

2.2.1 Baseline Tests

For the baseline tests, independent variables included primary reaction tank pH, liquid-to-gas ratio (L/G), which was varied by changing the number of recycle pumps in service, and flue gas velocity in the test module. The four operating modules receive flue gas from a common plenum so that the flue gas flow to the test module could not be independently controlled. During the baseline tests, a constant high load was maintained and the flue gas flow to the test module varied only slightly depending on the number of operating pumps. One baseline test was conducted with five operating modules to investigate the effect of changing flue gas velocity.

The baseline tests began with a two-day test at NYSEG's normal operating conditions. This test duration was sufficient to approach steady-state operating conditions with respect to solids properties in the test module. The performance measurements during the two-day test included SO_2 removal, limestone utilization, sulfite oxidation, solids dewatering properties, and relative saturations for precipitating and dissolving species.

The two-day test was followed by a series of half-day tests during which only SO_2 removal and limestone utilization were expected to represent steady-state conditions. During the half-day tests, the slurry pH set point and number of operating spray pumps were varied. During the final baseline test, the flue gas velocity in the test module was deliberately lowered by operating a spare module.

2.2.2 Parametric Tests

For the parametric tests, independent variables included reaction tank pH, number of recycle pumps in service, and sodium formate additive concentration. Flue gas velocity was not intentionally varied during the parametric tests, but the unit load varied substantially during this test series. The flow to the test module was controlled to the extent possible by varying the number of operating modules and by manually adjusting the module inlet dampers, but the flue gas velocity in the test module actually varied from 6.0 to 9.3 ft/s.

Three two-day tests (Tests 1, 2, and 9) were done at three increasing sodium formate levels so that the effect of sodium formate on steady-state performance could be measured. For these two-day tests, performance measurements included SO_2 removal, limestone utilization, sulfite oxidation, solids dewatering properties, and relative saturations of limited solubility species such as gypsum. A series of half-day tests (Tests 3 through 8) were completed at the mid-level formate concentration to investigate the effects of slurry pH and number of operating pumps on SO_2 removal. A final half-day test was done at a high sodium formate concentration to determine the maximum SO_2 removal capability of the test module.

For the parametric tests, sodium formate was fed continuously to the test module reaction tank to maintain the desired concentration during and between tests. The sodium formate concentration was measured prior to each test and adjusted if necessary by pumping additional sodium formate from the tanker into the reaction tank.

2.2.3 Sodium Formate Consumption Test

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 SO_2 removal efficiency with the entire FGD system. Sodium formate was added to the reaction tanks of each of the four operating modules and to the A and B thickeners to bring the entire system formate concentration to approximately 1000 mg/L (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 consumption test.

The sodium formate consumption rate was determined by liquid-phase material balance. The amount of formate added was carefully measured by gauging the tanker. The most straightforward and predictable loss of sodium formate from the system is with the liquor that remained adhered to the byproduct solids ("solution loss"). This loss rate was determined by measuring the filter cake moisture content and the formate concentration in that moisture, and by quantifying the filter cake production rate. The difference between the amount added and the amount lost with the filter cake, plus an "accumulation" term which accounts for changes in sodium formate concentrations in the system over the test duration, yielded the total amount of formate consumed by other mechanisms, including vaporization, precipitation, and oxidization. Formic acid vaporization was measured independently by flue gas analysis and formate precipitation was measured by analysis of the filter cake solids. Thus, the formate oxidation rate could be determined by difference.

For at least one hour during each day of the formate consumption test, the bypass damper was closed so that SO_2 removal efficiency could be determined using the inlet and stack continuous emissions monitors.

2.3 Test Measurements

2.3.1 Flue Gas Sampling

The primary performance measurements obtained at the site included inlet and outlet flue gas SO_2 concentrations and flue gas velocity for the test module. Inlet concentrations were determined using NYSEG's existing on-line certified SO_2 analyzer. The relative accuracy of this analyzer was verified by pre-test EPA Method 6 samples at the module inlet. Module outlet SO_2 concentrations were measured using a modified EPA Method 6 with a composite flue gas sample obtained by a 24-point isokinetic traverse of the module outlet duct. The total test module gas flow rate was measured during the same traverse. During some of the baseline tests, the outlet flue gas SO_2 concentrations were also measured at the individual traverse points using a portable flue gas analyzer.

During a typical half-day test, the performance of the test module was measured by completing duplicate flue gas SO_2 and velocity traverses at the module outlet, while inlet SO_2 concentrations were recorded at five-minute intervals and averaged over the duration of each outlet traverse. For tests with longer durations, the half-day gas sampling schedule was repeated, so that up to eight individual gas measurements were obtained during a two-day test.

Flue gas SO_2 concentrations were determined on site from the Method 6 samples using the barium perchlorate titration procedure. These on-site data were used to verify that test results were consistent and reasonable and to make testing decisions. The Method 6 impinger solutions were also analyzed off site by ion chromatography as a quality control check and to improve the accuracy of results for tests at very high SO_2 removal efficiency.

During selected parametric tests, the concentration of formic acid in the flue gas was also determined by drawing a measured amount of flue gas through an impinger train containing dilute sodium hydroxide. The amount of formic acid captured in the impinger solution was then determined by ion chromatography.

2.3.2 Slurry Sampling

During the baseline and parametric tests, slurry samples were obtained from the test module by sampling at the hydroclone feed location, which is the sampling point used by NYSEG for routine process monitoring. The slurry samples were timed to coincide with the Method 6 outlet flue gas traverses.

At the beginning of each set of duplicate outlet SO_2 traverses, the slurry pH was measured using a calibrated portable pH meter, and a slurry sample was obtained. In the time between each set of duplicate traverses, the pH was again measured, another slurry sample was obtained, and a set of diluted, stabilized filtered liquor samples was also obtained. At the conclusion of each set of duplicate flue gas SO_2 traverses, the pH was again measured and a final slurry sample was obtained.

During the second day of each two-day test, slurry samples were also obtained for dewatering tests. Settling rate tests were conducted on site with slurry samples at process temperature. Samples were also collected at the same time for off-site filter leaf tests.

During the formate consumption test, 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. Slurry and filtered liquor samples were also obtained from the operating modules during the consumption test to document any effects of sodium formate additive on the process chemistry during the week of operation in this mode.

2.3.3 Chemical Analyses of Slurry and Filtrate Samples

The number of solid and liquid chemical analyses made depended on the importance of the results to the performance evaluation and on the expected time constants for changes in concentrations of the various species.

All of the slurry samples were analyzed for weight percent solids content and solid-phase carbonate. These results were used to calculate limestone utilization, which is an important performance parameter. Limestone utilization can change relatively quickly with operating pH.

Complete solid-phase analyses including calcium, magnesium, sulfite, sulfate, and carbonate were done only for the slurry samples that were collected at the midpoint of each set of duplicate Method 6 traverses. The complete solid-phase analyses were used to calculate the sulfite oxidation fraction. This is also an important performance parameter, but the time constant for changes in slurry sulfite/sulfate content in the reaction tank is much longer than that for carbonate content. Therefore, it was not necessary to measure oxidation fraction as frequently as limestone utilization. The oxidation fraction is also not as sensitive to minor changes in operating pH as the limestone utilization.

Slurry solids samples from the two-day baseline test and from each of the two-day parametric tests were examined and photographed using scanning electron microscopy.

All of the filtered slurry liquid samples were analyzed for liquid-phase calcium, sulfite, sulfate, and carbonate. These results were used to estimate relative saturations for the precipitating and dissolving species. Relative saturations are important process chemistry indicators that can change relatively quickly with changes in operating conditions, especially pH. Only one liquid sample per day was analyzed for soluble species such as magnesium, sodium, chloride, and thiosulfate. The time constant for changes in soluble species concentrations is usually on the order of weeks. Therefore, these concentrations were not expected to vary significantly during a test day.

Filtered slurry liquid samples from the two-day baseline test and from each of the two-day parametric tests were analyzed for 32 elements using inductively-coupled plasma emissions spectroscopy (ICPES).

2.3.4 Other Process Data

Other process data including boiler load, ID fan motor current, recycle pump discharge pressures and motor current, FGD system temperatures and pressures, and stack CEM data were either logged automatically by the plant data acquisition system or recorded from local indicators as required. Flow rates of individual slurry recycle pumps on the test module were also measured using a portable ultrasonic flow meter.

2.4 SO_2 Removal Efficiency Test Conditions and Results

2.4.1 Baseline Test SO_2 Removal Efficiency

Table 2-1 summarizes the average test conditions and SO_2 removal efficiency results for the baseline tests. More detailed test data for the individual Method 6 traverses are included in Appendix A, Table A-1. In both tables, the "slurry pH" is that measured with a calibrated portable meter. In most cases (except Test 6), the portable meter agreed closely with the control room indicator. The "flue gas velocity" was calculated from the outlet duct pitot traverse, adjusted to the scrubber cross sectional area. The number of operating recycle pumps is shown for each test. Several slurry flow measurements were made for each recycle pump during the baseline test period. The "L/G" for each test was calculated using the average recycle pump flow rates and the average measured flue gas volume. The "inlet SO_2" for each test is the average of inlet CEM readings recorded every five minutes during the outlet flue gas traverses.

Table 2-1

Average Baseline Test Conditions and Results

				Liquid-to-Gas		
Test No.	Slurry pH	Flue Gas Velocity (ft/s)	No. of Pumps in Service	Ratio (gal/kacf)	Inlet SO_2 (ppm dry)	SO_2 Removal Efficiency (%)
1	5.63	9.0	4	86	1549	86.2
2	5.57	8.8	5	110	1526	92
3	5.59	9.8	3	61	1530	78.5
4	5.02	9.4	3	63	1804	68.5
5	5.18	8.7	5	110	1729	84.7
5A	4.94	9.4	4	82	1697	74
6	5.65*	9.3	3	63	1692	88.3
7	5.82	8.5	5	113	1708	96.1
8	5.6	6.3	5	154	1334	96.5

* This pH reading is questionable.

The baseline test series began 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). For this test at normal operating conditions, the SO_2 removal efficiency averaged about 86%.

For Tests 2 and 3, the pH set point remained at 5.6, and the number of operating pumps was varied (five pumps for Test 2 and three pumps for Test 3). The flue gas velocity changed slightly when the number of pumps was changed. Operation with five pumps increased SO_2 removal to an average of 92%, and operation with three pumps decreased removal to about 79%.

For Tests 4, 5, and 5A, the pH set point was lowered to 5.2, and the number of operating pumps was varied. At this low pH set point, the SO_2 removal efficiency averages ranged from about 68% with three pumps operating to 85% with five pumps operating.

The pH set point was increased to 5.8 for Tests 6 and 7. This was the highest pH that could be maintained by the limestone delivery system. Some difficulty in measuring the pH was encountered during Test 6. The portable meter was reading about 0.2 units lower than the on-line meter, even though they had agreed closely in all of the previous tests. At the high pH set point, the SO_2 removal efficiency ranged from 88% with three pumps operating to 96% with five pumps operating.

The final test, Test 8, was completed at the normal pH set point of 5.6, with five modules on line and five pumps operating to lower the gas velocity in the test module. This decreased the flue gas velocity from the normal 9 ft/s to only 6.2 ft/s. Under these conditions, the SO_2 removal efficiency increased to 96.5 % compared with 92% in Test 2 with five pumps operating at the normal flue gas velocity.

2.4.2 Baseline Test CEM Traverse Data

Figure 2-2 shows the results of the outlet duct traverses done with the portable SO_2 analyzer. The numbers inside the squares represent the measured SO_2 concentrations at the indicated positions in the duct. In this representation, the direction of flue gas flow is towards the reader. The numbers to the right of and below the squares are the average concentrations for the respective rows and columns.

Three tests were done to examine the distribution of SO_2 across the outlet duct. The first two were done at approximately the same gas velocity in the scrubber (4 Modules on line) but with different numbers of recycle pumps operating (3 and 5). The third test was done with lower gas velocity obtained by bringing a fifth module on line. The results show that there is some variation in SO_2 concentration across the outlet duct and presumably across the module. A comparison of the first two tests shows that the number of operating pumps did not have a strong effect on the SO_2 distribution across the duct. The lowest readings remained in the same relative position. The highest readings shifted from the top of the duct in the three-pump test to the bottom of the duct in the five-pump test, but these differences were not large.

The change in gas velocity had a more noticeable effect on SO_2 distribution across the duct. With the lower velocity, the lowest readings shifted to the top of the duct, and the average across the top of the duct was much lower than the average across the bottom of the duct. The averages down the right-hand side of the duct were also much lower than those down the left-hand side. Apparently, at low velocity, the inlet flue gas does not penetrate as well to the rear of the absorber module (across from the inlet).

2.4.3 Sodium Formate Parametric Test SO_2 Removal Efficiency

Table 2-2 summarizes the average test conditions and SO_2 removal efficiency results for the parametric tests with sodium formate additive. The format of this table is the same as Table 2-1, except that the measured concentrations of sodium formate (as formate ion) in the

Test 3
4 Modules, 3 Pumps, and pH 5.6

Top of Duct

275	265	205	235	245
272	230	159	215	219
255	160	98	160	168
220	136	43	170	142
210	194	170	185	190
217	226	220	216	220
240	202	149	197	

Test 5
4 Modules, 5 Pumps, and pH 5.2

Top of Duct

312	275	170	225	246
298	215	120	215	212
335	160	120	218	208
390	165	60	296	228
325	255	315	300	299
365	325	365	360	354
338	232	192	269	

Test 7A
5 Modules, 5 Pumps, and pH 5.8

Top of Duct

34	13	0	8	14
41	11	0	9	15
61	17	0	9	22
71	50	8	22	38
50	60	40	29	45
54	53	51	35	48
52	34	17	19	

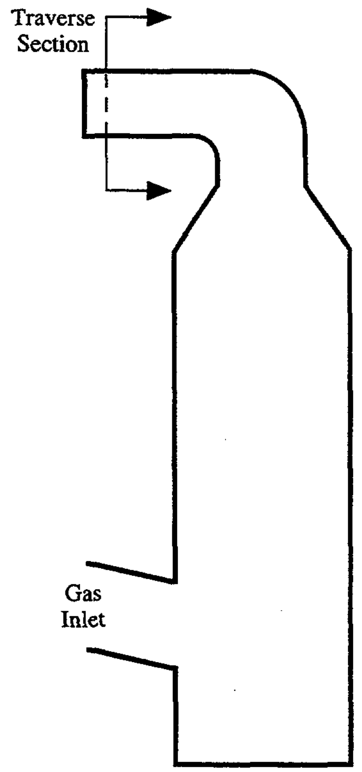

Figure 2-2. Results of CEM Traverses at Module E Outlet (ppm SO_2 dry)

Table 2-2
Average Sodium Formate Parametric Test Conditions and Results

Test No.	Slurry pH	Flue Gas Velocity (ft/s)	No. of Pumps in Service	Liquid-to-Gas Ratio (gal/kacf)	Formate Conc. (mg/L as COOH)	Inlet SO_2 (ppm dry)	SO_2 Removal Efficiency (%)
1	5.63	7.4	4	104	530	1569	96.8
2	5.65	8.7	4	87	1010	1343	98.1
3	5.63	7.4	5	127	1070	1799	99.1
4	5.59	8.1	3	72	1090	1734	96.6
5	5.82	6.1	5	155	1005	1630	99.3
6	5.88	8.1	3	71	1010	1805	97.4
7	5.16	8.4	3	69	1110	1872	92.3
8	5.2	8.4	5	112	1120	1873	96.5
9	5.65	8	4	96	1520	1752	98.4
10	5.68	8.6	4	87	3810	1524	99.4

test module reaction tank are also shown. More detailed test data for the individual Method 6 traverses are included in Appendix A, Table A-2.

The parametric test series began 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 mg/L formate additive (750 mg/L as sodium formate) in the test module. For this test, the SO_2 removal efficiency averaged about 97%.

Test 2, was also a two-day test. For this test, the pH set point and number of operating pumps remained at 5.6, and four pumps remained in operation. The formate additive concentration was increased to a nominal level of 1000 mg/L (1500 mg/L as sodium formate). Operation at Test 2 conditions with 1000 mg/L formate increased SO_2 removal to an average of 98%.

Tests 3 and 4 were conducted at the same nominal formate concentration (1000 mg/L) and operating pH (5.6), but the number of operating pumps varied (five pumps for Test 3 and three pumps for Test 4). In Test 3, with five pumps operating, SO_2 removal efficiency increased to 99%. In Test 4, with three pumps operating, SO_2 removal decreased to 96.6%.

The pH set point was adjusted to 5.8 for Tests 5 (five pumps) and 6 (three pumps) at 1000 mg/L formate. At the higher pH set point, the SO_2 removal efficiency ranged from 97.4% with three pumps operating to 99.3% with five operating.

The pH set point was lowered to 5.2 for Tests 7 (three pumps) and 8 (five pumps) with the formate additive concentration remaining at the nominal 1000 mg/L level. At this lower pH set point, the SO_2 removal efficiency was 92.3% with three pumps and 96.5% with five pumps operating.

Following Tests 7 and 8, the formate concentration in the test module reaction tank was increased to approximately 1500 mg/L for Test 9. The pH set point and number of operating pumps were returned to normal levels (pH 5.6 and four pumps). The average SO_2 removal efficiency was about 98.4% for this test.

Test 10, the final parametric test, was conducted after the formate concentration in the test module reaction tank was increased to 3800 ppm. With the pH set point at 5.6 and four pumps operating, SO_2 removal increased to 99.4%

2.4.4 SO_2 Removal Performance Correlations

Absorber performance can be approximately described by the following expression derived from the "two-film" theory of mass transfer:

$$\text{Number of Transfer Units (NTU)} = \ln (SO_{2in}/SO_{2out}) = K^*A/G \tag{2-1}$$

where:
SO_{2in} and SO_{2out} = inlet and outlet SO_2 concentrations;
K ($lb/hr\text{-}ft^2$) = average overall gas-phase, mass-transfer coefficient;
A (ft^2) = total interfacial area for mass transfer; and
G (lb/hr) = total gas flow rate.

It is assumed in the above expression that the equilibrium partial pressure of SO_2 above the FGD liquor is small compared with the inlet and outlet flue gas SO_2 concentrations.

The overall coefficient K can be expressed as a function of two individual coefficients, k_g and k_l, that represent mass-transfer rates across the gas and liquid films, respectively:

$$1/K = 1/k_g + H/k_l\phi \tag{2-2}$$

Where H is a Henry's Law constant, and ϕ is the liquid-film "enhancement factor" that includes the effects of changes in liquid alkalinity on the SO_2 mass-transfer rate. For a given absorber, operating at constant gas and liquid flow rates, NTU will be a function of slurry pH because of the effect of pH on the enhancement factor and, hence, on the value of K. NTU will also be a function of additive concentration for the same reason.

The form of Equation 2-2 suggests that the effects of increasing pH and additive concentration will diminish at some point when $H/k_l\phi$ becomes small compared with $1/k_g$. This is referred to as "gas-film-limited" mass transfer. When this point is reached for a given absorber, there is no further benefit to increasing the additive concentration.

Equation 2-1 shows that NTU should be inversely proportional to gas flow rate (if the product of K*A is independent of gas velocity) and proportional to liquid flow rate (if A is proportional to liquid flow rate). The SO_2 removal performance data from the baseline and parametric tests have been used to examine the actual effects of L, G, pH, and formate concentration on NTU.

During the baseline and parametric tests, performance was measured at controlled levels of slurry pH, slurry flow rate (number of pumps), and formate concentration. In addition to these controlled variables, the inlet SO_2 concentration and flue gas velocity in the test module varied throughout the tests. The detailed test data from Tables A-1 and A-2 were analyzed using a non-linear least-squares curve fit routine to examine how these uncontrolled changes in test conditions affected SO_2 removal efficiency. This calculation showed that NTU varied with inlet $SO_2^{-0.25}$, and $G^{-0.3}$.

The observed effect of gas velocity on NTU is less than predicted based on Equation 2-1, unless the product K*A increases significantly with increasing gas velocity. In practice, for the spray tower absorber used in the Kintigh FGD system, an increase in flue gas velocity will increase the "A" term in Equation 2-1 because the velocity of small droplets through the absorber will decrease with increasing gas velocity and therefore increase their contribution to surface area. It is also possible that the increase in relative velocity between the flue gas and droplets increases K because of increased turbulence at the droplet surface.

Another way that flue gas velocity can affect performance is through its effect on flue gas distribution in the absorber. The CEM traverse data showed that gas distribution appears to improve with increasing gas velocity. This could also contribute to the apparent increase in K*A with increasing gas velocity.

In order to examine the effects of the controlled variables, the NTU data from Tables A-1 and A-2 were adjusted to a constant gas velocity of 9 ft/s and a constant inlet SO_2 concentration of 1600 ppm using the observed dependence of NTU on these variables. Figure 2-3 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, much of the relative increase in mass transfer is obtained over the range from 0 to 1000 mg/L formate.

Figure 2-3 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 (L), which indicates that droplet surface area does not increase proportionately with increasing spray rate. At Kintigh, NTU was proportional to $L^{0.65}$. Results from some of the other absorber types in this project showed that NTU was directly proportional to L. Apparently, droplet agglomeration or other effects in the Kintigh spray tower reduce the effectiveness of increasing slurry spray rate.

Figure 2-4 shows the effect of slurry pH on NTU for tests with approximately 1000 mg/L formate and three or five pumps operating.

2.5 Results of Slurry Sample Chemical Analyses

2.5.1 Solid-Phase Analyses

Detailed results of solid-phase analyses for the baseline and parametric test slurry samples are included in Appendix A, Tables A-3 and A-4. These results were used to calculate

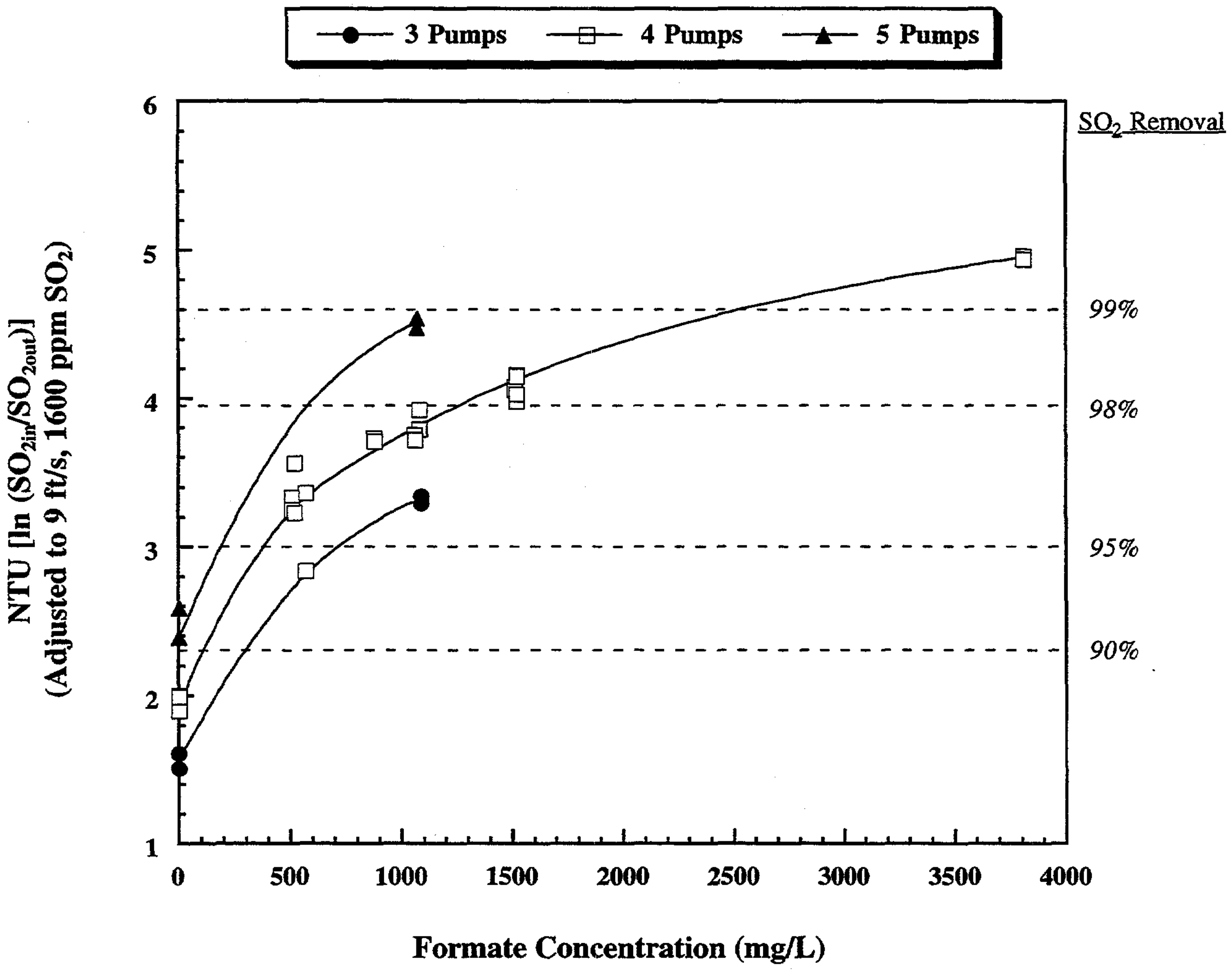

Figure 2-3. Adjusted NTU vs. Formate Concentration for Tests at pH = 5.6

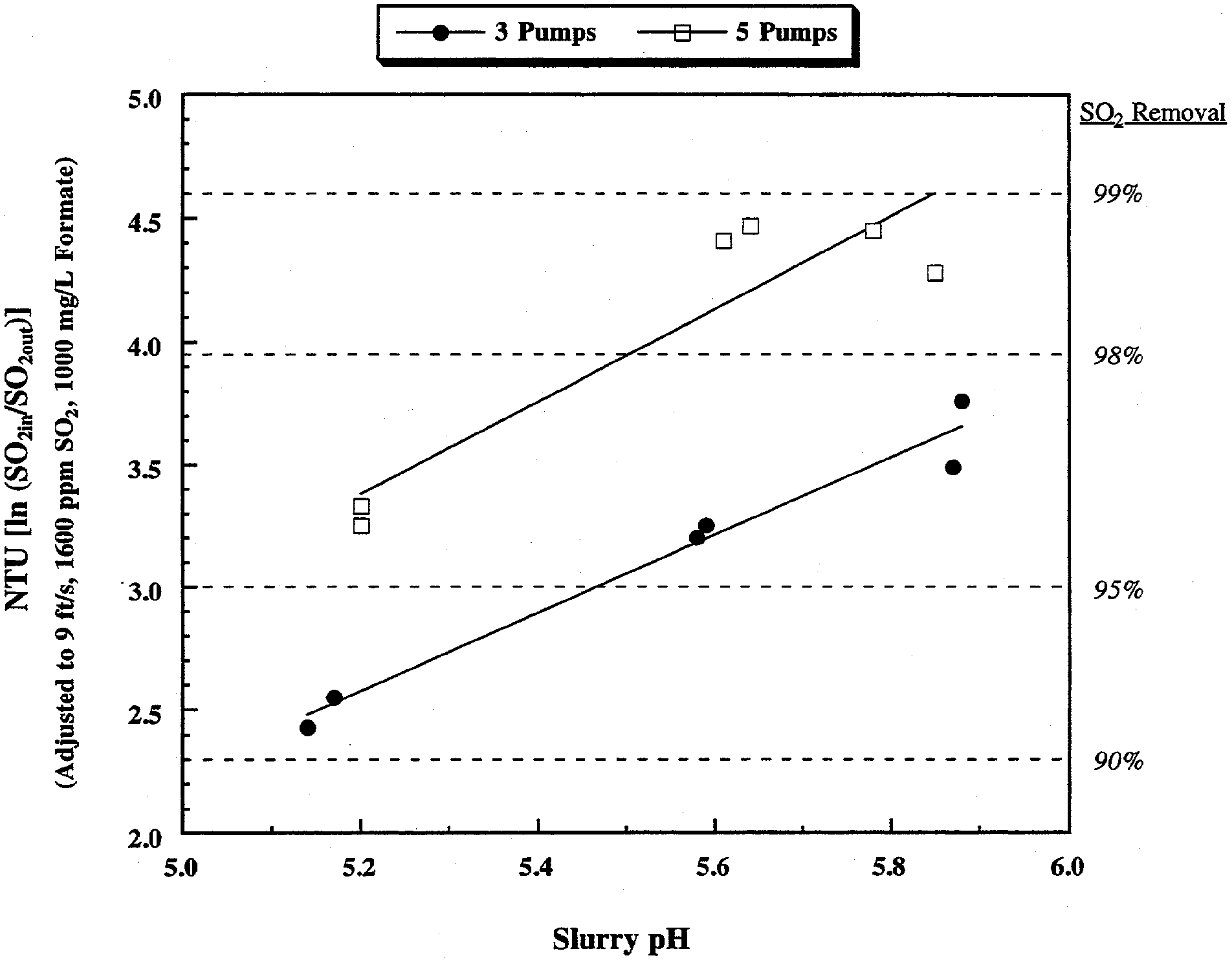

Figure 2-4. Adjusted NTU vs. pH for Tests with 1000 ppm Formate

limestone utilization and sulfite oxidation, which are important process performance parameters. Results are briefly summarized here.

Calculated limestone utilization values from Table A-3 for the baseline tests have been plotted as a function of slurry pH in Figure 2-5. This curve is typical of results seen at the other limestone FGD process test sites. At the low end of the operating pH range, utilization gradually decreases with increasing slurry pH. Then, at the high end of the operating pH range, where the liquor is nearly saturated with respect to calcium carbonate, utilization falls off very rapidly. In Figure 2-5, it can be seen that the results for Baseline Test 6 do not lie on the fitted curve because of a pH measurement problem during this test.

Limestone utilization results from the sodium formate parametric tests are plotted versus slurry pH in Figure 2-6. Utilization results for the baseline tests from Figure 2-5 are also shown as a curve fit to those data. This comparison shows that limestone utilization data for the parametric tests are very scattered. Duplicate carbonate analyses showed very good analytical data quality. Therefore, the scatter in the data is most likely due to pH measurement or slurry sampling problems (see discussion in Appendix A).

Calculated sulfite oxidation percentages from Table A-3 for the baseline tests averaged about 3.8%. There appears to be a slight decrease in oxidation percentage beginning with Baseline Test 6. However, only the solids from Test 1 would have been expected to reach a steady-state composition corresponding to conditions for that particular test.

Sulfite oxidation percentages during the parametric tests averaged 4.7%, which is slightly higher than the 3.8% average for the baseline test solids. On the average, the unit load was significantly lower during the parametric tests, so a slight increase in oxidation (caused by higher excess air in the flue gas) is not surprising. There appears to have been a slight decrease in oxidation during Parametric Test 9 compared with earlier tests, but the decrease was small. There was also an increase in thiosulfate concentration in the recirculating liquor between Tests 8 and 9 (see Liquid-Phase Analyses Table A-6), which could account for this change.

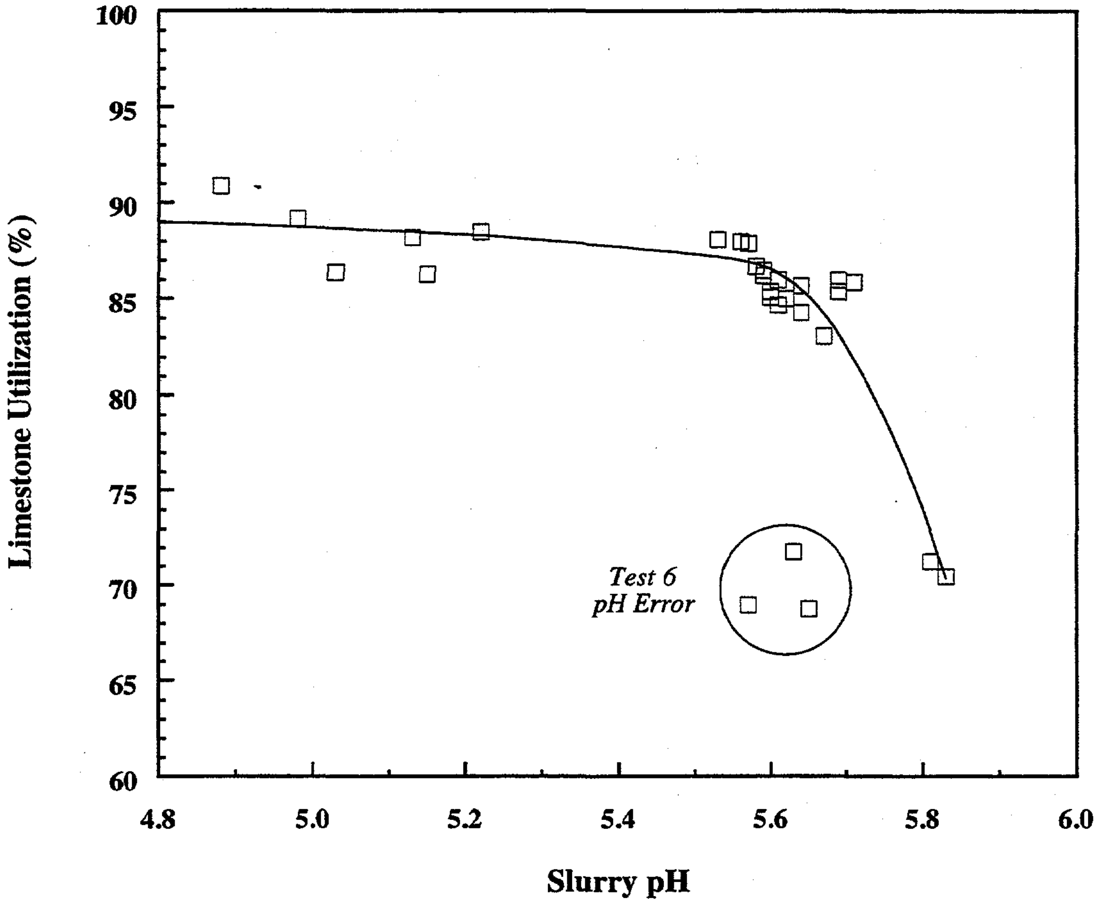

Figure 2-5. Baseline Test
Limestone Utilization vs. Slurry pH

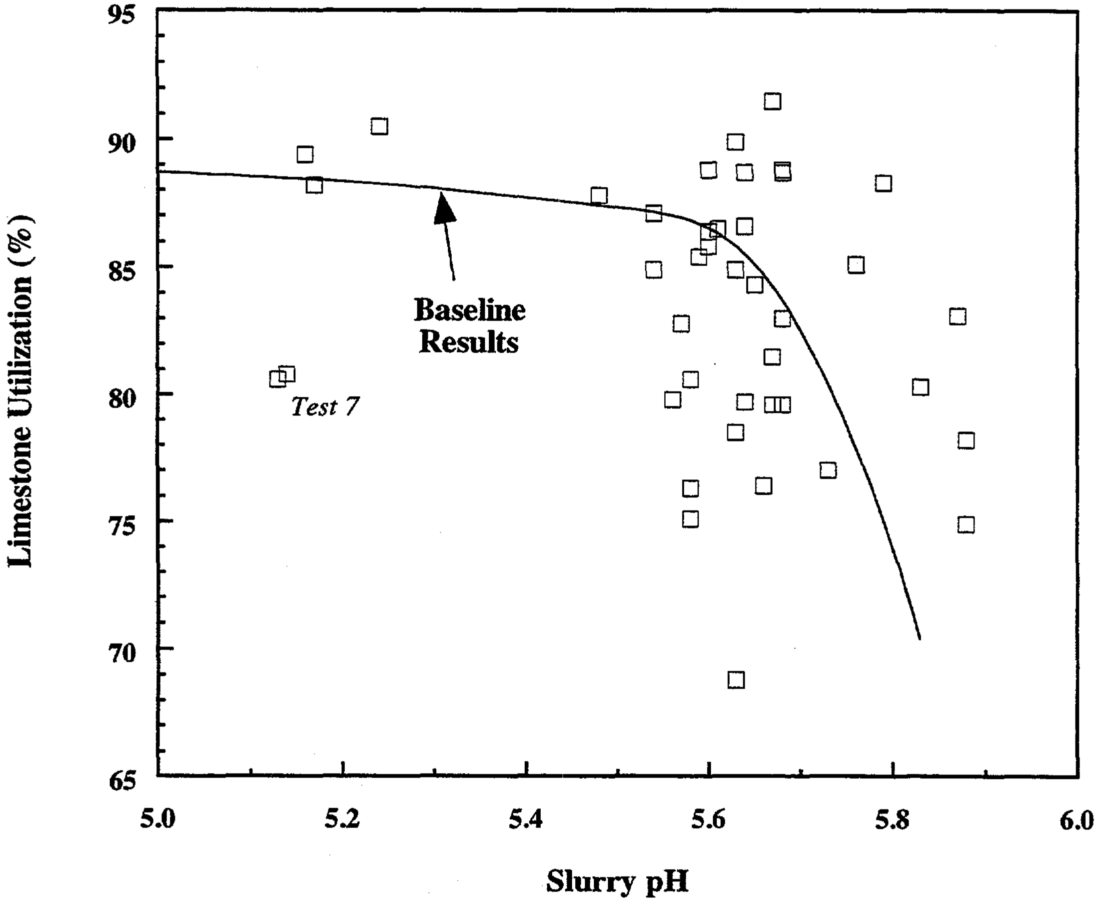

Figure 2-6. Parametric Tests
Limestone Utilization vs. Slurry pH

2.5.2 Liquid-Phase Analyses

Detailed results of liquid-phase analyses for the baseline and parametric test filtered slurry samples are shown in Appendix A, Tables A-5 and A-6. Calculated relative saturations are also shown in the liquid-phase analytical results table. Relative saturation for a specific compound is defined as the activity product for the ionic components in solution divided by the solubility product. These values were obtained using Radian's Aqueous Chemical And Physical Properties (ACAPP) computer routine, which calculates the equilibrium distribution of chemical species using the analytical results as inputs.

Of greatest interest in an inhibited-oxidation FGD system such as this is the gypsum relative saturation. The objective of inhibiting oxidation with sulfur (which reacts to produce thiosulfate in solution) is to prevent scaling by maintaining the gypsum relative saturation below 1.0. Previous research has shown that all of the sulfate produced by oxidation of absorbed SO_2 will precipitate as a solid solution with calcium sulfite, up to the point where the system oxidation percentage reaches about 15%. Above 15% oxidation, the balance of the sulfate (beyond 15% of the SO_2 absorbed) will precipitate as gypsum.

The results in Table A-5 show that the baseline liquor samples all had gypsum relative saturations well below 1.0. These results are consistent with the solids analyses, which showed that the baseline test oxidation percentage was well below 15%. The gypsum relative saturations decreased somewhat during and following Baseline Test 6, consistent with the solids analyses, which showed a corresponding decrease in sulfite oxidation percentage. Table A-6 for the parametric tests again shows that estimated gypsum saturations are well below 1.0, but they are slightly higher than for the baseline tests. This is consistent with solids analyses, which showed slightly higher sulfite oxidation percentages for the parametric tests.

The parametric liquid analyses results can be compared with the baseline values to examine effects of the sodium formate additive on process chemistry. There does not seem to be any change in process chemistry that can be specifically related to the formate additive other than the obvious increase in sodium concentration. There was about a 20% increase in dissolved magnesium and a 15% decrease in dissolved chloride between the baseline and parametric tests. The combined result of these changes in sodium, magnesium, and chloride concentrations was to lower the dissolved calcium concentration substantially in the parametric tests compared with the baseline tests.

Concentrations of 32 elements were also determined in selected samples using inductively coupled plasma emissions spectroscopy (ICPES). These data are summarized in Table A-7. There were no remarkable differences in the results for the baseline and parametric tests.

2.6 Sodium Formate Consumption Test Conditions and Results

The parametric tests were followed by a steady-state sodium formate consumption test. The cost-effectiveness of using additives to enhance SO_2 removal depends both on the performance increase and the consumption rate of the additive. The objective of the consumption test was to measure the amount of sodium formate required to maintain high SO_2 removal efficiency with the entire FGD system. Sodium formate was added continuously to the entire system for a period of six days, and the consumption rate was determined by material balance.

2.6.1 Consumption Rate Calculation

The consumption rate of sodium formate was determined by performing a liquid-phase formate ion mass balance on the FGD system. This required monitoring sodium formate addition rate, formate losses with liquor adhering to the filter cake, and changes in liquid-phase formate inventory over the duration of the test.

The sum of the following terms represents the total loss of sodium formate from the Kintigh FGD system during the consumption test:

1. Solution loss - formate lost in liquor adhering to the filter cake. Liquor blowdown from the FGD system would also contribute to the solution loss, but there was no separate liquor blowdown stream from this FGD system.

2. Degradation - formate lost due to chemical or biological oxidation of formate to produce CO_2 and water.

3. Coprecipitation loss - formate lost by incorporation into the calcium sulfite crystal structure.

4. Vaporization - formate lost by vaporization (as formic acid) into the flue gas.

The solution loss can be calculated for a given system based on the SO_2 removal rate, additive concentration, and filter cake moisture content. The sum of losses 2, 3, and 4 is normally termed the "nonsolution loss." The nonsolution loss is less easily predicted. The total nonsolution loss can be determined by subtracting the total solution loss from the total consumption, but the individual terms in the total nonsolution loss can only be estimated.

Using the terms defined above, the following form of the system mass balance gives the average nonsolution loss rate for a given test period:

Formate nonsolution loss (lb) =
Formate added (lb) - Formate inventory change (lb) - Formate solution loss (lb)

The formate addition term was obtained by measuring the change in the sodium formate tanker level. The solution loss term was obtained by multiplying the total filter cake production for a given test period by the average filter cake moisture content and filtrate formate concentration. The inventory change term was obtained by monitoring changes in formate concentration in all of the system vessels throughout the test. Details of the formate consumption test material balance are included in Appendix B.

The additive nonsolution loss rate is normally reported on an SO_2 removal basis (lb of formate or sodium formate per ton of SO_2 removed). SO_2 removal in the FGD system for a given test period was calculated using hourly averages for unit load, an assumed gross heat rate, and inlet and outlet SO_2 concentrations (in lb SO_2 per million Btu heat input) measured by the certified inlet and stack continuous emissions monitors (CEMs). As a check on this estimate, SO_2 removal was also estimated from the amount of limestone used by the FGD system.

2.6.2 Results

Sodium Formate Consumption

Table 2-3 is a summary of the liquid-phase formate material balance for the duration of the consumption test from 9/7/94 to 9/12/94. In this calculation, total formate consumption is divided into "solution losses," which includes formate leaving the system with the filter cake moisture; and "nonsolution losses," which includes all other loss mechanisms such as vaporization, degradation, and precipitation.

During the 120-hour test duration between the initial and final formate inventories, a total of 13,380 lbs of formate (20,220 lbs of sodium formate) was added to the system. The average feed rate was 168 lb/hr as sodium formate. The total system liquid-phase formate inventory decreased by 1,420 lbs out of a total of about 40,000 lbs. The total formate consumption for the test (the addition term plus the inventory decrease) was 14,800 lbs. A total of 1,700 lbs or 11% of the total formate consumption was accounted for by formate lost from the system in the liquor adhered to the filter cake solids. This 11% of the total formate consumption represents the solution losses. The remaining consumption (13,100 lbs of formate) represents the sum of the nonsolution losses.

During the test, a total of 1,346 tons of SO_2 were removed from the flue gas by the FGD system. The SO_2 removal efficiency averaged about 97% during periods when the bypass damper was closed. The average formate concentration in the module reaction tanks was about

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Table 2-3

Summary of Sodium Formate Consumption Test Results [a]

	Formate	Sodium Formate
Total added (lbs)	13,380	20,220
Total liquid-phase inventory change (lbs)	-1,420	-2,150
Total consumption (lbs)	14,800	22,360
Total loss with filter cake liquid (lbs)	1,700	2,570
Total non-solution loss (lbs)	13,100	19,790
Total SO_2 removed (tons) [b]	1,346	1,346
Total solution loss rate (lb/ton SO_2)	1.3	2.0
Total non-solution loss rate (lb/ton SO_2)	9.7	14.7
Total consumption rate (lb/ton SO_2)	11.0	16.6
Average feed rate (lb/hr)	111	168
Initial average module concentration (mg/L)	1,045	1,580
Final average module concentration (mg/L)	1,120	1,690
Average SO_2 removal (%)	97	97

[a] Results calculated between the 9/7 and 9/12 inventories.

[b] SO_2 removal based on the CEM data and boiler load.

1080 mg/L. Expressed on an SO_2 removal basis, the total additive consumption rate was 11 lb/ton SO_2 as formate or 16.6 lb/ton SO_2 as sodium formate. The solution and nonsolution loss rates were 1.3 and 9.7 lb/ton SO_2, respectively, on a formate basis and 2.0 and 14.7 lb/ton on a sodium formate basis.

An error propagation analysis was done to estimate the uncertainty in the formate consumption results using the procedure outlined in ANSI/ASME Power Test Code 19.1-1985, "Measurement Uncertainty." The uncertainty analysis indicated that the total calculated sodium formate consumption (16.6 lb sodium formate/ton SO_2 removed) is accurate to about ±3.5 lb/ton or ±21% at the 95% confidence level. The nonsolution loss term (14.7 lb sodium formate/ton SO_2 removed) is accurate to ±3.6 lb/ton or ±25%.

Relative Importance of Different Loss Mechanisms

The above sodium formate consumption measurement was based on the liquid-phase material balance. The results of filter cake solids analyses from the consumption test and flue gas analyses from the parametric tests can also be used to estimate the relative contributions of precipitation, vaporization, and degradation to the total nonsolution loss.

Analyses of daily filter cake samples obtained during the consumption test showed an average solid-phase formate concentration of 0.8 mg/g of dry solids, or 0.08 weight percent. The theoretical rate of filter cake solids production is about 2.2 tons dry filter cake/ton of SO_2 removed (at 90% limestone utilization, 3% oxidation, neglecting fly ash and other inerts). Using these data, the average loss rate of formate with the solids would be 3.5 lb formate/ton of SO_2 removed (5.3 lb/ton as sodium formate), which accounts for about 36% of the total nonsolution loss rate.

The flue gas was also analyzed for formic acid during several of the formate parametric tests. In many cases, the formic acid concentrations were less than the estimated 0.1 to 0.2 ppm detection limit for the sample. The maximum flue gas formic acid concentration measured was about 1 ppmv during Parametric Test 1. At full load, the flue gas flow rate at Kintigh is about 1,700,000 scfm, and the SO_2 removal rate averages about 11 ton/hr. A flue gas formic acid concentration of 1 ppmv corresponds to a vaporization loss rate of about 1 lb formic acid/ton of SO_2 removed. This loss rate accounts for a maximum of about 10% of the total nonsolution loss rate. The actual formate vaporization loss rate may have been much less than 10% of the nonsolution loss rate.

The formate degradation rate cannot be measured directly. However, based on measurement of the total nonsolution loss rate and estimates for two of the three nonsolution loss mechanisms, by difference, the degradation loss rate accounts for about 55 to 65% of the total nonsolution loss rate.

Results of Consumption Test Slurry Analyses

Tables B-2 and B-3, Appendix B, summarize the results of solid-phase and liquid-phase analyses for slurry samples obtained during the consumption test. The solid-phase results show that the FGD system continued to operate at very low oxidation percentages: an average of about 2.5% for the long-term test samples, compared with 3.8% for the baseline tests and 4.7% for the parametric tests.

The average system load for the long-term tests was similar to that for the baseline tests, but the thiosulfate concentration in the liquid (see Table B-3) averaged 750 mg/L during the long-term test compared with 240 mg/L for the baseline tests and 320 mg/L for the parametric tests. Therefore, the lower oxidation percentages seen during the long-term test may be a result of higher thiosulfate concentration. An oxidation-inhibiting effect of sodium formate additive was seen at another site in this project (SWEPCo's Pirkey FGD system), but the oxidation data from Kintigh are too confounded by unit load and thiosulfate concentration to determine if there was a similar effect.

Limestone utilization results from Table B-2 have been plotted for comparison with the baseline test results in Figure 2-7. These results did not exhibit the wide scatter that was seen during the parametric tests. The comparison in the figure indicates that the sodium formate additive had no significant effect on limestone utilization.

Referring to Table B-3, the liquid analyses for the long-term tests show trends that are consistent with the solids analyses. The lower oxidation during the long-term tests resulted in lower liquid-phase sulfate concentrations and lower gypsum relative saturations compared with the baseline and parametric tests.

2.7 Effect of Sodium Formate Additive on Solids Dewatering Properties

Tests were performed to examine the effect of sodium formate on other solids properties. If sodium formate is used as a performance-enhancing additive, changes in solids properties caused directly or indirectly by this additive could affect the operation of dewatering equipment.

Three methods were used to examine solids samples from Module E as part of this test program: settling tests, filter leaf tests, and scanning electron microscopy (SEM). Settling tests were performed on site using lower-loop slurry samples to ascertain the effect of sodium formate on sedimentation properties. The bulk settling procedure detailed in Method C2 of EPRI's FGD Chemistry and Analytical Methods Handbook was followed (rake action was not simulated). Filter leaf tests, as described in Method C3 of EPRI's Handbook, were performed to assess changes in the solids filtration rate and solids water retention under vacuum filtration. Finally, SEM was used qualitatively to examine changes in crystal structure.

2.7.1 Settling Test Results

Batch settling tests were performed on slurry samples from the Module E primary reaction tank from which slurry is bled to the dewatering system. These tests determine both

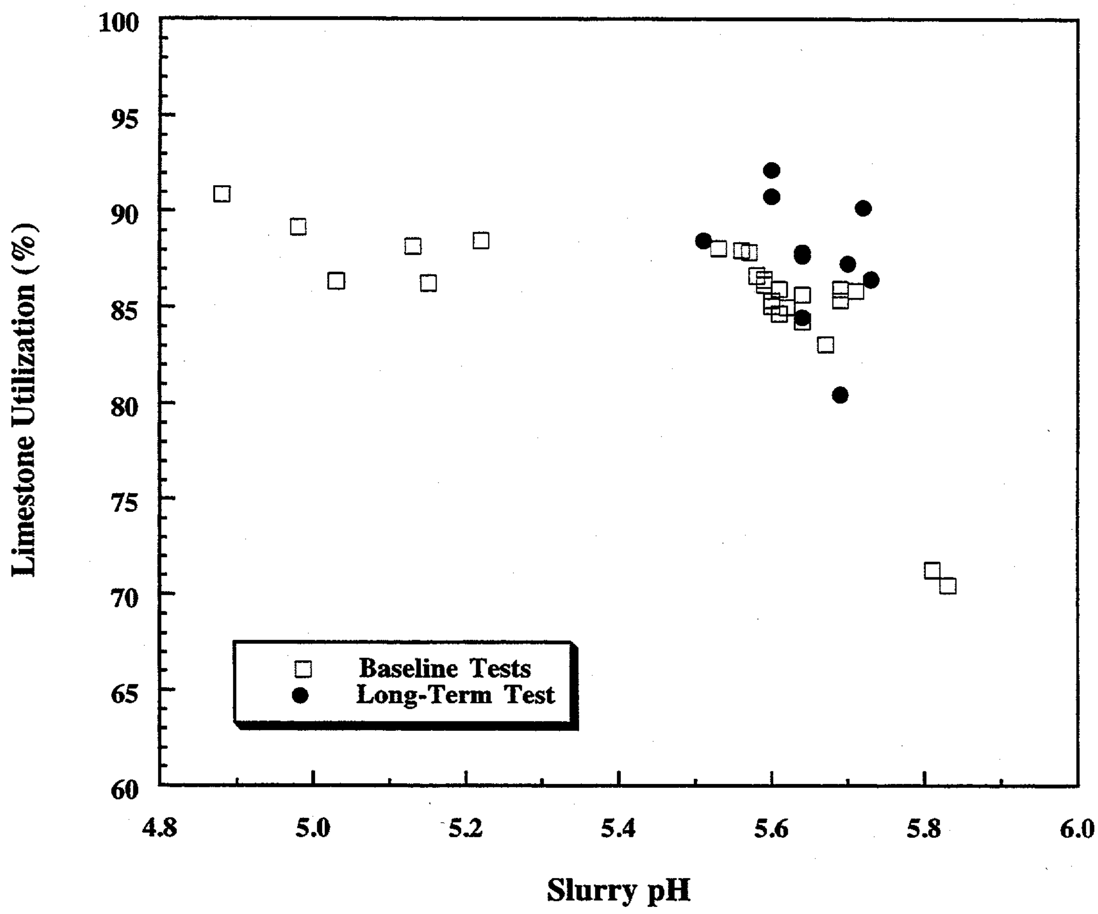

Figure 2-7. Comparison of Baseline and Long-Term Tests Limestone Utilization

settling rates and final solids underflow concentrations. Settling rates are reported as the thickener unit area (UA, ft^2/ton/day) required to reach a 30 wt.% underflow concentration. Lower unit areas correspond to slurries that settled faster.

Settling test results are summarized in Table 2-4. Four settling tests were done during Baseline Test 1. The average calculated unit area of about 2 ft^2/ton/day indicates a relatively fast-settling sulfite sludge, characteristic of inhibited-oxidation limestone FGD systems with very low oxidation percentages.

A total of eleven settling tests were done 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 done during the consumption test. The parametric and consumption test results are also summarized in Table 2-4 along with the baseline results. Also, shown in the table are average unit loads for a 48-hour period prior to each of the settling tests.

The first settling tests for the parametric test series were done during Test 1, after 500 ppm formate had been added to the test module. The results of these tests showed higher unit areas compared with the baseline results. The settling rate decreased markedly over the next few days, and the unit area increased to an average of 17 ft^2/ton/day during Parametric Test 2 with 1000 ppm formate in the test module reaction tank. Over the same time period, however, the unit was operated at a much lower load than usual, so that the observed increase in unit area may have been a result of increased oxidation percentages due to higher excess air in the flue gas. The unit returned to sustained high-load operation over the weekend prior to Test 9, and the settling rate increased (unit area decreased) to levels less than that of Parametric Test 1 and approaching that of the baseline tests. Therefore, it is unlikely that formate alone affected the settling rate to any great extent.

Table 2-4

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.

Settling tests done during the consumption test yielded estimated unit areas about the same as for the baseline results. The unit was operated at sustained high load throughout the consumption test. This confirmed that sodium formate had little effect on slurry settling rate.

2.7.2 Filter Leaf Tests

The results of the filter leaf tests are summarized in Table 2-5. The results include "form filtration rate (lb/hr-ft^2)," which is an indicator of the potential vacuum filter throughput per unit filter cloth area, and the final filter cake moisture contents under standard drying conditions. In Table 2-5, the test designation "B-1" refers to Baseline Test 1, and the designation "P-1" refers to Parametric Test 1.

The form filtration rates show a trend that follows the settling test results. That is, the filtration rates for the baseline and initial parametric test are similar, but the filtration rate decreased substantially during the second parametric test. By the end of the parametric tests, however, the filtration rate was at least as high and possibly higher than the initial rate for the baseline tests. Again, this trend is most likely related to the unit load and sulfite oxidation percentage rather than to the sodium formate additive.

2.7.3 Scanning Electron Microscope (SEM) Photographs

Figures 2-8a and b through 2-11 a and b are SEM photographs of slurry solids samples from the two-day baseline test (Baseline Test 1) and from the three two-day parametric tests at increasing formate levels (Parametric Tests 1, 2, and 9). These photos reveal no significant changes in crystal habit with sodium formate additive.

Table 2-5

Results of Filter Leaf Tests

Test	Date	Sample Time	Form Filtration Rate (lb/hr-ft^2)	Final Solids Content (wt%)
B-1	7/19/94	1045	520	69
B-1	7/19/94	1345	530	70
B-1	7/19/94	1520	450	71
P-1	8/23/94	1200	530	72
P-1	8/23/94	1500	550	71
P-1	8/23/94	1806	560	69
P-2	8/25/94	0815	270	70
P-2	8/25/94	1300	235	69
P-2	8/25/94	1626	210	72
P-9	8/29/94	0800	520	68
P-9	8/29/94	1124	530	70
P-9	8/29/94	1622	690	70

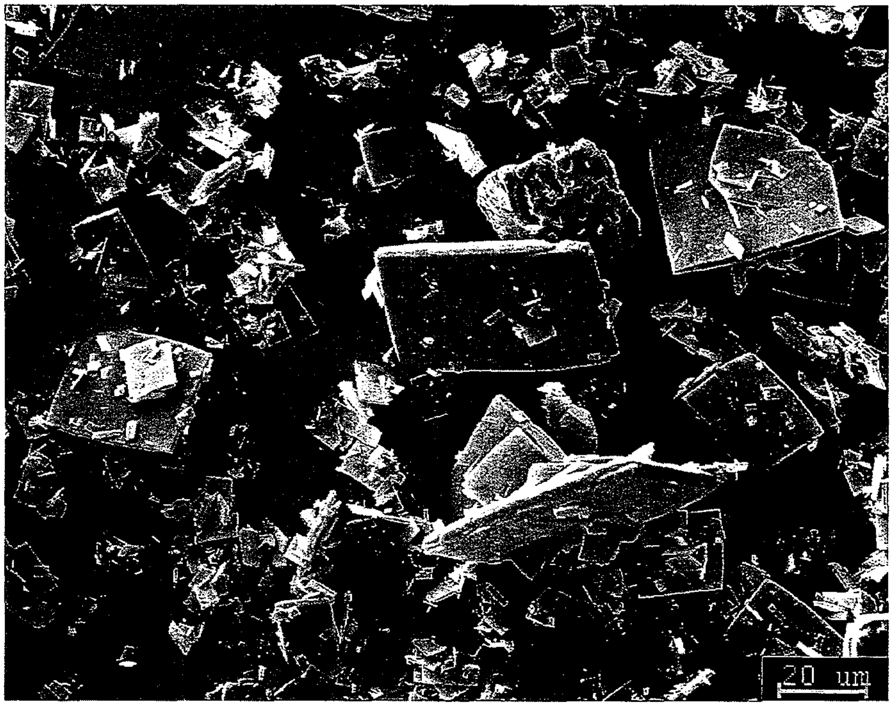

Figure 2-8a. Solids from Baseline Test 1 (500x)

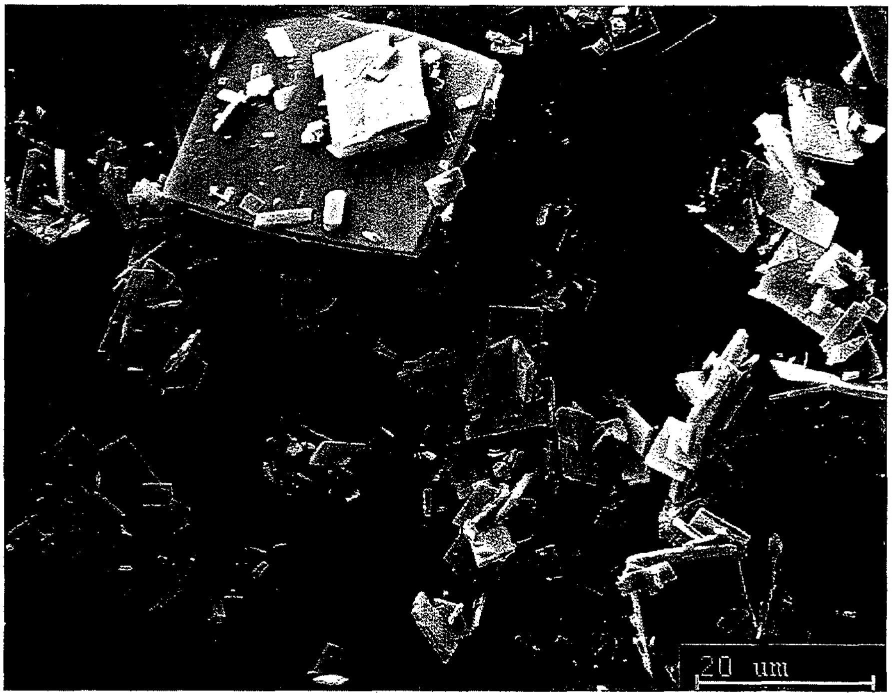

Figure 2-8b. Solids from Baseline Test 1 (1000x)

Figure 2-9a. Solids from Parametric Test 1 (500x)

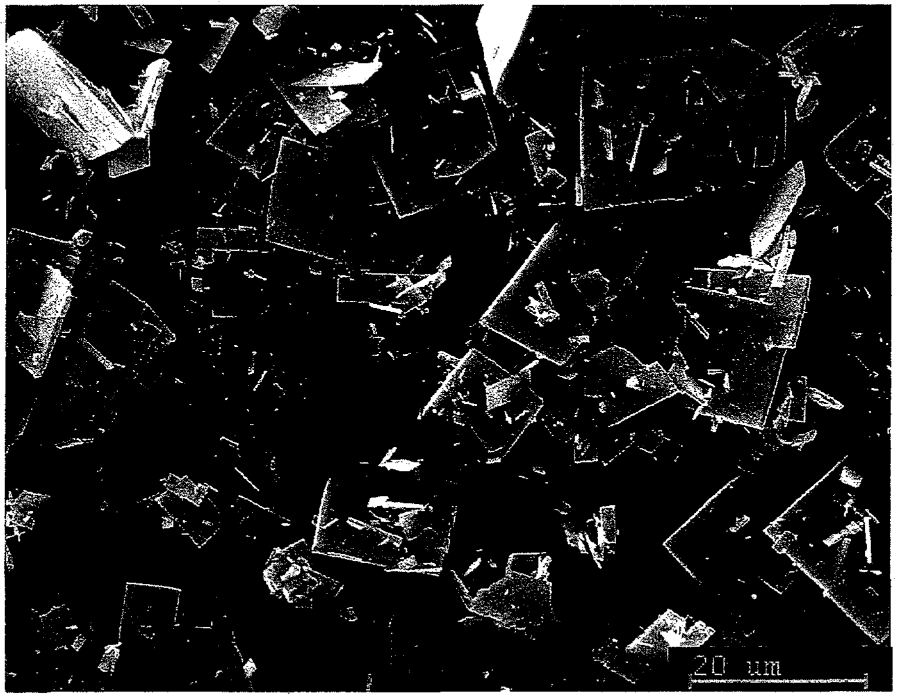

Figure 2-9a. Solids from Parametric Test 1 (1000x)

Figure 2-10a. Solids from Parametric Test 2 (500x)

Figure 2-10b. Solids from Parametric Test 2 (1000x)

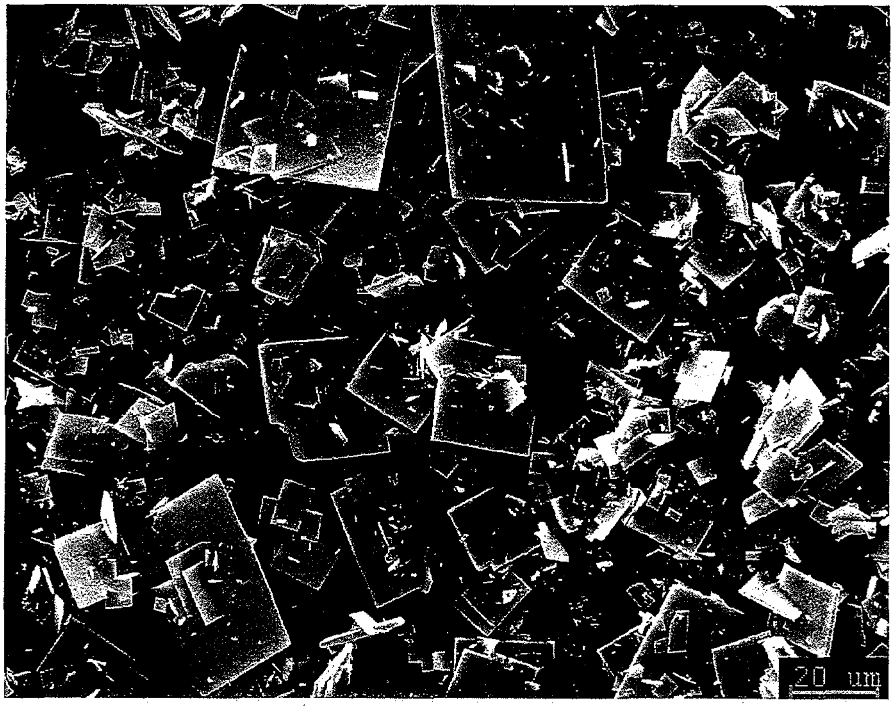

Figure 2-11a. Solids from Parametric Test 9 (500x)

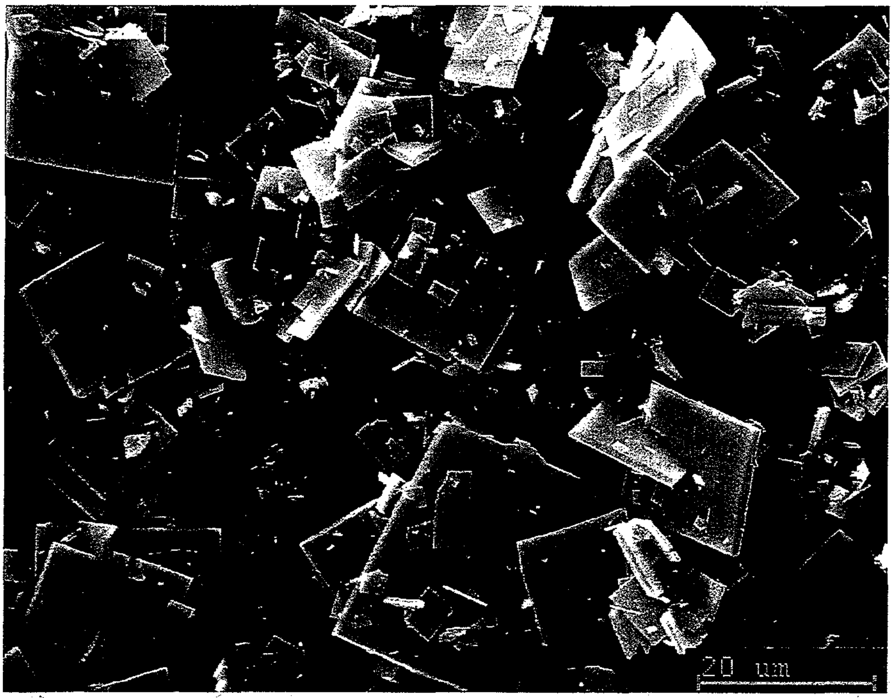

Figure 2-11b. Solids from parametric Test 9 (1000x)

2.8 Other Process Data

2.8.1 Control Room Data

Process data were recorded during the baseline, parametric, and formate consumption tests by the plant data acquisition system and from control-room indicators. These data are summarized in Appendix C, Tables C-1 and C-2.

2.8.2 Recycle Pump Slurry Flow Rate Measurements

Recycle pump slurry flow rates were measured using an ultrasonic Doppler-effect flow meter. Each pump was tested several times during the baseline and parametric tests. Pump motor current and discharge pressures were also recorded. Results are summarized in Table 2-6. The flow measurements were reproducible, and the recorded flows agreed well with those expected based on the 10,900 gpm nominal capacity rating for these pumps.

2.8.3 SO_2 Removal Data for the Consumption Test

Overall FGD system SO_2 removal efficiencies measured during the consumption test are summarized in Table 2-7. In order to measure overall SO_2 removal efficiency during the consumption test, it was necessary to close the system bypass damper so that the system efficiency could be measured 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 2-7 represent average removal efficiencies for one-hour periods each day during which the bypass damper was closed. With the bypass damper closed, the average SO_2 removal was nearly 97% with the unit operating at essentially full load. The average reaction tank formate concentration was about 1130 mg/L during periods when the bypass damper was closed. The SO_2 removal efficiency during the long-term test was slightly lower than the 98% level expected based on the parametric tests with a single module. However,

Table 2-6

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

Table 2-7

SO_2 Removal Efficiency During Consumption Test

Date	Time	Load (MW)	Average Formate Concentration (ppm)	SO_2 in (lb/10^6 Btu)	SO_2 out (lb/10^6 Btu)	SO_2 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 SO_2 estimated due to CEM malfunction.

performance differences among the modules or leakage of a small amount of inlet flue gas through the bypass damper could easily account for the overall FGD system SO_2 removal efficiency being slightly lower than the measured Module E efficiency.

3.0 FGDPRISM MODELING RESULTS

The FGD PRocess Integration and Simulation Model (FGDPRISM) is a computer program that simulates the performance of wet lime and limestone FGD systems. The model was calibrated to NYSEG's Kintigh Station with data collected during two of the baseline and one of the parametric tests. After calibration, the model was used to predict performance for the remaining tests and to investigate some additional options that were not tested. The performance of a finer limestone grind was predicted, and the option of operating the unit at current SO_2 removal levels with formate additive and fewer recycle pumps in service was evaluated. The results of the model calibration and the process simulations are summarized below. Detailed results are included in Appendix D.

3.1 FGDPRISM Calibration Results

The FGDPRISM model is calibrated to test results by adjusting several parameters. The parameters are adjusted to achieve the best fit with respect to liquid-phase chemistry, limestone utilization, and SO_2 removal efficiency for the cases used in the calibration. For the Kintigh FGD system, the main parameters of the calibration are:

- Limestone reactivity;
- Gas- and liquid-film thicknesses for the spray droplets; and
- Calcium sulfite/sulfate solid solution precipitation rate.

The limestone reactivity is adjusted by changing a variable called the surface area factor and the limestone reaction rate constant (k) to match the observed limestone utilization and pH in the reaction tank. The gas-film and liquid-film thicknesses are adjusted to match the mass-transfer characteristics of the absorber. The calcium sulfite/sulfate solid solution precipitation rate constant is adjusted to match predicted and measured relative saturation values for solid calcium sulfite and sulfate compounds.

In addition to these primary calibration parameters, several other input values are adjusted to match the liquid chemistry present in the absorber. For example, the HCl content of the flue gas is varied to match the chloride concentration in the slurry and the limestone $MgCO_3$ solubility and makeup water sodium and magnesium contents are varied to match the magnesium and sodium concentrations in the slurry.

Figure 3-1 compares predicted versus actual SO_2 removal efficiency for the calibrated FGDPRISM model.

3.2 Predictive Simulations

The calibrated model was used to make several predictive simulations to evaluate some conditions that were not actually tested. First, the model was used to evaluate the effect of limestone grind on SO_2 removal efficiency.

A screen size analysis of the limestone reagent used at Kintigh showed that the current grind is relatively coarse; 52% < 200 mesh, and 42% < 400 mesh. By comparison, the "standard" grind used at EPRI's Environmental Control Technology Center (ECTC) is about 93% < 200 mesh and 85% < 400 mesh. (Note that although the ECTC is located at the Kintigh station, the pilot- and full-scale FGD systems have independent limestone supplies and each has its own limestone grinding equipment.)

Experience has shown that limestone grind can have a significant effect on SO_2 removal efficiency at constant limestone utilization. The calibrated FGDPRISM model was used to predict performance for the Kintigh FGD system using the ECTC limestone grind instead of the measured grind. Under those conditions, FGDPRISM predicted that SO_2 removal efficiency at Kintigh could be increased to nearly 97% with four pumps operating. The predicted limestone utilization was 84%, a slight decrease from the baseline level of 85%, at an operating pH of about 5.8.

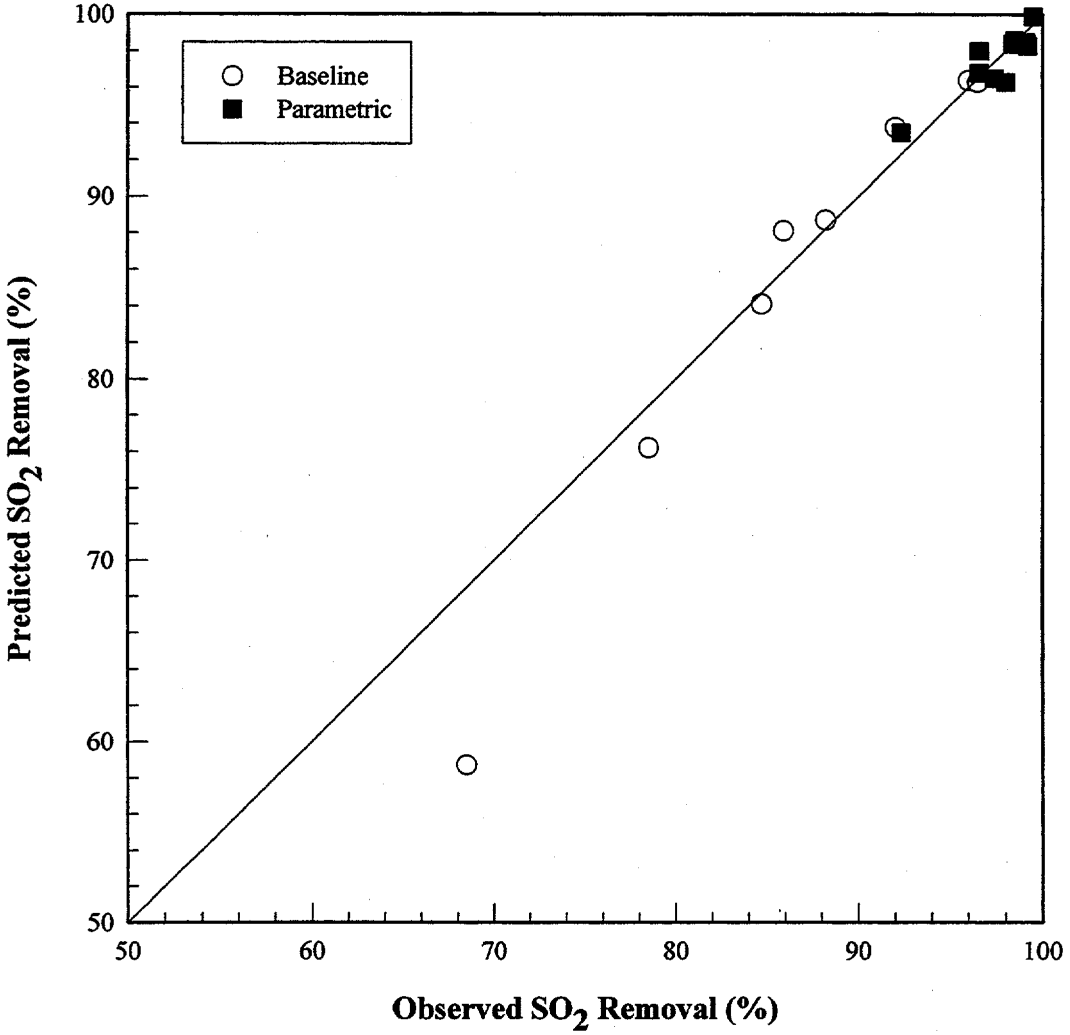

Figure 3-1. Kintigh FGDPRISM Calibration: Predicted vs. Observed Removal

The model was also used to predict limestone utilization for operation at the current SO_2 removal level with a finer grind. Using the ECTC grind as input, FGDPRISM predicted that the current SO_2 removal efficiency could be maintained with limestone utilization increasing from the baseline 85% to about 98%.

The calibrated model was also used to evaluate the option of maintaining current SO_2 removal efficiency (with partial bypass) using sodium formate additive to permit operation with fewer spray pumps. With three spray pumps per module, the model predicted that only 125 mg/L formate would be needed to maintain current SO_2 removal (88% removal in the modules, 85% overall removal including partial bypass). With two spray pumps per module, 670 mg/L formate would be needed. The cost effectiveness of these modeled conditions is discussed in the next section.

4.0 ECONOMIC EVALUATION

Performance data from the baseline, parametric, and long-term sodium formate consumption tests were used to evaluate the economics of upgrades to increase SO_2 removal efficiency with the current Kintigh FGD system configuration. Some additional operating cases that were not tested were evaluated based on performance predicted by the calibrated FGDPRISM model. Results of these economic evaluations are presented in this section.

4.1 Upgrade Options and Cost Basis

Options to upgrade the SO_2 removal performance at Kintigh include operating without flue gas bypass at otherwise current conditions and/or adding sodium formate to the system. A number of upgrade cases were considered involving each of these options separately and in combination. For the options that included sodium formate addition, cases were considered with either three or four recycle pumps per modules in service and with a range of pH set points and formate concentrations. Table 4-1 summarizes the system design basis, cost components, and other assumptions necessary for evaluating these options.

The maximum gross output of the Kintigh Station is about 700 MW. Based on 1985 to 1993 data, an average of 1,794,000 tons per year of coal with a sulfur content of 2.33% were burned at Kintigh. The average heating value of the coal was about 13000 Btu/lb. The average reported capacity factor was about 85%. For the economic evaluation, this capacity factor was approximated by assuming that the unit operates 8000 hours per year with an average load of 660 MW. The average flue gas flow rate at 660 MW was estimated by combustion calculation to be 7.3 million lb/hr.

The average equivalent SO_2 content of the fuel was 3.58 lb/million Btu, and the system outlet SO_2 was typically maintained at 0.52 lb/million Btu. Based on these 1985 to 1993 average data, the baseline annual amount of SO_2 removed is about 71,000 tons, and the baseline

Table 4-1

Economic Basis for Kintigh SO_2 Removal Upgrade Options

Maximum Continuous Rating	708 MW gross
Capacity Factor	86% (8000 hours at 660 MW avg.)
Average Flue Gas Flow	7.3 million lb/hr
Average Fuel Sulfur Content	3.58 lb/million Btu
Average Fuel Heating Value	12990 Btu/lb
Current Average Outlet SO_2	0.52 lb/million Btu
Current SO_2 Removal	71,000 tons/yr
Additional SO_2 Available for Removal	12,500 tons/yr
Capital Cost of Sodium Formate System	\$300,000 for 100 lb/hr
Annualization Factor	0.17
Delivered Cost of Sodium Formate	\$0.24/lb, \$0.30/lb
Cost of Power	\$0.017/kWhr
Sodium Formate Consumption Rate	16.6 lb/ton SO_2 at 1130 mg/L
Cost of Prepared Limestone	\$12.50/ton
Cost of Additional Sludge Disposal	\$7.50/ton
Increase in System ΔP to Treat all Flue Gas	0.6 in. H_2O
Decrease/Increase in System ΔP per Spray Pump	0.2 in. H_2O
Fan Efficiency	80%
Average Recycle Pump Power Consumption	280 kW
Current Average Limestone Utilization	85%

emissions are about 12,500 tons/year. These baseline emissions represent the additional amount of SO_2 available for removal by operating the FGD system at higher efficiency.

The capital cost of a sodium formate additive system sized for 100 lb/hr was previously estimated to be about $300,000. This cost was adjusted as a function of capacity ratio using an exponent of 0.15. An annual capital recovery factor of 0.17 was used. The delivered cost of sodium formate supplied by Perstorp during the test program was $0.24/lb. A cost of $0.30/lb was also used in the evaluation to look at the sensitivity of the results to the additive price. The results of the sodium formate consumption test indicated that the total consumption with 1080 mg/L formate in the reaction tanks was 16.6 lb/ton of SO_2 removed. Based on results from pilot-scale tests at EPRI's ECTC, sodium formate consumption should be directly proportional to concentration. A linear relationship between sodium formate concentration and consumption was, therefore, assumed for the economic evaluation.

Increases in system SO_2 removal will increase several operating costs, including limestone purchase and waste disposal costs. These costs were derived from data provided by NYSEG. Additional limestone reagent (prepared) was valued at $12.5/ton. The cost of dewatering and disposing of additional filter cake was estimated to be $7.5/ton.

Operation without flue gas bypass will increase FGD system pressure drop and fan power consumption. The average increase in overall system pressure drop due to treating all of the flue gas was estimated to be 0.6 in. H_2O based on data obtained during the consumption test. Operation with fewer recycle pumps will decrease system pressure drop. A decrease of 0.2 in. H_2O per spray pump taken out of service (in all operating modules) was estimated based on data obtained during the baseline and parametric tests. A fan efficiency of 80% was assumed, and the fan power was valued at $0.017/kWhr.

The limestone utilization at the normal pH set point was observed during baseline testing to be about 85%. Utilization values for other pH set points were estimated from the baseline data (Figure 2-5).

4.2 Results

The economic factors described above were included in a spreadsheet calculation that estimates the cost of additional tons of SO_2 removed for various operating conditions and levels of removal efficiency. Table 4-2 summarizes the results of these calculations for the most cost-effective options. Additional details of the calculation and results for some other options are shown in Appendix E, Table E-1. The cost of additional SO_2 removal was evaluated over a range of formate concentrations in each case to determine the optimum concentration. Only the optimum results are shown in the table. For higher formate concentrations than those shown in the table, the marginal cost of additional tons of SO_2 removed became greater than the assumed value of allowances.

The first row of entries in Table 4-2 is based on current operational practice. The FGD system is operated with four modules and four pumps per module at a nominal pH set point of 5.6, and with 85% limestone utilization. The overall system SO_2 removal is about 85% with partial bypass being used to control condensation in the absorber outlet plenum.

The first upgrade option in Table 4-2 is based on the option of closing the system bypass dampers, while maintaining FGD system operation at the current baseline conditions (pH 5.6, four pumps per module). Based on the temperatures of the inlet flue gas, scrubber module outlet flue gas, and the stack gas, the typical amount of flue gas bypass was estimated to be 3%. The individual module efficiency was assumed to be unchanged with the small additional gas flow. Closing the bypass damper increases the SO_2 removal efficiency from 85 to 88%, removing an additional 2,500 tons/yr of SO_2.

The costs associated with this option include fan power for increased pressure drop across the system with the bypass closed, as well as reagent, limestone, and sludge disposal costs for the additional SO_2 removed. The total cost increase is $128,000/yr, which results in an average cost of $51/ton of additional SO_2 removed by closing the bypass damper.

Table 4-2

Economic Comparison of SO_2 Removal Upgrade Options

						Net Annual Value ($1000)	
Option	SO_2 Removal %	Limestone Utilization %	Add'l SO_2 Removed (ton/yr)	Total Added Cost ($/yr)	Cost of Add'l SO_2 Removed ($/ton SO_2)	@ $250/ton SO_2	@ $150/ton SO_2
Current operation	85.0*	85	0	0	0	0	0
Close bypass	88	85	2,500	128,000	51	500	250
Close bypass use finer limestone grind	96.8	85	9,840	521,000	53	1940	960
Close bypass add 1000 mg/L formate	97.8	85	10,640	810,000	76	1850	790
Maintain bypass add 1000 mg/L formate	94.8	85	8,140	672,000	83	1360	550
Maintain current SO_2 removal with 2 Pumps and 670 mg/L formate	85	85	0	(98,000)	NA	NA	NA
Maintain current SO_2 removal with 4 pumps and finer limestone grind	85	98	0	(224,000)	NA	NA	NA

* Includes 3% partial bypass.

Note that NYSEG chooses to operate with this small amount of gas bypass as a means of keeping the absorber outlet plenum dry. Operating with no bypass would result in wet conditions in the plenum. This wet operation would bring an associated potential for increased corrosion in the plenum and for "rainout" of acidic droplets from the stack. Capital upgrades such as adding more corrosion resistant materials of construction in the outlet plenum and adding droplet weirs in the stack could be implemented to decrease the potential for these problems. However, such upgrade costs were not estimated and were not evaluated in determining the cost effectiveness of closing the bypass.

Instead, several upgrade options have been evaluated with and without gas bypass. The difference between the projected value of SO_2 credits generated with and without gas bypass represents the approximate annual amount that would be available to invest in capital upgrades to improve operation with the bypass closed.

For example, for this first option which includes no FGD system upgrades beyond closing the bypass damper, the additional SO_2 allowances removed would have an annual value of $250,000 if allowances are valued at $150/ton. If instead they are valued at $250/ton, the additional allowances would have an annual value of about $500,000. In the first instance, where the SO_2 allowances have a value of $150/ton, then capital upgrades amounting to up to $250,000 annually may be cost effective if they would allow continuous closed bypass operation.

The next option in the table is to use a finer limestone grind (93% < 200 mesh) at the same pH set point, also with the bypass closed and with the four-module, four-pump configuration. Under these conditions, FGDPRISM predicts that SO_2 removal efficiency should increase to 96.8%. With this substantial increase in removal efficiency, 9,840 additional tons of SO_2 are removed per year. The costs include additional fan power, reagent and waste disposal costs, plus an assumed cost differential ($100,000/yr) for operating the reagent preparation equipment at half of the current feed rate and for twice the current operating time to produce the finer limestone grind. The total cost of increased SO_2 removal using a finer limestone grind is

$521,000/yr or $53/ton for the additional SO_2 removal. The net annual value of this option ranges from $960,000 to $1.94 million, depending on the assumed value of allowances.

The next option in Table 4-2 is to close the bypass and add 1000 mg/L formate to the FGD system, while maintaining the current baseline pH set point (5.6) with four recycle pumps per module operating and with the current limestone grind. With these conditions, SO_2 removal efficiency should increase to 97.8%. This corresponds to 10,640 tons/yr of additional SO_2 removed. Additional costs include fan power, reagent and waste disposal, plus the annualized capital cost of the additive storage system and the purchase cost of the sodium formate additive. The total annual cost for this option is $810,000, or an average of $76/ton of additional SO_2 removed. The annual value of additional SO_2 removed is about $1.85 million if allowances are valued at $250/ton and $790,000 if allowances are valued at $150/ton.

As discussed previously, it is likely that NYSEG will not want to operate without partial bypass unless capital improvements are made. The next case evaluates the option of maintaining partial bypass, while adding formate to increase SO_2 removal. This option was most cost-effective with four recycle pumps per module and 1000 mg/L formate. The overall system SO_2 removal is 94.8% for this case, and the total annual value is $1.36 million (or $550,000 for $150 allowances). A comparison of the formate cases with and without partial bypass shows that closing the partial bypass can generate an extra $240,000 to $490,000/yr in allowance value. This is a significant potential revenue which might justify some capital improvements to permit operation without bypass.

The final two cases in Table 4-2 evaluate operation at the current SO_2 removal efficiency with partial bypass. In the first of these, sodium formate is added to maintain SO_2 removal with fewer recycle pumps. The required sodium formate concentrations (670 mg/L with two pumps per module) was predicted using FGDPRISM. The result shows that the fan and pump power savings exceed the cost of formate additive by nearly $100,000/yr.

In the final option in Table 4-2, the current SO_2 removal efficiency (with partial bypass) is maintained with four pumps per module using a finer limestone grind to increase limestone utilization. For this case, FGDPRISM predicted that limestone utilization could be increased to 98% at an operating pH of 5.5. The net annual savings for this case exceeds $200,000 even after allowing $100,000 for increased reagent preparation labor, power, and maintenance costs.

4.2.1 Effect of Sodium Formate Additive Price on Results

Additional economic cases were run to evaluate the effect of increased additive cost on the upgrade options. Increasing the cost of sodium formate by 25% to $.30/lb did not change the relative rankings of the additive options. The optimum formate concentration for the normal-pH, four pumps per module case remained at 1000 mg/L with sodium formate at $0.30/lb, but the net annual value of this option decreased by about $70,000.

4.3 Recommended Upgrade Option

Based on the results of the economic analysis and the available test data, the use of sodium formate additive at a level of 1000 mg/L with four recycle pumps per module and the bypass closed appears to be the best upgrade option. This would result in greater than 97% SO_2 removal, and remove an additional 10,000 tons of SO_2 per year. Under these conditions, the 10,000 additional tons/yr of SO_2 will be removed at an average cost of about $76/ton.

However, FGDPRISM predicts that use of a finer limestone grind might be a good approach, provided that the existing reagent preparation equipment can be adapted to produce the 93% < 200 mesh fineness assumed for these predictions. More full-scale testing would be required to fully evaluate this option. This is particularly true because the reagent utilization predictions using FGDPRISM are typically not as accurate as the SO_2 removal predictions.

The economic analysis also showed that sodium formate additive should be cost-effective for maintaining current SO_2 removal efficiency by allowing operation with fewer recycle pumps.

APPENDIX A

Detailed SO_2 Removal Data and Chemical Analyses Results for Baseline and Parametric Tests

Tables A-1 and A-2 summarize the detailed test conditions and SO_2 removal efficiency results for the baseline and parametric tests, respectively. In these tables, each "test" represents a period of operation at constant conditions, and each "run" represents an individual Method 6 traverse at the absorber outlet. The times were recorded at the beginning and end of each traverse. The "average slurry pH" is measured with a calibrated portable meter. A reading was taken at the beginning and end of each traverse, and the average result is shown. In most cases (except Baseline Test 6), the portable meter agreed closely with the control room indicator. The "absorber flue gas velocity" was calculated from the outlet duct pitot traverse, adjusted to the scrubber cross sectional area. The number of operating recycle pumps is shown for each test. (The relationship between pump number and spray header location is shown on Figure 2-1.) "Slurry flow" is the total recycle slurry flow to the test module spray headers calculated using the average of three separate recycle pump flow measurements made for each pump during the baseline test period. The "L/G" for each test was calculated using this flow rate and the measured flue gas volume for each individual run.

In Table A-2 for the parametric tests, the "on-site formate" concentration was determined by buffer capacity titration, and the "off-site formate" concentration was determined by ion chromatography. These results were in good agreement.

All SO_2 concentrations in Tables A-1 and A-2 are reported on a dry flue gas basis, which is the basis of the NYSEG inlet SO_2 analyzer data. The "on-line inlet SO_2" for each run is the average of inlet readings recorded every five minutes during the outlet flue gas traverses.

Two values are shown for the absorber outlet Method 6 SO_2 concentrations. The first value is based on the on-site titration for sulfate in the H_2O_2 impingers using the barium perchlorate titration procedure. The second value is based on the off-site ion chromatograph analyses for sulfate in both the isopropyl alcohol (IPA) and H_2O_2 impingers. In most cases, the IPA impinger sulfate is only a small fraction of the total and is attributed to SO_3 in the flue gas. However, occasionally, the IPA impingers contained more sulfate than could be accounted for by SO_3. Sulfate can be introduced to the IPA impinger as a result of water condensation and SO_2

Table A-1

Actual Baseline 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-line Inlet SO_2 (ppm)	Outlet SO_2 (ppm) On-site	Outlet SO_2 (ppm) Off-site	Overall Removal Efficiency	NTU
1	1	7/19/94	0900-1040	5.66	9.1	1,2,3,5	41900	85	1567	185	215	86.3	1.99
1	2	7/19/94	1104-1159	5.62	9.1	1,2,3,5	41900	85	1570	214	212	86.5	2.00
1	3	7/19/94	1353-1423	5.60	8.9	1,2,3,5	41900	87	1548	209	213	86.2	1.98
1	4	7/19/94	1444-1514	5.60	8.8	1,2,3,5	41900	88	1532	212	222	85.5	1.93
1	5	7/19/94	1534-1617	5.64	9.1	1,2,3,5	41900	86	1453	195	210	85.6	1.94
1	6	7/19/94	1635-1705	5.68	8.7	1,2,3,5	41900	85	1504	180	195	87.1	2.05
2	1	7/20/94	0943-1018	5.58	8.6	1,2,3,4,5	51900	111	1479	103	101	93.1	2.68
2	2	7/20/94	1040-1110	5.56	8.9	1,2,3,4,5	51900	108	1574	142	142	91.0	2.41
3	1	7/20/94	1403-1433	5.60	10.0	2,3,4	31900	59	1565	324	327	79.1	1.57
3	2	7/20/94	1452-1522	5.58	9.6	2,3,4	31900	62	1495	312	331	77.9	1.51
4	1	7/21/94	0824-0854	5.03	9.3	2,3,4	31900	63	1800	572	567	68.5	1.15
4	2	7/21/94	0916-0947	5.00	9.4	2,3,4	31900	62	1808	582	571	68.4	1.15
5	1	7/21/94	1032-1103	5.18	8.4	1,2,3,4,5	51900	113	1760	253	246	86.0	1.97
5	2	7/21/94	1121-1152	5.18	8.9	1,2,3,4,5	51900	107	1697	304	282	83.4	1.79
5A	1	7/21/94	1604-1632	4.94	9.4	1,2,3,5	41900	82	1697	408	442	74.0	1.35
6	1	7/22/94	0912-0939	5.65[a]	9.4	2,3,4	31900	62	1683	195	202	88.0	2.12
6	2	7/22/94	0956-1023	5.64[a]	9.2	2,3,4	31900	64	1700	193	195	88.5	2.16

Table A-1

(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-line Inlet SO_2 (ppm)	Outlet SO_2 (ppm) On-site	Outlet SO_2 (ppm) Off-site	Overall Removal Efficiency	NTU
7	1	7/22/94	1045-1112	5.81	8.5	1,2,3,4,5	51900	112	1724	73	76	95.6	3.12
7	2	7/22/94	1130-1157	5.82	8.4	1,2,3,4,5	51900	114	1692	54	60	96.5	3.35
8	1	7/23/94	0830-0857	5.60	6.2	1,2,3,4,5	51900	155	1315	51	43	96.8	3.43
8	2	7/23/94	0914-0941	5.60	6.3	1,2,3,4,5	51900	152	1353	51	51	96.2	3.27

[a] These pH readings are questionable.

Table A-2

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 A-2

(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

oxidation in the sample probe umbilical. The SO_2 concentrations in the "Off-site" column were corrected to include sulfate in the IPA impinger solution only if the amount in an individual sample greatly exceeded the average value for all of the samples. During the baseline tests, the only sample for which this correction was required was Test 1, Run 1. On the average, the on-site and off-site results agreed within about 1 percent. The reported "overall removal efficiency" for each run was calculated using the off-site results.

The final column in Tables A-1 and A-2 shows the number of transfer units ("NTU") calculated as ln (SO_{2in}/SO_{2out}) for each test. The use of NTU in correlating the SO_2 removal data was discussed in Section 2.4.

Solid Phase Analyses

Tables A-3 and A-4 show the solid-phase chemical analysis results for the baseline and parametric tests, respectively. The results are listed in chronological order. The sample description is based on the test number and run number designation used in Table A-1 for the SO_2 removal results. For example, sample B1-1 is the first slurry sample from Baseline Test 1, Run 1, taken at the beginning of the first Method 6 traverse period. Sample 1-1,2 is the slurry sample taken in between the first and second Method 6 traverses, and sample E1-2 is the slurry sample taken at the end of Test 1, Run 2.

Each slurry sample indicated in the table was filtered, and the filter cake was dried and weighed to determine the slurry solids content in weight percent. A portion of the dried solids was then digested in 0.1N HCl. The portion of solids that remained undissolved is reported as "inerts" in weight percent of the solids.

Also shown in the table are slurry density measurements recorded from the NYSEG operating logs ("NYSEG specific gravity"). These values were used to estimate the slurry solids content ("Estimated wt% Solids"), based on assumed values for the liquid- and solid-phase specific gravities.

Table A-3

Results of Baseline Test Solids Analyses

Description	B1-1	1-1,2	E1-2	B1-3	1-3,4	E1-4	1-5,6	E1-6	B2-1	2-1,2
Date	7/19/94	7/19/94	7/19/94	7/19/94	7/19/94	7/19/94	7/19/94	7/19/94	7/20/94	7/20/94
Time	0910	1000	1150	1345	1435	1520	1610	1710	0940	1020
Ca, mm/g		7.45			7.47		7.59			7.32
Mg, mm/g		0.29			0.23		0.24			0.24
SO_3, mm/g		6.05			6.42		6.17			6.25
SO_4, mm/g		0.22			0.27		0.23			0.27
CO_3, mm/g	1.07	1.15	1.09	1.07	1.13	1.15	1.31	1.04	0.90	0.99
Inerts, wt%		1.04			0.77		0.77			0.84
Solids, wt%	7.4	11.9	8.2	8.3	7.2	8.4	8.7	8.6	5.6	6.3
NYSEG	1.075	1.075	1.075	1.082	1.078	1.075	1.075	1.082	1.07	1.07
Estimated wt% Solids	10.1	10.1	10.1	11.2	10.6	10.1	10.1	11.2	9.3	9.3
pH	5.71	5.64	5.64	5.61	5.60	5.60	5.67	5.69	5.57	5.58
Temperature, C		NA			NA		51.9			51.9
Reagent Utilization, %										
Ca-Independent	85.4	84.5	85.6	85.8	85.5	85.1	83.0	86.0	87.9	86.8
SO_4-Independent	86.2	85.1	85.9	86.1	85.3	85.2	83.2	86.0	87.9	86.9
CO_3-Independent		81.0			86.8		81.8			86.3
Reagent Ratio										
Ca-Independent		1.18			1.17		1.21			1.15
SO_4-Independent		1.18			1.17		1.20			1.15
CO_3-Independent		1.23			1.15		1.22			1.16
Oxidation, %		3.5			4.0		3.6			4.1
Solid Solution, wt%		81.2			86.7		83.0			84.5
Gypsum wt%		0.0			0.0		0.0			0.0
$CaCO_3$, wt%		11.5			11.3		13.1			9.9
Inerts		1.0			0.8		0.8			0.8
Closures										
Weight, %		-5.4			-2.1		-3.1			-5.0
Molar, %		2.1			-0.7		0.7			0.3
Acceptable, %		6.4			6.4		6.4			6.4

Table A-3
(Continued)

Description	E2-2	B3-1	3-1,2	E3-2	B4-1	4-1,2	E4-2	Eb5-1	5-1,2	E5-2
Date	7/20/94	7/20/94	7/20/94	7/20/94	7/21/94	7/21/94	7/21/94	7/21/94	7/21/94	7/21/94
Time	1110	1410	1442	1530	0830	0900	0945	1040	1115	1150
Ca, mm/g			7.46			7.36			7.40	7.47
Mg, mm/g			0.20			0.27			0.20	0.24
SO_3, mm/g			6.29			6.28			6.41	6.49
Total S (as SO_4), mm/g			6.57			6.54			6.69	6.76
SO_4, mm/g			0.28			0.26			0.28	0.27
CO_3, mm/g	0.90	1.15	1.03	0.90	1.03	1.03	0.81	1.05	0.87	0.90
Inerts, wt%			0.89						0.96	1.02
Solids, wt%	6.0	9.4	7.8	6.6	9.5	9.6	9.7	9.2	7.9	8.0
NYSEG S.G.	1.07	1.075	1.075	1.078	1.082	1.082	1.084	1.079	1.076	1.075
Estimated wt% Solids	9.3	10.1	10.1	10.6	11.2	11.2	11.5	10.7	10.3	10.1
pH	5.53	5.62	5.59	5.56	5.03	5.03	4.98	5.15	5.22	5.13
Temperature, C			52.5			52.6			52.9	52.9
Reagent Utility, %										
Ca-Independent	87.9	85.1	86.5	88.0	86.4	86.4	89.1	86.3	88.5	88.2
SO_4-Independent	88.2	84.9	86.6	88.0	86.4	86.5	89.4	86.2	88.6	88.3
CO_3-Independent			85.8			85.8			88.1	87.8
Reagent Ratio										
Ca-Independent			1.16			1.16			1.13	1.13
SO_4-Independent			1.15			1.16			1.13	1.13
CO_3-Independent			1.17			1.17			1.13	1.14
Oxidation, %			4.3			4.0			4.2	4.1
Solid Solution, wt%			85.3			84.8			86.8	87.7
Gypsum wt%			0.0			0.0			0.0	0.0
$CaCO_3$, wt%			10.3			10.3			8.7	9.0
Inerts			0.9			0.0			1.0	1.0
Ca, mg/g			298			294			296	299
Mg, mg/g			5			7			5	6
SO_3, mg/g			503			502			513	519
Total S (as SO_4), mg/g			631			628			642	649
SO_4, mg/g			27			25			27	26
CO_3, mg/g			62			62			52	54
Closures										
Weight, %			-3.7			-5.1			-3.8	-2.5
Molar, %			0.4			0.4			0.2	0.2
Acceptable, %			6.4			6.4			6.5	6.5

Table A-3

(Continued)

Description	5A-1	B6-1	6-1,2	E6-2	7-1,2	E7-2	B8-1	8-1,2	E8-2	2-LS-KB
Date	7/21/94	7/22/94	7/22/94	7/22/94	7/22/94	7/22/94	7/23/94	7/23/94	7/23/94	NA
Time	1610	0920	0950	1035	1125	1200	0835	0900	9045	NA
Ca, mm/g			7.72		7.72			7.62		9.05
Mg, mm/g			0.23		0.25			0.28		0.37
SO_3, mm/g			5.50		5.44			6.28		
Total S (as SO_4), mm/g			5.70		5.63			6.46		
SO_4, mm/g			0.20		0.19			0.18		
CO_3, mm/g	0.69	2.51	2.24	2.52	2.28	2.36	1.13	1.18	1.07	9.14
Inerts, wt%			0.97		1.08			1.03		1.62
Solids, wt%	7.4	11.1	10.6	11.7	10.2	9.9	8.1	9.1	8.2	NA
NYSEG S.G.	1.085	1.09	1.092	1.091	1.087	1.084	1.08	1.08	1.08	
Estimated wt% Solids	11.6	12.3	12.6	12.5	11.9	11.5	10.9	10.9	10.9	
pH	4.88	5.57	5.63	5.65	5.81	5.83	5.69	5.61	5.59	NA
Temperature, C			52.5		52.6			52.3		NA
Reagent Utility, %										
Ca-Independent	90.7	69.4	71.8	69.2	71.2	70.5	85.1	84.5	85.8	
SO_4-Independent	91.0	68.5	71.9	68.4	71.4	70.4	85.7	85.0	86.5	
CO_3-Independent			71.7		70.6			81.8		
Reagent Ratio										
Ca-Independent			1.39		1.41			1.18		
SO_4-Independent			1.39		1.40			1.18		
CO_3-Independent			1.40		1.42			1.22		
Oxidation, %			3.5		3.4			2.8		
Solid Solution, wt%			73.9		72.9			83.6		
Gypsum wt%			0.0		0.0			0.0		
$CaCO_3$, wt%			22.3		22.8			11.8		
Inerts			1.0		1.1			1.0		
Ca, mg/g			309		309			305		362
Mg, mg/g			6		6			7		9
SO_3, mg/g			440		435			502		0
Total S (as SO4), mg/g			547		540			620		0
SO_4, mg/g			19		18			17		0
CO_3, mg/g			134		137			71		549
Closures										
Weight, %			-3.1		-3.3			-2.9		-6.4
Molar, %			0.1		0.4			1.6		1.5
Acceptable, %			6.1		6.1			6.4		6.9

Table A-4

Results of Parametric Test Solids Analyses

Description	B1-1	1-1,2	E1-3	B1-4	1-4,5	E1-5	1-6,7	B2-1	2-1,2	E2-2
Date	8/23/94	8/23/94	8/23/94	8/23/94	8/23/94	8/23/94	8/23/94	8/24/94	8/24/94	8/24/94
Time	0950	1026	1133	1400	1435	1558	1624	0953	1015	1052
Ca, mm/g		7.24			7.29		7.27		7.31	
Mg, mm/g							0.22			
SO_3, mm/g		6.52			6.21		6.56		5.84	
SO_4, mm/g		0.29			0.27		0.35		0.30	
CO_3, mm/g	1.13	0.87	1.14	9.94	1.11	0.85	0.77	0.98 (1.00)	1.80	2.47 (2.48)
Inerts, wt%		0.76			0.60		0.72		0.64	
Solids, wt%	7.7	6.2	7.3	11.2	8.0	8.1	6.2	6.7	8.7	10.4
NYSEG S.G.	1.07	1.07	1.07	1.07	1.07	1.072	1.073	1.068	1.068	1.068
Estimated wt% Solids	9.3	9.3	9.3	9.3	9.3	9.7	9.8	9.0	9.0	9.0
pH	5.76	5.79	5.61	5.58	5.63	5.6	5.63	5.6	5.58	5.63
Temperature, C		49.6			50.0		50.3		48.0	
Reagent Utilitzation, %	85.8	88.7	88.7	76.9	85.4	89.1	90.0	86.2	77.3	71.3
Ca-Independent	84.4	88.0	84.2	73.4	84.8	88.6	89.7	86.6	75.4	66.2
SO_4-Independent	94.1	94.1	94.1		88.8		92.4		83.9	
CO_3-Independent										
Reagent Ratio										
Ca-Independent		1.13			1.17		1.11		1.29	
SO_4-Independent		1.14			1.18		1.11		1.33	
CO_3-Independent		1.06			1.13		1.08		1.19	
Oxidation, %		4.2			4.1		5.1		4.8	
Solid Solution, wt%		88.3			84.0		89.8		79.6	
Gypsum wt%		0.0			0.0		0.0		0.0	
$CaCO_3$, wt%		8.7			11.1		7.7		18.0	
Inerts		0.8			0.6		0.7		0.6	
Closures										
Weight, %		-4.0			-5.5		-3.0		-4.2	
Molar, %		-3.0			-2.0		-1.3		-4.1	
Acceptable, %		6.6			6.5		6.5		6.3	

Table A-4

(Continued)

Description	B2-3	2-3,4	E2-4	B2-5	2-5,6	E2-6	B3-1	3-1,2	E3-2	4-1,2
Date	8/24/94	8/24/94	8/24/94	8/25/94	8/25/94	8/25/94	8/25/94	8/25/94	8/25/94	8/25/94
Time	1454	1520	1613	0920	0949	1037	1254	1342	1422	1608
Ca, mm/g		7.25			7.20			7.18		7.25
Mg, mm/g		0.36								0.30
SO_3, mm/g		6.03			5.91			6.13		6.25
Total S (as SO_4), mm/g										
SO_4, mm/g		0.35			0.34			0.39		0.36
CO_3, mm/g	1.69 (1.68)	1.43	1.3 (1.34)	1.52 (1.52)	1.53	0.8 (0.81)	0.61	0.98	1.82	1.12
Inerts, wt%		0.68			0.76			0.56		0.68
Solids, wt%	9.4	7.9	9.0	10.7	9.1	5.4	4.7	7.1	10.2	7.4
NYSEG S.G.	1.068	1.068	1.069	1.06	1.06	1.06	1.06	1.06	1.06	1.077
Estimated wt% Solids	9.0	9.0	9.2	7.8	7.8	7.8	7.8	7.8	7.8	10.4
pH	5.63	5.67	5.68	5.64	5.67	5.64	5.67	5.64	5.66	5.59
Temperature, C		49.2			49.8			51.8		51.9
Reagent Utility, %										
Ca-Independent	79.1	81.7	83.1	80.4	80.3	88.6	91.4	86.9	78.2	85.5
SO_4-Independent	77.8	81.2	82.9	78.9	78.8	8.9	91.5	86.3	74.6	85.2
CO_3-Independent		83.8			86.7			90.8		87.5
Reagent Ratio										
Ca-Independent		1.22			1.24			1.15		1.17
SO_4-Independent		1.23			1.27			1.16		1.17
CO_3-Independent		1.19			1.15			1.10		1.14
Oxidation, %		5.5			5.4			5.9		5.4
Solid Solution, wt%		82.8			81.1			84.7		85.8
Gypsum wt%		0.0			0.0			0.0		0.0
$CaCO_3$, wt%		14.3			15.3			9.8		11.2
Inerts		0.7			0.8			0.6		0.7
Ca, mg/g		290			288			287		290
Mg, mg/g		9			0			0		7
SO_3, mg/g		482			473			490		500
Total S (as SO_4), mg/g		0			0			0		0
SO_4, mg/g		33			32			37		34
CO_3, mg/g		86			92			59		67
Closures										
Weight, %		-3.6			-5.1			-6.2		-3.5
Molar, %		-1.3			-3.8			-2.2		-1.1
Acceptable, %		6.2			6.3			6.5		6.3

Table A-4

(Continued)

Description	E4-2	B5-1	5-1,2	E5-2	6-1,2	E6-2	By-1	7-1,2	E7-2	8-1,2
Date	8/25/94	8/26/94	8/26/94	8/26/94	8/26/94	8/26/94	8/26/94	8/26/94	8/26/94	8/26/94
Time	1644	0831	0942	1030	1123	1208	14455	1523	1602	1712
Ca, mm/g			7.15		7.32			7.12		7.12
Mg, mm/g					0.41					0.26
SO$_3$, mm/g			6.16		5.75			6.09		6.56
Total S (as SO$_4$), mm/g										
SO$_4$, mm/g			0.29		0.26			0.32		0.32
CO$_3$, mm/g	1.52	1.76	1.48	1.27	1.97	1.68	1.4	1.45	0.85	0.71
Inerts, wt%										
Solids, wt%	10.5	11.0	10.1	8.4	10.3	7.6	10.9	10.7	7.1	6.6
NYSEG S.G.	1.078	1.075	1.07	1.071	1.075	1.075	1.077	1.076	1.077	1.071
Estimated wt% Solids	10.6	10.1	9.3	9.5	10.1	10.1	10.4	10.3	10.4	9.5
pH	5.58	5.73	5.83	5.87	5.88	5.88	5.14	5.13	5.17	5.24
Temperature, C			49.7		50.6			51.8		52.3
Reagent Utility, %										
Ca-Independent	81.3	78.6	81.3	82.6	75.3	78.2	81.7	81.5	88.3	90.6
SO$_4$-Independent	79.9	75.4	79.3	83.6	74.5	78.3	79.8	79.6	88.1	90.4
CO$_3$-Independent			90.2		77.8			90.0		93.1
Reagent Ratio										
Ca-Independent			1.23		1.33			1.23		1.10
SO$_4$-Independent			1.26		1.34			1.26		1.11
CO$_3$-Independent			1.11		1.29			1.11		1.07
Oxidation, %			4.5		4.3			5.0		4.7
Solid Solution, wt%			83.6		78.0			83.2		89.3
Gypsum wt%			0.0		0.0			0.0		0.0
CaCO$_3$, wt%			14.8		19.7			14.5		7.1
Inerts			0.6		0.7			0.8		0.9
Ca, mg/g			286		293			285		285
Mg, mg/g			0		10			0		6
SO$_3$, mg/g			493		460			487		525
Total S (as SO$_4$), mg/g			0		0			0		0
SO$_4$, mg/g			28		25			31		31
CO$_3$, mg/g			89		118			87		43
Closures										
Weight, %			-4.0		-3.3			-4.5		-3.9
Molar, %			-5.2		-1.6			-4.9		-1.4
Acceptable, %			6.3		6.1			6.3		6.5

Table A-4

(Continued)

Description	E8-2	B9-1	9-1,2	E9-2	9-3,4	E9-4	B9-5	9-5,6	E9-6	B10-1	10-1,2
Date	8/26/94	8/29/94	8/29/94	8/29/94	8/29/94	8/29/94	8/29/94	8/29/94	8/29/94	8/30/94	8/30/94
Time	1750	0908	1000	1114	1213	1254	1504	1554	1635	0940	1122
Ca, mm/g			7.15		7.09			7.10			7.08
Mg, mm/g								0.30			0.23
SO_3, mm/g			6.47		5.96			6.39			6.53
Total S (as SO_4), mm/g											
SO_4, mm/g			0.27		0.24			0.27			0.26
CO_3, mm/g	0.8	1.13	0.90	1.02	1.49	1.25	1.59	0.97	0.83	1.2	0.84
Inerts, wt%			0.76		0.91			0.76			
Solids, wt%	7.5	8.3	7.6	8.4	9.2	9.9	11.9	6.5	6.9	7.9	6.0
NYSEG S.G.	1.076	1.068	1,068	1.068	1.068	1.065	1.068	1.068	1.068	1.067	1.069
Estimated wt% Solids	10.3	9.0	9.0	9.0	9.0	8.6	9.0	9.0	9.0	8.9	9.2
pH	5.16	5.54	5.48	5.6	5.56	5.57	5.68	5.54	5.68	5.65	5.68
Temperature, C			49.4		50.1			49.6			47.5
Reagent Utility, %											
Ca-Independent	89.6	85.6	88.2	85.9	80.6	83.2	80.7	87.3	88.9	85.0	89.0
SO_4-Independent	889.2	84.2	87.4	85.6	79.0	82.4	78.5	86.9	88.8	83.6	88.5
CO_3-Independent			94.3		87.5			90.0			92.9
Reagent Ratio											
Ca-Independent			1.13		1.24			1.15			1.12
SO_4-Independent			1.14		1.27			1.15			1.13
CO_3-Independent			1.06		1.14			1.11			1.08
Oxidation, %			4.0		3.9			4.0			3.8
Solid Solution, wt%			87.4		80.4			86.3			87.9
Gypsum wt%			0.0		0.0			0.0			0.0
$CaCO_3$, wt%			9.0		14.9			9.7			8.4
Inerts			0.8		0.9			0.8			0.8
Ca, mg/g			286		284			284			283
Mg, mg/g			0		0			7			6
SO_3, mg/g			518		477			511			522
Total S (as SO_4), mg/g			0		0			7			0
SO_4, mg/g			26		23			26			25
CO_3, mg/g			54		89			58			50
Closures											
Weight, %			-4.8		-6.2			-4.6			-4.5
Molar, %			-3.3		-4.1			-1.5			-2.2
Acceptable, %			6.6		6.3			6.4			6.5

The digested solids solution was analyzed for Ca^{++} and Mg^{++} by atomic absorption and for $SO_4^=$ by ion chromatography (IC). A separate portion of the dried solids was analyzed for $SO_3^=$ (sulfite) by thiosulfate/iodine titration. A third portion of the dried solids was analyzed for $CO_3^=$ (carbonate) by coulometric measurement of CO_2 gas evolved from an acidified sample. These analytical methods are described in detail in EPRI's FGD Chemistry and Analytical Methods Handbook.

Two calculated values for limestone utilization are reported in Tables A-3 and A-4 following the analytical results. Utilization is defined as [1 - moles of carbonate/(moles of product solids + moles of carbonate)]. The "Ca-independent" value for utilization is calculated using the total S (sulfite plus sulfate) analysis as the total moles of product. The "SO_4-independent" value is calculated using the Ca analysis as the total moles of product + moles of carbonate. For samples with only carbonate analyses, approximate utilizations were calculated by using the calcium and sulfite/sulfate analyses for the closest sample from the same test that was completely analyzed. The calculated utilization values are also expressed as reagent ratio, which is the inverse of utilization (expressed as a fraction rather than as a percentage).

Sulfite oxidation percentages reported in Tables A-3 and A-4 are calculated as 100 x [1 - moles of sulfite/moles of total sulfite plus sulfate].

The remaining entries in Tables A-3 and A-4 include solids analyses calculated on a weight basis, followed by calculated "closures" for the analytical results. Closures are calculated as a quality assurance indicator. The molar closure in percent is calculated for a given set of solids analyses as the difference between the sums of positively and negatively charged ionic species in moles/gram divided by the total of the positively and negatively charged species in moles/gram (times 100). The calculated "acceptable" closure in percent is the expected error in the calculated molar closure at the 95% confidence level based on the assumptions that each of the individual analyses has a standard deviation of ±5% and that all significant species have been included in the analyses. The calculated closures in Tables A-3 and A-4 indicate good data quality for the solids analyses. All of the molar closures are well below the acceptable limits.

The calculated limestone utilization values in Table A-4 (plotted in Figure 2-6) were scattered. This could be due to pH measurement, slurry sampling, or analytical problems. In order to check for analytical problems, six solid samples from Parametric Test 2, during which the slurry pH varied no more than ±0.05, were reanalyzed for carbonate. The results of these replicate analyses are shown in Table A-4 in parentheses below the original carbonate results. The analytical agreement was excellent, so the scatter in the utilization data is more likely related to slurry sampling problems.

Another discrepancy in the solid-phase analytical results for the parametric tests can be seen by examining the slurry solids contents ("solids, wt%" in the tables). Material balance calculations show that, at full load, the maximum rate of increase in the slurry solids content in the test module reaction tank should be about 0.5 wt% per hour even if no slurry was bled from the tank. Inspection of the parametric test data shows that the measured slurry solids content increased or decreased by as much as 3 or 4 percentage points in less than one hour.

There are two possible sampling problems that could account for these results. Either the slurry samples drawn from the sample tap were not representative of the hydroclone feed stream, or the tank was not well mixed at the location of the hydroclone feed pump suction. Because of this sampling problem, the NYSEG slurry specific gravity measurements have been used to estimate slurry solids contents when required for process calculations.

Liquid Analyses

Tables A-5 and A-6 show results of the liquid-phase analyses for the baseline and parametric test filtered slurry samples. Calcium, magnesium, and sodium were determined by atomic absorption spectrophotometry. Chloride, sulfite, sulfate, and thiosulfate were determined by ion chromatography. The reported result for "total hydrolyzable sulfate" is the total sulfate measured in the liquor sample after digestion under acidic oxidizing conditions, which converts all sulfur species to sulfate. The final result reported as "sulfur/nitrogen" species (S/N in the

Table A-5

Results of Baseline Test Liquid Analyses

Description	1-1,2	1-3,4	1-5,6	2-1,2	3-1,2	4-1,2	5-1,2	6-1,2	7-1,2	8-1,2
Date	7/19/94	7/19/94	7/19/94	7/20/94	7/20/94	7/21/94	7/21/94	7/22/94	7/22/94	7/23/94
Time	1000	1435	1610	1020	1442	0900	1115	0950	1125	0900
Ca, mm/L	106	105	106	104	105	107	106	99	97	94
Mg, mm/L	175	178	175	178	181	189	187	179	178	178
Na, mm/L	50.6	50.8	51.7	50.5	55.6	53.7	53.2	50.4	51.8	50.4
Cl, mm/L	564	585	580	563	580	588	598	566	570	564
CO_3, mm/L	3.6	4.4	4.2	3.7	4.2	4.3	4.1	4.5	4.3	3.1
SO_3, mm/L	5.64	5.92	5.58	5.75	5.74	6.90	7.06	5.26	2.39	5.32
SO_4, mm/L	2.32	2.01	1.99	2.91	1.90	2.58	2.66	0.62	0.59	0.59
S_2O_3, mm/L	1.96	2.09	2.02	2.15	2.05	2.21	2.20	2.31	2.34	2.40
Total Hyd SO_4, mm/L	23.0	23.3	22.5	20.1	24.3	23.2	26.9	20.3	18.9	21.2
S/N, mm/L	11.2	11.2	10.9	7.1	12.5	9.3	12.7	9.8	11.2	10.4
pH	5.64	5.60	5.67	5.58	5.59	5.03	5.22	5.80	5.81	5.61
Temperature, C	NA	NA	51.9	51.9	52.5	52.6	52.9	52.5	52.6	52.3
Ca, mg/L	4230	4200	4250	4180	4190	4270	4240	3960	3900	3750
Mg, mg/L	4260	4330	4260	4340	4410	4580	4540	4350	4340	4330
Na, mg/L	1160	1170	1190	1160	1280	1240	1220	1160	1190	1160
Cl, mg/l	20000	20700	20600	20000	20500	20900	21200	20100	20200	20000
CO_3, mg/L	219	262	253	224	251	259	248	270	255	183
SO_3, mg/L	451	474	446	460	460	553	565	421	191	426
SO_4, mg/L	223	193	191	279	183	248	256	60	56	57
S_2O_3, mg/L	220	234	226	241	229	247	247	259	262	269
Charge Imbalance										
Calculated, %	1.8	0.5	0.7	2.4	1.7	2.3	0.8	1.5	1.1	0.7
Acceptable, %	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	6.0	6.0
Relative Saturation										
Gypsum	0.10	0.09	0.09	0.12	0.08	0.11	0.11	0.03	0.02	0.02
$CaSO_3*0.5H_2O$	8.0	8.1	8.3	7.7	7.7	4.1	5.7	8.5	3.9	6.9
$CaCO_3$	0.13	0.14	0.18	0.11	0.13	0.014	0.03	0.29	0.29	0.10

Table A-6

Results of Parametric Test Liquid Analyses

Description	1-2,3	1-4,5	1-6,7	2-1,2	2-3,4	2-5,6	3-1,2	4-1,2	5-1,2	6-1,2
Date	8/23/94	8/23/94	8/23/94	8/24/94	8/24/94	8/25/94	8/25/94	8/25/94	8/26/94	8/26/94
Time	1026	1435	1624	1015	1520	0949	1342	1608	0942	1123
Ca, mm/L	47.2	48.6	47.9	48.6	48.1	47.0	45.9	45.4	42.3	42.3
Mg, mm/L			216		211			203		211
Na, mm/L			60.5		73.9			75.6		
Cl, mm/L			481		479			490		
CO_3, mm/L	4.64	4.91	4.41	4.70	5.05	1.13	4.60	5.42	3.71	5.26
SO_3, mm/L	4.04	4.66	3.96	4.94	4.07	4.36	4.20	4.10	3.23	3.30
SO_4, mm/L	8.43	12.08	9.66	10.40	11.34	9.77	9.37	8.55	5.01	4.97
S_2O_3, mm/L			1.90		2.01			2.20		
Total Hyd SO_4, mm/L	25.5	26.0	26.4	28.3	28.2	27.1	27.4	25.6	20.6	21.0
S/N, mm/L	13.0	9.3	8.9	12.9	8.8	13.0	13.8	8.5	12.4	12.8
HCO^{O-}, mm/L	12.7	11.4	11.5	19.6	24.0	23.5	23.8	24.2	22.3	22.5
pH	5.79	5.63	5.63	5.58	5.67	5.67	5.64	5.59	5.83	5.88
Temperature, C	49.6	50.0	50.3	48.0	49.2	49.8	51.8	51.9	49.7	50.6
Ca, mg/L	1890	1950	1920	1950	1930	1880	1840	1820	1690	1690
Mg, mg/L	0	0	5260	0	5130	0	0	4930	0	5130
Na, mg/L	0	0	1390	0	1700	0	0	1740	0	0
Cl, mg/l	0	0	17100	0	17000	0	0	17400	0	0
CO_3, mg/L	278	294	265	282	303	68	276	325	222	316
SO_3, mg/L	323	373	317	395	326	349	336	328	258	264
SO_4, mg/L	810	1160	928	999	1090	938	900	821	481	477
S_2O_3, mg/L	0	0	212	0	225	0	0	246	0	0
HCO^{O-}, mg/L	572	523	520	884	1080	1060	1070	1090	1000	1010
Charge Imbalance										
Calculated, %	4.9	4.9	5.3	4.4	4.2	1.8	1.5	2.0	5.4	5.2
Acceptable, %	7.7	7.5	6.0	7.6	5.9	7.8	7.7	6.0	8.1	8.1
Relative Saturation										
Gypsum	0.20	0.25	0.20	0.22	0.23	0.20	0.19	0.17	0.09	0.09
$CaSO_3{*}0.5H_2O$	3.4	3.4	2.9	3.3	3.1	3.3	3.0	2.7	2.6	2.8
$CaCO_3$	0.13	0.08	0.08	0.07	0.10	0.02	0.08	0.08	0.12	0.20

Table A-6

(Continued)

Description	7-1,2	8-1,2	9-1,2	9-3,4	9-5,6	10-1,2
Date	8/26/94	8/26/94	8/29/94	8/29/94	8/29/94	8/30/94
Time	1523	1712	1000	1213	1554	1122
Ca, mm/L	43.6	42.0	40.0	38.8	38.8	37.2
Mg, mm/L		213			222	219
Na, mm/L		78.4			90.3	147.9
Cl, mm/L		476			503	484
CO_3, mm/L	5.00	3.86	4.86	5.25	4.81	4.65
SO_3, mm/L	9.86	8.50	6.81	5.18	5.86	5.28
SO_4, mm/L	5.31	6.25	5.19	4.95	4.95	5.60
S_2O_3, mm/L		2.46			4.32	4.45
Total Hyd SO_4, mm/L	28.4	29.2	29.3	28.3	28.3	34.5
S/N, mm/L	13.2	9.6	17.3	18.2	8.8	14.8
HCO^{O-}, mm/L	24.6	24.9	33.8	33.5	33.9	84.6
pH	5.13	5.24	5.48	5.56	5.54	5.68
Temperature, C	51.8	52.3	49.4	50.1	49.6	47.5
Ca, mg/L	1750	1680	1600	1550	1550	1490
Mg, mg/L	0	5190	0	0	5390	5330
Na, mg/L	0	1800	0	0	2080	3400
Cl, mg/l	0	16900	0	0	17800	17200
CO_3, mg/L	300	232	292	315	289	279
SO_3, mg/L	789	680	545	415	469	423
SO_4, mg/L	511	600	499	476	475	538
S_2O_3, mg/L	0	275	0	0	484	498
HCOO-, mg/L	1110	1120	1520	1510	1520	3810
Charge Imbalance						
Calculated, %	4.7	4.7	2.7	2.6	3.3	4.0
Acceptable, %	7.8	6.0	8.3	8.4	6.1	6.8
Relative Saturation						
Gypsum	0.10	0.11	0.09	0.08	0.08	0.07
$CaSO_3*0.5H_2O$	3.0	3.0	3.4	2.8	3.1	3.1
$CaCO_3$	0.01	0.01	0.04	0.06	0.05	0.08

Table A-7

Results of ICPES Analyses for Baseline and Parametric Test Liquids

Analyte (mg/L)	Sample ID			
	Baseline 1	Parametric 1	Parametric 2	Parametric 9
Aluminum	ND	ND	ND	ND
Antimony	ND	ND	ND	ND
Arsenic	0.6	ND	ND	ND
Barium	0.3	0.1	0.1	0.1
Beryllium	ND	ND	ND	ND
Boron	640	560	540	550
Cadmium	0.008	ND	0.02	0.01
Calcium	4230	1860	1780	1470
Chromium	<0.03	ND	ND	0.01
Cobalt	<0.03	0.01	0.04	0.01
Copper	<0.06	<0.04	<0.03	0.02
Iron	0.5	ND	ND	0.6
Lead	ND	ND	ND	ND
Lithium	0.8	0.8	0.8	0.8
Magnesium	4310	4750	4550	4760
Manganese	0.9	0.3	0.4	0.3
Molybdenum	<0.05	<.03	0.1	0.05
Nickel	0.9	0.7	0.7	0.7
Potassium	61	54	53	54
Selenium	0.6	<0.4	0.5	0.4
Silicon	7.7	6.1	5.6	7.1
Silver	ND	<0.02	ND	ND
Sodium	1140	1340	1590	1890
Strontium	6.4	2.5	2.4	2.0

Table A-7

(Continued)

Analyte (mg/L)	Sample ID			
	Baseline 1	Parametric 1	Parametric 2	Parametric 9
Sulfur	1030	NA	NA	NA
Thallium	0.1	0.2	ND	ND
Tin	<0.09	<0.07	ND	ND
Titanium	ND	ND	ND	ND
Tungsten	0.2	NA	NA	NA
Uranium	1.6	ND	ND	ND
Vanadium	0.07	0.02	0.03	0.04
Zinc	ND	ND	ND	ND

NA = Not analyzed
ND = Not detected

table) represents the difference between the total hydrolyzable sulfate and the sum of the moles of sulfur in the other individually reported sulfur species.

Calculated molar closures (charge imbalances) have again been used as a data quality check. All of the calculated charge balances are well within acceptable limits.

APPENDIX B

Detailed Formate Material Balance Data and Chemical Analyses Results for the Sodium Formate Consumption Test

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Table B-1 shows detailed sodium formate material balance data for the consumption test. During the three inventory days of the consumption test, formate concentrations were measured in most of the major system vessels. The actual liquid formate concentrations were measured for the reaction tanks, limestone slurry tanks, thickeners, and filtrate. The concentrations in the underflow storage tanks were assumed to be the same as that in the filtrate. The concentration in the supernate tank was taken as the average of the concentrations in the two limestone slurry tanks.

Each page of Table B-1 represents one consumption test inventory. For tanks that operate with variable levels, the level of each tank was also measured. The formate inventory in each system vessel is calculated in the rows at the top of each page. For example, the "B" module reaction tanks contained 1,000 mg/L formate (as formate ion) on the first day (9/7/94). The total reaction tank volume was about 346,000 gallons. The estimated formate inventory in the liquid inventory for this module was 2,744 lbs. The formate content of the solids in each tank was not measured, but was assumed to be the same as that measured in the filter cake solids. The amount of formate in the solid phase is much less than that in the liquid phase. The formate inventory change term in the material balance for a given test period was calculated as the difference in the total liquid-phase formate inventory at the beginning and end of the test period.

The total system liquid- and solid-phase formate inventory is shown at the bottom of columns 8 and 10. On the first day of the test, the liquid inventory was about 39,000 lbs, and the solid inventory was about 1,700 lbs (as formate ion). The next entry below the inventory estimate is the total inventory change since the previous day. This entry (as well as other entries below) is "0" for the first day.

The next group of three entries are the amounts of 40% sodium formate solution in the tanker in gallons and pounds and the calculated amount added since the previous test day. These amounts were determined by gauging the tanker. Note that the tanker was refilled with 45,500 lbs of sodium formate solution between the second and final inventories.

Table B-1

Detailed Formate Material Balance Data

DATE: 9/07/94
Time: 0700

Sample location	Tank Multiplier (gal/ft)	Tank Height (%)	Tank Height (ft)	Tank Vol. (gal)	Liquid Formate (mg/L)	Estimated % Solids	Formate in Liquid (lb)	Formate in Solids (%)	Formate in Solids (lb)
A MODULE	14420	100	24	346080	0	9.3	0	0.000	0
B MODULE	14420	100	24	346080	1000	11.0	2744	0.074	254
C MODULE	14420	100	24	346080	1045	9.3	2891	0.074	213
D MODULE	14420	100	24	346080	0	9.3	0	0.000	0
E MODULE	14420	100	24	346080	1090	7.6	3040	0.074	173
F MODULE	14420	100	24	346080	1045	9.3	2891	0.074	213
A THICKENER	133000		10.5	1396500	810	0.0	9432	0.074	2
B THICKENER	133000		11.2	1489600	1170	3.0	14350	0.074	283
LS SLURRY STORAGE A	7200	64	20.5	147456	765	35.0	767	0.000	0
LS SLURRY STORAGE B	7200	90	28.8	207360	905	35.0	1276	0.000	0
UNDERFLOW STORAGE A	6400	42	13.0	83328	1080	40.0	586	0.074	271
UNDERFLOW STORAGE B	6400	50	15.5	99200	1080	40.0	697	0.074	322
SUPERNATE TANK	6790		9.5	64505	835	0.0	449		
FILTRATE TANK	1700		11.0	18700	1080	0.0	168		
TOTALS				5583129			39291		1732

TOTAL LIQUID-PHASE FORMATE INVENTORY CHANGE	0
TANKER LEVEL (GAL)	5999
40% SODIUM FORMATE IN TANKER (LBS)	63964
40% SODIUM FORMATE ADDED SINCE LAST INVENTORY (LBS)	0
LIMESTONE USED SINCE LAST INVENTORY (TONS)	0
ASSUMED AVERAGE UTILIZATION (%)	90
TONS SO2 REMOVED SINCE LAST INVENTORY (BASED ON LIMESTONE)	0
TONS SO2 REMOVED SINCE LAST INVENTORY (BASED ON CEM)	0
FILTER CAKE PRODUCED SINCE LAST INVENTORY (TONS)	0
AVERAGE CAKE SOLIDS CONTENT (%)	76
FORMATE LOST WITH CAKE LIQUID SINCE LAST INVENTORY (LBS)	0
FORMATE LOST WITH CAKE SOLIDS SINCE LAST INVENTORY (LBS)	0
FORMATE SOLUTION LOSS (LB/TON SO2)	0
FORMATE NON SOLUTION LOSS (LB/TON SO2)	0
TOTAL FORMATE CONSUMPTION (LB/TON SO2)	0
TOTAL SODIUM FORMATE CONSUMPTION (LB/TON SO2)	0

Table B-1

(Continued)

DATE: 9/09/94
Time: 0710

Sample location	Tank Multiplier (gal/ft)	Tank Height (%)	Tank Height (ft)	Actual Tank Vol. (gal)	Liquid Formate (mg/L)	Estimated % Solids	Formate in Liquid (lb)	Formate in Solids (%)	Formate in Solids (lb)
A MODULE	14420	100	24	346080	0	9.3	0	0.000	0
B MODULE	14420	100	24	346080	1050	15.1	2820	0.076	367
C MODULE	14420	100	24	346080	1140	12.9	3097	0.076	310
D MODULE	14420	100	24	346080	0	9.3	0	0.000	0
E MODULE	14420	100	24	346080	1080	11.2	2961	0.076	265
F MODULE	14420	100	24	346080	1200	18.3	3165	0.076	454
A THICKENER	133000		10.5	1396500	710	0.0	8267	0.076	2
B THICKENER	133000		11.2	1489600	1300	3.0	15945	0.076	291
LS SLURRY STORAGE A	7200	90	28.8	207360	970	35.0	1367	0.000	0
LS SLURRY STORAGE B	7200	64	20.5	147456	990	35.0	992	0.000	0
UNDERFLOW STORAGE A	6400	55	17.1	109120	1100	40.0	781	0.076	364
UNDERFLOW STORAGE B	6400	62	19.2	123008	1100	40.0	881	0.076	410
SUPERNATE TANK	6790		9.5	64505	980	0.0	527		
FILTRATE TANK	1700		11.0	18700	1100	0.0	172		
TOTALS				5632729			40975		2464

TOTAL LIQUID-PHASE FORMATE INVENTORY CHANGE SINCE 9/7 (LBS)	1684
TANKER LEVEL (GAL)	4103
40% SODIUM FORMATE IN TANKER (LBS)	43748
40% SODIUM FORMATE ADDED SINCE LAST INVENTORY (LBS)	20216
LIMESTONE USED SINCE 9/7 INVENTORY (TONS)	815
ASSUMED AVERAGE UTILIZATION (%)	90
TONS SO2 REMOVED SINCE 9/7 INVENTORY (BASED ON LIMESTONE)	427
TONS SO2 REMOVED SINCE 9/7 INVENTORY (BASED ON CEM)	522
FILTER CAKE PRODUCED SINCE 9/7 INVENTORY (TONS)	1316
AVERAGE CAKE SOLIDS CONTENT (%)	76
FORMATE LOST WITH CAKE LIQUID SINCE LAST INVENTORY (LBS)	697
FORMATE LOST WITH CAKE SOLIDS SINCE LAST INVENTORY (LBS)	1494
FORMATE SOLUTION LOSS (LB/TON SO2)	1.3
FORMATE NON SOLUTION LOSS (LB/TON SO2)	5.7
TOTAL FORMATE CONSUMPTION (LB/TON SO2)	7.0
TOTAL SODIUM FORMATE CONSUMPTION (LB/TON SO2)	10.6

Table B-1

(Continued)

DATE: 9/12/94
Time: 0710

Sample location	Tank Multiplier (gal/ft)	Tank Height (%)	Tank Height (ft)	Actual Tank Vol. (gal)	Liquid Formate (mg/L)	Estimated % Solids	Formate in Liquid (lb)	Formate in Solids (%)	Formate in Solids (lb)
A MODULE	14420	100	24	346080	0	9.3	0	0.000	0
B MODULE	14420	100	24	346080	1045	12.9	2839	0.089	363
C MODULE	14420	100	24	346080	1100	15.2	2952	0.089	434
D MODULE	14420	100	24	346080	0	9.3	0	0.000	0
E MODULE	14420	100	24	346080	1070	9.8	2953	0.089	270
F MODULE	14420	100	24	346080	1250	14.4	3370	0.089	407
A THICKENER	133000		10.5	1396500	850	0.0	9897	0.089	3
B THICKENER	133000		11.2	1489600	900	3.0	11039	0.089	341
LS SLURRY STORAGE A	7200	70	22.4	161280	990	35.0	1085	0.000	0
LS SLURRY STORAGE B	7200	91	29.1	209664	990	35.0	1411	0.000	0
UNDERFLOW STORAGE A	6400	51	15.8	101184	1100	40.0	725	0.089	395
UNDERFLOW STORAGE B	6400	63	19.5	124992	1100	40.0	895	0.089	488
SUPERNATE TANK	6790		9.5	64505	990	0.0	532		
FILTRATE TANK	1700		11.0	18700	1100	0.0	172		
TOTALS				5642905			37870		2702

TOTAL LIQUID-PHASE FORMATE INVENTORY CHANGE SINCE 9/9 (LBS)	-3105
TANKER LEVEL (GAL)	5534
40% SODIUM FORMATE IN TANKER (LBS)	59006
40% SODIUM FORMATE ADDED SINCE LAST INVENTORY (LBS)	30322
LIMESTONE USED SINCE 9/9 INVENTORY (TONS)	1525
ASSUMED AVERAGE UTILIZATION (%)	90
TONS SO_2 REMOVED SINCE 9/9 INVENTORY (BASED ON LS)	799
TONS SO_2 REMOVED SINCE 9/9 INVENTORY (BASED ON CEM)	824
CAKE PRODUCED SINCE 9/9 INVENTORY (TONS)	2007
AVERAGE CAKE SOLIDS CONTENT (%)	77
FORMATE LOST WITH CAKE LIQUID SINCE LAST INVENTORY (LBS)	1007
FORMATE LOST WITH CAKE SOLIDS SINCE LAST INVENTORY (LBS)	2557
FORMATE SOLUTION LOSS (LB/TON SO_2)	1.2
FORMATE NON SOLUTION LOSS (LB/TON SO_2)	12.3
TOTAL FORMATE CONSUMPTION (LB/TON SO_2)	13.5
TOTAL SODIUM FORMATE CONSUMPTION (LB/TON SO_2)	20.4

The next group of entries includes data used to estimate the total tons of SO_2 removal for each test day. Daily limestone weigh belt readings and differences in limestone slurry tank levels from day to day were used for one estimate of SO_2 removal. The solids content of the limestone slurry and the average utilization had to be assumed for this calculation. This result is shown as "tons SO_2 removed since last inventory (based on LS)." The next line, "tons SO_2 removed since last inventory (based on CEM)," 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. This value is expected to be more accurate than the value estimated from limestone consumption.

The next group of entries estimate the amount of formate leaving the system with the filter cake. 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 measured. The formate concentration in the filter cake liquid was assumed to be the same as that of the filtrate, which was measured.

On the second and third pages of Table B-1, the concentrations of formate in each vessel are shown for the second and third inventory days, and the calculated quantities appear as described above. The final four entries show the calculated solution and nonsolution loss rates and the total formate and sodium formate consumption rates since the previous inventory. The overall average consumption results shown in Table 2-3 were calculated for the period between the first and final inventories.

Slurry samples were obtained from each of the operating modules during the consumption test. Results of the solid- and liquid-phase analyses are shown in Tables B-2 and B-3. In these tables, the sample designation "B-9/7", for example, refers to the slurry sample from the B Module taken during the 9/7/94 inventory. The remainder of the tables have the same format as those presented for the baseline and parametric test slurry analyses. The molar closure results for the long-term solid and liquid analyses indicate good data quality for all of the samples except solid C-9/12. The calcium analysis for this sample appears to be low.

Table B-2

Results of Consumption Test Solids Analyses

Description	B-9/7	B-9/9	B-9/12	C-9/9	C-9/12	E-9/7	E-9/9	E-9/12	F-9/9	F-9/12
Date	9/7/9	9/9/94	9/12/94	9/9/94	9/12/94	9/7/94	9/9/94	9/12/94	9/9/94	9/12/94
Time	1126	0758	0744	0810	0756	1113	0747	0733	0824	0810
Ca, mm/g	7.32	7.18	7.21	7.22	6.15	7.22	7.17	7.20	7.22	7.13
Mg, mm/g	0.26	0.30	0.19	0.36	0.12	0.20	0.20	0.29	0.26	0.23
SO$_3$, mm/g	6.58	6.53	6.66	6.23	6.92	6.72	6.80	6.35	6.63	6.60
Total S (as SO$_4$), mm/g	6.77	6.68	6.85	6.37	7.08	6.93	7.01	6.53	6.78	6.75
SO$_4$, mm/g	0.19	0.15	0.19	0.14	0.16	0.21	0.21	0.19	0.15	0.15
CO$_3$, mm/g	0.97	1.02	0.87	1.51	0.60	0.74	0.64	1.18	0.92	0.92
Inerts, wt%	0.75	0.83	0.72	0.72	0.80	0.96	1.00	1.04	0.92	0.68
Solids, wt%	10.3	14.1	12.1	11.1	7.6	5.3	9.2	10.8	12.2	14.0
NYSEG S.G.	1.081	1.109	1.094	1.094	1.11	1.059	1.082	1.073	1.132	1.104
Estimated wt% Solids	11.0	15.1	12.9	12.9	15.2	7.6	11.2	9.8	18.3	14.4
pH	5.70	5.73	5.51	5.69	5.60	5.72	5.60	5.64	5.64	5.64
Temperature, C	50.9	50.9	50.1	50.9	50.6	50.6	50.1	51.1	51.1	50.5
Reagent Utility, %										
Ca-Independent	87.5	86.7	88.7	80.8	92.2	90.4	91.6	84.7	88.1	88.0
SO$_4$-Independent	87.2	86.4	88.2	80.1	90.4	90.0	91.3	84.3	87.7	87.5
CO$_3$-Independent	89.3	89.3	92.6	84.1	113.1	93.5	95.1	87.2	90.7	91.6
Reagent Ratio										
Ca-Independent	1.14	1.15	1.13	1.24	1.08	1.11	1.09	1.18	1.14	1.14
SO$_4$-Independent	1.15	1.16	1.13	1.25	1.11	1.11	1.10	1.19	1.14	1.14
CO$_3$-Independent	1.12	1.12	1.08	1.19	0.88	1.07	1.05	1.15	1.10	1.09
Oxidation, %	2.8	2.2	2.8	2.2	2.3	3.0	3.0	2.8	2.2	2.2
Solid Solution, wt%	87.6	86.4	88.7	82.4	91.6	89.7	90.8	84.6	87.7	87.3
Gypsum wt%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CaCO$_3$, wt%	9.7	10.2	8.7	15.1	6.0	7.4	6.4	11.8	9.2	9.2
Inerts	0.8	0.8	0.7	0.7	0.8	1.0	1.0	1.0	0.9	0.7
Ca, mg/g	293	287	288	289	246	289	287	288	289	285
Mg, mg/g	6	7	5	9	3	5	5	7	6	6
SO$_3$, mg/g	526	522	533	498	554	538	544	508	530	528
Total S (as SO$_4$), mg/g	650	641	658	611	680	665	673	627	651	648
SO$_4$, mg/g	18	14	19	13	16	20	20	18	14	14
CO$_3$, mg/g	58	61	52	91	36	44	38	71	55	55
Closures										
Weight, %	-3.0	-3.9	-3.4	-3.6	-7.4	-3.2	-3.3	-3.9	-3.5	-4.4
Molar, %	-1.0	-1.4	-2.1	-2.0	-10.2	-1.7	-1.9	01.4	-1.5	-2.0
Acceptable, %	6.5	6.4	6.5	6.3	6.7	6.6	6.6	6.4	6.5	6.5

Table B-3

Results of Consumption Test Liquids Analyses

Description	B-9/7	B-9/9	B-9/12	C-9/9	C-9/12	E-9/7	E-9/9	E-9/12	F-9/9	F-9/12
Date	9/7/94	9/9/94	9/12/94	9/9/94	9/12/94	9/7/94	9/9/94	9/12/94	9/9/94	9/12/94
Time	1126	0758	0744	0810	0756	1113	0747	0733	0824	0810
Ca, mm/L	30.2	30.1	29.7	32.9	30.7	31.4	30.0	29.7	32.3	31.2
Mg, mm/L	208.3	219.9	214.2	227.1	218.7	208.0	212.2	210.4	227.4	226.5
Na, mm/L	84.4	89.4	90.9	107.4	91.0	85.6	86.7	87.2	94.0	94.4
Cl, mm/L	470.6	495.3	498.0	532.3	510.2	482.0	491.7	479.7	542.5	537.8
CO_3, mm/L	6.4	5.3	7.2	6.0	7.0	5.9	5.5	7.4	6.6	10.0
SO_3, mm/L	4.7	4.4	6.2	4.6	5.7	5.6	5.3	6.8	4.6	4.5
SO_4, mm/L	3.4	3.2	3.9	2.9	3.3	4.5	4.0	3.7	2.9	2.6
S_2O_3, mm/L	6.2	6.4	6.8	7.0	6.8	6.0	6.4	6.8	7.1	7.5
Total Hyd SO_4, mm/L	33.7	32.7	38.3	36.0	39.1	36.1	37.5	38.0	36.5	36.9
S/N, mm/L	13.1	12.3	14.6	14.4	16.5	14.0	15.4	13.9	14.8	14.8
HCO^{O-}, mm/L	22.2	23.3	23.2	25.3	24.3	24.1	24.0	23.8	26.7	26.2
pH	5.70	5.73	5.51	5.69	5.60	5.72	5.60	5.64	5.64	5.64
Temperature, C	50.9	50.9	50.1	50.9	50.6	50.6	50.1	51.1	51.1	50.5
Ca, mg/L	1210	1205	1191	1319	1232	1258	1203	1190	1294	1250
Mg, mg/L	5063	5346	5208	5522	5318	5056	5160	5114	5528	5507
Na, mg/L	1939	2054	2090	2469	2092	1968	1993	2004	2161	2170
Cl, mg/l	16682	17559	17652	18869	18085	17087	17429	17007	19231	19064
CO_3, mg/L	387	319	432	358	422	356	332	446	397	598
SO_3, mg/L	376	349	494	372	457	451	421	541	364	358
SO_4, mg/L	331	311	376	280	315	431	381	351	279	253
S_2O_3, mg/L	697	714	759	788	762	672	722	764	796	839
HCO^{O-}, mg/L	999	1048	1045	1139	1096	1087	1081	1071	1202	1179
Charge Imbalance										
Calculated, %	2.7	2.9	1.3	2.4	1.0	1.5	1.2	1.9	0.3	0.4
Acceptable, %	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.2	6.2
Relative Saturation										
Gypsum	0.05	0.04	0.05	0.04	0.04	0.06	0.05	0.05	0.04	0.03
$CaSO_3$*$0.5H_2O$	2.5	2.4	2.5	2.5	2.6	3.1	2.4	3.3	2.3	2.2
$CaCO_3$	0.09	0.08	0.05	0.09	0.07	0.10	0.05	0.08	0.08	0.12

APPENDIX C

Other Process Data

Table C-1

Other Process Data for the Baseline and Parametric Tests

Test No.	Run No.	Date	Time	Gross Load (MW)	O_2 Boiler (%)[1]	O_2 FGD in (%)	No. of Mods	FGD In SO_2 (ppm)	FGD In SO_2 (lb/10^6Btu)	Stack SO_2 (lb/10^6Btu)	Stack CO_2 (%)	Stack Temp (F)	ID Fan Current (amps)[2]	FGD in Pressure (in WG)	Bypass Damper (% open)[3]	Module E ΔP (in WG)
Inlet	1	7/18/94	1412-1442	-	-	-	-	1338	-	-	-	-	-	-	-	-
Inlet	2	7/18/94	1450-1520	693	3	6.7	-	1352	3.17	0.59	12	129	510	4.5	6.2	-
Inlet	3	7/18/94	1533-1603	692	3	6.8	-	1329	3.14	0.59	12	129	510	4.5	6.2	-
B-1	1	7/19/94	0900-1040	690	3.1	6.7	4	1567	3.74	0.57	11.9	130	519	4.8	12.4	2.2
B-1	2	7/19/94	1104-1159	691	3	6.7	4	1567	3.75	0.56	11.9	130	520	4.7	8.0	2.3
B-1	3	7/19/94	1353-1423	699	3	6.8	4	1578	3.78	0.54	12	130	520	4.8	8.0	2.3
B-1	4	7/19/94	1444-1514	698	3.1	6.9	4	1530	3.68	0.55	11.9	129	536	5	8.0	2.3
B-1	5	7/19/94	1534-1617	700	3.8	7.3	4	1477	3.45	0.49	11.4	129	522	4.9	8.0	2.3
B-1	6	7/19/94	1635-1705	693	3.4	7.1	4	1472	3.54	0.51	11.6	129	517	4.8	8.1	2.3
B-2	1	7/20/94	0943-1018	694	3.3	7	4	1367	3.37	0.65	12	129	522	4.8	6.4	2.5
B-2	2	7/20/94	1040-1110	697	3.3	6.9	4	1543	3.78	0.58	11.9	129	527	5.1	8.6	2.5
B-3	1	7/20/94	1403-1433	697	3.5	7	4	1596	3.81	0.54	11.6	129	548	5.2	7.0	2.4
B-3	2	7/20/94	1452-1522	696	3.4	7	4	1538	3.61	0.5	11.6	129	538	5	6.9	2.4
B-4	1	7/21/94	0824-0854	695	3.2	7.2	4	1768	4.42	0.64	11.7	127	527	5.2	0.0	2.2
B-4	2	7/21/94	0916-0947	702	3	6.9	4	1801	4.42	0.62	11.9	128	526	5.2	8.4	2.2
B-5	1	7/21/94	1032-1103	704	3.2	7.1	4	1763	4.34	0.59	11.7	129	531	5.3	17.8	2.4
B-5	2	7/21/94	1121-1152	704	3.1	7.2	4	1734	4.28	0.59	11.7	131	530	5.3	17.2	2.6
B-5A	1	7/21/94	1604-1632	694	3.2	7	4	1804	4.38	0.59	11.4	130	530	5.4	0.0	2.4
B-6	1	7/22/94	0912-0939	693	3.0	6.6	4	1538	3.99	0.61	12.0	13.0	480	4.7	4.7	2.0
B-6	2	7/22/94	0956-1023	693	3.0	6.6	4	1660	4.03	0.57	11.9	12.9	478	4.7	11.6	2.0
B-7	1	7/22/94	1045-1112	696	3.1	6.7	4	1660	4.07	0.56	11.8	13.1	526	5.0	13.9	2.5

Table C-1

(Continued)

Test No.	Run No.	Date	Time	Gross Load (MW)	O_2 Boiler (%)[1]	O_2 FGD in (%)	No. of Mods	FGD In SO_2 (ppm)	FGD In SO_2 (lb/10^6Btu)	Stack SO_2 (lb/10^6Btu)	Stack CO_2 (%)	Stack Temp (F)	ID Fan Current (amps)[2]	FGD in Pressure (in WG)	Bypass Damper (% open)[3]	Module E ΔP (in WG)
B-7	2	7/22/94	1130-1157	698	3.1	6.7	4	1706	4.05	0.56	11.8	13.1	519	4.9	17.0	2.5
B-8	1	7/23/94	0830-0857	700	3.1	6.6	5	1267	3.09	0.51	11.9	12.7	505	3.7	0.8	2.0
B-8	2	7/23/94	0914-0941	709	3.0	6.6	5	1320	3.23	0.51	12.1	12.7	515	4.2	0.8	2.0
Inlet	-	8/22/94	0950-1010	690	3.0	6.8	4	1876	4.50	0.55	11.5	126	524	5.0	-6	N/A
Inlet	-	8/22/94	1036-1056	694	2.9	6.7	4	1875	4.51	0.56	11.6	126	525	4.9	2	N/A
Inlet	-	8/22/94	1114-1134	699	3.0	6.8	4	1905	4.54	0.57	11.7	127	523	5.0	2	N/A
P-1	1	8/22/94	1640-1720	690	3.0	6.7	4	1941	4.65	0.55	11.7	127	522	5.0	2	N/A
P-1	2	8/23/94	0950-1019	406	6.4	9.9	3	1430	4.28	0.54	8.8	129	430	4.0	22	N/A
P-1	3	8/23/94	1150-1218	386	6.6	10.1	3	1361	4.26	0.55	8.6	130	434	4.1	23	N/A
P-1	4	8/23/94	1351-1418	477	5.6	9.1	3	1531	4.40	0.57	9.5	128	454	4.9	15	N/A
P-1	5	8/23/94	1451-1521	489	5.5	9.0	3	1553	4.39	0.58	9.6	128	470	5.0	15	N/A
P-1	6	8/23/94	1555-1622	510	5.0	8.4	4	1603	4.42	0.49	9.9	127	-	3.6	15	N/A
P-1	7	8/23/94	1647-1714	502	5.3	8.8	4	1567	4.38	0.54	9.8	128	464	3.7	20	N/A
P-2	1	8/24/94	0938-1005	282	6.8	10.3	2	1272	4.04	0.54	8.4	128	283	4.4	22	N/A
P-2	2	8/24/94	1026-1053	290	6.7	10.2	2	1284	4.07	0.57	8.4	131	303	5.4	22	N/A
P-2	3	8/24/94	1445-1512	424	6.4	9.6	3	1451	4.20	0.95	-	124	333	4.6	22	N/A
P-2	4	8/24/94	1535-1602	382	6.5	9.6	3	1381	4.11	0.26	8.5	123	351	4.9	-3	N/A
P-2	5	8/25/94	1911-0939	398	6.3	9.5	3	1328	3.97	-	-	123	328	4.4	-6	N/A
P-2	6	8/25/94	1005-1032	432	6.0	9.0	3	1340	4.10	-	-	124	363	5.0	2	N/A
P-3	1	8/25/94	1253-1321	670	3.0	6.5	4	1809	4.22	-	-	127	481	5.0	-6	N/A
P-3	2	8/25/94	1347-1415	674	3.1	6.6	4	1789	4.20	-	-	127	477	4.8	-6	N/A

Table C-1

(Continued)

Test No.	Run No.	Date	Time	Gross Load (MW)	O_2 Boiler (%)[1]	O_2 FGD In (%)	No. of Mods	FGD In SO_2 (ppm)	FGD In SO_2 (lb/10^6Btu)	Stack SO_2 (lb/10^6Btu)	Stack CO_2 (%)	Stack Temp (F)	ID Fan Current (amps)[2]	FGD In Pressure (in WG)	Bypass Damper (% open)[3]	Module E ΔP (in WG)
P-4	1	8/25/94	1522-1539	673	3.0	7.1	4	1729	4.23	0.30	11.5	127	543	4.9	-6	N/A
P-4	2	8/25/94	1610-1637	682	3.0	-	4	1738	-	0.48	11.5	127	522	4.6	-6	N/A
P-5	1	8/26/94	0818-0910	535	4.7	8.0	4	1587	4.33	0.56	9.9	128	498	3.5	14	N/A
P-5	2	8/26/94	0929-1021	571	4.4	7.9	4	1654	4.38	0.57	10.5	128	388	3.7	14	N/A
P-6	1	8/26/94	1045-1113	643	3.3	7.0	4	1765	4.43	0.58	11.4	127	438	4.3	14	N/A
P-6	2	8/26/94	1133-1200	680	3.0	6.6	4	1844	4.40	0.58	11.5	129	481	4.6	15	N/A
P-7	1	8/26/94	1436-1505	665	3.0	6.7	4	1877	4.40	0.46	11.2	130	483	4.7	12	N/A
P-7	2	8/26/94	1524-1551	670	3.0	6.5	4	1867	4.41	0.48	11.3	130	492	4.9	-6	N/A
P-8	1	8/26/94	1632-1700	681	3.0	6.5	4	1878	4.38	0.51	11.3	129	496	5.3	-5	N/A
P-8	2	8/26/94	1718-1745	695	3.0	6.5	4	1868	4.39	0.40	11.4	129	516	5.2	3	N/A
P-9	1	8/29/94	0904-0954	574	4.2	8.0	4	1677	4.36	0.31	10.5	123	393	4.0	6	N/A
P-9	2	8/29/94	1016-1107	615	3.8	7.2	4	1755	4.36	0.36	10.9	126	462	4.5	15	N/A
P-9	3	8/29/94	1130-1157	655	3.2	6.9	4	1851	4.43	0.37	11.3	127	450	4.6	15	N/A
P-9	4	8/29/94	1219-1246	646	3.2	6.9	4	1827	4.48	0.39	11.3	127	455	4.6	16	N/A
P-9	5	8/29/94	1517-1544	555	4.7	8.1	4	1713	4.47	0.25	10.0	123	419	4.9	-6	N/A
P-9	6	8/29/94	1604-1631	552	4.7	8.1	4	1687	4.51	0.23	10.0	123	419	4.9	-6	N/A
P-10	1	8/30/94	0948-1108	373	6.5	9.8	3	1508	4.59	0.28	8.7	122	320	4.1	0	N/A
P-10	2	8/30/94	1133-1251	373	6.6	9.8	3	1540	4.63	0.28	8.7	120	316	4.0	0	N/A

Notes:

(1) Boiler % O_2 is average of east and west monitors.

(2) ID fan motor current is sum of amps on fans 1A, 1B, and 1C.

(3) Bypass damper A position is shown; other bypass dampers are closed.

Table C-2

Other Process Data for the Sodium Formate Consumption Test [a]

Date	Gross Load (MW)	Boiler O_2 (%)	FGD Inlet O_2 (%)	FGD Inlet SO_2 (lb/10^6Btu)	Stack SO_2[b] (lb/10^6Btu)	Stack CO_2 (%)	Stack Temp (F)	ID Fan Current (amps)	FGD Inlet Pressure (in WG)	Bypass Damper (% open)
9/7/94	573	4.2	7.7	3.69	0.48	10.6	129	440	3.7	24
9/9/94	662	3.1	6.9	4.02	0.50	11.3	130	472	3.8	20
9/10/94	667	3.1	6.9	3.96	0.43	11.4	129	467	3.8	21
9/11/94	627	3.6	7.4	4.46	0.54	10.9	128	450	3.8	19
9/12/94	652	3.3	7.0	4.42	0.54	11.1	128	453	3.8	19

[a] Data represent average conditions for the previous 24-hour period as of 0700 on each day.

[b] Stack SO_2 includes partial bypass.

APPENDIX D

FGDPRISM Calibration

The FGDPRISM calibration involves an iterative process in which the parameters are adjusted to obtain the best overall fit to the performance data. The steps used in the Kintigh FGDPRISM calibration procedure are summarized below:

1. Test results were reviewed to select data sets representative of each baseline and parametric test. Each test had two or more runs that provided SO_2 performance data and samples for laboratory analysis. Baseline Tests 2 and 5, and Parametric Test 10, were selected for use in the calibration. The intent was to select tests with similar gas velocities but a wide range of SO_2 removal efficiency.

2. Liquid-phase analyses from the selected tests were input into the FGDPRISM equilibrium module to determine partial pressure of CO_2 and relative saturations of $CaCO_3$, $CaSO_3 \bullet \frac{1}{2}H_2O$, $CaSO_4 \bullet \frac{1}{2}H_2O$, and $CaSO_4 \bullet 2H_2O$.

3. The FGDPRISM material balance module was run for each calibration case, and the following inputs were adjusted to best match the flue gas, liquid, and solid compositions:

    - Unit load (gas velocity);
    - Coal percent sulfur (FGD inlet SO_2 concentration);
    - Reagent ratio (LS utilization and slurry pH);
    - $CaSO_3$ RS multiplier (RS of $CaSO_3 \bullet \frac{1}{2}H_2O$);
    - Percent oxidation (SO_4 in liquid and solid);
    - Coal chloride content (Cl in liquid);
    - Limestone $MgCO_3$ solubility (Mg in liquid);
    - Makeup water sodium content (Na in liquid); and
    - Makeup water magnesium content (Mg in liquid).

4. Using the FGDPRISM complete system simulation, adjustments were made to the following FGDPRISM system simulation inputs to obtain the best fit to the three calibration cases:

    - Gas-film thickness;
    - Liquid-film thickness;
    - Limestone reaction rate constant;
    - Limestone surface area factor; and
    - Solid solution rate constant.

    Reagent ratio was also input and adjusted for each of the cases during this calibration.

5. The system simulation model was then run with data from the other baseline tests. However, SO_2 removal results did not match the observed results because of differences in gas velocity. Iterative runs were then made for each case by adjusting the reagent ratio to achieve desired pH levels and then changing the gas-film thickness to reach the desired SO_2 removal. The revised gas-film thickness results are shown in Figure D-1, with a straight line determined by regression analysis. The equation for the line is:

$$\text{Gas-film thickness } (\mu) = -2.016 * (\text{Gas velocity, ft/s}) + 22$$

6. All of the baseline and parametric test cases were then simulated using the gas-film thickness determined by the above equation.

The final calibration parameters were:

Input	Value
Gas-film thickness, microns (at 9 ft/sec)	4.0
Liquid-film thickness, % of droplet diameter	0.06
Reaction rate constant	1.6e-5
Surface area factor	1.0
Solid solution rate constant	3.0e-8

Table D-1 compares predicted and observed results for the calibration cases and the remaining tests. The results of the calibration were very good with respect to agreement between predicted and observed SO_2 removal efficiency. The only case for which the predicted SO_2 removal was substantially different than the actual removal was Baseline Test 4 (58.7% predicted vs. 68.5% actual SO_2 removal). This particular data point lies well outside the range of interest for this project, though. For the remaining 17 cases, the average predicted SO_2 removal efficiency was less than 0.1 percentage points higher than the average observed removal with a standard deviation of only 1.1 SO_2 removal efficiency percentage points.

The agreement between predicted and observed pH and limestone utilization, especially for the low-pH tests, was not as good as that for SO_2 removal. To match the observed

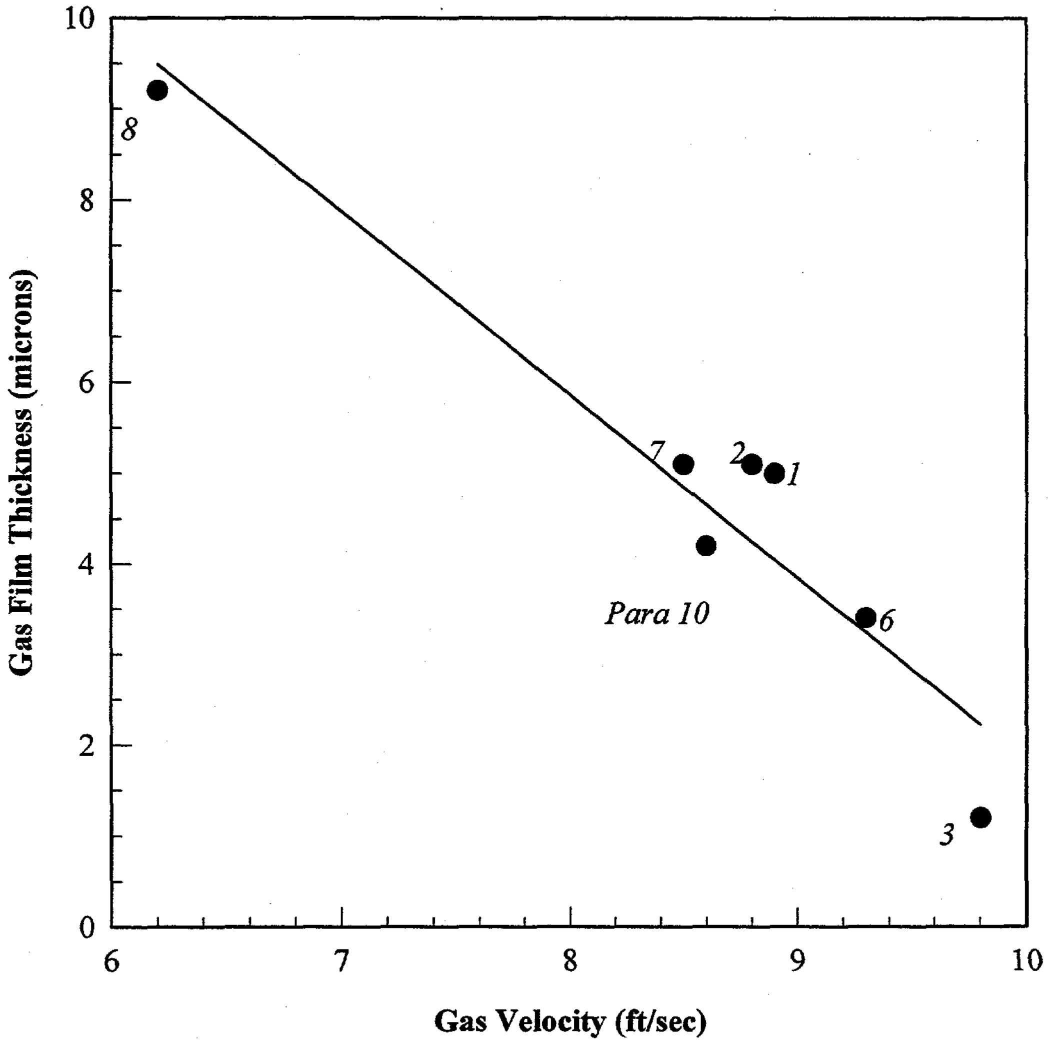

Figure D-1. Kintigh FGDPRISM Calibration: Gas Film Correction

Table D-1

FGDPRISM Calibration Results
Comparison of Observed and Predicted Performance

Test	Gas Velocity ft/sec	Gas Film Thickness microns	Slurry pH		Limestone Utilization		SO_2 Removal Efficiency	
			Predicted	Observed	Predicted	Observed	Predicted	Observed
B-1	8.9	4.05	5.54	5.60	84.0	85.3	88.1	85.9
B-2*	8.8	4.25	5.50	5.58	86.4	86.8	93.8	92.0
B-3	9.8	2.23	5.55	5.59	84.1	86.6	76.2	78.5
B-4	9.3	3.24	5.28	5.02	91.8	86.5	58.7	68.5
B-5*	8.6	4.65	5.28	5.18	90.0	88.5	84.1	84.7
B-6	9.3	3.24	5.77	5.80	63.1	71.9	88.7	88.2
B-7	8.5	4.85	5.75	5.81	63.2	71.4	96.4	96.0
B-8	6.2	9.49	5.64	5.61	86.2	85.0	96.3	96.5
P-1	6.2	9.49	5.61	5.63	89.3	89.7	96.3	98.0
P-2	8.3	5.25	5.68	5.67	83.7	81.2	98.6	98.5
P-3	7.4	7.07	5.62	5.64	86.3	86.3	98.5	99.1
P-4	8.1	5.66	5.56	5.59	85.2	85.2	96.8	96.6
P-5	6.1	9.69	5.86	5.83	79.8	79.3	98.3	99.2
P-6	8.1	5.66	5.84	5.88	62.9	74.5	96.5	97.4
P-7	8.4	5.05	5.12	5.13	94.0	79.6	93.5	92.3
P-8	8.4	5.05	5.21	5.24	94.2	90.4	98.0	96.6
P-9	8.5	4.85	5.49	5.54	88.9	86.9	98.4	98.4
P-10*	8.6	3.24	5.63	5.68	87.7	88.5	99.9	99.5

* These tests used in calibration.

pH for the low-pH tests (Baseline Tests 4 and 5, Parametric Tests 7 and 8), FGDPRISM required that significantly higher limestone utilization be used as input than was actually measured in three of the four cases. Conversely, to match the tests at high pH (Baseline Tests 6 and 7, Parametric Tests 5 and 6), FGDPRISM required significantly lower utilization as input than was actually observed in three of the four cases.

APPENDIX E

Detailed Economic Calculations

Table E-1 includes more detail with respect to the added costs of SO_2 removal for the cases shown in Table 4-2. Table E-1 also includes costs for additional options that were less cost-effective than those shown in Table 4-2.

Table E-1

Economic Comparison of SO_2 Removal Upgrade Options

						Additional $/Year						Cost of Add'l SO_2 Removal		Net Annual Value ($ Thousand)	
Option	pH	Formate (mg/L)	LS Util	SO_2 % Removal	Add'l SO_2 Removed (tons)	NaCOOH Capital	NaCOOH	Add'l Fan KW	Add'l Pump KW	Add'l Reagent	Add'l Sludge	Total Annual Cost $	Avg $/ton SO_2	@ $250/ton	@ $150/ton
Current operation (4 pumps)	5.6	0	85	85.0	0	0	0		0	0	0	0			
Close bypass (4 pumps)	5.6	0	85	88.0	2500	0	0	28000		57000	43000	128000	51	500	250
Close bypass (4 pumps) Use finer grind	5.8	0	85	96.8	9840	0	0	28000		326000[a]	167000	521000	53	1940	960
Close bypass (4 pumps) Add formate	5.6	1000	85	97.8	10640	55000	301000	28000		245000	181000	810000	76	1850	790
Close bypass (3 pumps) Add formate	5.6	1250	85	96.7	9730	57000	372000	19000	-152000	224000	165000	685000	70	1750	770
Maintain bypass (4 pumps) Add formate	5.6	1000	85	94.8	8140	55000	292000			187000	138000	672000	83	1360	550
Close bypass (4 pumps) Add formate, Lower pH	5.2	1250	89	95.4	8680	57000	367000	28000		117000	143000	712000	82	1460	590
Close bypass (4 pumps) Add formate, Higher pH	5.8	750	72	97.9	10770	53000	226000	28000		586000	199000	1092000	101	1600	520

Table E-1

(Continued)

						Additional $/Year						Cost of Add'l SO_2 Removal		Net Annual Value ($ Thousand)	
Option	pH	Formate (mg/L)	LS Util	SO_2 % Removal	Add'l SO_2 Removed (tons)	NaCOOH Capital	NaCOOH	Add'l Fan KW	Add'l Pump KW	Add'l Reagent	Add'l Sludge	Total Annual Cost $	Avg $/ton SO_2	@ $250/ton	@ $150/ton
Maintain current SO_2 removal (2 pumps)	5.6	670	85	85.0		51000	175000	-19000	-305000	0	0	-98000			
Add formate (3 pumps)	5.6	125	85	85.0		40000	33000	-9000	-152000	0	0	-88000			
Maintain current SO_2 removal, Finer grind (4 pumps)	5.5	0	98	85.0		0	0	0	0	-116000[a]	-108000	-224000			

[a] Increased reagent cost includes $100,000/year for increased reagent preparation O&M.