RCN 213-210-02-08

DOE/PC/91338--T24

High SO_2 Removal Efficiency Testing

DE-AC22-92PC91338

Topical Report
Evaluation of High Efficiency Test Results at Hoosier Energy's Merom Station

Prepared for:

Janice Murphy
U.S. Department of Energy
Pittsburgh Energy Technology Center
P.O. Box 10940
Pittsburgh, PA 15236

Prepared by:

Radian Corporation
P.O. Box 201088
Austin, TX 78720-1088

MASTER

22 April 1996

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENT

DOE wishes to acknowledge the Electric Power Research Institute for its contribution to all of the FGDPRISM modeling efforts documented in this report.

Portions of the baseline test data contained in this report are the results of an effort that has been jointly sponsored by the Rural Electric Research Program of the National Rural Electric Cooperative Association and EPRI, and conducted at Hoosier Energy's Merom Station.

SUMMARY

Tests were conducted at Hoosier Energy's Merom Station 535-MW Units 1 and 2 wet limestone flue gas desulfurization (FGD) systems to evaluate options for achieving high SO_2 removal efficiency. The options tested included use of dibasic acid (DBA) and sodium formate additives as well as operation at higher reagent ratios (higher pH set points). In addition to the tested options, the effectiveness of other potential options was simulated using the Electric Power Research Institute's FGD PRocess Integration and Simulation Model (FGDPRISM) after it was calibrated to the system. An economic analysis was done to determine the cost effectiveness of each option. The following is a summary of results.

SO_2 Removal Performance. Baseline tests showed that the SO_2 removal efficiency of the Merom absorbers was 86 to 87% when operating at a pH of about 5.7 with a reagent ratio of 1.03 and a total liquid-to-gas (L/G) ratio of approximately 85 gallons of slurry per thousand actual cubic feet (gal/kacf) of flue gas.

The maximum SO_2 removal efficiency obtained without additives, by increasing the pH set point and reagent ratio, was 93.5% when the system limestone reagent preparation and delivery system was operating at its maximum capacity. At this maximum limestone delivery rate, the measured limestone utilization values were approximately 80%. Upgrades to the limestone preparation system to increase the maximum delivery rate are not recommended as an approach for achieving higher SO_2 removal. Operation at limestone utilization values below 80% is likely to cause scaling or plugging problems, as well as significantly increasing the amount of solid byproduct produced by the FGD system.

With DBA additive, the SO_2 removal efficiency could be increased to more than 98% at high concentrations (6000+ ppm DBA) and nearly 98% at moderate concentrations (1600 ppm). Sodium formate additive was somewhat less effective at comparable mass concentrations. For example, with 1700 ppm formate ion in the limestone slurry, SO_2 removal efficiency increased to about 93% compared to nearly 98% with a similar DBA concentration. When the

two additives are compared on the basis of the concentration required to achieve a given SO_2 removal efficiency, the required formate additive concentration was about twice that for DBA.

Additive Consumption. A two-week DBA consumption test was conducted to measure the DBA additive rate required to maintain the system SO_2 removal performance at 95% removal or greater. The DBA concentration ranged from approximately 1000 to 1500 ppm during this test, and the system SO_2 removal averaged 96%. An average DBA feed rate of about 120 lb/hr was required at an average unit load of 360 MW. The measured DBA consumption rate averaged between 9 and 10 lb per ton of SO_2 removed by the FGD system. The DBA nonsolution loss rate (DBA losses other than with liquor leaving the FGD system) was approximately 7 lb per ton of SO_2 removed.

Two sodium formate consumption tests were conducted. The SO_2 removal efficiency was measured with only three rather than four modules in service, but while operating at a reduced unit load of 325 MW. During the first test, the system SO_2 removal averaged 93.4% at the normal slurry pH set point of 5.55 with an average formate ion concentration of 2300 to 2800 ppm in the absorber slurry liquor. The total formate consumption averaged 15 lb of formate ion consumed per ton of SO_2 removed (23 lb sodium formate per ton of SO_2). The nonsolution loss rate averaged 11 lb of formate ion consumed per ton of SO_2 removed (17 lb sodium formate per ton of SO_2).

Increasing the pH set point to 5.8 for the second consumption test achieved a higher average SO_2 removal (95.5%) at a slightly higher average formate concentration of 2800 to 3000 ppm. The sodium formate consumption rate during this test was also higher than in the first test, at 24 lb of formate ion consumed per ton of SO_2 removed (36 lb sodium formate per ton of SO_2). The nonsolution loss rate for the second consumption test averaged about 20 lb of formate ion per ton of SO_2 removed (30 lb sodium formate per ton of SO_2).

SO_2 Removal Upgrade Economics. The results of the additive consumption tests were combined with the performance test results to calibrate EPRI's FGDPRISM (Version 2.0) computer model to the Merom Station FGD system. Using system SO_2 removal performance predicted by the calibrated model, an economic evaluation was performed for the options of adding DBA or sodium formate, increasing the system reagent ratio, and/or increasing the amount of packing in the absorbers to increase SO_2 removal efficiency. Options requiring significant capital investment, such as increasing liquid to gas ratio (L/G) or adding another module, were not considered in this study. The economics of each option were evaluated based on the capital costs of the additive system, additive costs, limestone costs, limestone preparation O&M costs, the cost of landfilling FGD solids, and the cost of additional packing.

All of the options were compared with the normal FGD operation where a small amount of flue gas is bypassed around the absorbers to control stack emissions at 1.1 lb SO_2/million Btu. Closing off the bypass stream at otherwise normal operating conditions increases the SO_2 removal from 83 to 87%.

Both additive options (DBA and sodium formate) appear to be a cost-effective means of achieving 95% or greater SO_2 removal with the Merom FGD systems. DBA appears to be more attractive than sodium formate due to the lower concentration required to achieve equivalent SO_2 removal, and the lower additive consumption rate. With DBA addition, and the current mode of system operation, the cost estimates show that 95% removal can be achieved at an average incremental cost of $44 per additional ton of SO_2 removed. That is, the cost of removing additional SO_2 beyond the baseline level of 83% removal averages $44 for each additional ton removed. Closing the FGD system water balance to eliminate liquor blowdown would lower this cost further to $42/ton.

The incremental costs with sodium formate additive are nearly double those of DBA, or about $82/ton with the current mode of operation and $62/ton with closed loop operation.

For removals above 95%, the additive costs (DBA and sodium formate) increase dramatically. The practical limit for achieving higher levels of SO_2 removal with DBA alone appears to be about 97%. For sodium formate, achieving 97% SO_2 removal is not cost effective due to the high additive concentration necessary and the corresponding high consumption rate.

The third SO_2 removal upgrade option tested at Merom, increasing the limestone reagent ratio, was not able to achieve the target of 95% removal or greater. Therefore, corresponding cost-effectiveness values are not available for this option.

A fourth upgrade option was not tested at full-scale, but was modeled with FGDPRISM. This option involved adding more packing to the absorbers. There is a limit to the amount of additional packing that can be added; at most, a 2-foot increase in the level of packing in the absorbers can be obtained. This amount of additional packing alone was not sufficient to achieve 95% SO_2 removal, but a combination of more packing and DBA additive appears to be a cost-effective approach to achieving this removal level. The combination of 2 additional feet of packing and DBA additive was predicted to achieve 95% removal at an incremental cost of only \$39/ton of additional SO_2 removed. This combination was also predicted to be capable of achieving 98% SO_2 removal, whereas the options that used additive alone were not (the maximum predicted removal at full load with DBA was 97.8% and with sodium formate was 97.0%). Full-scale testing of this combination would be required to verify these model predictions, however.

These costs for achieving upgraded SO_2 removal levels appear to be very attractive. The incremental costs for Merom Station to implement the DBA additive options are less than \$50 per additional ton of SO_2 removed. In the first EPA auction for SO_2 allowances, the average successful bid price was about \$150/ton. EPRI estimates that during the "transition" period for Phase 2 of the Clean Air Act Amendments (the years 2000 through 2005), emission allowance market prices will range from \$250 to \$500/ton SO_2 (in 1992 dollars).[1] Furthermore, we estimate that the cost of generating SO_2 allowances by installing new FGD capacity on units firing medium- to high-sulfur coal would be at the upper end of this \$250/ton to \$500/ton range.

Thus, SO_2 allowances generated at a cost of less than $100/ton in existing FGD systems should be very desirable.

Reference

1. I. Torrens and J. Platt, "Update on Electric Utility Response to the CAAA, "ECS Update, No. 30, Fall 1993, p.3.

1.0 INTRODUCTION

This report describes the results of high-efficiency SO_2 removal testing conducted at Hoosier Energy's Merom Station. Testing was performed on the flue gas desulfurization (FGD) systems of Units 1 and 2 at Merom Station with dibasic acid (DBA) and sodium formate additives, and with increased reagent ratio (higher pH set points for the FGD recirculating slurry), to evaluate these options for increasing SO_2 removal efficiency. The overall objective was to assess the cost effectiveness of upgrading an existing FGD system as one part of a strategy for meeting the requirements of the 1990 Clean Air Act Amendments.

1.1 Background

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

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

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

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

This Topical Report covers results from the second site, Hoosier Energy's Merom Station. Separate Topical Reports are being issued for each of the other sites.

1.2 Project Description

Three types of performance tests were completed at Merom Station. First, baseline tests were completed to obtain performance data under normal operating conditions. Then, short-term tests (one day or less) were conducted with each upgrade option over a range of additive concentrations and pH values. Finally, long-term tests (five days to two weeks each) were done to measure additive consumption rates for the Merom FGD system.

The tests were conducted with funding from three sources. The majority of the tests were conducted as a Tailored Collaboration project for the Electric Power Research Institute (EPRI) with co-funding from the Rural Electric Research Program of the National Rural Electric Cooperative Association (NRECA). The tests performed under the EPRI contract included parametric testing of the DBA additive, sodium formate additive, reagent ratio upgrade options, and a two-week DBA consumption test. Additional testing was funded by the DOE PETC. This testing included a short-term baseline repeat test and two longer-term (five- to seven-day) sodium formate consumption tests.

Results from these tests were used to calibrate EPRI's FGD PRocess Integration and Simulation Model (FGDPRISM) to the Merom Station FGD system. Following the calibration, FGDPRISM was used to predict system performance over a range of DBA and sodium formate concentrations and as a function of reagent ratio (i.e., recirculating slurry pH). FGDPRISM was also used to predict system SO_2 performance with increased levels of packing in the FGD system absorbers. However, there were no full-scale test results to verify the calibration of the model for this option.

The FGDPRISM simulation results were used to evaluate and compare the costs of options for obtaining higher SO_2 removal levels. The alternatives considered were using additives (DBA or sodium formate), increasing the limestone reagent ratio, and adding more packing to the absorber modules. In this evaluation, the net marginal cost of additional tons of SO_2 removed was estimated for each option over a range of SO_2 removal levels (90, 95, 97, and 98% or the maximum percentage achievable if less than 98%). Also, these costs were compared with a range of expected values for SO_2 allowances ($150/ton to $250/ton) to determine the net annual value (or cost) for each option at each SO_2 removal level. In addition, the sensitivity of total costs to DBA price and coal sulfur content was evaluated.

1.3 Report Organization

The performance tests are described and results are presented in Section 2 of this report. The FGDPRISM calibration procedure and subsequent SO_2 removal performance predictions are discussed in Section 3. A description of the economic evaluation and a discussion of the results of this evaluation are found in the final section, Section 4.

There are also four appendices. These summarize detailed chemical analyses and process data, describe the FGDPRISM model and calibration, and summarize the capital cost estimate for an additive feed system.

2.0 TEST DESCRIPTION AND RESULTS

The tests were conducted over a period of 14 months, from October 1991 through November 1992. This section presents and discusses the test results. The Merom FGD system is first described and the overall test approach is outlined. The results of the three SO_2 removal performance test series are then presented, followed by the results of the additive consumption tests. The final portion of this section discusses the observed effects of additives on the properties of solids produced by the Merom FGD system.

2.1 FGD System Description

Hoosier Energy Rural Electric Cooperative, Inc. owns and operates the Merom Generating Station, which is located near Merom, Indiana. Merom Station is a coal-fired facility consisting of two units, each with a maximum generating capacity of 535 MW. The two units are similar in design and operation, and each has a four-module FGD system. The FGD systems are described below.

The coal fired in the boilers is obtained from local mines, and typically has a sulfur content of 3.2 to 4.0% and an average heating value of about 11,000 Btu/lb. From each boiler, combustion gases pass through an air preheater and into an electrostatic precipitator (ESP) to remove fly ash. After passing through the ESP, the gas travels through two parallel ID fans into a common duct that feeds the four FGD system absorber modules for that unit. At normal full-load conditions, each of the two FGD systems treats about 1,756,000 acfm of flue gas at a temperature of 280°F.

A bypass duct diverts a portion of the flue gas from the FGD system inlet directly to the stack. The amount bypassed is varied to control the overall system SO_2 removal. SO_2 monitors are installed at the ID fan exit and in the stack to provide a continuous evaluation of the SO_2 removal across the FGD system, and to measure the SO_2 emission rate. Under current operating conditions, the SO_2 removal across each module is approximately 86 to 90%. The overall SO_2 removal is slightly lower, averaging about 83% for a 3.5% sulfur coal, due to flue gas bypass.

The FGD system at Merom Station is illustrated in Figure 2-1. Only one of four parallel modules of each unit is depicted. The FGD systems were designed by Mitsubishi Heavy Industries of Japan. Each unit has four L-shaped packed absorbers. The flue gas and recirculated slurry enter the absorber at the top and pass through cocurrently. Three levels of packing in the vertical section of each absorber account for most of the surface area available for absorbing SO_2.

The flue gas is cooled and saturated by a separate spray of slurry prior to entering the packed sections. Both this quench spray and the absorption sprays are directed upward above the top level of packing, from nozzles that operate at very low discharge pressures. The slurry droplets fall down through the packing, contacting the flue gas and absorbing SO_2. The droplets are collected in an integral reaction tank located in the bottom of the absorber. The slurry recirculation rate to each absorber results in a liquid-to-gas ratio of about 85 gal/kacf (saturated) at design conditions.

The total packing height and the layout of the packing have been changed from design specifications. The space between each level was increased, and a strip of packing was removed around the top perimeter of each stage to improve the ability to maintain the packing. With these changes, the total height of the packing was reduced from the original design value of 17 feet by slightly more than 2 ft. This loss in packing surface area decreases the potential SO_2 performance, but the Merom FGD system is still capable of very high SO_2 removal.

After passing through the vertical, packed section of the scrubber, the flue gas stream turns and flows through a horizontal section, which contains a mist eliminator (ME) to remove any slurry that remains entrained in the gas. The ME's are of a single-stage, four-pass, horizontal-gas-flow design. The ME's are washed with fresh makeup water; the wash water then flows into the reaction tank of the absorber module.

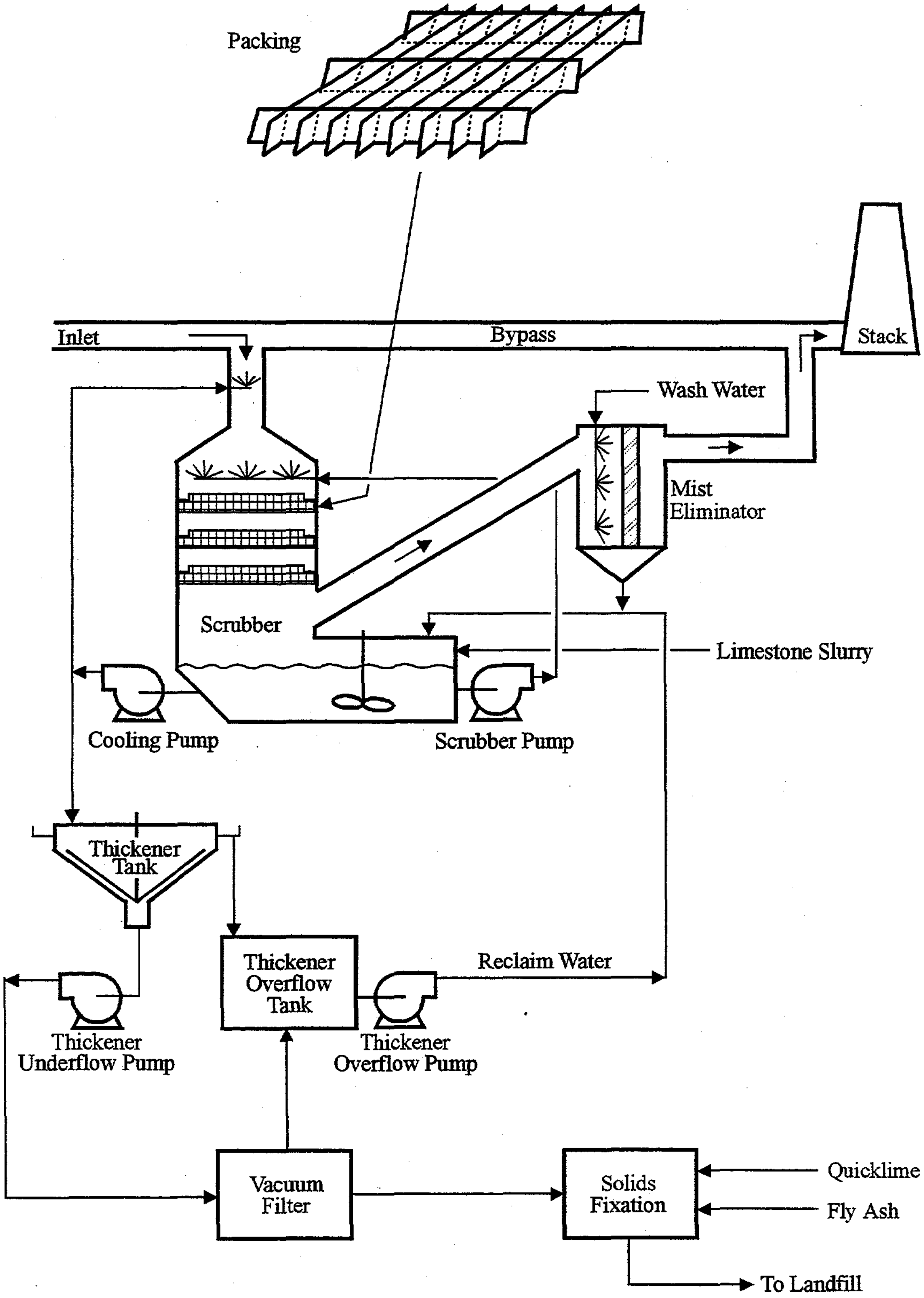

Figure 2-1. Process Diagram of Hoosier Energy's Merom Station FGD System

Limestone reagent is used in the FGD absorbers. The feed rate is modulated to control the pH of the recirculating slurry. At the normal recirculating slurry pH set point of 5.55, the limestone utilization is typically 90 to 98%. The limestone contains approximately 3.2% inerts and 1% $MgCO_3$, and has an available calcium carbonate fraction of 95.8%. However, only about 40% of the $MgCO_3$ is reactive, based on the results of laboratory-scale dissolution tests. The remaining $MgCO_3$ is thought to exist as dolomite, which does not dissolve appreciably in FGD liquors.

The limestone is fed to the absorber reaction tanks as a slurry. The slurry is prepared in a limestone grinding system that consists of a precrusher followed by a tower mill, with two tower mills per unit. The tower mill grinding system produces a limestone grind of 90% passing 325 mesh, in a 25 wt.% solids slurry.

On occasion, bags of adipic acid are added to the FGD system when additional SO_2 removal capability is needed (e.g., a module out of service or a high coal sulfur content). Adipic acid is usually added in lots of 500 to 750 lb, in 50-lb bag increments. More adipic acid can be added as needed, depending on the SO_2 removal requirement.

The FGD system currently operates in an inhibited sulfite oxidation mode. At the beginning of this program, elemental sulfur emulsion was added to the FGD system in a batch-wise manner. Elemental sulfur reacts with sulfite in the absorber liquor to produce thiosulfate, an oxidation inhibitor. With the addition of sulfur, the percent oxidation of sulfite to sulfate is controlled at 5% to 10%. A capital project performed later in the program installed a system for the semi-continuous addition of elemental sulfur emulsion.

A portion of the recirculating slurry is blown down from the absorber modules to a thickener, where it is concentrated to about 35% solids. The thickener underflow is sent to rotary drum vacuum filters for secondary dewatering. There is a thickener for each unit, but the two units share a common vacuum filtration system. The filter cake produced is generally 65 wt.% solids. After dewatering, the filter cake solids are blended with quicklime and fly ash before disposal in a landfill.

Two tanks (375,000 gal capacity per tank) operated in series are used to provide secondary dewatering surge capacity, since the vacuum filters are not operated continuously. The first receives slurry from the underflow of each of the two thickeners. The second provides additional surge capacity between the first surge tank and the vacuum filters. Both tanks have rakes to prevent a buildup of solids at the bottom.

The overflow from the thickeners and filtrate from the vacuum filter are mixed in a thickener overflow tank (one for each unit). This mixture is used as makeup water to the absorber reaction tanks and is also used to prepare limestone slurry. Any excess from the two thickener overflow tanks goes to a surge vessel, called the FGD Hold Tank, where it is stored until there is greater demand for reclaimed water by either unit.

The main source of makeup water for the FGD system is well water. Additional sources of water are a holding pond and an emergency hold tank. The plant occasionally has a positive water balance requiring a discharge of reclaimed water and, when operating at high loads, has a shortage of fresh makeup water available.

2.2 Test Approach

The effects of DBA additive, sodium formate additive, and reagent ratio on the SO_2 removal performance of the Merom Station FGD system were evaluated in a series of short-term tests. These performance tests were followed by two long-term additive consumption tests. The test approach for each of these test series is described below.

As mentioned earlier in this section, the plant sometimes adds adipic acid to the FGD system to enhance SO_2 removal performance. Adipic acid is convenient for the plant to use occasionally because it can be purchased and stored as a dry powder. However, DBA (a mixture of adipic, glutaric, and succinic acids) is considerably less expensive at approximately $0.20/lb dry basis versus $0.65/lb for pure adipic acid. Results of previous testing at other sites have shown that for continuous use, DBA is more cost effective as an FGD additive than pure adipic acid. Consequently, adipic acid was not considered as an upgrade option for the current project.

2.2.1 SO_2 Removal Performance Tests

The test plan for DBA additive was designed to measure the SO_2 removal performance of a single module of the Unit 2 FGD system (Module 2B) at three additive levels, for both the normal recirculating slurry pH set point and a lower set point. The planned test matrix consisted of seven tests, one at baseline conditions and six with DBA added to the test module. All four modules were in service during these tests, but the gas flow to the test module was controlled near full-load conditions.

The baseline and DBA performance tests were conducted during a one-week period in October 1991. SO_2 removal performance with DBA additive was the primary focus of the testing, although other information about the operating conditions of the absorber was collected to provide complete data sets for use in calibrating/validating FGDPRISM.

The test crew measured the flow rate, SO_2 concentration, and moisture content of the flue gas exiting the module during each test. The SO_2 concentration was measured by the Reich test method with a gas sample drawn from a single point in the duct. The concentrations of O_2 and CO_2 in the gas stream were measured twice during each test by Orsat analysis. Also, liquid and solid samples of the recirculating slurry from the test module were collected for later analysis.

After a baseline set of samples was taken to characterize normal system operation at a pH set point of 5.55, DBA was spiked into the test module from a tanker trailer. Sufficient DBA was added to achieve the highest planned DBA concentration. During the next two days, the concentration of DBA in the module was allowed to decrease naturally (i.e., due to slurry blowdown to the thickener and other losses) to reach the planned intermediate and low DBA concentrations.

During each test day, the performance of the test module was evaluated at two sets of operating conditions. The first test of the day was conducted at the normal recirculating slurry pH set point (5.55), then the pH set point was lowered to approximately 5.10 for the second test. A small metering pump was used to maintain the DBA concentration relatively constant during each test day.

The sodium formate tests were conducted during December 1991. Test conditions were similar to those for the DBA tests, except the concentration of sodium formate was increased rather than decreased over the test period. A set of baseline samples was taken on the first day to characterize normal operation at a pH set point of 5.55. Over the next three days, a 39 wt.% sodium formate solution was added to the test module from a tanker trailer, with a small metering pump. The concentration of sodium formate in the test module reaction tank was increased each day, so the additive could be evaluated over a broad range of conditions. As in the DBA tests, the first test each day was conducted at the normal pH set point, then the pH was lowered to determine the performance at conditions corresponding to improved limestone utilization.

The final phase of short-term testing consisted of performance tests to evaluate the effect of reagent ratio or recirculating slurry pH set point. Based on the results of the additive performance tests and FGDPRISM simulations, increasing the system pH and using additive each appeared to be effective at increasing system SO_2 removal performance. The model results also suggested that a combination of higher pH and DBA addition would be very effective. This third performance test series provided full-scale results for the effects of a higher pH set point on system SO_2 removal performance, with and without DBA additive, for comparison with the FGDPRISM predictions.

As with the previous two series, the reagent performance test series was performed on Unit 2 at Merom Station. However, in this series, SO_2 removal was measured for the entire Unit 2 FGD system, while the previous series concentrated on a single module. The FGD system was operated with no gas bypass, so the measured removals should represent the average performance for the modules in service. No flue gas testing was conducted on individual modules. SO_2 removal efficiency was measured using the continuous emissions monitors at the ID fan outlets and on the stack.

The reagent ratio performance tests were conducted during a one-week period in August 1992. The testing began with a baseline test, which was followed by five performance tests. For the baseline test, Unit 2 was operated at the normal pH set point of 5.55 with all four modules in service. One module was taken out of service for the five performance tests due to low-load conditions.

Following the baseline test, two tests were performed at successively higher reagent ratios. The on-line pH controller set points were increased to 5.7 and 5.85, respectively, for these tests. The pH set point of 5.85 (measured with a portable pH meter at actual values of 5.98 to 6.12) resulted in the highest reagent ratio achievable, because the flow of fresh limestone slurry to the FGD system became a limiting factor. Next, a test was conducted at a lower pH set point of 5.40.

The remaining two reagent ratio performance tests investigated the SO_2 removal that could be achieved by adding DBA to the system at an elevated pH set point of 5.70. DBA was added to levels of approximately 500 and 1000 ppm in the FGD system recirculating liquor on consecutive days. On each day, the limestone slurry feed tank was spiked with the amount required to achieve the desired concentration in the absorber reaction tanks, then a small metering pump was used to maintain the desired DBA concentration following the spike.

2.2.2 Additive Consumption Tests

The performance tests described above provided the information required to calibrate FGDPRISM for the Merom Station Units 1 and 2 FGD systems. This calibrated model can be used to estimate the additive concentrations required to achieve higher SO_2 removals. To determine the cost effectiveness of DBA or sodium formate addition as an SO_2 removal upgrade option, it is also important to know how much of either must be added to maintain the required concentration in the FGD system recirculating slurry.

Additive lost in the liquor adhered to the dewatered calcium sulfite sludge must continually be replaced. This amount (referred to as solution losses) can be estimated with reasonable accuracy by material balance calculations. Usually, however, losses through other mechanisms account for the majority of the additive make-up requirements. These other loss mechanisms can include oxidative degradation of the organic acids, vaporization into the flue gas, and coprecipitation of the additives into the solid byproduct from the FGD system. The rates for these other loss mechanisms (referred to as nonsolution losses) are affected by variables such as FGD system operating temperature, sulfite oxidation percentage, liquor composition, and additive type. Consequently, the rates are specific to individual FGD systems.

Additive loss rates have been measured over a range of conditions at EPRI's Environmental Control Technology Center (ECTC) and in the laboratory. Additive loss rates are modeled by FGDPRISM as a function of FGD system design and operating conditions. However, full-scale measurements are needed to confirm and improve model predictions. One 14-day DBA consumption test was conducted as part of the EPRI/NRECA-co-funded program, and two sodium formate consumption tests (seven and five days duration) were conducted with funding from DOE PETC.

The DBA and formate additive consumption rates were determined by performing a mass balance on the FGD system. This required monitoring the amounts of additive fed, discharged, and accumulated in the FGD system tanks and vessels throughout the test period.

Since DBA and sodium formate were added directly from a tanker trailer, the amount added over a specific time period could be estimated directly from the change in level in the tanker.

To track DBA discharges, the Unit 2 FGD system dewatering and liquor reclaim system was separated from that of the Unit 1 FGD system, so there would be no unmeasured losses of DBA from the test unit. To effect the isolation, all crossovers between the units were closed, all filtrate from the vacuum filters was returned only to the Unit 2 thickener overflow tank, and no reclaimed water was used in the Unit 1 limestone grinding process.

With the Unit 2 FGD system isolated in this manner, the only liquid-phase DBA solution losses were with the liquor adhered to the dewatered FGD byproduct filter cake, and with any blowdown from the FGD Hold Tank when the amount of reclaimed thickener overflow and filtrate exceeded the tank capacity. Blowdown was expected during the consumption test because all filtrate from the vacuum filters, which treat sludge from both units, was returned to Unit 2. When the liquid level in the FGD Hold Tank needed to be lowered, the tank was valved into Unit 1 for a short period of time. A portable flow meter located on the piping recorded the volume of liquor released to Unit 1. This record and the daily analysis of the DBA concentration in the FGD Hold Tank allowed an estimate of the DBA loss to Unit 1.

A baseline repeat test and the sodium formate consumption test were performed on the Unit 1 FGD system due to a fire in one module of Unit 2. All previous testing had been performed on Unit 2. The two units are mirror images of one another, however, so the results from one unit should be applicable to the other. During the formate consumption test, Unit 1 was isolated from Unit 2. As in the previous DBA consumption test, all crossovers between the units were closed, all reclaimed water from the solids dewatering system was returned only to Unit 1, and no reclaimed water was used in grinding limestone for Unit 2.

The remaining information needed to calculate the consumption rates were the amounts of DBA or formate additive accumulated in the system during each consumption test. The accumulation was determined by measuring the inventory of DBA or formate in the system five times during each consumption test. An inventory measurement consisted of recording the level of liquor or slurry in each major tank or vessel in the system, taking samples from all those vessels, and measuring the specific gravity, weight percent suspended solids, and liquid-phase additive concentration in each. This information allowed calculation of the amount of liquid-phase additive contained in the system.

2.2.3 Chemical Analyses of Slurry Samples

During each baseline and performance test and periodically during the additive consumption tests, slurry samples were obtained from the absorber reaction tanks. Some of these samples were used to determine the solids content of the slurry and to provide solids for chemical analyses. Solids were analyzed for calcium, magnesium, carbonate, sulfite, and sulfate. These results were used to calculate limestone utilization and extent of sulfite oxidation for the tests. Other samples were filtered and preserved so that the liquid phase could be analyzed. Liquids were analyzed for calcium, magnesium, sodium, carbonate, chloride, sulfite, sulfate, thiosulfate, and DBA or formate additive. Liquid-phase results were used to estimate relative saturations of calcium sulfite, sulfate, and carbonate.

2.2.4 Other Process Data

Other appropriate process data, including stream temperatures, pressures, and flow rates, were gathered from plant instrumentation where available. Boiler loads were also recorded. Average SO_2 removal rates during the additive consumption tests were estimated using the plant inlet and outlet SO_2 monitor results and flue gas flow rates. The latter were determined from combustion calculations based on coal analyses and stack O_2 measurements.

Slurry samples were also used to conduct settling rate tests during the additive consumption tests so that potential effects of the additives on slurry dewatering properties could be evaluated. Scanning electron microscopy was used to compare the size and shape of product solids crystals formed with and without the presence of additives in the FGD system.

2.3 DBA Performance Test Results

2.3.1 SO_2 Removal Efficiency

The completed DBA performance test matrix is summarized in Table 2-1. During the first additive test (high DBA concentration at normal pH), it was discovered that the on-line pH meter for controlling limestone makeup to the module had malfunctioned. The meter was reading near the set point of 5.55, while the actual pH measured with a portable meter was approximately 4.6. The on-line meter was repaired before the next test, but the first test condition had to be repeated following completion of the planned tests, so that eight rather than the planned seven tests were conducted.

SO_2 removals of 90.5 to 98.6% were achieved with the addition of DBA to the FGD system at the normal pH set point (Tests 4, 6, and 8), compared with 86.1% removal with no additive (Test 1A). The actual pH values during these tests, as measured with a portable pH meter, were generally higher than the planned level of 5.55. The measured pH values ranged from 5.79 for the baseline test down to 5.57 during the low DBA concentration test.

In the lower pH set point tests (Tests 3, 5, and 7), the measured SO_2 removal efficiency ranged from 82.3% at the low DBA concentration to 98.1% at the highest DBA concentration. There was no baseline (zero DBA) test at the lower pH value. The actual pH values measured during these tests were about 0.1 to 0.2 pH units above the set point of 5.1, ranging from 5.22 to 5.27.

As expected, at similar pH levels, the SO_2 removal increased with higher DBA concentrations. However, at the high DBA concentration, the test module appeared to be at or near the point where SO_2 removal was limited by gas film resistance to mass transfer. That is, the SO_2 removal across the module was limited by the effectiveness of slurry contact with flue gas, such that further increases in DBA concentration did not greatly improve SO_2 removal performance. This is illustrated by comparing the SO_2 removals measured for the high and

Table 2-1

Results of DBA Performance Tests

Test No.	DBA Conc. (mg/L)	Absorber pH [1]	SO_2 Removal (%)	Reagent Ratio	Oxidation (%)	Utilization (%)
1A	0	5.79	86.1	1.03	2.5	97.1
2	4780	4.63	83.5	1.01	2.2	98.9
3B	5410	5.27	98.1	1.01	2.7	98.6
4	1640	5.72	97.8	1.02	2.7	97.6
5	1510	5.22	91.3	1.01	2.6	98.9
6	605	5.57	90.5	1.02	2.3	98.4
7C	605	5.24	82.3	1.01	2.1	98.8
8D	6320	5.64	98.6	1.03	2.1	96.8

[1] As measured with a portable pH meter.

intermediate DBA levels at the higher pH set point. Although the high DBA concentration was almost four times the intermediate level, the resulting SO_2 removal was less than one percentage point greater.

2.3.2 Results of Slurry Sample Chemical Analyses

Limestone reagent ratios (the inverse of utilization), limestone utilization, and sulfite oxidation percentages measured during the DBA tests are also shown in Table 2-1. These results were calculated from the slurry sample solid-phase chemical analyses. Detailed results for chemical analyses are included in Appendix A.

Limestone utilization during the DBA performance tests was significantly different from previously reported data for this unit. Based on historical data, the reagent ratio at the normal pH set point was expected to be near 1.10 (91% utilization), whereas the values measured during the normal pH tests were in the range of 1.02 to 1.03 (97 to 98% utilization). The difference between the measured values and the historical data suggests a change in the system's operation. Potential explanations for the relatively high utilization values include the possibility that the limestone used was more reactive than normal during this test period, or that a finer limestone grind was produced. It is also possible that the previous data for reagent ratio and limestone utilization were not accurate. The fact that the utilization was also very high for the baseline test (97.1%) suggests that higher limestone utilization was not an effect of DBA addition.

The sulfite oxidation percentages were expected to be in the range of 5 to 10%, but the measured values ranged from 2.1 to 2.7%. The low oxidation percentages were at first assumed to be a result of batch-wise addition of elemental sulfur emulsion to the FGD system a few days before these tests. (In the FGD system, elemental sulfur reacts with liquid-phase sulfite to produce thiosulfate ion ($S_2O_3^{=}$), which inhibits sulfite oxidation.) However, the liquid-phase thiosulfate ion concentrations measured during these tests were no higher than were measured in later tests where sulfite oxidation percentages in the range of 5 to 10% were observed. Thus, the cause of the very low sulfite oxidation percentages during these DBA performance tests has not been determined conclusively.

In general, low sulfite oxidation percentages are desirable, as liquid-phase gypsum relative saturation levels tend to be very low at low oxidation percentages. This means that the tendency for gypsum scaling in the absorber is minimized. Also, the nearly pure calcium sulfite crystals that form at very low oxidation percentages (less than 5%) tend to grow larger than those formed at higher oxidation percentages. This can improve solids dewatering properties, but in some cases can also cause operating problems, if oxidation drops to a low percentage on an infrequent basis. The larger crystals that form at low oxidation percentages tend to settle more rapidly and to a higher density in a thickener. If the operators of the dewatering system are not expecting such a change in dewatering properties, problems with excessive thickener rake torque may result.

Such operational problems actually did develop during the DBA parametric testing. The problems began when the settling and compaction of solids in the first of the two thickener underflow surge tanks increased the torque on the rake at the bottom of that tank. Eventually the rake drive tripped. This event was probably caused by the bulkier shape of the solids formed with DBA present. The effect of DBA (and formate) on solids properties is discussed in Section 2.7.

During the later DBA consumption test, it was demonstrated that solids dewatering problems could be avoided with careful control of the amount of slurry in the two thickener underflow surge tanks and of the bed level in the thickeners. The levels of solids in the these two surge tanks and in the thickeners were kept low during this later test so as to have a small solids inventory in the system. However, it should also be noted that the DBA concentrations of 1000 to 1500 ppm during this later consumption test were well below the maximum levels of 5000 to 6000 ppm experienced during the performance test series.

Several trends were noted in the liquid-phase analytical data from the DBA tests. First, the calcium concentration increased with increasing DBA level. The direct relationship between DBA concentration and the liquid-phase calcium concentration is an expected result of maintaining charge balance. The components of DBA are negatively charged ions, so to maintain a neutral solution, the calcium concentration in the liquid phase must increase. A second trend showed higher liquid-phase sulfite concentrations as the pH decreased. This is also an expected result due to the higher solubility of calcium sulfite at a lower pH. Finally, the thiosulfate concentration was observed to decrease with time. This was also an expected result. Thiosulfate was produced by the addition of elemental sulfur, which was added batch-wise to the FGD system immediately prior to these tests. Correspondingly, the concentration decayed over time due to degradation and blowdown losses.

A number of process parameters were also measured and recorded during the DBA performance tests. A summary of these data is provided in Appendix B. Many of these values were used as inputs for the calibration of FGDPRISM.

2.4 Sodium Formate Performance Test Results

2.4.1 SO_2 Removal Efficiency

The sodium formate performance test results are summarized in Table 2.2 Note that the baseline data point repeated well from that of the DBA test series (86.5 vs. 86.1% removal for the DBA baseline). The formate ion concentrations achieved during these tests were lower than planned. It was desired to test the same levels as in the earlier DBA additive tests, but these levels were not achieved. However, the levels tested were sufficient to significantly improve the module SO_2 removal performance.

The molecular weight of formate ion, a monocarboxilic acid, is 45. The average molecular weight of DBA, a mixture of dicarboxilic acids, is about 130. If the full buffering capacity of and formate and DBA were used as the FGD slurry absorbed SO_2, the

Table 2-2

Results of Sodium Formate Performance Tests

Test No.	Formate Ion Concentration (mg/L)	Absorber pH[1]	SO_2 Removal (%)	Reagent Ratio	Oxidation (%)	Utilization (%)
1A	0	5.73	86.5	1.03	6.4	96.9
2	900	5.64	93.4	1.03	5.7	97.3
3B	1000	5.26	84.2	1.01	5.7	99.1
4	1730	5.60	93.3	1.02	5.3	98.1
5	1860	5.21	85.7	1.01	5.1	99.2
6	3600	5.69	96.6	1.02	5.7	98.5
7C	3530	5.11	87.3	1.01	5.2	99.2

---

[1] As measured with a portable pH meter

milliequivalents of buffer capacity provided per unit mass of formate would be expected to be nearly 50% greater than for DBA. In practice, however, because the two additives buffer over different pH ranges, the relative effectiveness of DBA and formate is a function of the absorber configuration and the operating pH.

Overall, SO_2 removals were significantly lower with sodium formate additive than in tests with DBA additive, when compared at similar formate ion concentrations (by weight). However, a relatively high SO_2 removal level of 96.6% was still achieved at the normal pH set point and at the highest formate concentration of 3600 ppm.

For the lower pH formate tests, a steady increase in SO_2 removal was measured as the formate ion concentration increased. However, this was not the case for the tests at the normal pH level. A marked increase in removal was noted as the formate concentration increased from zero to the low sodium formate level, but no increase was observed when the formate concentration increased from the low level to the intermediate level. A significant improvement was again noted as formate increased from the intermediate level to the high concentration. Based on FGDPRISM simulations, a two percentage point increase in removal would be expected with increased formate from the low to the intermediate formate level. This indicates a potential error in the SO_2 or pH measurements during the normal-pH set point test at either the low or intermediate formate level.

2.4.2 Results of Slurry Sample Chemical Analyses

Limestone utilization and sulfite oxidation results calculated from solid-phase chemical analyses are also shown in the table. Similar to the DBA results, the limestone utilization levels measured during the sodium formate performance tests were much higher than were expected based on historical data.

The results in Table 2-2 also show that the oxidation percentages measured during the sodium formate testing were more typical of what had been measured previously at Merom

Station. The oxidation percentages were approximately twice those measured during the DBA additive parametric tests and were in the expected range of 5 to 10%. Detailed solids analytical results for the formate tests are provided in Appendix A.

Liquid-phase analyses are also included in Appendix A. As in the DBA tests, higher sulfite concentrations were measured at the low pH levels due to the increased solubility of calcium sulfite. Higher liquid-phase sodium levels were observed with each increase in formate ion concentration, as would be expected since formate was added as a sodium salt. Also, because sulfur was still being added to the Merom FGD system in a batch-wise manner at the time of this test, the thiosulfate concentration decreased with time. The liquid-phase thiosulfate ion concentrations during these sodium formate parametric tests were similar to those during the previous DBA tests, but as mentioned above, the sulfite oxidation percentages were higher.

A summary of the process data recorded during each formate performance test is included in Appendix B.

2.5 Reagent Ratio Performance Test Results

2.5.1 SO_2 Removal Efficiency

The results of the reagent ratio performance tests are summarized in Table 2-3. The full-scale results demonstrated that the previous FGDPRISM calibration had over-predicted the effect of reagent ratio on SO_2 removal. With the earlier FGDPRISM calibration, an SO_2 removal of 98% was predicted for a pH value of approximately 6. However, with measured pH values of 5.98 to 6.12 in the recirculating slurry of the operating modules, the SO_2 removal for the Unit 2 FGD system was only 93.5%. These full-scale data were subsequently used to improve the FGDPRISM calibration to more accurately predict the effects of pH.

The data in Table 2-3 also show the combined effects of increasing the pH set point and adding DBA. An SO_2 removal level of 94.5% was achieved at a DBA concentration of

Table 2-3

Results of Reagent Ratio Performance Tests

Test	Test Conditions	Unit Load (MW)	Controller Setpoint pH	Measured pH		DBA Conc. (ppm)	SO_2 Removal (%)	SO_2 Inlet (ppm, dry)	SO_2 Outlet (ppm, dry)	Reagent Ratio [1]	Percent Oxidation [1] (%)	Util'n [1] (%)
				Module B	Module D							
1	Baseline [2]	420	5.55	5.82	5.82	0	87.0	2800	365	1.07	7.6	93.7
2	High pH [3]	421	5.70	5.93	5.98	0	92.0	2150	173	1.13	5.7	88.8
3	High pH [3]	421	5.85	5.98	6.12	0	93.5	2200	142	1.23	5.3	81.2
4	Low pH [3]	420	5.4	5.48	5.42	0	84.0	2000	320	1.03	7.2	97.5
5	High pH & DBA [3]	420	5.7	5.61	5.60	650	93.5	2600	170	1.08	5.1	93.0
6	High pH & DBA [3]	382	5.7	5.59	5.68	1100	94.5	2710	150	1.09	4.6	92.0

[1] Based on Module 2B analysis.

[2] Four-module operation.

[3] Three-module operation.

1100 ppm and a pH controller set point of 5.70. However, the combined effects of reagent ratio and DBA were also less than predicted, most likely due to the over-predicted effect of reagent ratio.

It is important to note the unit load and the actual pH for each performance test. Although the load was constant during the first five tests, Test 1 (baseline) was conducted with all four modules in service, while only three modules were in service for the remaining performance tests. Based on the unit load and the number of modules in service, the flue gas velocity through the FGD system absorbers during Test 1 averaged slightly less than 80% of the full-load value, while the velocities through the three absorbers in service during Tests 2 through 5 were almost 5% greater than the equivalent full-load value. In Test 6, where the unit load was down slightly, the velocities through the three absorbers in service were estimated to be about 95% of the design full-load value.

The SO_2 removal for the baseline reagent performance test (87%) was slightly higher than in the baseline tests for the previous parametric series (86.1 and 86.5%, respectively) but lower than might have been expected at the lower gas flow rate. The measured pH value for this baseline test (5.82 in the two modules that were measured) was also slightly higher than in the baseline tests for the previous parametric series (5.79 and 5.73, respectively).

During this parametric test period, the on-line pH controller probes were calibrated daily in an attempt to reduce the difference between the pH values measured with portable meters and the on-line values. As can be seen in Table 2-3, the difference between the measured and on-line values decreased as the tests progressed. Note that because of the improved agreement between the on-line pH controller values and those of the portable meter, the measured pH values for the high pH (5.70 set point) DBA addition tests (Tests 5 and 6) were no higher than in the earlier DBA parametric tests at the normal set point. The measured values for Tests 5 and 6 ranged from 5.59 to 5.68, while in the earlier test series at the normal pH set point, the measured pH values ranged from 5.57 to 5.79.

2.5.2 Results of Slurry Sample Chemical Analyses

Samples were collected from Unit 2 to characterize the liquid and solids chemistries during each reagent ratio performance test. The results of chemical analyses on the absorber liquid and solids and the baseline filter cake solids are summarized in Appendix A.

The values in Table 2-3 show the expected oxidation percentages of 5 to 10%. Although these oxidation percentages are higher than in the initial DBA test results, they are similar to those of the sodium formate additive test series and are still in the preferred range for an inhibited-oxidation system (10% or less). One observed trend was that the oxidation appeared to be slightly lower for the highest pH cases (Tests 2 and 3) and with DBA addition (Tests 5 and 6). However, the limited quantity of data and the potential error in measuring solid-phase sulfate content at low oxidation percentages prevent a strong conclusion about these relationships.

Hoosier Energy installed a semi-continuous emulsified sulfur addition system at Merom Station just prior to this phase of testing. Although the new addition system still operates batch-wise, the sulfur is added daily rather than once per month, and 5 to 10% oxidation is regularly maintained. The amount added each day is based on a thiosulfate analysis performed on site by Merom personnel.

The solid-phase analytical results for the highest pH test showed that a reagent ratio of about 1.25 (~80% utilization) was achieved. This was the maximum reagent ratio achievable without making equipment modifications at the plant. However, there was no interest in testing at higher reagent ratio values. Operation at reagent ratios above 1.25 is not recommended due to the potential for scaling or plugging in the absorber packing and mist eliminator (particularly during excursions of low thiosulfate concentration) and because of increased operating costs.

No major changes in liquid-phase chemistry were observed as a result of changes in operating pH. The new sulfur addition schedule (batch-wise addition on a daily basis) kept the thiosulfate concentration at about 1300 to 1600 ppm. This level was sufficient to keep the sulfite oxidation percentage below 10% and the liquid-phase gypsum relative saturation levels well below 1.0 (at 0.05 to 0.10). In contrast, during the previous tests, when sulfur was added once per month, measured thiosulfate levels decreased from about 2500 ppm to 1500 ppm over the course of each series.

2.6 Additive Consumption Test Results

2.6.1 DBA Additive Consumption Test

In August 1992, a 14-day DBA consumption test was conducted on Unit 2 to verify the DBA concentration required to achieve 95% SO_2 removal and to determine the DBA addition rate required to maintain that concentration. Although the liquid and solid phases of the slurry in the Unit 2 FGD system would reach a steady state after only three to four days, a two-week test period was employed to improve the accuracy of the DBA consumption rate measurement. By continuing the test for two weeks, a large quantity of DBA was added to the unit relative to the amount of the initial charge. This minimized the effect of changes in DBA concentration and slurry or liquor level in the various tanks and vessels in the FGD system on the accuracy of the consumption calculation.

The two-week DBA consumption test began immediately after the reagent ratio test series described in the previous subsection. The DBA concentration in the Unit 2 absorbers' recirculating slurry liquor was increased slightly to about 1100 to 1200 ppm. Other than the addition of DBA, the Unit 2 FGD system was operated at the normal pH set point of 5.55 with daily batch-wise sulfur addition.

Performance Results from the DBA Consumption Test

The performance of the Unit 2 FGD system during the consumption test is summarized in Table 2-4. The table contains the daily average Unit 2 load, inlet SO_2

Table 2-4

Performance of Unit 2 FGD System During DBA Consumption Test

Day	Unit Load (MW)			SO_2 Inlet (ppm)	SO_2 Removal (%)	DBA Level [1] (ppm)	Average pH [1]
	Minimum	Maximum	Average				
08/10	301	511	452	2404	91.8	1111	5.45
08/11	301	471	393	2440	92.5	1109	5.50
08/12	297	474	384	2194	95.2	927	N/A
08/13	241	472	334	2376	95.0	852	5.70
08/14	246	404	349	2299	95.8	1174	5.65
08/15	233	421	366	2247	96.0	1503	5.70
08/16	211	413	303	1555	97.1	1396	5.60
08/17	212	453	367	1886	97.7	1476	5.50
08/18	211	486	346	2326	97.7	1487	5.45
08/19	230	492	378	2484	97.6	1427	5.55
08/20	225	483	383	2670	98.2	1245	N/A
08/21	262	475	371	2649	97.0	1155	5.65
08/22	235	312	287	2235	97.2	1200	5.65
08/23	220	401	287	1742	96.8	1090	5.60

[1] Unit average.

concentration, and SO_2 removal values, as well as daily average values for module recirculating liquor pH and DBA concentration. The daily average unit load was near the target value of 70% of full load, which is approximately the annual capacity factor for Merom Station. However, full-load conditions were not achieved for extended periods of time during the consumption test. Although full-load operation did not occur during the day, the desired daily average load was achieved by holding the load higher during off-peak hours. This did not allow determination of whether the DBA concentrations tested were sufficient to achieve 95% SO_2 removal during sustained periods of full-load operation, though.

Another goal of the test was to determine the DBA consumption rate while the unit was operating at an average of 95% SO_2 removal with no flue gas bypass. The average SO_2 removal for the test period was nearly 96%, although the daily removal averages ranged from a low of 91.7% to a high of 98.2% during the test. The fluctuation in removal is attributed mostly to variations in the recirculating slurry pH and in the concentrations of DBA in the modules during the first two days of the test. The low removal recorded during the first two days of the test was caused by artificially high readings from the on-line pH meters (i.e., the actual recirculating slurry pH values were lower than the indicated value) on the first day and by problems with the limestone slurry reagent preparation system on the second day. Pluggage problems in the limestone mill caused a low inventory of fresh slurry for the Unit 2 FGD system, forcing the operator to conserve limestone by reducing the pH set point.

Another factor that affected SO_2 removal was the increase in DBA concentration during the middle period of the test. The DBA concentration increased to an average of 1500 ppm in the modules near the end of the first week, increasing SO_2 removals to between 96 and nearly 98%. During this period, the rate of DBA addition to the system was not sufficiently reduced to account for increased DBA concentrations in the filtrate returned to Unit 2 from the vacuum filters. The DBA addition rate was eventually reduced to account for this change, and the concentration of DBA in the Unit 2 modules returned to normal levels during the last four days of the test.

DBA Consumption Results

The fluctuations in SO_2 removal and DBA concentration do not reduce the validity of the consumption rate results, because they reflect typical variations in operation that can occur in a full-scale unit. The consumption test was conducted over a two-week time period to minimize the effects of any one upset on the accuracy of the results. Five inventories were taken during the test, so the DBA consumption rates from different time periods could be compared to identify anomalies.

Two DBA consumption rates calculated between Inventories 1 and 3 and between Inventories 3 and 5 are shown in Table 2-5, and the four DBA consumption rates between each of the five inventories are shown in Table 2-6. The data in Table 2-5 presumably provide the more accurate measure of the DBA consumption rate during the two-week period, because the inventory accumulation terms were based on more accurate ion chromatography analyses for DBA concentrations in tanks and vessels. In Table 2-6, the accumulation terms for Inventories 2 and 4 were based on the results of on-site buffer capacity titration analyses. The buffer titration method is not species-specific and can be subject to background interferences, so these inventories are presumably less accurate. Although the rates calculated from Inventory 2 and 4 in Table 2-6 have a higher uncertainty than the two rates in Table 2-5, having rates for four separate periods is useful for identifying trends in the data.

In both tables, the DBA consumption rates are presented in terms of DBA consumed per ton of SO_2 removed. Consumption is defined as the amount of DBA added to the system less the accumulation of DBA in the system tanks and vessels. The observed consumption consists of losses by three pathways: with the blowdown of DBA-containing liquor from the FGD system, with the small amount of liquor adhered to the dewatered FGD byproduct sludge, and through "nonsolution" loss mechanisms such as oxidative degradation, coprecipitation with the FGD byproduct solids, and vaporization into the flue gas.

Table 2-5

DBA Consumption Test Results Based on Three Inventories

			DBA Addition		DBA Solution Losses								
Inventory	Date	Time	Tanker/ Height	DBA Added (lbs)	Solution Discharges (Blowdown) (lbs)	With FGD Byproduct Sludge (lbs)	Inventory Accumulation (lbs)	Observed Consumption (lbs)	Avg. SO_2 Removal (%)	Tons of SO_2 Removed	Observed lbs of DBA per ton of SO_2 Removed	Estimated "Closed-Loop" lbs of DBA per ton of SO_2 Removed	Nonsolution Loss Rate (lbs of DBA per ton of SO_2 Removed)
1	8/10/92	14:30	2/23"										
3	8/17/92	14:00	4/41"	27,770	1,750	2,910	8,780[1]	18,990	95.0	1,939	9.8	8.9	7.4
5	8/23/92	14:00	4/26.5"	9,110	240	4,000	-6,310[1]	15,420	97.5	1,616	9.5	9.4	6.9

[1] Based on off-site DBA analyses by ion chromatograph.

Table 2-6

DBA Consumption Test Results Based on All Five Inventories

			DBA Addition		DBA Solution Losses								
Inventory	Date	Time	Tanker/ Height	DBA Added (lbs)	Solution Discharges (Blowdown) (lbs)	With FGD Byproduct Sludge (lbs)	Inventory Accumulation (lbs)	Observed Consumption (lbs)	Avg. SO_2 Removal (%)	Tons of SO_2 Removed	Observed lbs of DBA per ton of SO_2 Removed	Estimated "Closed-Loop" lbs of DBA per ton of SO_2 Removed	Nonsolution Loss Rate (lbs of DBA per ton of SO_2 Removed)
1	8/10/92	14:30	2/23"										
2	8/13/92	12:00	3/38"	9,460	660	1,070	2,450[2]	7,010	93.6	906	7.7	7.0	5.8
3	8/17/92	14:00	4/41"	18,310	1,090	1,840	6,330[1]	11,980	96.3	1,032	11.6	10.5	8.8
4	8/20/92	15:00	4/32"	5,670		2,400	-3,830[2]	9,490	97.8	914	10.4	10.4	7.8
5	8/23/92	14:00	4/26.5"	3,450	240	1,600	-2,480[1]	5,930	97.3	702	8.4	8.1	5.8

[1] Based on off-site DBA analyses by ion chromatograph.
[2] Based on on-site DBA analyses by buffer capacity titration.

Of these three loss pathways, the latter two cannot be readily controlled by the FGD system operator. However, the first loss pathway listed, with liquor blowdown, could be eliminated through closed-loop operation of the FGD system (i.e., operation with no blowdown). Consequently, the next to last column in each table represents a calculated "closed-loop" DBA consumption rate. To calculate this rate, the amount of DBA lost through blowdown of FGD liquor was subtracted from the observed losses, then divided by the tons of SO_2 removed. This is labeled an "estimated" closed-loop operation rate, because the calculation assumes that with true closed-water-loop operation, the resulting increases in concentrations of soluble species such as chloride, magnesium, and sodium would not measurably affect the nonsolution loss rate.

In Table 2-5, the observed DBA consumption rate was 9.8 lbs of DBA per ton of SO_2 removed for the first week of the test and 9.5 lbs/ton for the second week. The estimated closed-loop operation rates were 8.9 and 9.4 lbs/ton, respectively.

In Table 2-6, where DBA consumption rates are calculated for four periods during the two-week test, the dependence of the "closed-loop" consumption rate on DBA concentration is evident. For example, between Inventories 1 and 2, the estimated closed-loop consumption rate was 7.0 lbs/ton, while between Inventories 2 and 3, the rate increased to 10.5 lbs/ton. Referring to the data in Table 2-4, the average DBA concentration between Inventories 1 and 2 was about 1000 ppm, while between Inventories 2 and 3 the average was nearly 1400 ppm.

The DBA consumption rates measured during this two-week test were lower than were expected, based on results from prior testing at the EPRI ECTC. However, the ECTC wet FGD system treats a flue gas produced by a coal with a higher chlorine content than at Merom Station. This raises the chloride content in the ECTC recirculating slurry liquor relative to that at Merom. To maintain charge balance, the liquid-phase calcium concentrations are in turn higher at the ECTC than at Merom station, by approximately a factor of three. The higher calcium concentrations at the ECTC result in a greater tendency for precipitation of the calcium salts of the DBA components, thus greatly increasing coprecipitation losses. While the differences in additive consumption rates can be explained by differences in the liquor chemistry for these two systems, this example illustrates the need to evaluate the effects of all site-specific factors when considering additives for a particular application.

The amount of DBA lost with the filter cake can be subtracted from the closed-loop DBA consumption rate to determine the DBA nonsolution loss rate. The nonsolution loss rate is due to additive degradation, vaporization, and/or coprecipitation. The nonsolution loss rates indicated in Table 2-5 were 7.4 lb DBA per ton of SO_2 removed the first week and 6.9 lb/ton the second week. These two results are not significantly different.

Results of Slurry Sample Chemical Analyses

Samples of the recirculating slurry from one module for Inventories 1, 3, and 5 were submitted for more complete chemical analyses. These results are presented in Appendix A. The concentrations of several chemical species increased significantly during the consumption test. For example, the concentrations of magnesium, sodium, chloride, sulfate, and thiosulfate increased by 20 to 40% over the course of the test. This is because the FGD system was operated in a nearly closed-loop fashion during the DBA consumption test.

2.6.2 Sodium Formate Additive Consumption Test

In November 1992, two sodium formate consumption tests were conducted at the Merom Station as part of the DOE PETC-funded High-Efficiency SO_2 Removal Testing project. Since several months had elapsed since previous testing on this FGD system, the consumption test was preceded by a baseline test to determine the current system performance without sodium formate addition. The results of these tests are described below.

Performance Results from the Formate Consumption Baseline Test

For the baseline test, Unit 1 operated at approximately 474 MW with four modules in operation. This was less than full load (535 MW) but was the highest load possible due to limited demand. The one-day baseline test was intended to characterize the system under normal operating conditions. During the test, a set of slurry and liquor samples were collected from two modules, for liquid and solids analyses and slurry settling tests. Liquor samples were also taken from the Units 1 and 2 thickener overflows and from one module of Unit 2 to determine the background buffer capacity of the system. This was to improve the accuracy of the buffer capacity titration that was used on site to measure the liquor formate ion concentration.

Table 2-7 summarizes the data for daily average Unit 1 load, inlet SO_2 concentration, SO_2 removal, module pH, and formate concentration measured during the baseline and sodium formate consumption test periods. During the baseline test, the unit achieved an average SO_2 removal of 90.2% (based on Unit 1 continuous emissions monitor readings). The Module A slurry pH, as measured with a portable pH meter, was 5.66, while the Modules B, C, and D slurry pH values were higher at 5.91 to 5.92. The on-line pH controllers indicated pH values closer to 5.5 for Module A and 5.65 for Modules B, C, and D. Although the SO_2 removal for this baseline case was higher than the values of 86.1 to 87% measured for baseline tests during the previous DBA, sodium formate, and reagent ratio performance tests, the lower unit load and high slurry pH values in Modules B, C, and D appear to account for the higher SO_2 removal.

Performance Results from the First Formate Consumption Test

After isolating the unit, 39 wt.% sodium formate solution was spiked into the Unit 1 thickener and limestone classifier to raise the system formate concentration to the desired value of about 2500 ppm. The 2500 ppm target concentration was selected based on results from the previous sodium formate parametric tests and subsequent FGDPRISM simulations. The concentration was maintained by adding the sodium formate solution into the Unit 1 limestone classifier with a small positive-displacement pump.

Two consumption tests were performed during the two-week test period. Due to an unscheduled shutdown of one of three Unit 1 coal grinding ball mills, the maximum

Table 2-7

Performance of Unit 1 FGD System During Sodium Formate Consumption Tests

Day	Unit Load (MW)			SO_2 Inlet (ppm)	SO_2 Removal (%)	Module pH				Formate Concentration[1] (ppm)			
	Minimum	Maximum	Average			A	B	C	D	A	B	C	D
Baseline													
11/11	473	475	474	2773	90.2	5.66	5.92	5.91	5.91	0	0	0	0
Consumption 1													
11/12	228	326	307	2760	95.2	5.90	6.00	--	5.91	2180	2210	--	2520
11/13	302	328	293	2591	93.8	--	--	--	--	--	--	--	--
11/14	303	325	309	2337	92.2	5.59	5.78	--	5.68	2460	2530	--	2650
11/15	303	329	306	1928	92.2	5.63	5.73	--	5.73	2720	--	--	2970
11/16	304	333	318	2279	93.2	5.80	5.86	--	--	3200	3260	--	--
11/17	302	333	319	2456	93.9	5.50	--	--	5.71	3570	--	--	3600
11/18	323	326	324	2576	93.5	5.76	5.90	--	5.88	3080	3030	--	3070
Consumption 2													
11/19	323	326	325	2441	95.0	6.04	6.15	--	6.13	2890	2970	--	3110
11/20	321	325	324	2569	95.7	6.07	6.14	--	--	3140	3080	--	--
11/21	323	326	324	2693	96.3	6.10	6.11	--	6.17	3190	3140	--	3460
11/22	323	330	325	2730	95.9	6.06	6.02	--	6.02	3410	--	--	3320
11/23	299	330	323	2491	94.9	5.98	5.99	--	6.03	4220	4000	--	4620

[1] On-site analyses.

sustainable load on Unit 1 during these two weeks was only 325 MW. To better simulate full-load operation of the FGD system absorber modules, only three modules were in service for both consumption tests.

The objective of the first test (November 12 to 18) was to achieve 95% SO_2 removal at the normal operating pH by adding sodium formate. For the second consumption test (November 19 to 23), the sodium formate level was to be held constant and the reagent ratio increased to achieve 98% SO_2 removal. However, these SO_2 removal targets were not achieved. As shown in Table 2-7, daily SO_2 removal averages ranged from 92.2 to 95.2% for the first consumption test. The pH values measured by a portable pH meter ranged from 5.50 to 5.90 in Module A, 5.73 to 6.00 in Module B, and 5.68 to 5.91 in Module D. Module C was off line during both consumption tests.

Formate ion concentrations (based on the on-site buffer capacity titration) for each module are also shown in Table 2-7. On days when an inventory measurement was not made, typically only two modules were sampled. All three modules were sampled on inventory days. On these days, samples were also obtained for off-site analyses by ion chromatograph. On November 13, problems were encountered with the sodium formate feed system; and no formate samples were taken from the absorber modules.

Formate concentrations varied among the modules. As Table 2-7 illustrates, the concentrations steadily increased until November 17, then decreased on November 18. The increase in concentration over most of the test was due to two factors: formate addition was limited by pump problems during the first two days, and later in the test, the formate level was increased above the original target of 2500 ppm in an attempt to achieve 95% SO_2 removal. Although the formate ion concentrations increased, the SO_2 removal performance of the FGD system actually decreased from the value at the beginning of the test. This decrease was mainly because improved calibration of the pH controllers lowered the actual recirculating slurry pH values from where they had been during the baseline repeat and at the beginning of the consumption test.

Following Inventory 2 on November 14, the formate concentrations in the system were increased slightly in an attempt to obtain 95% SO_2 removal. However, on-site buffer capacity titrations on samples taken the evening of November 16 and the morning of November 17 indicated higher formate concentrations than desired, so Inventory 3 was delayed one day to allow formate levels to decrease. The first consumption test concluded when Inventory 3 was taken on the morning of November 18. Although the concentrations throughout the system were still higher than intended, 95% SO_2 removal was not being attained.

Performance Results from the Second Sodium Formate Consumption Test

The pH set points were increased to 5.8 at the start of the second consumption test in an attempt to obtain 98% SO_2 removal. The results in Table 2-7 show that formate concentrations continued to increase throughout this test. The concentrations increased slightly between Inventories 4 and 5 but jumped significantly from Inventories 5 to 6. Concentrations in the absorber modules averaged approximately 2800 ppm for Inventory 4, 3000 ppm for Inventory 5, and 3750 ppm for Inventory 6.

Even at the elevated reagent ratio in the second consumption test, 98% removal was not attained. The daily average SO_2 removals for the second consumption test ranged from 94.9 to 96.3%, while the measured module pH values ranged from 5.98 to 6.17. The average SO_2 removal was about 95.5%. However, 98% removal had not been attained in the previous sodium formate parametric tests either. The expectation of achieving 98% SO_2 removal at these conditions was largely based on preliminary FGDPRISM results. These model results were later found to have over-predicted the effects of elevated reagent ratio on SO_2 removal performance.

Formate Consumption Results

Sodium formate consumption test results are summarized in Table 2-8. The total and nonsolution loss rates (as formate ion) are reported on an SO_2 removal basis (lbs of formate ion per ton of SO_2 removed). The SO_2 removal was estimated from the FGD system inlet and

Table 2-8

Sodium Formate Consumption Test Results

Inventory	Date	Time	Formate Addition		Formate Solution Losses		Inventory Accumulation (lbs)	Formate Added From Unit 2 (lbs)
			Tanker/Height	COOH$^-$ Added (lbs)	Solution Discharges (lbs)	With FGD Byproduct Sludge (lbs)		
1	11/12/92	16:00	1/48"					
2	11/14/92	17:00	1/12"	9,760	0	1,500	2,570	0
3	11/18/92	11:00	3/22"	16,530	0	2,350	8,070	0
1 to 3				26,290	0	3,850	10,640	0
4	11/19/92	19:00	4/48"					
5	11/21/92	14:00	4/24"	6,530	0	1,590	-560	2,530
6	11/23/92	17:00	5/24"	11,650	540	1,790	13,250	940
4 to 6				18,180	540	3,380	12,690	3,470

Inventory	Date	Time	Observed Consumption (lbs)	Observed Nonsolution Losses (lbs)	Average SO_2 Removal (%)	Tons of SO_2 Removed	Observed Consumption in lbs of COOH$^-$ per ton of SO_2 Removed	Observed Nonsolution Losses in lbs of COOH$^-$ per ton of SO_2 Removed
1	11/12/92	16:00						
2	11/14/92	17:00	7,190	5,690	93.7	315	23	18
3	11/18/92	11:00	8,460	6,120	92.9	733	11	8
1 to 3			15,650	11,810	93.4	1,048	15±3	11
4	11/19/92	19:00						
5	11/21/92	14:00	9,620	8,030	95.5	409	23±5	20
6	11/23/92	17:00	-660	-2450	95.5	378	-2	-6
4 to 6			8,960	5,580	95.5	787	11	7

outlet flue gas SO_2 concentrations measured by the continuous emissions monitors and an estimated flue gas flow rate. The flue gas flow rate was in turn estimated from a combustion calculation based on unit load, unit net plant heat rate, flue gas O_2 concentrations, and an average of several coal analyses taken during the consumption tests. Hourly averages of process data collected during the consumption tests were used in these calculations.

The calculated formate consumption is defined as the amount of formate added to the system less the accumulation of formate in the system liquid inventories. The observed consumption includes both solution and nonsolution losses. For Merom Station, the solution losses included discharges from the FGD Hold Tank to Unit 2 and losses with the liquor contained in the filter cake. The return of formate from Unit 2 with the filtrate from that unit was also included as formate addition during the second test.

There were a number of process upsets during the formate consumption test that affect the accuracy of the consumption rate measurements. First, while samples were being collected for Inventory 3 at the end of the first test (at 12:00 noon on November 18), the torque on the Unit 1 thickener rake increased abruptly. The rake was raised, but the problem persisted. Sodium formate addition was stopped while the system operators assessed the cause of the thickener problem. Sodium formate addition resumed November 19 at 11:00 a.m. after a mechanical check revealed that a belt on one of the rake drives had broken. The belt was replaced, and the thickener was placed back on-line with normal torque values at approximately 1:00 p.m. The second consumption test began that same day.

The plant operated smoothly from that point until November 22, when the FGD Hold Tank was valved into Unit 2 for approximately 50 minutes to reduce the inventory of liquor in Unit 1. Based on the drop in level and the formate concentration in the FGD Hold Tank, 543 pounds of formate were lost to Unit 2 in that blowdown event.

Late on November 22, a broken water main caused a shortage of fresh water makeup to the FGD system. Limestone reagent slurry production was temporarily stopped, and the Unit 1 scrubbers were taken out of service for approximately 1 hour. This time period was not included in the daily average SO_2 removal reported in Table 2-8.

During the night of November 22 or early morning of November 23, the sodium formate tanker trailer in use emptied, and another full tanker trailer was connected to the additive feed pump. The level in this new tanker dropped significantly overnight (20 inches, representing 2036 gallons of solution in 11 hours), causing a large increase in the formate concentrations in the modules. At the correct sodium formate solution feed rate, only one-third that amount (700 gallons of solution) should have been fed to the FGD system over that time period. Samples taken the morning of November 23 showed very high formate concentrations, so the final inventory was delayed until mid-afternoon to allow the formate level to decrease. However, the concentrations were still extremely high during Inventory 6.

No blowdown of formate-containing liquor had been recorded during the first consumption test. Samples from the Unit 2 thickener overflow and Unit 2 module(s) were taken during Inventory 3, at the end of the first test, and analyzed to confirm that no formate was present in the Unit 2 liquor. Surprisingly, on-site analyses indicated a significant formate concentration in the Unit 2 liquor. Consequently, Unit 2 liquor samples were taken during each subsequent inventory to track any unrecorded formate losses to Unit 2.

Based on those results, it appears that there was an unrecorded discharge to the Unit 2 thickener prior to or during Inventory 3. This observation coincides with the timing of the Unit 1 thickener problems that began during Inventory 3, at the end of consumption test 1. It could be that the isolation between the two units was broken when the thickener bed volume was being reduced to alleviate torque problems. For example, it is possible that the Unit 1 thickener underflow was pumped out faster than could be handled by the dewatering system, so a portion was pumped back to the Unit 2 thickener.

The sodium formate loss to Unit 2 did not seem to continue into the second consumption test, as indicated by the decreasing Unit 2 formate concentrations between

Inventories 4 and 5. The loss of sodium formate to Unit 2 appeared to occur right at the end of the first consumption test, but before the beginning of the second consumption test (i.e., before Inventory 4). Therefore, the possibility of unrecorded sodium formate discharges to Unit 2 was not included in the material balance calculations for either consumption test. However, the presence of formate in the Unit 2 liquor during the second consumption test was considered as a make-up source to Unit 1 during that test, since the filtrate from both units was returned to Unit 1 during the consumption tests. It was assumed that there was no sodium formate in the Unit 2 filtrate during the first consumption test.

The total formate ion consumption rate averaged 15 lbs/ton of SO_2 removed for the first consumption test, while the nonsolution losses averaged 11 lbs/ton. Expressed as a quantity of sodium formate, rather than the formate ion, the overall consumption and nonsolution loss rates were 23 and 17 lbs/ton of SO_2 removed, respectively. As described earlier in this subsection, the target test-average SO_2 removal level of 95% was not attained. The actual average SO_2 removal was about 93.4%.

The formate consumption rate for the second test is best calculated between Inventories 4 and 5. As mentioned earlier, a large amount of sodium formate was added overnight just before Inventory 6. For the period between Inventories 5 and 6, the sum of the inventory accumulation and solution loss terms is greater than the amount of formate added to the system, indicating significant errors in the data collected for Inventory 6, presumably because of uncertainty in the large accumulation term. Therefore, the consumption rate for the second test should be based on the value measured between Inventories 4 and 5. The accumulation during that period was only about 6% of the sodium formate added. Between Inventories 4 and 5, the formate ion consumption rate was measured at 23 lbs/ton of SO_2 removed. The formate ion nonsolution loss rate was measured at 20 lbs/ton of SO_2 removed, which is well above the rate measured during the first consumption test.

An error propagation analysis was done to estimate the uncertainty in the sodium formate consumption test results using the procedure outlined in ANSI/ASME Power Test Code

19.1-1985, "Measurement Uncertainty." Table 2-9 lists the parameters that were used in the sodium formate material balance calculations along with the assumed bias or precision errors.

The actual amount of sodium formate added to the system during the test was known quite accurately. A 2% bias error was assumed in the delivered weight of sodium formate. The measured amount of 39% sodium formate remaining at the end of each inventory, which was determined by gauging the tanker, was assumed to have a precision error (standard deviation) of 1/4-inch. This was equivalent to 300 lbs in the tanker.

The formate analyses from which the inventories were calculated were assumed to have a standard deviation of 10%.

The total slurry volume in the system did not vary significantly during the test, because nearly all of the large tanks operate at a constant level. The level in the thickener is constant, and it accounts for roughly half the liquid inventory in the unit. A 5% bias error was assumed for the total calculated liquid volume. Most of this error is accounted for by the uncertainty in the liquor volume in the thickener, because the volume of the solids accumulated within the thickener is not well known. This uncertainty is described in the next paragraph.

An assumption had to be made to determine the amount of formate ion present in the thickener. The thickener underflow and overflow were both sampled to determine the average formate concentration in the liquor. However, it was not possible to accurately measure the volume of liquor present, as the solids inventory (or the height of the bed of solids) in the thickener could not be measured. An assumption was made that the entire thickener volume averaged 15 wt.% solids, which allowed a liquid volume to be calculated.

The uncertainty analysis indicates that the total calculated sodium formate consumption should be accurate to about ±20% at the 95% confidence interval. Thus, the total consumption rate for the first test should be reported as 15 ± 3 lb formate ion/ton of SO_2 removed, and the total consumption rate for the second test should be reported as 23 ± 5 lb/ton.

Table 2-9

Assumptions Used in Sodium Formate Consumption Uncertainty Analysis

Variable	Estimated Error
NaCOOH Concentrations	10%
Tank Volumes	5%
SO_2 Outlet Concentrations	10%
SO_2 Inlet Concentrations	10%
Coal Heating Value	55 Btu/lb
Delivered Weight of Sodium Formate	2%
Measured NaCOOH in Tanker	300 lb
Unit Load	5%
Unit Heat Rate	5%
Specific Gravity	0.005
Percent Solids	2.5

Distribution of Formate Nonsolution Losses

As described earlier, the calculated consumption rate based on the liquid-phase inventory provides information about the solution and nonsolution loss rates. During the formate consumption tests, data were also collected to estimate the individual contributions of coprecipitation and vaporization to the overall nonsolution loss rate.

Formate vaporization (as formic acid) was quantified by analyzing several absorber outlet flue gas samples for formic acid concentration. The flue gas was sampled by an adaptation of EPA Reference Method 6, and the resulting impinger solutions were analyzed for formate ion concentration. Flue gas formic acid concentrations were then calculated from the impinger concentrations, impinger liquid volumes, and the quantity of flue gas sampled.

Formic acid vapor concentrations measured during the first consumption test ranged from 1.0 to 1.6 ppm. The corresponding vaporization loss was calculated for each inventory segment (Inventory 1 to Inventory 2, 2 to 3, etc.). The vaporization loss was based on the calculated hourly flue gas flow rate for Unit 1 and the average formic acid concentration for that time period. The data indicate that the formate lost due to vaporization represented less than 4% of the formate added to the system during the first consumption test.

The gas sampling results from the second consumption test indicated a decrease in vaporization losses at the higher pH set points. Although the absorber liquid-phase formate concentrations increased during this test, the amount lost in the vapor phase decreased. Formic acid concentrations measured in the outlet flue gas steadily decreased from 1.2 to 0.1 ppm over the course of the second test. This corresponded to a decrease in the calculated vaporization losses to less than 1% of the total formate added to the system.

Coprecipitation losses were estimated from the results of solid-phase formate analyses for slurry samples collected during system inventories. Based on previous testing at EPRI's ECTC, it was expected that the balance of the formate nonsolution loss could be accounted for by formate found in the solid phase. However, the solid-phase formate concentrations for these tests were relatively low, and high variability in the solid-phase formate analyses resulted in poor agreement between nonsolution loss rates calculated from the results of liquid-phase and solid-phase analyses.

Results of Slurry Sample Chemical Analyses

Samples of the module recirculating slurry were collected during Inventories 1, 3, and 5, for subsequent liquid- and solid-phase analyses. These results are summarized in Appendix A.

As in the previous DBA consumption test, the concentrations of most chemical species in the liquid phase increased over time. These increases were most likely due to operating the unit in a more closed-loop fashion. The levels of magnesium, chloride, and thiosulfate increased by approximately 50 to 75% over the time period from the formate baseline test until Inventory 6. Sodium levels increased more dramatically, from less than 50 ppm to about 2000 ppm, because formate was added as a sodium salt. Sulfate levels more than doubled during the formate consumption test. However, calculated gypsum relative saturation levels remained low with values ranging from 0.05 to 0.08 in a fairly random fashion over the course of the test period. Most of the observed increase in liquid-phase sulfate concentration also resulted from the change to nearly closed-loop operation.

Samples were analyzed from two of the three operating modules to determine the solids composition during each test. The solid-phase results indicate that the reagent utilization values for the baseline and first formate consumption tests were in the range of 98 to 99%, while the reagent utilization values for the second consumption test dropped to approximately 90% and lower. The high utilization values during the baseline and first consumption tests were similar to those observed during the sodium formate performance series. The lower utilization values during the second consumption test were apparently a result of the higher pH set point, which is expected.

As mentioned above, the solid-phase results indicated that the sulfite oxidation percentages were quite low during the baseline and sodium formate consumption tests, at approximately 3%. These percentages are well below the 5 to 10% expected during normal operation. However, similar low oxidation percentages were observed during the DBA performance tests in August 1991. At the time, the low oxidation percentages were thought to be related to the batch-wise addition of sulfur to the FGD system immediately before those tests. During the sodium formate consumption tests, though, sulfur was added on a daily basis rather than in a monthly spike.

The cause of the low system oxidation percentages remains unclear. They were apparently not a result of the sodium formate addition, as the oxidation percentage was measured at only 3.5% for the baseline test before any sodium formate was added. The system thiosulfate concentrations were within normal levels throughout these tests.

In the past, Hoosier Energy has experienced some solids dewatering problems (e.g., high IST and thickener rake torques) at extremely low oxidations (3% or lower). However, no such problems were encountered during these sodium formate consumption tests.

2.7 Effects of Performance Additives on FGD Solids Properties

Solids samples obtained during the DBA performance tests and the sodium formate consumption test were examined and photographed by scanning electron microscopy to evaluate potential effects of the additives on crystal morphology that could affect dewatering properties.

Figures 2-2 and 2-3 show solids from tests without and with DBA. A definite increase in crystal thickness was observed after DBA addition. Both solids samples depicted in the photographs were collected during periods when the sulfite oxidation was in the range of 2 to 3%. Thus, the observed change in solids crystal shape was not due to differences in sulfite oxidation percentage. Figure 2-4 shows solids from the consumption test with sodium formate

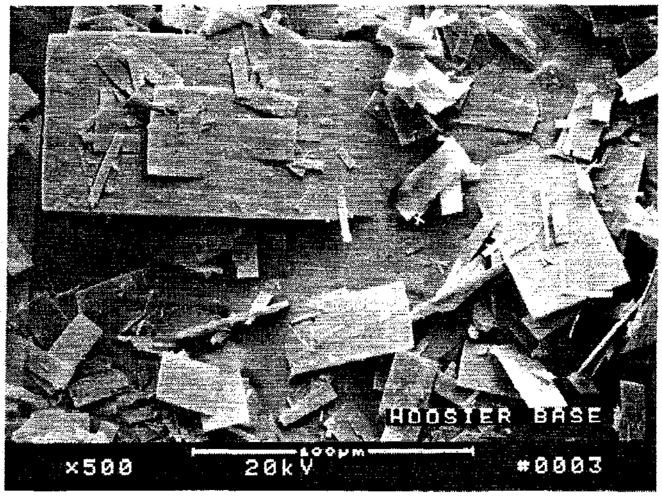

Figure 2-2. Solids Formed in the Absence of Additives (500x)

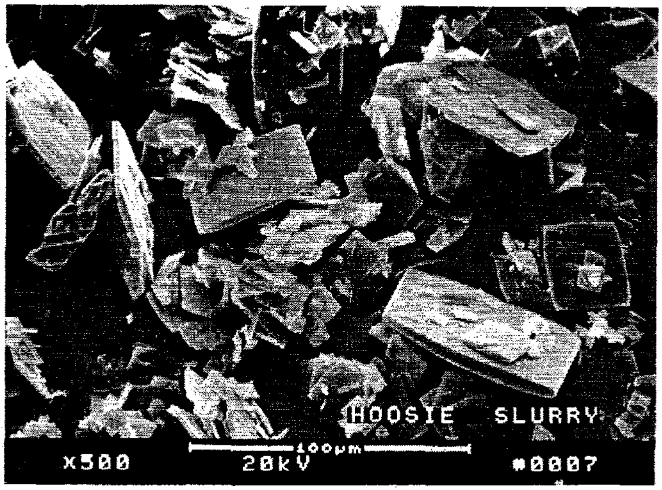

Figure 2-3. Solids Formed in the Presence of DBA (500x)

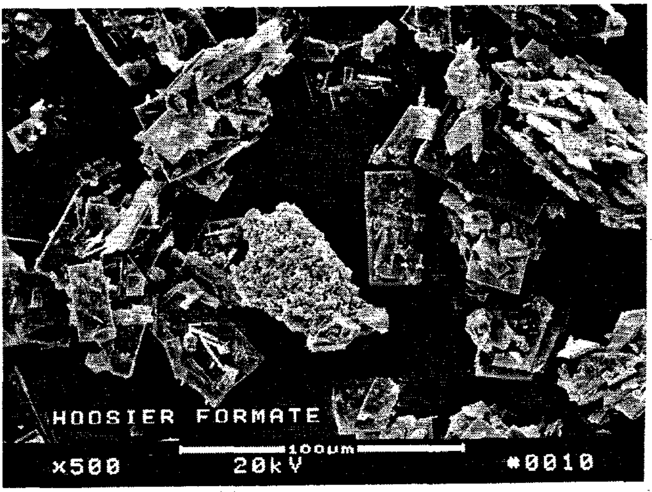

Figure 2-4. Solids Formed in the Presence of Formate (500x)

additive. The change in crystal thickness seen during the DBA tests was not seen during the formate tests.

Settling tests were also performed on samples from the absorber modules during each of the different test series. A baseline sample was tested before each of the additive test series so that the effect of the additives on settling rate could be seen. Results of settling tests, reported as calculated thickener unit area (ft^2/ton/day) required to produce a 30%-solids underflow slurry, are summarized in Table 2-10. Because of the elapsed time between the different test series and differences in FGD system operating conditions, changes in settling rate can only be compared within each of the test series. The results show that DBA additive had little effect on settling rate during the October 1991 performance tests, but appeared to increase the settling rate (reduce the unit area) during the August 1992 consumption test. Formate additive had little or no effect on settling rate in either test series.

Table 2-10

Settling Test Results

Test Series	Sample Location	DBA or Formate Concentration (ppm)	Unit Area (ft^2/ton/day) for 30% Underflow Solids
DBA Performance (10/91)[1]	Module 2B	0	2.7
	Module 2B	600	3.6
	Module 2B	5400	3.3
Formate Performance (12/91)	Module 2B	0	17
	Unit 1Thickener Feed	0	8.3
	Module 2B	840	12
	Module 2B	1460	7.9
DBA Consumption (8/92)	Module 2B	0	82
	Module 2B	0	60
	Module 2B	1070	11
	Module 2D	1990	12
	Module 2B	1270	47
	Module 2D	870	50
Formate Consumption (11/92)	Module 1A	0	9.2
	Module 1A	2180	8.2
	Module 1A	2460	6.8
	Module 1A	2720	9.1
	Module 1A	3080	11
	Module 1A	2890	14
	Module 1B	3080	11
	Module 1D	3460	8
	Module 1A	3410	9.1
	Module 1A	4220	13

[1] These settling tests were done with aged samples. All others were done onsite with fresh samples.

3.0 FGDPRISM SIMULATIONS

The FGD PRocess Integration and Simulation Model (FGDPRISM) is a computer program that simulates the performance of FGD systems. The model was calibrated to Hoosier Energy's Merom Station using performance data from the Tailored Collaboration Project sponsored by EPRI, NRECA, and Hoosier Energy as described in Section 2.

After calibration, model predictions were compared with test results and used to evaluate the use of DBA, sodium formate, and reagent ratio as options to increase the SO_2 removal performance of the system. Also, the effect of operating the FGD system with a closed-loop water balance (no liquid discharges) on the predicted additive consumption rate was investigated. Finally, the model was used to predict the effectiveness of adding more packing to the absorbers; however, there are no full-scale results to verify the modeled closed-loop or added packing predictions.

The results of the model calibration and the process simulations follow. These results form the basis for the economic analysis discussed in Section 4.

3.1 FGDPRISM Calibration

FGDPRISM had been calibrated to the Merom Station FGD system with Version 1.1 as part of the previously mentioned EPRI project. The calibration for the DOE High-Efficiency project utilized a larger database and was performed on the most recent version of FGDPRISM, Version 2.0. The major modifications that affect the Merom Station calibration are more rigorous gas/liquid interface calculations, an improved limestone dissolution methodology, and better additive consumption correlations. More details of the model and calibration results are included in Appendix C.

Figure 3-1 compares the measured SO_2 removals with the predicted results from the calibration cases. For all the tests performed in the normal pH range or higher, the model

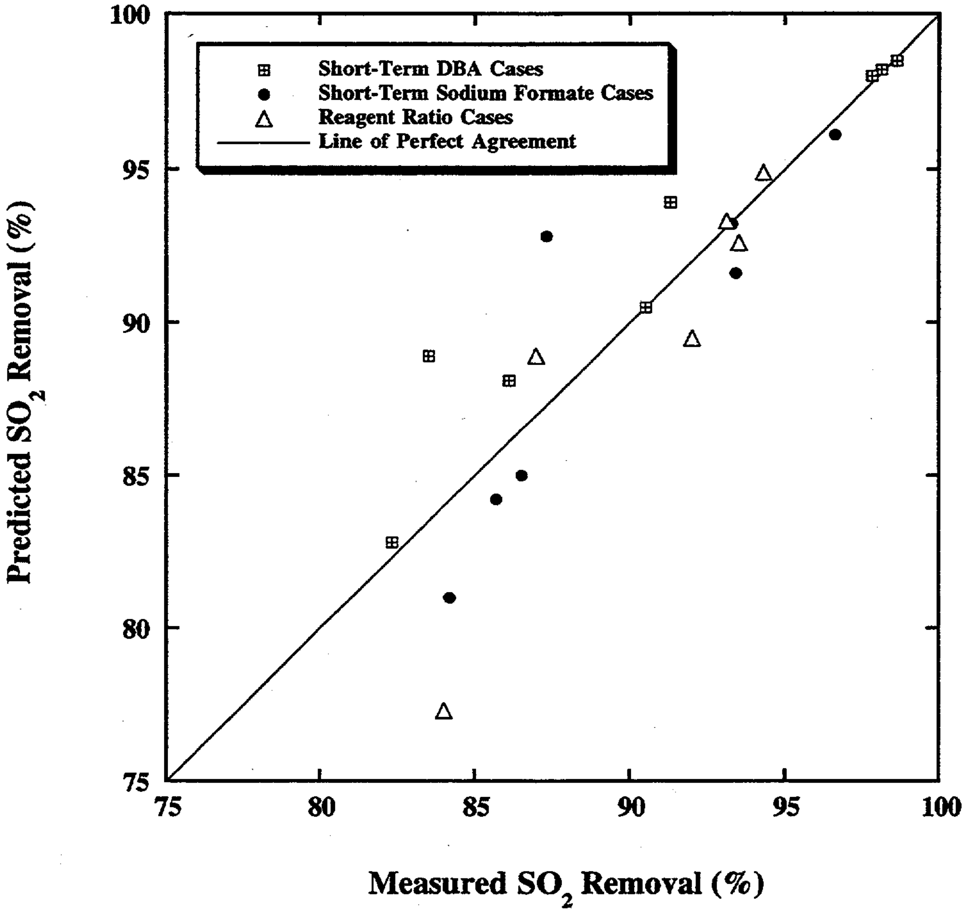

Figure 3-1. Comparison of Measured and FGDPRISM Predicted SO_2 Removal

predicted the effects of additives and additional limestone very well. During the calibration, more emphasis was placed on those cases because the economic evaluation of options to increase SO_2 removal was based on simulations in that pH range.

With FGDPRISM calibrated to the performance data, the ability of the model to estimate additive consumption rates was validated by comparing results of the full-scale DBA and sodium formate consumption tests to the predicted rates. The predicted rate for the DBA consumption test was within about 25% of the actual result; and for the sodium formate tests, the predicted rates were within about ±20%. For the DBA consumption test, the model predicts an average DBA consumption of 7 lb/ton SO_2 removed, compared with the measured value of 9.5 lb DBA/ton of SO_2. For the sodium formate test conditions, the model predicts consumption of 18 to 20 lb formate/ton of SO_2 removed, compared with the measured range of 15 to 23 lb formate/ton of SO_2 removed for the two tests.

The uncertainty in the full-scale sodium formate consumption rate calculations was estimated to be 20%, as discussed in Section 3. Thus, the predicted consumption rates compare well with the observed consumption rates for sodium formate. However, the apparent low bias of the predicted DBA consumption rate should be considered when making economic predictions. This apparent bias may be insignificant if the cost contribution of DBA additive is small in comparison to other upgrade cost components, but could be significant for conditions where the DBA additive cost is a major portion of the upgrade cost estimate.

3.2 Predictive Simulations

After calibration, the model was used to compare the addition of DBA and sodium formate, the use of high pH set points, and the addition of more packing to the absorbers to increase SO_2 removal to 90, 95, 97%, and (if possible) 98%.

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, four-module operation at normal design conditions and with no gas bypass. The FGDPRISM inputs for this case are also included in Appendix C. The absorber slurry pH for the base case was adjusted to match the average measured pH for the performance tests rather than the set point for the pH control system. The pH set point of the control system is typically 5.55 at base conditions, whereas field measurements during the parametric tests indicated values of 5.7 to 5.8 during baseline operation. The field measurements are believed to be more accurate.

In the model base case, a blowdown stream was used to balance the magnesium present in the absorber slurry against the amount entering the system. A continuous blowdown is not actually employed at Merom Station, but periodic discharges to the wastewater treatment are occasionally experienced. If an organic additive were to be used at Merom Station, it would be beneficial to operate the water balance in a closed-loop manner to reduce the additive consumption rate. Thus, each additive (DBA and sodium formate) was evaluated under the current conditions and alternately with a closed-loop water balance.

A recent water balance study at Merom showed that most of the occasional discharge from the FGD system was caused by unsteady-state operation of the dewatering system. Thickener underflow slurry generated during daytime high-load operation was collected in surge tanks. This slurry was then filtered at night when low-load operation caused lower demand for thickener overflow and filtrate. As a result, excess liquor from the dewatering system was discharged. Better coordination of the dewatering system operation has since reduced this discharge so that the closed-loop assumption should more closely represent actual plant operation.

Using the base case conditions, the DBA concentration, formate concentration, reagent ratio, and packing level were independently increased until SO_2 removals reached 90, 95, 97%, and (if possible) 98%. Additive concentrations of 10,000 ppm for DBA and 12,000 ppm for formate ion were set as upper limits in the modeling effort to determine the practical upper SO_2 removal limit for the upgrade options. An upper limit of 1.25 was set for the reagent ratio, based on the current capacity of the limestone preparation system at the Merom Station.

The predicted effects of DBA and sodium formate on system performance are shown in Figure 3-2. As in the actual parametric test results discussed in Section 2, the predictions showed that compared to DBA additive, higher formate concentrations are required to achieve equivalent SO_2 removal levels. Also shown in Figure 3-2 is the rapid increase in SO_2 removal achieved at low additive concentrations and the asymptotic approach to maximum removal at high concentrations.

The SO_2 removal predictions for operation at higher reagent ratios agreed reasonably well with the trends of performance test data. For example, a maximum removal of 93.5% was attained at the highest pH setting (5.98 to 6.12) possible during the parametric tests. In comparison, FGDPRISM predicted an SO_2 removal of 94.2% at approximately the same reagent ratio and pH setting. Thus, increased reagent ratio alone will not be considered as an effective method for achieving high SO_2 removal levels at the Merom Station.

In addition to predicting the effectiveness of DBA and sodium formate, the model was used to predict the effect of eliminating the blowdown stream on additive consumption rate. The consumption rate of DBA was reduced roughly 20% by eliminating the blowdown. The large amount of sodium formate consumed to achieve high SO_2 removals was also reduced by eliminating the blowdown stream; however, considerably greater quantities of sodium formate than DBA were still required to achieve the same level of removal.

Two levels of additional packing were modeled—1 foot and 2 feet. The two additional feet of packing represents the maximum amount that can be practically installed in the absorbers with the current configuration. Additional packing alone was not sufficient to raise the system SO_2 removal performance to 95% or greater. However, additional packing plus DBA was predicted to readily achieve such levels.

Figure 3-3 compares DBA feed rates required to achieve high levels of SO_2 removal with the normal packing level to those predicted for increasing the packing height by 1 and 2 feet (all with liquor blowdown). The figure illustrates that, with additional packing, the

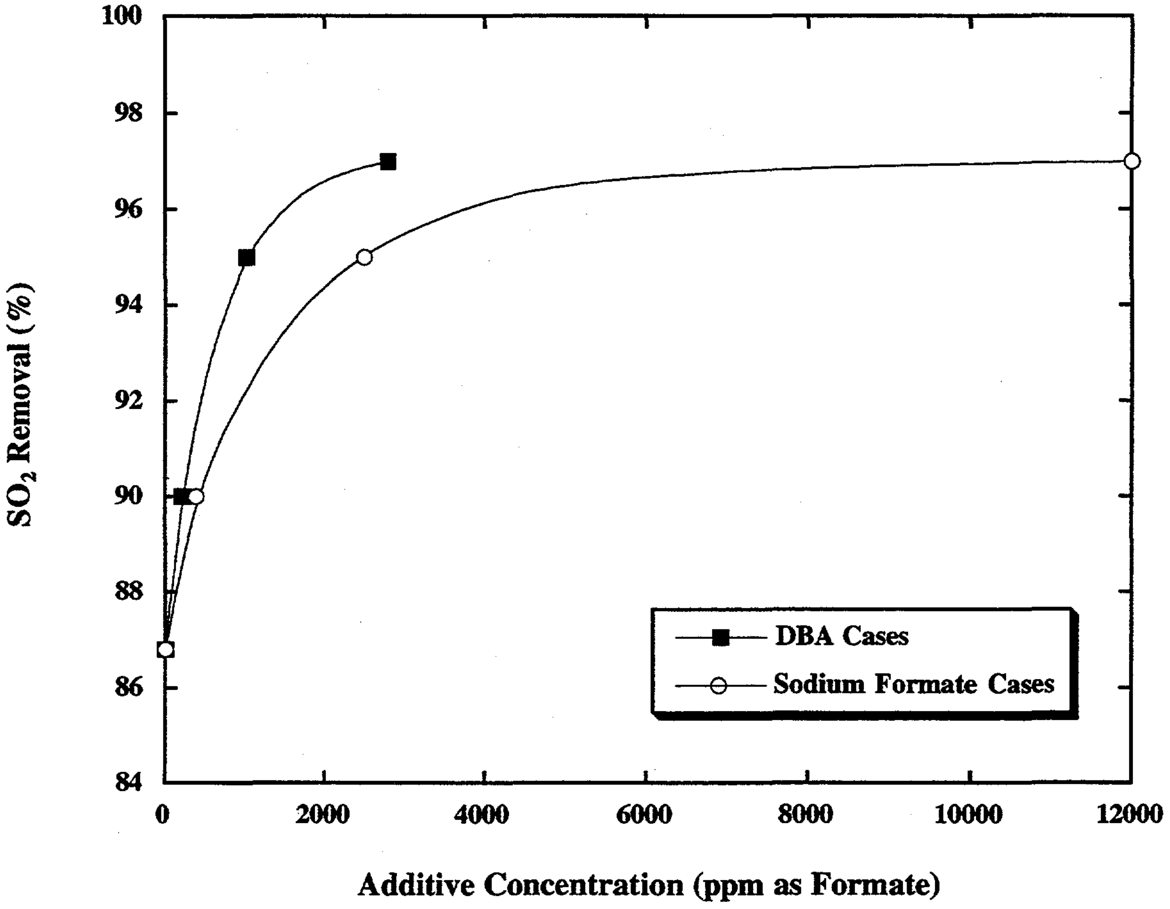

Figure 3-2. FGDPRISM Predictions:
Effect of DBA and Sodium Formate on SO_2 Removal Efficiency

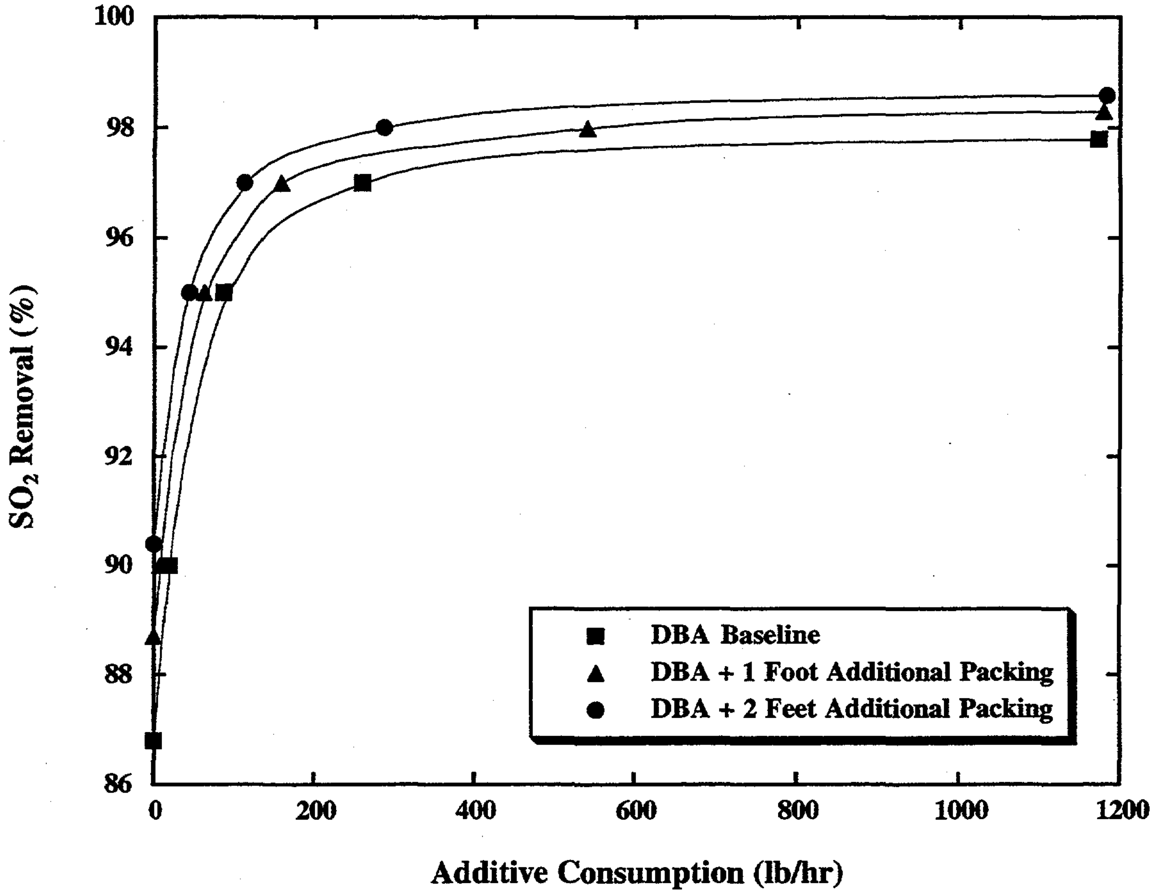

Figure 3-3. FGDPRISM Predictions: Effect of Additional Packing on DBA Requirements for High SO_2 Removal

DBA concentrations required to achieve 95 to 97% SO_2 removal are greatly reduced and that 98% SO_2 removal is possible. However, there are no full-scale results to support the predicted effects of additional packing. Also, there are possible adverse effects of additional packing in the absorbers, such as an increased possibility for scaling or more difficult access for maintenance in the modules that are not reflected in the modeled results.

It is important to note that the percent sulfur in the coal composition for the base case (3.5%) was set to match the FGD system design inlet SO_2 loading of 37,000 lb/hr/unit. By using the design inlet SO_2 loading for the base case, the comparison and economic evaluation of options to improve SO_2 removal will be conservative for more typical conditions where lower inlet SO_2 loadings are encountered. However, these comparisons may be optimistic for cases where a higher sulfur-content coal is being fired.

Changes in coal sulfur content were modeled for the DBA option. Merom Station typically fires a 3.2 to 4.0% sulfur coal. DBA performance results for a 4% sulfur coal were simulated at otherwise base case conditions to compare with the 3.5% sulfur coal cases discussed earlier. The results of the 4.0% sulfur coal cases are not presented here, but are reflected in some of the economic cases in Section 4.

4.0 ECONOMIC EVALUATION

The FGDPRISM SO_2 removal predictions described in Section 3 were used to evaluate the economics of four possible SO_2 removal upgrade options. The options evaluated included using DBA additive, using sodium formate additive, increasing the limestone reagent ratio, and increasing the amount of packing in the absorbers. Results of these economic evaluations are presented in this section.

4.1 Upgrade Options and Cost Basis

Table 4-1 summarizes the upgrade options evaluated for Merom Station and lists the cost components that were considered in the evaluation of each option. All four upgrade options and combinations of some options have been compared with a base case that represents the design operation of the Merom FGD system. By comparing the predictions of the calibrated FGDPRISM to this base case, the options were compared on an equal basis.

The cost components considered in the economic evaluation were consistent for each option. Each option accounted for the cost of additional limestone usage, the additional O&M cost associated with processing more limestone, and the costs for disposal of more FGD solids caused by higher SO_2 removals. Other cost components for some options were the organic additive cost, the additive system capital cost, and the costs associated with additional packing.

Table 4-2 summarizes the values used for the various economic factors described above. All options will result in an increase in limestone consumption in at least equimolar amounts relative to the increase in SO_2 removed. Hoosier Energy provided the cost parameters associated with limestone consumption. The delivered cost of limestone to Merom Station is currently $8.50/ton. The O&M costs ($1.60/ton) were estimated from the annual consumption and budgeted costs for the limestone preparation system.

Table 4-1

Upgrade Options for Merom Station

Option	Cost Components	Cost Basis
1) Add DBA using current system configuration	DBA capital	SWEC capital cost estimate
	DBA additive	Vendor quote
	Additional limestone	Hoosier Energy estimate
	Additional O&M	Hoosier Energy estimate
	Solids disposal	Hoosier Energy estimate
2) Add sodium formate using current system configuration	Sodium formate capital	EBASCO capital cost estimate
	Sodium formate additive	Vendor quote
	Additional limestone	Hoosier Energy estimate
	Additional O&M	Hoosier Energy estimate
	Solids disposal	Hoosier Energy estimate
3) Increase reagent ratio of current system	Additional limestone	Hoosier Energy estimate
	Additional O&M	Hoosier Energy estimate
	Solids disposal	Hoosier Energy estimate
4) Increase packing levels with and without DBA addition	Additional packing quantity	Hoosier Energy packing cost estimate
	DBA capital	EBASCO capital cost estimate
	DBA additive	Vendor quote
	Additional O&M	Hoosier Energy estimate
	Solids disposal	Hoosier Energy estimate

Table 4-2

Economic Factors Used to Compare SO_2 Removal Upgrade Options for Merom Station

Cost Item	Cost or Range	Source
DBA Capital	\$460,000 for a 200-lb/hr system	EBASCO
DBA Additive	\$0.20/lb (dry basis) delivered as a 50% solution	DuPont Monsanto
Sodium Formate Additive	\$0.20/lb (dry basis) delivered as a 39% solution	Perstorp
Limestone	\$8.50/ton delivered	Hoosier Energy
Limestone O&M	\$1.6/ton of limestone	Hoosier Energy
Disposal of Solids	\$5/dry ton	Hoosier Energy
SO_2 Credit	\$150-250/ton of SO_2 removed	Estimate

The capital cost for the additive system at Merom Station was based on an estimate prepared by Ebasco Services, Inc. Ebasco provided a cost estimate for two specific flow rates (150 and 250 lb/hr) and developed a cost equation to size the additive system to other flow rates. For the economic evaluation, the cost of an additive system with a 200 lb/hr design capacity was specified for each option involving DBA or sodium formate. At this flow rate, SO_2 removals greater than 95% could be achieved with either additive, and the size of the additive system was still cost effective. The system is slightly oversized for the use of DBA, but having the flexibility to use either DBA or sodium formate would allow Hoosier Energy the option of switching additives based on the market price. The additive system design is described in Appendix D.

DBA costs are based on quotes from two U.S. vendors of that additive, DuPont and Monsanto, for 50% aqueous DBA delivered to Merom Station. DuPont would ship from a plant in Victoria, Texas, and Monsanto would ship from a plant in Pensacola, Florida. Both companies quoted a delivered price of $0.20/lb DBA (dry basis). Sodium formate costs are based on quotes from two vendors of that additive, Perstorp Polyols and Aqualon. Each vendor provided quotations for the 39% aqueous sodium formate solution delivered to Merom Station for the performance and consumption tests in November 1991 and November 1992. Perstorp's delivered costs were at least $0.10/lb less for each test, so their quotations are used as a basis for these economic calculations.

The cost of sodium formate solution, delivered to the Merom site, has fluctuated from $0.19/lb in 1991 to the most recent price of $0.25/lb (both on a dry basis). These prices reportedly represent the high and low prices for sodium formate over the past several years. For these cost calculations, an estimate of $0.20/lb (dry basis), which is at the lower end of the range, has been used as the delivered cost for sodium formate. By using this value, DBA and sodium formate are being compared on the same price basis.

Each option increases the SO_2 removal of the system, producing a larger quantity of byproduct solids, which increases the cost of disposal. The FGD solids are landfilled on site.

Hoosier Energy estimates that the incremental cost of landfilling additional byproduct solids is \$5/ton of dry solids.

The third option considered to obtain higher SO_2 removals was to increase the limestone reagent ratio from current values. The only additional costs involved are for the increased limestone preparation and use and for increased byproduct solids production. Capital improvements to increase the capacity of the limestone system were not considered in this analysis. The full-scale parametric test results (discussed in Section 2) and the FGDPRISM simulations indicate that SO_2 removal greater than 95% cannot be achieved by raising the reagent ratio alone without also increasing the capacity of the limestone slurry preparation system. However, the reagent ratios required to achieve 95% SO_2 removal (greater than 1.25) would not be recommended because of possible system operating problems at high excess limestone conditions.

The fourth option considered was to add an additional 1 to 2 feet of packing in each absorber module. The cost associated with this option is primarily in the purchase price of the packing. Hoosier Energy supplied this dollar amount, which comes to approximately \$4700 per additional foot of packing in each module. The packing in these absorbers has been lasting approximately seven years, so the purchase price of the packing can be amortized over that period. If the packing is added as a retrofit on top of the existing packing, there would be O&M costs associated with the installation. However, if the additional packing is added during normal packing replacement, the incremental cost would be negligible. This latter assumption has been made for these estimates.

Additional packing can increase the pressure drop across the modules, which, in some circumstances, can result in increased power consumption by the ID fans. However, the open-grid packing used at Merom Station operates at a relatively low pressure drop at normal flue gas velocities. Merom personnel estimate from prior experience that the addition of 1 to 2 feet of packing in each module would increase the pressure drop by only a small amount, such as 0.1 in. H_2O. Furthermore, their ID fans run at two discrete speeds, and flue gas flow is modulated with dampers. If the module pressure drop is increased by 0.1 in. H_2O by the addition of packing, the dampers would be opened slightly to accommodate the small increase. Thus, there would be no impact on fan power consumption if 1 to 2 feet of packing were added.

There could be adverse effects from adding the additional packing to the absorbers that were not considered as part of this economic evaluation. For example, the additional packing depth may increase the potential for scaling within the absorber, resulting in more frequent packing replacement. Also, the additional packing would make personnel access for maintenance in the absorbers more difficult and may increase the costs and/or down time for future maintenance efforts.

4.2 Results

The economic factors described above were included in a spreadsheet calculation that estimates the marginal cost of the additional tons of SO_2 removed at increasing levels of removal efficiency. The cost estimates to achieve 90, 95, 97, and 98% (or the maximum SO_2 removal achievable if less than 98%) were calculated for each option (DBA, sodium formate, reagent ratio, and additional packing). The resulting costs were compared with the cost of normal operation (some gas bypass). Table 4-3 summarizes results of the economic analyses for each option based on one unit at Merom Station.

The cost for normal FGD system operation at Merom Station was based on a system emissions rate of 1.1 lb SO_2/million Btu and a reagent ratio of 1.06. The resulting SO_2 removal estimate of 83% for operation with a small amount of flue gas bypass appears to be consistent with plant data. The first step toward higher SO_2 removal with each option was closing the bypass. The predicted overall SO_2 removal value obtained by closing the bypass (86.8%) is shown for each option.

For Options 1 and 2 (DBA and sodium formate additives), costs were calculated both for the current FGD system mode of operation (with occasional liquor blowdown) and for

Table 4-3
Economic Evaluation of Options to Increase SO_2 Removal Efficiency - (Based on one Unit)

SO_2 Removal	SO_2 Emitted (tons/yr)	Additive Concentration (ppm)	Limestone Reagent Ratio	Change in Total Annual Cost ($/yr)	Marginal Cost ($/ton of SO_2)	Average Cost ($/ton of SO_2)	Net Annual Value ($K) @ $150/ton	Net Annual Value ($K) @ $250/ton
Option 1 - DBA with Occasional Blowdown								
83.0%	18,340	0	1.06	0	0	0	0	0
86.8%	14,240	0	1.06	87,000	21	21	528	938
90%	10,760	220	1.06	298,000	61	39	839	1,597
95%	5,420	1,030	1.06	568,000	51	44	1,370	2,662
97%	3,220	2,800	1.06	927,000	163	61	1,341	2,853
97.8%	2,350	10,000	1.06	2,556,000	1,872	160	-158	1,441
Option 1 - DBA - 0 gpm Blowdown								
83.0%	18,340	0	1.06	0	0	0	0	0
86.8%	14,240	0	1.06	87,000	21	21	528	938
90%	10,780	220	1.06	287,000	58	38	847	1,603
95%	5,360	1,030	1.06	540,000	47	42	1,407	2,705
97%	3,240	2,800	1.06	833,000	138	55	1,432	2,942
97.8%	2,320	10,000	1.06	2,330,000	1,627	145	73	1,675
Option 2 - Sodium Formate with Occasional Blowdown								
83.0%	18,340	0	1.06	0	0	0	0	0
86.8%	14,240	0	1.06	87,000	21	21	528	938
90%	10,790	380	1.06	414,000	95	55	718	1,473
95%	5,400	2,500	1.06	1,062,000	120	82	879	2,173
97%	3,190	12,000	1.06	3,208,000	971	212	-935	580
Option 2 - Sodium Formate - 0 gpm Blowdown								
83.0%	18,340	0	1.06	0	0	0	0	0
86.8%	14,240	0	1.06	87,000	21	21	528	938
90%	10,820	380	1.06	364,000	81	48	764	1,516
95%	5,420	2,500	1.06	799,000	81	62	1,139	2,431
97%	3,230	11,000	1.06	1,944,000	522	129	323	1,834

NOTE: Numerical inconsistencies are because of rounding and FGDPRISM convergence criteria. All rates and values are for one unit.

Table 4-3

(Continued)

SO_2 Removal	SO_2 Emitted (tons/yr)	Additive Concentration (ppm)	Limestone Reagent Ratio	Change in Total Annual Cost ($/yr)	Marginal Cost ($/ton of SO_2)	Average Cost ($/ton of SO_2)	Net Annual Value ($K) @ $150/ton	Net Annual Value ($K) @ $250/ton
Option 3 - Reagent Ratio								
83.0%	18,340	0	1.06	0	0	0	0	0
86.8%	14,240	0	1.06	87,000	21	21	528	938
90%	10,850	0	1.09	232,000	43	31	892	1,641
90.5%	10,240	0	1.10	263,000	51	32	952	1,762
92.6%	8,000	0	1.15	410,000	66	40	1,141	2,175
93.6%	6,880	0	1.20	527,000	105	46	1,192	2,338
94.2%	6,220	0	1.25	631,000	157	52	1,188	2,400
SO_2 Removal	**SO_2 Emitted (tons/yr)**	**Packing Addt'l Height**	**Limestone Reagent Ratio**	**Change in Total Annual Cost ($/yr)**	**Marginal Cost ($/ton of SO_2)**	**Average Cost ($/ton of SO_2)**	**Net Annual Value ($K) @ $150/ton**	**Net Annual Value ($K) @ $250/ton**
Option 4 - Adding Packing with No Additive								
83.0%	18,340	0	1.06	0	0	0	0	0
86.8%	14,240	0	1.06	86,000	21	21	529	939
88.7%	12,220	1.0	1.06	146,000	29	24	772	1,384
90%	10,800	1.8	1.06	189,000	31	25	942	1,696
90.4%	10,400	2.0	1.06	202,000	30	25	989	1,783

Table 4-3

(Continued)

SO_2 Removal	SO_2 Emitted (tons/yr)	Additive Concentration (ppm)	Limestone Reagent Ratio	Change in Total Annual Cost ($/yr)	Marginal Cost ($/ton of SO_2)	Average Cost ($/ton of SO_2)	Net Annual Value ($K) @ $150/ton	Net Annual Value ($K) @ $250/ton
1 Ft. Additional Packing + DBA								
83.0%	18,340	0	1.06	0	0	0	0	0
86.8%	14,240	0	1.06	87,000	21	21	528	938
88.7%	12,220	0	1.06	146,000	29	24	772	1,384
90%	10,810	90	1.06	280,000	95	37	850	1,603
95%	5,400	730	1.06	529,000	46	41	1,412	2,706
97%	3,270	1,800	1.06	754,000	106	50	1,506	3,013
98%	2,140	4,000	1.06	1,455,000	620	90	975	2,595
2 Ft. Additional Packing + DBA								
83.0%	18,340	0	1.06	0	0	0	0	0
90.4%	10,400	0	1.06	202,000	25	25	989	1,784
95%	5,400	505	1.06	500,000	60	39	1,441	2,735
97%	3,230	1,300	1.06	681,000	83	45	1,586	3,097
98%	2,140	3,500	1.06	1,011,000	303	62	1,088	2,925

closed-loop operation (no blowdown). Closed-loop operation decreases the additive solution losses, thus improving additive cost effectiveness. For Option 4 (additional packing), additional levels from 1 to 2 feet were considered. Packing plus DBA was also considered at both the 1-foot and 2-foot additional packing levels, assuming the current open-loop operating scheme. Packing plus sodium formate was not considered, as the DBA options were clearly more cost effective in the previous cases.

Referring to Table 4-3, the first two columns describe the SO_2 removal of the system for each case and the potential to remove more SO_2 from the flue gas. The value in Column 2 represents the tons per year remaining in the flue gas after the removal level in Column 1 is achieved and assuming a 70% annual capacity factor. Merom Station has averaged approximately a 70% capacity factor over the past several years.

Columns 3 and 4 show the additive concentration (or increased packing depth for Option 4) and reagent ratio required to obtain the SO_2 removal efficiency specified in Column 1.

Column 5 is the estimated total annual increase in operating cost at each indicated level of SO_2 removal for each option. This total includes direct costs such as DBA or formate additive, additional reagent, and additional operating and maintenance charges associated with the increased SO_2 removal. Also included are annualized capital charges for the additive feed system and for additional packing when it is used. The cost calculation is shown in more detail in Appendix E.

The calculated marginal cost of additional tons of SO_2 removed (Column 6) for each case is the incremental cost increase when going from case to case within each option (e.g., the cost to go from 86.8 to 90% or from 90 to 95%). The information in this column is useful for determining at what level achieving additional SO_2 removal efficiency is no longer cost effective. The "Average Cost" (Column 7) for each case is another representation of the cost of additional tons of SO_2 removed; however, in this case, the values are relative to the normal FGD operation with gas bypass (e.g., the cost to go from 83 to 90% or from 83 to 95%). The information in this column is useful for comparing the cost effectiveness of the various options in achieving a given level of SO_2 removal.

Columns 8 and 9 show net annual values for additional tons of SO_2 removed, calculated for allowance values of $150/ton and $250/ton, respectively. The net value of each option is referred to the base case. This allows the various options to be compared for cost effectiveness and also helps identify the SO_2 removal level above which each option is no longer cost effective.

Only the additional packing plus DBA cases were predicted to be able to achieve the upper SO_2 removal target for this DOE project of 98%. However, the additional additive costs required to exceed 97% SO_2 removal make achieving this higher target removal less attractive. Also, there are no full-scale test data to confirm the predicted effect of additional packing with DBA.

4.3 Cost Sensitivity

As discussed in Section 2, the predicted DBA consumption rates used in these economic calculations appeared to be biased low by 25%, compared with the results of the full-scale DBA consumption test. However, the possible low bias in the predicted DBA consumption rate has very little effect on the economic evaluation. Increasing the DBA additive consumption by 25% reduces the annual value of each removal level by less than 5% and does not change the economic comparison of the various removal levels. Also, a 25% increase in DBA consumption does not change the significant cost difference between using DBA and sodium formate additives as SO_2 removal upgrade options. For equivalent removal levels, the average costs for additional SO_2 removal with sodium formate additive costs are still 2 to 3 times greater than for DBA.

A sensitivity analysis on the effect of coal sulfur content was also performed as part of the economic analysis. A 3.5% sulfur coal was used in the previous cases to simulate the design inlet SO_2 loading under full-load conditions. The annual average sulfur content ranges from 3.2 to 4.0% at Merom Station, so a 4.0% sulfur coal was used for comparison.

In order to compare the effect of coal sulfur content on a consistent basis, it was necessary to increase the reagent ratio and close the bypass to simulate compliance with the 1.1 lb SO_2/million Btu emission limit for the base case. The reagent ratio had to be increased from 1.06 to 1.098; however, in the cases simulating addition of DBA, the reagent ratio was returned to the normal value of 1.06 in order to realize a savings in limestone cost. Based on past experience, utilities that run continuously with DBA reduce the reagent ratio to take advantage of the increased liquid-phase alkalinity with the DBA.

The effect of coal sulfur content is summarized in Table 4-4. Only Option 1 (adding DBA to the FGD system in the current water balance configuration) was compared, as this was the most economical of the potential upgrades tested at full scale. It was assumed that Merom Station had sufficient limestone handling and solids dewatering capacity to operate with a higher sulfur coal, so no capital costs were considered as part of the economics. If additional costs were necessary, the net annual value of using a higher sulfur coal would decrease. Overall operating costs might be reduced, though, if the higher sulfur coal had a lower delivered cost.

In general, a higher DBA concentration was needed for the 4.0% S cases to achieve equivalent SO_2 removal levels, and the additive consumption rates were higher. Not only do the higher DBA concentrations increase the DBA consumption rates, but the higher sulfur content results in greater filter cake (solution) losses and increased coprecipitation (nonsolution) losses. The higher sulfur cases also incur a larger limestone cost, operation and maintenance cost, and solids disposal cost.

The results in Table 4-4 show that the net annual values for the 3.5% S cases were higher than for the 4% S cases at every SO_2 removal level. Although the higher sulfur coal cases removed more tons of SO_2, the increased costs associated with achieving higher SO_2 removals offset this advantage. These results suggest that, although net annual values would be slightly

Table 4-4

Coal Sulfur Content Effects on the Economic Evaluation

SO_2 Removal	SO_2 Emitted (tons/yr)	Additive Concentration (ppm)	Limestone Reagent Ratio	Change in Total Annual Cost ($/yr)	Marginal Cost ($/ton of SO_2)	Average Cost ($/ton of SO_2)	Net Annual Value ($K) @ $150/ton	Net Annual Value ($K) @ $250/ton
3.5% S Coal DBA								
83.0%	18,340	0	1.06	0	-	-	-	-
86.8%	14,240	0	1.06	87,000	21	21	528	939
90%	10,760	220	1.06	298,000	61	39	839	1,597
95%	5,420	1,030	1.06	568,000	51	44	1,370	2,662
97%	3,220	2,800	1.06	927,000	163	61	1,341	2,853
97.8%	2,350	10,000	1.06	2,557,000	1,872	160	-158	1,441
4.0% S Coal DBA								
85.1%	18,370	0	1.098	0	0	0	0	0
90%	12,370	540	1.06	290,000	48	48	610	1,210
95%	6,170	1,475	1.06	626,000	54	51	1,204	2,424
97%	3,710	3,500	1.06	1,145,000	211	78	1,054	2,520
97.7%	2,850	10,000	1.06	2,798,000	1,922	180	-470	1,082

NOTE: All rates and values are for one unit.

lower, the economic analysis presented in Table 4-3 for the 3.5% sulfur coal should also apply for choosing the most cost-effective upgrade options for a higher sulfur coal.

4.4 Recommended Upgrade Options

To achieve 95% SO_2 removal at the Merom Station, the most cost-effective options appear to be, in order, DBA plus 2 feet of additional packing, DBA plus 1 foot of additional packing, DBA alone in closed-loop operation, and DBA alone in the current, open-loop mode of operation. The options rank in the same order at the 97% SO_2 removal level.

Note that the first three of these options, involving additional packing in the absorbers and operation with a closed-loop water balance, have not been verified with full-scale results. Full-scale testing would be required to confirm that additional packing would indeed be more cost effective than operating at the current level and to confirm the closed-loop predictions. Also, the costs for all four of the most cost-effective options are relatively close, ranging from \$39/ton of SO_2 removed to \$44/ton, respectively, at the 95% SO_2 removal level. All four should be considered very cost-effective approaches to achieving system SO_2 removal levels within the target range of 95% or greater. These values are all considerably lower than the expected market price for SO_2 allowances.

The sodium formate option cases were clearly not as cost effective as the similar DBA options. At the 95% SO_2 removal level, the sodium formate cases had nearly twice the cost per ton of SO_2 removed of the equivalent DBA cases. At the 97% removal level, the difference was roughly a factor of three. This is due to two effects: 1) the performance test results showed that higher sodium formate concentrations were required to achieve a given level of SO_2 removal performance than with DBA; and 2) the consumption test results showed that, when adding sodium formate to adequate levels to equal the SO_2 removal performance with DBA, sodium formate consumption rates were two to three times those of DBA.

In Table 4-3, the net economic value of each option was calculated for SO_2 allowance values of $150/ and $250/ton of SO_2. These values represent the approximate range over which allowances have actually traded. The value will be market driven, so some price fluctuations should be expected. The results show that achieving higher SO_2 removal is extremely attractive ($1.5-3 million per year for each unit) if SO_2 allowances are worth $150-250/ton to the Merom Station.

Over this range, the assumed SO_2 allowance value does not change the ranking of the various upgrade options. Increased packing plus DBA appears to be slightly advantageous over the two DBA options at the current packing level, at both the $150/ton and the $250/ton SO_2 allowance values. Again, this result has not been validated with full-scale tests. Also, the sodium formate cases are clearly less cost effective than the DBA cases, regardless of the allowance value used.

The assumed allowance value does change the most cost effective SO_2 removal level for the option of using DBA with the current packing level and water balance configuration. At the $150/ton SO_2 allowance value, it is slightly more cost effective to operate at a 95% overall SO_2 removal, but at a $250/ton SO_2 credit value. The 97% overall SO_2 removal level has a higher net annual value.

APPENDIX A

Liquid- and Solid-Phase Chemical Analyses

Table A-1

Liquid Analytical Results for DBA Short-Term Testing

Description	1A	Baseline TU	2	3B	4	5	6	7C	8D
Date	10/21/91	10/21/91	10/22/91	10/22/91	10/23/91	10/23/91	10/24/91	10/24/91	10/24/91
Time	14:45	14:00	11:00	15:00	09:00	18:30	08:20	10:45	15:45
pH	5.79	6.46	4.63	5.27	5.72	5.22	5.57	5.24	5.64
Temperature, °C	51.6	38.4	53.0	53.3	53.4	53.7	54.0	53.4	53.5
Ca, mg/L	288	421	1393	1331	528	581	191	275	1272
Mg, mg/L	1303	1151	1300	1457	1474	1586	1276	1204	1141
Na, mg/L	50	45	49	54	58	61	43	41	40
K, mg/L	0	0	0	0	0	0	0	0	0
Cl, mg/L	1437	1324	1412	1486	1690	1754	1273	1240	1095
F, mg/L	0	0	0	0	0	0	0	0	0
CO_3, mg/L	317	290	261	309	377	301	392	352	0
NO_3, mg/L	0	0	0	0	0	0	0	0	0
SO_3, mg/L	1127	355	3027	1508	1241	2234	1580	2076	1084
SO_4, mg/L	231	613	286	290	272	289	330	336	221
S_2O_3, mg/L	2535	2610	2381	2124	2376	2706	1993	1851	1545
DBA, mg/L [1]	0.0	NA	5250	5770	1805	1767	630	837	6040
Charge Imbalance [2]									
Calculated, %	1.0	1.5	8.7	16.4	6.7	4.4	3.5	1.1	13.3
DQO, %	6.2	6.0	5.3	5.6	6.0	5.9	6.2	5.9	5.6
Relative Saturations									
$CaCO_3$	0.027	0.313	0.001	0.020	0.049	0.007	0.015	0.004	0.093
$CaSO_4 \cdot 2H_2O$	0.025	0.102	0.114	0.102	0.046	0.051	0.025	0.038	0.083
$CaSO_3 \cdot 1/2H_2O$	3.86	3.908	5.25	8.74	6.45	5.70	3.02	2.91	1.15

DQO = Data Quality Objective

[1] Results of laboratory analyses (see Table 5-2 for on-site titration results).

[2] Does not include charge from DBA species.

Table A-2

Solids and Slurry Analytical Results for DBA Short-Term Testing

Description	1A	Baseline TU	2	3B	4	5	6	7C	8D
Date	10/21/91	10/21/91	10/22/91	10/22/91	10/23/91	10/23/91	10/24/91	10/24/91	10/24/91
Time	14:45	14:00	11:00	15:00	09:00	18:30	08:20	10:45	15:45
Ca, mm/g	7.10	7.10	7.12	7.04	7.05	7.09	7.24	7.038	7.146
Mg, mm/g	0.03	0.03	0.03	0.0295	0.04	0.03	0.03	0.0281	0.0296
SO_3, mm/g	7.05	7.10	7.17	7.08	7.06	7.15	7.08	7.14	7.09
SO_4, mm/g	0.18	0.20	0.20	0.193	0.19	0.19	0.16	0.155	0.15
CO_3, mm/g	0.22	0.21	0.09	0.1	0.18	0.08	0.12	0.089	0.243
Inerts, wt.%	2.17	2.08	2.50	2.11	2.12	2.44	3.39	2.23	2.24
Solids wt.%	19.84	34.93	17.51	19.16	20.57	21.28	21.65	21.99	22.87
Reagent Utilization, %									
Ca-Independent	97.1	97.2	98.9	98.6	97.6	98.9	98.4	98.8	96.8
SO_4-Independent	96.9	97.1	98.8	98.6	97.5	98.9	98.4	98.7	96.6
CO_3-Independent	101.3	102.3	102.6	102.6	102.3	103.1	99.7	103.2	100.9
Reagent Ratio									
Ca-Independent	1.03	1.03	1.01	1.01	1.02	1.01	1.02	1.01	1.03
SO_4-Independent	1.03	1.03	1.01	1.01	1.03	1.01	1.02	1.01	1.04
CO_3-Independent	0.99	0.98	0.97	0.97	0.98	0.97	1.00	0.97	0.99
Oxidation, %	2.5	2.7	2.2	2.7	2.7	2.6	2.3	2.1	2.1
Solid Solution, wt.%	93.6	94.4	94.8	94.1	93.9	95.0	93.7	94.4	93.6
Gypsum, wt.%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$CaCO_3$, wt.%	2.2	2.1	0.9	1.0	1.8	0.8	1.2	0.9	2.4
Inerts, wt.%	2.2	2.1	2.5	2.1	2.1	2.4	3.4	2.2	2.2
Closures									
Weight, %	-3.4	-2.9	-3.0	-4.0	-3.7	-3.0	-2.1	-3.8	-3.0
Molar, %	-2.1	-2.5	-1.9	-2.1	-2.3	-2.0	-0.6	-2.2	-2.1
DQO, %	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9

DQO = Data Quality Objective

Table A-3

Liquid Analytical Results for Sodium Formate Short-Term Testing

Description	1A	1A Thick	2	3B	4	5	6	7C
Date	12/09/91	12/09/91	12/10/91	12/10/91	12/11/91	12/11/91	12/12/91	12/12/91
Time	15:12	16:30	10:40	14:00	12:00	14:50	10:30	13:45
pH	5.73	6.41	5.64	5.26	5.60	5.21	5.69	5.11
Temperature, °C	52.5	40.9	51.9	49.9	51.4	51.5	52.3	52.0
Ca, mg/L	143	147	149	264	158	244	150	330
Mg, mg/L	1795	1777	1665	1711	1560	1531	1504	1468
Na, mg/L	39	36	472	557	931	1002	1760	1763
K, mg/L	0	0	0	0	0	0	0	0
Cl, mg/L	1321	1254	1347	1374	1204	1249	1227	1250
COOH, mg/L	2	<0.58	897	996	1733	1856	3598	3529
CO_3, mg/L	402	650	382	326	382	333	405	325
NO_3, mg/L	0	0	0	0	0	0	0	0
SO_3, mg/L	2852	913	2770	4003	2868	4249	3015	4395
SO_4, mg/L	808	1560	688	583	718	624	694	745
S_2O_3, mg/L	2617	2547	2298	2296	1960	1795	1642	1541
Charge Imbalance								
Calculated, %	-0.3	1.1	-0.3	-0.5	0.9	-2.7	-1.7	-4.4
DQO, %	6.1	6.2	5.3	5.0	4.8	4.4	4.5	4.2
Relative Saturations								
$CaCO_3$	0.016	0.177	0.011	0.003	0.010	0.003	0.014	0.002
$CaSO_4 \cdot 2H_2O$	0.032	0.065	0.029	0.044	0.034	0.047	0.029	0.073
$CaSO_3 \cdot 1/2H_2O$	3.17	2.78	3.57	4.49	3.64	4.11	3.92	4.51

DQO = Data Quality Objective

Table A-4

Solids and Slurry Analytical Results for Sodium Formate Short-Term Testing

Description	1A	1A Thick	2	3B	4	5	6	7C	Filter Cake	Filter Cake
Date	12/09/91	12/09/91	12/10/91	12/10/91	12/11/91	12/11/91	12/12/91	12/12/91	12/09/91	12/12/91
Time	15:12	16:30	10:40	14:00	12:00	14:50	10:30	13:45	17:11	13:10
Ca, mm/g	7.29	7.33	7.19	7.35	7.33	7.40	7.28	7.21	7.28	7.30
Mg, mm/g	0.07	0.05	0.06	0.07	0.06	0.06	0.04	0.04	0.06	0.05
SO_3, mm/g	6.87	6.89	6.93	7.08	7.04	7.11	7.01	7.08	6.58	6.91
SO_4, mm/g	0.47	0.60	0.42	0.43	0.40	0.38	0.42	0.39	0.67	0.55
CO_3, mm/g	0.24	0.12	0.20	0.07	0.14	0.06	0.12	0.06	0.17	0.10
COOH, mm/g	0.003	<0.0018	0.005	0.008	0.012	0.012	0.018	0.026	<0.0018	<0.0018
Inerts, wt.%	2.47	2.24	2.39	2.44	2.48	3.68	2.45	2.33	2.42	2.44
Solids wt.%	15.27	36.22	15.64	17.33	17.08	17.57	25.61	15.50	69.12	74.45
Reagent Utilization, %										
Ca-Independent	96.9	96.4	97.3	99.1	98.1	99.2	98.5	99.2	97.7	98.7
SO_4-Independent	96.8	98.3	97.2	99.0	98.1	99.2	98.4	99.2	97.7	98.7
CO_3-Independent	99.9	101.4	101.4	101.2	100.5	100.6	101.4	103.0	98.8	101.4
Reagent Ratio										
Ca-Independent	1.03	1.02	1.03	1.01	1.02	1.01	1.02	1.01	1.02	1.01
SO_4-Independent	1.03	1.02	1.03	1.01	1.02	1.01	1.02	1.01	1.02	1.01
CO_3-Independent	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.97	1.01	0.99
Oxidation, %	6.4	8.0	5.7	5.7	5.3	5.1	5.7	5.2	9.3	7.3
Solid Solution, wt.%	95.5	97.5	95.5	97.5	96.5	97.3	96.6	97.0	94.7	97.0
Gypsum, wt.%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$CaCO_3$, wt.%	2.4	1.2	2.0	0.7	1.4	0.6	1.2	0.6	1.7	1.0
Inerts, wt.%	2.5	2.2	2.4	2.4	2.5	2.7	2.5	2.3	2.4	2.4
Closures										
Weight, %	-0.7	0.0	-1.4	-0.1	-0.4	0.1	-0.8	-1.2	-1.6	-0.4
Molar, %	-1.5	-1.5	-2.1	-1.1	-1.2	-0.7	-1.5	-1.9	-0.5	-1.4
DQO, %	6.7	6.7	6.8	6.8	6.8	6.8	6.8	6.8	6.7	6.8

DQO = Data Quality Objective

Table A-5

Liquid Analytical Results for Reagent Ratio Performance Tests

Description	2B-1	2D-1	2B-2	2B-3	2B-4	2B-5	2B-6
Date	08/03/92	08/03/92	08/04/92	08/04/92	08/06/92	08/07/92	08/08/92
Time	14:17	14:45	12:13	17:30	10:44	14:48	11:47
pH	5.82	5.82	5.93	6.02	5.48	5.61	5.59
Temperature, °C	50.8	52.0	53.1	52.4	53.5	54.0	52.0
Ca, mg/L	243	221	246	140	202	198	271
Mg, mg/L	1223	1220	1240	1294	1208	1294	1199
Na, mg/L	39	40	42	44	41	49	47
Cl, mg/L	1209	1201	1230	1289	1249	1407	1338
CO_3, mg/L	373	361	384	456	367	436	422
SO_3, mg/L	1283	1082	1230	1117	1676	1437	1266
SO_4, mg/L	1588	1327	1253	1013	1217	744	599
S_2O_3, mg/L	1378	1355	1456	1590	1411	1602	1378
DBA, mg/L	0	0	0	0	0	650	1015
Charge Imbalance							
Calculated, %	2.0	5.5	5.1	5.1	1.5	6.6	10.1
DQO, %	5.7	5.8	5.8	6.1	5.7	6.0	6.0
Relative Saturations							
$CaCO_3$	0.04	0.04	0.06	0.07	0.01	0.02	0.03
$CaSO_4 \cdot 2H_2O$	0.15	0.12	0.12	0.05	0.10	0.06	0.07
$CaSO_3 \cdot 1/2H_2O$	4.27	3.63	4.99	3.14	2.69	3.00	3.73

DQO = Data Quality Objective

Table A-6

Solids and Slurry Analytical Results for Reagent Ratio Performance Tests

Description	2B-1	2D-1	Filter Cake-1	2B-2	2B-3	2B-4	2B-5	2B-6
Date	08/03/92	08/03/92	08/03/92	08/04/92	08/04/92	08/06/92	08/07/92	08/08/92
Time	14:17	14:45		12:13	17:30	10:44	14:48	11:47
Ca, mm/g	7.88	7.85	7.36	7.42	7.83	7.35	7.64	7.65
SO_3, mm/g	6.50	6.59	6.69	6.25	5.84	6.55	6.64	6.64
SO_4, mm/g	0.53	0.48	0.42	0.38	0.33	0.51	0.36	0.32
CO_3, mm/g	0.47	0.37	0.17	0.84	1.43	0.18	0.53	0.60
Inerts, wt.%	2.64	2.34	2.31	3.56	3.62	5.30	3.26	2.97
Solids wt.%	7.38	7.71	69.59	10.35	12.44	8.01	12.28	12.49
Reagent Utilization, %								
Ca-Independent	93.7	95.0	97.7	88.8	81.2	97.5	93.0	92.0
SO_4-Independent	94.0	95.3	97.7	88.7	81.7	97.5	93.1	92.1
CO_3-Independent	89.2	90.1	96.9	89.3	78.8	96.0	91.6	91.0
Reagent Ratio								
Ca-Independent	1.07	1.05	1.02	1.13	1.23	1.03	1.08	1.09
SO_4-Independent	1.06	1.05	1.02	1.13	1.22	1.03	1.07	1.09
CO_3-Independent	1.12	1.11	1.03	1.12	1.27	1.04	1.09	1.10
Oxidation, %	7.6	6.8	6.2	5.7	5.3	7.2	5.1	4.6
Solid Solution, wt.%	91.5	92.0	92.8	86.1	80.1	91.9	90.8	90.3
Gypsum, wt.%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$CaCO_3$, wt.%	4.7	3.7	1.7	8.4	14.3	1.8	5.3	6.0
Inerts, wt.%	2.6	2.3	2.3	3.6	3.6	5.3	3.3	3.0
Closures								
Weight, %	0.4	-0.3	-3.0	-2.1	-1.1	-0.5	-0.2	-0.4
Molar, %	2.5	2.7	0.4	-0.3	1.5	0.7	0.7	0.6
DQO, %	6.7	6.7	6.8	6.5	6.4	6.8	6.7	6.7

DQO = Data Quality Objective

Table A-7

Liquid Chemistry of Module B During DBA Consumption Test

	2B-I1	2B-I3	2B-I5
pH	5.40	5.50	5.67
Temperature, °C	54.5	53.3	54.0
Ca, mg/L	263	386	316
Mg, mg/L	1428	1979	2097
Na, mg/L	49	56	55
Cl, mg/L	1578	2212	2104
CO_3, mg/L	326	284	237
SO_3, mg/L	1885	1960	1802
SO_4, mg/L	842	1341	1564
DBA, mg/L	1030	1551	1157
S_2O_3, mg/L	1512	1915	1960
Charge Imbalance			
Calculated, %	7.4	9.8	11.3
DQO, %	5.0	5.1	5.3
Relative Saturation			
Gypsum	0.08	0.14	0.12
$CaSO_3 \cdot 0.5H_2O$	3.39	5.02	4.92
$CaCO_3$	0.01	0.01	0.02

DQO = Data Quality Objective

Table A-8

Solids and Slurry Chemistry of Module B During DBA Consumption Test

	2B-I1	2B-I3	2B-I5
Date	08/10/92	08/17/92	08/23/92
Time	14:25	13:07	13:33
Ca, mm/g	7.38	7.67	7.85
Mg, mm/g			
SO_3, mm/g	6.93	6.63	6.75
SO_4, mm/g	0.316	0.39	0.39
CO_3, mm/g	0.133	0.13	0.18
Solids, wt.%	10.89	7.08	6.72
pH	5.44	5.46	5.67
Temperature, °C	54.5	52.8	54
Reagent Utilization, %			
Ca-Independent	98.2	98.1	97.6
SO_4-Independent	98.2	98.3	97.8
CO_3-Independent	98.2	91.5	91.0
Reagent Ratio			
Ca-Independent	1.02	1.02	1.02
SO_4-Independent	1.02	1.02	1.02
CO_3-Independent	1.02	1.09	1.10
Oxidation, %	4.4	5.5	5.4
Solid Solution, wt.%	94.0	91.2	92.7
Gypsum, wt.%	0.0	0.0	0.0
$CaCO_3$, wt.%	1.3	1.3	1.8
Inerts, wt.%	0.0	3.4	2.4
Ca, mg/g	295	307	314
Mg, mg/g	0	0	0
SO_3, mg/g	554	530	540
SO_4, mg/g	30	37	37
CO_3, mg/g	8	8	11
Closures			
Weight, %	-4.7	-2.1	-1.0
Molar, %	0.0	3.5	3.5
DQO, %	6.9	6.8	6.8

DQO = Data Quality Objective

Table A-9

Results of Liquid-Phase Analyses for Module A During Formate Consumption Test

	1-1A	I1-1A	I2-1A	I3-1A	I4-1A	I5-1A	I6-1A
pH	5.69	5.88	5.61	5.73	6.07	6.08	5.99
Temperature, °C	53.40	53.50	52.1	51.80	52.70	53.20	52.00
Ca, mg/L	188	149	259	148	120	129	165
Mg, mg/L	1089	1218	1148	1329	1328	1529	1620
Na, mg/L	46	1129	1323	1573	1727	1820	2202
Cl, mg/L	1258	1336	1447	1758	1864	1933	2181
F, mg/L	51	0	0	70	0	0	0
CO_3, mg/L	431	386	296	378	393	412	364
SO_3, mg/L	1744	1769	2507	2845	2121	1809	1761
SO_4, mg/L	644	872	872	1161	1258	1341	1497
$COOH^-$, mg/L	2.3	2228	2439	2912	2768	3024	3713
S_2O_3, mg/L	1211	1370	1484	1580	1561	1905	1784
Charge Imbalance							
Calculated, %	2.0	0.7	-2.3	-5.9	-2.2	0.2	1.1
DQO, %	5.7	5.1	4.8	4.8	4.9	5.1	5.1
Relative Saturation							
Gypsum	0.05	0.05	0.08	0.05	0.04	0.05	0.06
$CaSO_3 \cdot 0.5H_2O$	4.1	3.7	5.6	3.9	3.8	3.4	3.6
$CaCO_3$	0.03	0.03	0.01	0.01	0.04	0.05	0.04

DQO = Data Quality Objective

Table A-10

Results of Solids and Slurry Analyses for Module A During Formate Consumption Test

	1-1A	I1-1A	I1-1D	I2-1A	I2-1D	I3-1A	I3-1D
Date	11/11/92	11/12/92	11/12/92	11/14/92	11/14/92	11/18/92	11/18/92
Time	11:50	16:36	17:20		16:20	11:30	10:35
Ca, mm/g	8.29	8.10	7.44	8.15	7.33	7.98	7.32
SO_3, mm/g	6.96	7.08	6.81	7.12	7.03	7.14	6.96
SO_4, mm/g	0.26	0.24	0.21	0.23	0.21	0.25	0.22
CO_3, mm/g	0.15	0.15	0.16	0.05	0.05	0.05	0.19
Solids, wt.%	14.6	13.6	14.1	15.0	15.1	11.4	8.7
pH	5.69	5.88	5.90	5.61	5.67	5.73	5.88
Temperature, °C	53.4	35.5	52.6	52.1	52.0	51.8	51.3
Reagent Utilization, %							
Ca-Independent	98.0	98.0	97.8	99.4	99.3	99.4	97.4
SO_4-Independent	98.2	98.2	97.9	99.4	99.3	99.4	97.4
Reagent Ratio							
Ca-Independent	1.02	1.02	1.02	1.01	1.01	1.01	1.03
SO_4-Independent	1.02	1.02	1.02	1.01	1.01	1.01	1.03
Oxidation, %	3.5	3.3	3.0	3.1	2.9	3.4	3.1
Solid Solution, wt.%	93.4	94.9	90.9	95.1	93.7	95.7	93.0
Gypsum, wt.%	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$CaCO_3$, wt.%	1.5	1.5	1.6	0.5	0.5	0.5	1.9
Inerts, wt.%	2.0	2.3	2.3	2.2	1.9	1.6	2.1
Closures							
Weight, %	0.7	1.2	-4.1	0.8	-3.6	-0.1	-3.1
Molar, %	5.9	4.0	2.0	4.9	0.5	3.5	-0.1
DQO, %	6.9	6.9	6.9	7.0	6.9	6.9	6.9

Table A-10

(Continued)

	I4-1A	I4-1D	I5-1A	I5-1D	I6-1A	I6-1D
Date	11/19/92	11/19/92	11/21/92	11/21/92	11/23/92	11/23/92
Time	18:48	19:40	13:13	14:10	17:23	16:55
Ca, mm/g	8.14	7.52	7.80	7.40	8.22	7.62
SO_3, mm/g	6.86	6.67	6.70	5.98	6.70	6.38
SO_4, mm/g	0.23	0.20	0.20	0.19	0.22	0.20
CO_3, mm/g	0.29	0.71	0.72	1.25	0.71	1.00
Solids, wt.%	14.4	15.7	16.3	17.8	10.5	10.5
pH	6.07	6.12	6.08	6.10	5.99	6.02
Temperature, °C	52.7	52.4	53.2	53.0	52.0	51.7
Reagent Utilization, %						
Ca-Independent	96.0	90.6	90.5	83.1	90.7	86.8
SO_4-Independent	96.4	90.6	90.7	83.2	91.4	87.0
Reagent Ratio						
Ca-Independent	1.04	1.10	1.10	1.20	1.10	1.15
SO_4-Independent	1.04	1.10	1.10	1.20	1.09	1.15
Oxidation, %	3.2	2.9	2.9	3.0	3.2	3.1
Solid Solution, wt.%	91.7	88.9	89.3	79.8	89.6	85.2
Gypsum, wt.%	0.0	0.0	0.0	0.0	0.0	0.0
$CaCO_3$, wt.%	2.9	7.1	7.2	12.5	7.1	10.0
Inerts, wt.%	2.5	2.1	1.8	2.2	1.7	2.3
Closures						
Weight, %	0.3	-2.0	-1.0	-5.5	0.7	-2.3
Molar, %	4.9	-0.1	1.2	0.2	3.8	0.6
DQO, %	6.9	6.7	6.7	6.5	6.7	6.6

DQO = Data Quality Objective

APPENDIX B

Additional Process Data

Table B-1

Summary of Process Data for DBA Testing

Test Date Time	1A 10/21 1420	2 10/22 1100	3B 10/22 1455	4 10/23 0900	5 10/23 1330	6 10/24 0800	7C 10/24 1030	8D 10/24 1530
Barometric Pressure (in. Hg)	29.56	29.63	29.58	29.68	29.62	29.67	29.67	29.60
Unit Load (MW)[1]	396	463	459	459	459	499	499	499
DBA Concentration (ppm), Titration[2]		4780	5410	1640	1510	605		6320
DBA Concentration (ppm), Lab Result[2]		5250	5770	1805	1767	630	837	6040
Inlet Gas (Unit 2)								
SO_2 Concentration (ppm), Dry Basis	2500	2500	2550	2820	2875	2950	2965	2825
Temperature (°F)	295	315	313	309	310	310	309	315
Pressure (in. H_2O)	3.2	5.87.	5.48	5.05	5.30	6.50	6.40	6.30
Outlet Gas (Unit 2)								
SO_2 Concentration (ppm), Wet Basis	252	418	211	233	250	327	315	233
O_2 Concentration (%)	6.6	6.0	6.2	6.3	5.6	6.2	6.5	5.7
Bypass Exit Gas O_2 Concentration (%)	6.5	6.6	6.6	6.7	6.73	6.9	7.0	6.87
Module 2B Readings								
pH (On-line)	5.47	5.54	5.17	5.54	5.03	5.41	5.11	5.51
pH (Measured)	5.69	4.63	5.27	5.65	5.22	5.57	5.20	5.62
Bleed Flow (gpm)	208	207	210	206	212	203	192	210
Limestone Slurry Rate (gpm)	62.6	65.8	76.1	87.0	66	89	67	105
Thickener Return Flow (gpm)			240	159	228	185	325	?
Gas Flow Rate (DSCFM x 10^3)	246	279	269	280	262	297	297	305
SO_2 Concentration								
Reich Test (Dry)	348	413	49	63	250	280	524	38.5
Portable Analyzer (Wet)		420	43-70	50-55	125	208	560	23

[1] Four modules were in operation for all tests.

[2] Titration values were measured on site; Lab DBA results were performed off site using preserved samples.

Table B-2

Summary of Process Data for Sodium Formate Testing

Test	1A	2	3B	4	5	6	7C
Date (1991)	12/09	12/10	12/10	12/11	12/11	12/12	12/12
Time	1500	1040	1410	1150	1440	1025	1335
Barometric Pressure (in. Hg)	29.61	29.78	29.74	29.75	29.75	29.47	29.38
Unit Load (MW) - 3 modules	375	379	379	379	379	378	379
Formate Concentration (ppm)							
Titration (On Site)	244	688	839	1456	1567	2806	2854
Lab Result	2	897	996	1733	1856	3598	3529
Inlet Gas (Unit 2)							
SO_2 Concen. (ppm, dry basis)	3500	3100	3175	2870	3150	2980	2970
Temperature (°F)	305	308	311	303	306	300	305
Pressure (in. H_2O)	4.4	4.9	5.0	5.0	5.05	4.3	4.3
Outlet Gas (Unit 2)							
SO_2 Concen. (ppm, wet basis)	397	264	386	274	500	347	395
O_2 Concentration (%)	6.1	6.2	6.2	6.1	6.0	6.2	6.6
Bypass Exit Gas O_2 Conc. (%)	6.4	6.7	6.6	6.4	6.7	6.5	6.6
Module 2B Readings							
pH (on-line)	5.41	5.55	5.16	5.53	5.07	5.54	5.10
pH (measured)	5.71	5.64	5.26	5.59	5.21	5.70	5.10
Bleed Flow (gpm)	184	184	184	184	183	183	104
Limestone Slurry Rate (gpm)	103	84.5	82	82	89	91	62
Thickener Return Flow (gpm)	---	21.7	362	20.3	26.4	21.2	243.7
Gas Flow Rate (dscfm x 10^3)	334	321.1	344.7	324.6	325.2	299	305.8
SO_2 Concentration							
Reich Test (dry)	472.6	206	503	191	452	102	376
Portable Analyzer (wet)				115	324	82	280

APPENDIX C

Details of FGDPRISM Model Calibration and Predictions

The calibration of FGDPRISM to Hoosier Energy's Merom Station utilized all of the performance test data presented in Section 2. By combining the test data from the parametric testing of each system-enhancing agent (DBA, sodium formate, and additional limestone), the model is able to compare the effects of each on a common base case. As described above, the calibration involved adjusting the limestone reaction rate constant and surface area factor, and the gas- and liquid-film thicknesses to achieve the best overall fit of limestone utilization, SO_2 removal, and reaction tank pH for these cases.

The calibration began with the determination of the calibration parameters for the reagent ratio performance tests. These tests were used as the basis of the calibration because the performance of the entire unit was measured, not just one module as with the DBA and sodium formate performance test results, and the parameters were refined. It was necessary to perform the calibration in two parts due to the large amount of data.

The scrubber chemistry for each case was approximated by adjusting the coal chloride content, the reactive magnesium content in the limestone, the scrubber sulfite oxidation percentage, solid solution precipitation rate constant, and the limestone reagent ratio. For the tests performed on one module, the gas flow was based on the unit load and the number of modules in service.

The final calibration parameters were:

- Gas-film thicknesses of 110 microns;
- Liquid-film thickness set at 0.2% of the droplet diameter;
- Reagent surface area factor of 1.00;
- A limestone reaction rate constant of 3×10^{-6}; and
- Solid solution precipitation rate constant of 5×10^{-7}.

The same gas- and liquid-film thicknesses were used in the packed and droplet rain sections of the absorber.

Table C-1 compares the calibration results with the measured SO_2 removal, utilization, and pH for all of the performance test cases. The model was least accurate in predicting the performance of the FGD system at low reagent ratios (low pH range). For the reagent ratio tests, the simulated results were close to the measured results in all tests except at the lowest reagent ratio (Test #4). The model underestimated the effect of reagent ratio in this case. However, in the DBA cases, the model slightly overpredicted the effect of DBA at a low reagent ratio. For the sodium formate cases, the additive effect at a low reagent ratio is overpredicted for the highest concentration and underpredicted for the lower concentration. The difficulty in predicting the low pH (low reagent ratio) cases could be due to inaccuracies in measuring the small amount of excess $CaCO_3$ in the solids or due to model sensitivity at reagent ratios close to 1.0. Regardless, the model performs adequately in this pH range--the model overpredicts and underpredicts some test points in this operating range (low reagent ratio), but is not biased in either direction.

After calibration, the model was used to compare the addition of DBA and sodium formate, the use of high pH set points, and the addition of more packing to the absorbers to increase SO_2 removal to 90%, 95%, 97%, and (if possible) 98%. The economic impacts of a closed water balance on the DBA and sodium formate consumption rates were also studied by simulating the system with no blowdown (closed-loop water balance).

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, four-module operation at normal design conditions and with no gas bypass. The FGDPRISM inputs for this case are shown in Table C-2. The inputs are based on current operating conditions, test measurements, and design operating parameters.

Table C-1

Comparison of Observed and Predicted Performance for the FGDPRISM Calibration

Test	Observed			Predicted		
	SO_2 Removal (%)	Reagent Utilization (%)	pH	SO_2 Removal (%)	Reagent Utilization (%)	pH
DBA Parametric Tests						
1	86.1	97.1	5.69	88.1	98.8	5.67
2	83.5	98.9	4.63	88.9	99.6	4.59
3	98.1	98.6	5.27	98.6	98.2	5.27
4	97.8	97.6	5.65	98.0	97.0	5.67
5	91.3	98.9	5.22	93.9	99.4	5.17
6	90.5	98.4	5.57	90.5	98.3	5.53
7	82.3	98.8	5.2	82.8	99.4	5.15
8	98.6	96.8	5.62	98.5	95.1	5.62
Sodium Formate Parametric Tests						
1	86.5	96.9	5.73	85.0	93.9	5.72
2	93.4	97.3	5.64	91.6	95.7	5.65
3	84.2	99.1	5.26	81.0	98.9	5.30
4	93.3	98.1	5.6	93.2	97.3	5.62
5	85.7	99.2	5.21	84.2	99.0	5.24
6	96.6	98.5	5.69	96.1	95.1	5.71
7	87.3	99.2	5.11	92.8	99.3	5.01
Reagent Ratio Parametric Tests						
1	87.0	93.7	5.82	88.9	90.3	5.71
2	92.0	88.8	5.93	89.5	86.5	5.95
3	93.5	81.2	6.1	93.3	80.2	6.06
4	84.0	97.5	5.48	77.3	96.0	5.53
5	93.5	93.0	5.61	92.6	93.9	5.67
6	94.5	92.0	5.65	94.9	96.0	5.57

Table C-2

FGDPRISM Inputs for the General System Case

System Variables	Actual Values	Reference
General Unit Parameters		
Coal High Heating Value (Btu/lb)	10,800	Calibration
Turbine Output (MWe)	535	
Unit Heat Rate (Btu/kWh)	10,160	Calibration
Flue Gas Temperature (°F)	280	Current operation
Flue Gas Oxygen Content (%)	6.0	Design operation
Flue Gas Dust Content (gr/acf)	0.025	Design operation
Number of Absorber Modules	4	Design operation
Coal Composition		
Carbon	0.5833	Test results
Hydrogen	0.0380	Test results
Nitrogen	0.0086	Test results
Sulfur	0.0350	Test results
Oxygen	0.0948	Test results
Chlorine	0.0002	Test results
Moisture	0.1403	Test results
Ash	0.0998	Test results
Additive Parameters		
$S_2O_3^=$ Concentration (mg/L)	1,500	Current operation
Additive Concentration	Test variable	
System Parameters		
SO_2 Removal (%)	88.0	Initial guess
Oxidation (%)	5.0	Current operation
Reagent Ratio	1.06	
Blowdown Flow (gpm)	10.0	Test results
Recycle Solids Content (%)	15.0	Current operation
Scrubber Feed Flow Rate (gpm)	31,200	Calibration
Reaction Tank Parameters		
PCO_2 (initial guess)	0.21	Calibration
$CaCO_3$ RS (initial guess)	0.02	Calibration
$CaSO_3$ RS (initial guess)	4.0	Calibration
$CaSO_4$ RS (initial guess)	0.96	Calibration

The predicted additive concentrations, additive consumption rates, and limestone consumption rates associated with each method of increasing the SO_2 removal to 90%, 95%, 97%, and 98% (or the maximum removals within the constraints listed above) are presented in Table C-3. As in the actual parametric test results discussed in Section 3, the predictions showed that higher sodium formate concentrations are required to achieve equivalent SO_2 removal levels compared to DBA. The SO_2 removal predictions associated with operation at higher reagent ratios also appear to correlate reasonably well with the trends of performance test data. For example, a maximum removal of 93.5% was attained at the highest pH setting (5.98 to 6.12) possible during the parametric tests. In comparison, the FGDPRISM results summarized in Table C-3 predicted an SO_2 removal of 94.2% at approximately the same reagent ratio and pH setting.

Table C-3

Predictive Simulation Results for the DOE High Efficiency SO_2 Removal Project

Tests	SO_2 Removal (%)	Limestone Utilization (%)	Slurry pH	Additive Concentration (ppm)	Additive[1] Consumption Rate (lb/hr)	Limestone[1] Consumption Rate (lb/hr)
Baseline	86.8	94.6	5.79	0	0	13,160
DBA Cases	90	94.6	5.77	220	4.6	13,690
	95	94.6	5.74	1,030	21.7	14,460
	97	94.8	5.67	2,800	64.4	14,770
	97.8	95.3	5.39	10,000	290	14,890
No Blowdown, Baseline Cases with DBA	90	94.5	5.78	220	3.6	13,660
	95	94.5	5.75	1,030	17.6	14,470
	97	94.6	5.69	2,800	51.1	14,770
	97.9	95.0	5.40	10,000	260	14,890
Sodium Formate Cases	90	94.6	5.78	380	21.4	13,680
	95	94.6	5.77	2,500	92.2	14,470
	97	94.6	5.77	12,000	390	14,780
No Blowdown, Sodium Formate Cases	90	94.5	5.79	380	14.6	13,660
	95	94.5	5.78	2,500	54.8	14,460
	97	94.5	5.78	11,000	210	14,770

Table C-3

(Continued)

Tests	SO_2 Removal (%)	Limestone Utilization (%)	Slurry pH	Additive Concentration (ppm)	Additive[1] Consumption Rate (lb/hr)	Limestone[1] Consumption Rate (lb/hr)
Baseline	86.8	94.6	5.79	0	0	13,160
Excess Limestone Cases	90	91.9	5.88	0	0	14,050
	94.2	80.3	6.09	0	0	16,900
Additional Packing						
1 ft	88.7	94.6	5.78	0	0	13,440
1.2 ft	90	94.6	5.78	0	0	13,660
2.0 ft	90.4	94.6	5.78	0	0	13,710
1 Ft Additional Packing + DBA	88.7	94.6	5.78	0	0	0
	90	94.6	5.78	85	1.90	13,440
	95	94.6	5.75	750	15.4	13,670
	97	94.7	5.72	1,800	39.3	14,470
	98	95.0	5.57	5,000	135	14,770
2 Ft Additional Packing + DBA	90.4	94.6	5.78	0	0	13,440
	95	94.6	5.76	505	10.8	14,470
	97	94.7	5.73	1,300	28.1	14,770
	98	94.8	5.67	3,000	71.0	14,920

[1] Rate for one module.

APPENDIX D

EBASCO Conceptual System Design for Hoosier Energy FGD Additive System

EBASCO

August 23, 1993

Mr. Joe Lundeen
Radian Corporation
Site Engineer
8501 North Mopac Boulevard
Austin, TX 78759

Dear Mr. Lundeen:

Subject: **HOOSIER ENERGY**
FGD ADDITIVE SYSTEM
CONCEPTUAL SYSTEM DESIGN

Based on our recent discussions, attached is the conceptual system design for the dibasic acid (DBA) and sodium format flue gas desulfurization (FGD) additive systems. This conceptual system design includes the following:

1. System descriptions for a 150-lb/hr/unit DBA and 250-lb/hr/unit sodium format additive systems. This includes capital costs associated with each system.

2. A flow schematic (Figure 1) for a typical FGD additive system.

3. A plot plan for the DBA system (Drawing L22899-A) and a plot plan for the sodium format system (Drawing L22899-B).

We trust that this should meet your needs. Should you have any questions, please do not hesitate to call me at (404) 662-2349 or Chuck Altin at (404) 662-2347.

Sincerely,

Jeffrey Whitmer

Jeffrey Whitmer
Consulting Engineer

cc: C. A. Altin

A:4HOOSIER.JMW

EBASCO SERVICES INCORPORATED
145 TECHNOLOGY PARK • NORCROSS, GEORGIA 30092-2979 • (404) 449-5800

FGD Additive System Descriptions

The additives are generally aqueous solutions used in flue gas desulfurization (FGD) systems for the following:

- Scale control
- Increased buffing capacity
- Increased limestone utilization
- Increased sulfur dioxide removal efficiency

Figure 1 provides a typical flow schematic for an FGD additive system.

Dibasic Acid System

Dibasic acid (DBA) is a 50% acid aqueous solution primarily composed of glutaric, succinic and adipic acids. The DBA feed will be provided to the reagent storage tanks. The feed rates to each tank will be manually controlled. The feed system includes three pumps, one per unit and a shared spare. All piping and wetted areas of the pumps are 316L stainless steel. The DBA storage tanks have a 52,000 gallon total capacity. The tanks are enclosed in a concrete containment system which is internally lined with a vinyl ester coating. The storage capacity is divided between two 26,000 gallon atmospheric pressure 316L stainless steel tanks. Each tank is 17 feet in diameter and 17 feet high (straight side). Based on the 150 lb/hr/unit DBA requirement, this will provide a thirty day storage capacity for each unit. Each tank shall be agitated, hot water heated and insulated to maintain the DBA at 130°F in order to prevent the acid from coming out of solution and crystallizing. All valves and piping shall also be insulated and process heat traced in order to maintain a temperature of 130° F. A plot plans for the DBA system is provided in Drawing L22899-B.

Budgetary direct and total construction costs were developed for the DBA system and are provided in Table 1. The direct construction cost of the DBA system is $301,500 on a furnish and erect basis for the two Merom Station Units. The contingency is assumed to be 10% of the direct construction cost and the engineering services is assumed to be 5% of the direct construction cost.

Sodium Formate System

The sodium formate feed will be provided to the reagent storage tanks. The feed rates to each tank will be manually controlled. The feed system includes three pumps, one per unit and a shared spare. All piping and wetted areas of the pumps are 316L stainless steel. The sodium formate storage tanks have a 88,000 gallon total capacity. The tanks are enclosed in a concrete containment system which is internally lined with a vinyl ester coating. The storage capacity is divided between two 44,000 gallon atmospheric pressure 316L stainless steel tanks. Each tank is 18 feet in diameter and 23 feet high (straight side). Based on the 250 lb/hr/unit sodium formate requirement, this will provide a thirty day storage capacity for each unit. Each tank shall be agitated, hot water heated and insulated to maintain the sodium formate at 120°F in order to prevent the acid from coming out of solution and crystallizing. All valves and piping shall also be insulated and process heat traced in order to maintain a temperature of 120° F. A plot plan for the sodium formate system is provided in Drawing L22899-A.

Budgetary direct and total construction costs were developed for the sodium formate additive system and are provided in Table 1. The direct construction cost of the sodium formate system is $395,500 on a furnish and erect basis for the two Merom Station Units. The contingency is assumed to be 10% of the direct construction cost and the engineering services is assumed to be 5% of the direct construction cost.

Cost Analysis

A cost analysis was performed to determine the range of direct construction costs associated with different mass flow rates. It was assumed that the system configuration and materials of construction are similar to the described in the DBA and sodium formate system descriptions. The mass flows rates analyzed ranged from 70 lb/hr/unit to 300 lb/hr/unit. This resulted in the following equation:

$$DCC=0.2M+1.3M^{0.9}+160.56$$

where:

DCC = Direct Construction Cost ($1,000)
M = Mass Flow Rate (lb/hr/unit)

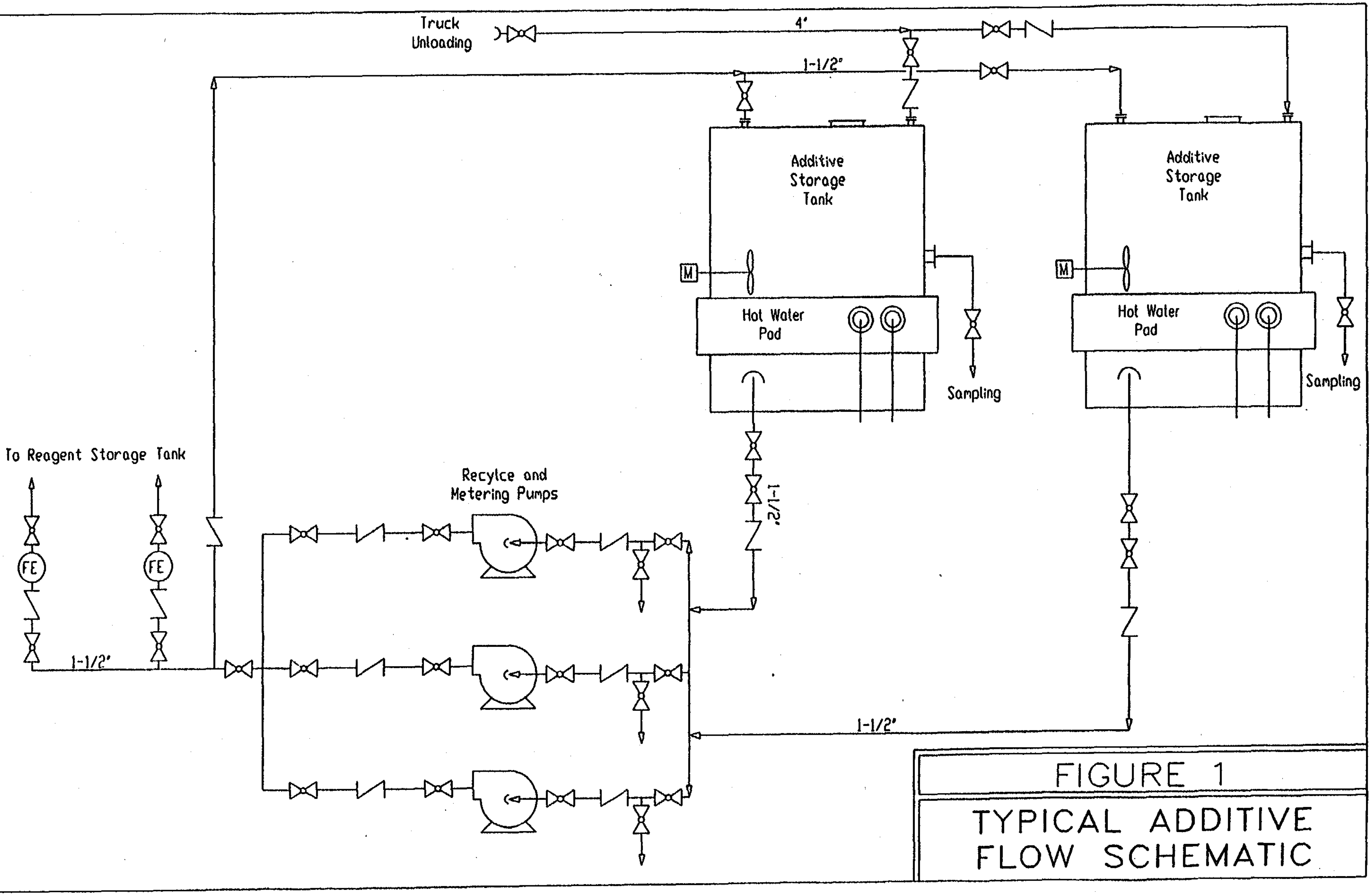

FIGURE 1

TYPICAL ADDITIVE FLOW SCHEMATIC

TABLE 1

TOTAL CAPITAL COSTS

(1993 $)

	DBA ADDITIVE SYSTEM	SODIUM FORMATE ADDITIVE SYSTEM
TANKS, INSULATION, AND HEATER	$228,000	$305,000
PUMPS AND PIPING	$8,500	$9,500
FOUNDATIONS & CONTAINMENT	$65,000	$81,000
SUBTOTAL - DIRECT CONTRUCTION	$301,500	$395,500
SALES/USE TAX	-	-
INDIRECT CONSTRUCTION COSTS	$3,400	$3,400
ARCHITECTURAL/ENGINEERING SERVICES	$15,075	$19,775
CONTINGENCY	$30,150	$39,550
TOTAL CONSTRUCTION COST	$350,125	$458,225

APPENDIX E

Detailed Cost Calculation

Referring to Tables E-1 and E-2, the first two columns describe the SO_2 removal of the system for each case and the potential to remove more SO_2 from the flue gas. The value in Column 2 represents the tons per year remaining in the flue gas after the removal level in Column 1 is achieved and assuming a 70% annual capacity factor. Merom Station has averaged approximately a 70% capacity factor over the past several years.

Columns 3 and 6 show the concentration, consumption rate, and annual additive and capital costs associated with the use of DBA or sodium formate. Note that the base case, the reagent ratio cases, and packing-only cases do not incur an additive cost. The additive consumption rate shown in Column 4 is for full-load operation for an entire unit. This consumption rate includes a 70% capacity factor which is used to calculate the annual estimate in the next column. Additive system annual capital charges (amoritized over 10 years at 11.5%) are shown in Column 6.

The required reagent ratio, limestone consumption rate, and annual costs associated with additional limestone reagent for reach option are shown in Columns 7, 8, 9, and 10. The limestone consumption rate is based on a 70% capacity factor, which is reflected in both the limestone purchase and slurry preparation O&M costs.

The calculated marginal cost of additional tons of SO_2 removed (Column 12) for each case is the incremental cost increase when going from case to case within each option (e.g., the cost to go from 86.8% to 90%, from 90% to 95%, etc.). The information in this column is useful for determining at what level achieving additional SO_2 removal efficiency is no longer cost-effective. The "Average Cost" (Column 13) for each case is another representation of the cost of additional tons of SO_2 removed; however, in this case, the values are relative to the normal FGD operation with gas bypass (e.g., the cost to go from 83% to 90% or from 83% to 95%). The information in this column is useful for comparing the cost-effectiveness of the various options in achieving a given level of SO_2 removal.

Columns 14 and 15 show a net annual value for additional tons of SO_2 removed, calculated for allowance values of $150/ton and $250/ton, respectively. The net value of each option is referred to the base case. This allows the various options to be compared for cost-effectiveness and also helps identify the SO_2 removal level above which each option is no longer cost-effective.

Table E-1

Economic Evaluation of Options to Increase SO_2 Removal Efficiency

SO_2 Removal	SO_2 Emitted (tons/yr)	Additive Concentration		Additive Cost ($K/yr)	Additive Capital Cost ($K/yr)	Limestone		Addt'l Limestone Cost ($K/yr)	Addt'l Lime-stone O&M Cost ($K/yr)	Addt'l Cost of Sol. Disposal ($K/yr)	Marginal Cost ($/ton of SO_2)	Average Cost ($/ton of SO_2)	Net Annual Value ($K) @ $150/ton	Net Annual Value ($K) @ $250/ton
		ppm	lbs/hr			Reagent Ratio	tons/yr							
Option 1 - DBA with Occasional Blowdown														
83.0%	18,340	0	0	0	0	1.06	157,000	0	0	0	0	0	0	0
86.8%	14,240	0	0	0	0	1.06	162,000	38.0	7.1	41.6	21	21	528	938
90%	10,760	220	18.4	32.2	78.2	1.06	168,000	93.0	17.4	76.9	61	39	839	1,597
95%	5,420	1,030	86.7	151.8	78.2	1.06	178,000	174.0	32.7	131.0	51	44	1,370	2,662
97%	3,220	2,800	257.4	451.0	78.2	1.06	181,000	206.0	38.7	153.3	163	61	1,341	2,853
97.8%	2,350	10,000	1,174.1	2,057.0	78.2	1.06	183,000	218.0	41.1	162.2	1,872	160	-158	1,441
Option 1 - DBA - 0 gpm Blowdown														
83.0%	18,340	0	0	0	0	1.06	157,000	0	0	0	0	0	0	0
86.8%	14,240	0	0	0	0	1.06	162,000	38.0	7.1	41.6	21	21	528	938
90%	10,780	220	14.4	25.2	78.2	1.06	168,000	90.0	17.0	76.7	58	38	847	1,603
95%	5,360	1,030	70.5	123.6	78.2	1.06	178,000	174.0	32.8	131.6	47	42	1,407	2,705
97%	3,240	2,800	204.2	357.8	78.2	1.06	181,000	205.0	38.7	513.1	138	55	1,432	2,942
97.8%	2,320	10,000	1,044.6	1,830.0	78.2	1.06	183,000	218.0	41.1	162.5	1,627	145	73	1,675
Option 2 - Sodium Formate with Occasional Blowdown														
83.0%	18,340	0	0	0	0	1.06	157,000	0	0	0	0	0	0	0
86.8%	14,240	0	0	0	0	1.06	162,000	38.0	7.1	41.6	21	21	528	938
90%	10,790	380	85.8	150.3	78.2	1.06	168,000	92.0	17.4	76.6	95	55	718	1,473
95%	5,400	2,500	368.8	646.2	78.2	1.06	178,000	174.0	32.8	131.2	120	82	879	2,173
97%	3,190	12,000	1,558.5	2,731.0	78.2	1.06	181,000	206.0	38.8	153.6	971	212	-935	580
Option 2 - Sodium Formate - 0 gpm Blowdown														
83.0%	18,340	0	0	0	0	1.06	157,000	0	0	0	0	0	0	0
86.8%	14,240	0	0	0	0	1.06	162,000	38.0	7.1	41.6	21	21	528	938
90%	10,820	380	58.5	102.5	78.2	1.06	168,000	90.0	17.0	76.3	81	48	764	1,516
95%	5,420	2,500	219.0	383.6	78.2	1.06	178,000	174.0	32.7	131.0	81	62	1,139	2,431
97%	3,230	11,000	838.2	1,468.5	78.2	1.06	181,000	205.0	38.7	153.2	522	129	323	1,834

NOTE: Numerical inconsistencies are because of rounding and FGDPRISM convergence criteria. All rates and values are for one unit.

Table E-1

(Continued)

SO_2 Removal	SO_2 Emitted (tons/yr)	Additive Concentration		Additive Cost ($K/yr)	Additive Capital Cost ($K/yr)	Limestone		Addt'l Limestone Cost ($K/yr)	Addt'l Lime-stone O&M Cost ($K/yr)	Addt'l Cost of Sol. Disposal ($K/yr)	Marginal Cost ($/ton of SO_2)	Average Cost ($/ton of SO_2)	Net Annual Value ($K) @ $150/ton	Net Annual Value ($K) @ $250/ton
		ppm	lbs/hr			Reagent Ratio	tons/yr							
Option 3 - Reagent Ratio														
83.0%	18,340	0	0	0	0	1.06	157,000	0	0	0	0	0	0	0
86.8%	14,240	0	0	0	0	1.06	162,000	38.0	7.1	41.6	21	21	528	938
90%	10,850	0	0	0	0	1.091	172,000	131.0	24.7	76.0	43	31	892	1,641
90.5%	10,240	0	0	0	0	1.10	175,000	152.0	28.7	82.2	51	32	952	1,762
92.6%	8,000	0	0	0	0	1.15	187,000	257.0	48.3	104.9	66	40	1,141	2,175
93.6%	6,880	0	0	0	0	1.20	198,000	346.0	65.2	116.2	105	46	1,192	2,338
94.2%	6,220	0	0	0	0	1.25	207,000	428.0	80.5	122.9	157	52	1,188	2,400

SO_2 Removal	SO_2 Emitted (tons/yr)	Packing		Additive Cost ($K/yr)	Additive Capital Cost ($K/yr)	Limestone		Addt'l Limestone Cost ($K/yr)	Addt'l Lime-stone O&M Cost ($K/yr)	Addt'l Cost of Sol. Disposal ($K/yr)	Marginal Cost ($/ton of SO_2)	Average Cost ($/ton of SO_2)	Net Annual Value ($K) @ $150/ton	Net Annual Value ($K) @ $250/ton
		Addt'l Height	Mat'l Cost ($K/yr)			Reagent Ratio	tons/yr							
Option 4 - Adding Packing with No Additive														
83.0%	18,340	0	0	0	0	1.06	157,000	0	0	0	0	0	0	0
86.8%	14,240	0	0	0	0	1.06	162,000	37.8	7.1	41.6	21	21	529	939
88.7%	12,220	1.0	4.1	0	0	1.06	165,000	67.0	12.7	62.1	29	24	772	1,384
90%	10,800	1.8	7.2	0	0	1.06	168,000	89.0	16.8	76.5	31	25	942	1,696
90.4%	10,400	2.0	8.1	0	0	1.06	168,000	95.0	17.9	80.5	30	25	989	1,783

Table E-1

(Continued)

SO_2 Removal	SO_2 Emitted (tons/yr)	Additive Concentration		Additive Cost ($K/yr)	Additive + Packing Capital Cost ($K/yr)	Limestone		Addt'l Limestone Cost ($K/yr)	Addt'l Lime-stone O&M Cost ($K/yr)	Addt'l Cost of Sol. Disposal ($K/yr)	Marginal Cost ($/ton of SO_2)	Average Cost ($/ton of SO_2)	Net Annual Value ($K) @ $150/ton	Net Annual Value ($K) @ $250/ton
		ppm	lbs/hr			Reagent Ratio	tons/yr							
1 Ft. Additional Packing + DBA														
83.0%	18,340	0	0	0	0	1.06	157,000	0	0	0	0	0	0	0
86.8%	14,240	0	0	0	0	1.06	162,000	38.0	7.1	41.6	21	21	528	938
88.7%	12,220	0	0	0	4.1	1.06	165,000	67.0	12.7	62.1	29	24	772	1,384
90%	10,810	90	7.5	13.2	82.3	1.06	168,000	91.0	17.1	76.4	95	37	850	1,603
95%	5,400	730	61.7	108.1	82.3	1.06	178,000	175.0	32.9	131.2	46	41	1,412	2,706
97%	3,270	1,800	157.3	275.5	82.3	1.06	181,000	205.0	38.7	152.8	106	50	1,506	3,013
98%	2,140	4,000	539.9	946.0	82.3	1.06	183,000	221.0	41.6	164.3	620	90	975	2,595
2 Ft. Additional Packing + DBA														
83.0%	18,340	0	0	0	0	1.06	157,000	0	0	0	0	0	0	0
90.4%	10,400	0	0	0	8.1	1.06	168,000	95.0	17.9	80.5	25	25	989	1,784
95%	5,400	505	43.2	75.6	86.3	1.06	178,000	174.0	32.8	131.2	60	39	1,441	2,735
97%	3,230	1,300	112.2	196.6	86.3	1.06	181,000	206.0	38.7	153.2	83	45	1,586	3,097
98%	2,140	3,500	283.8	497.3	86.3	1.06	183,000	221.0	41.7	164.3	303	62	1,088	2,925

Table E-2

Coal Sulfur Content Effects on the Economic Evaluation

SO_2 Removal	SO_2 Emitted (tons/yr)	Additive Concentration		DBA Cost ($K/yr)	DBA Capital Cost ($K/yr)	Limestone		Addt'l Limestone Cost ($K/yr)	Addt'l Lime-stone O&M Cost ($K/yr)	Addt'l Cost of Sol. Disposal ($K/yr)	Marginal Cost ($/ton of SO_2)	Average Cost ($/ton of SO_2)	Net Annual Value ($K) @ $150/ton	Net Annual Value ($K) @ $250/ton
		ppm	lbs/hr			Reagent Ratio	tons/yr							
3.5% S Coal DBA														
83.0%	18,340	0	0	0	0	1.06	157,000	0	0	0	-	-	-	-
86.8%	14,240	0	0	0	0	1.06	162,000	37.8	7.2	41.6	21	21	528	939
90%	10,760	220	18.40	32.2	78.2	1.06	168,000	93.0	17.4	76.9	61	39	839	1,597
95%	5,420	1,030	86.65	151.8	78.2	1.06	177,000	174.0	32.7	131.0	51	44	1,370	2,662
97%	3,220	2,800	257.4	451.0	78.2	1.06	181,000	206.0	38.7	153.3	163	61	1,341	2,853
97.8%	2,350	10,000	1,174.1	2,057.0	78.2	1.06	183,000	218.0	41.1	162.2	1,872	160	-158	1,441
4.0% S Coal DBA														
85.1%	18,370	0	0.0	0	0	1.098	187,000	0	0	0	0	0	0	0
90%	12,370	540	50.6	88.6	78.2	1.06	192,000	39.0	7.4	77.0	48	48	610	1,210
95%	6,170	1,475	147.7	258.8	78.2	1.06	203,000	132.0	24.9	131.9	54	51	1,204	2,424
97%	3,710	3,500	407.6	714.2	78.2	1.06	207,000	168.0	31.6	153.4	211	78	1,054	2,520
97.7%	2,850	10,000	1,337.4	2,343.0	78.2	1.06	208,000	180.0	33.9	162.8	1,922	180	-470	1,082

NOTE: All rates and values are for one unit.