RCN 213-210-04-08

DOE/PC/91338--T22

High SO_2 Removal Efficiency Testing

DE-AC22-92PC91338

Topical Report

PSI Energy's Gibson Station
High SO_2 Removal Efficiency
Test Program

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20 May 1996

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ACKNOWLEDGMENT

DOE wishes to acknowledge the Electric Power Research Institute for its contribution of the FGDPRISM modeling efforts documented in this report, as well as the contributions and efforts of PSI Energy and the staff at the Gibson Station.

SUMMARY

A program was conducted at PSI Energy's Gibson Generating Station to evaluate options for achieving high sulfur dioxide (SO_2) removal efficiency with the Unit 5 wet limestone flue gas desulfurization (FGD) system. This 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 (CAAA). The Gibson FGD system employs four absorber modules of the Kellogg/Weir horizontal gas flow design and uses limestone reagent with two additives. Dolomitic lime is added to introduce magnesium to increase liquid-phase alkalinity, and sulfur is added to inhibit sulfite oxidation.

The high-efficiency options tested involved using sodium formate or dibasic acid (DBA) as a performance additive, increasing the absorber liquid-to-gas ratio (L/G), and/or increasing the limestone reagent stoichiometry. The unit changed coal sources during the test program. However, the Electric Power Research Institute's (EPRI) FGD PRocess Integration and Simulation Model (FGDPRISM) was calibrated to the system and used to compare options on a consistent basis. An economic analysis was then done to determine the cost-effectiveness of each high-efficiency option. The results from this program are summarized below.

SO_2 Removal Performance. Baseline tests on one module of the Gibson FGD system showed an SO_2 removal efficiency of 86% at design operating conditions but while the unit was firing a coal with a lower-than-normal 2.4% sulfur content. System design operating conditions include a pH set point of 5.3, with three of four modules and four pumps per module in service. These conditions produce a superficial gas velocity of 27 ft/sec through the absorbers and an L/G of 73 gallons per 1000 actual cubic feet (gal/kacf) of flue gas treated.

During subsequent performance additive tests, the unit fired a coal with a higher, 3.5% sulfur content. Prior to introducing the performance additive, a test was conducted at an elevated L/G ratio (four modules with four pumps each in service) and an elevated pH set point (~5.7). This test showed that the module SO_2 removal efficiency could be increased to nearly

96% without using additional performance additives. However, at this higher pH set point, limestone utilization decreased to about 73%. Operation at limestone utilization lower than about 80% may cause mist eliminator scaling and is not recommended.

Parametric tests with sodium formate additive showed that, with the higher-sulfur coal, SO_2 removal efficiency could be increased to 88% at design baseline conditions (three-module/four-pump operation and 5.3 pH) with a formate ion concentration of 2750 ppm. This compares with a predicted SO_2 removal of less than 75% at these same high-sulfur-coal conditions without additive. At a formate ion concentration of 1410 ppm, an SO_2 removal efficiency of 97.5% was observed during operation at an elevated L/G ratio of 95 gal/kacf (four-module, four-pump operation) and 5.7 pH.

Additive Consumption. A longer-term, system-wide sodium formate consumption test was conducted at an average unit load of 476 MW and showed that a sodium formate feed rate of about 123 lb/hr (dry basis) was required to maintain a formate ion concentration of 1200 mg/L in the reaction tanks. The consumption rate measured during the test was equivalent to 10.6 lb of sodium formate per ton of SO_2 removed by the FGD system. Approximately half of the consumption was due to non-solution losses from the system, primarily coprecipitation of the additive with the byproduct solids.

Laboratory measurements during these tests suggest that sodium formate has a detrimental effect on solids dewatering properties in the Gibson FGD system. After sodium formate was added to the FGD system, the solids settling rate in slurry samples decreased significantly, and the filter cake solids content measured by the filter leaf test method decreased from 56 to 53%. However, scanning electron microscope (SEM) photographs of solids samples with and without sodium formate present showed no apparent change in crystal size or shape. Longer-term testing would be required to determine if these laboratory test results would be reflected in full-scale dewatering performance.

A system-wide DBA performance and consumption test was also performed. This test, conducted at an average unit load of 534 MW, showed that an average feed rate of about 161 lb/hr of DBA (dry basis) was required to maintain a DBA concentration of 1350 mg/L in the reaction tanks. The measured consumption rate was equivalent to 9.0 lb of DBA per ton of SO_2 removed by the FGD system. Approximately three-fourths of the consumption was due to non-solution losses, with that equally split between coprecipitation and degradation of the additive.

In contrast to the sodium formate results, laboratory measurements during this test suggest that DBA has a beneficial effect on solids dewatering properties in this FGD system. After DBA was added to the FGD system, the measured solids settling rate increased, and the filter-leaf-test filter cake solids content increased by up to 10 percentage points. However, as with the sodium formate test results, SEM photographs of solids samples with and without DBA present showed no apparent change in crystal size or shape.

SO_2 Removal Modeling. Results of the baseline and parametric tests were used to calibrate EPRI's FGDPRISM model to the Unit 5 FGD system. Because the two test series were conducted at significantly different inlet SO_2 levels, FGDPRISM simulations were used to predict a consistent set of performance data to allow a consistent comparison of the various upgrade options. The model was used to evaluate raising the L/G ratio (four-module/four-pump operation), decreasing reagent utilization (higher absorber slurry pH), using sodium formate additive, and using DBA additive, all at a common coal sulfur content of 3.0 wt.%.

Increasing the liquid-phase magnesium concentration (increasing the dolomitic lime feed rate) was also evaluated with the model; however, subsequent economic evaluations showed no clear advantage of this option over those actually tested. Therefore, the increased magnesium option is not discussed further in this summary.

SO_2 Removal Upgrade Economics. The results of the upgrade options were compared with the design baseline operating conditions. These conditions include three-module/four-pump-per-module operation, 85% limestone utilization, 9500 ppm dissolved magnesium concentration, and 6% flue gas bypass around the absorbers, at a unit load of 620 MW. For these conditions, the baseline SO_2 removal efficiency was predicted by the model to be approximately 80% (including the effects of the partial flue gas bypass).

Closing the flue gas bypass and increasing the L/G ratio by operating with all four modules in service resulted in the largest increase in SO_2 removal at the lowest incremental cost. These changes increased the predicted SO_2 removal efficiency to 93%, at an average cost of $48 per additional ton of SO_2 removed. As a result, an additional 13,200 tons of SO_2 could be captured. The other options, when evaluated for the design baseline three-module operation, resulted in smaller increases in SO_2 removal at higher costs.

Therefore, no upgrade option was individually capable of increasing the SO_2 removal to 95% or greater. Since operation with a closed bypass at the high L/G ratio was determined to be the single most cost-effective upgrade, this option was evaluated in combination with the other options. With a closed bypass and high L/G, 95% SO_2 removal could be achieved either with a higher pH set point, thereby lowering the limestone utilization from 85% to 80%, or by using sodium formate or DBA additive at a concentration of 500 ppm. The average costs for achieving 95% SO_2 removal with these options ranged from $59 per ton (80% limestone utilization or 500 ppm DBA) to $65 per ton of additional SO_2 removed (500 ppm formate). At 95% removal, a total of 15,000 additional tons of SO_2 per year can be removed relative to design baseline performance.

The net annual value of each option was also determined by subtracting estimated costs from the potential marketplace value of additional tons of SO_2 or "allowances" (as defined by the 1990 CAAA) removed by that option. Allowances were evaluated at both $250 per ton and $150 per ton. The net annual value of achieving 93% SO_2 removal by operating with a closed bypass and the high L/G was estimated at $2.6 million, assuming an SO_2 allowance value of $250/ton, or $1.3 million at $150/ton. When combined with one of the other three options tested to achieve approximately 95% SO_2 removal, a maximum net annual value of approximately \$2.9 million could be realized at a \$250/ton allowance value or \$1.4 million at \$150/ton.

A sensitivity analysis was performed to examine the impact of more demanding operating conditions: a higher unit load (650 MW), a minimum level of flue gas bypass (5%), and a higher coal sulfur content (3.4%). Again, FGDPRISM was used to predict FGD system performance at these conditions. The model predicted that four-module, four-pump operation would be required to achieve the 82% overall SO_2 removal efficiency necessary for compliance, although this would allow a greater flue gas bypass rate of 12.5%.

For the sensitivity analysis, with four-module, four-pump operation and the flue gas bypass rate reduced to the specified minimum of 5%, sodium formate and DBA additives were each considered as upgrade options. This analysis showed that an overall SO_2 removal of 90% could be achieved with 1000 ppm of either additive. However, a greater maximum net annual value was predicted for DBA additive than for sodium formate. For DBA additive, a maximum net annual value of \$1.5 million was predicted at an allowance value of \$250/ton, and \$0.7 million was predicted for an allowance value of \$150/ton.

1.0 INTRODUCTION

This report describes the results of tests conducted at PSI Energy's Gibson Generating Station to evaluate options for upgrading the Unit 5 flue gas desulfurization (FGD) system's SO_2 removal efficiency. Upgrade options investigated included the use of sodium formate or dibasic acid (DBA) additives, and increases in absorber liquid-to-gas ratio (L/G) and reagent ratio (increased pH set point). The objective of these tests was to obtain performance data needed to evaluate the effectiveness of low capital cost upgrades to an existing FGD system as part of a utility's strategy for meeting Phase I or II requirements of the 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 low capital cost 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's Elrama Station, and New York State Electric and Gas Corporation's 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 includes only the results from the fourth site, at PSI Energy's Gibson Generating Station near Owensville, Indiana.

1.2 Project Description

Four test series were completed at Gibson Station. First, baseline tests were done to obtain performance data without additives. Then, "parametric" tests were done to obtain performance data using sodium formate additive at various concentrations. The baseline and parametric tests were conducted using only one of the four scrubber modules. Following the parametric tests, a steady-state sodium formate consumption test was done, during which sodium formate was added to the entire FGD system. Finally, a similar steady-state performance and consumption test was conducted with DBA additive. DBA is a mixture of adipic, glutamic, and succinic acids, that is a byproduct from the production of adipic acid.

Under a separate project funded by the Electric Power Research Institute (EPRI), the results of the baseline and parametric tests were used to calibrate EPRI's FGD PRocess Integration and Simulation Model (FGDPRISM) to the Gibson scrubber configuration.

FGDPRISM was then used to predict system performance for evaluating conditions other than those tested.

Economic calculations were conducted to determine the most cost-effective approach for achieving the project target of 95 to 98% SO_2 removal with the Gibson FGD system. Actual and predicted performance results, actual steady-state additive consumption data, plus other pertinent cost information provided by PSI Energy provided the basis for the economic evaluation. In this evaluation, the net annual cost increase and average cost of additional tons of SO_2 removed were estimated for different operating conditions. These costs can be compared with the expected market value of SO_2 allowances or the expected cost of allowances generated by other means, such as fuel switching or new scrubbers, to help PSI Energy arrive at the most cost-effective operating conditions for Clean Air Act compliance. Other utilities may use the same methodology used in this project to determine if low capital cost upgrades to their existing FGD systems would also be cost effective.

1.3 Report Organization

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

2.0 TEST CONDITIONS AND RESULTS

This section describes the full-scale FGD system tests conducted at PSI Energy's Gibson Station Unit 5 and provides an overview of the results. The tests evaluated methods for achieving high SO_2 removal efficiency at Gibson and followed a methodology that has been used for other sites included in this DOE-PETC program.

Two different types of tests were conducted in a total of four test series. First, short-term tests were conducted on a single module of the FGD system. These short-term tests included baseline tests to establish the "as-found" performance of the system and parametric tests to determine the effects of sodium formate additive. Next, longer-term additive consumption tests were conducted on the entire Unit 5 FGD system. A sodium formate performance and consumption test was performed immediately following the parametric tests, and a DBA performance and consumption test was performed about four months later. In these long-term tests, the sodium formate and DBA addition rates required to maintain high SO_2 removal efficiency were measured so that the costs of these upgrade approaches could be more accurately determined.

This section presents and discusses the results from each of these four test series at the Gibson site. 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 and DBA additive consumption tests are described in Section 2.6. Following these test results, the effects of the additives on FGD byproduct solids dewatering properties are discussed in Section 2.7. Other process data including slurry flow rate measurements are presented in Section 2.8.

2.1 FGD System Description

The testing described in this section was conducted on the FGD system for Unit 5 of PSI Energy's Gibson Generating Station, located in Gibson County near Owensville, Indiana. Figure 2-1 illustrates the arrangement of a single scrubber module of the Unit 5 FGD system. Flue gas exits the boiler and passes through an ESP for particulate control. From the ESP, the flue gas passes through two ID fans before entering the FGD system. Four modules, each with its own dedicated booster fan, are available to treat flue gas from the 650-MW unit. At full load, the unit can be operated with all four modules in service, or with only three modules in service and the fourth off-line as a spare.

The absorber modules are of the Kellogg/Weir horizontal configuration. In this configuration, flue gas flows horizontally through a rectangular cross-section absorber vessel. Recirculating slurry is introduced through spray headers at the top of the absorber so the spray is directed across the flue gas flow. This is unlike most vertical spray towers where the recirculating slurry flows countercurrent to the direction of gas flow. There are four spray headers on each absorber, with one slurry recirculation pump per header. At full load and for high-sulfur-coal operation, all four pumps and spray headers are normally operated. Flue gas exiting the absorber section flows through a two-stage, horizontal, gas-flow mist eliminator to the stack. A portion of the flue gas bypasses all four absorbers and goes directly to the stack.

After contacting the flue gas, the recirculating slurry drains to a rectangular reaction tank below the absorber. Waste slurry is bled to dewatering from the discharge of the first recycle pump (with respect to the direction of flue gas flow). Fresh limestone reagent slurry is fed at the opposite end of the tank. Dolomitic lime is slaked and mixed with the limestone slurry to introduce magnesium as an additive to increase SO_2 removal efficiency. Elemental sulfur is also added to the reagent slurry tank for in-situ generation of thiosulfate to inhibit sulfite oxidation.

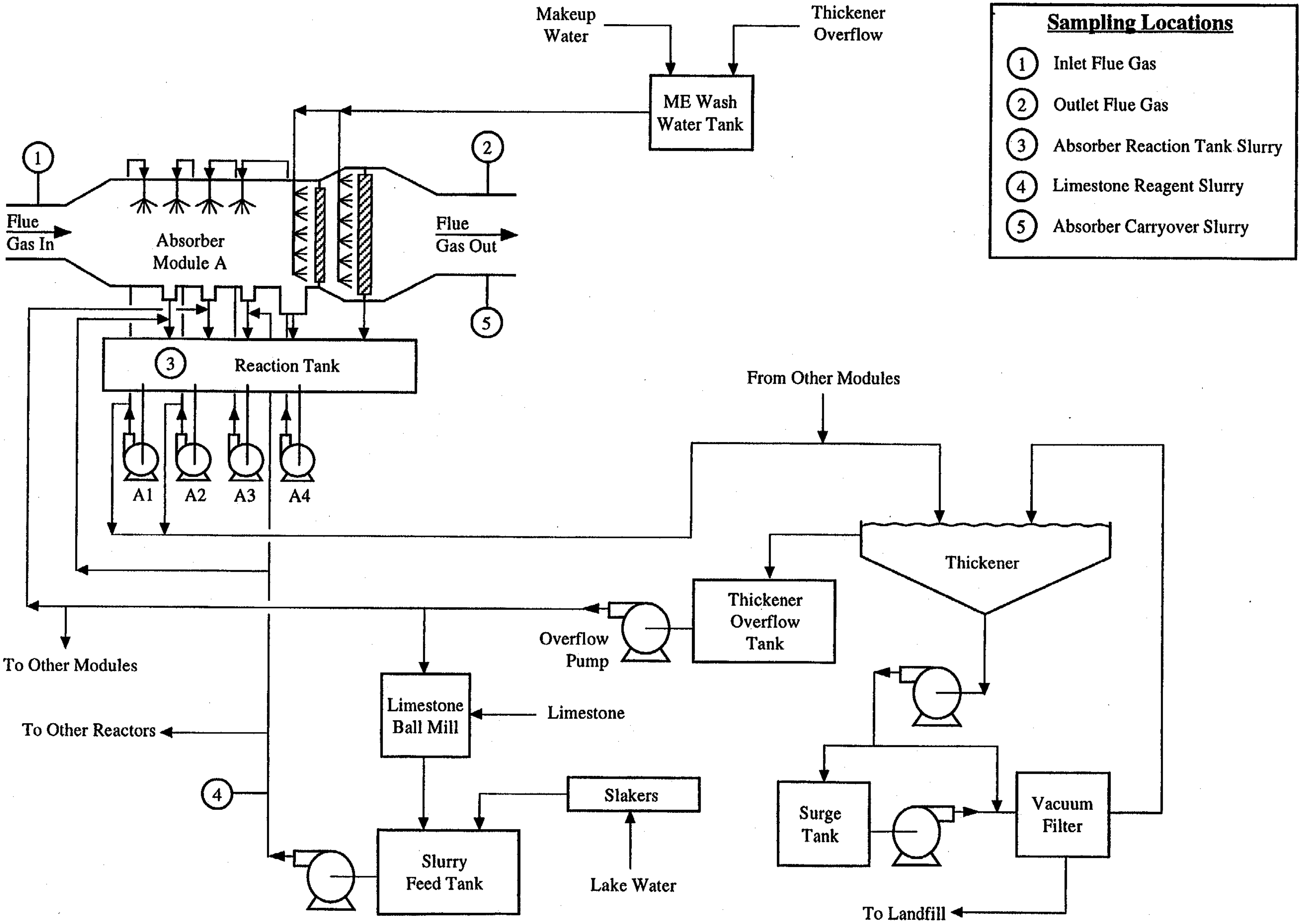


Figure 2-1. Flow Diagram for Gibson Station's FGD System (One of Four Absorber Modules Shown)

Waste slurry blowdown from the absorber is fed to either of two thickeners. The overflow from the thickeners flows to a reclaim-water tank. The underflow sludge is pumped to a surge tank and then to vacuum filters for secondary dewatering. The filtrate is sent to the reclaim-water tank, and the filter cake is sent to pug mills and blended with fly ash for on-site disposal. Reclaimed water from the thickeners and vacuum filters are used for limestone grinding, mist eliminator wash, and make up to the absorber reaction tanks.

The system normally operates at about 80% SO_2 removal efficiency, although this includes the effects of partial flue gas bypass around the FGD absorbers. The normal sulfur content of the coal fired in Unit 5 is approximately 3.0 wt.%, which produces an inlet SO_2 loading to the FGD system of approximately 5.5 lbs SO_2 per 10^6 Btu. The coal sulfur during the baseline testing produced an inlet loading of only 4.5 lbs SO_2 per 10^6 Btu, which is about 20% lower than the normal value. The SO_2 inlet loading for the parametric tests was about 10% higher than the normal value, at 6.0 lbs SO_2 per 10^6 Btu.

2.2 Test Approach

During the baseline and parametric tests, the performance of a single module (Module A) was measured by sampling the flue gas at the module 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. Each of the four modules has a separate inlet booster fan. The flue gas volume treated by Module A was held constant at the desired operating condition by keeping the A booster fan power usage constant. In this manner, Module A test conditions were maintained independent of boiler load.

2.2.1 Baseline Tests

For the baseline tests, the independent variables examined included slurry pH, liquid-to-gas (L/G) ratio, and absorber flue gas velocity. Flue gas velocity was changed by changing the number of absorber modules in service. The first baseline test was conducted at

PSI Energy's design operating conditions, which were held constant for several days. This test duration was adequate to approach steady-state conditions in the test module with respect to solids properties. During this test, measured performance indicators included SO_2 removal efficiency, limestone utilization, sulfite oxidation fraction, slurry liquor relative saturations, and solids dewatering properties. The remaining baseline tests were half-day in duration. For these shorter tests, SO_2 removal efficiency and limestone utilization were the primary performance indicators measured, as the other properties were not expected to reach steady-state conditions during these tests.

The conditions for Baseline Tests 1 through 6 were chosen to provide a wide range of performance under high absorber gas velocity conditions. Measurements of SO_2 removal efficiency and limestone utilization were made over a wide range of reaction tank pH set points with either three or four recycle pumps in service. These data were collected to provide useful information for calibrating FGDPRISM.

For Test 7, the absorber gas velocity was decreased by putting a fourth absorber module in service, the pH remained at the normal set point of 5.3, and only three recycle pumps were in service on the test module. This resulted in the same L/G ratio and pH as in Baseline Test 1, but at the lower absorber gas velocity conditions.

2.2.2 Parametric Tests

The primary objective of the parametric tests was to evaluate the conditions required to obtain high SO_2 removal efficiencies with sodium formate additive. Independent variables for the parametric tests were the same as those for the baseline tests, except with slurry liquor formate ion concentration as an additional variable. The parametric tests were arranged in order of increasing formate ion concentrations from 0 to about 5000 mg/L.

The baseline test data suggested that SO_2 removal efficiency levels greater than 95% may not be achieved under the design, high absorber gas velocity conditions, even with additive present. Consequently, the parametric tests were conducted at both the high and low gas velocity conditions at each formate ion concentration. At some formate ion concentrations, pH was an additional variable. Four recirculation pumps remained in service on the test module during all tests.

The first two tests during the parametric test period were performed without additive. These tests were performed because the inlet SO_2 concentration was higher than during the baseline tests, because a different coal was being fired. Consequently, base (no additive) performance data were needed at the higher inlet SO_2 conditions. Test 1 was a two-day test at high slurry pH conditions. Performance indicators included SO_2 removal efficiency, limestone utilization, sulfite oxidation fraction, slurry liquor relative saturations, and solids dewatering properties. SO_2 removal efficiency and limestone utilization were measured during Test 2, which was a one-day test at the same conditions as Test 1 except with a normal operating pH of 5.3.

Test 7 was also a two-day test, conducted at the mid-level additive concentration to evaluate the effect of sodium formate on solids properties. All the other tests were half-day tests for which the primary performance indicators were SO_2 removal efficiency and limestone utilization.

During the parametric tests, sodium formate was fed continuously from a tanker trailer to the Module A reaction tank to maintain the desired concentrations. Additive concentrations were measured by buffer capacity titration before each test. The additive concentration was adjusted, if necessary, by pumping additional sodium formate from the tanker to the Module A reaction tank.

Because the parametric tests were conducted on a single module, additive concentrations did not reach steady-state levels in other portions of the FGD system. As the tests proceeded, the additive concentration gradually increased in the process water returning to the module with the limestone slurry feed and mist eliminator wash. This concentration was measured during the test program, and the additive feed rate to the test module was adjusted accordingly to compensate.

2.2.3 Additive Consumption Tests

The cost effectiveness of using additives to enhance SO_2 removal largely depends on the consumption rate of the additive. Therefore, long-term additive consumption tests were performed on the entire FGD system. Sodium formate was selected initially as the preferred additive over DBA, based on a preliminary economic comparison following the baseline tests. After reevaluating the economics following the sodium formate testing, a DBA performance and consumption test was added to the test program. The objective of each consumption test was to measure the additive feed rate required to maintain overall system SO_2 removal above 95% while operating with minimum flue gas bypass. This level of performance would allow PSI Energy to generate a substantial quantity of additional SO_2 allowances.

For the sodium formate test, a target formate ion concentration (1000 mg/L as formate ion) and pH set point (5.6 in all four absorber reaction tanks) were selected, based on the results of the parametric tests. For the DBA test, the target concentration was also 1000 mg/L, but a lower pH set point was selected (pH 5.4 versus pH of 5.6 during the sodium formate test) after an economic analysis using sodium formate data showed that the lower pH set point would be more cost effective. Four-module operation (low absorber flue gas velocity) with four recycle pumps in service was also chosen for both consumption tests, based on results from the baseline and parametric tests. These operating conditions were expected to yield the desired SO_2 removal performance.

The sodium formate consumption test was begun two days after the completion of the parametric tests. As a result, the formate concentration throughout the rest of the FGD system was close to the desired level. Therefore, it was not necessary to spike additive to the FGD system before the consumption test was begun. Prior to the DBA test, additive was spiked to each system vessel to bring the concentration to the target level. During each test, additive was fed continuously to the limestone slurry storage tank. From the storage tank, the additive was distributed to each absorber reaction tank with the limestone feed.

The consumption rates of the sodium formate and DBA additives were determined by performing liquid-phase mass balances around the FGD system. This required monitoring sodium formate and DBA addition rates, losses with liquor adhering to the filter cake (solution losses), and changes in the formate ion or DBA inventory over the duration of the test.

The addition rates were obtained by measuring the change in the additive tanker level during the tests. Solution-loss rates were obtained by multiplying the total filter cake production during the test period by the average filter cake moisture content and the filtrate additive concentration. The sodium formate or DBA inventory change term in the material balance was calculated as the difference between the total liquid-phase inventory at the beginning and end of the consumption test period.

To quantify the inventory change during each test, sodium formate or DBA inventories were conducted once each day. These inventories consisted of recording all system tank levels and taking samples from each tank, and analyzing them for formate ion or DBA concentration. All of the samples were analyzed on site for formate or DBA concentration by buffer capacity titration. Several of the inventory sample sets were also analyzed in Radian's Austin FGD laboratory. These tank levels and concentration data were then used to calculate system inventories.

2.3 <u>Test Measurements</u>

2.3.1 Flue Gas Sampling

The primary performance measurements obtained at the site included inlet and outlet flue gas SO_2 concentrations, and inlet and outlet flue gas velocity. The inlet SO_2 concentration was measured a minimum of twice per test with a Method 6 sampling train, by collecting a flue gas sample at a single point in the inlet duct. The outlet SO_2 concentration was also measured a minimum of twice per test using Method 6, but with an 18-point isokinetic traverse to allow for potential stratification of SO_2 and gas flow in the outlet duct.

Flue gas velocity was measured by pitot traverse at the scrubber inlet once a day, or twice a day if the test plan called for the flue gas velocity to be varied. Flue gas velocity was measured by pitot traverse at the scrubber outlet twice per test simultaneously with the SO_2 concentration traverses. Flue gas samples for Orsat analyses of diluent gases (i.e., CO_2 and O_2) were obtained during each test at both sample locations.

Flue gas SO_2 concentrations were determined on site from aliquots of the Method 6 impinger solutions using the barium perchlorate titration procedure. These on-site analyses were used to verify that the results were reasonable and to make testing decisions. The remaining Method 6 impinger solutions were shipped to Radian's Austin laboratory where the analyses were repeated using the more sensitive ion chromatography (IC) method.

2.3.2 Slurry Sampling

Slurry samples were collected at the discharge of a Module A recycle pump during each Method 6 traverse. For the baseline tests, an additional slurry sample was collected in the time between the Method 6 traverses for each test. One set of filtered and stabilized slurry samples was collected during each test for off-site analysis of liquid-phase species. For the parametric tests, a filtered slurry sample was also collected during each test to determine formate concentrations on site using the buffer capacity titration method described in EPRI's FGD Chemistry and Analytical Methods Handbook (Method S1).

Extra slurry samples were also obtained for additional weight percent solids and solid-phase carbonate analyses. The reason for these supplemental samples was to ensure at least two to three measurements of limestone utilization and limestone loading in the recirculating slurry for each test. These values are important in the calibration of the FGDPRISM model.

2.3.3 Chemical Analyses of Slurry and Filtrate Samples

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

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

Complete solid-phase analyses including calcium, magnesium, sulfite, and sulfate content were done for one slurry sample from each half-day test and two from each one- and two-day test. The complete solid-phase analyses are used to calculate the sulfite oxidation fraction. This is also an important performance parameter, but the time constant for changes in total slurry solids composition is much longer than for changes in utilization alone. The oxidation fraction is also not as sensitive to minor changes in operating pH.

All of the filtrate samples were analyzed for liquid-phase calcium, sulfite, sulfate, and carbonate concentration. These results were used to estimate calcium sulfite, gypsum, and calcium carbonate relative saturations, which are important process chemistry indicators that can change relatively quickly with changes in test conditions, especially pH. Only one filtrate sample per day was analyzed for soluble species such as magnesium, sodium, and chloride. The time constant for changes in these soluble species concentrations depends primarily on the overall system volume and water balance and is usually on the order of weeks. Therefore, these concentrations were not expected to vary significantly during a test day.

One liquor sample from the baseline test series and two samples from the parametric test series were also analyzed for trace species using inductively coupled plasma emissions spectroscopy (ICPES). These analyses were conducted to determine if the concentrations of any trace species that might affect FGD system performance changed markedly from the baseline to the parametric test series.

2.3.4 Other Process Data

Various means were used to collect other process data. Slurry flow rates to the spray headers in the test module were measured using a portable ultrasonic flow meter. During the additive consumption tests, SO_2 removal efficiency was determined from the plant continuous monitors by occasionally operating the FGD system without bypass. Other appropriate process data were gathered from plant instrumentation.

Slurry settling rate tests were conducted on site to document any variation in solids settling properties. Samples for off-site form filtration tests, which provide a measure of solids vacuum filtration properties, were obtained concurrently with those for the settling tests. A fraction of each sample set used to measure the settling properties was observed by scanning electron microscope (SEM) and photographed to study the sizes and shapes of the calcium-sulfur crystals.

2.4 SO_2 Removal Performance 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. All of the SO_2 concentrations are reported on a dry flue gas basis.

During the baseline test series, inlet SO_2 concentrations remained fairly steady, with test average concentrations ranging from 1730 to 1890 ppm. More detailed test data for the individual Method 6 runs are included in Appendix A, Table A-1.

Table 2-1

Average Baseline Test Conditions and Results

Test Number	Slurry pH	Flue Gas Velocity (ft/sec)	No. of Pumps in Service	Liquid-to-Gas Ratio (gal/kacf)	Inlet SO_2 (ppm dry)	SO_2 Removal Efficiency (%)
1	5.33	26.5	4	73	1750	86.0
2	5.66	25.5	4	75	1750	89.8
3	5.61	26	3	56	1730	82.4
4	5.10	25	4	78	1890	76.6
5	5.11	25	3	59	1790	67.4
6	5.31	25	3	58	1840	78.8
7	5.36	20	3	73	1730	84.3

Baseline tests were conducted at three pH levels, two flue gas velocities, and two L/G values in the test module. The pH levels corresponded to the normal pH set point of 5.3 and both a lower and higher value (5.1 and 5.6, respectively). The high value of 5.6 was estimated by Radian to be the maximum level that could be maintained without significantly increasing the potential for scaling and plugging of the mist eliminators at the module outlet.

The two flue gas velocities relate to the system design condition of operating three modules at full load (corresponding to a superficial velocity of approximately 25 to 26.5 ft/sec) or a lower velocity resulting from operating all four modules (20 ft/sec). The normal L/G value of approximately 75 gal/kacf was achieved by operating all four slurry recycle pumps on the test module at the higher design velocity, or three of four pumps at the lower velocity. The lower L/G value of about 58 gal/kacf was achieved by operating three of four pumps at the higher flue gas velocity.

The SO_2 removal efficiencies measured during the baseline tests ranged from 67% at low pH, low L/G conditions (Baseline Test 5) to almost 90% at high pH, normal L/G conditions (Baseline Test 2). At the normal pH set point and design values for velocity and L/G, 86% SO_2 removal was measured across the test module.

2.4.2 Sodium Formate Parametric Test SO_2 Removal Efficiency

Table 2-2 summarizes average test conditions and SO_2 removal efficiency results for the sodium formate parametric tests. Detailed test data are included in Appendix A, Table A-2.

The inlet SO_2 concentrations were about 30% higher during the parametric tests than during baseline testing, because of a higher sulfur coal being fired in Unit 5. The measured inlet concentration ranged from 2170 ppm to 2500 ppm.

Table 2-2

Average Sodium Formate Parametric Test Conditions and Results

Test Number	Slurry pH	Flue Gas Velocity (ft/sec)	Liquid-to-Gas Ratio* (gal/kacf)	Sodium Formate Concentration (mg/L as COOH$^-$)	Inlet SO_2 (ppm dry)	SO_2 Removal Efficiency (%)
1	5.67	20	97	0	2370	95.4
2	5.29	20	97.5	0	2470	87.8
3	5.30	27.5	69.5	510	2170	83.3
4	5.30	21	92.5	400	2190	90.3
5	5.74	26.5	73	1180	2490	92.5
6	5.67	20	95	1410	2500	97.5
7	5.31	27.5	70.5	1540	2320	86.1
8	5.34	19	100	1430	2260	94.8
9	5.32	27	72.5	2750	2405	87.7
10	5.27	21	94	3240	2350	93.2
11	5.67	27.5	71	4590	2340	93.1
12	5.62	20	94.5	4940	2180	97.4

* All tests conducted with all four slurry recirculation pumps in service.

The parametric tests were conducted at four different formate levels, two pH levels, and two flue gas velocity levels. The low pH level for the parametric tests (5.3) in Table 2-2 is the typical operating pH for the FGD system. As during the baseline tests, the two flue gas velocities correspond to full-load operation with three modules (high velocity) or four modules (low velocity) in service.

The first two tests of the parametric series were run without additive to establish baseline performance at the higher inlet SO_2 concentration. The conditions for Parametric Test 1 were intended to represent the maximum SO_2 removal achievable with the Unit 5 FGD system without additives. The reaction tank slurry pH was controlled at 5.7, which is higher than the normal operating set point of 5.3. The average flue gas velocity was lowered to 20 ft/sec, which represents four-module operation. All four slurry pumps were in operation, which, at this flue gas velocity, results in an L/G ratio of approximately 97 gal/macf. Parametric Test 2 was conducted at the same conditions, except at Gibson's normal reaction tank slurry pH of 5.3.

The resulting overall SO_2 removal efficiency for Module A averaged 95.4% for Test 1 and dropped to 87.8% for Test 2. Note that the results of these and all of the subsequent parametric tests cannot be directly compared to results from the baseline tests discussed previously, because of the higher inlet SO_2 concentration during this parametric test series.

For Parametric Tests 3 through 12, sodium formate was added to the recirculating liquor in the Module A reaction tank. Four sodium formate concentration levels were tested: a low level of about 400 to 500 ppm, an intermediate level of 1200 to 1500 ppm, a high level of 2800 to 3200 ppm, and a very high level of 4500 to 5000 ppm (all concentrations expressed as ppm of formate ion). The SO_2 removal measured during these tests ranged from 83% at the normal pH set point and L/G and only 500 ppm of formate ion in the liquor, to more than 97% at the higher pH set point, higher L/G, and with 1410 ppm of formate in the slurry liquor.

2.4.3 SO_2 Removal Performance Correlation

Absorber performance can be approximately described by the following expression:

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

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

It is assumed in the above expression that the equilibrium partial pressure of SO_2 above the FGD liquor is small compared to the inlet and outlet concentrations. This should be a reasonable assumption for the Gibson performance data. For example, at full-load conditions with 3%-sulfur coal (three-module operation, pH 5.3, 5.5 lb SO_2 in per 10^6 Btu, 80% SO_2 removal), the partial pressure of SO_2 above the FGD liquor predicted by FGDPRISM is 80 ppm. This concentration is small compared with the inlet and outlet SO_2 concentrations of 2130 and 430 ppm, respectively.

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." For a given absorber operating at constant gas and liquid flow rates, the NTU will be a function of slurry pH because of the effect of pH on the liquid-film 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 on the overall mass transfer coefficient (and therefore on NTU or SO_2 removal efficiency) will diminish at some point when $H/k_l\phi$ becomes small compared to $1/k_g$. This is referred to as "gas-film-limited" mass transfer. When this point is reached for a given absorber, there is no benefit to increasing the additive concentration or operating pH.

Equation 2-1 also shows that NTU should be inversely proportional to gas flow rate (if the product of K and A is independent of gas velocity) and proportional to liquid flow rate (if A is proportional to liquid flow rate). The validity of these assumptions is discussed below.

Baseline SO_2 Removal

Figure 2-2 presents a plot of NTU versus absorber slurry pH for the baseline tests. For convenience, SO_2 removal efficiency is also indicated on the graph. In the figure, data for tests at different absorber gas velocities and number of recycle pumps in service (L/G ratio) are shown. The overall scrubber performance can be approximately correlated with absorber slurry pH. However, the data show that, as the slurry pH is increased, the SO_2 removal begins to approach a "maximum" value for those gas/liquid contacting conditions. As discussed above, this represents the "gas-film-limited" mass transfer capability for those contacting conditions.

Figure 2-2 also shows the effect of L/G ratio on SO_2 removal efficiency. The upper curve on the graph represents operation at an L/G of approximately 74 gal/kacf, while the lower curve represents operation at approximately 57 gal/kacf. As shown, the increase in NTU is approximately proportional to the increase in L/G ratio (about 30%) at any given set of operation conditions. The figure also shows that tests conducted at different gas and slurry flows, but at the same L/G ratio, resulted in approximately the same SO_2 removal efficiency. If K and A in Equation 1 are independent of gas velocity and A is proportional to the absorber slurry rate, then SO_2 removal should not be affected by gas velocity at constant L/G. The results in Figure 2-2 suggest that these assumptions are valid for the Gibson absorber module.

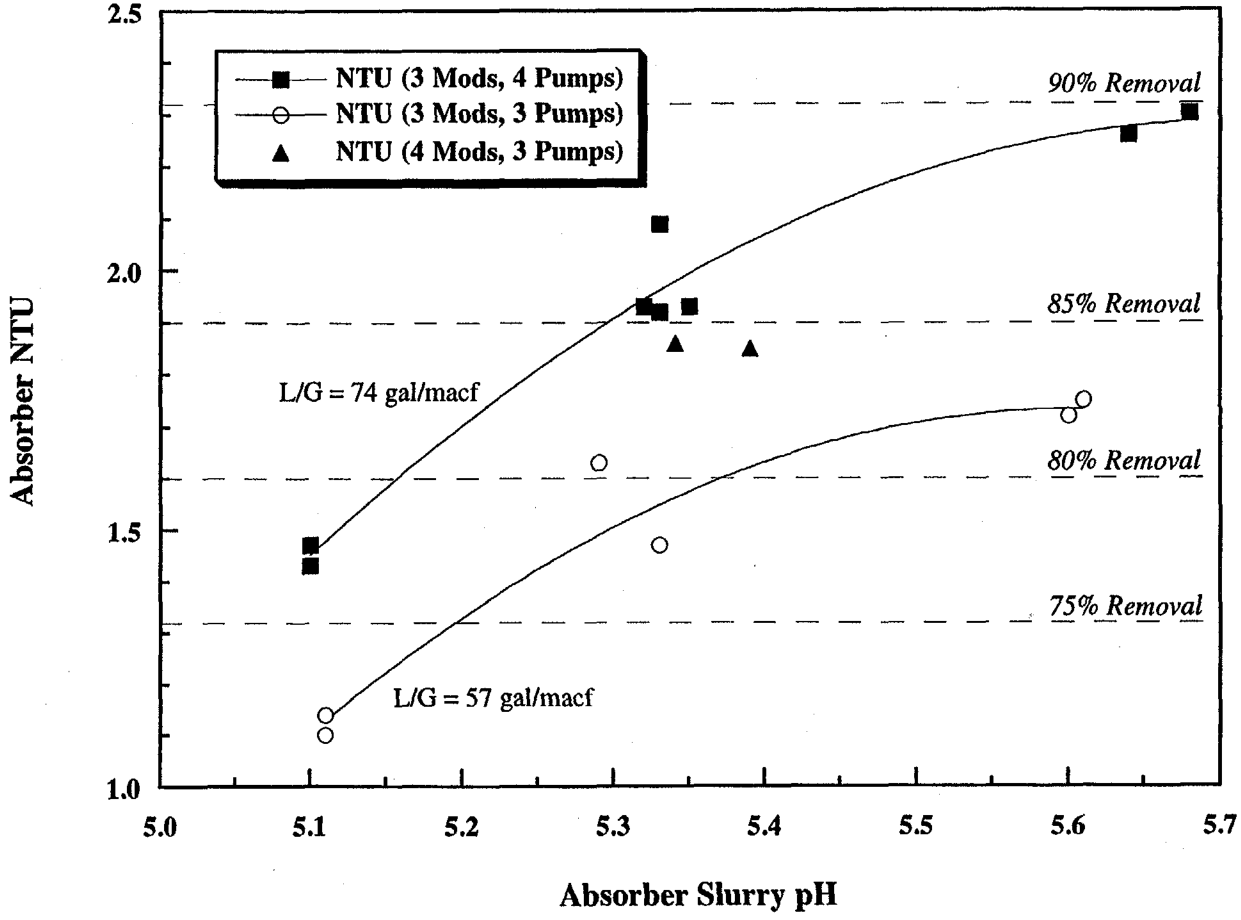


Figure 2-2. Gibson Baseline Tests: Absorber NTU vs. Absorber Slurry pH

Parametric Test SO_2 Removal

Figure 2-3 presents a plot of the sodium formate parametric test results. In the figure, SO_2 removal performance (shown in NTU) is plotted versus formate concentration. SO_2 removal efficiency is also indicated on the graph. The data are grouped by L/G ratio and slurry pH. The upper two curves on the graph represent operation at an L/G of approximately 96 gal/kacf, while the lower two curves represent operation at approximately 71 gal/kacf. The results again show that NTU was approximately proportional to L/G.

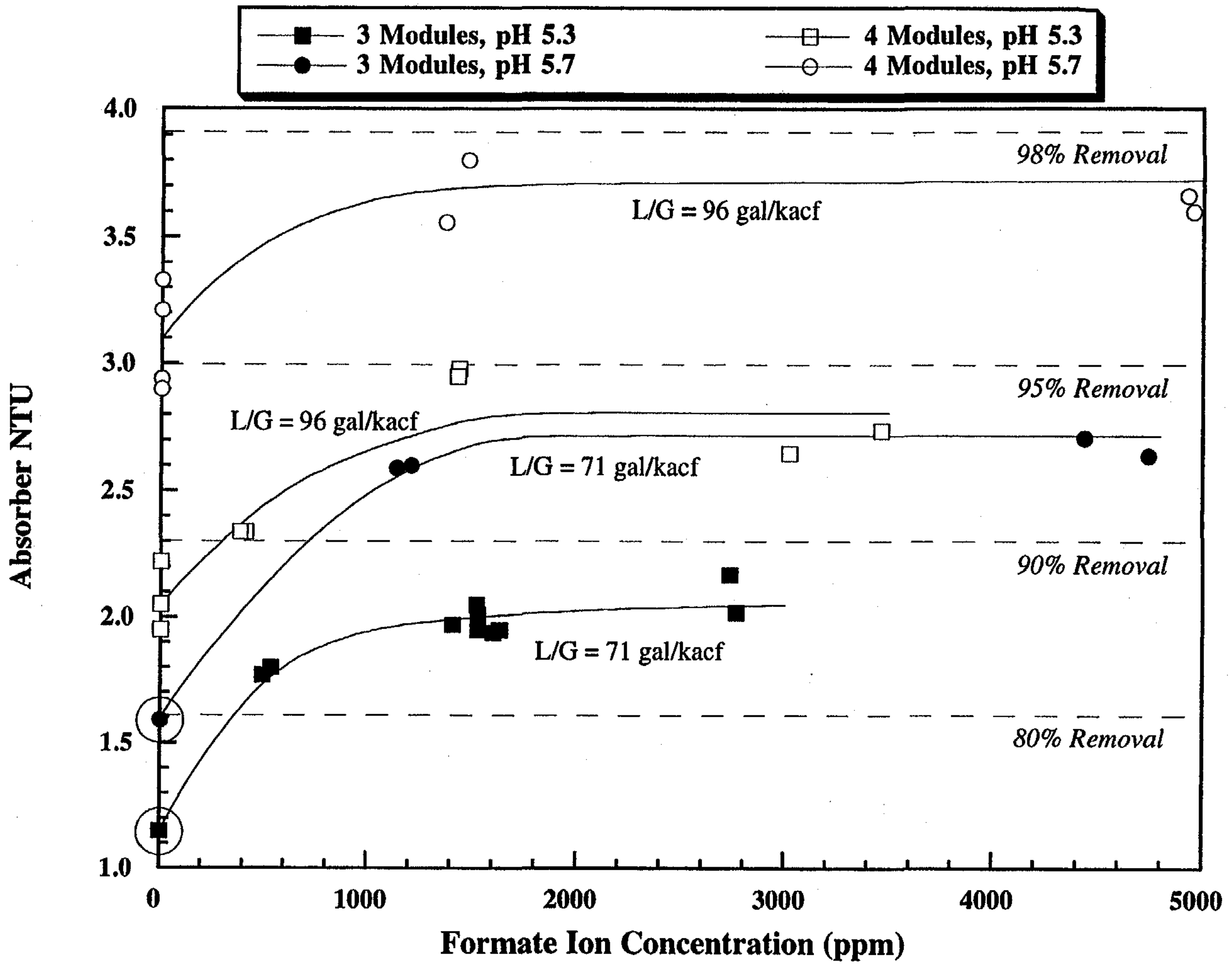
Note that the "zero formate concentration" data points for the three-module tests at both normal and high pH set points are predicted rather than test data. These data points were predicted by using FGDPRISM to adjust the results of baseline test series tests at these conditions to the higher inlet SO_2 values for the parametric test series. There were no parametric series tests conducted at three-module conditions and the higher inlet SO_2 concentration without formate additive.

For both flue gas velocity conditions (low and high L/G), the test results show that there was little improvement in SO_2 removal above a formate concentration of approximately 1500 mg/L. This suggests that the absorber had approached gas-film-limited performance at this formate level and at the higher pH. Further improvements in SO_2 removal can only be achieved by increasing the L/G ratio or improving the gas/liquid contacting (i.e., improving the effective mass transfer surface area, A).

2.5 Results of Baseline and Parametric Test 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, A-4, and A-5. These results were used to



○ *SO_2 removal predicted by FGDPRISM for Baseline Tests 1 and 2 under high inlet SO_2 conditions.*

Figure 2-3. Gibson Parametric Tests: Absorber NTU vs. Additive Concentration calculate limestone utilization and sulfite oxidation, which are important process performance parameters. Results are briefly described here.

Calculated limestone utilization values for the baseline and parametric tests have been plotted versus slurry pH in Figure 2-4. This figure shows that, at a given pH, limestone utilization was lower during the parametric test period than during the baseline period. Even Parametric Tests 1 and 2 with no additive are lower in limestone utilization compared to baseline test period values.

There are several factors that may have contributed to reduced limestone utilization during the parametric test period, compared to that of the baseline test period. First, the average limestone grind fineness was observed to have decreased from 94% passing 325 mesh during the baseline test period to 81% passing 325 mesh during the parametric test period. This would be expected to reduce utilization. Second, there was an observed increase in the relatively unreactive dolomitic content of the limestone between the two periods, which would also be expected to reduce utilization. As will be discussed further below, there was also an increase in the dissolved chloride concentration in the recirculating slurry from about 6260 mg/L to 13,960 mg/L, which might also have contributed to reduced limestone dissolution rates and lower utilization. Finally, an increase in the inlet SO_2 concentration and, correspondingly, the SO_2 absorption rate tended to increase the total amount of limestone dissolution required in the absorbers, and would thus tend to reduce limestone utilization. Based on these factors and because there was no change in limestone utilization between the parametric tests with and without additive, it does not appear that the addition of sodium formate had a significant effect on limestone utilization.

Sulfite oxidation during the baseline test period averaged about 12.7%. While there did not appear to be any significant changes in oxidation percentages during these tests, it should be noted that only the solids from Baseline Test 1 would have been expected to reach their true steady-state composition. However, it is worth noting that none of the solids are above the 15% oxidation threshold above which gypsum scaling generally occurs. The sulfite oxidation

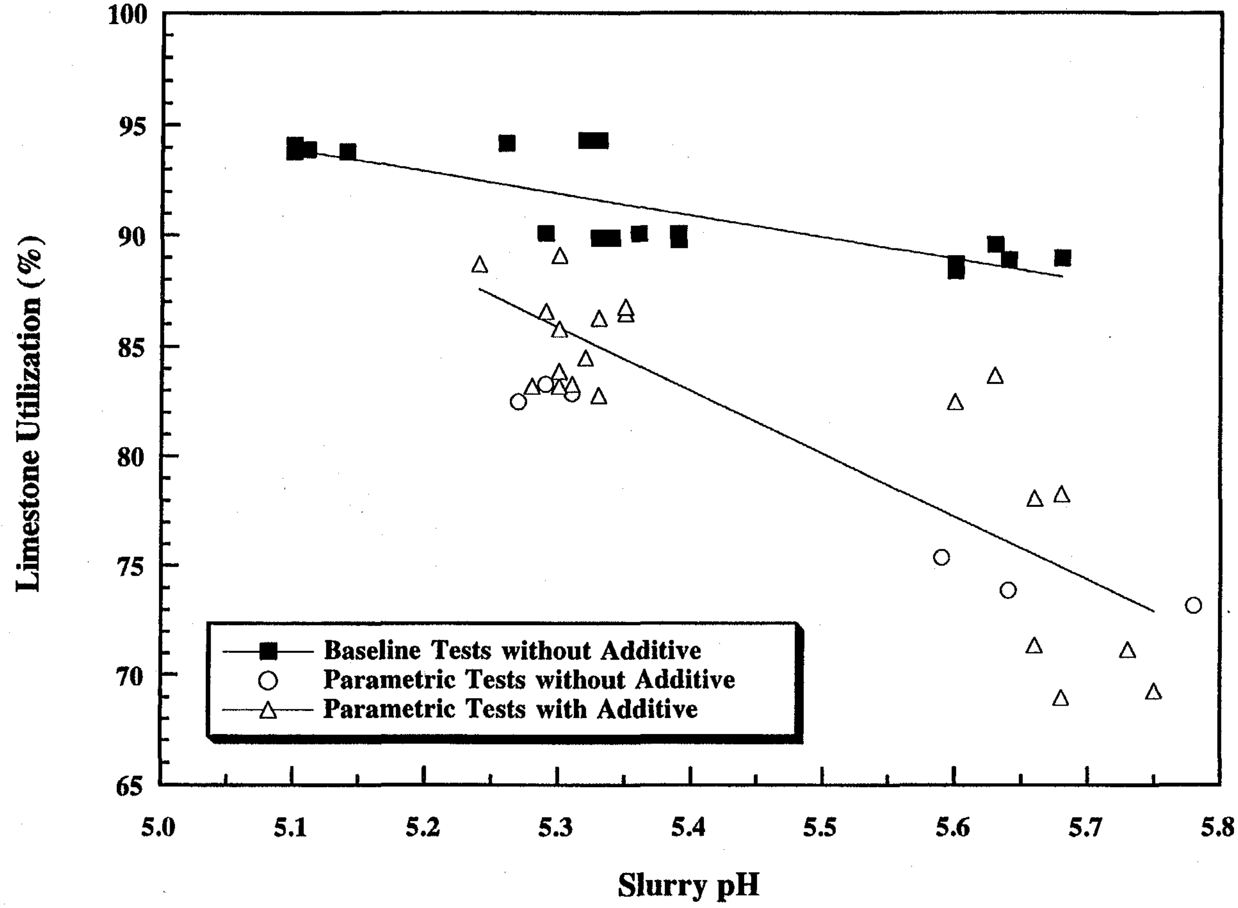


Figure 2-4. Limestone Utilization vs. Absorber Slurry pH
Baseline and Parametric Test Results

percentages for the parametric tests average about 11.1%. This average oxidation percentage is lower than was measured during the baseline test series, but this would be expected because of the higher coal sulfur content during the parametric tests.

2.5.2 Liquid-Phase Analyses

Detailed results of liquid-phase analyses for the baseline and parametric test filtered slurry samples are included in Appendix A, Tables A-7 and A-8. Calculated relative saturations are also shown in the liquid-phase analytical results tables. Relative saturation (RS) 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 the equilibrium template in EPRI's FGDPRISM model. The equilibrium model calculates the equilibrium distribution of chemical species using the analytical results as inputs. For these calculations, magnesium, sodium, and chloride concentrations were estimated for samples where these species were not analyzed.

Of greatest interest in an inhibited-oxidation FGD system is the gypsum RS. The objective of inhibiting oxidation through sulfur addition (which reacts to produce thiosulfate in solution) is to prevent gypsum scaling by maintaining the gypsum RS 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 sulfite 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-7 show that the baseline liquor samples all had gypsum RS's close to 1.0, with some samples slightly supersaturated and some slightly subsaturated. However, since the measured sulfite oxidation in the scrubber solids was less than 13.5% for all baseline samples, one would expect the calculated gypsum RS to be less than 1.0 for all samples also. The apparent positive bias in the gypsum RS results may be the result of inaccuracies in the FGDPRISM equilibrium calculations for process chemistries with very high total dissolved solids levels. For this system, the high total dissolved solids levels result from very high levels of dissolved magnesium. The variations in the calculated gypsum RS levels may also be due to the transient nature of the baseline tests. The short duration of these tests may have resulted in short-term spikes or drops in the gypsum RS in the liquid phase that do not correspond to the longer-term average oxidation levels represented by the solids analyses.

The results for the parametric test liquids in Table A-8 show that all but one of the results for gypsum RS during the parametric tests are less than 1.0. The one data point in the supersaturated region corresponds with the solid sample results which indicated sulfite oxidation percentages slightly above 15%. This would be expected. There does not appear to be a relationship between the gypsum RS and formate concentration. Comparing the parametric test period to the baseline test period, the average gypsum RS was significantly lower (0.44 vs. 1.03) during the parametric test period. This result is consistent with the lower solid-phase sulfite oxidation percentages measured during the parametric test period. As discussed previously, the lower oxidation percentages can most likely be attributed to the higher inlet SO_2 concentrations observed during the parametric tests. Sulfite oxidation percentages are typically lowered at higher inlet SO_2 levels.

The average concentrations of important soluble species in the liquid phase have been calculated using the data in Tables A-7 and A-8. Table 2-3 summarizes these results. The concentrations for the baseline and parametric tests can be compared to evaluate potential effects of changes in the background chemistry on the interpretation of additive performance data. Table 2-3 shows that the average concentration of magnesium was nearly identical during the two test periods, as would be expected since this was a controlled variable. The average sodium concentration was higher during the parametric tests, which was also expected due to formate addition to the FGD system as a sodium salt. Results also show that the chloride concentration was much higher during the parametric tests than during the baseline tests. The higher chlorides resulted from firing a coal with a higher chloride-to-sulfur content during the parametric tests. Finally, the concentration of the thiosulfate ion ($S_2O_3^=$), an oxidation inhibitor, decreased by

Table 2-3

Average Soluble Species Concentrations

Species	Baseline	Parametric
Mg^{++}, mmol/L	396	391
Na^{+}, mmol/L	18	52
Cl^{-}, mmol/L	177	394
$S_2O_3^{=}$, mmol/L	26	17
Mg^{++}, mg/L	9,640	9,510
Na^{+}, mg/L	400	1,210
Cl^{-}, mg/L	6,260	14,000
$S_2O_3^{=}$, mg/L	2,930	1,890

35%. Although the thiosulfate concentration was lower during the parametric tests, the oxidation percentage did not increase. This is, again, most likely an effect of the higher sulfur coal.

Concentrations of 26 metals were also determined in selected samples using inductively coupled argon plasma emissions spectroscopy. These data are summarized in Table A-10. Some differences in a few of the trace species concentrations were observed during the baseline and parametric tests. The iron concentration ranged from <0.02 mg/L to 3 mg/L during the baseline and the parametric tests, then decreased consistently to <0.02 mg/L for the long-term tests. Aluminum concentrations increased somewhat over the time period between the baseline and DBA consumption test periods while copper, magnesium, potassium, and selenium concentrations decreased somewhat. It is not clear whether changes in these metal concentrations were related to the use of the additives, or merely reflect normal variations.

2.6 Sodium Formate and DBA Consumption Test Conditions and Results

The cost effectiveness of using additives to enhance SO_2 removal depends both on the increase in SO_2 removal performance realized and on the consumption rate of the additive in the FGD system. To measure consumption rates, long-term steady-state tests were conducted with both sodium formate and DBA by adding them to the entire FGD system.

2.6.1 Consumption Rate Calculation

The summation of the following terms represents the gross loss of sodium formate or DBA additive from Gibson's FGD system during the consumption tests:

1. Solution loss--Additive lost in liquor adhering to the filter cake. There is no separate liquor blowdown stream from the FGD system.
2. Coprecipitation loss--Additive lost as a result of co-precipitation of additive into the calcium sulfite crystal structure. Based on previous data from EPRI's Environmental Control Technology Center (ECTC), co-precipitation is expected to be the predominant nonsolution loss

mechanism of formate or DBA additive in an inhibited-oxidation FGD system.

3. Degradation loss--Additive lost by reactions (primarily by oxidation) to form other chemical species that do not contribute to the buffering capacity of the scrubber liquor.

4. Vaporization loss--Additive lost by vaporization into the flue gas. Based on experience at EPRI's ECTC, vaporization losses (as formic acid) can be as high as 10 to 20% of total formate consumption at typical inhibited-oxidation FGD system conditions. In contrast, vaporization losses of DBA into the flue gas were assumed to be negligible, also based on EPRI's ECTC test results.

The solution loss (1) can be calculated for a given system based on the SO_2 removal rate, additive concentration, and filter cake moisture content. Rates for losses 2, 3, and 4 are less easily predicted. The sum of losses 2, 3, and 4 is normally termed the "nonsolution" loss.

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

$$\text{Nonsolution Loss (lb)} = \text{Addition (lb)} - \text{Solution Loss (lb)} - \text{Inventory Change (lb)} \qquad \textbf{(2-3)}$$

The additive nonsolution loss rate is normally reported on an SO_2 removal basis (lb sodium formate or DBA per ton SO_2 removed). The total amount of SO_2 removed was calculated using the average sulfite oxidation, limestone utilization, and filter cake solids content along with the recorded amount of waste byproduct during the test period. The recorded amount of waste product agreed well with the estimated amount calculated from coal consumption, sulfur content, and system SO_2 removal efficiency data.

2.6.2 Results

Sodium Formate Consumption Test

The sodium formate consumption test was conducted over a seven-day period. The first sodium formate inventory was completed during the morning of the first day. Continuous addition to the limestone slurry storage tank was used to maintain the formate concentration at the desired steady-state level. Additional sodium formate inventories were completed on the third day and on the final day of testing. The average load for the test period was 454 MW and the average inlet and stack SO_2 concentrations were equivalent to 6.0 and 0.40 lb SO_2 per 10^6 Btu, respectively. The overall SO_2 removal averaged 93% but the average absorber SO_2 removal was near the target value, approximately 96%. The overall SO_2 removal was lowered by flue gas bypass of approximately 3.0% of the total unit flue gas flow. The absorber SO_2 removal performance was determined by observing stack SO_2 emission data during brief periods with no bypass, and confirmed by material balance based on the average amount of flue gas bypass.

The sodium formate consumption material balance was based on the test interval between the first inventory and the final inventory. Table 2-4 summarizes results of the material balance and consumption computations described above. The inventory values are shown as lb of formate ion ($COOH^-$) and sodium formate (NaCOOH) on a dry basis. The total consumption rate and both the solution and nonsolution loss rates are also reported. These are expressed in terms of lbs of formate ion per ton on SO_2 removed, or lbs of sodium formate per ton of SO_2 removed. Detailed inventory data for all system vessels are included in Appendix B, Table B-1.

A total of 20,950 lb of sodium formate (52,380 lb of 40% NaCOOH solution) was added to the system during the one-week (170 hr) duration between the first and last inventories. The total inventory change of 950 lb as sodium formate represents less than 5% of the amount added during the test period. Thus, inventory changes should have little impact on the accuracy of the consumption rate measurement. The total sodium formate consumed, 21,900 lb, is calculated as the amount added plus the decrease in inventory. Of the total consumed, about

Table 2-4

Summary of Sodium Formate Additive Consumption

Condition	Amount	Units
Initial Additive Inventory	37,280 (56,330)	lb COOH (lb NaCOOH), dry basis
Final Additive Inventory	36,650 (55,380)	lb COOH (lb NaCOOH), dry basis
Inventory Change	-630 (-950)	lb COOH (lb NaCOOH), dry basis
Additive Introduced to System	13,860 (20,950)	lb COOH (lb NaCOOH), dry basis
Total Additive Consumed	14,490 (21,900)	lb COOH (lb NaCOOH), dry basis
SO_2 Removed, Based on Filter Cake Production	2070	ton
Average Limestone Utilization	79	%
Sulfite Oxidation	8	%
Filter Cake Produced	9,470[a]	ton
Filter Cake Solids Content	58.3	wt. %
Total Additive Consumption	7.0 (10.6)	lb COOH/ton SO_2 rem.(lb NaCOOH/ton SO_2 rem.)
Solution Loss	3.2 (4.9)	lb COOH/ton SO_2 rem.(lb NaCOOH/ton SO_2 rem.)
Non-Solution Loss	3.8 (5.7)	lb COOH/ton SO_2 rem.(lb NaCOOH/ton SO_2 rem.)
Co-precipitation Loss	3.6 (5.4)	lb COOH/ton SO_2 rem.(lb NaCOOH/ton SO_2 rem.)
Average Concentration in Reaction Tanks	1200 (1800)	mg/L COOH (mg/L NaCOOH)

[a] Total waste byproduct weight measured was 10,013 tons during the test period, but PSI Energy personnel indicated that the weigh-belt scales read ~6% high.

46% (10,140 lb) of the sodium formate was accounted for by losses with liquor adhering to the filter cake. The remaining sodium formate consumed, 11,760 lb, is the amount of nonsolution loss from the system.

The total calculated SO_2 removed during the material balance interval was estimated at 2070 tons, based on the recorded tons of filter cake produced. This compares within 5% of an estimated 2170 tons of SO_2 removed based on combustion calculations. On an SO_2 removed basis, the overall total sodium formate consumption was 10.6 lb sodium formate per ton SO_2 removed. Of this total, 4.9 lb sodium formate/ton SO_2 was lost with the filter cake liquor, and the remaining 5.7 lb sodium formate/ton SO_2 was the nonsolution loss. During the test, an average sodium formate feed rate of 123 lb/hr (dry basis) was required to maintain an average concentration of about 1200 mg/L in the FGD system reaction tanks.

Based on data from EPRI-sponsored studies, coprecipitation was expected to be the most significant nonsolution loss mechanism. This loss rate was estimated by measuring the formate leaving the FGD system incorporated in the filter cake solids. The average concentration of formate in the waste slurry solids was 0.7 mg/g. The waste solids production rate, on a dry basis, was 5330 lb/ton SO_2 removed. Therefore, the measured concentration of solid-phase formate corresponds to a coprecipitation loss rate of 5.4 lb sodium formate/ton SO_2. This value is approximately 95% of the total nonsolution loss rate measured (i.e., 5.7 lb/ton SO_2). No measurements of formic acid vapor or formate degradation products were made during the test program, but it appears that these other individual nonsolution loss rates were minor.

DBA Consumption Test

DBA additive consumption testing was conducted over an 18-day period. The first DBA inventory was completed during the afternoon of the first day. Continuous addition to the limestone slurry storage tank was used to maintain the DBA concentration at the desired steady-state level. Additional DBA inventories were completed on the fourth, seventh, and final day of testing. There were six days during this test period when the unit was down, from the eighth through the fourteenth day of the test. Data were not collected during this time.

The average load for the test period was 540 MW and the average inlet and stack SO_2 concentrations were equivalent to 6.3 and 0.57 lb SO_2 per 10^6 Btu, respectively. Although the average absorber SO_2 removal was approximately 97%, the overall SO_2 removal averaged 91%. The lower overall removal was due to approximately 6.5% flue gas bypass around the absorbers. The absorber SO_2 removal performance and flue gas bypass were determined by observing stack SO_2 emission data during brief periods of operation without flue gas bypass.

The DBA consumption material balance was based on the test interval between the first inventory and the final inventory. Table 2-5 summarizes results of the material balance and consumption computations described above. The inventory values are shown as lb of DBA on a dry basis. The total consumption rate and solution and nonsolution loss rates are reported on the basis of lb_{dry} DBA/ton of SO_2 removed. Detailed inventory data for all system vessels are included in Appendix B, Table B-2.

A total of 38,510 lb of DBA (77,020 lb of 50% DBA solution) was added to the system during the 275-hr on-line duration between the first and last inventories. The total inventory change during this period of -9880 lb represents approximately 25% of the amount added during this two-week period. Such a large inventory change could have adversely affected the accuracy of the consumption rate measurement. However, this value is high due to extraneous losses of DBA during the consumption test. Significant losses of DBA occurred when the additive feed line froze and cracked, allowing DBA solution to spill onto the ground for several hours overnight. Additional DBA losses occurred when a thickener was emptied during the outage that occurred in the middle of this test. The extraneous losses of DBA are estimated to be 4,740 lb. The total DBA consumed, 43,640 lb, is calculated as the amount added minus extraneous DBA losses plus the decrease in inventory. Of the total consumed, about 25% (10,980 lb) of the DBA was accounted for by losses with liquor adhering to the filter cake. The remaining DBA consumed, 32,660 lb, is considered to be the amount of nonsolution loss.

Table 2-5

Summary of DBA Additive Consumption

Condition	Amount	Units
Initial Additive Inventory	38,800	lb DBA, dry basis
Final Additive Inventory	28,920	lb DBA, dry basis
Inventory Change	-9,880	lb DBA, dry basis
Additive Introduced to System	38,510	lb DBA, dry basis
Extraneous Process Discharges	4,740	lb DBA, dry basis
Total Additive Consumed	43,640	lb DBA, dry basis
SO_2 Removed, Based on Filter Cake Production	4,840	ton
Average Limestone Utilization	90	%
Sulfite Oxidation	9	%
Filter Cake Produced	18,840[a]	ton
Filter Cake Solids Content	61.5	wt. %
Total Additive Consumption	9.0	lb DBA/ton SO_2 removed
Solution Loss	2.3	lb DBA/ton SO_2 removed
Non-Solution Loss	6.7	lb DBA/ton SO_2 removed
Co-precipitation Loss	3.1	lb DBA/ton SO_2 removed
Average Concentration in Reaction Tank	1350	mg/L DBA

[a] Total waste byproduct weight measured was 20,041 tons during the test period, but PSI Energy personnel indicated that the weigh-belt scales read ~6% high.

The total calculated SO_2 removed during the DBA consumption test interval was estimated at 4840 tons, based on the measured tons of filter cake produced. This value is approximately 20% higher than the calculated SO_2 removed based on combustion calculations. However, the amount calculated from the filter cake production is thought to be the more accurate of the two estimates. Based on filter cake produced, the overall total DBA consumption was 9.0 lb DBA per ton SO_2 removed. Of this total, 2.3 lb/ton SO_2 was lost with the filter cake liquor, and the remaining 6.7 lb/ton SO_2 was nonsolution loss. However, it should be noted that the consumption rate would be approximately 20% greater, in terms of lb/ton SO_2 removed, if combustion calculations were instead used to estimate SO_2 removed.

During the test, an average DBA feed rate of 161 lb/hr (dry basis) was required to maintain an average DBA concentration of about 1350 mg/L in the FGD system reaction tanks. The DBA feed rate is higher than reported for sodium formate (even though the consumption rate is slightly lower) because of higher-load operation during the DBA consumption test.

Coprecipitation loss for DBA was also estimated by measuring the DBA leaving the FGD system incorporated in the filter cake solids (rather than with the liquor adhered to the filter cake solids). The average concentration of the DBA in the waste slurry solids was 0.6 mg/g. The waste solids production rate on a dry basis was 4790 lb/ton SO_2 removed. Therefore, the measured concentration of solid-phase DBA corresponds to a coprecipitation loss rate of 3.1 lb DBA/ton SO_2. This value is approximately 46% of the total nonsolution loss rate (6.7 lb DBA/ton SO_2) measured. No measurements of DBA degradation products were made during the test program, but degradation is thought to account for the remainder of the nonsolution loss rate.

Comparing the DBA and sodium formate consumption results, the DBA solution loss rate (2.3 lb DBA/ton SO_2) is approximately 30% less than the formate solution loss rate (3.2 lb formate/ton SO_2) even though the tests were conducted at similar concentrations in the absorber. This difference can be accounted for by three factors. First, the average concentration of additive in the liquor adhering to the filter cake was 614 ppm during DBA testing compared to 851 ppm during formate testing. Second, the filter cake solids content was greater during the

DBA test (61.5%) compared to the sodium formate test (58.3%). Finally the higher limestone utilization during the DBA test resulted in less filter cake produced per ton of SO_2 removed compared to the sodium formate test. These three factors account for the lower solution losses observed during the DBA consumption test compared to that during the formate consumption test.

Results of Consumption Test Slurry Sample Chemical Analyses

Three sets of solids samples were obtained during the final three days of the sodium formate consumption test. Six sets of solids samples were obtained during the DBA consumption test to determine limestone utilization and sulfite oxidation. The first sample was collected as a baseline, the second sample was collected at a low DBA concentration of 480 ppm, and the last four samples were collected at each inventory.

Detailed results of chemical analyses of solids and liquids from the consumption tests are included in Appendix A, Tables A-6 and A-9. For the sodium formate consumption test, the limestone utilization averaged 79% at an average pH of 5.7. This is consistent with the parametric test results at a similar pH (see Figure 2-4). The limestone utilization averaged 90% at an average pH of 5.5 for the DBA consumption test.

The average sulfite oxidation percentages were approximately 8.2% for the sodium formate consumption test and 8.8% for the DBA consumption test. The average oxidation percentage during the sodium formate consumption test was about 2 to 3 percentage points lower than during the parametric tests and 4 to 5 percentage points lower than during the baseline tests. The average oxidation percentage during the DBA consumption test was about 1 to 2 percentage points lower than during the parametric tests. These data suggest that the long-term use of formate or DBA may have an oxidation-inhibiting effect on the FGD system. Such an effect was observed at SWEPCo's Pirkey FGD system. However, this cannot be confirmed at Gibson without more extensive testing because of changes in coal and boiler operation conditions during the parametric and consumption test periods.

As with the samples from the other test series, the liquid-phase results were used to calculate relative saturations for calcium sulfate (gypsum), calcium sulfite, and calcium carbonate. These results are included in Appendix A, Table A-9. Gypsum relative saturations were well below 1.0. The sodium formate additive consumption test results are comparable to those during the parametric tests with sodium formate additive at similar pH levels and additive concentrations.

2.7 Effect of Additives on Solids Dewatering Properties

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

Three methods were used to examine solids samples from Module A as part of this test program: settling tests, filter leaf tests, and scanning electron microscopy (SEM). Settling tests were performed on site using the reaction tank slurry samples to determine the effect of additive 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 photographs were used to qualitatively examine changes in crystal structure and size.

2.7.1 Settling Tests

Batch settling tests were performed on slurry from Module A to determine both settling rates and final underflow solids concentrations. Settling rates are reported as the thickener unit area (ft^2-day/ton) required to achieve a 30 wt.% underflow solids concentration.

The final underflow concentration was also determined by allowing the solids to compact to their equilibrium point. Detailed settling test results are included in Appendix C, Table C-1.

During the baseline tests, a total of three settling tests were conducted. The unit area for the baseline test samples averaged 13 ft^2-day/ton and the final underflow solids content averaged 44%. During the sodium formate parametric tests, three settling tests were done before the addition of sodium formate and three settling tests were done after three days of operation at 1560 mg/L formate ion concentration. The results show that sodium formate addition appeared to decrease the settling rate (increased unit area) and the final settled solids content.

The settling tests conducted at the beginning of the parametric tests series (no additive) resulted in unit areas nearly three times those for the baseline settling tests. The decrease in settling rate was initially speculated to be a result of increased oxidation in the system, which might have been caused by low boiler load during the weeks prior to parametric testing. However, the sulfite oxidation percentage during this test was actually slightly lower than during the baseline tests. As a result, this variable would not be expected to have a significant effect on the solids properties. No other reason for these lower settling rates at the beginning of the parametric test series has been determined.

Results for settling tests during the sodium formate Parametric Test 7 show that the formate increased the unit area from 33 ft^2-day/ton (Parametric Test 1 - no additive) to 56 ft^2-day/ton. The final settled solids content decreased by 9 percentage points from 40 wt.% to 31 wt.% solids. Results of samples collected during the sodium formate consumption test are also included in Table C-1. These results exhibit similar unit areas in the range of 50 to 70 ft^2-day/ton, with formate present in the FGD system. The detrimental change in settling properties was persistent, and therefore appears to be related to the sodium formate present in the FGD system.

Results of samples collected during the DBA consumption test are also included in Table C-1. Two settling tests were conducted after DBA was in the FGD system for a minimum of 11 days. The unit area for the DBA consumption samples averaged around 14 ft^2-day/ton. The final underflow solids content concentration averaged 43%. These results were comparable to the baseline settling test results collected in May. However, a settling test performed immediately prior to the long-term DBA test indicated that the solids settling properties were relatively poor. Therefore, the results appear to show that DBA addition had a positive effect on settling rate and final settled solids content.

2.7.2 Filter Leaf Tests

Filter leaf tests simulate the performance of a rotary drum vacuum filter. Two separate results are typically determined from these tests: form filtration rate and cake moisture content. The form filtration test was performed on reaction tank slurry samples to determine the effective solids filtration rates (lb/hr-ft^2 filter area). The test was performed by measuring the time from the start of the slurry vacuum filtration step until liquor was no longer visible on the surface of the filter cake. The test results give an indication of the required filtration surface area to filter the slurry solids, and indicate the ease with which water is drawn from the solids. Samples were adjusted initially to 30 wt.% solids so individual test results could be more easily compared. The cake moisture test was performed by applying a vacuum to a sample for a constant period and measuring the water content in the resulting cake. This test measures the tendency of the filtered solids to retain water.

Detailed results for the filter leaf tests are also included in Appendix C, Table C-2. The form filtration rate measurements were scattered, ranging from 120 to 370 lb/hr-ft^2. In general, the variability in the form filtration rate results makes it difficult to draw conclusions regarding the effect of the additives on filtration rate. However, the final cake solids content measured during the filter leaf tests dropped from 56 wt.% to 53 wt.% after sodium formate was added to the FGD system. Before adding DBA to the FGD system, the final cake solids measured during the filter leaf test was 54%. During the DBA consumption test, the final cake solids measured during the filter leaf tests increased from 54% midway through the test to 64%

on the last day. Based on these data, it appears that sodium formate may have adversely affected filtration properties while DBA may have positively affected them.

2.7.3 SEM Photographs

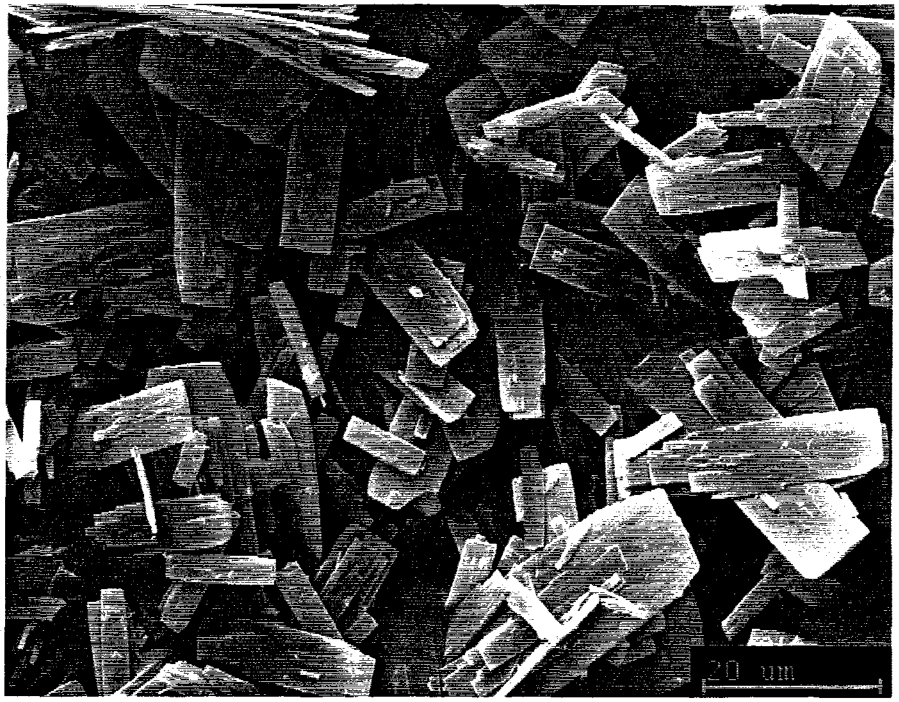
Figures 2-5 through 2-11 are scanning electron microscope photographs of solids samples from the baseline test, parametric test, and the two consumption test periods. No differences in crystal size are readily apparent between the samples from the base tests without additive (Baseline Test 1, Parametric Test 1, and Baseline before the addition of DBA) and those from the sodium formate tests (Parametric Test 7 and Day 6 of the sodium formate consumption test) or from the DBA consumption test (Day 5 and Day 11). In each sample photographed, the crystals appear to be thin platelets with a length-to-width ratio (L/W) of about 3:1.

Thus, although the settling test and filter leaf tests appear to indicate that sodium formate adversely affected solids dewatering properties, and that DBA additive may have improved dewatering properties, the SEM photographs do not substantiate these observations. There was no change in crystal size or shape noted that would correlate with changes in solids dewatering properties. It would take longer operation with either additive to determine whether the trends observed in the settling rate and filter leaf tests would be reflected in the operation of the full-scale dewatering equipment.

2.8 Other Process Data

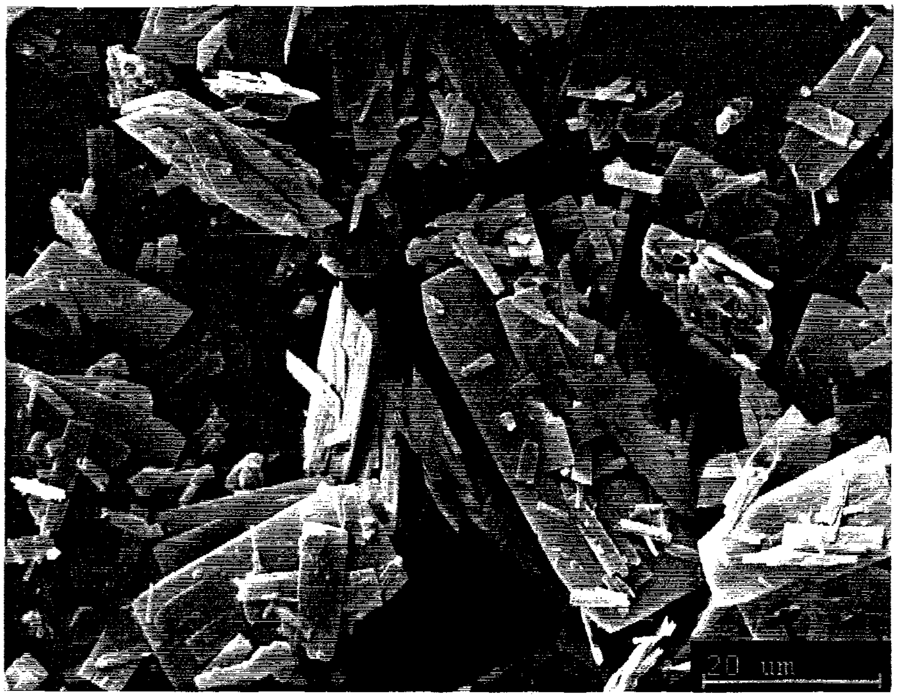
2.8.1 Control Room Data

During the tests, other process data were recorded manually from the control room indicators or retrieved from PSI Energy's data acquisition system. These data are included in Appendix D, Tables D-1 through D-3.



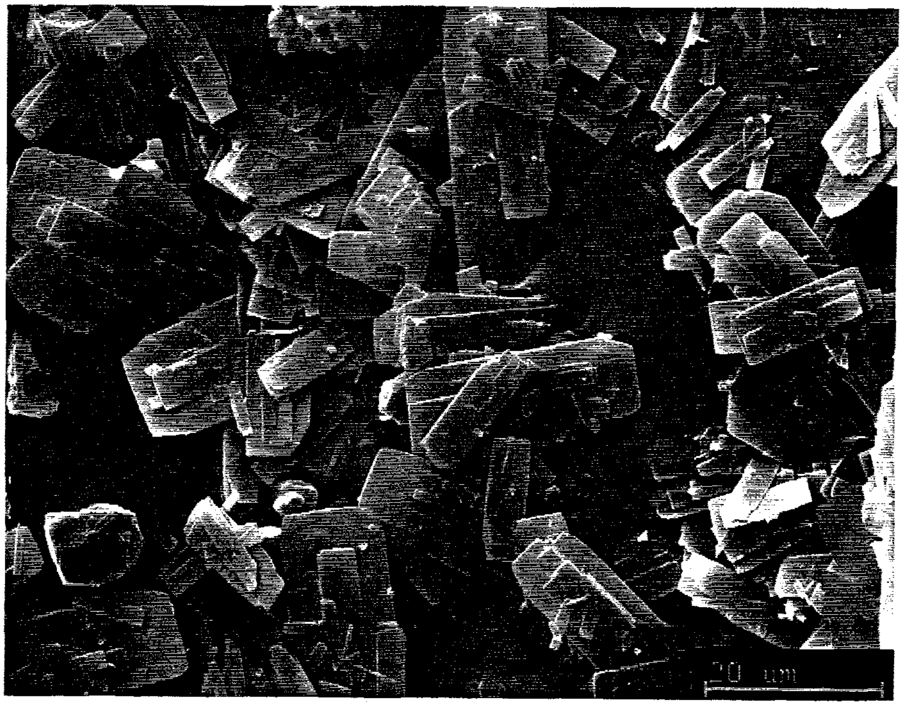
Sample: 1C Magnification: 1000x

Figure 2-5. Baseline Test 1 Solids (w/o additive)



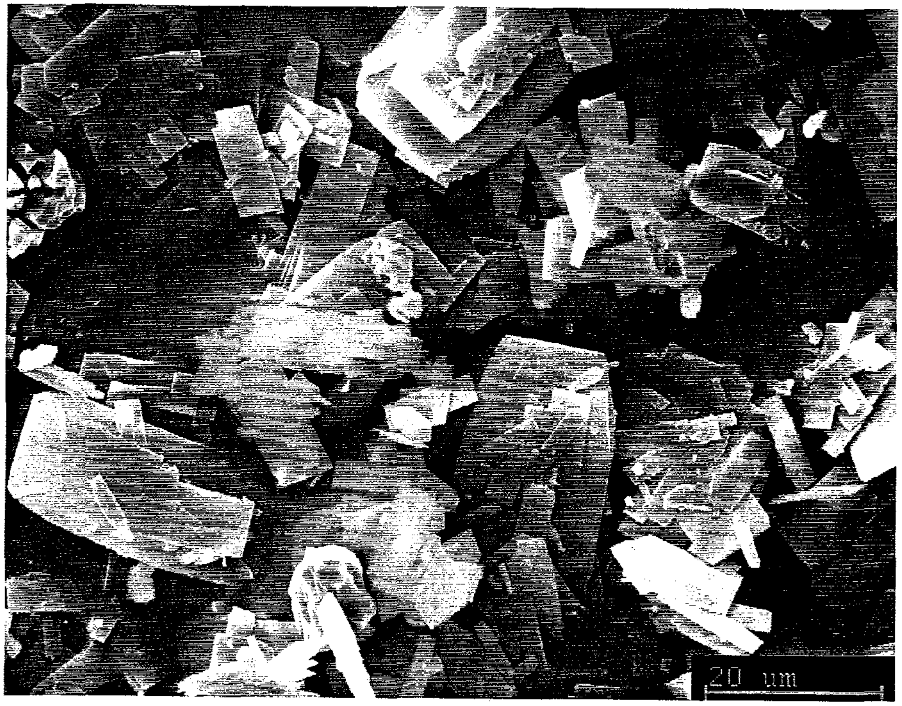
Sample: 1-3-GP Magnification: 1000x

Figure 2-6. Parametric Test 1 Solids (w/o additive)



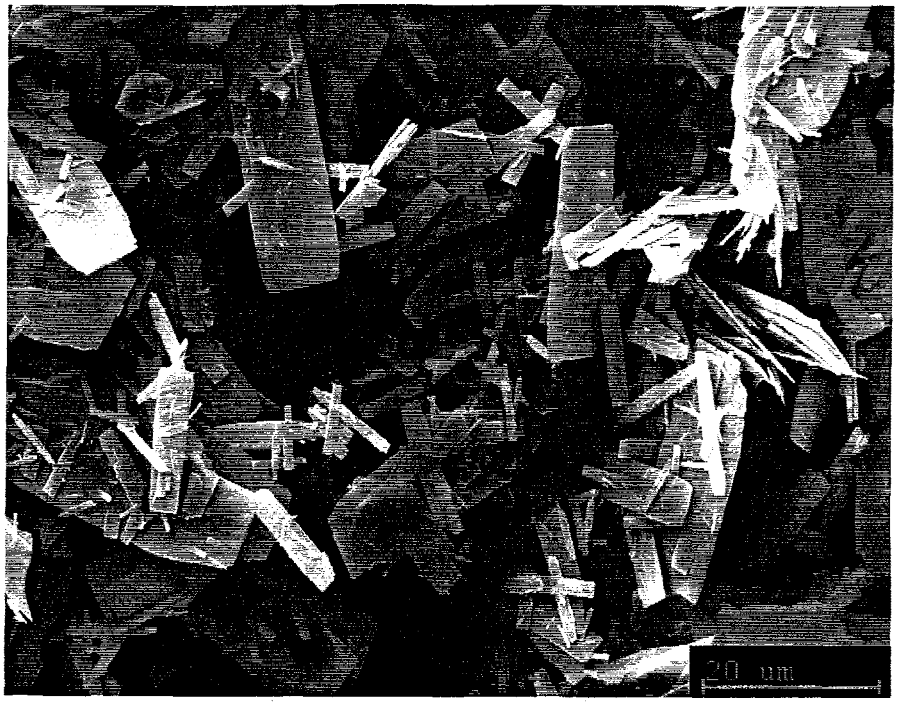
Sample: 7-6-GP   Magnification: 1000x

Figure 2-7. Parametric Test 7 Solids (w/ sodium formate)



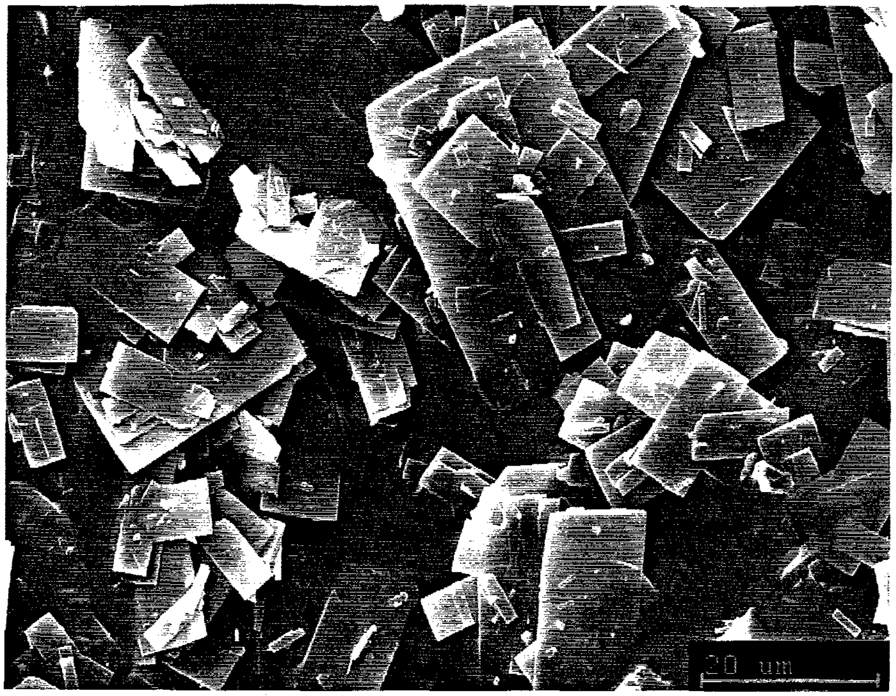
Sample: A-2GLT   Magnification: 1000x

Figure 2-8. Sodium Formate Consumption Test Day 6 Solids (w/ sodium formate)



Sample: A2B-GP2 Magnification: 1000x

Figure 2-9. Baseline Test Before DBA Consumption Test Solids (w/o additive)



Sample: A2M-GP2 Magnification: 1000x

Figure 2-10. DBA Consumption Test Day 5 Solids (w/ DBA)

Sample: A2-GP2   Magnification: 1000x

Figure 2-11. DBA Consumption Test Day 11 Solids (w/ DBA)

Some changes in process conditions occurred that are known to affect sulfite oxidation in the system. Tables 2-1 and 2-2 showed that the inlet flue gas SO_2 concentrations were higher during the parametric test period, compared to those during the baseline period. Higher inlet SO_2 levels tend to decrease the sulfite oxidation percentages. Unit load dropped during Parametric Tests 3 and 4. A decrease in boiler load can promote sulfite oxidation, because of a corresponding increase of excess combustion air and flue gas oxygen levels. This is evidenced by a decrease in the measured flue gas CO_2 levels during these periods, which suggests that the O_2 levels were correspondingly higher. The solids samples collected during these two tests showed higher oxidation percentages than any of the other parametric test samples.

2.8.2 Slurry Flow Rate Measurements

Slurry flow rate measurements were conducted on the spray headers twice during the baseline tests, using an ultrasonic Doppler-effect flow meter. This instrument processes a signal from a pair of transducers placed on the pipe. The normally recommended location for the transducers is on opposite sides of the pipe, away from flow disturbances. Problems getting stable readings were experienced when the transducers were positioned in this manner. To get stable flow readings, it was necessary to place the transducers on the same side of the pipe. This was recommended by the instrument supplier as an alternative when stable readings are not achieved with the transducers opposite one another.

Details of the slurry flow measurements are included in Appendix D, Table D-4. Each reported flow rate is based on the totalized flow measured over a five-minute period. The average recycle pump flow was approximately 12,500 gpm. Based on the measured slurry flows, an L/G ratio of approximately 75 gal/kacf is achieved during three-module operation when four recycle pumps are in service, as well as during four-module operation when three recycle pumps are in service. During three-module operation when three recycle pumps are in service, the operating L/G ratio drops to about 60 gal/macf. The highest L/G ratio possible under full-load conditions is about 95 gal/kacf during four-module operation with four recycle pumps in service.

3.0 FGDPRISM MODELING RESULTS

The EPRI FGD PRocess Integration and Simulation Model (FGDPRISM) is a computer program that simulates the performance of FGD systems. The model was calibrated to PSI Energy's Gibson Station Unit 5 with data from the baseline and parametric tests. After calibration, a general system case was developed to evaluate low absorber gas velocity (four-module operation), high reagent ratio, sodium formate addition, DBA addition and high magnesium concentration as options to increase the SO_2 removal performance of the system. The results of the calibration and the process simulations follow. These results form the basis for the economic analysis in the next section.

Details of the FGDPRISM model adapted to the Gibson absorber configuration and subsequent calibration procedures are described in Appendix E. Results of the calibration and predictive simulations are summarized below.

3.1 FGDPRISM Calibration Results

The calibration of FGDPRISM to PSI Energy's Gibson Station utilized all the performance test data presented in Section 2. By combining the test data from the testing of sodium formate addition, increased limestone addition, and increased L/G ratio, the model is able to compare the effects of each on a general system case. The calibration involved adjusting the limestone dissolution rate and surface area constants and the gas-liquid mass transfer film thicknesses to achieve the best overall fit of SO_2 removal, limestone utilization, and pH for these cases.

The scrubber chemistry for each case was approximated by adjusting the coal sulfur and chlorine content, the reactive magnesium in the limestone, the scrubber sulfite oxidation, and the limestone reagent ratio.

The final calibration parameters were:

- Liquid-film thickness of 2.0 microns;
- Gas-film thickness of 7.3 microns;
- Limestone reaction rate constant of 1×10^{-5}; and
- Reagent surface area factor of 0.10.

Appendix E, Table E-1 compares the calibration results with the measured SO_2 removal, limestone utilization, and pH for all of the performance test cases. Figure 3-1 compares measured SO_2 removals with the predicted results from these cases. Figure 3-2 compares measured NTU with the predicted results. The calibrated model predicted the results on average within ±1% (SO_2 removal basis) for 75% of the parametric tests and within ±3% (SO_2 removal basis) for all the parametric tests. The baseline tests were more difficult. Changes in limestone composition and grind may be a factor in matching the predicted baseline SO_2 removals to the measured results and/or getting all the cases to converge. More data on the baseline limestone grind would be required to determine a limestone surface area for the different operating conditions during baseline tests. Furthermore, additional investigation of the numerical methods involved with modeling the limestone dissolution rate may be required.

With FGDPRISM calibrated to the performance data, the ability of the model to estimate the additive consumption rate was validated by comparing the full-scale results of the sodium formate and DBA consumption tests to the predicted rates. The rate predicted by FGDPRISM for the sodium formate consumption test agrees within approximately 20% (higher) of the full-scale result, predicting 12.8 lb/ton vs. the measured value of 10.6 lb/ton of SO_2 removed. The consumption rate predicted by FGDPRISM for the DBA consumption test was approximately 25% lower than the full-scale result, 6.7 lb/ton vs. 9.0 lb/ton SO_2 removed. The consumption rate data utilized by FGDPRISM are mostly bench- or pilot-scale data. The relatively good agreement of the simulation to full-scale results serves to validate the fundamentals of the model.

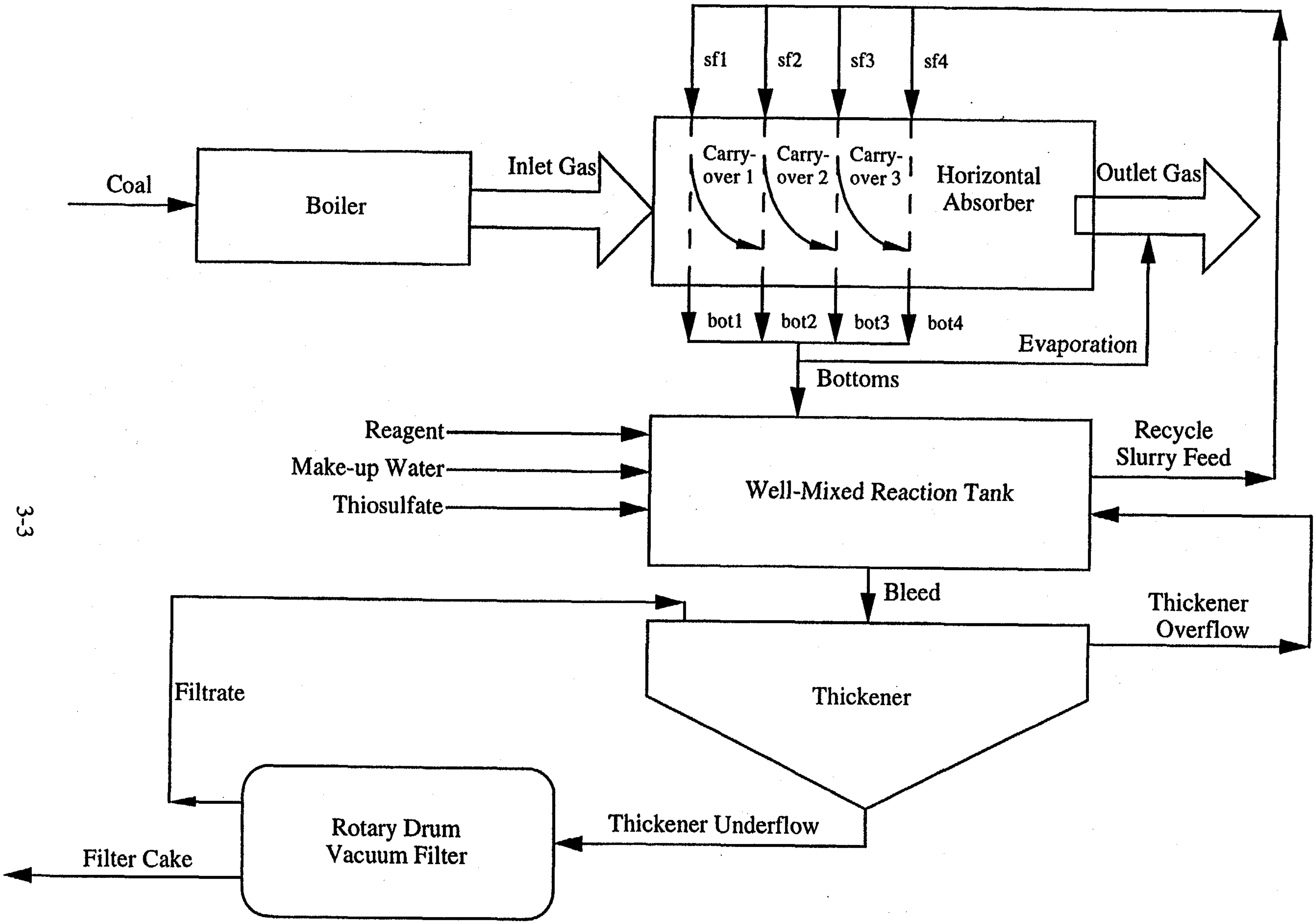


Figure 3-1. Flow Diagram of Horizontal Scrubber for PSI Energy Gibson

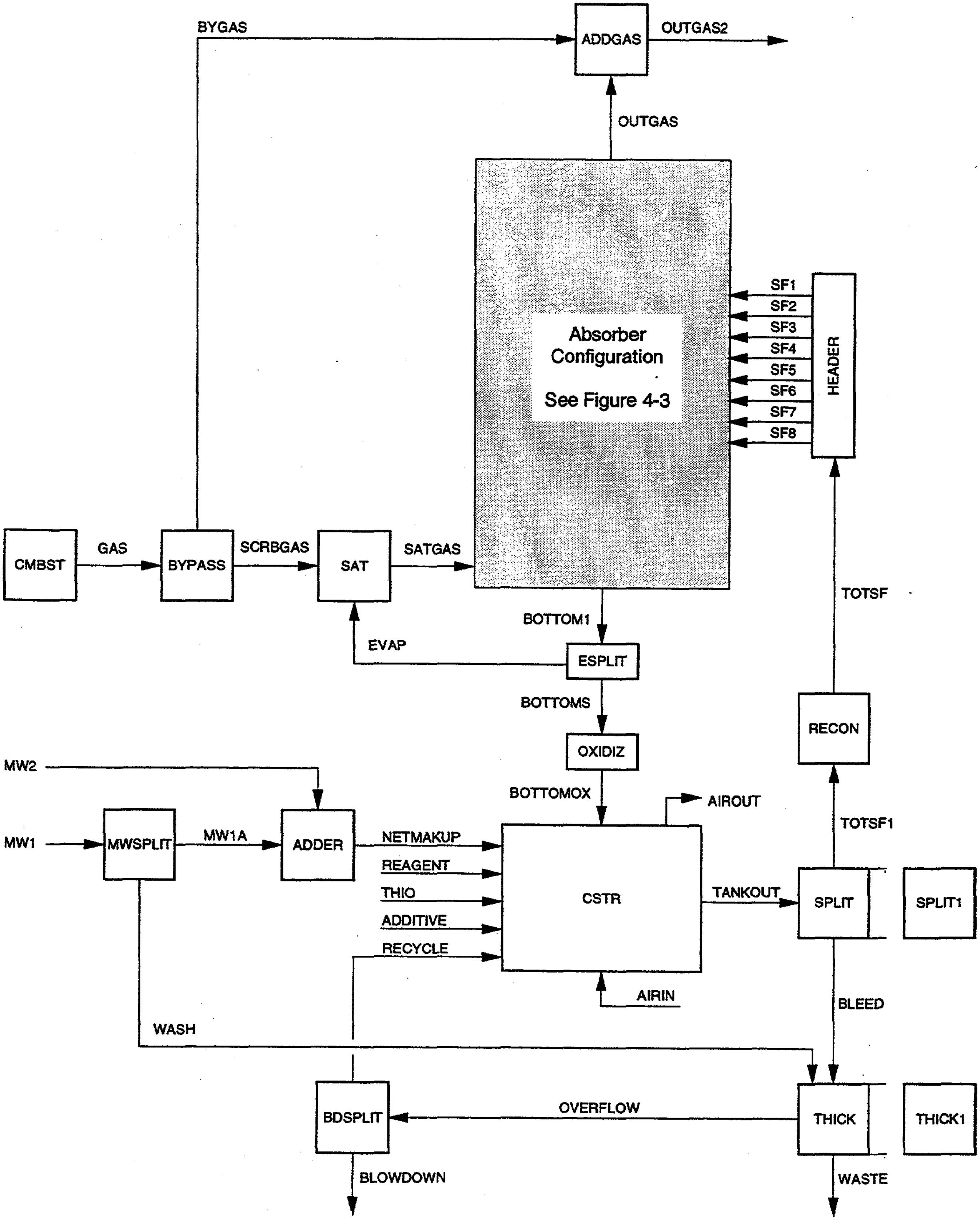


Figure 3-2. FGDPRISM System Simulation Template

3.2 Predictive Simulations

As discussed earlier, significant differences in operating conditions between the baseline and parametric test period (i.e., inlet SO_2 concentration, dissolved chloride concentration, and limestone grind fineness) make it difficult to accurately compare the options for improving SO_2 removal. To illustrate this, the calibrated FGDPRISM model was used to simulate some of the baseline tests at operating conditions representative of those experienced during the parametric tests. For example, Baseline Test 1 was simulated at a higher inlet SO_2 and dissolved chloride concentration, as well as with a coarse limestone grind. As a result, the predicted SO_2 removal for this test dropped from 86 to 71%. A similar drop from 90 to 82% was predicted for Baseline Test 2. These predictions were included in Figure 2-3 as the "zero concentration" values for the sodium formate parametric tests to better illustrate the effect of sodium formate additive on SO_2 removal.

Because the baseline and parametric test results were not directly comparable, it was necessary to use FGDPRISM to fully and accurately evaluate the options being considered for improving SO_2 removal efficiency. Options considered include operating with four modules, increasing pH, sodium formate and DBA addition, and increasing the dissolved magnesium concentration. The options were evaluated for their ability to achieve 90, 95, and 97.5% SO_2 removal.

To compare each method of increasing SO_2 removal on the same basis, a general system base case was developed. The general case was based on full-load, three-module operation at normal design conditions with no gas bypass. The FGDPRISM inputs for this case are shown in Table E-2. The inputs are based on current operating conditions, test measurements, and design operating parameters. Using the base case conditions, the number of absorbers in service, sodium formate concentration, DBA concentration, reagent utilization, and magnesium concentration were independently adjusted to increase SO_2 removal.

Table 3-1 summarizes the different operating conditions simulated with FGDPRISM and the corresponding SO_2 removal predictions used in the economic evaluation. The first row of results is the summary of the general system case. SO_2 removal was 80% with three modules in service, four recycle pumps in operation, 9,500 ppm Mg, and 5.3 pH. Each case contains highlighted numbers to show what variables were changed in the general system case to obtain the higher SO_2 removal in each case.

In Table 3-1, the SO_2 removal predictions associated with changes in pH, absorber flue gas velocity, or addition of sodium formate appear to correlate well with the performance test data. No tests were performed at the higher magnesium concentration during baseline or parametric testing. Therefore, the validity of the SO_2 removal predictions for this option cannot be confirmed. Only performance testing with variable magnesium concentrations will confirm the actual benefit achieved by operating at higher magnesium concentrations.

In addition to the above simulations, a sensitivity analysis was performed. The analysis considered the impact of operating with 5% higher unit load, a minimum of 5% flue gas bypass, and a higher inlet coal sulfur content of 3.4 wt.%. Using sensitivity base case conditions, the amount of flue gas bypass, sodium formate concentration, and DBA concentration were independently adjusted to increase SO_2 removal.

Table 3-2 summarizes the different operating conditions simulated with FGDPRISM and the corresponding SO_2 removal predictions for the sensitivity cases. Each case in Table 3-2 contains highlighted numbers to show what variables were changed from the general system case conditions to obtain higher SO_2 removal.

The first row of results in Table 3-2 is the summary of the general system case performance, with three modules in service with four pumps per module. Because of the higher unit load, higher coal sulfur content and a minimum of 5% flue gas bypass, FGDPRISM predicts only 73% overall SO_2 removal, which is not adequate to achieve SO_2 emissions compliance for this unit. Changing to four-module operation at the same L/G (three pumps per module) resulted

Table 3-1

FGDPRISM Modeling Results for Economic Evaluation

Mod. in Service	Pumps in Service	Formate Conc. (mg/L)	DBA Conc. (mg/L)	Mg^{++} Conc. (ppm)	Utilization (%)	SO_2 Removal (%)
3	4	0	0	9500	85	80.0
4	3	0	0	9500	85	85.3
4	4	0	0	9500	85	93.2
3	4	0	0	9500	**80**	85.7
3	4	0	0	9500	**70**	90.5
3	4	**500**	0	9500	85	86.2
3	4	**1000**	0	9500	85	87.8
3	4	**1500**	0	9500	85	88.9
3	4	**2000**	0	9500	85	89.6
3	4	0	**500**	9500	85	84.8
3	4	0	**1000**	9500	85	87.8
3	4	0	**1500**	9500	85	89.4
3	4	0	**2000**	9500	85	90.3
3	4	0	0	**11500**	85	88.9
4	4	0	0	9500	**80**	95.4
4	4	0	0	9500	**70**	96.8
4	4	**250**	0	9500	85	94.8
4	4	**500**	0	9500	85	95.2
4	4	**1000**	0	9500	85	95.7
4	4	**1500**	0	9500	85	96.0
4	4	0	**500**	9500	85	95.4
4	4	0	**1000**	9500	85	96.2
4	4	0	**1500**	9500	85	96.7
4	4	0	0	**11500**	85	95.9

Table 3-2

FGDPRISM Modeling Results for Economic Evaluation of Sensitivity Cases

Mod. in Service	Pumps in Service	Flue Gas Bypass (%)	Formate Conc. (mg/L)	DBA Conc. (mg/L)	Utilization (%)	SO_2 Removal (%)
3	4	5	0	0	85	73.0
4	**3**	5	0	0	85	77.9
4	4	**12.5**	0	0	85	82.3
4	4	5	0	0	85	87.0
4	4	5	**500**	0	85	89.4
4	4	5	**1000**	0	85	90.0
4	4	5	**1500**	0	85	90.4
4	4	5	0	**500**	85	89.4
4	4	5	0	**1000**	85	90.4
4	4	5	0	**1500**	85	91.0

in a small increase in overall SO_2 removal (to 77.9%), but this is still not sufficient to achieve compliance. The calculated SO_2 removal required to achieve compliance was 82.3% (1.1 lb SO_2 per 10^6 Btu emission rate). This was predicted to be achieved at high L/G conditions, with four modules in service and four recycle pumps in operation per module, but the amount of flue gas bypass could be increased to 12.5%.

Decreasing the bypass amount back to the minimum 5% for the fourth case listed in Table 3-2 raised the overall SO_2 removal to 87%. All of the subsequent cases in Table 3-2 show the effects of using sodium formate or DBA at four-module, four-pump, and 5% bypass conditions.

4.0 ECONOMIC EVALUATION

An analysis was performed to evaluate the economics of several SO_2 removal upgrade options for PSI Energy's Gibson FGD system. The SO_2 removal performance of each option was estimated using the calibrated FGDPRISM model described in Section 3. Results of the economic evaluation are presented in this section.

4.1 Upgrade Options and Evaluation Basis

The options evaluated include:

- Increasing the number of absorber modules in service;
- Increasing absorber slurry pH;
- Using sodium formate or DBA as an additive; and
- Increasing the dissolved magnesium concentration.

All four upgrade options and combinations of options were compared to a base case, representing the design operating conditions for the Gibson FGD system. A sensitivity analysis was also performed which considered alternative coal and boiler operating conditions.

The first step in the economic evaluation was to establish a base case for FGD system operating conditions and performance, from which to compare the upgrade options. The technical bases for the base case and sensitivity case are presented in Table 4-1. The base case for the evaluation assumes three-module operation with four recycle pumps per module, which is the original design of the Gibson FGD system. Full-load conditions were modeled with no flue gas bypass for all upgrade options to maximize overall SO_2 removal efficiency. For the sensitivity case, the FGD system was modeled at a higher boiler load and coal sulfur content, as well as with a minimum of 5% flue gas bypass.

Table 4-2 summarizes the cost basis used for the economic evaluation. All upgrade options require an increase in reagent consumption and waste solids production because

Table 4-1

Technical Basis for Economic Evaluation

	Base	Sensitivity
Unit Load	620 MW	650 MW
Flue Gas Bypass	0%	5%
Plant Capacity Factor	70%	70%
Modules in Service	3	4
Recycle Pumps in Service	4	4
Coal Sulfur Content	3.0 wt.%	3.4 wt.%
Coal Chlorine Content	~0.1 wt.% (~12,000 ppm)	~0.1 wt.% (~12,000 ppm)
Dolomitic Lime Purity	41 wt.% MgO	41 wt.% MgO
Limestone Grind Fineness	80% < 325 mesh	80% < 325 mesh
Limestone Utilization	~85%	~85%
Slurry pH	~5.3	~5.3
Mg^{++} Concentration	9,500 ppm	9,500 ppm
Thiosulfate Concentration	2,000 ppm	2,000 ppm
Filter Cake Solids Content	60 wt.%	60 wt.%

Table 4-2

Cost Basis for Economic Evaluation

Cost Item	Cost or Range	Source
Limestone	\$9.56/ton delivered	PSI Energy
Dolomitic Lime	\$53.50/ton delivered	PSI Energy
Reagent O&M	20% of total limestone costs	PSI Energy
Electricity	\$0.02/kw-hr	PSI Energy
Waste Solids Disposal	\$2.25/ton (wet basis)	PSI Energy
Additive Capital	\$277,000 for either additive	Sargent & Lundy
Sodium Formate	\$0.246/lb (dry basis) delivered as 40% sln.	Perstorp Polyols
DBA Additive	\$0.236/lb (dry basis) delivered as 50% sln.	Monsanto
SO_2 Allowance	\$150 & \$250/ton of SO_2 removed	Assumed

of the increase in SO_2 removed. PSI Energy provided the cost parameters associated with reagent purchase and preparation. The cost of limestone is currently $9.56/ton, which reflects the cost of delivery and on-site storage. The operating and maintenance (O&M) costs associated with reagent preparation are calculated as 20% of the total limestone reagent costs. If the tonnage of limestone required for a particular option exceeds the capacity of the existing Unit 5 ball mill, it was assumed that the excess limestone would be supplied by the reagent preparation system for a new FGD system on the adjacent unit at Gibson Station.

Other operating costs were also provided by PSI Energy. The cost of dolomitic lime is currently $53.50/ton. The cost of additional electricity consumed by the FGD system is $0.02/kw-hr. The incremental cost for disposal of additional filter cake is approximately $2.25/ton, wet. This estimate includes the cost of lime addition to stabilize the waste solids.

For operation with additive, an estimated capital cost of $277,000 for the additive feed system at Gibson Station was developed by Sargent & Lundy. For this analysis, the capital costs were amortized over 10 years at an interest rate of 11.5%.

The cost of sodium formate additive is based on a quote provided by Perstorp Polyols. The cost of 40 wt.% sodium formate solution, delivered to the Gibson Station, ranged from $0.216/lb to $0.246/lb (on a dry basis). These prices represent the high and low price for sodium formate estimated by Perstorp Polyols. They predict the price may fluctuate up and down within this range through 1995. For the cost calculations, $0.246/lb was used as the more conservative value for the delivered cost of sodium formate.

The cost of DBA additive is based on a quote provided by Monsanto. The cost of 50 wt.% DBA solution, delivered to the Gibson Station, is $0.236/lb (on a dry basis). This estimate is based on the cost of DBA delivered to a nearby electric utility.

The value of SO_2 allowances is subject to market forces. As a result, the economic evaluation was based on a range of values for SO_2 allowances: $150/ton and $250/ton of additional SO_2 removed. The lower value, $150/ton, is approximately the average value from the first EPA auction, while $250/ton is the lowest value predicted for SO_2 allowances during Phase II. During Phase II, the value is expected to increase as high as $500/ton. (1)

4.2 Results

The technical and economic factors described above were used along with the performance predictions described in Section 3 in a spreadsheet calculation that estimates the marginal and average costs for additional SO_2 removal at increasing levels of SO_2 removal efficiency. The results of these calculations are summarized in Table 4-3 for the base case coal sulfur without flue gas bypass. Only the optimum conditions are shown for each upgrade option. The use of additives and increased slurry pH were also evaluated with three-module operation, but four-module operation was more cost effective in all cases.

The first column in Table 4-3 describes the upgrade options. For each option, the predicted SO_2 removal efficiency and annual amount of additional SO_2 removed (above that of the base case condition) are shown in the third and fourth columns. The fifth column shows the limestone utilization, which is 85% except for the increased-pH option, for which it is reduced to 80%.

All of the upgrade options evaluated result in increased SO_2 removal. Thus each case includes increased limestone and dolomitic lime consumption and costs, as well as increased waste solids production and disposal costs. In addition, all of the upgrade options incur additional fan and pump power costs for four-module operation. Options with performance additives include annualized capital costs for the storage and delivery system plus purchase costs for the additives. The sixth column shows the total annual cost increase for each option, again referred to the base case condition. Details of the individual cost items as well as the predicted performance and costs for cases other than the optimum are given in Appendix F.

Table 4-3

Economic Comparison of SO_2 Removal Upgrade Options (3.0% S coal, no flue gas bypass)

Option	Modules in Service	Flue Gas Bypass (%)	%SO_2 Removal	Additional SO_2 Removed (ton/yr)	% Limestone Utilization	Total Added Cost ($1000/yr)	Average Cost ($/ton SO_2)	Net Annual Value ($1000)	
								@ $250/ton SO_2	@ $150/ton SO_2
Base Case (3% S coal)	3	5	80	0	85	0	0	0	0
Increase number of modules in service	4	0	93.2	13,200	85	640	48	2,600	1,300
Increase number of modules in service, increase slurry pH	4	0	95.4	15,400	80	910	59	2,900	1,400
Increase number of modules in service, add 500 mg/L formate	4	0	95.2	15,200	85	980	65	2,800	1,300
Increase number of modules in service, add 500 mg/L DBA	4	0	95.4	15,400	85	910	59	2,900	1,400
Increase number of modules in service, increase soluble Mg	4	0	95.9	15,900	85	940	59	3,000	1,400

The seventh column shows the average cost per ton of additional SO_2 removed, and the final two columns show the estimated annual value of each upgrade option based on the two different assumed values for SO_2 allowances.

In Table 4-3, the first option evaluates the results of increasing the number of modules in service and therefore the L/G ratio. FGDPRISM predicts SO_2 removal will increase from 80% (baseline with 5% flue gas bypass) to about 93% with this option (without flue gas bypass). The total annual costs for this case increase by $640,000, and the average cost is about $48 per additional ton of SO_2 removed. The net annual values for this option are $1.3 million and $2.6 million, assuming SO_2 allowance values of $150/ton SO_2 and $250/ton SO_2, respectively.

The next option presents results obtained by raising the slurry operating pH, hence raising the reagent ratio and decreasing limestone utilization (also with four-module operation). FGDPRISM predicts SO_2 removal will increase to 95.4% when the limestone utilization decreases from 85 to 80%. The total cost increase for this option, relative to the base case, is $910,000/yr, and the average cost of additional SO_2 removal is $59/ton. The annual value of this option is slightly higher, compared to operation at the normal pH set point, at either $1.4 million or $2.9 million, depending on the assumed value for allowances.

The next two options show results of adding sodium formate and DBA, respectively, to the FGD system in the four-module configuration, at the base case pH set point with 85% limestone utilization. FGDPRISM predicts that SO_2 removal will increase to slightly more than 95% when either additive is used at 500 mg/L. The results show that DBA is slightly more cost effective than sodium formate, but the difference is probably not significant within the accuracy of these cost estimates. The estimated annual values for these options are similar to those for the increased-pH option.

The final option in Table 4-3 involves increasing the soluble magnesium concentration in the slurry from the base case level of 9500 mg/L to 11,500 mg/L, by increasing the dolomitic lime feed to the FGD system. No full-scale testing of this option was performed. FGDPRISM predicts SO_2 removal will increase to nearly 96% with this option, removing 15,900 additional tons of SO_2 at an average cost of $59/ton. The estimated annual value of this option is slightly higher than for the previous options. Although this option appears attractive, PSI Energy personnel have indicated that operation at elevated dissolved magnesium levels significantly degrades the settling characteristics of the waste solids. As a result, they have been unable to maintain the required thickener overflow clarity when operating under these conditions (even with polymer addition to the thickener). Therefore, this option does not appear to be technically feasible unless acceptable solids properties can be maintained at the elevated dissolved magnesium levels.

Figure 4-1 shows the net annual value versus SO_2 removal efficiency for the options that include operation with four modules at high L/G. This includes the high L/G option alone, as well as in combination with each of the three options described above. Results are shown for SO_2 allowance values of both $150 and $250 per ton of SO_2 removed. The figure shows that operation with four modules at high L/G alone results in a significant net annual value of approximately $1.3 and $2.6 million annually for the assumed $150/ton and $250/ton SO_2 allowance values, respectively. For an SO_2 allowance value of $150/ton, the other upgrade options provide little additional net annual value. However, for an SO_2 allowance value of $250/ton, the three additional options to increase SO_2 removal result in an increase in net annual value to approximately $2.8 to $3.0 million annually.

For the sensitivity analysis, FGDPRISM was again used to simulate the performance of the Gibson FGD system. Table 4-4 presents the results of the analysis. As discussed in Section 3, with three modules in service the predicted overall SO_2 removal was only 73%. To achieve the required minimum SO_2 removal of 82%, operation with four modules and four pumps was required, although the amount of flue gas bypass could be increased to 12.5%. This represents the base case condition for the sensitivity analysis. As shown in Table 4-4, the overall SO_2 removal increases to 87% when the amount of flue gas bypass is decreased from 12.5

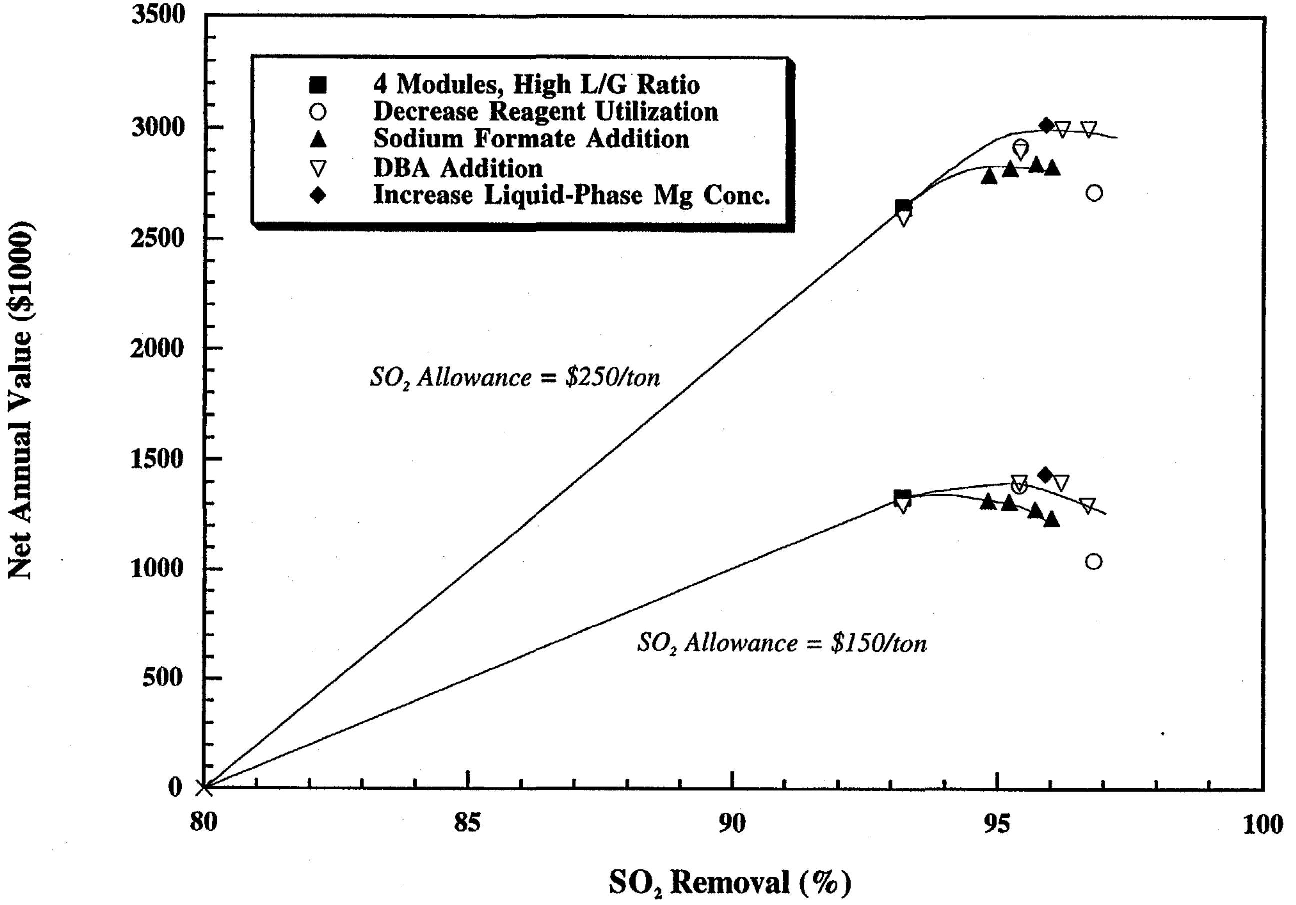


Figure 4-1. Net Annual Value vs. SO_2 Removal for High L/G Ratio Upgrade Options (3% S Coal, Without Bypass)

Table 4-4

Economic Comparison of SO_2 Removal Upgrade Options (3.4% S coal, 5% flue gas bypass)

Option	Modules in Service	Flue Gas Bypass (%)	%SO_2 Removal	Additional SO_2 Removed (ton/yr)	% Limestone Utilization	Total Added Cost ($1000/yr)	Average Cost ($/ton SO_2)	Net Annual Value ($1000)	
								@ $250/ton SO_2	@ $150/ton SO_2
Base Case	4	12.5	82.3	0	85	0	0	0	0
Decrease bypass to 5%	4	5	87	4,700	85	150	32	1,000	550
Decrease bypass to 5%, add sodium formate at 1000 mg/L	4	5	90	7,700	85	600	78	1,300	550
Decrease bypass to 5%, add DBA at 1000 mg/L	4	5	90.4	8,100	85	510	63	1,500	700

to 5% in Option 1. However, Options 2 and 3 show that even with the use of additives, the overall SO_2 removal can only be increased to about 90%. This is due in part to limiting the minimum amount of flue gas bypass to 5% for this sensitivity analysis.

Figure 4-2 shows the net annual value for the sensitivity case options. These include operation with four modules at high L/G at the minimum bypass of 5%, as well as in combination with either of the two additives. Results are shown for SO_2 allowance values of both \$150 and \$250 per ton of SO_2 removed. The figure shows that operation with four modules at high L/G and 5% flue gas bypass results in a net annual value of approximately \$0.55 and \$1.0 million annually for the \$150/ton and \$250/ton SO_2 allowance values, respectively. For the lower SO_2 allowance value of \$150/ton, the additive upgrade options provide little additional net annual value. However, for an SO_2 allowance value of \$250/ton, the additives result in an increase in net annual value to approximately \$1.3 to \$1.5 million annually.

4.3 Recommended Upgrade Option

Based on the results described above, and considering the current market value of allowances (about \$150/ton) the most cost-effective upgrade option to increase SO_2 removal at the Gibson Station appears to be operating without flue gas bypass and increasing the system L/G by operating the fourth module. With this option, the system removal efficiency can be increased to about 93%, and more than 13,000 tons/year of additional SO_2 can be removed at an average cost of only \$48/ton. This cost is very attractive compared to the cost of purchasing allowances, which is estimated at \$150 to \$250 per ton, or constructing a retrofit FGD system on an existing unit. The latter is expected to result in SO_2 removal costs in the range of \$250 to \$500 per ton.

The goal of this project, of cost effectively achieving 95% SO_2 removal with the existing FGD system, could be met by raising the pH set point or adding sodium formate or DBA additive. However, if SO_2 allowances are valued at \$150 per ton, achieving 95% SO_2 removal offers little advantage over the 93% removal case. The incremental costs for going from 93% removal to 95% removal are nearly equal to the \$150/ton allowance value.

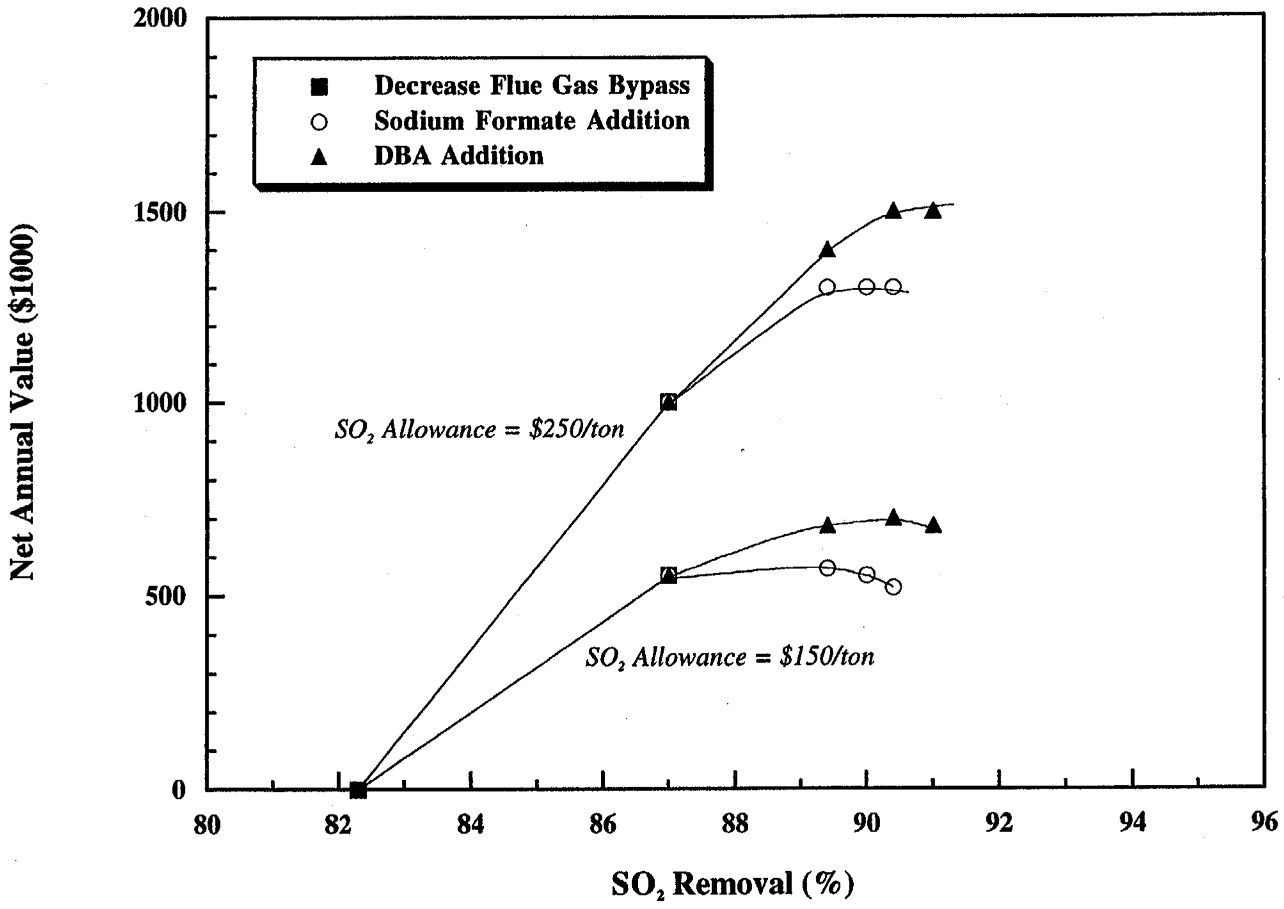


Figure 4-2. Net Annual Value vs. SO_2 Removal for Sensitivity Cases (3.4% S Coal, 5% Bypass)

If the market price of SO_2 allowances exceeds $150 per ton, though, achieving 95% removal could be the most cost-effective operating mode. For example, at an SO_2 allowance value of $250 per ton, the additional tons of SO_2 removed by adding DBA or raising the pH set point to go from 93% to 95% removal would have a net value of approximately $300,000 per year.

4.4 Reference

1. Torrens, Ian and Jeremy Platt. "Update on Electric Utility Response to the CAA." EPRI ECS Update, No. 30, Fall 1993.

Appendix A

Detailed SO_2 Removal Data and Chemical Analyses Results

Detailed SO_2 Removal Data

Table A-1 summarizes the detailed test conditions and SO_2 removal efficiency results for the baseline tests. All of the SO_2 concentrations are reported on a dry flue gas basis. Two values are shown for the Method 6 results. The first value is based on the on-site titration for sulfate in the H_2O_2 impingers using the barium perchlorate method. 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. The SO_2 removal values shown in the table are calculated on the basis of the off-site SO_2 concentration results, which are considered the more accurate of the two measurements. However, 75% of the on-site SO_2 removal results for the baseline tests agree within ±0.8 percentage points of the off-site results, and all of the on-site SO_2 removal results agree within ±1.4 percentage points of the off-site results.

Table A-2 summarizes the detailed test conditions and SO_2 removal efficiency results for the sodium formate parametric tests. The parametric tests were conducted at four different formate levels, two pH levels, and two flue gas velocity levels. The low pH level for the parametric tests (5.3) in Table 3-8 is the typical operating pH for the FGD system. The two flue gas velocities correspond to full-load operation with three (high velocity) or four modules (low velocity) in service.

Results for the on-site and off-site Method 6 analyses of SO_2 concentration are again shown in the table. For the sodium formate parametric tests, 87.5% of the on-site SO_2 removal results agree within ±0.5 percentage points of the off-site results, and all of the on-site SO_2 removal results agree within ±1.4 percentage points of the off-site results. The inlet SO_2 concentrations were about 32% higher during the parametric tests than during baseline testing, because of a higher sulfur coal being fired in Unit 5.

Formate concentrations are also shown in the table, and are based on the off-site analyses. Formate concentrations determined by on-site buffer capacity titration averaged 4%

higher than the off-site results. The off-site results are presumed to be more accurate, because the analysis results are specific to the formate ion while the buffer capacity results could be influenced by other buffering species.

Solid-Phase Analyses

Results of solid-phase analyses for the baseline test slurry samples are summarized in Table A-3. Each slurry sample was filtered, dried, and weighed to determine the slurry solids content in weight percent. A portion of the dried solids was then digested in HCl. The insoluble portion of the solids is reported as "inerts" in weight percent of solids.

The digested solids solution was analyzed for calcium (Ca^{++}) and magnesium (Mg^{++}) by atomic absorption and for sulfate ($SO_4^=$) by ion chromatography (IC). A separate portion of the dried solids was analyzed for sulfite ($SO_3^=$) by thiosulfate /iodine titration. A third portion of the dried solids was analyzed for carbonate ($CO_3^=$) 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 Table A-3 following the analytical results. Percent reagent utilization is defined as [1.0 - moles of CO_3/(moles of FGD byproduct solids + moles CO_3)]*100. The "Ca-independent" value for utilization is calculated using the total sulfur (sulfite plus sulfate) analysis as the total moles of FGD byproduct. The "SO_4-independent" value is calculated using the Ca analysis as the sum of the moles of FGD byproduct + moles of carbonate. The calculated utilization values are also expressed as reagent ratio, the inverse of utilization.

Additional slurry samples other than those shown in Table A-3 were analyzed for carbonate content to improve the accuracy of the limestone utilization data. Table A-4 shows all of the slurry solids carbonate analyses, including those listed in Table A-3. Also shown in Table A-4 are calculated limestone utilizations in percent. For samples with only carbonate analyses, approximate utilizations were calculated by using the calcium analyses from the same test.

Sulfite oxidation percentages are also reported in Table A-3, calculated as 100 x [1 - moles of sulfite/(moles of sulfite + sulfate)].

The remaining entries in Table A-3 include solids analyses calculated on a weight basis, followed by calculated "closures" for 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 positively- and the negatively-charged ionic species in moles/gram divided by the total of the positively and negatively-charged species in moles/gram. The weight closure indicates the extent to which the weight of the sample analyzed is accounted for by the individual species.

The calculated "acceptable" closure in percent is the expected error in the calculated molar closure at the 95% confidence level. This is based on the assumption that each of the individual analyses has a standard deviation of ±5%. The calculated closures in Table A-3 indicate good data quality for the baseline solids analyses. All of the molar closures are well within the acceptable limits.

Results of solids analyses for the formate parametric tests are summarized in Table A-5. The format of this table is the same as that described for the baseline solids analyses. The analytical results have been used to calculate limestone utilization and sulfite oxidation, which are also shown in the table. The values in the parentheses are the results of the additional slurry samples analyzed for carbonate content to improve the accuracy of the limestone utilization data. The molar closures again indicate good data quality.

Table A-6 shows results of solids analyses for the long-term sodium formate and DBA consumption test solids.

Liquid-Phase Analyses

Results of liquid-phase analyses for the baseline filtered slurry samples are shown in Table A-7. Calcium, magnesium, and sodium concentrations were determined by atomic absorption spectrophotometry. Chloride, sulfite, sulfate, and thiosulfate concentrations 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), represents the difference between the total hydrolyzable sulfate and the total moles of sulfur in the other individually reported sulfur species.

Calculated molar closures (charge imbalances) have again been used as an indicator of data quality. All of the baseline liquid samples show calculated molar closures within the acceptable level.

Tables A-8 and A-9 show liquid-phase analytical results for the sodium formate parametric tests and the long-term sodium formate and DBA consumption tests.

Table A-10 shows the results of chemical analyses for trace species by inductively-coupled plasma emissions spectroscopy.

Table A-1

Detailed Baseline Test Conditions and Results

Test	Run	Date	Time	Slurry pH	Gas Velocity (ft/sec)	L/G (gal/macf)	Inlet SO_2 (ppmd)		Outlet SO_2 (ppmd)		SO_2 Removal[a]	
							On-site	Off-site	On-site	Off-site	(%)	(NTU)
1	1	5-4-93	11:08-12:17	5.35	26	75	1871	1701	258	247	85.5	1.93
	2	5-4-93	12:55-14:02	5.33	26	73	1837	1632	259	239	85.4	1.92
	3	5-4-93	14:28-15:42	5.33	27	71	1771	1863	243	231	87.6	2.09
	4	5-4-93	16:41-17:54	5.32	26	73	1831	1788	269	261	85.4	1.93
	Average SO_2 Removal										86.0	1.97
2	1	5-5-93	08:17-09:32	5.68	25	76	1803	1831	159	183	90.0	2.30
	2	5-5-93	10:00-11:08	5.64	26	74	1725	1665	169	173	89.6	2.26
	Average SO_2 Removal										89.8	2.28
3	1	5-5-93	13:40-14:51	5.61	26	56	1836	1737	312	301	82.7	1.75
	2	5-5-93	15:18-16:36	5.60	26	55	1868	1725	322	310	82.1	1.72
	Average SO_2 Removal										82.4	1.73
4	1	5-6-93	08:45-09:42	5.10	25	78	1976	1926	440	441	77.1	1.47
	2	5-6-93	10:05-11:01	5.10	25	78	1913	1861	462	445	76.1	1.43
	Average SO_2 Removal										76.6	1.45
5	1	5-6-93	12:50-13:46	5.11	25	58	1939	1780	593	568	68.1	1.14
	2	5-6-93	14:26-15:20	5.11	25	59	1886	1797	636	599	66.7	1.10
	Average SO_2 Removal										67.4	1.12
6	1	5-7-93	07:21-08:14	5.33	25	58	1860	1782	399	408	77.1	1.47
	2	5-7-93	08:52-09:50	5.29	25	57	1913	1894	387	370	80.4	1.63
	Average SO_2 Removal										78.8	1.55
7	1	5-7-93	11:10-12:02	5.39	20	72	1877	1729	281	273	84.2	1.85
	2	5-7-93	12:24-13:21	5.34	20	73	1901	1736	287	271	84.4	1.86
	Average SO_2 Removal										84.3	1.85

[a] Based on off-site analyses.

Table A-2

Detailed Parametric Test Conditions and Results

Test	Run	Date	Time	Slurry pH	Gas Velocity (ft/sec)	L/G (gal/macf)	Off-site Formate (ppm)	Inlet SO_2 (ppmd)		Outlet SO_2 (ppmd)		SO_2 Removal[a]	
								On-site	Off-site	On-site	Off-site	(%)	NTU
1	1	9/14/93	1025-1112	5.67	20	96		2617	2348	123	124	94.7	2.94
	2	9/14/93	1200-1254	5.59	20	97		2634	2390	140	132	94.5	2.90
	3	9/14/93	1525-1608	5.64	19	99		2652	2388	105	96	96.0	3.21
	4	9/14/93	1646-1749	5.78	20	95		2522	2338	95	83	96.4	3.33
	Average SO_2 Removal											95.4	3.08
2	1	9/15/93	0956-1048	5.29	20	97		2540	2436	359	346	85.8	1.95
	2	9/15/93	1112-1201	5.29	20	97		2551	2447	331	315	87.1	2.05
	3	9/15/93	1423-1511	5.31	20	97		2518	2478	285	268	89.2	2.22
	4	9/15/93	1552-1642	5.27	20	99		2553	2510	290	274	89.1	2.22
	Average SO_2 Removal											87.8	2.10
3	1	9/16/93	0924-1014	5.31	27	70	535	2148	2137	364	353	83.5	1.80
	2	9/16/93	1039-1127	5.30	28	69	493	2170	2205	398	374	83.0	1.77
	Average SO_2 Removal											83.3	1.79
4	1	9/16/93	1436-1528	5.28	21	92	412	2195	2143	221	207	90.3	2.34
	2	9/16/93	1548-1638	5.33	21	93	387	2193	2120	214	205	90.3	2.34
	Average SO_2 Removal											90.3	2.34
5	1	9/17/93	0916-1002	5.73	26	74	1210	2468	2517	188	187	92.6	2.60
	2	9/17/93	1026-1113	5.75	27	72	1140	2509	2409	189	181	92.5	2.59
	Average SO_2 Removal											92.5	2.59
6	2	9/17/93	1631-1720	5.68	20	95	1474	2492	2746	63	62	97.8	3.80
	3	9/17/93	1905-1951	5.66	20	95	1368	2514	2401	82	68	97.2	3.56
	Average SO_2 Removal											97.5	3.68

Table A-2

(Continued)

Test	Run	Date	Time	Slurry pH	Gas Velocity (ft/sec)	L/G (gal/macf)	Off-site Formate (ppm)	Inlet SO_2 (ppmd)		Outlet SO_2 (ppmd)		SO_2 Removal[a]	
								On-site	Off-site	On-site	Off-site	(%)	NTU
7	1	9/20/93	0921-1011	5.28	27	70	1528	2534	2449	366	350	85.7	1.95
	2	9/20/93	1038-1127	5.30	27	72	1407	2467	2346	345	327	86.1	1.97
	3	9/20/93	1345-1432	5.37	27	70	1631	2432	2276	341	324	85.8	1.95
	4	9/20/93	1457-1547	5.32	28	70	1600	2404	2243	350	322	85.6	1.94
	5	9/21/93	0859-0947	5.30	28	70	1528	2394	2339	327	313	86.6	2.01
	6	9/21/93	1040-1129	5.30	27	71	1524	2394	2275	332	294	87.1	2.05
	Average SO_2 Removal											86.1	1.98
8	1	9/21/93	1415-1509	5.33	19	100	1435	2386	2312	130	118	94.9	2.98
	2	9/21/93	1530-1620	5.35	19	100	1430	2373	2203	129	116	94.8	2.95
	Average SO_2 Removal											94.8	2.96
9	1	9/22/93	0832-0925	5.35	27	73	2735	2523	2495	306	284	88.6	2.17
	2	9/22/93	0952-1040	5.29	27	72	2764	2537	2315	327	308	86.7	2.02
	Average SO_2 Removal											87.7	2.09
10	1	9/22/93	1203-1253	5.24	21	94	3022	2512	2296	172	162	93.0	2.65
	2	9/22/93	1609-1959	5.30	21	94	3462	2494	2413	165	157	93.5	2.74
	Average SO_2 Removal											93.2	2.69
11	1	9/23/93	0835-0918	5.68	27	72	4435	2504	2356	155	156	93.4	2.71
	2	9/23/93	0945-1033	5.66	28	70	4741	2508	2330	174	166	92.9	2.64
	Average SO_2 Removal											93.1	2.68
12	1	9/23/93	1424-1518	5.63	20	95	4952	2351	2172	64	59	97.3	3.60
	2	9/23/93	1540-1634	5.60	20	94	4925	2410	2194	58	56	97.4	3.66
	Average SO_2 Removal											97.4	3.64

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[a] Based on off-site analyses.

Table A-3

Baseline Solid-Phase Analytical Results

Radian Number:	1A	1B	1C	2B	3B	4B	5B	6B	7B
Date	5/4/93	5/4/93	5/4/93	5/5/93	5/5/93	5/6/93	5/6/93	5/7/93	5/7/93
Time	09:00	13:35	16:02	09:48	14:44	09:55	13:43	11:58	07:41
Ca, mm/g	7.19	7.17	7.27	7.55	7.27	7.20	7.33	7.19	7.13
Mg, mm/g	0.22	0.21	0.16	0.21	0.26	0.22	0.20	0.38	0.38
SO_3, mm/g	6.08	6.11	6.17	5.91	5.88	6.08	6.05	5.90	5.84
SO_4, mm/g	0.86	0.89	0.86	0.82	0.83	0.92	0.90	0.86	0.89
CO_3, mm/g	0.43	0.42	0.42	0.85	0.85	0.46	0.46	0.77	0.76
Inerts, wt.%	2.63	2.40	2.74	2.24	2.24	2.13	2.51	2.12	1.95
Solids, wt.%	16.8	18.2	16.7	16.4	16.3	16.0	16.2	16.0	16.3
pH	5.26	5.33	5.32	5.68	5.60	5.10	5.11	5.39	5.33
Temperature, °C	52.3	54.8	52.6	53.7	54.2	54.1	54.2	54.5	53.5
Reagent Utilization, %									
Ca-Independent	94.2	94.3	94.4	88.8	88.8	93.8	93.8	89.8	89.9
SO_4-Independent	94.2	94.3	94.3	89.0	88.7	93.8	93.9	89.8	89.9
Reagent Ratio, mol CO_3/mol SO_2 rem.	1.06	1.06	1.06	1.12	1.13	1.07	1.06	1.11	1.11
Oxidation, %	12.4	12.8	12.2	12.2	12.4	13.1	12.9	12.7	13.3
Solid Solution, wt.%	90.9	91.8	92.0	88.1	87.9	91.7	91.0	88.5	88.3
Gypsum, wt.%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$CaCO_3$, wt.%	2.1	2.1	2.6	6.4	5.9	2.4	2.6	4.0	3.8
$MgCO_3$, wt.%	1.9	1.8	1.3	1.7	2.2	1.9	1.7	3.2	3.2
Inerts, wt.%	2.6	2.4	2.7	2.2	2.2	2.1	2.5	2.1	2.0
Ca, mg/g	288	287	291	302	291	288	293	287	285
Mg, mg/g	5	5	4	5	6	5	5	9	9
SO_3, mg/g	486	489	494	473	470	486	484	472	467
SO_4, mg/g	82	86	82	79	80	88	86	82	86
CO_3, mg/g	26	25	25	51	51	28	28	46	46
Closures									
Weight, %	-2.4	-2.1	-1.4	-0.7	-1.8	-2.0	-1.7	-2.1	-2.7
Molar, %	0.3	-0.3	-0.2	1.2	-0.2	-0.2	0.8	0.2	0.1
Acceptable, %	6.4	6.4	6.4	6.3	6.2	6.4	6.4	6.2	6.2

Table A-4

Complete Baseline Slurry Carbonate Analyses and Calculated Utilizations

Sample	CO_3 (mm/g)	pH	Utilization (%)
1A	0.43	5.26	94.2
1B	0.42	5.33	94.3
1C	0.42	5.32	94.3
2A	0.81	5.63	89.6
2B	0.85	5.68	89.0
2C	0.86	5.64	88.9
3A	0.86	5.60	88.6
3B	0.85	5.60	88.7
3C	0.87	5.60	88.4
4A	0.45	5.10	93.9
4B	0.46	5.10	93.8
4C	0.44	5.10	94.1
5A	0.47	5.14	93.8
5B	0.46	5.11	93.9
5C	0.46	5.11	93.9
6A	0.75	5.39	90.1
6B	0.77	5.39	89.8
6C	0.75	5.29	90.1
7A	0.74	5.36	90.1
7B	0.76	5.33	89.9
7C	0.76	5.34	89.9

Table A-5

Parametric Solid-Phase Analytical Results

Radian Number	1-2	1-3	1-4	2-2	2-3	2-4	(3-1) 3-2	(4-1) 4-2	(5-1) 5-2
Date	9/14/93	9/14/93	9/14/93	9/15/93	9/15/93	9/15/93	9/16/93	9/16/93	9/17/93
Time	11:45	14:35	16:45	11:20	14:20	16:00	10:45	15:45	10:45
Ca, mm/g	7.05	7.18	7.24	7.14	7.33	7.20	7.16	7.09	7.27
Mg, mm/g	0.64	0.65	0.65	0.58	0.61	0.55	0.50	0.52	0.62
SO_3, mm/g	5.26	5.16	5.19	5.54	5.54	5.55	5.07	5.11	4.76
SO_4, mm/g	0.57	0.58	0.55	0.67	0.67	0.67	1.11	1.01	0.64
CO_3, mm/g	1.89	2.04	2.12	1.29	1.36	1.28	(1.28) 1.29	(1.28) 1.31	(2.27) 2.42
Inerts, wt.%	2.75	2.75	2.70	2.42	2.41	2.71	2.31	2.32	2.31
Solids, wt.%	19.3	19.9	20.4	21.6	22.1	22.2	19.0	17.4	19.1
pH	5.59	5.64	5.78	5.29	5.31	5.27	(5.31) 5.30	(5.28) 5.33	(5.73) 5.75
Temperature, °C	56.6	55.9	56.2	55.5	55.8	56.0	53.8	54 .0	54.5
Reagent Utilization, %									
Ca-Independent	75.5	73.7	73.0	82.8	82.1	82.9	82.7	82.4	69.1
SO_4-Independent	75.4	73.9	73.2	83.3	82.9	83.5	(83.3) 83.2	(83.2) 82.8	(71.2) 69.3
Reagent Ratio, mol CO_3/mol SO_2rem.	1.33	1.35	1.37	1.20	1.21	1.20	(1.20) 1.20	(1.20) 1.21	(1.40) 1.44
Oxidation, %	9.8	10.1	9.5	10.8	10.8	10.8	17.9	16.5	11.9
Solid Solution, wt.%	76.1	74.9	74.8	81.2	81.2	81.2	78.3	79.0	70.7
Gypsum, wt.%	0.0	0.0	0.0	0.0	0.0	0.0	3.7	1.8	0.0
$CaCO_3$, wt.%	18.9	20.4	21.2	12.9	13.6	12.8	12.9	13.1	24.2
Inerts, wt.%	2.8	2.8	2.7	2.4	2.4	2.7	2.3	2.3	2.3
Ca, mg/g	282	287	290	286	293	288	286	284	291
Mg, mg/g	16	16	16	14	15	13	12	13	15
SO_3, mg/g	421	413	415	443	443	444	405	409	381
SO_4, mg/g	55	55	52	64	65	64	106	97	62
CO_3, mg/g	113	123	127	78	81	77	(77) 77	(77) 79	(136) 145
Closures									
Weight, %	-3.3	-2.7	-2.2	-3.5	-2.3	-3.1	-2.8	-3.8	-3.5
Molar, %	-0.2	0.3	0.3	1.4	2.4	1.7	1.3	1.2	0.4
Acceptable, %	5.9	5.8	5.8	6.0	6.0	6.0	5.9	5.9	5.8

Table A-5

(Continued)

Radian Number	(6-1) 6-2	7-2	7-4	7-6	(8-1) 8-2	(9-1) 9-2	(10-1) 10-2	(11-1) 11-2	(12-1) 12-2
Date	9/17/93	9/20/93	9/20/93	9/21/93	9/21/93	9/22/93	9/22/93	9/23/93	9/23/93
Time	16:20	10:30	15:10	10:15	15:35	10:10	16:05	09:45	15:45
Ca, mm/g	7.17	7.23	7.15	7.14	7.13	7.10	7.11	7.32	7.46
Mg, mm/g	0.64	0.48	0.48	0.39	0.39	0.35	0.41	0.41	0.47
SO_3, mm/g	5.08	5.63	5.67	5.78	5.76	5.79	5.69	5.28	5.55
SO_4, mm/g	0.63	0.67	0.66	0.65	0.65	0.66	0.67	0.58	0.59
CO_3, mm/g	(2.42) 2.23	1.24	1.18	1.07	(1.03) 1.02	(0.98) 1.00	(0.85) 0.82	(1.68) 1.69	(1.29) 1.38
Inerts, wt.%	2.32	2.37	2.78	3.17	3.22	3.34	3.39	3.99	3.78
Solids, wt.%	18.5	16.7	18.4	17.2	16.8	16.3	16.3	16.7	16.9
pH	(5.68) 5.66	5.3	5.32	5.3	(5.33) 5.35	(5.35) 5.29	(5.24) 5.30	(5.68) 5.66	(5.63) 5.60
Temperature, °C	55	55.1	55	54.3	55.3	56	54.5	55.1	54.5
Reagent Utilization, %									
Ca-Independent	71.9	83.5	84.2	85.7	86.3	86.6	88.6	77.6	81.6
SO4-Independent	(69.0) 71.4	83.9	84.5	85.8	(86.3) 86.5	(86.8) 86.6	(88.7) 89.1	(78.3) 78.1	(83.7) 82.5
Reagent Ratio, mol CO_3/mol SO_2rem.	(1.45) 1.40	1.19	1.18	1.17	(1.16) 1.16	(1.15) 1.15	(1.13) 1.12	(1.28) 1.28	(1.19) 1.21
Oxidation, %	11.0	10.6	10.5	10.1	10.1	10.2	10.5	9.9	9.7
Solid Solution, wt.%	74.7	82.3	82.7	83.9	83.7	84.2	83.1	76.5	80.3
Gypsum, wt.%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$CaCO_3$, wt.%	22.3	12.4	11.8	10.7	10.2	10.0	8.2	16.9	13.8
Inerts, wt.%	2.3	2.4	2.8	3.2	3.2	3.3	3.4	4.0	3.8
Ca, mg/g	287	289	286	286	285	284	285	293	298
Mg, mg/g	16	12	12	10	9	9	10	10	11
SO_3, mg/g	406	450	454	462	461	463	455	422	444
SO_4, mg/g	60	64	64	62	62	63	64	56	57
CO_3, mg/g	(145) 134	75	71	64	(62) 61	(59) 60	(51) 49	(101) 102	(77) 83
Closures									
Weight, %	-2.2	-2.9	-3.0	-2.7	-3.1	-3.0	-4.6	-2.5	-1.3
Molar, %	-0.9	1.2	0.7	0.2	0.6	0.1	2.4	1.2	2.5
Acceptable, %	5.8	6.1	6.1	6.2	6.2	6.2	6.2	6.0	6.1

Table A-6

Long-Term Additive Test Solid-Phase Analytical Results

Radian Number	A1-GLT	A2-GLT	A3-GLT	A2B	A2L	A2In	A2M	A21	A22
Date	9/29/93	9/30/93	10/1/93	02/21/94	02/22/94	02/24/94	02/28/94	03/03/94	03/14/94
Time	12:36	13:35	09:44	17:05	11:15	15:49	14:23	09:46	11:50
Ca, mm/g	7.29	7.17	7.17	7.39	7.38	7.27	7.37	7.38	7.37
Mg, mm/g	0.46	0.46	0.42	0.29	0.29	0.32	0.29	0.24	0.28
SO_3, mm/g	5.32	5.38	5.54	6.06	6.04	6.00	6.08	6.44	5.90
SO_4, mm/g	0.49	0.47	0.50	0.59	0.69	0.57	0.55	0.49	0.73
CO_3, mm/g	1.76	1.70	1.43	0.78	0.89	0.97	0.81	0.53	0.82
Inerts, wt.%	3.24	3.46	3.41	2.49	2.68	2.52	2.55	2.24	2.48
Solids, wt.%	16.90	16.80	16.70	15.68	20.02	21.02	17.74	22.96	19.73
pH	5.69	5.68	5.68	5.26	5.39	5.52	5.54	5.37	5.51
Temperature, °C	51.7	53.4	52.6	53.0	52.6	53.1	52.3	53.0	52.4
Reagent Utilization, %									
Ca-Independent	76.8	77.5	80.9	89.5	88.3	87.1	89.1	92.9	89.1
SO_4-Independent	77.3	77.7	81.2	89.8	88.4	87.2	89.4	93.0	89.3
Reagent Ratio, mol CO_3/mol SO_2 rem.	1.29	1.29	1.23	1.12	1.13	1.15	1.12	1.08	1.12
Oxidation, %	8.4	8.1	8.2	8.9	10.2	8.6	8.3	7.0	11.1
Solid Solution, wt.%	75.7	76.3	78.6	86.8	87.9	85.6	86.5	90.2	86.8
Gypsum, wt.%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$CaCO_3$, wt.%	13.0	12.4	10.1	4.9	8.9	9.7	8.1	5.3	8.2
$MgCO_3$, wt.%	3.9	3.9	3.5	2.4	2.4	2.7	2.4	2.0	2.4
Inerts, wt.%	3.2	3.5	3.4	2.5	2.7	2.5	2.6	2.2	2.5
Ca, mg/g	292	287	287	295	295	291	295	295	295
Mg, mg/g	11	11	10	7	7	8	7	6	7
SO_3, mg/g	426	431	443	485	483	480	487	515	472
SO_4, mg/g	47	45	48	57	66	55	53	47	70
CO_3, mg/g	106	102	86	47	53	58	49	32	49
Closures									
Weight, %	-3.4	-3.7	-3.8	-2.4	-0.8	-2.4	-2.5	-2.0	-2.2
Molar, %	1.2	0.5	0.8	1.6	0.3	0.3	1.4	1.0	1.3
Acceptable, %	6.0	6.0	6.1	6.4	6.3	6.3	6.4	6.5	6.3

Table A-7

Baseline Liquid-Phase Analytical Results

Radian Number	1A	1B	1C	2B	3B	4B	5B	6B	7B
Date	5/4/93	5/4/93	5/4/93	5/5/93	5/5/93	5/6/93	5/6/93	5/7/93	5/7/93
Time	08:43	13:35	16:02	09:48	14:44	09:55	13:43	07:41	11:58
Ca, mm/L	18.6	17.6	19.6	13.9	13.8	21.4	18.2	11.9	11.2
Mg, mm/L	405		404		383		411		380
Na, mm/L	17.7		18.0		16.5		18.4		17.3
Cl, mm/L	168		179		168		189		179.3
CO_3, mm/L	3.1	4.9	4.2	5.5	4.9	3.8	3.1	4.8	3.6
SO_3, mm/L	49.4	62.2	48.4	41.0	41.5	63.2	68.0	63.7	62.9
SO_4, mm/L	241	266	245	234	208	226	241	227	241
S_2O_3, mm/L	24.5	26.0	24.6		25.2		28.3		28.2
Tot Hyd SO_4, mm/L	367	388	367	374	347	380	405	386	381
S/N, mm/L	27.7	7.4	24.4	74.0	47.4	63.7	39.4	67.0	21.5
pH	5.33	5.33	5.32	5.68	5.61	5.10	5.11	5.33	5.39
Temperature, °C	52.5	54.8	52.6	53.7	54.2	54.1	54.2	53.5	54.5
Ca, mg/L	746	705	785	557	555	856	730	479	447
Mg, mg/L	9840		9810		9310		10000		9230
Na, mg/L	407		414		379		422		399
Cl, mg/L	5960		6340		5970		6700		6360
CO_3, mg/L	186	292	250	330	296	227	188	290	217
SO_3, mg/L	3950	4980	3870	3280	3330	5060	5450	5100	5030
SO_4, mg/L	23200	25500	23500	22500	19900	21700	23100	21800	23100
S_20_3, mg/L	2750	2910	2750		2820		3170		3160
Charge Imbalance									
Calculated, %	5.3		4.4		5.6		2.5		-0.2
Acceptable, %	6.1	8.5	6.1	8.7	6.2	8.2	6.0	8.5	6.0
Relative Saturation									
Gypsum	1.1	1.2	1.2	1.2	0.8	1.2	1.1	0.7	0.7
$CaSO_3$*0.5H_2O	5.3	5.9	5.4	5.7	5.4	5.1	4.7	4.4	4.3
$CaCO_3$	0.01	0.01	0.01	0.03	0.02	0.00	0.00	0.01	0.00

Table A-7

(Continued)

Radian Number	(6-1) 6-2	7-2	7-4	7-6	(8-1) 8-2	(9-1) 9-2	(10-1) 10-2	(11-1) 11-2	(12-1) 12-2
Date	9/17/93	9/20/93	9/20/93	9/21/93	9/21/93	9/22/93	9/22/93	9/23/93	9/23/93
Time	16:20	10:30	15:10	10:15	15:35	10:10	16:05	09:45	15:45
Ca, mm/g	7.17	7.23	7.15	7.14	7.13	7.10	7.11	7.32	7.46
Mg, mm/g	0.64	0.48	0.48	0.39	0.39	0.35	0.41	0.41	0.47
SO_3, mm/g	5.08	5.63	5.67	5.78	5.76	5.79	5.69	5.28	5.55
SO_4, mm/g	0.63	0.67	0.66	0.65	0.65	0.66	0.67	0.58	0.59
CO_3, mm/g	(2.42) 2.23	1.24	1.18	1.07	(1.03) 1.02	(0.98) 1.00	(0.85) 0.82	(1.68) 1.69	(1.29) 1.38
Inerts, wt.%	2.32	2.37	2.78	3.17	3.22	3.34	3.39	3.99	3.78
Solids, wt.%	18.5	16.7	18.4	17.2	16.8	16.3	16.3	16.7	16.9
pH	(5.68) 5.66	5.3	5.32	5.3	(5.33) 5.35	(5.35) 5.29	(5.24) 5.30	(5.68) 5.66	(5.63) 5.60
Temperature, °C	55	55.1	55	54.3	55.3	56	54.5	55.1	54.5
Reagent Utilization, %									
Ca-Independent	71.9	83.5	84.2	85.7	86.3	86.6	88.6	77.6	81.6
SO4-Independent	(69.0) 71.4	83.9	84.5	85.8	(86.3) 86.5	(86.8) 86.6	(88.7) 89.1	(78.3) 78.1	(83.7) 82.5
Reagent Ratio, mol CO_3/mol SO_2rem.	(1.45) 1.40	1.19	1.18	1.17	(1.16) 1.16	(1.15) 1.15	(1.13) 1.12	(1.28) 1.28	(1.19) 1.21
Oxidation, %	11.0	10.6	10.5	10.1	10.1	10.2	10.5	9.9	9.7
Solid Solution, wt.%	74.7	82.3	82.7	83.9	83.7	84.2	83.1	76.5	80.3
Gypsum, wt.%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$CaCO_3$, wt.%	22.3	12.4	11.8	10.7	10.2	10.0	8.2	16.9	13.8
Inerts, wt.%	2.3	2.4	2.8	3.2	3.2	3.3	3.4	4.0	3.8
Ca, mg/g	287	289	286	286	285	284	285	293	298
Mg, mg/g	16	12	12	10	9	9	10	10	11
SO_3, mg/g	406	450	454	462	461	463	455	422	444
SO_4, mg/g	60	64	64	62	62	63	64	56	57
CO_3, mg/g	(145) 134	75	71	64	(62) 61	(59) 60	(51) 49	(101) 102	(77) 83
Closures									
Weight, %	-2.2	-2.9	-3.0	-2.7	-3.1	-3.0	-4.6	-2.5	-1.3
Molar, %	-0.9	1.2	0.7	0.2	0.6	0.1	2.4	1.2	2.5
Acceptable, %	5.8	6.1	6.1	6.2	6.2	6.2	6.2	6.0	6.1

Table A-8

Parametric Test Liquid-Phase Analytical Results

Radian Number	1-2	1-3	1-4	2-2	2-4	3-2	4-2	5-2	6-2
Date	9/14/93	9/14/93	9/14/93	9/15/93	9/15/93	9/16/93	9/16/93	9/17/93	9/17/93
Time	11:45	14:35	16:45	11:20	16:00	10:45	15:45	10:45	16:20
Ca, mm/L	10.3	10.0	9.3	16.8	14.2	23.6	23.7	9.2	8.5
Mg, mm/L	320		373	403	432		392		386
Na, mm/L	16.7		19.1	20.3	21.3		29.8		56.4
Cl, mm/L	341		361	393	432		420		387
CO_3, mm/L	8.3	5.7	6.4	7.2	8.1	6.9	6.2	8.7	8.0
SO_3, mm/L	24.8	24.4	25.6	32.4	35.0	28.3	29.1	31.2	33.4
SO_4, mm/L	113	110	111	143	140	153	156	121	116
S_2O_3, mm/L	14.5	16.7	16.5	15.7	16.9	13.1	13.6	18.2	18.4
Tot Hyd SO_4, mm/L	210	209	215	257	267	274	255	238	231
S/N, mm/L	42.5	41.3	45.0	50.2	58.4	65.9	42.8	50.0	44.0
COOH, mm/L						10.9	8.6	25.3	30.4
pH	5.59	5.64	5.78	5.29	5.27	5.30	5.33	5.75	5.66
Temperature, °C	56.6	55.9	56.2	55.5	56.0	53.8	54.0	54.5	55.0
Ca, mg/L	414	399	373	674	567	948	952	368	342
Mg, mg/L	7790	0	9070	9790	10500	0	9530	0	9380
Na, mg/L	385	0	439	467	491	0	684	0	1300
Cl, mg/L	12100	0	12800	13900	15310	0	14900	0	13700
CO_3, mg/L	496	340	387	433	487	412	369	523	477
SO_3, mg/L	1990	1960	2050	2590	2800	2260	2330	2500	2670
SO_4, mg/L	10900	10600	10700	13700	13400	14700	14900	11600	11200
S_20_3, mg/L	1620	1870	1850	1760	1890	1470	1520	2030	2060
COOH, mg/L	0	0	0	0	0	493	387	1140	1370
Charge Imbalance									
Calculated, %	0.9		6.4	4.0	4.3		1.2		4.9
Acceptable, %	6.0	8.2	6.0.	6.0	6.1	7.9	5.8	7.7	5.9
Relative Saturation									
Gypsum	0.4	0.3	0.3	0.7	0.5	1.0	1.0	0.3	0.3
$CaSO_3$*0.5H_2O	2.7	2.7	3.1	3.3	2.8	4.0	4.4	3.5	3.1
$CaCO_3$	0.03	0.02	0.04	0.01	0.01	0.02	0.02	0.05	0.03

Table A-8

(Continued)

Radian Number	7-2	7-4	7-6	8-2	9-2	10-2	11-2	12-2
Date	9/20/93	9/20/93	9/21/93	9/21/93	9/22/93	9/22/93	9/23/93	9/23/93
Time	10:30	15:10	10:15	15:35	10:10	16:05	09:45	13:45
Ca, mm/L	10.3	9.5	11.4	11.0	10.0	10.6	8.4	8.7
Mg, mm/L	392		421	423		403		357
Na, mm/L	62.7		61.9	57.0		102		131
Cl, mm/L	389		406	414		401		388
CO_3, mm/L	5.1	6.6	6.9	5.5	7.2	6.2	8.3	7.6
SO_3, mm/L	41.5	46.2	42.5	41.6	43.1	44.7	31.3	31.2
SO_4, mm/L	119	116	130	129	120	119	106	103
S_2O_3, mm/L	18.1	18.5	18.2	19.4	18.2	17.9	17.3	16.2
Tot Hyd SO_4, mm/L	256	250	268	246	237	260	209	204
S/N, mm/L	59.1	50.6	59.2	36.2	37.2	60.6	37.7	37.4
COOH, mm/L	31.3	35.6	33.9	31.8	61.4	76.9	105	109
pH	5.30	5.32	5.30	5.35	5.29	5.30	5.66	5.60
Temperature, °C	55.1	55.0	54.3	55.3	56.0	54.5	55.1	54.5
Ca, mg/L	411	381	456	439	401	426	338	349
Mg, mg/L	9530	0	10200	10300	0	9790	0	8680
Na, mg/L	1440	0	1420	1310	0	2330	0	3010
Cl, mg/L	13800	0	14400	14700	0	14200	0	13800
CO_3, mg/L	3320	393	414	329	429	373	501	459
SO_3, mg/L	11400	3700	3400	3330	3450	3580	2500	2500
SO_4, mg/L	2030	11200	12480	12400	11500	11400	10200	9910
S_20_3, mg/L	1410	2070	2040	2170	2040	2000	1940	1820
COOH, mg/L		1600	1520	1430	2760	3460	4740	4930
Charge Imbalance								
Calculated, %	4.3		4.9	6.0		4.0		3.3
Acceptable, %	5.8	7.2	5.8	5.9	6.9	5.6	6.5	5.4
Relative Saturation								
Gypsum	0.4	0.3	0.4	0.4	0.3	0.4	0.3	0.3
$CaSO_3$*0.5H_2O	2.7	4.6	3.0	3.1	2.7	3.0	3.0	2.9
$CaCO_3$	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.02

Table A-9

Long-Term Additive Test Liquid-Phase Analytical Results

Radian Number	DF1-GLT	DF2-GLT	DF3-GLT	A2B	A2L	A2In	A2M	A21	A22
Date	9/29/93	9/30/93	10/1/93	2-21-94	2-22-94	2-24-94	2-28-94	3-3-94	3-14-94
Time	12:36	13:35	09:44	17:05	11:15	15:49	14:23	09:46	11:50
Ca, mm/L	8.5	7.7	8.6	6.9	7.4	7.7	8.0	5.4	6.8
Mg, mm/L	327	331	310	328.1	376.9	349.9	322.3	368.1	299.9
Na, mm/L	58.5	54.6	51.7	9.6	10.3	11.1	9.4	9.5	7.7
Cl, mm/L	368	373	363	236.0	287.8	295.6	279.7	273.8	216.0
CO_3, mm/L	8.5	5.5	6.8	4.7	5.7	7.3	6.1	7.1	6.4
COOH, mm/L	35.5	37.0	28.2	0	0	0	0	0	0
SO_3, mm/L	31.5	28.9	26.8	71.2	66.8	50.9	47.1	91.9	49.6
SO_4, mm/L	131	83.9	90.4	107.0	125.2	100.9	92.6	140.6	117.2
S_2O_3, mm/L	17.4	17.0	15.1	45.2	44.8	39.5	30.5	22.1	13.6
Tot Hyd SO_4, mm/L	195	199	199	285.1	321.8	255.7	230.0	308.4	217.6
S/N, mm/L	-3.1	52.0	51.4	16.6	40.1	24.9	29.3	31.8	23.6
pH	5.69	5.68	5.68	5.26	5.39	5.52	5.54	5.37	5.51
Temperature, °C	51.7	53.4	52.6	53.0	52.6	53.1	52.3	53.0	52.4
Ca, mg/L	342	310	344	275	297	310	322	217	274
Mg, mg/L	7940	8050	7540	7977	9163	8507	7834	8949	7290
Na, mg/L	1350	1260	1190	221	237	255	216	217	178
Cl, mg/L	13100	13200	12900	8366	10203	10479	9915	9706	7657
CO_3, mg/L	512	329	406	279	343	436	363	426	386
COOH, mg/L	1600	1670	1270	0	0	0	0	0	0
SO_3, mg/L	2520	2310	2150	5696	5346	4078	3771	7357	3969
SO_4, mg/L	12600	8060	8690	10280	12029	9696	8896	13509	11262
S_2O_3, mg/L	1950	1910	1700	5058	5021	4421	3419	2470	1521
Succinic, mg/L					25	145	238	100	54
Glutaric, mg/L					391	1070	973	998	927
Adipic, mg/L					65	201	171	178	188
Charge Imbalance									
Calculated, %	-0.2	2.6	0.4	3.8	2.3	3.6	3.4	0.8	4.2
Acceptable, %	5.7	6.0	5.9	6.1	6.1	6.2	6.2	6.0	6.1
Relative Saturation									
Gypsum	0.3	0.2	0.3	0.2	0.3	0.2	0.2	0.2	0.3
$CaSO_3$*0.5H_2O	3.2	2.8	2.9	2.9	3.4	3.5	3.6	3.1	3.0
$CaCO_3$	0.03	0.02	0.03	0.00	0.01	0.01	0.01	0.00	0.01

Appendix B

Detailed Inventory Data for the Additive Consumption Tests

Table B-1

Summary of Sodium Formate Inventory

Tank	Tank Capacity (gal)		Solids (wt.%)		Specific Gravity		Formate (ppm)		Formate Inv. (lb as $COOH^-$)	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Mod. A	280,051	280,051	16.5	17.3	1.13	1.13	1600	1270	3,500	2,770
Mod. B	280,051	280,051	19.9	18.0	1.15	1.14	1040	1260	2,230	2,730
Mod. C	280,051	280,051	13.9	12.6	1.11	1.10	1090	1140	2,420	2,550
Mod. D	280,051	280,051	16.9	14.9	1.13	1.11	1030	1190	2,250	2,640
Thickener	2,113,848	2,113,848	10.0	10.0	1.08	1.08	1130	1010	19,300	17,200
TUF Tank	250,000	337,500	30.0	30.0	1.23	1.23	656	1040	1,180	2,530
TOF Tank	287,963	295,162	0	0	1.02	1.02	1130	1010	2,760	2,520
ME Tank	135,374	132,151	0	0	1.02	1.02	436	821	500	920
LS Tank	359,550	359,550	20.0	20.0	1.15	1.15	1130	1010	3,110	2,770
Total									37,280	36,650

Notes:
TUF - Thickener Underflow
TOF - Thickener Overflow
ME - Mist Eliminator Wash
LS - Limestone Slurry
Numbers in table may not add to total due to the effects of rounding.

Table B-2

Summary of DBA Inventory

Tank	Tank Capacity (gal)		Solids (wt.%)		Specific Gravity		DBA (ppm)		DBA Inventory (lb)	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Mod. A	280,051	280,051	20.8	20.0	1.16	1.15	1420	1170	3,020	2,510
Mod. B	280,051	280,051	23.7	22.5	1.18	1.17	1690	1440	3,540	3,050
Mod. C	280,051	280,051	18.9	16.8	1.14	1.13	1400	1160	3,030	2,530
Mod. D	280,051	280,051	17.3	18.4	1.13	1.14	1380	1150	3,020	2,490
Thickener	2,113,848	2,113,848	10.0	10.0	1.08	1.08	1240	819	21,300	14,030
TUF Tank	157,500	165,000	37.2	38.0	1.29	1.30	50	785	53	869
TOF Tank	165,578	158,379	0	0	1.02	1.02	1040	711	1,470	957
ME Tank	131,990	131,990	0	0	1.02	1.02	846	132	949	148
LS Tank	329,940	342,630	20.0	20.0	1.15	1.15	960	891	2,430	2,340
Total									38,800	28,920

Notes:
TUF - Thickener Underflow
TOF - Thickener Overflow
ME - Mist Eliminator Wash
LS - Limestone Slurry
Numbers in table may not add to total due to the effects of rounding.

Appendix C

Detailed Results for Settling and Filtration Tests

Table C-1

Settling Test Results for Baseline and Parametric Tests

Test Description	Test ID	Date	Time	Additive Concentration, ppm	Sulfite Oxidation, %	Initial Solids Concentration, wt.%	Thickener Unit Area @ 30 wt.%, ft^2-day/ton	Final Solids Concentration, wt.%
Baseline	1A	5-4-93	09:00	0	12.4	16.8	15	44
	1B	5-4-93	13:52	0	12.8	18.2	10	45
	4A	5-6-93	07:46	0	13.1	16.0	11	43
	Average			*0*	*12.8*	*17.0*	*12*	*44*
Parametric Test, w/o Formate	1-3A	9-14-93	14:35	0	10.1	19.9	37	40
	1-3B[a]	9-14-93	15:20	0	10.1	19.9	31	40
	1-4[a]	9-14-93	17:30	0	9.5	20.4	32	41
	Average			*0*	*9.9*	*20.1*	*33*	*40*
Parametric Test, w/Formate	7-3	9-20-93	13:40	1,630	10.5	17.5	(83)[b]	31
	7-5	9-21-93	09:00	1,540	10.1	17.2	55	32
	7-6	9-21-93	10:15	1,520	10.1	17.2	57	31
	Average[c]			*1,560*	*10.2*	*17.3*	*56*	*31*

[a] Settling tests were performed the next day (9-15-93).

[b] Not enough data were collected during the test to calculate an accurate unit area.

[c] Data of unknown quality excluded from average.

Table C-1

(Continued)

Test Description	Test ID	Date	Time	Additive Concentration, ppm	Sulfite Oxidation, %	Initial Solids Concentration, wt. %	Thickener Unit Area @ 30 wt. %, ft^2-day/ton	Final Solids Concentration, wt. %
Long Term w/Formate	LT1	9-29-93	12:50	1,100	8.4	20.6	50	36
	LT2	9-30-93	13:45	1,100	8.1	20.6	70	34
	LT3	10-1-93	10:00	1,100	8.2	20.6	(93)[b]	34
	Average[c]			*1,100*	*8.2*	*20.6*	*60*	*35*
Long Term before DBA	A2B	2-21-94	17:05	0	8.9	15.7	(99)[b]	34
Long Term w/DBA	A21	3-4-94	09:05	1,300	7.0	23.0	14	42
	A22	3-14-94	11:50	1,200	11.1	19.7	15	44
	Average			*1,250*	*9.0*	*21.3*	*14*	*43*

[a] Settling tests were performed the next day (9-15-93).

[b] Not enough data were collected during the test to calculate an accurate unit area.

[c] Data of unknown quality excluded from average.

Table C-2

Filter Leaf Test Conditions and Results

Summary of Test Conditions	
Filter Cloth Type	POPR 873
Cloth Area	0.0873 ft^2
Form Filtration Vacuum	20.00 in. Hg
Cake Solids Drying Time	120 sec.
Cake Solids Test Vacuum	15-18 in. Hg
Cake Thickness	0.44-0.88 in.

Test Results				
Test	Sample Rxn Tank	Date	Final Cake Solids, wt.%	Form Filtration Rate (lb/hr/ft^2)
Baseline Test 1A	A	5-4-93	56	251
Baseline Test 1B	A	5-4-93	54	305
Baseline Test 4A	A	5-6-93	58	358
Average			*56*	*305*
Parametric Test 1-3	A	9-14-93	56	154
Parametric Test 1-4A	A	9-14-93	56	174
Parametric Test 1-4B	A	9-14-93	57	183
Average			*56*	*170*
Parametric Test 7-3	A	9-20-93	52	281
Parametric Test 7-5	A	9-21-93	52	248
Parametric Test 7-6	A	9-21-93	53	235
Average			*52*	*255*
Formate Consumption A1	A	9-29-93	53	193
Formate Consumption B1	B	9-29-93	53	205
Formate Consumption C1	C	9-29-93	52	223
Formate Consumption D1	D	9-29-93	53	219
Average			*53*	*210*
Formate Consumption A2	A	9-30-93	53	189
Formate Consumption C2	C	9-30-93	52	218
Formate Consumption D2	D	9-30-93	53	190
Average			*53*	*199*
Formate Consumption A3	A	10-1-93	52	134
Formate Consumption B3	B	10-1-93	53	187
Formate Consumption C3	C	10-1-93	52	229
Formate Consumption D3	D	10-1-93	53	175
Average			*53*	*181*
DBA Consumption A2*	A	2-21-94	54	171
DBA Consumption A2	A	3-4-94	54	124
DBA Consumption A2	A	3-14-94	64	368

* This sample was collected as a baseline sample before the addition of DBA, therefore no additive is present in this sample.

Appendix D

Online Process Data and Slurry Flow Rate Measurements

Table D-1

Average Values for On-Line Process Data

Test	Run	Load (MW)	Stack CO_2 (%)	Stack SO_2 (lb/MMBTU)	Recycle Solids (%)	LS Feed (gpm)	Fan Current (amp)	North pH	South pH
Baseline									
1	1	610	10.3	1.02	20.8	160	110	5.31	5.28
	2	593	11.1	0.93	22.1	167	110	5.31	5.28
	3	570	10.6	0.81	21.8	170	110	5.30	5.28
	4	544	11.5	0.66	21.0	174	110	5.26	5.25
2	1	575	11.8	0.83	21.0	205	110	5.55	5.56
	2	612	11.3	0.93	20.8	199	110	5.56	5.56
30	1	604	11.8	0.95	20.4	179	110	5.55	5.57
	2	614	11.6	1.00	20.9	177	110	5.54	5.55
4	1	561	11.6	0.84	20.6	164	111	5.00	4.93
	2	588	11.7	0.97	20.8	156	110	4.98	4.89
5	1	612	11.4	0.89	20.4	146	110	5.00	4.95
	2	608	11.8	0.97	20.2	160	110	5.00	4.94
6	1	615	12.0	0.93	19.4	213	110	5.30	5.27
	2	622	12.3	1.00	19.6	203	109	5.30	5.27
7	1	619	12.3	0.99	20.2	214	91	5.31	5.29
	2	617	12.4	1.04	20.4	179	91	5.31	5.31
Parametric									
1	1	605	11.7	0.91	21.0	202	91	5.68	5.67
	2	621	12.2	0.70	21.2	228	91	5.67	5.67
	3	635	12.1	0.97	21.6	243	91	5.65	5.65
	4	625	12.2	0.94	21.7	279	91	5.66	5.66
2	1	626	12.3	0.90	24.0	166	91	5.24	5.26
	2	626	12.6	0.79	24.4	137	91	5.29	5.30
	3	626	13.1	0.88	24.6	161	91	5.30	5.32
	4	624	12.9	0.86	24.1	155	91	5.29	5.30
3	1	415	11.1	0.68	20.7	178	111	5.29	5.30
	2	418	10.3	0.73	21.1	201	111	5.32	5.30
4	1	421	10.8	0.47	19.9	159	91	5.30	5.31
	2	422	10.1	0.53	20.0	145	91	5.31	5.32
5	1	621	13.0	0.82	20.7	284	110	5.66	5.68
	2	621	12.8	0.80	20.8	349	110	5.67	5.72

Table D-1

(Continued)

Test	Run	Load (MW)	Stack CO_2 (%)	Stack SO_2 (lb/MMBTU)	Recycle Solids (%)	LS Feed (gpm)	Fan Current (amp)	North pH	South pH
6	1	619	13.4	0.90	21.0	59	91	5.68	5.71
	2	615	12.6	0.96	20.7	196	91	5.65	5.68
	3	571	12.4	0.73	20.3	228	92	5.68	5.70
7	1	587	12.3	0.92	19.3	191	110	5.30	5.30
	2	578	12.4	0.99	19.2	219	110	5.28	5.30
	3	532	12.2	0.69	20.2	24	110	5.30	5.30
	4	524	12.3	0.7	20.4	220	110	5.29	5.29
	5	549	11.9	0.66	21.4	250	109	5.27	5.28
	6	526	12.2	0.64	21.3	266	110	5.27	5.26
8	1	597	11.3	0.83	20.9	184	91	5.30	5.30
	2	582	11.5	0.60	21.1	210	91	5.29	5.29
9	1	563	11.6	0.81	20.0	255	110	5.26	5.32
	2	577	12.3	0.88	19.6	176	110	5.30	5.35
10	1	538	12.6	0.68	19.1	211	91	5.24	5.26
	2	525	12.0	0.89	20.4	191	91	5.28	5.29
11	1	598	11.6	0.66	19.7	290	111	5.65	5.70
	2	591	12.0	0.79	20.0	233	111	5.65	5.66
12	1	545	10.8	0.44	20.5		90	5.60	5.64
	2	528	10.6	0.56	20.5		90	5.63	5.67

Table D-2

Average Values for On-Line Process Data During Sodium Formate Consumption Test

Date	Test	Load (MW)	Stack CO_2 (%)	Stack SO_2 (lb/MMBTU)	Recycle Solids (%)	Fan Current (amp)	Slurry pH
9-25-93	0700-1900	544	11.2	0.54	20.1	86	
9-26-93	1900-0700	427	10.1	0.48	22.1	83	
9-26-93	0700-1900	535	11.6	0.43	22.5	86	
9-27-93	1900-0700	588	11.6	0.47	20.3	89	5.62
9-27-93	0700-1900	568	11.4	0.72	20.6	86	5.63
9-28-93	1900-0700	363	9.5	0.26	21.1	80	5.67
9-28-93	0700-1900	530	11.8	0.39	21.8	84	5.59
9-29-93	1900-0700	401	10.3	0.29	20.6	80	5.63
9-29-93	0700-1900	578	11.9	0.32	20.6	86	5.64
9-30-93	1900-0700	395	9.9	0.26	22.2	80	5.68
9-30-93	0700-1900	496	11.5	0.39	18.1	74	5.62
10-1-93	1900-0700	388	9.2	0.30	20.6	80	5.64
10-1-93	0700-1900	444	10.2	0.42	20.6	85	5.58
10-2-93	1900-0700	367		0.34		79	5.58
10-2-93	0700-1900	516		0.39		85	

Table D-3

Average Values for On-Line Process Data During DBA Consumption Test

Date	Test	Load (MW)	Stack CO_2 (%)	Stack SO_2 (lb/MMBTU)	Recycle Solids (%)	Fan Current (amp)	Slurry pH
2-21-94	0000-0700	302	9.3	0.88		76	5.37
2-21-94	0700-1900	586	11.7	0.81	15.8	88	5.42
2-22-94	1900-0700	496	10.9	0.64	19.0	83	5.45
2-22-94	0700-1900	629	11.8	0.56	20.6	89	5.41
2-23-94	1900-0700	514	10.7	0.55	20.3	81	5.45
2-23-94	0700-1900	612	10.3	0.61	20.1	87	5.42
2-24-94	1900-0700	532	9.8	0.55	21.1	82	5.43
2-24-94	0700-1900	627	11.2	0.62	21.4	87	5.44
2-25-94	1900-0700	532	11.1	0.51	22.1	83	5.45
2-25-94	0700-1900	601	12.2	0.54	22.2	87	5.45
2-26-94	1900-0700	565	12.3	0.51	22.1	83	5.43
2-26-94	0700-1900	581	11.1	0.43	21.5	84	5.44
2-27-94	1900-0700	535	10.8	0.49	21.6	82	5.44
2-27-94	0700-1900	481	10.8	0.48	20.0	80	5.44
2-28-94	1900-0700	485	10.5	0.59	19.2	80	5.41
2-28-94	0700-1900	575	11.3	0.57	18.5	84	5.43
3-1-94	1900-0700	503	10.6	0.52	19.1	81	5.40
3-1-94	0700-1900	564	11.1	0.58	21.7	84	5.42
3-2-94	1900-0700	542	11.0	0.57	22.4	82	5.38
3-2-94	0700-1900	602	11.0	0.65	21.3	87	5.42
3-3-94	1900-0700	523	10.9	0.53	39.8	81	5.41
3-3-94	0700-1900	569	10.8	0.52	47.9	85	5.40
3-4-94	1900-0700	517	10.4	0.60	47.7	82	5.38
3-11-94	1900-0700	331	10.2	0.46	46.2	72	5.99

Table D-3

(Continued)

Date	Test	Load (MW)	Stack CO_2 (%)	Stack SO_2 (lb/MMBTU)	Recycle Solids (%)	Fan Current (amp)	Slurry pH
3-11-94	0700-1900	538	11.4	0.67	46.2	85	5.34
3-12-94	1900-0700	482	10.4	0.58	46.2	81	5.38
3-12-94	0700-1900	562	10.8	0.65	45.9	87	5.44
3-13-94	1900-0700	499	10.4	0.54	46.1	82	5.45
3-13-94	0700-1900	577	10.5	0.67	46.4	87	5.44
3-14-94	1900-0700	553	10.1	0.67	46.3	85	5.44
3-14-94	0700-1900	559	9.8	0.71	46.3	86	5.44

Table D-4

Results of Absorber Slurry Flow Rate Measurements

Date	Probe Position (relative to each other)	Location	Flow Rate (gpm)
5-4-93	Same Side	Pump 1	12,800
5-4-93	Same Side	Pump 2	12,900
5-4-93	Same Side	Pump 3	12,400
5-4-93	Opposite	Pump 4	9,890
5-6-93	Same Side	Pump 1	13,100
5-6-93	Same Side	Pump 2	13,400
5-6-93	Same Side	Pump 3	11,700
5-6-93	Same Side (right)	Pump 4	13,400
5-6-93	Same Side (left)	Pump 4	10,500
5-6-93	Opposite	Pump 4	10,200

Appendix E

Details of FGDPRISM Calibration and Predictive Simulations

Model Description

The latest version of FGDPRISM was calibrated to the Gibson Unit 5 FGD system. The version of FGDPRISM that was used includes upgrades developed after the initial release of Version 2.0. These upgrades have been released as so-called "patches" to the Version 2.0 executable program. Patch levels A, B, C, and a test version of patch level D were applied for this calibration effort. In addition, a special template was developed to model the horizontal gas flow scrubbers at Gibson. Figure E-1 shows a flow diagram for modeling the Gibson horizontal scrubbers with FGDPRISM. Figure E-2 shows the actual arrangement of the model's calculational template used to simulate the Gibson Unit 5 FGD system absorbers.

A modification included in the version of FGDPRISM used here, which affects the modeling of the Gibson Station FGD system, is the improved calculations for estimating droplet surface area for a horizontal scrubber. In previous modeling efforts, conducted primarily by PSI Energy personnel, the droplet surface area was determined separately, in stages, and input directly into FGDPRISM. The template (process configuration) developed for this work contains an absorber arrangement that has been reconfigured to be more representative of a horizontal spray absorber, as seen in Figure E-2.

Due to the high gas velocities in the Gibson absorbers, it is believed that a portion of the droplets are swept along with the gas as it flows through the absorber, similar to co-current flow in a vertical scrubber. To simulate this effect, the absorber was modeled as four co-current absorbers in series, with each absorber containing one spray header. Each co-current absorber used in FGDPRISM represents a spray zone in the Gibson horizontal scrubber, with the absorber dimensions based on the spacing between the actual spray headers.

The model simulated the carryover of the spray droplets through the horizontal scrubber by taking a portion of the scrubber bottoms stream from each of the first three spray zones and adding it to the following absorber section feed slurry. No carryover was estimated for the spray zone closest to the mist eliminators. Using a stand-alone droplet trajectory program and a typical absorber flue gas flow rate, this carryover portion was estimated to be 25% of the scrubber liquor volume. The carryover is expected to decrease as the gas velocity decreases, but the 25% carryover was held constant for all of the simulations. Additional modeling would be required to determine the impact of varied carryover rates on model predictions. With the improved surface area calculations, the FGD system at PSI Energy Gibson can be simulated at high/low absorber flue gas velocities (3/4-module operation) and with either three or four recycle pumps in service.

Another important modification in the current version of FGDPRISM is the limestone dissolution methodology. In earlier versions, the model computed the limestone dissolution rate in the reaction tank and in the absorber by using a simple dissolution rate equation where only a single rate constant was required. The new methodology used in this calibration is a combined surface reaction/diffusion rate model. Here, the limestone dissolution rate is controlled by two series resistances:

1) Diffusion of chemical species through a stagnant "film" surrounding the dissolving limestone particle; and

2) A surface reaction rate that includes an empirical factor designed to account for the inhibiting effects of species such as sulfite and magnesium.

The diffusion rate is a function of the film thickness and the concentrations of species such as calcium and carbonate at the limestone surface and in the bulk solution. Values for the diffusion film thicknesses in the absorber and the reaction tank are calculated by FGDPRISM using correlation data obtained from limestone testing at EPRI's Environmental Control Technology Center (ECTC). The particle size distribution of the limestone is the main factor used to determine the diffusion film thickness. The overall diffusion rate is calculated using the rate for each particle size (typically the particle size distribution is divided into 20 discrete particle sizes) and summing over the entire limestone particle size distribution.

The surface reaction rate is a function of the solution composition at the limestone surface and the limestone reactivity. The model iterates on the surface (interface) composition until the surface reaction rate is equal to the diffusion rate. This calculation is performed at every integration step in the absorber to determine the contribution of solid-phase $CaCO_3$ dissolving to provide alkalinity needed to absorb SO_2. The calculation is also performed in the reaction tank module to predict the absorber feed slurry pH.

A "surface area factor" has also been included as an adjustable parameter to modify the surface area calculated by the model to allow a better fit to the pH vs. utilization data to be made. For the PSI Energy Gibson FGD system, the reaction rate constant was set at a typical value and the surface area factor was adjusted to match observed pH levels as a function of reagent utilization.

Besides the previously mentioned parameters that are varied to account for limestone reactivity, there are other input parameters that must be adjusted in the calibration. These parameters are liquid- and gas-side mass transfer film thicknesses which determine SO_2 removal as a function of operating conditions. It is important to note that any effects of unique features (i.e., gas/liquid maldistribution) of a particular absorber will be incorporated into the mass transfer film thicknesses determined through the model calibration procedure.

Related to the gas/liquid surface area and gas/liquid maldistribution is a droplet agglomeration factor constant which calculates the rate at which the slurry droplet size increases as droplets fall down across the spray absorber. Although this constant is not normally adjusted, it can be varied to predict the effect of absorber height on scrubber performance. A default value was developed from previous FGDPRISM calibrations of open spray towers. The default value was assumed for modeling Gibson's scrubbers.

The model does predict gas/liquid surface area by determining the trajectory of each slurry droplet as it passes through the absorber and calculating its residence time. These calculations cannot be verified, however, since there is no method of measuring the surface area of the spray in an absorber. In addition, the model is unable to predict the gas/liquid distribution in a tower, which can greatly affect scrubber performance. To address these non-idealities, the mass transfer film thicknesses must be varied to match observed SO_2 removals.

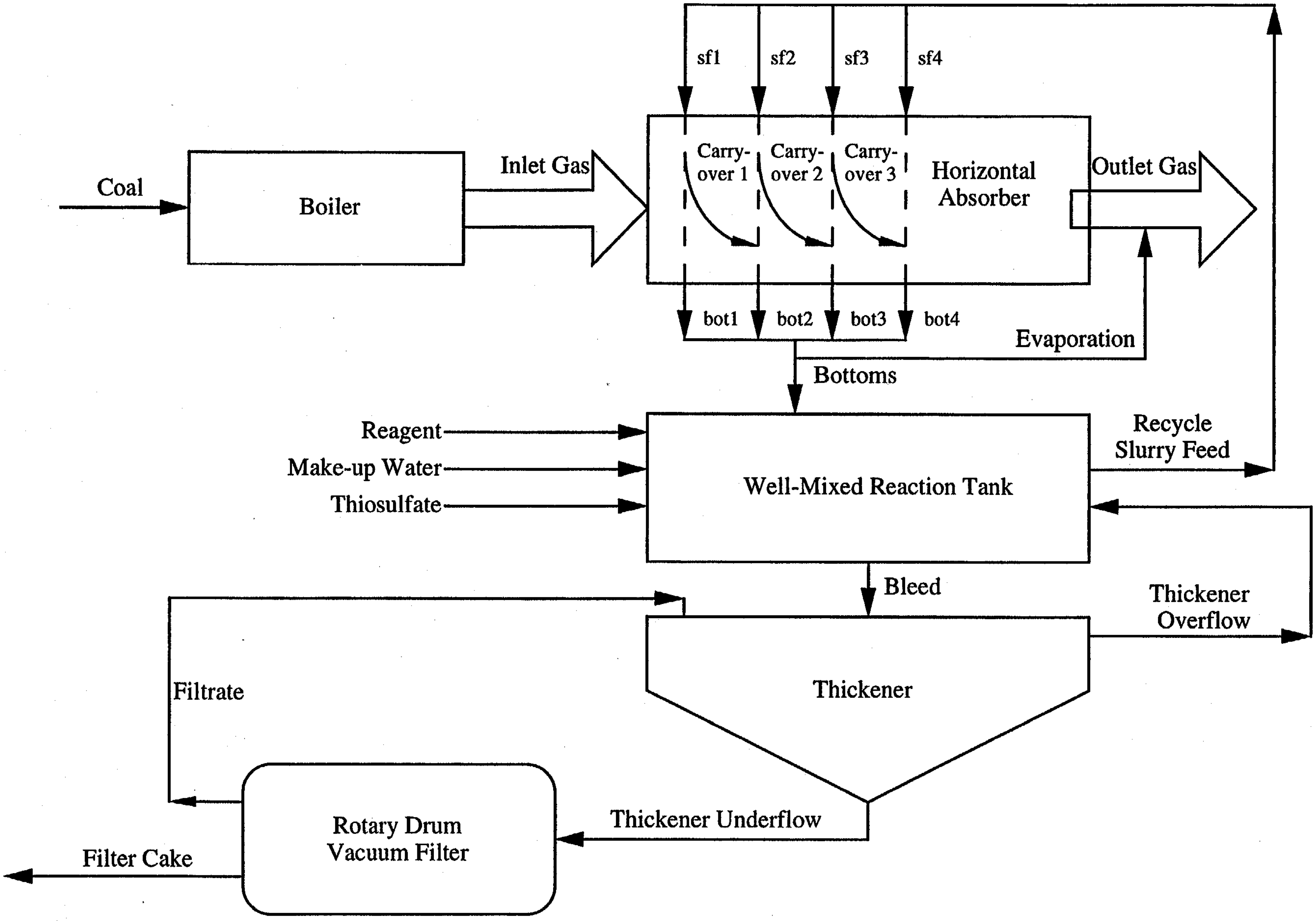

Figure E-1. Flow Diagram of Horizontal Scrubber for PSI Energy Gibson

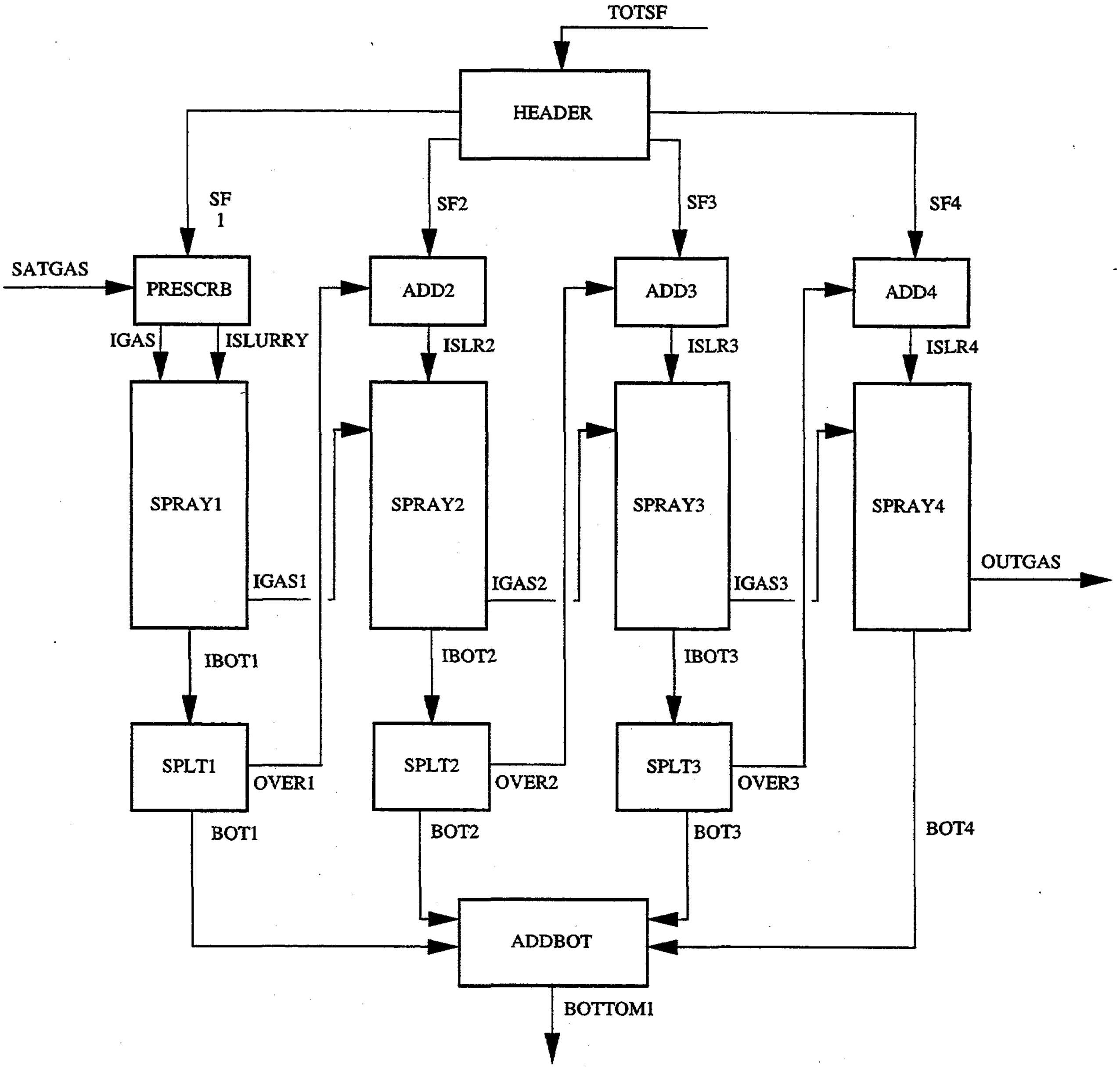

Figure E-2. Horizontal Absorber Configuration for PSI Energy Gibson FGDPRISM Template

Table E-1

Comparison of Observed and Predicted Performance

Test	SO_2 Removal, %		Reagent Utilization, % (100*[mole S/mole Ca])		Absorber pH	
	Observed	Predicted	Observed	Predicted	Observed	Predicted
Baseline Tests						
1	86.0	NC	97.0	NC	5.33	NC
2	89.8	92.6	89.1	91.2	5.66	5.64
3	89.4	86.9	92.3	91.4	5.60	5.56
4	76.6	79.1	97.2	94.4	5.10	5.10
5	67.4	NC	94.8	NC	5.11	NC
6	78.7	NC	94.0	NC	5.31	NC
7	84.3	NC	94.4	NC	5.36	NC
Sodium Formate Parametric Tests						
1	95.4	94.6	80.6	80.9	5.59 - 5.78	5.67
2	87.8	87.6	84.7 - 87.0	88.7	5.28	5.27
3	83.3	80.7	86.2	87.1	5.30	5.31
4	90.3	91.1	86.3	87.8	5.33	5.33
5	92.5	92.1	74.3	71.8	5.75	5.72
6	97.5	96.9	79.7	80.1	5.66	5.68
7	86.1	86.0	88.5	88.4	5.31	5.27
8	94.8	95.5	89.9	90.0	5.35	5.32
9	87.7	88.8	90.8	87.2	5.29	5.24
10	93.2	95.0	89.3	89.2	5.30	5.26
11	93.1	92.7	80.1	73.1	5.66	5.60
12	97.4	97.3	82.4	82.3	5.62	5.60

NC - These cases did not converge due to problems the limestone dissolution calculational method in the absorber section of the simulation.

Table E-2

FGDPRISM Inputs for the General System Case

System Variables	Actual Values	Reference
General Unit Parameters		
Coal High Heating Value, Btu/lb	10,900	Normal Operation
Turbine Output, MWe	620	Full Load
Plant Capacity, %	70	Normal Operation
Flue Gas Bypass, %	0	Maximize SO_2 Removal
Unit Heat Rate Btu/kW-hr	9,516	Normal Operation
Flue Gas Temperature, °F	310	Current Operation
Number of Absorber Modules	3	Design Operation
Number of Recycle Pumps	4	Design Operation
Coal Composition, wt.%		Normal Operation
Carbon	58.9	
Hydrogen	4.1	
Nitrogen	1.1	
Sulfur	3.0	
Oxygen	8.2	
Chlorine	0.1	
Moisture	15.7	
Ash	8.9	
Additive Parameters		
Mg^{++} Concentration, ppm	9,500	Normal Operation
$S_2O_3^=$ Concentration, ppm	2,000	Normal Operation
System Parameters		
SO_2 Removal, % (lb/10^6 Btu emission rate)	80 (1.1)	Design Operation
$CaCO_3$ Utilization, %	85	Normal Operation
Limestone Grind, % < 325 mesh	80	Normal Operation
Absorber Slurry pH	5.3	Normal Operation
Recycle Solids Content, wt.%	20	Normal Operation
Filter Cake Solids Content, wt.%	60	Normal Operation

Appendix F

Detailed Upgrade Cost Calculations

Using the calibrated FGDPRISM model for the Gibson FGD system, the SO_2 removal performance was predicted for each of the upgrade options. Predicted performance was then used in the economic evaluation. For each option, several cases were evaluated; for example, for sodium formate addition, cases at varying formate ion concentrations were considered. For each option, however, the first case presented is always the base (three-module, four-pump) case. Using these results and the cost information previously described, the cost-effectiveness was determined for each option. Table F-1 summarizes the results of this analysis.

Table F-2 summarizes the corresponding results for the sensitivity cases. For the sensitivity analysis, because of the higher unit load, higher coal sulfur content, and corresponding higher SO_2 removal requirement for maintaining compliance, the base case is for four-module, four-pump operation, although with 12.5% flue gas bypass.

The number of modules and number of pumps in service for each option and case is described in the first two columns of Table F-1 and Table F-2. Three-module operation with four recycle pumps in service and four-module operation with three recycle pumps in service correspond to an L/G ratio around 75 gal/macf. Four-module operation with four recycle pumps in service results in a higher L/G ratio of approximately 100 gal/macf.

The SO_2 removal performance, additive concentrations (sodium formate, dibasic acid, and magnesium), and limestone usage (reagent utilization) associated with each case are presented in the next five columns. Overall SO_2 removal performance is shown in terms of percent removal in Column 3 and tons of SO_2 removed per year in Column 4. Additive concentrations are presented as formate ion or DBA concentration in Column 5 and liquid-phase magnesium concentration in Column 6. Limestone usage is described as percent utilization in Column 7.

The additional capital and operating costs associated with each case, compared to the base case, are presented next. Annual increases in additive costs (including both capital and operating), reagent costs (the sum of limestone, dolomitic lime, and reagent preparation O/M costs), waste product disposal costs, and power costs associated with each case are presented in Columns 8 through 11, respectively. The total additional cost, representing the sum of columns 8 through 11, is presented in Column 12.

The marginal cost associated with the additional tons of SO_2 removed for each case is presented in Column 13. The marginal costs in Column 13 are all relative to the case directly above within each option. For each option, the first case listed represents the base case. In Table F-1, the base case is for three-module, four-pump, no bypass operation. For the sensitivity cases in Table F-2, the base case is for four-module, four-pump operation, but 12.5% flue gas bypass. For the second case under each option, the marginal cost represents the annual additional costs for that case relative to the base case, divided by the annual increase in SO_2 removed, also relative to the base case. For the third case, the marginal costs represent the additional costs beyond those of the second case divided by the additional SO_2 removed, also beyond those of the second case.

Column 14 shows the average cost for each case. The calculations are the same as for the marginal cost, except each case is relative to the base case rather than to the case directly above it in the table. Finally, to determine the benefit associated with each case, the net annual value of additional tons of SO_2 removed is calculated, assuming SO_2 allowance values of \$150/ton and \$250/ton, respectively, in Columns 15 and 16. This net annual value represents the value of the additional SO_2 credits generated minus the additional costs, all relative to the base case.

Table F-1

Detailed Economic Evaluation of Options to Increase SO_2 Removal Efficiency

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Absorber Modules in Service	Pumps in Service per Module	SO_2 Removal		Additive Concentrations		Limestone Reagent Utilization	Additive Capital & Operating Cost	Addt'l Reagent Cost	Addt'l Waste Cost	Addt'l Power Cost	Total Addt'l Cost	Marginal Cost	Average Cost	Net Annual Value @ \$150/ton SO_2	Net Annual Value @ \$250/ton SO_2
		%	ton/yr	ppm	Mg^{++} ppm	%	\$1000/yr	\$1000/yr	\$1000/yr	\$1000/yr	\$1000/yr	\$/ton SO_2	\$/ton SO_2	\$1000/yr	\$1000/yr
OPTION 1: Effect of Modules and Pumps in Service (L/G Ratio)															
3(Base Case)	4	80.0	79,600	0	9500	85	0	0	0	0	0	0	0	0	0
4	3	85.3	84,900	0	9500	85	0	120	48	42	210	40	40	580	1,100
4	4	93.2	92,800	0	9500	85	0	300	120	220	640	54	48	1,300	2,600
OPTION 2: Effect of pH at Base L/G Ratio															
3(Base Case)	4	80.0	79,600	0	9500	85	0	0	0	0	0	0	0	0	0
3	4	85.7	85,300	0	9500	80	0	270	91	0	360	63	63	490	1,100
3	4	90.5	90,100	0	9500	70	0	760	240	0	1,000	140	96	560	1,600
OPTION 3: Effect of Sodium Formate at Base L/G Ratio[a]															
3(Base Case)	4	80.0	79,600	0	9500	85	0	0	0	0	0	0	0	0	0
3	4	86.2	85,800	500	9500	85	190	180	98	0	460	75	75	470	1,100
3	4	87.8	87,400	1000	9500	85	280	210	110	0	610	91	78	560	1,300
3	4	88.9	88,500	1500	9500	85	360	240	120	0	720	100	81	610	1,500
3	4	89.6	89,200	2000	9500	85	440	250	130	0	820	150	86	610	1,600

[a] Modeled sodium formate additive cases with a drop in filter cake solids content from 60 wt.% to 57 wt.%.

Note:

The cost values in Columns 8 through 16 of the table were rounded to two significant figures after all calculations were completed.

Table F-1

(Continued)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Absorber Modules in Service	Pumps in Service per Module	SO$_2$ Removal		Additive Concentrations		Limestone Reagent Utilization	Additive Capital & Operating Cost	Addt'l Reagent Cost	Addt'l Waste Cost	Addt'l Power Cost	Total Addt'l Cost	Marginal Cost	Average Cost	Net Annual Value @ \$150/ton SO$_2$	Net Annual Value @ \$250/ton SO$_2$
		%	ton/yr	ppm	Mg^{++} ppm	%	\$1000/yr	\$1000/yr	\$1000/yr	\$1000/yr	\$1000/yr	\$/ton SO$_2$	\$/ton SO$_2$	\$1000/yr	\$1000/yr
OPTION 4: Effect of DBA at Base L/G Ratio															
3(Base Case)	4	80.0	79,600	0	9500	85	0	0	0	0	0	0	0	0	0
3	4	84.8	84,400	500	9500	85	160	110	43	0	310	64	64	410	890
3	4	87.8	87,400	1000	9500	85	260	180	72	0	510	67	65	660	1,400
3	4	89.4	89,000	1500	9500	85	350	210	86	0	650	93	70	750	1,700
3	4	90.3	89,900	2000	9500	85	450	230	94	0	770	140	75	760	1,800
OPTION 5: Effect of Liquid-Phase Magnesium at Base L/G Ratio [b]															
3(Base Case)	4	80.0	79,600	0	9500	85	0	0	0	0	0	0	0	0	0
3	4	88.9	88,500	0	11,500	85	0	300	160	0	460	52	52	870	1,800
OPTION 6: Effect of pH at High L/G Ratio															
3(Base Case)	4	80.0	79,600	0	9500	85	0	0	0	0	0	0	0	0	0
4	4	93.2	92,800	0	9500	85	0	300	120	220	640	48	48	1,300	2,600
4	4	95.4	95,000	0	9500	80	0	500	190	220	910	120	59	1,400	2,900
4	4	96.8	96,400	0	9500	70	0	930	310	220	1,500	400	87	1,000	2,700

[b] Modeled high liquid-phase magnesium cases with a drop in filter cake solids content from 60 wt.% to 55 wt.%.

Note:

The cost values in Columns 8 through 16 of the table were rounded to two significant figures after all calculations were completed.

Table F-1

(Continued)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Absorber Modules in Service	Pumps in Service per Module	SO_2 Removal		Additive Concentrations		Limestone Reagent Utilization	Additive Capital & Operating Cost	Addt'l Reagent Cost	Addt'l Waste Cost	Addt'l Power Cost	Total Addt'l Cost	Marginal Cost	Average Cost	Net Annual Value @ \$150/ton SO_2	Net Annual Value @ \$250/ton SO_2
		%	ton/yr	ppm	Mg^{++} ppm	%	\$1000/yr	\$1000/yr	\$1000/yr	\$1000/yr	\$1000/yr	\$/ton SO_2	\$/ton SO_2	\$1000/yr	\$1000/yr
OPTION 7: Effect of Sodium Formate at High L/G Ratio[a]															
3(Base Case)	4	80.0	79,600	0	9500	85	0	0	0	0	0	0	0	0	0
4	4	93.2	92,800	0	9500	85	0	300	120	220	640	48	48	1,300	2,600
4	4	94.8	94,400	250	9500	85	140	370	180	220	910	170	62	1,300	2,800
4	4	95.2	94,800	500	9500	85	200	380	180	220	980	180	65	1,300	2,800
4	4	95.7	95,300	1000	9500	85	290	390	190	220	1,100	230	70	1,300	2,800
4	4	96.0	95,550	1500	9500	85	380	400	190	220	1,200	320	75	1,200	2,800
OPTION 8: Effect of DBA at High L/G Ratio															
3(Base Case)	4	80.0	79,600	0	9500	85	0	0	0	0	0	0	0	0	0
4	4	93.2	92,800	0	9500	85	0	300	120	220	640	48	48	1,300	2,600
4	4	95.4	95,000	500	9500	85	160	390	140	220	910	120	59	1,400	2,900
4	4	96.2	95,700	1000	9500	85	260	400	150	220	1,000	160	64	1,400	3,000
4	4	96.7	96,200	1500	9500	85	360	420	150	220	1,100	230	69	1,300	3,000
OPTION 9: Effect of Liquid-Phase Magnesium at High L/G Ratio[b]															
3(Base Case)	4	80.0	79,600	0	9500	85	0	0	0	0	0	0	0	0	0
4	4	93.2	92,800	0	9500	85	0	300	120	220	640	48	48	1,300	2,600
4	4	95.9	95,500	0	11,500	85	0	490	220	220	940	110	59	1,400	3,000

[a] Modeled sodium formate additive cases with a drop in filter cake solids content from 60 wt.% to 57 wt.%.

[b] Modeled high liquid-phase magnesium cases with a drop in filter cake solids content from 60 wt.% to 55 wt.%.

Note:

The cost values in Columns 8 through 16 of the table were rounded to two significant figures after all calculations were completed.

Table F-2

Detailed Economic Evaluation of Sensitivity Cases

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Absorber Modules in Service	Pumps in Service per Module	SO_2 Removal		Additive Conc.	Flue Gas Bypass	Limestone Reagent Utilization	Additive Capital & Operating Cost	Addt'l Reagent Cost	Addt'l Waste Cost	Addt'l Power Cost	Total Addt'l Cost	Marginal Cost	Average Cost	Net Annual Value @ \$150/ton SO_2	Net Annual Value @ \$250/ton SO_2
		%	ton/yr	ppm	%	%	\$1000/yr	\$1000/yr	\$1000/yr	\$1000/yr	\$1000/yr	\$/ton SO_2	\$/ton SO_2	\$1000/yr	\$1000/yr
OPTION 1: Effect of Modules and Pumps in Service (L/G Ratio)															
3	4	73.0	72,700	0	5	85	NA	NA	NA	NA	NA	NA	NA	NA	NA
4	3	77.9	77,500	0	5	85	NA	NA	NA	NA	NA	NA	NA	NA	NA
4(Base Case)	4	82.3	81,900	0	12.5	85	0	0	0	0	0	0	0	0	0
4	4	87.0	86,600	0	5	85	0	110	44	0	150	32	32	550	1,000
OPTION 2: Effect of Sodium Formate at Base L/G Ratio[a]															
4(Base Case)	4	82.3	89,100	0	12.5	85	0	0	0	0	0	0	0	0	0
4	4	87.0	86,600	0	5	85	0	110	44	0	150	32	32	550	1,000
4	4	89.4	89,000	500	5	85	190	190	110	0	490	140	69	570	1,300
4	4	90.0	89,600	1000	5	85	270	210	120	0	600	180	78	550	1,300
4	4	90.4	90,000	1500	5	85	350	220	120	0	690	240	86	520	1,300
OPTION 3: Effect of DBA at Base L/G Ratio															
4(Base Case)	4	82.3	81,900	0	12.5	85	0	0	0	0	0	0	0	0	0
4	4	87.0	86,600	0	5	85	0	110	44	0	150	32	32	550	1,000
4	4	89.4	89,000	500	5	85	160	160	66	0	380	100	54	680	1,400
4	4	90.4	90,000	1000	5	85	250	190	75	0	510	130	63	700	1,500
4	4	91.0	90,600	1500	5	85	340	200	79	0	620	180	71	680	1,500

[a] Modeled sodium formate additive cases with a drop in filter cake solids content from 60 wt.% to 57 wt.%.