Evaluation of Chiyoda Thoroughbred 121 FGD Process and Gypsum Stacking
Volume 1: Chiyoda Evaluation

EPRI

EPRI CS-1579
Volume 1
Project 536-4
Final Report
October 1980

Keywords:
Scrubber
Limestone
FGD
Flue Gas
Sulfur Dioxide
Gypsum

MASTER

Prepared by
Radian Corporation
Austin, Texas

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Evaluation of Chiyoda Thoroughbred 121 FGD Process and Gypsum Stacking
Volume 1: Chiyoda Evaluation

CS-1579, Volume 1
Research Project 536-4

Final Report, October 1980

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Austin, Texas

ABSTRACT

A six-month evaluation of the Chiyoda Thoroughbred 121 Prototype Process (CT-121) was conducted at the Scholz Electric Generating Station of Gulf Power Company. The 23-megawatt CT-121 prototype was modified from existing CT-101 process equipment at Scholz by Chiyoda International Corporation, a subsidiary of Chiyoda Chemical Engineering and Construction Company, Ltd. Chiyoda operated the prototype, and the Electric Power Research Institute and Southern Company sponsored technical evaluations of the prototype process performance and gypsum waste disposal options in the 1978-1980 time period. This report summarizes the findings of these evaluations.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

Volume 1 of this final report summarizes results of an eight-month evaluation of a 23-MW Chiyoda Thoroughbred 121 (CT-121) SO_2 scrubbing system, conducted at Gulf Power Company's Scholz plant under RP536. Volume 2 contains appendixes including all process and operating data. Chiyoda's development of CT-121 was partly an outgrowth of our evaluation of the Chiyoda Thoroughbred 101 process, also under RP536. The new design eliminates the use of recycle pumps by bubbling the gas through a limestone slurry. Our preliminary assessment indicated that CT-121 offers utility operators a more reliable limestone-based SO_2 control device that produces a gypsum product and is less expensive to operate and maintain than conventional scrubbers. This assessment led us to undertake a thorough evaluation of the CT-121 system on the coal-fired Scholz plant from October 1978 through May 1979.

PROJECT OBJECTIVE

The objective was to provide a pilot-scale evaluation of the limestone-gypsum flue gas desulfurization (FGD) system developed by Chiyoda Chemical Engineering and Construction Company Ltd. The goals were to determine the system's capabilities and limits and to test the numerous claims of the developer under a wide range of operating conditions including those outside the design range.

PROJECT RESULTS

This pilot-scale evaluation indicates that the CT-121 scrubbing system is an attractive alternative to other available FGD technologies based on lime and limestone. The prototype scrubber at the Scholz plant operated reliably and efficiently, under a variety of test conditions, while treating flue gas from a coal-fired utility boiler.

The process has the potential of reducing levelized costs by about 10%, compared to conventional limestone scrubbing. The major results are as follows:

SO_2 removal efficiency with SO_2 inlets of 1200-3000 ppm		90-95%
System reliability		99.5%
Limestone utilization in the absorber	>	98%
Gypsum purity	>	98%
Total-system pressure drop		19-21 in. H_2O (4.7-5.2 kPa)

Conventional limestone-system reliabilities range from 50 to 90%. They normally operate with a limestone utilization of approximately 70%; if the system employs an oxidation loop to produce gypsum, they generate up to 90% pure gypsum.

The evaluation quantified fairly wide ranges of pH and pressure drop that can result in equivalent SO_2 removals. The existence of these pH and pressure-drop trade-offs can be important in optimizing the CT-121 system operating costs. This report will benefit those utility engineers who are responsible for specifying and recommending SO_2 control devices.

In view of the success of these prototype tests, EPRI is now arranging a 100-MW demonstration of this process.

Thomas M. Morasky, Project Manager
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ACKNOWLEDGMENTS

The authors would like to thank many individuals for the suggestions, guidance, and insight provided during this program.

Of particular importance was the guidance of both Tom Morasky of the Electric Power Research Institute and Randall Rush of Southern Company Services. Without the enthusiasm generated by both men, this project would not have been undertaken. We would also like to thank Lamar Larrimore and David Burford of SCS for their continued efforts throughout the project.

The value of the support and understanding of George O. Layman of Gulf Power Company cannot be overstated. The hospitality and cooperation of Gulf Power Company employees at the plant site were also greatly appreciated. Specifically, we would like to thank William T. Lyford.

The invaluable aid given by Chiyoda Chemical Engineering and Construction Company (CCEC), Chiyoda International Corporation (CIC) and their subcontractor, Catalytic Incorporated (CI) personnel in understanding the CT-121 Process must also be acknowledged. Specifically, we would like to thank Mr. M. Noguchi (CCEC) and Mr. Y. Kameoka (CIC).

We would also like to thank the members of the project review committee for their suggestions and input to the testing schedule. Members not previously acknowledged are:

Mike Maxwell (EPA)
Archie Slack (SAS Corporation)
Murray Wells (Radian)

Finally, the authors would like to thank all Radian personnel who have contributed both analytical and technical support throughout the program.

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EXECUTIVE SUMMARY

The Electric Power Research Institute and Southern Company Services sponsored an evaluation of a 20 MW prototype of the Chiyoda Thoroughbred 121 (CT-121) Flue Gas Desulfurization (FGD) Process which was built and operated by Chiyoda Chemical Engineering and Construction Company, Ltd. (CCEC) at Gulf Power's Scholz Station. The salient feature of this forced oxidation limestone FGD system which produces gypsum as a by-product is the Jet Bubbling Reactor (JBR), a single vessel in which SO_2 absorption, oxidation, neutralization, and crystallization all occur.

The design and operating features of the CT-121 process which may result in improved operability and reduced costs relative to existing lime/limestone systems include:

- no large slurry recirculation pumps,
- no nozzles or screens,
- high limestone utilization,
- less effect of limestone source and grind size on operation due to the low operating pH,
- low slurry entrainment in the gas, enhancing mist eliminator performance,
- low scrubber profile which may lower capital costs, and
- the ability to operate successfully over a wide range of operating conditions with a minimum of scale deposition.

The concept of the JBR, therefore, represents a potentially attractive alternative to other available FGD technologies. The prototype at Scholz was tested over a nine month period and was shown to operate reliably and efficiently under a variety of conditions while treating flue gas from a coal-fired utility boiler.

Although the technical evaluation of the CT-121 prototype system is positive, the results presented in this report should be considered in conjunction with independent cost evaluations when considering the CT-121 system for a specific utility application.

Section 1

SUMMARY

In order to evaluate the capabilities of an advanced FGD system which was claimed to have both technical and economical advantages relative to currently available technology, the Electric Power Research Institute and Southern Company Services sponsored a program to evaluate the Chiyoda Thoroughbred 121 (CT-121) process. As part of this program, Chiyoda built and operated a prototype (23 MW) CT-121 process at the Scholz Power Station with the cooperation of Gulf Power Company. This system was constructed by modifying the existing CT-101 demonstration equipment at Scholz (Reference 1). The CT-121 process at Scholz is designated as a prototype because it was the first large-scale application of the CT-121 process.

This section summarizes the findings of the evaluation program. First, the system is described briefly and the test program objectives are discussed. Then, test program results are summarized and conclusions derived from the testing are presented.

SYSTEM DESCRIPTION

Figure 1-1 shows a schematic of the Scholz prototype CT-121 plant. This system was designed to treat 53,000 standard cubic feet per minute (25 normal cubic meters per second) of flue gas (23 MW of electrical production at Scholz). However, during the test program, gas flows ranging from 25,000 to 55,000 scfm were studied.

As shown in the figure, the inlet gas was cooled and saturated by water in a venturi before entering the jet bubbling reactor (JBR) where the bulk of the SO_2 removal occurred. Compressed air was injected into the JBR to completely oxidize the sorbed SO_2 and to maintain a gypsum solids suspension in the slurry. From the JBR, the gas passed through a mist eliminator prior to exiting the system through a glass reinforced polyester stack. There was no provision in the prototype system for reheating the saturated flue gas. Powdered limestone was slurried and added to the JBR to control pH. Limestone grinding facilities were not included in the prototype. The gypsum produced during the evaluation program was disposed of in a gypsum stack, a disposal technique commonly used in the phosphate fertilizer industry. A gypsum stack is a free standing body in which solid-liquid separation

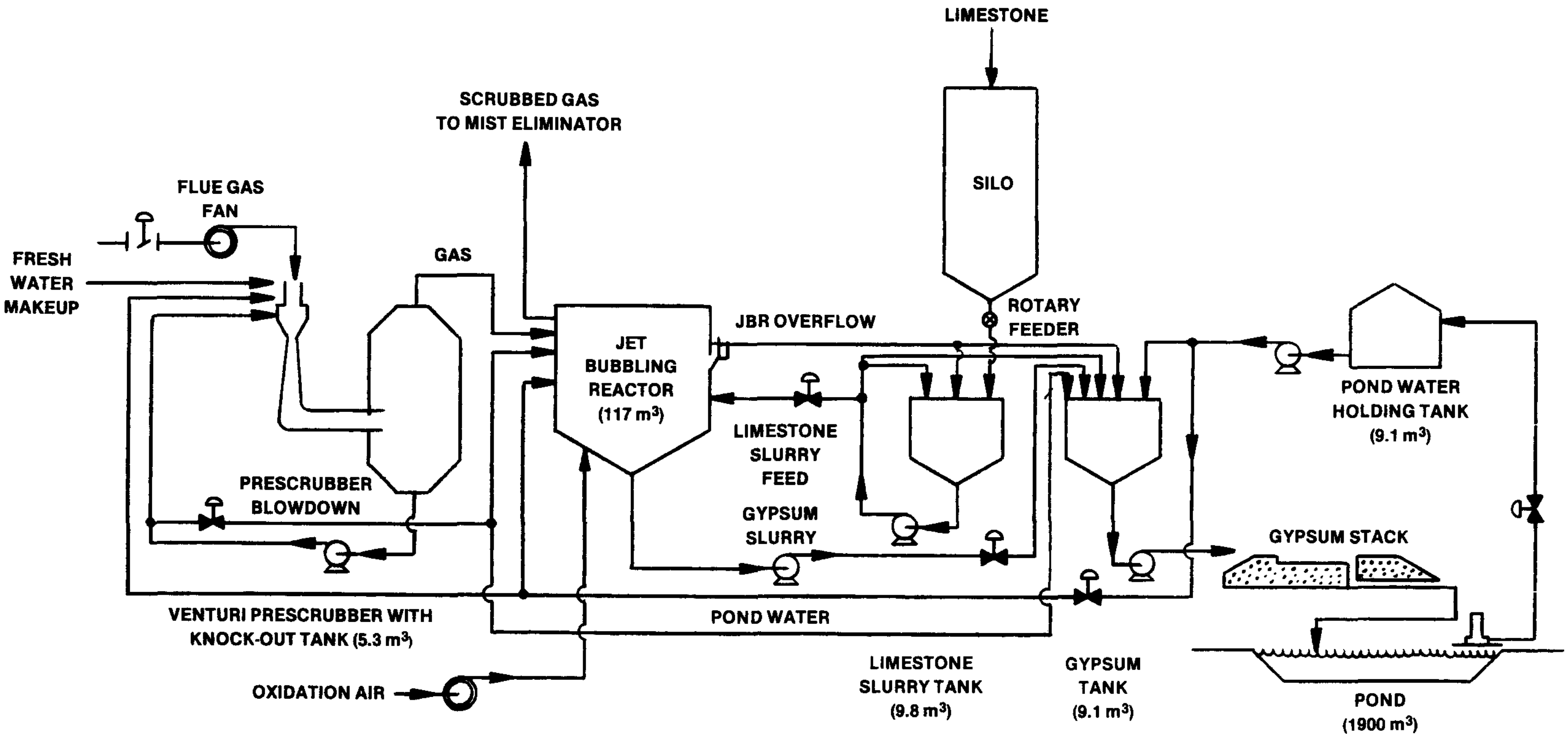

Figure 1-1
Simplified Process Flow Diagram of Scholz Prototype CT-121 Flue Gas Scrubbing System

is achieved by solids settling in a hollowed out section on the top of the stack. The supernatant liquid flows through the walls of the stack to form a "moat" around the stack. This disposal was evaluated independently by Ardaman & Associates under EPRI Research Project 536-3 during the CT-121 demonstration.

The unique and central feature of the CT-121 process is the jet bubbling reactor. SO_2 removal, sulfite oxidation, limestone dissolution, and gypsum crystallization reactions are all accomplished within this one vessel. This concept, which deviates from the conventional limestone system approach of providing separate absorption and reaction tanks, is a primary factor which can affect the overall capital cost of a FGD system. In the JBR, the gas is dispersed several inches beneath the slurry, thus minimizing the liquid phase mass transfer resistance, which can limit SO_2 removal in spray tower systems. The liquid pumping power requirements are also low in the CT-121 system because large slurry recirculation pumps are not used; however, the power required to overcome the high gas-side pressure drop tends to offset this saving somewhat.

TEST PLAN AND OBJECTIVES

The objective of this program was to evaluate the performance of the CT-121 system under a wide range of operating conditions and to measure the reliability of this prototype. By varying both site-specific and some non-site-specific parameters, an "operating envelope" in which the CT-121 system can function successfully was determined. This performance evaluation therefore provides a basis for cost evaluation activities as well as for some of the design parameters required for commercial units.

The EPRI CT-121 test program was comprised of two test phases.

- Phase I - Baseline tests at Chiyoda-specified design conditions.
- Phase II - Perturbation tests in which unit is operated outside of design conditions.

Phase I was a continuous two-month duration run which quantified some of the operating variable fluctuations that might be expected during routine operation. A week of testing was also conducted in which the flue gas entering the unit was varied to simulate a varying boiler load. In addition, the Phase I results provided a baseline for comparison with Phase II operating results.

Phase II was a four month test series to evaluate CT-121 performance under conditions which might be encountered in a number of utility applications. The first test series was designed to measure the effects of pH, JBR pressure drop, oxidation air rate, and limestone particle size on SO_2 removal. Subsequent tests evaluated the effects of lower-than-design JBR slurry solids concentrations, higher flue gas SO_2 concentrations, lower oxidation air rates, higher chloride concentrations in the scrubber liquor, and high particulate loadings in the inlet flue gas. During the high particulate loading tests, Radian completed material balances for 15 trace elements to determine their fate within the CT-121 system. This will also serve as a basis for EPRI to help identify the fate of fine particulates and trace elements within limestone FGD systems in general. The system water balance was also monitored throughout the evaluation program, and several metals were tested for corrosion resistance in five different locations in the system.

In addition to the tests included as part of the EPRI program, Chiyoda conducted testing during two other periods. Chiyoda performed three months of tests prior to the beginning of the EPRI evaluation program. This initial testing, designated as Phase 0 (zero), consisted of startup, shakedown, and some initial parametric tests. These tests are briefly discussed later in this section. Chiyoda also conducted an additional three-week test at the end of Phase II to evaluate some internal JBR modifications designed to simplify the JBR design and further reduce capital cost. This testing has been designated as Phase III. While EPRI, SCS, and Radian were invited to observe Phase III testing, Chiyoda actually set the test conditions and monitored system performance during this test period.

TEST RESULTS

When judged by four critical performance criteria: SO_2 removal efficiency, solid waste quality, limestone utilization, and resistance to chemical scaling, the performance of the CT-121 process throughout the EPRI evaluation program was quite good. SO_2 removal efficiencies were up to 95 percent with 3500 ppm SO_2 in the inlet flue gas, and the gypsum produced settled rapidly and dewatered easily. The operation of the prototype system was particularly outstanding from the standpoint of limestone utilization and chemical scale control. Limestone utilization within the JBR averaged over 98% for the evaluation program. A detailed inspection at the conclusion of Phase II revealed only minimal chemical scale deposition, which had not posed a significant operating problem. This was after nine months of testing including three months of Chiyoda shakedown operation and six months of EPRI-sponsored tests. These performance results are excellent in view of test conditions which deviated significantly from Chiyoda's design operating set points. These results thus indicate that the system is flexible and can withstand significant process upsets.

This summary of the CT-121 evaluation program results is organized in the following subsections:

- Phase 0 Test Results
- Phase I Test Results
- Phase II Test Results
- Phase III Test Results
- EPA Performance Parameters
- Gypsum Disposal
- Mist Eliminator Performance
- System Water Balance
- Particulate and Trace Elements Testing
- Instrument Performance
- Corrosion Test Results

Phase 0 (Zero) Test Results

During Phase 0, Chiyoda started operation of the prototype scrubber and checked system performance. Although Radian was not on site during this period, operating data from Phase 0 are included in this report (Appendix A). During Phase 0 the only major outage identified by Chiyoda was a bearing failure in the oxidation air compressor. The performance parameters measured in Phase 0 are included in the discussion of equipment and instrumentation performance in Section 5.

Phase I Test Results

Table 1-1 summarizes the operational parameters for the Phase I test period. This set of operating conditions was specified by Chiyoda to attain 90% SO_2 removal.

Table 1-1

SUMMARY OF PHASE I OPERATING CONDITIONS

Set Points	
JBR Pressure Drop	11.5 inches H_2O (2.9 kPa)
JBR Overflow pH	3.5
Oxidation Air Rate	1300 scfm (0.58 Nm^3/s)
Underflow Solids Content	17 wt%
Variables (Average Values)	
SO_2 Removal	92%
Flue Gas Flow	45,000 scfm (20 Nm^3/s)
Inlet SO_2 Concentration	1000-1200 ppm
Coal Properties	
Sulfur Content	2.0 wt%
Ash Content	11.0 wt%
Higher Heating Value	12,600 Btu/lb (29,300 J/g)
JBR Underflow	
Unreacted $CaCO_3$	1.1 wt% in solids
Limestone Utilization	98.3%
Gypsum Tank Effluent	
Unreacted $CaCO_3$	1.4 wt% in solids
Limestone Utilization	97.5%

The system had no downtime in Phase I. It operated stably throughout the two-month period. The average SO_2 removal* was 92% with minimum and maximum values of 80 and 97% and most readings between 90 and 95% removal. Only 2 days of the 63 total days in Phase I had a daily average removal of less than 90%. On 9 of the 63 days, SO_2 analyzer malfunctions precluded calculating daily averages.

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*The inlet and outlet continuous monitors were calibrated on a routine basis but not certified according to EPA procedures.

Two control variables were specified by Chiyoda as being most important to reliable operation: the JBR pH and JBR underflow solids concentration. During this phase these were held fairly constant. The overflow pH remained within ±0.2 units of the set point and control of the process set point for the solids content was normally maintained between 15-19%. The operators did tend to control to the high side of the solids concentration control point. Limestone utilization calculations and gypsum relative saturation measurements also indicated the system was functioning well. After addition of limestone to the gypsum tank for neutralization, the average limestone utilization observed in the tank effluent was above 97% even though there was not a continuous pH monitor on this stream. This utilization figure is quite good for limestone systems. The relative gypsum saturation in the JBR overflow stream remained between 1.0 and 1.1. This is well beneath the scaling threshold relative saturation of 1.3 (2).

The Oxidation of sulfite to sulfate remained essentially 100%. No solid phase sulfite could be detected, and the liquid phase sulfite levels were low. High oxidation rates are necessary to achieve the design SO_2 removals at the relatively low slurry pH's maintained in the JBR.

One test conducted during Phase I was designed to simulate the load changes of a boiler by altering the gas flow to the system. The pH response to such gas flow changes was good. However, from a pressure drop standpoint the JBR responded somewhat sluggishly to rapid changes of gas flow. This was confirmed again in Phase II. A change from half design gas flow to full design gas flow (equivalent to a change from 20 MW to 10 MW) in fifteen minutes caused a rise in the pressure drop of over 1 in. H_2O (0.25 kPa) due to the volume of slurry which had to be purged through the overflow weir of the JBR to reach the new pressure equilibrium. However, in a commercial system the weir width, which was only about 18 inches (0.46 meters) in the prototype JBR, could be widened or an alternative liquid level control method used to allow for more rapid pressure equalization.

Phase II Test Results

In Phase II, a wide range of operating conditions was tested. The first test series in this phase was conducted to evaluate the effects of the following variables:

- JBR overflow pH
- JBR pressure drop
- Oxidation air rate
- Limestone particle size

Additional tests were conducted to measure the effects of:

- Lower JBR underflow slurry solids concentration
- Lower air rates
- Higher flue gas SO_2 concentrations
- Higher flue gas particulate loadings
- Higher soluble chloride concentrations
- Low flue gas flow rates

The influence of each of these variables on system performance is described below with respect to its effect on:

- SO_2 removal efficiency
- Limestone utilization
- Solids characteristics and gypsum scale control

$\underline{SO_2}$ <u>Removal Efficiency.</u> Five variables were found to have an impact on SO_2 removal. They were 1) JBR pH, 2) JBR pressure drop, 3) SO_2 concentration, 4) oxygen/SO_2 ratio, and 5) flue gas rate. No statistically significant difference in the SO_2 removal was seen due to changing the limestone particle size from 90% less than 325 mesh to 90% less than 200 mesh.

Three parameters--pH, pressure drop, and SO_2 concentration--were fit to a theoretically derived equation for predicting SO_2 removal. This theoretical equation, was first presented by Chiyoda in 1978 (3), is discussed in more detail in Section 5 and Appendix E. The two remaining parameters, oxygen to sulfur dioxide (O/SO_2) ratio and gas flow, were not varied in conjunction with variations in other process conditions, so they were not included in the mathematical model. However, the O/SO_2 ratio and gas flow did have a measurable effect on SO_2 removal under constant conditions of pH, ΔP, and inlet SO_2. The SO_2 removal decreased significantly at O/SO_2 mole ratios of 4 or below, and reductions in gas flow resulted in slightly higher SO_2 removal efficiencies.

The 229 data points used for this analysis were best fit by using two equations, the first for inlet gas SO_2 concentrations less than 2200 ppm and the second for higher SO_2 levels. The primary reason for using two equations is that nearly all the testing was at SO_2 concentrations less than 2200 ppm (200 data points). A single equation fit the results for SO_2 levels less than 2200 ppm but did not adequately fit the removals observed at higher SO_2 concentrations.

Eq. 1-1 predicts the removal for inlet SO_2 levels less than 2200 ppm while Eq. 1-2 describes the results achieved at the higher inlet concentrations.

Fractional SO_2 removal (for inlet gas SO_2 concentrations less than 2200 ppm)

$$\text{Fractional } SO_2 \text{ removal} = \frac{1 - \exp\left[-3.49 \left(\frac{\Delta P}{15.4}\right)^{1.07}\right]}{1 + 56.9 \left(\frac{15.4}{\Delta P}\right)\left(10^{-pH}\right)\left(\frac{SO_2}{1000}\right)^{.11}} \qquad (1\text{-}1)$$

Fractional SO_2 removal (for inlet gas SO_2 concentrations greater than or equal to 2200 ppm)

$$\text{Fractional } SO_2 \text{ removal} = \frac{1 - \exp\left[-3.85 \left(\frac{\Delta P}{15.4}\right)^{1.44}\right]}{1 + 0.84 \left(\frac{15.4}{\Delta P}\right)\left(10^{-pH}\right)\left(\frac{SO_2}{1000}\right)^{5.26}} \qquad (1\text{-}2)$$

Where ΔP is the JBR pressure drop expressed as inches of water, SO_2 is the inlet flue gas sulfur dioxide concentration in ppm and the pH is that measured at the JBR overflow. Both of the equations are applicable only to the range of Phase II test conditions at full load gas flow and with O/SO_2 ratios greater than 8. A detailed explanation of the derivation of these equations and their confidence intervals is presented in Section 5 and Appendix E. Figure 1-2 is a plot comparing the measured removal with the values generated by these two equations. Confidence intervals are not shown in Figure 1-2 since the predicted SO_2 removal efficiencies are calculated from two different equations each having a difference confidence limit.

The equations show the important effects of the pressure drop, pH, and SO_2 concentration on SO_2 removal. As the pressure drop increases, the exponential term decreases, thus predicting a higher SO_2 removal. Likewise, as the pH increases, increased SO_2 removal is predicted since the denominator approaches unity.

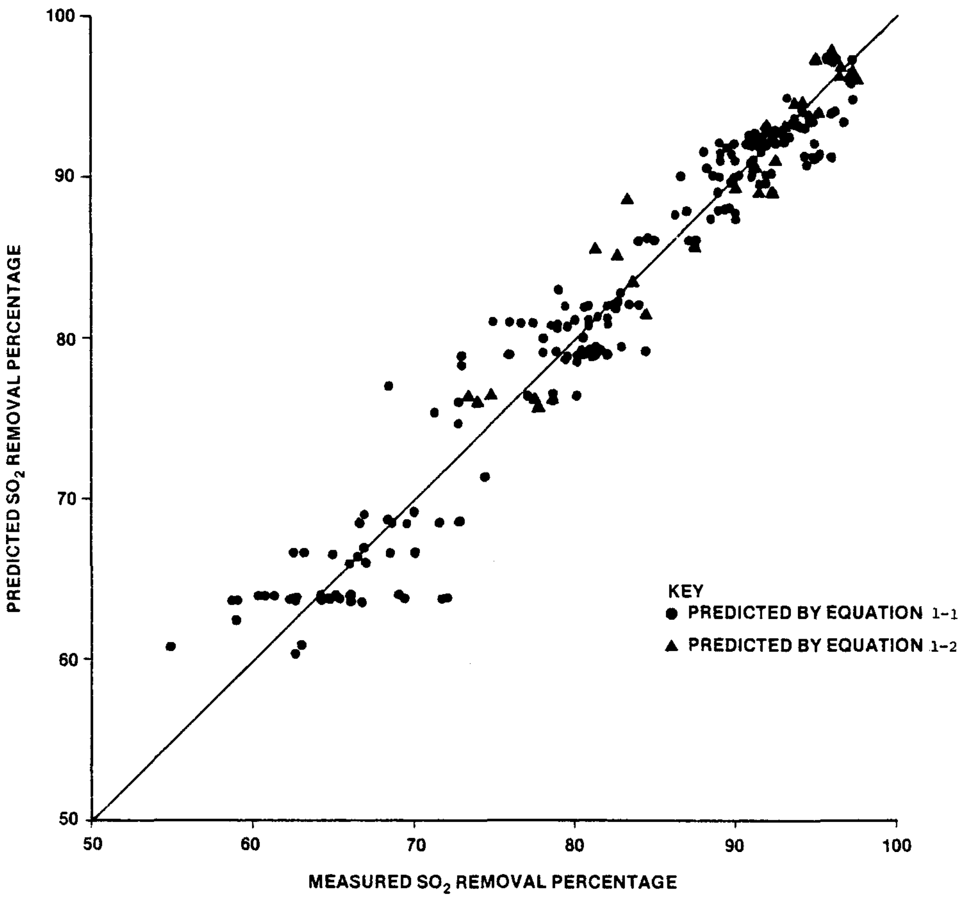


Figure 1-2
Predicted Versus Measured SO_2 Values for Phase II Data Using Equations 1-1 and 1-2

Dependence of SO_2 removal on SO_2 concentration above a certain SO_2 concentration is probably related to mass transfer in the JBR. When compared to spray towers the JBR offers a major advantage in that the gas is bubbled through a liquid layer which results in a greater mass transfer area. In addition, the liquid surface surrounding each bubble is continually being renewed as the bubble rises. In contrast, when flue gas contacts a liquid droplet in a spray tower, this interfacial surface is not renewed as rapidly. Consequently, a liquid phase mass transfer limitation can develop at the droplet surface, limiting the SO_2 removal. This film depletion phenomenon is minimized in the JBR. Up to a certain gas-phase SO_2 concentration, the liquid surrounding the gas bubble apparently can absorb a constant fraction of the SO_2 in the flue gas since the sorption reaction is gas film limited. However, as the concentration of SO_2 is increased the sorption step becomes limited by the calcium availability in the surrounding liquid. The removal efficiency then begins to drop. This liquid film limit occurs at higher concentrations of SO_2 in the JBR than in a spray tower.

From the evaluation program it appears that this effect became important in the prototype unit at about 2500 ppm SO_2. This observation is reflected in the two equations. In Eq. 1-1, the SO_2 exponent is 0.11 while in Eq. 1-2 it is 5.26, which indicates that higher SO_2 concentrations have a much greater influence on the SO_2 removal efficiency.

Judging from the results of the half-factorial test matrix, no second-order variable interactions were significant. Pressure drop and pH exhibited strong primary effects, and because of this, fairly wide ranges of operating conditions can result in equivalent SO_2 removals. This is shown in Figure 1-3 which is a plot generated using Eq. 1-1. This figure indicates the SO_2 removal efficiency expected with an inlet flue gas SO_2 concentration of 2000 ppm at different combinations of ΔP and pH. The existence of these pH and ΔP tradeoffs can be important in optimizing the CT-121 system's operating costs.

Even though the flue gas flow rate and the oxidation air rate were not included in the predictive equations, under certain conditions these variables have a measurable impact on the SO_2 removal rate. The boiler variable load tests in Phase I indicated that flue gas flows lower than 30,000 scfm (13 Nm^3/s) resulted in an average SO_2 removal of 94% from a flue gas containing 1000-120C ppm SO_2.

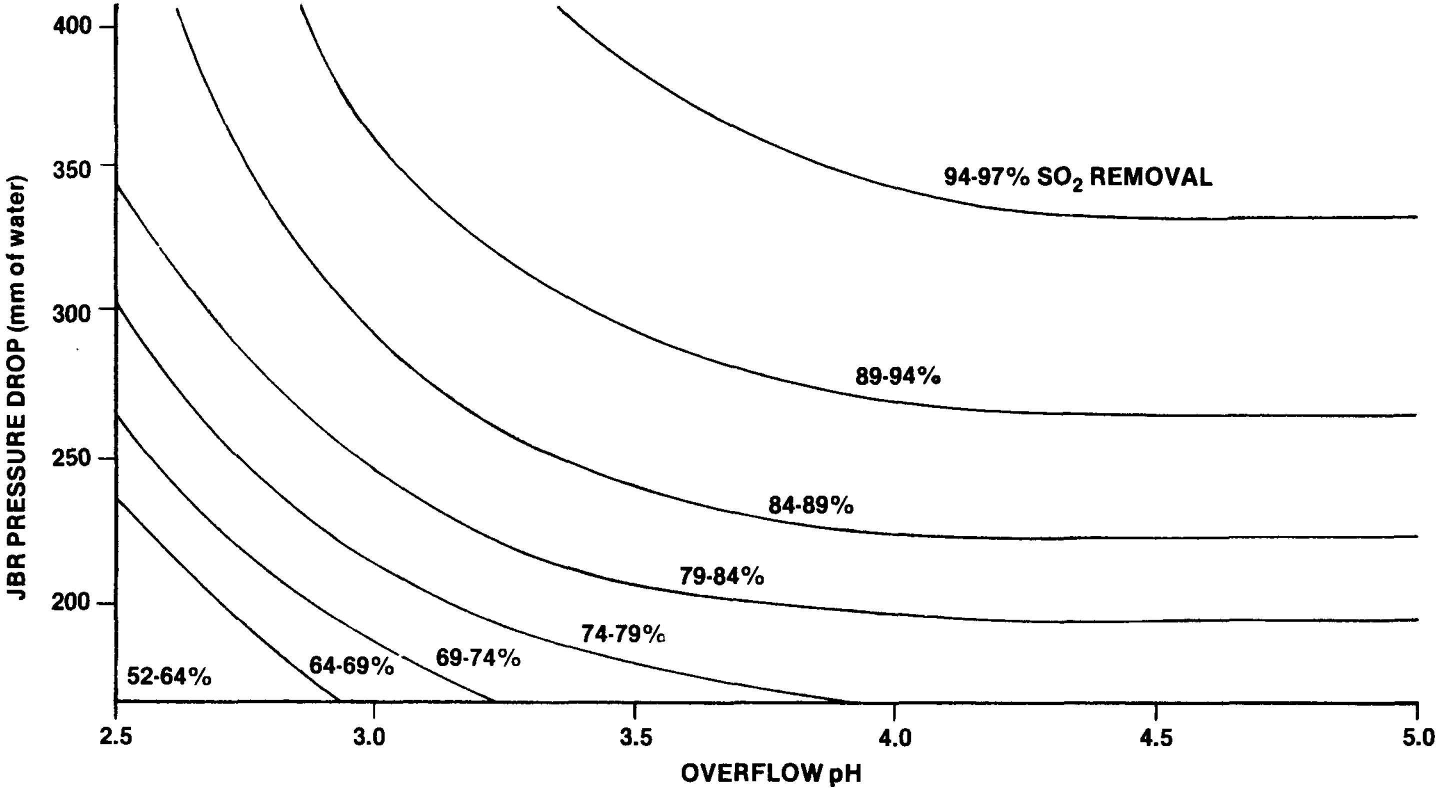


Figure 1-3
SO_2 Removal Percentage as a Function of pH and Pressure Drop Predicted
by Eq. 1-1 2000 ppm SO_2 Inlet Concentration

Flows of above 45,000 scfm (20 Nm^3/s) during the variable load test period resulted in an average removal of 90%. Unfortunately, there was not sufficient time to test the impact of low gas flows at different pH's, ΔP's, and SO_2 concentrations.

Results of several short term tests quantified the effect of air rate (O/SO_2 ratio) on SO_2 removal as shown in Figure 1-4. While no difference between 1000 and 1300 scfm air rates (O/SO_2 ratios ranging from 8 to 11) was seen in the statistical tests, Figure 1-4 shows a reduction in SO_2 removal efficiency to about 77% at an air rate of 480 scfm (0.2 Nm^3/s) (O/SO_2 about 4). With the air shut off, the SO_2 removal dropped to below 40%. In addition to the O/SO_2 ratio, distribution of air in the JBR (which is influenced by such factors as air sparger, mixer, and draft tube system designs) is also important in maintaining high oxidation. These design factors were not examined in detail in this evaluation program.

No effect on SO_2 removal was observed as the chloride level in the liquid slurry was increased from 1000 to 6000 ppm. Eq. 1-3 represents the SO_2 absorption mechanism.

$$SO_2\ (g) \overset{H_2O}{\rightleftarrows} H_2SO_3\ (aq) \rightleftarrows H^+\ (aq) + HSO_3^-\ (aq) \qquad (1\text{-}3)$$

The SO_2 mass transfer rate is maintained by rapid dissolution of limestone to maintain the desired pH and by rapid oxidation of the bisulfite ion to keep the SO_2 back pressure low. Since the increased chloride concentration from 1000 to 6000 ppm had no effect on SO_2 removal, the chloride ion apparently does not interfere with either the limestone dissolution or sulfite oxidation steps over the range of chloride concentrations tested.

Limestone Utilization. The observed limestone utilization in the CT-121 system was high. Overall for both phases of the evaluation, the utilization measured around the JBR remained above 98%. Varying the overflow pH set point or changing the limestone particle size did not cause a measurable change in the utilization. The JBR overflow pH was varied from 2.5 to above 4.5 during Phase II, and the limestone grind was changed from 90% less than 325 mesh (44 μm) to 90% less than 200 mesh (74 μm). Although the two limestones were obtained from different sources, the compositions were quite similar.

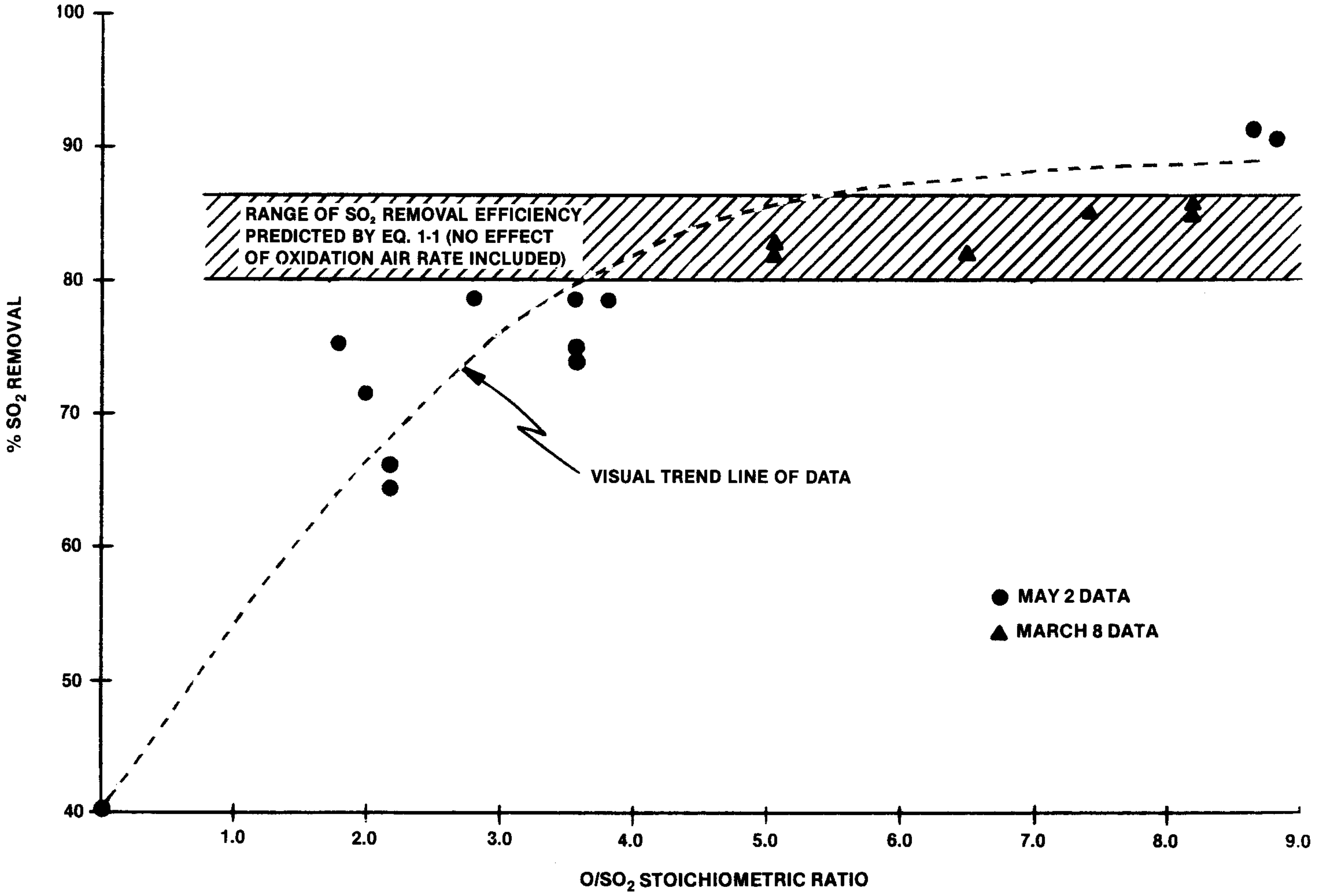


Figure 1-4
Low Oxidation Air Test Results - Phase II ($\Delta P = 9.0$ to 9.5″ H_2O; pH = 3.2 to 3.8; Inlet $SO_2 = 1400$-1600 ppm)

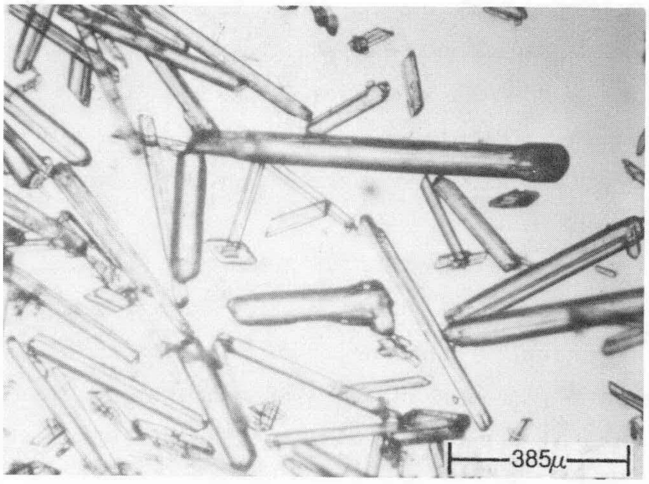
The overall utilization was also good even when one considers the limestone added to the gypsum tank for final neutralization of the gypsum slurry to a pH of 6. Optimization of this process step was not an objective of the program. The limestone flow to the gypsum tank was only occasionally adjusted manually; there were no on-line pH monitors or controllers. Samples indicated that the overall limestone utilization was somewhat lower in Phase II (∿93%) than in Phase I (>97%). The primary cause of the lower utilizations in Phase II was probably the result of changes in process conditions which could have easily upset pH conditions for neutralization.

Solids Characteristics/Gypsum Scaling Tendency. The solids produced in the JBR during the evaluation generally contained over 97% gypsum. There were no sulfite solids measured since the pH was always low enough that calcium sulfite would remain in solution until it was oxidized. Also, as discussed in the preceding limestone utilization section, there were only small amounts of calcium carbonate remaining in the JBR underflow slurry. The gypsum solids settled very rapidly with no measurable differences in the free-fall characteristics between samples.

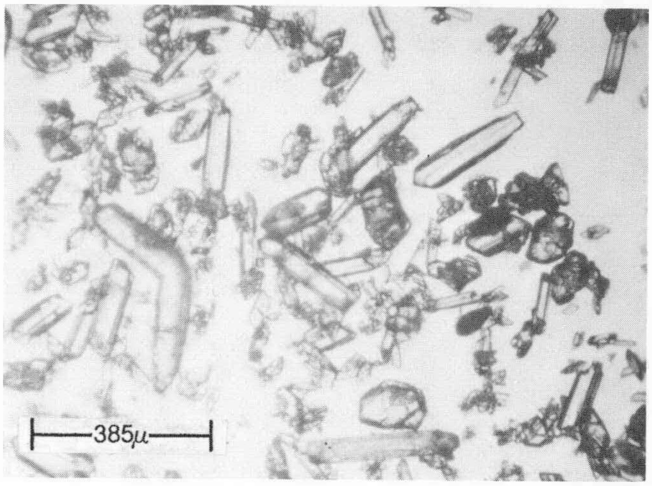
Figure 1-5 shows typical differences between solids formed when testing with lower sulfur coal (nominal 1.8% sulfur) and those formed with higher sulfur coal (nominal 3.2% sulfur). The crystals formed when cleaning the flue gas from the lower sulfur coal were long rod-shaped crystals. Many were over 400 μm in length with length to diameter (L/D) ratios from 10 to 20. The crystals produced with the higher sulfur dioxide loadings were less than 100 μm in length with L/D ratio from 2 to 5. This difference in crystal size can be explained by examining the general precipitation rate expression presented in Eq. 1-4.

$$R = k \cdot a \cdot V \cdot C \cdot (RS-1) \qquad (1-4)$$

where R is the precipitation rate, k is a temperature-dependent rate constant, a is the specific solid-liquid interfacial area of the crystal, V is the volume of the reaction vessel, C is the solids concentration, and RS is the relative saturation (product of the activities of calcium and sulfate ions divided by the solubility product). In a system where the reaction volume and the solids concentration are set, the surface area and the driving force would be expected to increase with increasing SO_2 removal rates. Figure 1-5 shows the results of doubling the SO_2 removal rate, which reduces the solid phase residence time by



JBR Underflow Solids 11/29/78
1.8 Percent Sulfur Coal



JBR Underflow Solids 4/13/79
3.2 Percent Sulfur Coal

Figure 1-5
Comparison of Solids Produced With Two SO_2 Loading

about 50%. Smaller crystals (which have a greater surface area per mass of solids) were formed in the tests with the shorter solid phase residence time.

Likewise, there was a general trend of rising gypsum relative saturation (precipitation driving force) with increasing SO_2 removal rate. When 1.8% sulfur coal was fired, the gypsum relative saturation (RS) in the JBR overflow remained between 1.0 and 1.1. With the 3.2% sulfur coal, the relative saturation ranged between 1.1 and 1.17. During the experiments with SO_2 inlet concentrations above 3000 ppm, the gypsum relative saturation of the overflow liquor was measured as high as 1.23.

These relative saturations would not be expected to lead to general scaling of the reactor since they are all less than the critical level of 1.3. Inspections at the conclusion of Phase II confirmed this. Scale deposition in the JBR was minimal. There were some random patches of gypsum scale on various surfaces, but none of the depositions were threatening system performance, and the scale thickness was less than 1/16 in. (2 mm). Even though the scale build-up was minimal, routine periodic cleaning (perhaps at boiler outages) might be necessary in a commercial application. The required cleaning frequency was not determined in the evaluation program, but nine months of operation was logged and no operating difficulties were experienced.

Two additional comments are pertinent to this discussion of scaling tendency. First, there was not sufficient operating time with 3000 ppm SO_2 concentrations to conclude that chemical scaling would not occur at this level. Sufficient time was logged with about 2200 ppm SO_2 inlet concentrations to determine that successful operation was possible under these conditions. For most of the test program, the prototype system operated with inlet SO_2 concentrations of less than 1500 ppm which resulted in gypsum solids residence times of 1.5 to 2 times that which Chiyoda feels are necessary for a commercial system. Operation with this safety factor during most of the program may have enhanced the prototype JBR's performance.

The second point is that solids control is extermely important in maintaining a nonscaling mode of operation. The higher the solids content, the less likely scale will form on scrubber surfaces. Solids stratification in the JBR due to the rapid gypsum settling rate means that the solids concentration is lowest in the froth area where the scaling potential is highest. Continual, low concentrations of suspended solids in the froth zone could cause scale buildup. It is apparent that sufficient seed crystals were maintained in the froth zone since minimal scale was observed at the conclusion of the test program.

During the high particulate loading test, the JBR solids were approximately half gypsum and half fly ash. No difference was noted in the gypsum crystal structure, nor was any significant change observed in the relative saturation. However, to insure that adequate gypsum surface area would be present for precipitation, the solids concentration set point was raised.

Phase III Results

After EPRI completed its evaluation program, Chiyoda performed some internal modifications on the JBR. These included:

- modifying the slurry mixing pattern in the JBR by removing the draft tube and reversing agitator movements
- increasing the flue gas flow through individual flue gas spargers by blanking off 40% of the spargers
- increasing the gas velocity through the gas-slurry disengaging section of the JBR by blanking off 60% of the gas risers
- enhancing flue gas quenching and cooling by adding slurry lines to the inlet gas chamber

The effects of these changes on the SO_2 removal efficiency appeared to be minor. Operation during Phase III resulted in SO_2 removal efficiencies which were 1 to 2% lower than those measured at equivalent set points in Phase II. It is likely that the higher gas rates through the flue gas spargers caused this lower removal, although the effect of a change in limestone feed line location cannot be ruled out. The effects of changes in inlet SO_2 concentration also seemed to be greater than those observed in Phase II, although this was not quantified.

The elimination of the draft tube apparently resulted in the bigger change in the system performance. The solids loading in the overflow remained between 3 and 6 wt% while the overflow solids in Phase II were above 8 wt% for equivalent conditions. The gypsum relative saturation in the overflow ranged between 1.15 and 1.3.

Other key tests during Phase III involved reducing the venturi liquid-to-gas (L/G) ratio and testing a vacuum filter for solid-liquid separation. The vacuum filter results are covered under the topic of gypsum disposal later in this section.

The test to determine the effects of reducing venturi L/G required the venturi recirculating liquor pump (600 gpm, 0.04 m^3/s) to be turned off. However, the flue gas continued to be sprayed with 40 gpm (0.0025 m^3/s) of pond water and 15 gpm (0.0009 m^3/s) of fresh makeup water. The purpose of the test was to simulate the effect of a spray quench on JBR performance.

Although about 3 times the amount of water required to saturate the gas was added, the gas-liquid contact was such that the flue gas was only partially saturated. The gas temperature was cooled to about 150°F (66°C) compared to a saturation temperature of about 130°F (54°C). Inspection at the end of the program showed areas of dried solids above the openings in some of the gas spargers. These areas of solids deposition could have been caused by slurry splashing up and drying in the partially saturated gas. Other spargers which had a spray wash system above them did not have significant internal deposits. The results of this test emphasize the importance of adequate flue gas cooling to prevent interface problems in the spargers.

Overall, the Phase III testing showed that 1) a reduced number of spargers and gas risers could be used with only a minimal impact on SO_2 removal efficiency and 2) insufficient flue gas saturation may create plugging problems.

EPA Performance Parameters

The four performance parameters employed by EPA to measure an FGD system's reliability are presented in Table 1-2. The overall figures include both the Phase 0 shakedown and the Phase III test period. Both of these periods involved some planned outages which penalized both the operability and utilization factors. However, during the EPRI program, (Phases I and II) all four factors were extremely good -- there were only 22 hours of forced outages during the EPRI evaluation program, of which 21 hours were due to limestone feeder problems. When inspection time was added to the total downtime, the fraction of the period in which the FGD system operated was 97.3%, as reflected in the utilization factor for Phases I and II.

Table 1-2

CT-121 RELIABILITY PARAMETERS

Parameter	Overall Program 8-30-78 → 6-29-79	EPRI Program 11-15-78 → 5-22-79
Availability[a], %	98.8	99.3
Reliability[b], %	99.6	99.5
Operability[c], %	90.0	97.3
Utilization Factor[d], %	90.0	97.3

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[a] Availability - Hours the FGD system is available for operation (whether operated or not), divided by the hours in the period.

[b] Reliability - Hours the FGD system was operated divided by the hours the FGD system was called upon to operate.

[c] Operability - Hours the FGD was operated divided by the boiler operating hours in the period.

[d] Utilization Factor - Hours that the FGD system operated divided by total hours in the period.

These performance parameters indicate the CT-121 prototype performed with exceptional reliability during the evaluation program. These figures cannot be used to accurately predict the performance of a commercial system, but the evaluation program indicates that a properly designed CT-121 system could be expected to operate with a minimum of process or mechanical problems.

During the program, the CT-121 system was operated by local operators who had been trained by Chiyoda. Chiyoda supervisory personnel were present only during the day shift. Approximately 2200 maintenance manhours were charged during the ten month program (Phases 0 through III).

Gypsum Disposal

The gypsum produced was disposed in a gypsum stack similar to ones used in the phosphate industry. Ardaman & Associates Inc. of Orlando, Florida designed and constructed the gypsum stack under a separate EPRI Project (RP536-3). The results of this work are discussed in detail in Vol. III of this report. Figure 1-6 is a picture of the final stack configuration. Although there was some initial sloughing at the base of the stack, the performance of the stack to date has been good. The gypsum settled to about 70 wt% solids under the water surface. As the stack walls were raised by dredging the solids from the pond in the middle of the stack, the gypsum at the top of the stack increased to over 90% solids. The liquor was decanted from the stack to a holding pond and then pumped back to the process.

During Phase III, Chiyoda tested a 1 ft. Bird-Young high-speed rotary vacuum filter. This filter was capable of processing between 1.5 and 2.0 t/h of gypsum. The JBR underflow stream was used as the feed stream without employing a thickener. The filter cake was typically 85 wt% solids after about two seconds residence on the filter. A 40 μm x 40 μm filter cloth was used, which resulted in a cloudy filtrate indicating the presence of some suspended solids in the filtrate.

Chiyoda has conducted some wallboard and cement utilization studies with some of the solids produced in the evaluation program. These tests show that the CT-121 gypsum can be made into wallboard or used in the production of cement. The wallboard manufacturers reported little difference between the natural and FGD-produced gypsum products. Results of the various tests are presented in Appendix J.

Mist Eliminator Performance

The mist eliminator performance during the program deserves special mention. The mist eliminator was composed of two banks of chevron blades mounted in a horizontal run of duct downstream of the JBR. The mist eliminator was washed on an average of once a week for one minute with about 300 gpm (0.019 m^3/s) of pond water. No signs of gypsum scaling or plugging were noted during the program.

This excellent performance is attributed to two major factors. First, the superficial gas velocity leaving the froth zone of the JBR was only about 2 ft/s (0.6 m/s), resulting in most of the entrained slurry being separated from the flue gas in the interior of the JBR or in the JBR outlet gas chamber. Secondly, the slurry escaping the JBR contained very little solid phase alkalinity ($CaCO_3$ or $CaSO_3$).

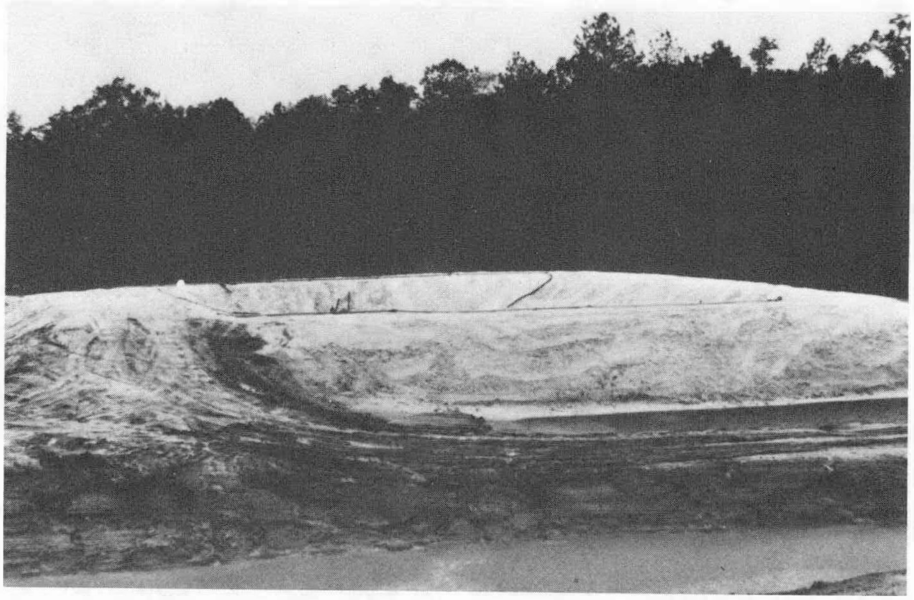

Figure 1-6
Filled Stack, End of Phase II 5/22/79

Therefore, the dissolution of calcium solids and subsequent sorption of SO_2 on the mist eliminator blades which has caused scaling problems in many systems did not occur in the CT-121 prototype.

System Water Balance

During the evaluation program, the system's water balance was closely monitored. A rain gauge and evaporation pan were used to measure the daily rainfall or evaporation rate, and flows from the gypsum stack-pond area were measured to estimate any outflows.

Freezing and rainy weather forced the operators to run the system open-loop for a few days in late December and during much of January and early February. In late December, rainfall filled the gypsum stack liquor collection pond, and the pond started overflowing to the Gulf Power ash pond. During early January, it was necessary to circulate fresh water through exposed supernatant return pipes to avoid freezing and bursting. Excess water overflowed to the Gulf Power ash pond at an estimated average rate of 7.5 gpm (0.0005 m^3/s) during December-February.

During Phase II the pond overflow pipe was sealed to better monitor the water balance. Once the freezing weather subsided, intentional outflows from the pond were recorded when the gypsum stack was raised. No unintentional outflows were observed. In a commercial design, provisions could be made at the gypsum stack site to eliminate the need for excess liquor discharge.

During Phase II, the liquor overflow from the CT-121 gypsum stack holding pond to the Gulf Power ash pond averaged about 2.4 gpm (0.0002 m^3/s). Most of this occurred in January and February. A concerted effort was made to use more pond water in the last three months of Phase II. Fresh water to the venturi was reduced. At the same time, both the pond water rate to the venturi and the bleed rate from the venturi were increased to minimize the scaling potential in the venturi recycle stream. Pond water was also employed as seal water for two sets of pumps for almost 3 months at the end of Phase II. All pumps sealed with pond return water performed acceptably, although the seal design were somewhat different from typical lantern ring and packing seal systems (see Section 5.0 - Equipment Performance). During the final month of Phase II, these steps resulted in a net reduction of 2.6 gpm (0.0002 m^3/s) in the amount of fresh water required by the process.

Trace Elements and Particulate Testing

One of the Phase II tests measured the CT-121 system's particulate removal capability and determined the fate of trace elements in the system. This task was performed because of EPRI's interest in the fate of trace elements in lime/limestone FGD systems. Results show that:

- The venturi-JBR combination removed 99.4% of the inlet particulate (inlet loading = 3.4 grains/scf)
- An increase in particulate matter larger than 4 μm in diameter was seen across the JBR; a damaged mist eliminator from the initial CT-101 demonstration may have been partly responsible for this (see Section 6).
- Ninety-nine percent removal of 10 trace metals was seen (Ca, Mg, Ti, Cr, Cu, Pb, Ni, V, Be, Zn).
- Approximately 90% removal of the remaining 5 volatile metals (As, Sb, Cd, Hg, Se) was observed.
- Greater than 95% of the chloride in the coal is found in the gas phase after combustion; removal of 92% of the gas phase chloride was seen across the scrubbing system.

Two points which should be discussed with respect to particulate removal in the CT-121 system are the JBR's particulate removal capability and the effect of fly ash in the slurry.

During this test the electrostatic precipitator was totally deenergized, but the prequench venturi remained in service to protect the reinforced plastic duct downstream of the venturi. As a result, the inlet grain loading to the JBR was only about 0.025 grain/scf (57 mg/Nm3) and consequently the JBR itself showed only 40% particulate removal. It is difficult to assess how the JBR would perform with a higher inlet grain loading. To simulate capture of all the fly ash by the JBR, the fly ash removed by the venturi was pumped to the JBR. No significant amounts of fly ash reentrainment from the froth layer were observed. However, since capture of particulates from the gas phase is accomplished by a different mechanism than that involved in reentrainment of particles from the liquid phase, no conclusions can be made as to the JBR's effectiveness as a primary particulate removal device based on these test results.

No noticeable effect on the process chemistry was seen as a result of the high fly ash loadings. The slurry solids were approximately half gypsum and half fly ash. During this test period, the inlet SO_2 concentration was about 1500 ppm and a gypsum relative saturation of about 1.1-1.15 resulted. This is the approximate relative saturation range seen previously with this SO_2 level. Had the SO_2 level been higher, the displacement of gypsum solids by fly ash might have increased the relative saturation and the potential for scale formation.

Instrument Performance

Key instruments in the CT-121 system functioned acceptably during the program. A potentiometer malfunction in the outlet gas Du Pont SO_2 analyzer resulted in the automatic zero function being out of service for most of Phase I. This was not a major problem since more attention was given to the Du Pont instrument in Phase II as a result. The system needed manual calibration only once per week. There were occasionally some low readings recorded which indicated leaks in the sampling lines. On the whole, however, the SO_2 analyzer and sampling system functioned well.

The JBR pH and underflow solids concentration measurements are important control parameters. The pH measurement was made with a dip sensor at the overflow weir. A neoprene wiper was used continuously to keep a stagnant film from building up around the probe. This instrument was checked daily and calibrated weekly. The pH measurement was judged to be quite reliable throughout the entire program. A Kay-Ray on-line nuclear density meter for measuring slurry solids concentration was installed during Phase II. In general, this instrument performed acceptably. System operators also manually measured the solids concentration once every four hours.

Finally, a Polysonics Flow Meter (Model UFM-PD) was evaluated during the program for measuring slurry flow rates. This is a noninvasive flowmeter with a single transponder which related an ultrasonic frequency Doppler shift due to slurry flow to the actual velocity in the pipe. The instrument was easy to use, accurate, and portable. Since a portable unit was tested, however, information concerning the reliability and resistance to weather and other continuous operating hardships was not obtained. The instrument also does not perform on homogeneous streams such as clear liquids, because solids or gas bubbles are required for correct flow readings.

Corrosion Test Results

Test spools of various metal coupons prepared by Radian and the International Nickel Company were placed throughout the system. Nearly all of the specimens showed good corrosion resistance in three locations: the JBR liquid, the outlet gas from the JBR, and the stack gas. Most of the samples placed in the venturi liquid and venturi outlet gas streams were significantly affected because of the low liquor pH (1.9 to 2.5). Only the Inconel 625, Uddeholm Type 904L and Hastelloys G and C-276 showed no adverse effects in these two locations.

CONCLUSIONS

Based on the results of the CT-121 evaluation program, the following conclusions can be drawn:

1. The CT-121 prototype system operated reliably and efficiently under a variety of test conditions. After 9 months of testing, only a minimum of scale deposition was seen on the JBR internals. It is reasonable to expect that a properly designed commercial CT-121 system should also give reliable performance.

2. The CT-121 system has several potential advantages over conventional lime/limestone FGD systems. These include:

   --The lack of large slurry recirculation pumps, slurry nozzles, slurry screens, or thickeners significantly simplifies the CT-121 system design. This simplified process flow scheme and the proprietary JBR gas-liquid contact mechanism should improve FGD system reliability and allow the CT-121 system to operate successfully over a wide range of process conditions.

   --Operation at design pH's in the JBR results in high limestone utilization (98% with either 200 or 325 mesh limestone).

   --JBR design results in low slurry entrainment in the gas. The low entrainment and high limestone utilization in the JBR enhance mist eliminator performance and reliability.

   --The low scrubber profile and compact design (elimination of thickener and separate absorber reaction vessels) may reduce FGD system capital costs.

   One application in which the CT-121 system may encounter operating difficulties involves scrubbing the flue gas resulting from combustion of a low-sulfur, high-ash coal. If the JBR is used for combined particulate and SO_2 removal, the gypsum production rate must be high enough and the crystallizer section of the JBR must be large enough to maintain adequate seed crystals in the slurry; otherwise, scaling could occur. In certain applications, the coal/ash/sulfur ratio may be sufficiently high that a separate JBR and dry particulate control device would be more economical than combined particulate and SO_2 removal in the JBR.

3. pH and ΔP are the most important variables that influence SO_2 removal. There are a number of pH and ΔP combinations which can give equivalent SO_2 removal efficiencies. Variations in pH between 2.7 and 4.5 do not affect the process operability but do significantly change SO_2 removal efficiency. SO_2 removal of 96.5% was obtained during a short test with an SO_2 inlet concentration of about 1900 ppm, pH 4.3 and ΔP of 15 inches of water (3.8 kPa). Over 90% removal was routinely obtained with 2000 ppm of SO_2 at pH 4.0 and a pressure drop of 11.5 inches (2.9 kPa).

4. The solids produced in the program were generally contained over 97% gypsum by weight. No sulfite solids were measured and the limestone utilization in the JBR averaged above 98%. The gypsum crystals exhibited rapid settling rates. Gypsum stacking and gypsum use for wallboard production appear to be acceptable means of disposing of the CT-121 gypsum. A vacuum filter was also successfully demonstrated as an alternate solid-liquid separator.

5. With this prototype JBR design, inlet SO_2 concentrations of 3000 to 3500 ppm were treated without producing scale in the JBR, although long duration runs were not made with SO_2 concentrations this high. Long duration runs were conducted with inlet gas concentrations of 2200 ppm SO_2, and inspections revealed only minimal amounts of scale deposits at the end of Phase II. However, it should be noted that a significant portion of the program was conducted with inlet SO_2 concentrations of less than 1500 ppm, which resulted in gypsum solid phase residence time in the JBR of 1.5 to 2 times that which Chiyoda plans for commercial units. Operation with this safety factor during portions of the program undoubtedly enhanced the prototype JBR's ability to operate without scaling problems.

6. In combination, the venturi-JBR system removed an average of 99.6% of an inlet particulate loading of 3.4 grains/per standard cubic foot. Removal was measured for 15 trace metals found in the inlet flue gas. Better than 99% removal from the flue gas was observed for 10 of the less volatile metals.

Section 2

INTRODUCTION

The Electric Power Research Institute (EPRI) is interested in identifying and promoting flue gas desulfurization (FGD) technology which can best meet the requirements of its member utilities. Earlier work sponsored by EPRI and Southern Company* has evaluated three FGD process technologies, including the Chiyoda Thoroughbred 101 System (CT-101) (see EPRI Report FP-713-SY, Project 536-1). Innovations to the CT-101 process by Chiyoda Chemical Engineering and Construction (CCEC) Company has produced the Chiyoda Thoroughbred 121 System (CT-121). A preliminary evaluation of the CT-121 Process indicated that this system was sufficiently promising to warrant an evaluation of its applicability to coal-fired utility boilers.

The salient feature of the CT-121 process is the Jet Bubbling Reactor (JBR) which incorporates the absorption, oxidation, neutralization, and crystallization steps in one process vessel. As a result of this novel design concept, the capital and operating costs may be favorable compared to competing technologies. Based on these potentially favorable characteristics, Gulf Power, Southern Company Services (SCS), and EPRI entered into an agreement with CCEC and their American subsidiary, Chiyoda International Corporation (CIC), to operate, test, and evaluate a prototype system at Gulf Power's Scholz electric generating station. This prototype was constructed by modifying the existing CT-101 equipment at Scholz to incorporate the CT-121 Process.

EPRI's role in this program was to ensure that an adequate objective evaluation was conducted and that the information derived from the evaluation would be distributed in a timely manner and be of maximum benefit to the utility industry. In this capacity, EPRI contracted with SCS to perform an evaluation of the CT-121 Process. SCS, in turn, subcontracted to Radian Corporation to act as an independent test and evaluation contractor for the program. SCS also contracted with Ardaman and

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*The Southern Company electric system is an electric utility holding company operating in the Southeast. It includes Alabama Power Company, Georgia Power Company, Gulf Power Company, Mississippi Power Company, and Southern Company Services, Inc.

Associates (EPRI Project 536-3) to test the feasibility of disposing the gypsum produced by the CT-121 system in a gypsum stack, a disposal method commonly employed in the phosphate fertilizer industry. The technical process evaluation conducted by Radian is included in Vols. I and II of this report while Ardaman's gypsum stack work is documented in Vol. III.

The test and evaluation portion of this program was divided into four test phases:

- Phase 0 - Three-month process start-up and line out testing conducted by Chiyoda.
- Phase I - Two-month duration baseline testing at Chiyoda's specified conditions to quantify some of the control variable fluctuation that might be encountered during routine operation.
- Phase II - four-month duration test series over a wider range of variable set points to evaluate system response under operating conditions that are representative of a broad scope of utility applications.
- Phase III - Three-week duration testing by Chiyoda after meeting potential cost saving internal modifications to the JBR and with a vacuum filter for gypsum dewatering.

The information derived from this evaluation program is presented in this document as follows:

Section 2.0 - Summary

Section 3.0 - Process Description

Section 4.0 - Test Plan

Section 5.0 - Results

Section 6.0 - Particulate Testing and Trace Element Sampling

Section 7.0 - Comments on CT-121 Commercialization

Section 8.0 - Gypsum Stacking

Section 9.0 - References

In addition, the detailed data, sampling and analytical procedures, statistical analysis equipment descriptions, gas phase SO_2 analysis system description, and results of gypsum utilization studies are presented in Appendices A through J.

Section 3

PROTOTYPE SYSTEM DESCRIPTION

This section describes the Chiyoda CT-121 prototype system which has been built and operated at the Scholz Plant of Gulf Power Company. The power system at Scholz includes two Babcock and Wilcox 40 megawatt (MW_e) nominal pulverized coal-fired boilers. The ductwork is arranged so that flue gas from either boiler can be directed to Chiyoda's CT-121 prototype plant which is designed to handle about 53,000 scfm (about one-half of the full load gas flow from one boiler).

The operating philosophy of the CT-121 process has evolved from Chiyoda's experience in SO_2 scrubbing including the development of the CT-101 process which had been demonstrated at Scholz in an earlier program (5). At the heart of this scrubbing concept is Chiyoda's proprietary absorber-reaction vessel, the jet bubbling reactor (JBR). Since Chiyoda's primary objective was to demonstrate the application of the JBR concept at a semi-commercial scale, equipment from the existing CT-101 demonstration plant was modified as needed for the CT-121 testing.* For this reason, the CT-121 system tested at Scholz did not incorporate all of the features that a commercial CT-121 system might include. Also, since this was the first commercial CT-121 system, it was designated as a prototype unit. This distinction should be kept in mind since the difficulty in extrapolation of prototype unit data at times limited the evaluation of some proposed commercial design concepts. Section 7 describes briefly some of the differences Chiyoda has proposed for a commercial system which were not present at Scholz.

The remainder of this section will describe in some detail the prototype system which was actually tested during the evaluation program. A flow schematic which presents the overall process is shown in Figure 3-1. To facilitate the system description, the process has been divided into the following general areas:

- Flue gas handling system
- Venturi quench system

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*The CT-101 system is a commercially proven process being used at 13 sites in Japan.

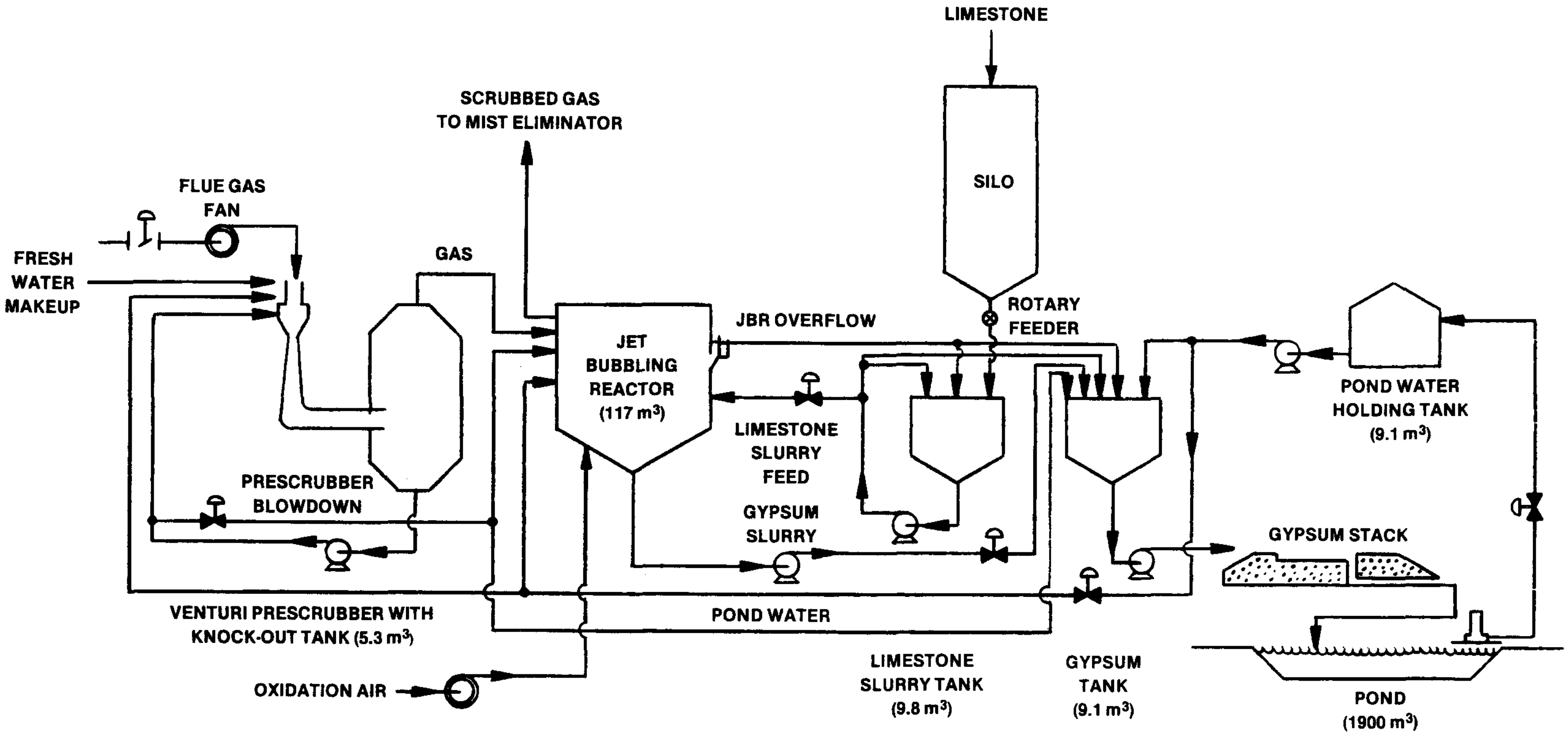

Figure 3-1
Simplified Process Flow Diagram of Scholz Prototype CT-121 Flue Gas Scrubbing System

- JBR operation
- Limestone addition system
- Gypsum disposal system
- Mist eliminator operation

Each of these areas is discussed in the following subsections.

FLUE GAS HANDLING SYSTEM

Boiler flue gas first passes through a high efficiency electrostatic precipitator. The ductwork is designed so that gas may be directed either to the CT-121 system or up the Scholz stack. The flue gas split is determined by a set of guillotine dampers. This identical arrangement for both boilers allows gas to be sent to the CT-121 system from either Unit 1 or 2.

In addition, the scrubber operator controls another damper system upstream of the CT-121 system's forced draft fan. By adjusting this damper setting the scrubber operator can set the gas flow to the CT-121 system within certain limits. The maximum gas flow, which is limited by the fan output pressure, is about 53,000 scfm (about 23 MW_e) under normal JBR operation. As a result of fan vibration at lower gas flow rates, the minimum flow is about 25,000 scfm (about 10 MW_e).

After passing through the fan, the gas flows to a fixed-throat venturi contactor. Here, the gas is cooled by adiabatic saturation from about 300°F (150°C) to 120-130°F (49-54°C) with a combination of fresh water and pond water (supernatant from the gypsum stack).

From the venturi, the gas flows through a fiberglass duct to the jet bubbling reactor (JBR). SO_2 removal, neutralization with limestone, oxidation of sulfite to sulfate, and gypsum crystallization are all accomplished in the JBR.

The gas exiting the JBR first passes through a gas-slurry disengaging chamber at the top of the JBR vessel. Then, the gas passes through two banks of vertical chevron mist eliminators to achieve final gas-slurry separation before exiting the system through a fiberglass duct and stack. The prototype system has no provisions for reheat.

Normally, the inlet flue gas treated by the CT-121 prototype system ranged between 1000 and 2500 ppm in SO_2 concentration. This resulted from combustion of coals containing between 1.5 and 3.5 weight percent sulfur. The flue gas was also spiked with SO_2 to a level of 3500 ppm for brief periods during the program. A Southern Company Services designed SO_2 extractive sample conditioning system utilizing Dupont model 400 analyzers continuously monitored the inlet and outlet flue gas SO_2 content.

VENTURI QUENCH SYSTEM

The venturi quench system was part of the original CT-101 demonstration system. To conserve capital costs, the venturi was incorporated into the CT-121 system to saturate the flue gas before it entered the JBR. The venturi was not intended to be a primary particulate removal device since there are ESP's upstream. In addition, although there were physical means of isolating the prescrubber liquor from the rest of the system (i.e. pumping prescrubber liquor to the Scholz station ash pond), no liquor segregation was attempted during the program. Prescrubber blowdown was either pumped to the JBR, to the sump, or directly to the gypsum tank. In all cases, the prescrubber liquor was neutralized either in the JBR or directly in the gypsum tank where it was mixed with other system liquors.

When the system was operating at full load, gas flow through the venturi resulted in about 8 to 9 inches water gauge (2000-2250 N/m^2) of gas side pressure drop. This provides excessive gas-liquid contact for saturating the flue gas, but as stated before, the venturi was pre-existing and not designed specifically for the gas saturation function required in the CT-121 system. Temperature indicators in the ducts at the inlet and outlet of the venturi were used by system operators to ensure proper venturi operation and to protect the fiberglass duct downstream of the venturi from a temperature excursion.

Figure 3-2 shows typical stream flows around the venturi system at the end of the program. About 15 to 20 gpm (57-76 ℓpm) of water was theoretically required to saturate the flue gas when the system was operating at full load. Two sources of prescrubber makeup water were used: 1) fresh plant water and 2) pond water. Approximately 10 to 15 gpm (38-57 ℓpm) of fresh water was added through a distribution ring directly above the venturi-throat. Pond water was added to the system through a separate nozzle above the throat at a rate of 35-40 gpm (132-151 ℓpm).

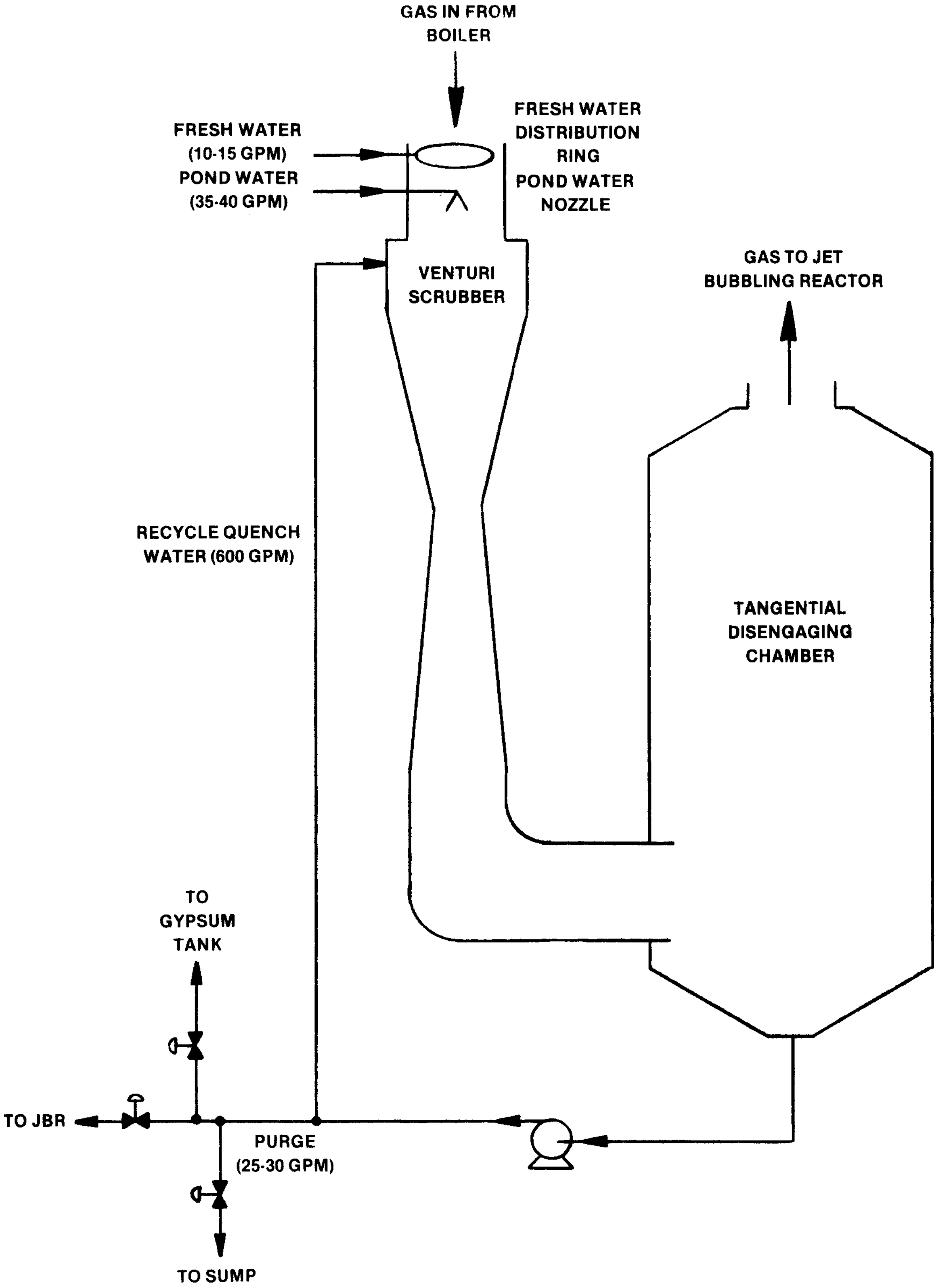

Figure 3-2
Venturi Quench System Flow Diagram

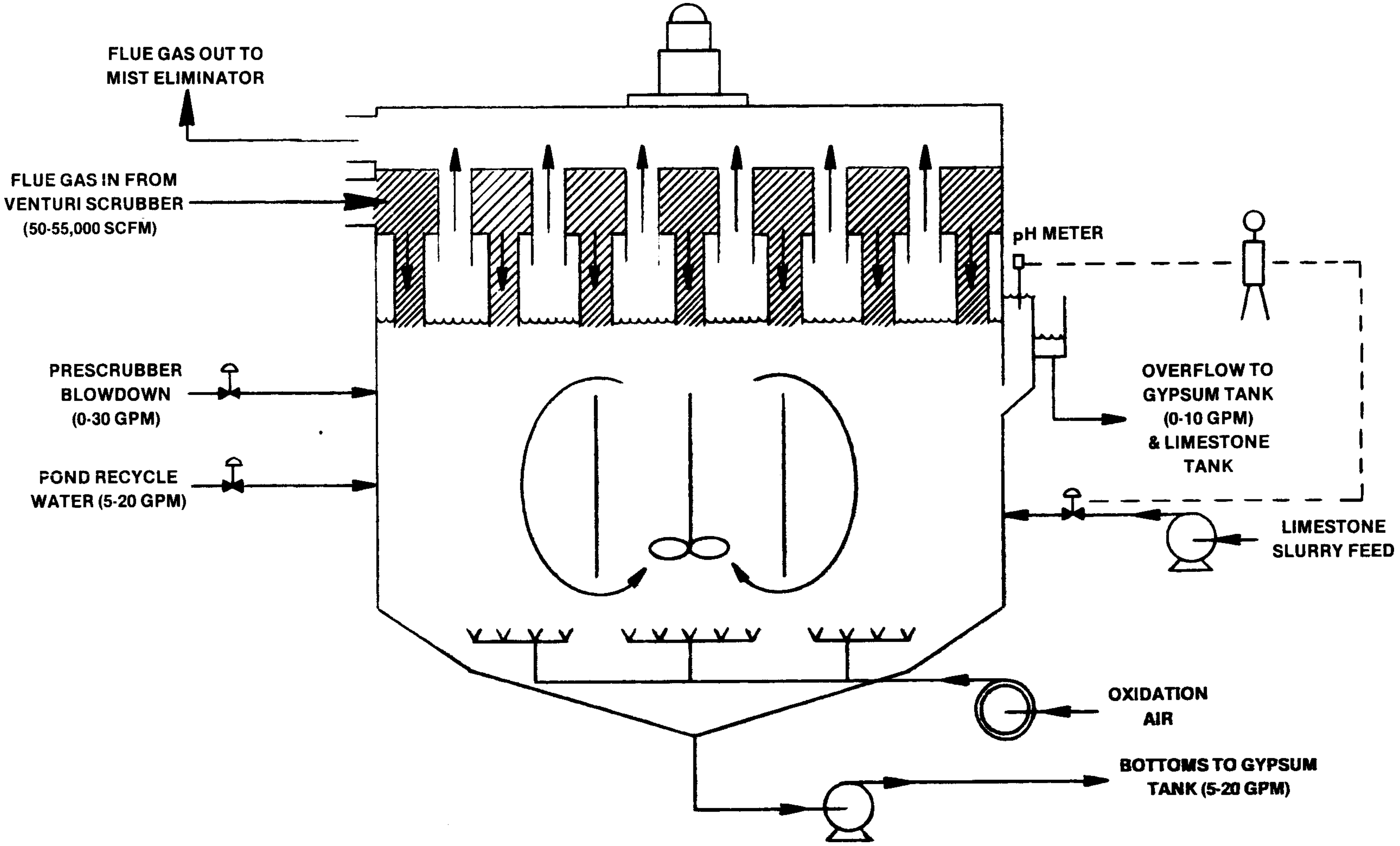

Figure 3-3
Schematic of Jet Bubbling Reactor (JBR)

About 600 gpm (2270 ℓpm) of venturi recycle water was added through tangential ports above the throat to ensure saturation. The gas and liquid separate in a tangential disengaging chamber with the gas flowing to the JBR and the liquor being recirculated to the venturi throat. Venturi liquor was purged from the prescrubber to prevent excess gypsum supersaturation due to evaporative concentration of the pond water. The pH ranged from 1.9 to 2.5 during the course of the program being dependent on the purge rate. Minimal SO_2 removal in the venturi was achieved at this low pH (<1 percent). Section 5 discusses the problems encountered with the venturi level controller during the early part of the program.

JET BUBBLING REACTOR SYSTEM

As stated previously, the JBR is the key equipment item in the CT-121 system. In this vessel, there are a number of mass transfer operations occurring simultaneously:

- SO_2 transfer from the gas to the liquid phase.
- Neutralization of sulfurous acid by limestone addition and dissolution.
- Oxidation of liquid phase sulfite to sulfate.
- Gypsum crystallization and growth.

Each of these steps is important in the operation and control of the JBR. Figure 3-3 is a schematic of the JBR which will be used for discussion purposes below. Figure 3-4 is a photograph of the JBR at Scholz.

Gas-Liquid Distribution

The first step in achieving good SO_2 removal is establishing efficient gas-liquid contact. In the CT-121 system, efficient gas-liquid contact is accomplished by dispersing the gas into the slurry rather than spraying the slurry into gas as is done in existing lime/limestone systems. As a result, large recirculating slurry pumps are not required and pumping energy is saved. However, the gas-side pressure drop is greater in a CT-121 system than in a typical spray tower.

The saturated gas from the venturi prescrubber enters the JBR through the inlet gas chamber which distributes the gas into a number of flue gas sparger tubes. Pressure forces the gas below the slurry level in the JBR where the gas enters the slurry horizontally through openings located in each sparter. The injection of gas beneath the surface of the slurry creates a froth layer in which SO_2 mass transfer is enhanced.

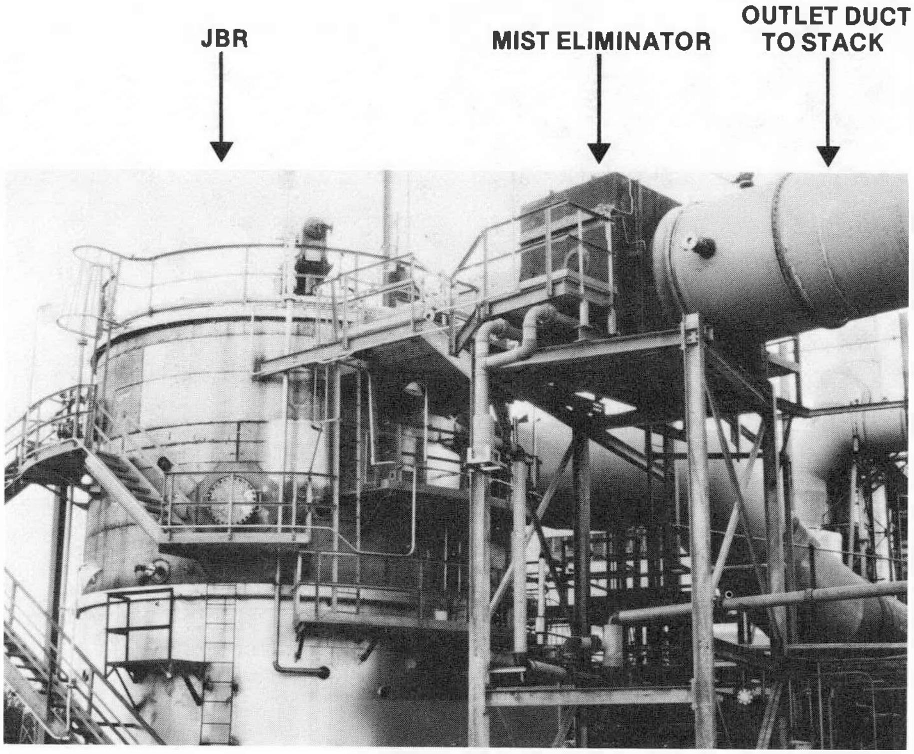

Figure 3-4
Jet Bubbling Reactor, Gas Ducts, and Mist Eliminator

The mass transfer in this froth layer is influenced by both the velocity of gas through the sparger openings and the height of the froth layer. The gas velocity affects the size of the gas bubble which is formed, the superficial gas velocity ($m^3/hr \cdot m^2$), and therefore the mixing in the froth layer. The velocity through the spargers must be sufficiently high to ensure jet bubbling. For a given JBR-sparger design, the gas velocity and therefore the dynamic pressure drop through the spargers, will remain constant if the gas flow does not change. This pressure drop through the sparger openings impacts the gas liquid mixing in the froth layer and the bubble size which sets the specific gas-liquid interfacial area. Increases in pressure drop (velocity) increase the mixing and interfacial area and therefore make SO_2 transfer more efficient. Chiyoda has reported that the escaping bubbles range from 1/8 to 7/8 inch (3-22 mm) in diameter (6). This approximate size range has been verified by observation through sight glasses on the JBR.

The height of the froth layer also affects the SO_2 removal efficiency by setting the gas liquid contact time and therefore the hydrostatic pressure drop. Higher froth layers and longer residence times generally result in greater SO_2 mass transfer. The height of the froth layer can be changed in the CT-121 prototype system by altering the setting of the overflow weir which controls the level of sparger immersion. However, this was a manual change not easily accomplished during steady-state operation. Chiyoda has designed an automatic weir system for commercial units which will permit the pressure drop to change as needed for SO_2 removal.

The pressure drop across the JBR was varied between 5 and 15 inches (127-381 mm) of water gauge during the program by setting the weir at different heights. However, for most of the program the ΔP was maintained between 10 and 13 inches (254-330 mm).

Neutralization

As SO_2 is absorbed into the slurry, the liquid phase reactions shown in Eq. 3-1 occur quickly.

$$SO_2(g) + H_2O \rightleftarrows H_2SO_3(aq) \rightleftarrows H^+ + HSO_3^- \rightleftarrows 2H^+ + SO_3^= \qquad (3\text{-}1)$$

Since the liquid-liquid reactions are rapid compared to gas-liquid or solid-liquid reactions, the liquid phase approaches equilibrium steady-state conditions. In order to maintain a driving force for SO_2 sorption, the CT-121 system relies on: 1) forced oxidation to reduce the amount of sulfite in solution (this topic is discussed in the next section) and 2) neutralization to control the hydrogen ion (H^+) concentration. The depletion of the sulfite ions by oxidation and the H^+ ions by neutralization allows continuing SO_2 removal. It can be seen in Eq. 3-1 that if the $SO_3^=$ and H^+ concentrations are lowered by oxidation and neutralization, respectively, the system will seek to reestablish equilibrium by allowing more sulfite and hydrogen ions to form. This results in greater SO_2 removal.

The pH in the JBR is controlled by the addition of limestone. The pH generally remains fairly uniform throughout the JBR due to mixing by both oxidation air and the agitator. At Scholz the overflow stream pH was recorded in the CT-121 system control room, and the operator manually adjusted the rate of limestone fed to the JBR to respond to changes in pH.

The effect of $CaCO_3$ dissolution can be represented by the following set of reactions:

$$CaCO_3(s) \overset{H_2O}{\rightleftarrows} CaCO_3(aq) \rightleftarrows Ca^{++} + CO_3^= \qquad (3\text{-}2)$$

$$CO_3^= + H^+ \rightleftarrows HCO_3^- \qquad (3\text{-}3)$$

$$HCO_3^- + H^+ \rightleftarrows H_2CO_3 \rightleftarrows H_2O + CO_2(g) \qquad (3\text{-}4)$$

Eqs. 3-3 and 3-4 involve the neutralization of the hydrogen ions that are present. As $CaCO_3$ is added to an acidic slurry, the $CaCO_3$ dissolves and the CO_3 ion acts as a proton acceptor and tends to raise the pH. At sufficiently low pH's the equilibrium is shifted in favor of the H_2CO_3 species and most of the solid phase $CaCO_3$ dissolves. As a result, the pH is very sensitive to the amount of $CaCO_3$ solids added. As additional $CaCO_3$ solids are added, the pH rises and the HCO_3^- and $CO_3^=$ concentrations increase. If enough $CaCO_3$ solids are added, the liquid phase becomes buffered by the carbonate-bicarbonate-carbonic acid shifts, and the effect of $CaCO_3$ solids addition on pH is diminished. Any further addition of limestone solids does not raise the pH or increase the SO_2 removal capability. As a result, the limestone utilization decreases substantially. Below pH's of 5.0, however, the utilization increases to near 100 percent. This is due to the increased limestone solubility as the bicarbonate ion becomes the predominant specie.

Sulfite Oxidation

Although operation at a low pH allows the system to operate with good limestone utilization, acidic pH's usually result in decreased SO_2 removal efficiency because the H_2SO_3 concentration increases rapidly. The CT-121 system maintains the driving force for SO_2 absorption at a low pH by oxidizing the dissolved sulfite to sulfate. The oxidation reaction is enhanced by the low pH.

Oxidation air was added through sparger rings located in the cone-shaped bottom section of the JBR. The air is mixed throughout the tank both by action of the rising air itself and the agitator-draft tube system in the center of the JBR. This mixing action ensures that the remaining unoxidized sulfite absorbed in the froth layer is dispersed throughout the tank and oxidized. The mixing also ensures that liquor that is lower in dissolved sulfite is continually recycled to the froth layer so that the driving force for SO_2 removal is maintained.

The oxidation air in the prototype system is supplied from a two-stage compressor which was part of the original CT-101 system at Scholz. This compressor is over-designed for the needs of the CT-121 system. As such, the second stage of the compressor was used to throttle the air from 18 to about 13 psig.

The air is introduced into the JBR through four sparger rings. Two-thirds to three-fourths of the air was normally introduced at the bottom of the outer edge of the draft tube. The remainder is injected through the three inner rings. The maximum air flow rate employed during the program was about 1800 scfm. Normal operation usually ranged between 1000 and 1300 scfm which resulted in stoichiometries of between 4 and 12 atoms of oxygen per molecule of SO_2 absorbed, depending on the SO_2 concentration in the flue gas, the gas flow, and the percentage removal.

Gypsum Crystallization

Oxidation of sulfite to sulfate and neutralization with limestone results in supersaturation with respect to gypsum ($CaSO_4 \cdot 2H_2O$) and subsequent precipitation of gypsum solids as shown in Eq. 3-5.

$$Ca^{++}(aq) + SO_4^{=}(aq) + 2H_2O \rightleftarrows CaSO_4 \cdot 2H_2O(s) \qquad (3\text{-}5)$$

One key to operating a reliable limestone FGD system is controlling the gypsum relative saturation level below the point where the onset of scaling occurs. In order to minimize the possibility of gypsum scaling, Chiyoda designed the CT-121 prototype system to operate with a large reaction volume and a relatively high suspended solids inventory. This results in a relatively long solids retention time.

The JBR volume in the prototype system is about 31,000 gallons. Although the JBR is well mixed by mechanical agitation and by air injection, some stratification of solids occurs due to the high settling rates which result from the formation of relatively large gypsum crystals. The underflow solids typically ranged from 15-25 weight percent while the overflow was between 6-12 weight percent solids.

Once the reaction volume has been selected, the other variable for scale prevention in the CT-121 system is the percent solids. During the test program, the solids content in the underflow was monitored continually and recorded on an hourly basis by CT-121 system operators and controlled by adjusting the JBR underflow stream flow rate [normally 6 to 25 gpm (23-95 ℓpm)] to the gypsum tank. The set point for the solids in the underflow was determined by the relationship between the solids content in the overflow and in the underflow. Chiyoda's objective was to maintain the solids in the froth zone at a sufficiently high concentration to reduce the chances of scaling in the area where the maximum gypsum relative saturation occurs.

Because the liquor in the upper portion of the JBR has a lower solids concentration, a second line from just below the froth layer to the gypsum tank was used at times to control the JBR water balance without depleting the solids inventory in the JBR. This line was employed primarily when the liquor feed rate from the prescrubber loop exceeded the withdrawal rate from the JBR underflow. Otherwise, when the underflow rate was increased to balance the water levels, the solids inventory would be lowered.

Summary of JBR Concept

In summary, the JBR performs four functions which are accomplished in at least two vessels in most limestone systems. These are:

- SO_2 removal,
- limestone dissolution and pH control,
- neutralization and sulfite oxidation, and
- gypsum desupersaturation and crystal growth.

The JBR sparges the flue gas into the slurry to achieve SO_2 transfer. This eliminates large recirculation pumps because there is no slurry recycle stream. The liquid film resistance to mass transfer is also reduced since the liquid surface is continually renewed as the gas passes upward.

Neutralization of sulfurous acid is accomplished by limestone addition. The pH is acidic so that high limestone utilization is possible. As a result, the pH in the JBR is responsive to changes in limestone flow. Limestone dissolution provides the calcium required for gypsum precipitation.

The relatively low pH also enhances the oxidation reaction. Oxidation air is introduced to the JBR in the cone-shaped bottom. The mixing provided by oxidation air and the flow pattern created by the agitator and draft tube ensure that oxidation and crystallization can occur throughout the JBR. The mixing also ensures that liquor low in sulfite is continuously sent to the froth layer to enhance SO_2 removal.

LIMESTONE ADDITION SYSTEM

The limestone addition system consists of a silo for powdered limestone storage, a slurry tank beneath the silo, and a slurry feed system. A schematic of the limestone addition system is shown in Figure 3-5.

Powdered limestone is delivered to the Scholz site via truck and blown into the silo with compressed air. The silo can hold enough limestone for one to two weeks operation (about 200 tons). The silo is pulsed with dry compressed air periodically to minimize bridging and compaction problems.

Limestone powder is fed into the limestone slurry tank by a rotary feeder. The CT-121 operator can control the limestone solids addition by manually setting the speed of the rotary feeder.

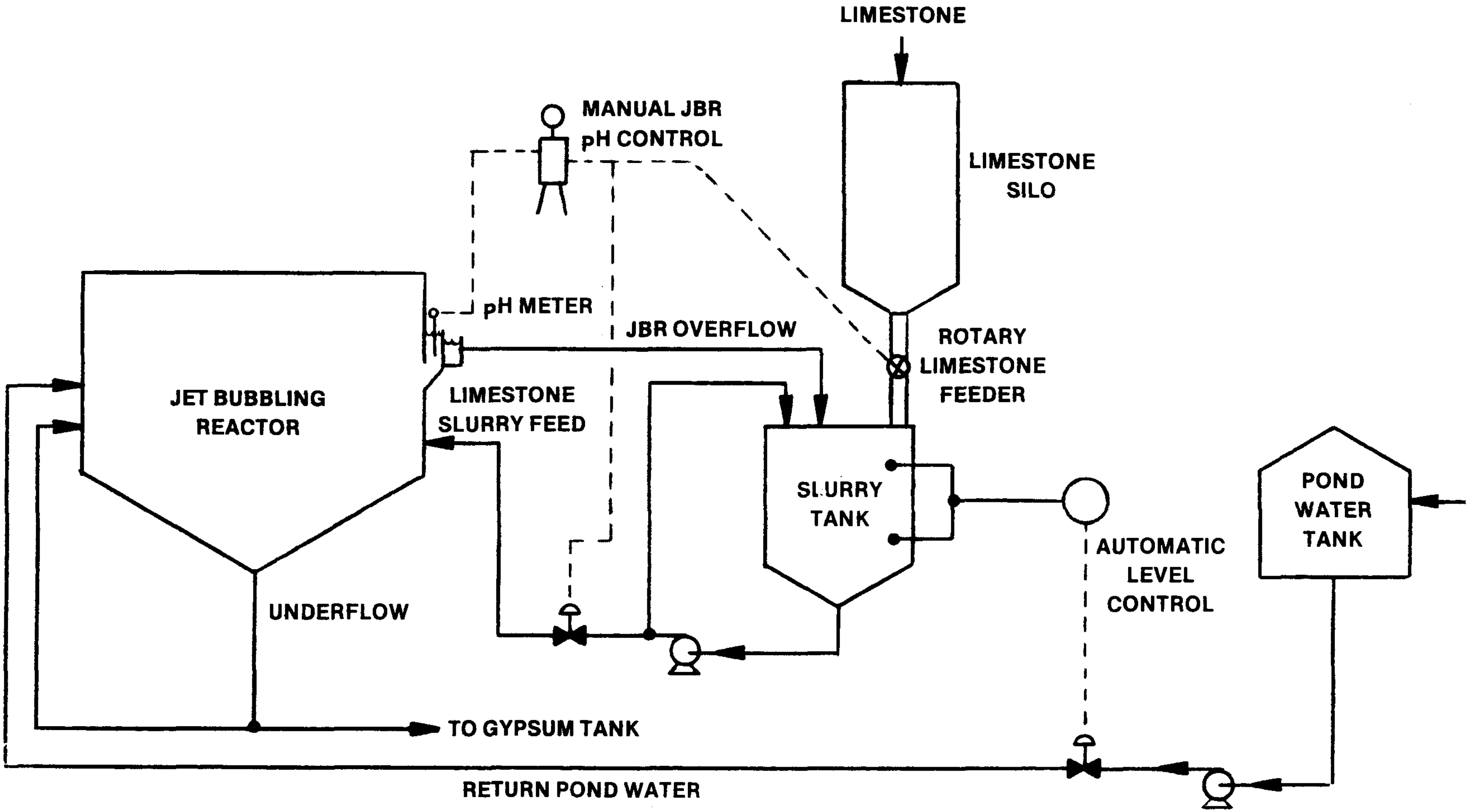

Figure 3-5
Simplified Schematic of Limestone Addition System

Makeup liquor for limestone slurrying is normally provided from the JBR overflow stream which drains by gravity to the limestone slurry tank. Pond return liquor or fresh makeup water may also be used for slurry liquor on an as needed basis. An agitator keeps the slurry well mixed. As shown in Figure 3-5, the limestone tank has a level controller which automatically sets the rate of addition of pond return water to the JBR. When the level in the limestone tank begins dropping, the pond water flow rate to the JBR is increased. This in turn increases the overflow rate and raises the slurry level in the limestone tank.

Limestone slurry is pumped to the JBR for addition to the froth layer or the liquid layer by using either of two sets of feed pipes. A control valve is used to set the actual limestone rate into the JBR. The remainder of the limestone/gypsum slurry is recirculated to the limestone slurry tank. This recirculation system is used to minimize the chances of plugging, particularly under low flow conditions.

The CT-121 system operator can respond to JBR overflow pH changes in two ways. First, for a quick pH response, the limestone slurry flow rate to the JBR can be changed. The operator may also alter the rotary feeder rate which will change the limestone solids inventory in the limestone tank and therefore in the limestone slurry stream. Generally, the operator will alter the slurry feed rate to respond to short term changes in flue gas SO_2 concentration and will change the rotary feeder rate only if the change in the SO_2 concentration appears to be of longer duration. This is of course necessary to keep the pH constant in the JBR.

GYPSUM DISPOSAL SYSTEM

Slurry from the JBR was pumped to the gypsum slurry transfer tank before final disposal. For most of the program, the JBR underflow was the only source of gypsum slurry. A portion of the JBR underflow is pumped to the gypsum tank through a recirculation system which is similar to the limestone recirculation system. The feed rate to the gypsum tank is set to maintain the desired JBR solids concentration. The solids concentration in the JBR underflow is controlled by CT-121 prototype operators by varying the withdrawal rate. The remainder of the JBR overflow is recycled back to the JBR.

At times during the program, gypsum slurry from immediately below the froth layer was fed by gravity to the gypsum tank. As discussed previously, this line was employed to satisfy both water balance and solids inventory requirements in the JBR. A valve was adjusted manually to control this flow.

The pH of the slurry in the gypsum tank was raised to about 6 by adding limestone slurry. This was done primarily for environmental reasons because laboratory work indicated that FGD gypsum should stack equally well with an acidic pore fluid. The operator of the prototype system had no means of continuously monitoring this pH since demonstration of this portion of the process was not an objective of the program. The limestone flow was therefore very approximate and does not represent optimum limestone utilization.

The slurry in the gypsum tank is diluted to 5-10 weight percent by pond water or prescrubber liquor to prevent solids settling in the line to the gypsum stack area. Once in the gypsum stack, the gypsum settles within the dikes of the stack. Stacking simulations in the laboratory indicated that the deposited gypsum had an initial solids content of 70-75 percent. This increased to 85 percent after sedimentation. The liquor is decanted to a separate pond from which it is pumped to the pond water recycle tank and reused in the system. This pond normally contains about 500,000 gallons (1900 m^3). The details of the gypsum stack operation will be discussed in a separate report by Ardaman and Associates (7).

During the final phase of testing in which Chiyoda funded some of their own tests, a high speed Bird-Young vacuum filter was tested for solid-liquid separation efficiency. After these tests, the gypsum cake was reslurried and sent to the gypsum tank before being pumped to the stack.

MIST ELIMINATOR OPERATION

The mist eliminator in the CT-121 prototype system consists of two banks of plastic chevron blades in the horizontal duct between the JBR and the stack. Both banks of chevrons have sections which were damaged by high temperatures during previous operation of the CT-101 system.

The wash system consists of 4 headers and 12 nozzles. Two headers with 3 nozzles on each header are used to wash each mist eliminator bank. Because the superficial gas velocity in the gas-liquid disengaging chamber is low [1 to 2 feet per second (.3-.6 m/s)], minimum slurry is entrained in the gas and the wash requirements are low. Generally, the mist eliminators were washed with about 300 gpm (1140 ℓpm) of pond water for one minute once per week. Frequency of washing at times dropped to once every two weeks or less. The liquor and the solids cleaned from the mist eliminator were inadvertently drained to the pond water tank during the demonstration program, but created no problems.

Section 4

TEST PLAN DESCRIPTION

The objective of the test program was to evaluate the CT-121 system at both design steady-state conditions and non-optimum operating conditions. There were four test phases during the evaluation, each of which are discussed in this section:

- Phase 0 - Two month initial operating period by Chiyoda
- Phase I - Two month baseline test at Chiyoda specified operating conditions
- Phase II - Four months of parametric test to determine system sensitivity to variable operation conditions
- Phase III - Chiyoda testing to modifications to JBR internals

Phase 0 was the initial shakedown period when only Chiyoda personnel were present. Originally, only Phases I and II were planned by EPRI and SCS for evaluation purposes. However, at the end of this six month testing period, Chiyoda modified the internals of the JBR and performed an additional test series of one month duration which EPRI, SCS, and Radian were invited to observe.

Table 4-1 summarizes the parameters which were of interest during the test program. In addition, stressed and unstressed corrosion coupons were placed in several locations. The unstressed coupons were located in the following positions:

- prescrubber liquor (slipstream)
- prescrubber outlet gas duct
- JBR overflow slurry
- JBR outlet gas chamber
- gas stack

Stressed coupons were placed in each of the same locations except the gas stack. The metals tested and the results are discussed in Section 5.

Table 4-1

PROCESS AND PERFORMANCE VARIABLES OF INTEREST
IN CT-121 DEMONSTRATION PROGRAM

Control Variables	Uncontrolled Process Variables	Performance Parameters
• pH (limestone stoichiometry)	• Inlet SO_2 and particulate concentrations	• SO_2 removal efficiency
• ΔP	• Liquor soluble species concentration (Mg^{++}, Na^{+}, Cl^{-})	• Sulfite oxidation rate
• Percent solids	• Boiler load (flue gas* flow and composition)	• Gypsum quality
• Oxidation air rate		• Chemical scaling potential
		• Mechanical or process failures (especially those related to .the JBR)
		• Limestone utilization

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*At Scholz the flue gas flow could be controlled by the CT-121 system operator.

The test conditions for the three test phases after the Chiyoda shakedown are summarized in Table 4-2. The order of the tests was somewhat different from that originally planned. For instance, the low solids and low air tests were run with the lower SO_2 concentrations because the delivery of the high sulfur coal and the SO_2 spiking equipment was delayed. Additionally, a boiler load test was repeated with low sulfur coal in Phase II due to the late arrival of the high sulfur coal. Likewise, the chloride spiking test preceeded the particulate testing rather than being the last test in the program because approval from the Florida Department of Environmental Resources for testing with the precipitators de-energized was delayed. None of these alterations in the test sequence affected the results of the evaluation of the CT-121 prototype system's performance however.

PHASE 0

Phase 0 incorporated the mechanical testing, start-up and shakedown of the system. Chiyoda carried out this phase of the evaluation program prior to the Radian test crew moving onsite. Reconditioned piping, duct work, valves, pumps, and vessels or tanks that had been used in the prior CT-101 demonstration as well as new equipment installed for the CT-121 demonstration were checked for leaks and other malfunctions. All instruments and controls were also tested.

Table 4-2

SUMMARY OF PROGRAM TEST OBJECTIVES AND OPERATING CONDITIONS

Date	Test Objective	Process Set Points	pH	Weir Height[a] (inches)	Air Rate (scfm)	Total Test Hours
11-15-78/ 1-9-78	Phase I - Reliability and operability demonstration period	Held constant during period	3.5	11	1350	1368
1-10/1-15	Simulate following boiler load	Vary gas flow according to boiler MW	3.5	11	1350	120
1-17/1-20	Shutdown - Inspection, Phase II					
1-22/2-28	Determine effect of process variables on SO_2 removal	Vary pH, weir, air, and limestone size	2.7-4.3	7-12	1000-1350	888
3-2,5	Determine scaling potential with low suspended solids at medium and high pH	Lower suspended solids concentrations	3.5-4.3			16
3-7,8	Determine minimum air requirement for mixing and oxidation	Lower air flow	3.5	10.5	Varies	16
3-12	Shutdown - Inspection, repair venturi nozzle					
3-15,16	Simulate following boiler load	Vary gas flow according to boiler MW	3.5	10.5	1340	48
3-19/3-31	Chiyoda optimization on high sulfur coal	Vary parameters to determine effect on higher SO_2 levels	2.7-4.3	8,13	1300-1800	288
4-2/4-6	Ninety percent removal demonstration on high SO_2		3.5	12	1530	96
4-6/4-11	Determine effect of pH on gypsum relative saturation	Vary pH, weir to obtain same removal	2.7-4.3	12.5,8	1530	120
4-11/4-15	Obtain high percentage removal	High weir, pH setting	4.3	18	1530	96
4-15,16	Determine removal versus pH at constant weir height	Vary pH	2.7-4.8	11.5	1530	48
4-18,19,20	Observe performance at low weir heights	Vary pH, weir height	3.6-4.8	5,6,9	1530	72
4-23/4-27	Observe effect of high chloride concentration	6000 ppm Cl^-	3.5	11.5	1530	96
5-1,2	Determine effect of low air/no air to JBR	Lower air rate and then stop it	3.5	11.5	1200-0	16
5-3	Observe effect of stopped agitator on JBR	Stop and reverse agitator direction				.1
5-7/5-14	Determine particulate and trace element removal capability of system	Deenergize ESP's	3.5	11.5	1000	168
5-15/5-22	Observe removal behavior with 3000 ppm SO_2	Spike SO_2 to 3000 ppm	3.5-4.8	10-15	1000-1800	168
5-22	End of Phase II					
5-23,24	Baseline run for Phase III		4.3	10	1000	48
5-25/6-8	Shutdown - JBR modifications					
6-8/6-14	Determine effect of JBR modifications on performance	Same as baseline	4.3	10	1000	144
6-14/6-16	Observe high pH operation	pH up to 5.8	3.5-5.8	10	1000	48
6-17	Observe low air rate effect		4.8	10	525	24
6-18/6-20	Test spray tower saturator concept	Operate without prescrubber recycle pump	4.8	10	1070	72
6-20/6-28	Produce solids for vacuum filter testing		4.5	13	1580	192
6-29	Final shutdown and inspection					

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[a] Multiply x 25.4 to obtain millimeters.

After mechanical testing Chiyoda started the system and began shakedown of the various subsystems. The JBR was spiked with gypsum seed crystals from the CT-101 program and fresh water prior to startup. After flue gas and oxidation air flows were established, the system pH was slowly increased from an initial point of about 2.5. This low pH was desirable on startup to maintain low SO_2 removal and, therefore, low relative saturations. The solids concentration in the JBR increased slowly until the proper operating level was reached.

Chiyoda planned to conduct several tests at different weir settings and raised the pH up to 4.0. For the most part, however, Phase 0 operation was at steady-state conditions. At the conclusion of the Phase 0 period, the sixth month test period (Phases I and II) planned by EPRI and SCS was begun.

PHASE I

The objective of Phase I was to measure the performance of the CT-121 system at Chiyoda specified operating conditions. Operating conditions were selected that were expected to achieve about 90 percent removal from a flue gas containing 1000 to 1400 ppm of SO_2. The Chiyoda specified Phase I set points are shown in Table 4-3.

Table 4-3

CHIYODA SPECIFIED PHASE I OPERATING CONDITIONS

pH	3.5
JBR ΔP	11 inch weir setting (280 mm)
JBR Underflow Solids	17 weight percent ±2
Limestone Size	90 percent <325 mesh
Flue Gas SO_2 Content	1000-1400 ppm (as received from the generating unit)
Gas Flow Rate	45,000 scfm
Oxidation Air Flow Rate	1300 scfm

During Phase I, the effect of normal process fluctuations on system performance were monitored. The magnitude of routine variations was noted and particular attention was paid to the effort the operators had to expend to maintain stable operating conditions. Observing the degree of operator attentiveness to process operation was also an objective in Phase I and throughout the program.

In addition to monitoring routine steady-state operation, the CT-121 system's response to simulated boiler load changes was measured. Since the CT-121 prototype system was designed to accept only one-half of the flue gas from one unit operating at full load, the CT-121 system was not affected until the load dropped below one-half. Normally, the boilers only operated at half-load or less at night and during the weekends. Consequently, boiler load swings were simulated by varying the inlet gas damper openings. Variation in the damper opening changed the gas flow resulting in a corresponding change in the amperage required for the scrubber fan. Every two hours the CT-121 operator would obtain the boiler megawatt output from the unit operator and then adjust the damper opening until the proper scrubber fan amperage for a given load was attained as shown in Figure 4-1. Using this procedure, the CT-121 system's responsiveness to boiler load and flue gas flow changes were estimated.

One final aspect of the Phase I evaluation involved monitoring changes in the process chemistry and equipment performance which might be indicative of long-term system reliability. It is obvious, however, that operation at specified control variable set points for two is not sufficient to determine long term system reliability.

PHASE II

The objective of Phase II was to determine the sensitivity of the CT-121 process to changes in system operating conditions which might normally be encountered in a utility application. Two types of variables of interest were:

- process control variables
- site specific variables which are not normally under the control of the scrubber operator

Perturbations of the process control set points specified during Phase II were made. By changing the JBR pH, JBR underflow solids content, oxidation air rate, and JBR ΔP, variable changes due to process upset or operator inattention can be simulated and the system's response to these changes can be evaluated. By changing the limestone particle size and source, SO_2 concentration, coal, and the chloride level, several site-specific factors can be investigated also.

The control variables which change most frequently and rapidly are the JBR pH and the JBR underflow solids concentration. The pH can change dramatically in a matter of minutes if the limestone feed is not regulated properly. The solids loading may

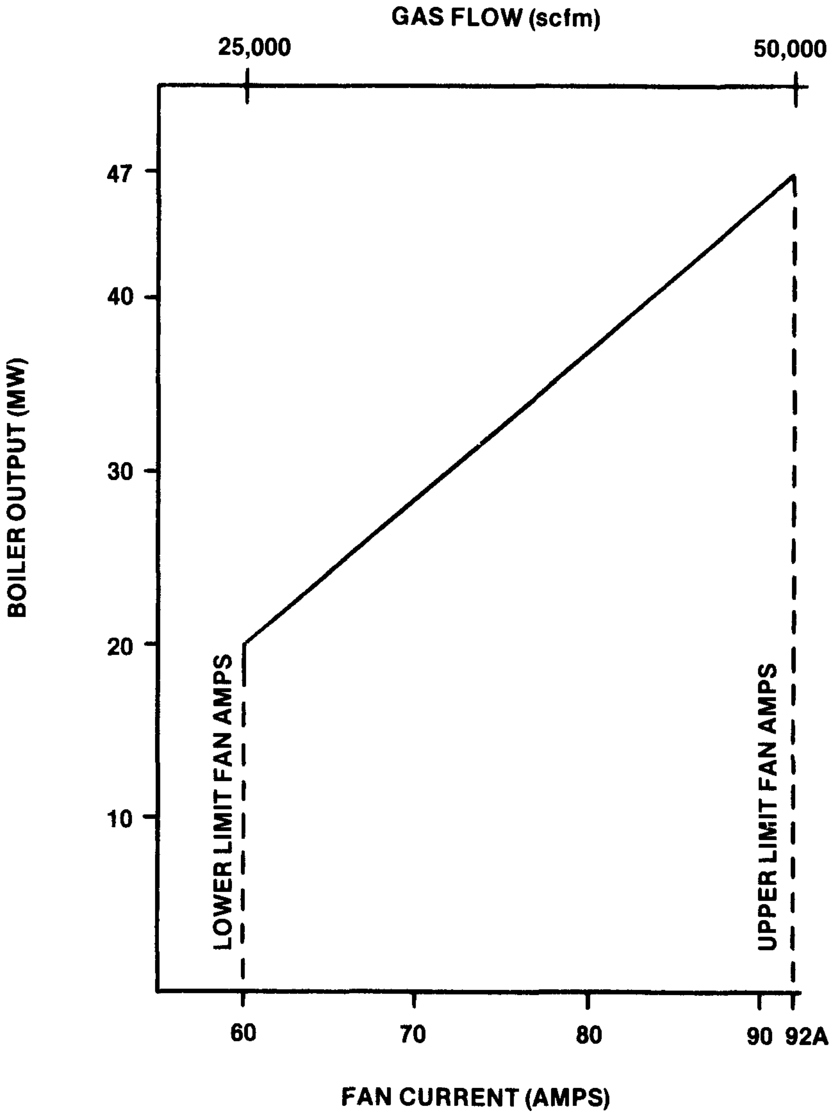


Figure 4-1
Variable Load Test-Boiler MW vs. Fan Amps

change also if the solids withdrawal rate does not balance the solids production rate or if an agitator or air compressor should fail. Both pH and solids concentration can have a marked impact on the performance of the CT-121 system. It was therefore appropriate to define the envelope within which the CT-121 system can operate without the onset of major operating problems.

Two variables which are not expected to change as often are the oxidation air rate and the limestone particle size. The main cause for changes in these variables would be malfunctions in the compressor or limestone grinder systems. The extent to which the air rate could be reduced (due to partial compressor failure in a commercial system for instance) with the system remaining operable was of interest. Operation under several different oxidation air flow conditions were evaluated during the program. It was also desirable to examine the effect of limestone particle size so that the extent of limestone grinding could be optimized in commercial systems. Since no limestone grinding was performed on site, limestones from two sources were tested: (1) a 90 percent less than 325 mesh from Georgia Marble Company in Sylacauga, Alabama, and, (2) a 90 percent less than 200 mesh from Southern Materials Company in Ocala, Florida.

The JBR ΔP is another important variable which could be altered in the prototype system by adjusting the overflow weir height. Tests at several ΔP's were made to document the effects of the gas side pressure drop on system operation and performance.

In addition to measuring the system's response to changes in process control variables, it was also desirable to determine the manner in which the CT-121 process responded to changes in certain site-specific variables which are not as easily controlled. Major variables of concern include the coal composition (which influences flue gas SO_2 and HCl concentrations and particulate loading) and the degree of particulate removal upstream of the JBR. The limestone composition and size may also be considered a site specific variable although the compositions of the two limestones tested did not differ substantially. Because these site-specific variables would be considered in designing a new CT-121 system, a number of tests were conducted to evaluate the CT-121 system over a range of conditions.

In order to gain the maximum information during a short time period and to screen variable effects so that additional testing with the more important variables could be conducted, a test matrix was set up to measure the impact of pH, ΔP, oxidation air rate, and limestone particle size. It was originally planned that the flue gas SO_2 content and the JBR solids concentration would be included in this test matrix. However, a higher sulfur coal could not be obtained in the time frame required. In addition, Chiyoda expressed concern over changing the JBR overflow solids set point and operating the system for significant periods of time at low solids levels with minimum supervision such as on the swing and night shifts. At low solids loading Chiyoda was concerned that the solids concentration in the froth zone would be low enough that gypsum scaling might occur. For these reasons, the effects of higher flue gas SO_2 concentrations and lower JBR solids inventories were investigated in separate single variable tests.

The variable set points for the test matrix conducted in Phase II are shown in Table 4-4. Tests A through I represent a half-factorial test design. The main advantage of such a test matrix over changing each variable one at a time is that variable interactions as well as individual variable effects can be measured. Table 4-5 indicates how this statistical design was used to develop the specific test program shown in Table 4-4. Tests A-1 and I-1 were added so that the impact of the individual variables could be examined on a preliminary basis prior to the full data reduction and statistical analysis.

The main variable effects can be measured by comparing the runs with the high set points with those runs with low set points. For instance, the effect of limestone size on SO_2 removal can be measured by comparing the removal efficiency in Tests A-D with efficiencies in Tests F-I. The test design is such that other variable effects should cancel when these test groups are compared. However, this canceling effect occurs only if the conditions specified are reproduced throughout the test series.

In addition to analyzing the main effect of each variable, some information about the two-variable interactions was also gathered in this test series. In this case, there is some confounding (one variable effect or interaction cannot be separated from others) of the two-factor interactions since only a half test replicate was possible due to time constraints. However, an attempt to minimize the effects of this confounding was made by combining the interactions which should have minimal effect with interactions which have a higher probability of being important. For example, the interaction of ΔP and pH (ΔP*pH) is confounded with the interaction of air rate and limestone type (air*limestone). It was expected that the ΔP*pH interaction might have more of an effect on SO_2 removal than the air*limestone interaction. However, no statistical confirmation of this judgement is possible from the results of the test matrix shown in Table 4-4.

Table 4-4

HALF FACTORIAL TEST CONDITIONS FOR PHASE II

Test	pH	Weir Height* (inches)	Air Flow (scfm)	Limestone Size
Phase I	3.5	11	1350	90% < 325 mesh
A-1	4.3(+)	12(+)	1350(+)	90% < 325 mesh (+)
A	4.3(+)	12(+)	1000(-)	90% < 325 mesh (+)
B	2.7(-)	12(+)	1350(+)	90% < 325 mesh (+)
C	4.3(+)	7(-)	1350(+)	90% < 325 mesh (+)
D	2.7(-)	7(-)	1000(-)	90% < 325 mesh (+)
E**	3.5	11	1350	90% < 325 mesh
F	4.3(+)	12(+)	1350(+)	90% < 200 mesh (-)
G	2.7(-)	12(+)	1000(-)	90% < 200 mesh (-)
H	4.3(+)	7(-)	1000(-)	90% < 200 mesh (-)
I	2.7(-)	7(-)	1350(+)	90% < 200 mesh (-)
I-1	2.7(-)	7(-)	1000(-)	90% < 200 mesh (-)

---

*Multiply by 25.4 to obtain millimeters
**Phase I set points
+Above Phase I set point
-Below Phase I set point

To make the statistical testing meaningful, at least two criteria had to be satisfied. First, the duration of each test had to be long enough to ensure that the data collected were representative of steady-state operation at the specific test conditions. Secondly, the appropriate data had to be gathered to properly evaluate the process' response to the variable changes.

In addition to the statistical test series which defined the effects of many of the control variables, a test was conducted to quantify the impact of JBR slurry solids content on system performance.

Chiyoda's operating philosophy includes continuous monitoring of the percent solids in the JBR slurry. Therefore, it was felt that a long term deviation in the solids concentration would not occur in actual commercial operation.

Table 4-5

VARIABLE EFFECTS EVALUATED IN PHASE II STATISTICAL TESTS

	Main Effects				Two-Factor Interactions					
Test*	ΔP	pH	Air	Limestone	ΔP*pH	Air*Limestone	ΔP*Air	pH*Limestone	ΔP*Limestone	pH*Air
A	+	+	-	+	+	-	-	+	+	-
B	+	-	+	+	-	+	+	-	+	-
C	-	+	+	+	-	+	-	+	-	+
D	-	-	-	+	+	-	+	-	-	+
F	+	+	+	-	+	-	+	-	-	+
G	+	-	-	-	-	+	-	+	-	+
H	-	+	-	-	-	-	+	-	+	-
I	-	-	+	-	+	-	-	+	+	-

Note: Confounded two-factor interactions
1) pH*Limestone/ΔP*Air
2) ΔP*pH/Air*Limestone
3) pH*Air/ΔP*Limestone

*Test E was a repeat of Phase I set points and was not included in the test matrix

+Above Phase * set point

-Below Phase I set point

However, several factors such as operator inattention, opening of the wrong valves, agitator failure, etc., could result in short term deviations from the percent solids set point. Two day-long tests were planned and conducted to observe any impact of lower solids levels on the system performance. Also, supplemental low air tests were conducted based on the results of the test matrix. Since the air rates originally tested had no major impact on system performance, air rates below 1000 scfm were examined. This included a short duration "failure" test in which the air was shut off.

In addition to the variables which may be considered control variables, several of the more important site specific variables were tested or monitored including:

- SO_2 flue gas concentration (or S in coal)
- soluble chloride concentration (or Cl in coal)
- fly ash loading
- plant water balance (rainfall/evaporation)

Two different coals were tested. One was a nominal 1.8 percent sulfur, 11 percent ash coal which resulted in an SO_2 content of 1000-1400 ppm in the flue gas. This coal came from the Alabama Byproduct Company Maxine Mine, America seam, and was used in Phase I and the initial portion of Phase II. The second coal was a nominal 3.2 percent sulfur, 11 percent ash coal which resulted in flue gas SO_2 levels of between 1700 and 2400 ppm. This coal came from Hallmark Mines in Sipsey, Alabama, the Jefferson seam, and was used through the latter stages of Phase II and during Phase III. In addition, the flue gas SO_2 concentration was raised as high as 3500 ppm by spiking with liquid SO_2 during the final week in Phase II. A number of different pH and ΔP tests were conducted at various SO_2 concentrations.

Another variable in an FGD system which is dependent on the coal composition is the soluble chloride level resulting from sorption of HCl in the flue gas. Moderate chloride levels in the coal were simulated by spiking the system with $CaCl_2$ to attain chloride levels of 6000 ppm.

The fly ash loading can also vary widely depending on the coal ash content and the level of removal achieved upstream of the CT-121 system. It was therefore desirable to run the CT-121 system at more than one flue gas particulate loading.

As stated in the system description, the Scholz plant has high efficient electrostatic precipitators upstream of the CT-121 prototype system. These were totally de-energized to test the impact of higher fly ash loadings on system operation. This test also provided EPRI with information of a generic nature on the fate of fine particulates and trace elements in limestone FGD systems.

Unfortunately, the CT-121 prototype system included a venturi quench system which will probably not be included in commercial systems. The venturi could not be removed from service due to constraints on operating temperatures on the downstream lining and duct materials. In addition, the cost of adding a spray quench and wash down system in the JBR gas inlet chamber was prohibitive. The particulate tests were therefore conducted under normal operating conditions with the venturi in service. As a result, the particulate removal capability of a quench/JBR configuration could not be measured. It was possible, however, to route all of the fly ash solids collected in the venturi system to the JBR. The presence of fly ash in the JBR froth layer somewhat simulated using the JBR for particulate removal or carry-over from a quench tower upstream of the JBR.

The amount of rainfall can also vary from site to site and may affect the system's water balance if ponds or gypsum stacks are employed. The net precipitation and liquor discharged from the prototype system were monitored throughout the program to define the impact of rainfall in the Sneads area so that water balance extrapolations might be made to other locations in the U.S.

PHASE III

Phase III testing was not part of the original EPRI-SCS evaluation program. During Phase II, Chiyoda decided to test some internal JBR modifications. EPRI was invited to observe, and Radian as a representative of EPRI and SCS remained on site during Phase III. Radian's level of involvement was reduced to a sampling and observation effort during this phase since the actual test conditions were set by Chiyoda.

Chiyoda's main objectives in Phase III were:

- to evaluate the possibility of reducing the complexity and size of the JBR,

- to investigate the possibility of operating the JBR with a spray quencher rather than a venturi, and
- to compare a vacuum filter for solid-liquid separation to the gypsum stack.

Chiyoda first blocked some of the flue gas spargers and risers so that more flue gas passed through the remaining spargers. As a result, the gas velocity and pressure drop through each sparger increased. In addition, Chiyoda reduced the liquor pumped to the venturi throat by turning the recirculation pumps off so that only about 55 gallons per minute (208 ℓpm) of liquor were contacted with the gas during a portion of the Phase III testing. The resultant L/G was about 1 gallon/1000 scf. Although this is about three times the theoretical amount required for adiabatic saturation, it is only about one tenth the normal operating L/G used previously in the venturi and may be close to that used in a spray quench system. Chiyoda sought indications of possible problems which might be encountered when using a spray quenching system. Testing was also performed to determine the suitability of vacuum filtration for separation of CT-121 produced gypsum.

Section 5

RESULTS AND DISCUSSION

As discussed in Section 4, the CT-121 evaluation program was divided into four test phases:

- Phase 0 - Chiyoda startup and shakedown operation
- Phase I - Baseline testing at Chiyoda specified conditions
- Phase II - Evaluation of system response to variable perturbations
- Phase III - Chiyoda testing with modified JBR internals

A discussion of the significant test results from each phase is presented in this section. A summary of the mechanical and instrumentation experience gained throughout the program follows the discussion of the test results.

To facilitate a more concise discussion, much of the detailed data are presented in the appendices. For instance, detailed operating data plots are provided in Appendix A. These plots give an indication of the variations in flue gas flow, SO_2 concentrations, SO_2 removal efficiency, SO_2 pickup rate, JBR slurry solids content, JBR overflow pH, JBR ΔP, JBR liquor dissolved solids, and gypsum relative saturations which occurred throughout the test program. Appendix B includes the analytical data generated during the program and Appendix C discusses the sampling and analytical procedures. Detailed results such as these will be referred to or summarized in this section where appropriate.

PHASE 0 TEST RESULTS

During Phase 0, Chiyoda started operation of the prototype system and checked system performance over a range of operating variables. Although Radian was not on site during this period, Chiyoda has allowed operating data from Phase 0 to be included in this report (Appendix A). Chiyoda reported few operating problems and little downtime. The only major outage was caused by a bearing failure in the oxidation air compressor which was also used in the CT-101 demonstration. The performance parameters of the prototype in Phase 0 are included in the comments on mechanical and instrumentation experience which appear later in Section 5.

PHASE I TEST RESULTS

As stated in Section 4, the objectives of Phase I were (1) to demonstrate that the CT-121 system could achieve 90 percent SO_2 removal with minimal operating problems and (2) to provide baseline data for comparison with Phase II test results.

The control set points for this phase were based on Chiyoda's esperience with their pilot unit in Japan and on about two months operating experience with the prototype unit in Phase 0. The control variable set points for Phase I are listed below:

JBR ΔP - 11.5 inches H_2O (2.88 kPa)

Overflow weir height - 11 inches (27.9 cm)

JBR overflow pH - 3.5

Oxidation air flow - 1300 scfm (0.61 Nm^3/s)

Flue gas flow - full load conditions

JBR underflow solids content - 17 weight percent

Process control was easily maintained throughout Phase I with a minimum of operator attention. As would be expected, there were some fluctuations in the operating conditions. For instance, the JBR pressure drop varied between 10.9 and 11.9 inches of water (27.7 to 30.2 cm water). The extremes in JBR overflow pH recorded in Phase I were 2.9 and 4.0, but the majority of pH readings were between 3.3 and 3.7. The flue gas flow rate varied between 41,000 and 49,000 scfm (69,600 to 83,200 Nm^3/hr) when the system was being operated under full load conditions. These flows were determined by manual measurements performed by Radian because the annubar for on-line flue gas flow measurement was out of service for most of Phase I.

The coal used in Phase I had a higher heating value of about 12,600 Btu/lb (29,400 J/g), an ash content of about 11 weight percent, and a sulfur content varying between 1.3 and 3.5 weight percent. Combustion of this coal resulted in a flue gas with an SO_2 concentration of 850 to 1500 ppm. The discrepancy between the sulfur content of different cars of coal and the SO_2 content of the flue gas is probably due to coal pile mixing. In Phase I, the limestone, obtained from Georgia Marble in Sylacauga, Alabama, contained about 98 weight percent calcium carbonate.

The CT-121 prototype performed well in Phase I tests. The daily average SO_2 removal percentage based on an arithmetic average of 24 hourly readings ranged from 89 to 95 percent. An average of 92 percent was obtained for the total Phase I test period.

The minimum and maximum in hourly readings were 80 and 97 percent SO_2 removal efficiency although the majority of the data were in the range of 90 to 95 percent SO_2 removal. Complete oxidation of the sorbed SO_2 to sulfate was observed, and no sulfite solids were detected. The low pH necessary for complete oxidation also produced excellent limestone utilization, 98.3 percent for the JBR and 97.5 percent around the overall system for the total Phase I test duration. These analytical results are supported by material balances for the gas phase SO_2 removal rate, the limestone consumption, and the gypsum production rate. Analyses of the JBR slurry streams revealed no gypsum scaling tendency in the liquor. The gypsum crystals formed were very large and easy to dewater. Variable boiler load tests conducted at the end of Phase I revealed that the JBR slurry pH and SO_2 removal efficiency quickly returned to specified conditions following changes in the flue gas flow rate. Lastly, the system water balance was open loop during Phase I due to unexpected freezing weather and heavy rains.

Seven topics of interest are addressed in more detail in the following summary of Phase I results:

- SO_2 removal
- Sulfite oxidation
- Limestone utilization
- System material balances
- Gypsum crystal structure and scaling potential
- Variable boiler load
- System water balance

SO_2 Removal

The daily average SO_2 removal consistently ranged from 90 to 95 percent during Phase I testing at the Chiyoda-specified set points. Only two days, January 9 and 16, had average removals below 90 percent with the average being 89 percent in both cases. The average SO_2 removal efficiency for the cumulative Phase I testing was 92 percent which corresponded to an average pickup rate of 50 gram moles of SO_2 per minute.

The ranges and daily averages of the inlet and outlet flue gas SO_2 compositions and removal efficiencies for Phase I are plotted on Figures 5-1, 5-2, and 5-3. These summary data were obtained from on-line DuPont SO_2 analyzer readings which were

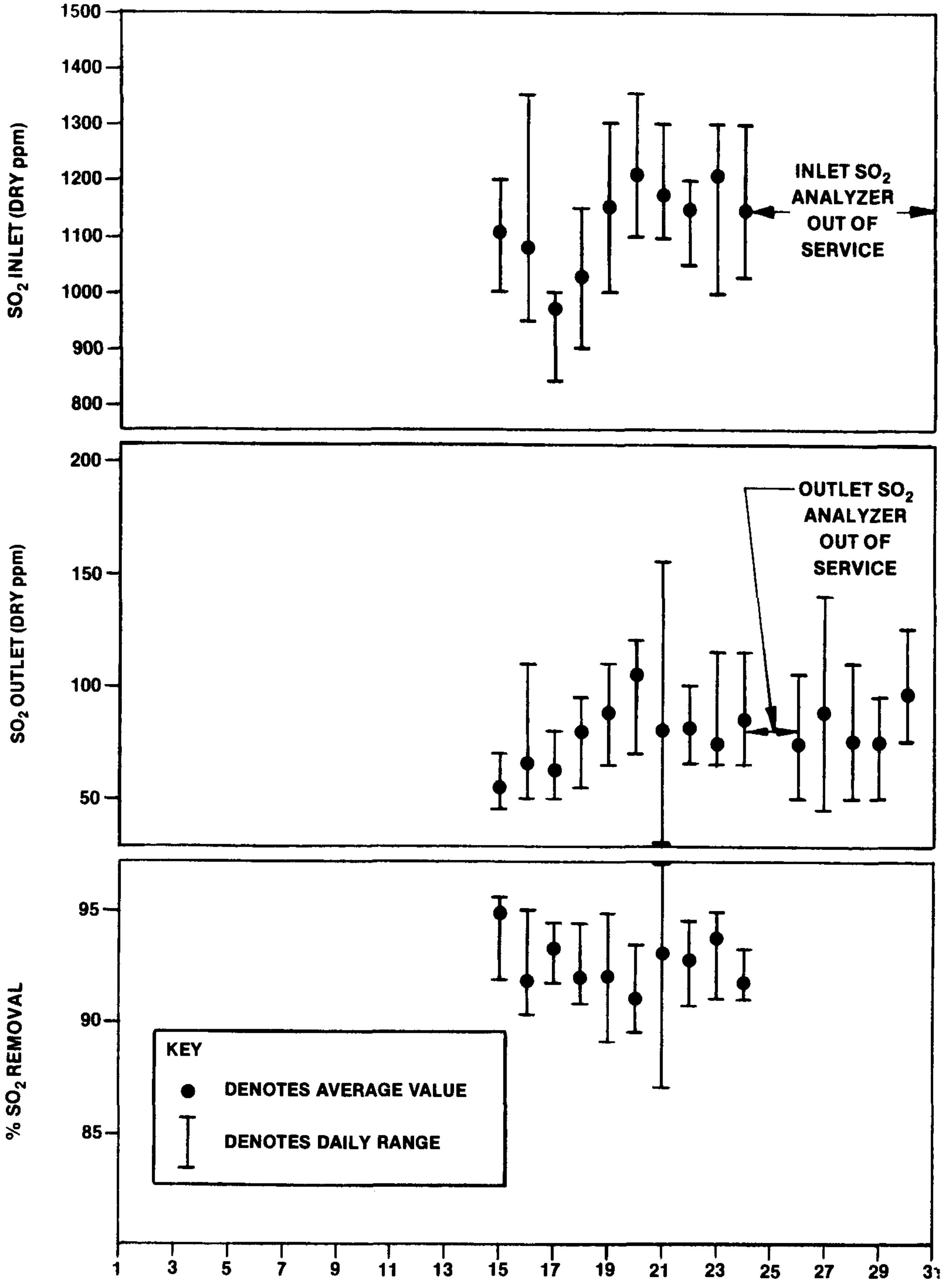


Figure 5-1
Summary of SO$_2$ Removal Data in November, 1978 (Phase I)

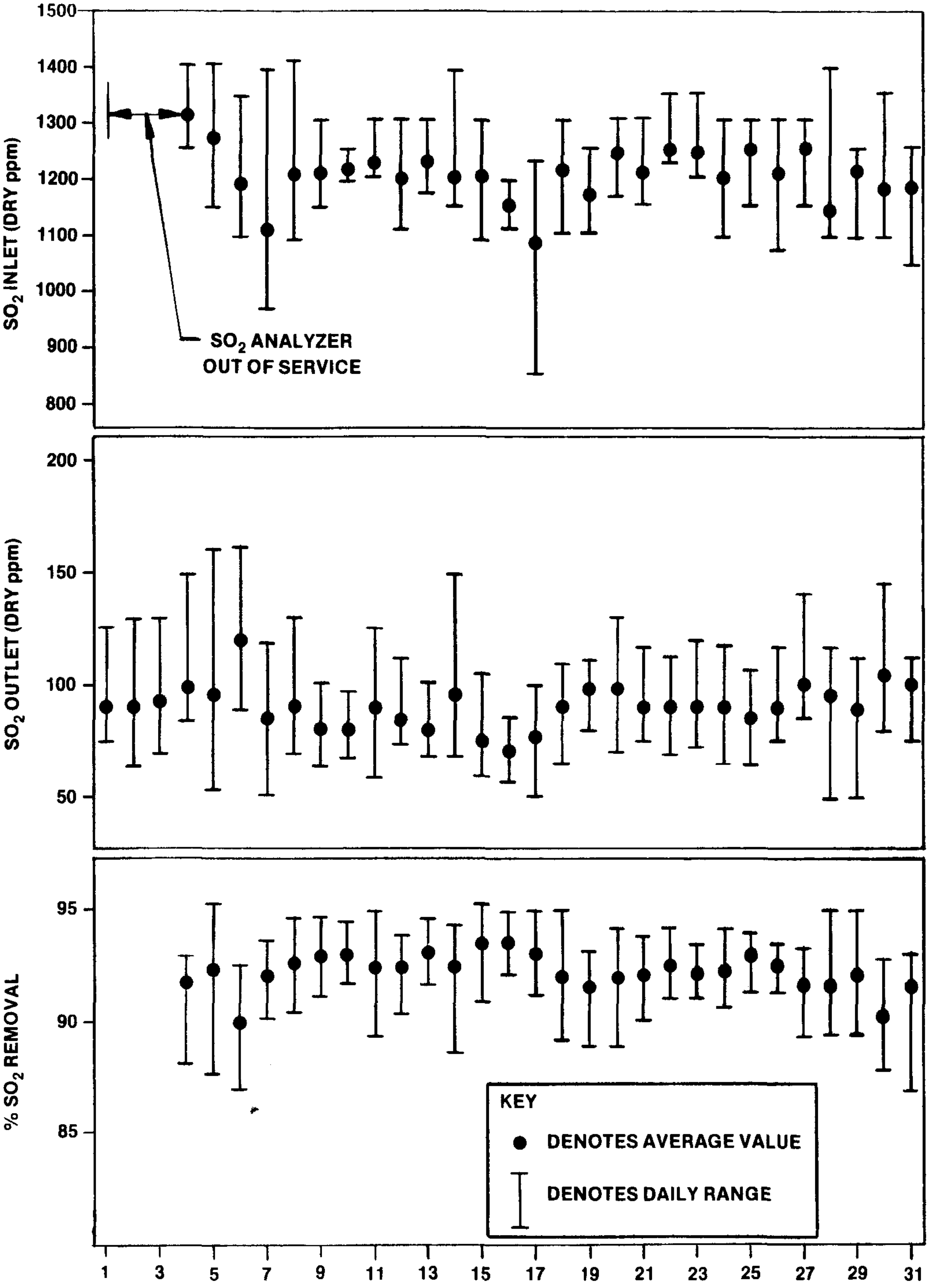


Figure 5-2
Summary of SO_2 Removal Data in December, 1978 (Phase I)

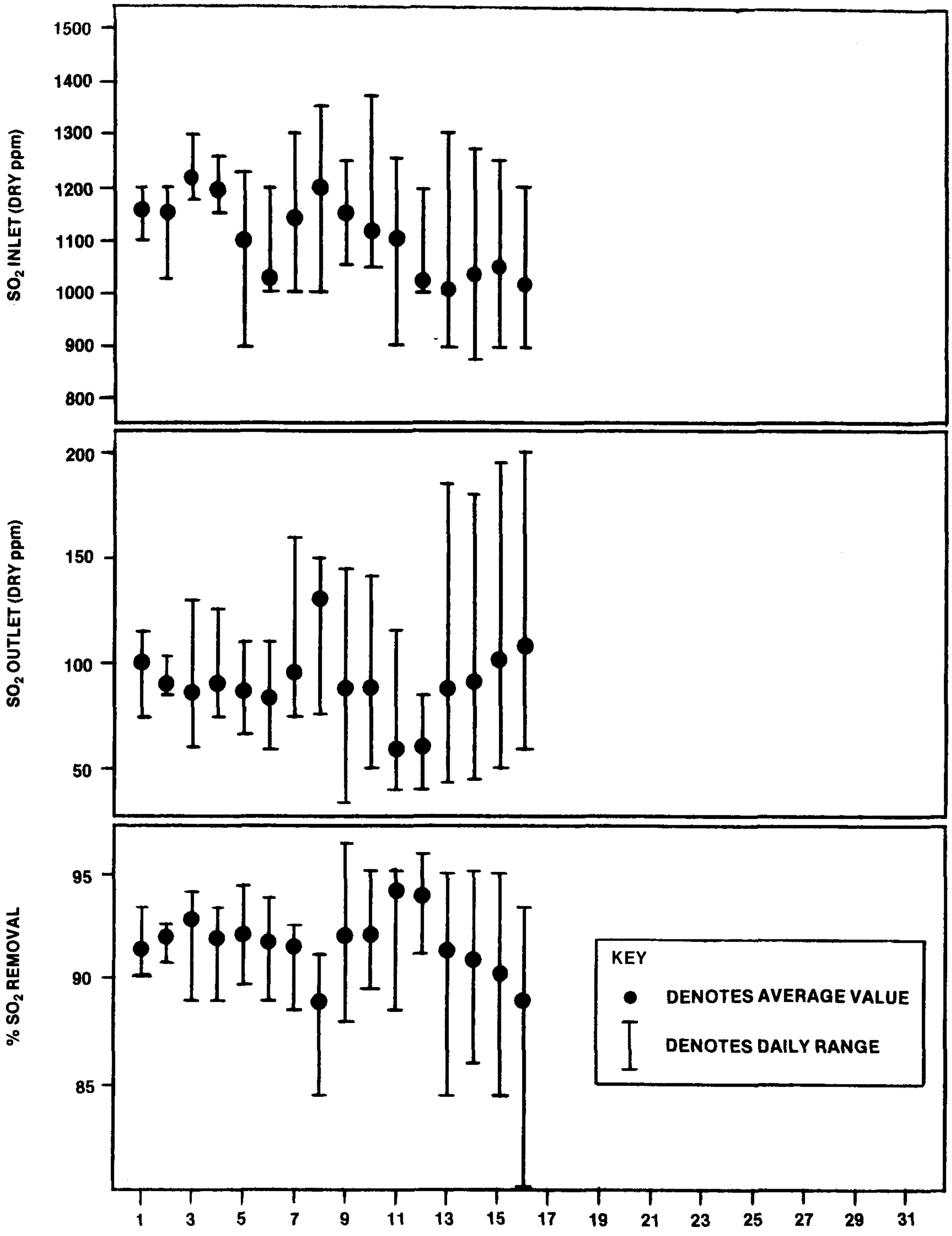


Figure 5-3
Summary of SO_2 Removal Data in January, 1979 (Phase I)

taken hourly during the program. The SO_2 removal data and other gas phase data are given in Appendix A in Figures A-4 through A-21.

Due to fluctuations in control variables such as pH and uncontrolled variables such as inlet SO_2 concentrations, the hourly SO_2 removal ranged from a high of about 97 percent on November 21 to a low of 80 percent on January 16. The 80 percent removal can be attributed in part to a low pH of 2.9 in the JBR on that day.

Sulfite Oxidation

Essentially complete oxidation of sulfite to sulfate was achieved during Phase I. Analysis of the JBR slurry indicated that no calcium sulfite solids and only very low levels of soluble sulfite were present. This is to be expected because at a pH below 5.0, the predominant sulfite species are HSO_3^- and H_2SO_3 and solid phase calcium sulfite is not formed. The stoichiometric ratios of oxygen to sorbed SO_2 were about 10 to 13 during Phase I. At these high ratios, soluble sulfite was effectively oxidized to sulfate in the bulk liquor of the JBR. Only occasionally was sulfite in the JBR overflow measured above the detection limit of the analytical sulfite method (0.1 millimole per liter or 8 mg/ℓ). The complete analytical results are presented in Appendix B.

The low soluble sulfite levels present in the JBR during Phase I maintained a high driving force for SO_2 sorption in spite of the relatively low pH. A 3.5 pH overflow slurry containing less than 8 mg/ℓ of liquid phase sulfite has an equilibrium SO_2 partial pressure of less than 1 ppmv (as determined from the Radian aqueous inorganic equilibrium model). The liquid phase sulfite concentration measured in the JBR liquors during Phase I was routinely below this 8 mg/ℓ level. This indicates that the driving force for SO_2 absorption was quite high during Phase I. However, it should also be noted that this judgment concerning the driving force is based on overflow slurry stream measurements which are actually average concentrations for the entire slurry surface layer in the JBR. The localized instantaneous driving force in the froth layer where the SO_2 sorption occurs may differ somewhat from that determined for the overflow slurry, but no reliable methods existed for obtaining a representative sample from the froth layer.

Limestone Utilization

Limestone utilization was excellent during Phase I. Based on the direct measurement of the solid phase carbonate, limestone utilization (molar ratio of solid phase carbonate to solid phase calcium) averaged 98.3 percent in the JBR and 97.5 percent around the prototype CT-121 system. These results were supported by material balances which closed to within 5 percent. The potential for even higher utilization around the entire system exists since the addition rate to the gypsum tank was not optimized to attain the maximum limestone utilization in the effluent stream to the gypsum stack. However, no tests were performed to determine what improvements in utilization could be attained.

Limestone utilization was also estimated from the sulfate/calcium ratio in the solids. This ratio method, which is inherently more inaccurate, resulted in a slightly higher utilization, averaging about 101.4 percent. The amount of residual carbonate is calculated implicitly by difference using this method assuming that sulfate and carbonate are the only anions present in the solid lattice.

$$\frac{Ca^{++} - CO_3^{=}}{Ca^{++}} = \frac{Ca^{++} - [Ca^{++} - SO_4^{=}]}{Ca^{++}} = \frac{SO_4^{=}}{Ca^{++}}$$

Such a mathematical model which computes a small quantity by taking the difference of large values will generally result in more scattered, less accurate results. As a result the limestone utilization figures for the JBR and gypsum tank determined by direct measurement of solid phase carbonate provide a more accurate indication of actual utilization. Additionally, the presence of more negative species than positive in the solids based on the ratio method indicates that a slight analytical bias may exist. The solid phase analytical data which were used to calculate utilization are presented in Table 5-1.

Material Balances

Material balances were calculated to confirm the results of the Phase I SO_2 removal rate and limestone consumption. These material balances, which generally closed within 5 percent, support the significant results discussed in the previous subsections dealing with SO_2 removal, sulfite oxidation, and limestone utilization.

Gas phase SO_2 removal and limestone consumption material balances for Phase I are shown in Table 5-2. One complicating factor in calculating the SO_2 mass balance is that the annubar, used for continuous flue gas flow measurements, was not installed and calibrated until January 8. Prior to this date, the gas flow was estimated using a curve developed during the CT-101 program relating the fan amperage

Table 5-1

PHASE I LIMESTONE UTILIZATION-ANALYTICAL DATA

		JBR Underflow Stream						Gypsum Tank Effluent Stream					
			Solid Phase Analyses (mmole/g)			Utilization (%)			Solid Phase Analyses (mmole/g)			Utilization (%)	
Date	JBR Overflow pH	pH	Ca^{++}	$SO_4^=$	$CO_3^=$	Carbonate Data[a]	Sulfate Date[b]	pH	Ca^{++}	$SO_4^=$	$CO_3^=$	Carbonate Data[a]	Sulfate Data[b]
11/15/78		3.8	6.11	6.07			99.4						
11/16	3.5	3.9	5.60	5.70			101.8						
11/20	3.6	3.8	5.55	5.78			104.1						
11/29	3.5	3.7	5.84	5.49	0.030	99.5	94.0	6.1	5.25	5.20	0.150	97.1	99.0
11/30	3.8	3.8	5.90	5.85			99.2						
12/1	2.9	3.2	6.06	6.08			100.3						
12/4	3.6	4.7	5.32	5.59	0.040	99.2	105.1	7.8	5.82	5.67	0.114	98.0	97.4
12/6	3.5	3.3	5.61	5.81	0.140	97.5	103.4	6.5	5.55	5.73	0.250	95.5	103.2
12/8	3.7	4.0	5.91	6.02			101.9						
12/11	3.5	3.7	5.45	5.97			109.5	6.3	5.95	5.98			100.5
12/13	3.6	3.9	5.60	6.13			109.5	7.3	5.71	5.66	0.110	98.1	99.1
12/15	3.7	4.0	6.09	5.72			93.9						
12/18	3.7	3.8	5.60	5.50	0.203	96.4	98.2	6.8	5.55	6.01	0.129	97.7	108.3
12/20	3.3	3.4	5.55	6.07	0.059	98.9	109.4	6.5	6.07	6.01	0.115	98.1	99.0
1/4/79	3.8	3.7						7.6	5.62	6.23	0.107	98.1	110.9
1/8	3.5	3.6						6.8	5.52	5.47	0.132	97.6	99.1
1/10	3.9	3.8	5.95	5.75			96.6		5.57	5.45			97.8
1/16	3.4	3.7	5.76	5.53	0.107	98.1	96.0						
						98.3 average	101.4 average					97.5 average	101.4 average

---

[a] % Utilization = $100[Ca^{++} - CO_3^=]/Ca^{++}$ (solid phase)

[b] % Utilization = $100 \cdot SO_4^=/Ca^{++}$ (solid phase)

Table 5-2

PHASE I SO_2 AND LIMESTONE MATERIAL BALANCES

	Gas Phase Sulfur Material Balance				Limestone Material Balance		Gypsum Production	
Date	Average Flue Gas Flow Rate (mscfm dry)[a]	Average SO_2 Inlet (ppm dry)	Average Removal Efficiency (%)	SO_2 Removal Rate (gmole/min)	Limestone Delivered (metric tons)	Limestone Silo Inventory (metric tons)	Gypsum Tank Percent Solids (wt)	Gypsum Removal Rate[d] (gmol/minute)
11/14/78					22	61		
11/15					22			
11/16	45[b]	1080	93.7	55	24	105		
11/17	45	970	93.3	49	23			
11/18	45	1030	92.0	51				
11/19	44	1160	92.1	56				
11/20	47	1210	91.1	62				
11/21	47	1180	93.1	62				
11/22	47	1150	92.7	60	24			
11/23	45	1210	93.7	61				
11/24	45	1150	92.1	57		109		
11/25								
11/26								
11/27								
11/28		SO_2 Analyzer out of service			22			
11/29					23		8.7	96
11/30					24			
12/1					23	126		
12/2								
12/3								
12/4	47	1310	91.6	68		136	4.9	54
12/5	47	1270	92.3	66				
12/6	48	1190	90.0	62				
12/7	50	1110	92.0	61				
12/8	50	1220	92.5	68				
12/9	46	1220	93.0	63				
12/10	45	1210	93.1	61				
12/11	47	1230	92.0	64		105	3.1	34
12/12	47	1220	92.5	63				
12/13	47	1230	93.1	64			7.6	83
12/14	47	1200	92.5	61				
12/15	47	1210	93.5	63	25			
12/16	46	1160	93.5	60	25			
12/17	46	1090	93.0	56				
12/18	46	1220	92.2	61	23	97	2.4	26
12/19	46	1180	91.6	59	23			
12/20	49	1240	91.9	67	24		4.7	52
12/21	47	1220	92.2	64				
12/22	47	1230	92.5	63				
12/23	47	1260	92.4	65				
12/24	46	1210	92.3	61				
12/25	47	1260	92.9	65				
12/26	47	1210	92.5	63		87		
12/27	51	1250	91.5	70				
12/28	49	1140	91.7	61				
12/29	47	1220	91.1	64				
12/30	50	1180	90.2	64				
12/31	48	1150	91.5	61				

Table 5-2

PHASE I SO_2 AND LIMESTONE MATERIAL BALANCES (Continued)

	Gas Phase Sulfur Material Balance				Limestone Material Balance		Gypsum Production	
Date	Average Flue Gas Flow Rate (mscfm dry)[a]	Average SO_2 Inlet (ppm dry)	Average Removal Efficiency (%)	SO_2 Removal Rate (gmole/min)	Limestone Delivered (metric tons)	Limestone Silo Inventory (metric tons)	Gypsum Tank Percent Solids (wt)	Removal Rate[d] (gmol/minute)
1/1/79	48	1160	91.5	61				
1/2	51	1150	92.1	65				
1/3	52	1210	92.8	70	22	37		
1/4	51	1180	91.9	66	25		6.7	74
1/5	48	1110	92.1	60	23			
1/6	47	1030	91.7	54	24			
1/7	47	1130	91.5	59				
1/8	43	1200	89.0	49	25		4.8	53
1/9	36[c]	1150	92.2	43				
1/10	39	1120	92.0	45		100	3.9	43
1/11	30	1110	94.3	33				
1/12	28	1030	94.0	30				
1/13	37	1010	91.4	36				
1/14	35	1040	91.0	36				
1/15	44	1060	90.4	47	87			
1/16	49	1020	89.1	49			3.4	37
Downtime (End of **Phase I)**								
1/20						65[e]		
				Average = $\overline{58}$	Total = $\overline{446}$		Average = $\overline{5.0}$	Average = $\overline{55}$

---

[a] **Based on estimate of 7% inlet moisture during Phase I.**

[b] Gas flows from 11/16/78 until 1/8/79 were estimated from fan amps - pitot measurements indicated an average of 18% lower flow.

[c] Gas flows from 1/9/79 through the remainder of the program were determined from annubar measurements.

[d] Removal rate = $\frac{50 \text{ gal slurry}}{\text{min}} \Big| \frac{3.785 \ell}{\text{gal}} \Big| \frac{1000 \text{ g slurry}}{\text{liter slurry}} \Big| \frac{\text{wt. fract. solids in gypsum tank}}{} \Big| \frac{.0058 \text{ gmole}}{\text{g solids}}$

Adjusted gas phase SO_2 removal = 50 gmoles SO_2/min (based on pitot measurements versus flow rate estimation from fan amps).

Limestone consumed = delivered - inventory

= 446 - 4 = 442 metric tons in 1527 hours

$$CaCO_3 \text{ consumption rate} = \frac{442 \times 10^6 \text{ g limestone}}{(1527)(60) \text{ min}} \Big| \frac{0.99 \; CaCO_3}{\text{g limestone}} \Big| \frac{\text{gmole}}{100 \text{ g } CaCO_3} = \underline{48 \text{ gmole } CaCO_3/\text{min}}$$

[e] Four hours after Phase II startup.

and gas temperature to the gas flow rate. Using the flow estimated from the fan amperage readings and the DuPont SO_2 analyzer readings, the average SO_2 removal in Phase I was 58 gmoles/minute. However, pitot traverses throughout Phase I indicated that the fan amp method yielded gas flows which were about 18 percent high. If the gas flows through January 8 are adjusted by this factor, then the average SO_2 removal during Phase I was 50 gmoles/minute. This compares favorably with the $CaCO_3$ consumption rate of 48 gmoles/minute estimated from limestone deliveries and inventory readings.

Due to the design of the JBR, the rate of sulfite oxidation to sulfate must also have equaled 50 gmoles/minute. However, there was no means of verifying this fact by material balance around the JBR because the flow rates and solids concentrations for several streams were unmonitored and the solids concentration in the gypsum tank was not routinely recorded. It was also difficult to obtain a representative solids concentration due to the location of the sample point and the stratification which occurs in the line to the gypsum stack. Based on spot samples taken during Phase I (average 5.0 weight percent solids and 50 gpm flow), a gypsum production rate of 55 gmoles/minute is estimated. This value is about 10 percent higher than the SO_2 removal and limestone consumption rates indicate.

Gypsum Crystal Structure, Settling, and Scaling Potential

During Phase I, large rod-like gypsum crystals were formed which settled very quickly. The gypsum relative saturation remained in the range of 1.0 and 1.1 which is well below the level where the onset of scaling would be expected. The gypsum crystal size and structure are related to the solid phase residence time and the level of supersaturation in the slurry where precipitation is occurring. Generally, the gypsum crystal growth precipitation rate may be related to these factors by an equation of the form:

$$R = k \cdot a \cdot V \cdot C \cdot (RS-1) \qquad (5\text{-}1)$$

where R is the precipitation rate, k is a temperature dependent rate constant, a is the specific solid-liquid interfacial area of the crystal, V is the volume of the reaction vessel, C is the solids concentration, and RS is the relative saturation (product of the activities of calcium and sulfate divided by the solubility product). Therefore, (RS-1) is the mass transfer driving force (8). For a given precipitation rate (equal to the SO_2 pickup rate), reaction volume and solids concentration, the driving force will be smaller when smaller crystals which have a larger specific surface area are present.

In Phase I tests, the combination of the large reaction volume, relatively high slurry solids concentration, and relatively low sulfur pickup rate resulted in a CT-121 prototype system solid phase residence time that was substantially longer than for most commercial operating limestone systems. This reaction time was about double that which was successfully demonstrated in Phase II. Due to the long residence time in Phase I tests, the gypsum crystals formed were very large and settled very quickly. In fact, the settling rates were so fast that free fall settling tests could not be performed to determine difference in crystal structure as had been originally planned. These settling characteristics also resulted in a gypsum stack which dewatered easily. Prior to the first dike raising, the solid cake at the liquid surface level in the gypsum stack was 70 weight percent solids or higher.

The upper portion of the JBR is the most susceptible region to chemical scaling for two reasons. First, this region has a lower solids concentration because of solids stratification due to gravitational effects; second, the SO_2 sorption reaction occurs primarily in this region. The gypsum relative saturation in the JBR overflow stream remained between 1.0 and 1.1 during most of Phase I. This is well below the 1.3 level where the onset of scaling would be expected (9). However, representative data for the froth zone could not be obtained and localized relative saturations in this zone may be higher than in the JBR overflow. On the other hand, major scale buildup was not observed at the conclusion of the test program. These results indicate that, while seed crystal generation had to occur to satisfy the particle balance constraint, uncontrolled nucleation which would cause severe scaling or create a large number of small crystals did not happen.

The long solid phase residence time and low relative saturation resulted in relatively orderly crystal growth, and much of the precipitation occurred along the preferred crystal face. Figures 5-4 through 5-8 are photomicrographs showing representative samples of the crystals formed in Phase I.

Figure 5-4 includes two photomicrographs of the JBR underflow solids taken on 29 November 1978. The largest crystals shown are about 850 microns in length. There are a number of crystals about 400 microns in length as well as several small crystals, most of which were probably formed through attrition. The length-to-diameter ratio (L/D) for the longer crystals is between 10 and 20.

Figures 5-5, 5-6 and 5-7 are photomicrographs of solids taken on 11 December 1978 from the JBR underflow, overflow, and limestone feed streams, respectively. The gypsum crystals shown in these figures appear to be slightly smaller than those

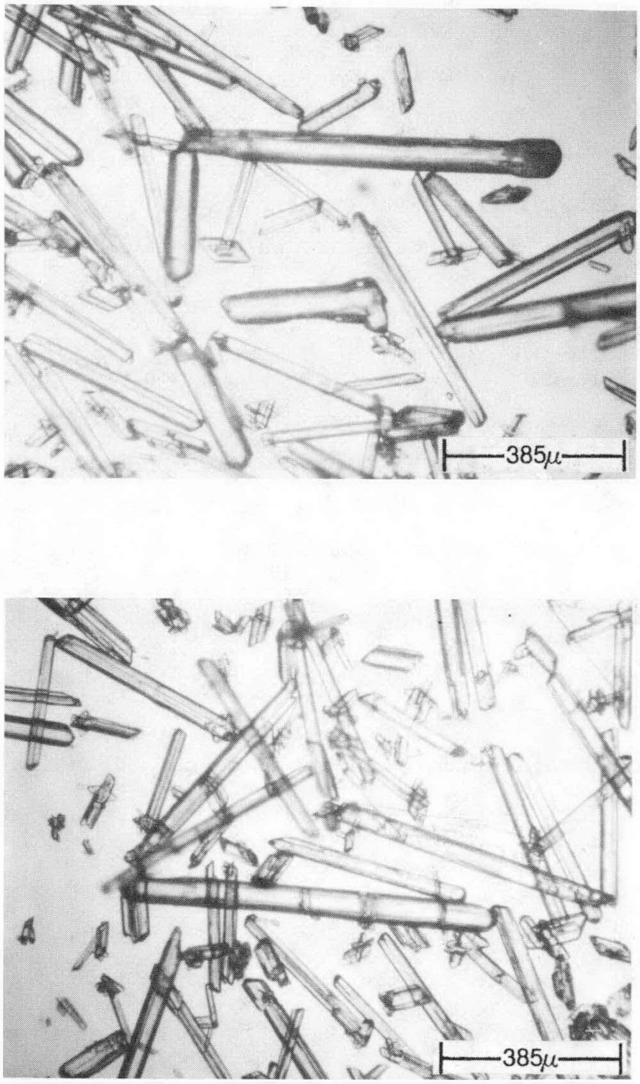


Figure 5-4
Phase I JBR Underflow Solids 11/29/78

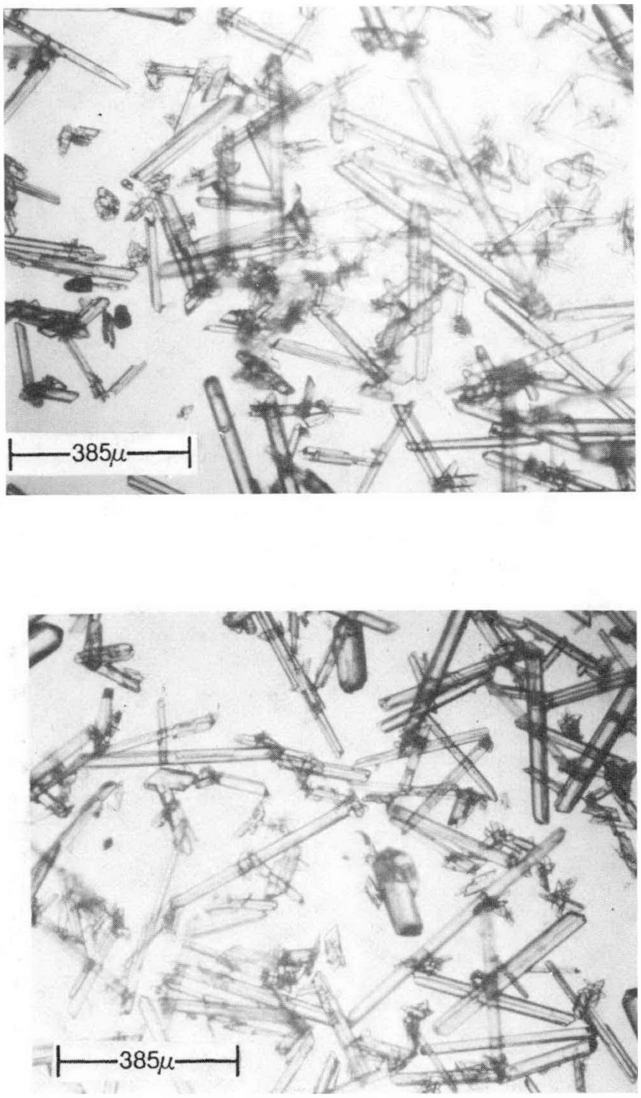


Figure 5-5
Phase I JBR Underflow Solids 12/11/78

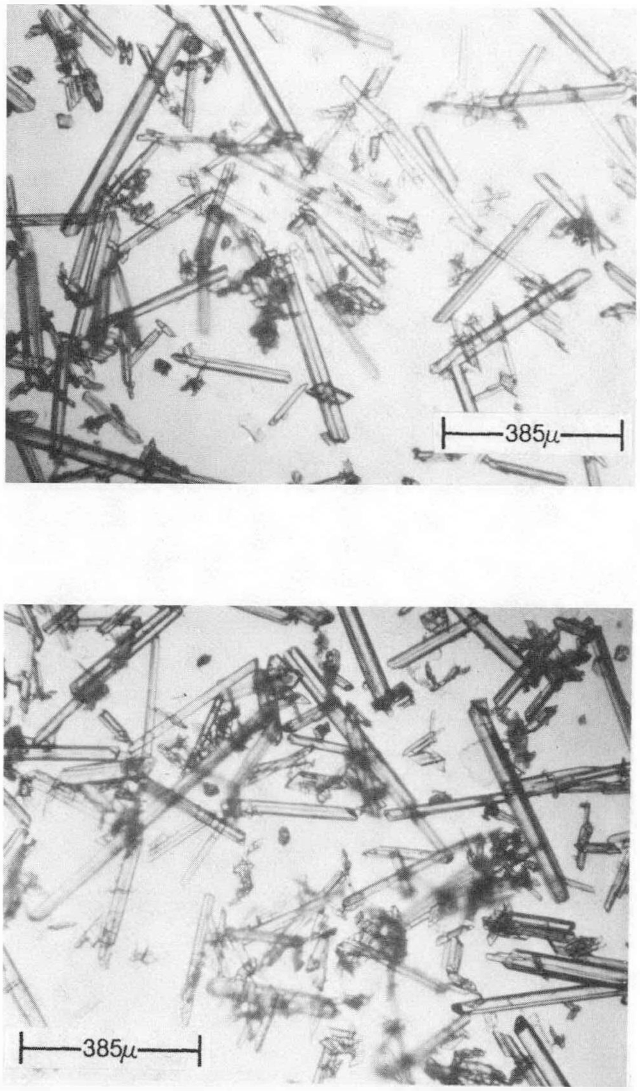


Figure 5-6
Phase I JBR Overflow Solids 12/11/78

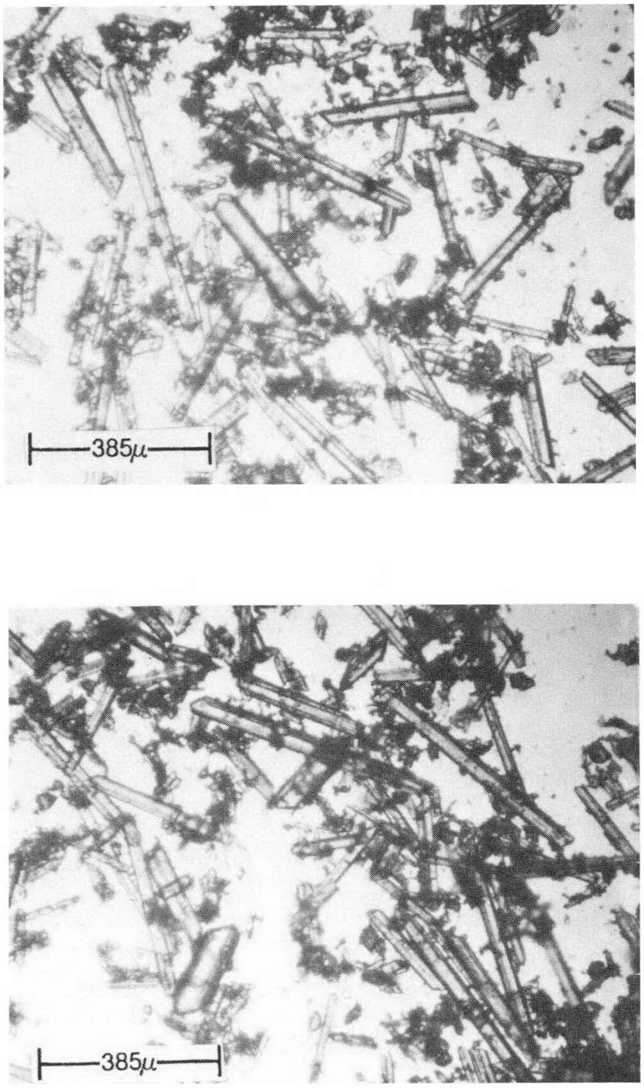


Figure 5-7
Phase I Limestone Feed Slurry 12/11/78

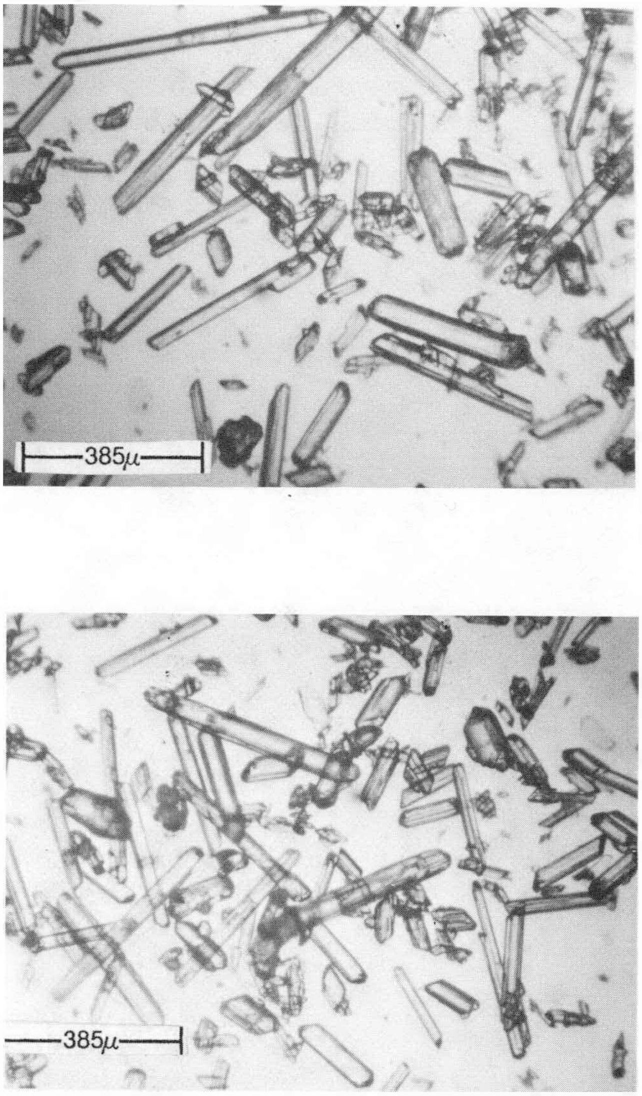


Figure 5-8
Phase I JBR Underflow Solids 1/16/79
Conclusion of Variable Boiler Load Tests

from November 29, but there are still many rods in the 300 to 400 micron range. This difference may be due to routine fluctuations in process conditions such as SO_2 inlet concentration, SO_2 removal efficiency, JBR slurry solids concentration, and the solids residence time.

Perhaps of more significance is the fact that there are no visually discernible differences between the crystal structures of the gypsum in the JBR overflow and those in the other streams. This indicates that the stratification in solids concentration in the JBR is more a result of the mixing, slurry density, and bulk gypsum settling rate than a difference in settling rate due to different sized crystals.

There are also undissolved limestone solids apparent in the photomicrographs of the JBR overflow, underflow, and limestone feed stream solids. These are the darker, less crystalline forms which are most noticeable in the limestone feed stream solids shown in Figure 5-7.

Figure 5-8 is a photomicrograph of the solids from the JBR underflow on 16 January 1979, the last day of Phase I. These gypsum crystals are more similar in appearance to the November 29 solids than to the December 11 solids. However, the January 16 crystals appear to be somewhat shorter and thicker than the November 29 solids. Differences could be due to variable load tests conducted from January 10 to 15. There also appear to be more broken crystals, but this may be due to the density of the crystals on the slides rather than to actual differences in particle size distribution.

Variable Boiler Load Simulation

The CT-121 system responded well to the variable boiler loads which were simulated during the period between January 10 and 15. During this period, the CT-121 system operator obtained the boiler load once every two hours from the boiler operator and adjusted the gas damper setting until the actual gas flow/design gas flow ratio for the CT-121 prototype was about equal to the actual boiler load/design full load ratio for the boiler. In Phase I, these flue gas flow changes were made after the operator manually made an appropriate change in the limestone feed rate. For instance, if a decrease in the gas flow was scheduled, the operator would first reduce the limestone feed rate to the JBR to minimize the pH fluctuation. Under these manual feed forward control conditions, the pH deviations were generally within ±0.2 pH units, and the pH returned to within ±0.1 pH unit of the set point within about 5 minutes after the gas flow change. Boiler load changes were also simulated in Phase II without the operator anticipating the flue gas flow change to simulate a more severe set of conditions.

This Phase I test also showed that the steady-state gas phase pressure drop across the JBR is fairly insensitive to changes in gas flow. Table 5-3 indicates the variations in ΔP which were experienced in a short-term flow variation test conducted with a 12 inch (30.5 cm) weir height. The response of the JBR to gas flow changes can be explained by examining the JBR configuration shown in Figure 5-9. As seen in Table 5-3, the pressure drop across the mist eliminator decreased with decreased flow. Therefore, in a forced draft configuration the pressure at points 1 and 2 (P_1, P_2) are higher at higher gas flows. Since level control in the JBR is accomplished with an overflow weir, the pressure difference between the flue gas inside the JBR above the froth layer and the outside atmosphere, in effect, sets the level in the JBR. Because the overflow rate (liquid velocity) is relatively low, the effective liquid height is determined by the pressure balance:

$$P_2 + h_2 = P_A + h_w \tag{5-2}$$

or

$$P_2 - P_A = h_w - h_2 \tag{5-3}$$

where P_2 is the pressure above the froth layer, P_A is atmospheric pressure, h_2 is the liquid head in the JBR and h_w is the liquid head at the weir. $P_2 - P_A$ is equivalent to the system pressure drop downstream of the JBR. At high gas flows, the difference in the weir and JBR liquid levels is greater than at low gas flows because the difference in P_2 and P_A is greater. This increased pressure at point 2 means the effective liquid level in the JBR is lower, and the liquid head the gas must overcome at high gas flows is less. On the other hand, the gas pressure drop through the sparger tubes and sparger openings is higher at higher loads so the impact of the two effects tends to be offsetting. This was seen as the JBR pressure drop remained fairly constant in the prototype unit with changes in gas flow.

The effects of sparger pressure drop and liquid head on SO_2 removal at different gas flows also tend to be offsetting. At higher gas flows, the pressure drop through the sparger openings is higher and the gas bubbles tend to be smaller creating greater mixing in the froth layer. This should improve SO_2 removal efficiency.

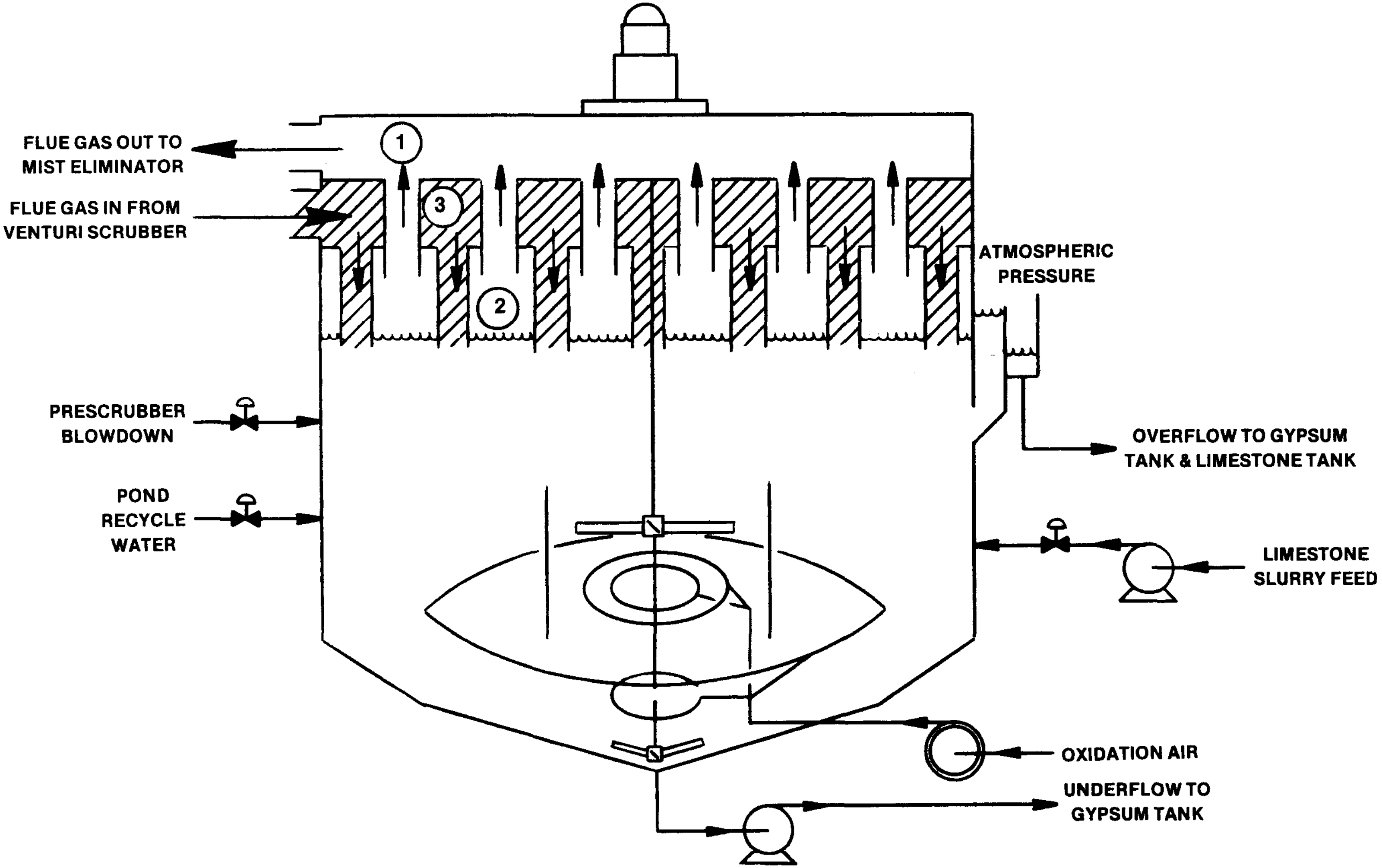


Figure 5-9
Schematic of Gas Flow Pattern through JBR

However, the lower liquid level and higher superficial gas velocity reduce the residence time of the gas in the froth zone and tend to decrease removal efficiency. Likewise, the effects at low gas flows tend to be offsetting. The gas bubbles are larger and the mixing less vigorous, but the gas-liquid residence time is greater. Lower gas flow also lowers the SO_2 transfer per volume of slurry in the froth zone, which also tends to improve SO_2 removal efficiency.

Table 5-3

EFFECT OF LOAD VARIATIONS ON PRESSURE DROP

Time	Fan	Gas Flow	Pressure Drop (inches H_2O)			
(EST)	Amperage	(scfm)	System	JBR	Mist Eliminator	Venturi
1504	92	48,000	26	12.4	3.4	10.2
1514	87	44,000	24.5	12.8	2.9	8.8
1530	83	40,000	23.5	12.5	2.4	8.6
1540	72	30,000	19	12.5	1.3	5.2
1552	61	23,000	17	13	0.8	3.2

Note: Test was performed on 14 February 1979 with a 12 inch weir setting.
For conversion from inches H_2O to centimeters H_2O: multiply by 2.54.

The results from Phase I indicate that slightly higher SO_2 removal efficiencies were achieved at lower gas flow conditions. The average removal efficiency at conditions where the gas flow was 30,000 scfm or less was about 94 percent during the Phase I boiler variable load tests based on 47 hourly readings. The average removal efficiency under operating conditions where the gas flow was greater than 45,000 scfm was 90 percent, based on 66 readings taken during the same variable load test period. Although this is not a large difference, the results of a "t" test indicate that the gas flow rate is significant with respect to SO_2 removal efficiency (5 percent probability of error level). Details of this "t" test procedure are presented in Appendix E. It appears that the longer retention time and lower SO_2 transfer per volume of slurry more than offset the reduced contact efficiency and less vigorous mixing which may result from lower gas throughput rates.

The results of the Phase I (and the Phase II) variable load tests also indicated that pressure equalization on the prototype JBR was somewhat constrained under conditions of rapidly increasing flue gas flow rate. When the flue gas flow increased from half load to full load in 15 minutes, the JBR pressure drop rose from about 12 inches to 13 inches because the weir was not wide enough to allow rapid pressure equalization. However, this did not adversely affect the prototype system operation. A commercial module would be expected to have a larger weir (or other level control device) and would probably not be subjected to this rapid of a fractional load increase.

Water Balance

This section summarizes the Phase I water balance during two time periods, November 16-30 and December 24-January 16. A detailed presentation of the water balance data for both Phases I and II is presented in Appendix D.

The rain gauges and evaporation pan were not installed until December 19, so quantitative measures of rainfall and evaporation were not possible until that time. When these devices were installed, a concerted effort was made to monitor any system discharges to the Gulf Power Company fly ash pond since this pond was considered to be outside of the CT-121 system's battery limits.

November 16-30. Table 5-4 summarizes the monitored flow rates during the first two weeks of Phase I. An expanded version of this table is presented in Appendix D. As Table 5-4 shows, the net average accumulation for this period, based strictly on process flow measurements, was 1.4 gpm (5 liters/min), but this does not include rainfall or evaporation from the pond. Since the instruments needed to quantify the rainfall and evaporation rates were not received until mid-December, the actual rate of liquor accumulation in the pond cannot be determined for this period. At least once during the November 16 to 30 period, fairly heavy rainfall caused pond water to overflow into the Gulf Power Company's fly ash pond. One circumstance which contributed to this open-loop operation was the insufficient capacity of the pond liquor return pumping system that led to higher rates of fresh makeup water consumption. Piping changes were made later which increased the pond liquor return rate to the system, but even with these changes the return rate limitations constrained the use of pond water in the CT-121 prototype system throughout the program.

Table 5-4

NOVEMBER 16-30 WATER BALANCE[a]

Date	Evaporation in Flue Gas (gpm) (-)	Water With Gypsum to Stack (gpm) (-)	Net Fresh Water in (gpm) (+)	Daily Accumulation (gpm)
11-16	16.3	1.0	19.0	1.7
11-17	16.3	1.0	21.9	4.6
11-18	16.3	1.0	24.8	7.5
11-19	15.8	1.0	21.8	5.0
11-20	18.7	1.0	18.9	-0.8
11-21	18.5	1.0	18.0	-1.5
11-22	18.5	1.0	18.3	-1.2
11-23	14.8	1.0	17.2	1.4
11-24	16.1	1.0	23.9	6.8
11-25	16.1	1.0	17.4	0.3
11-26	16.1	1.0	18.0	0.9
11-27	18.0	1.0	17.4	-1.6
11-28	15.9	1.0	17.6	0.7
11-29	15.9	1.0	16.2	-0.7
11-30	17.0	1.0	15.7	-2.3
			Average =	1.4

---

[a] Multiply by 3.785 to obtain liters/min
Daily accumulation = Net fresh water in
- Evaporation
- Water with gypsum to stack

December 24 - January 16. During the last month of Phase I the system operated in an open-loop manner for two reasons. First, inadequate freeze protection was included in the design of the prototype system. As a result, it was necessary to keep water flowing through many of the exposed drain valves which increased the system makeup water rate and the liquor flow rate to the pond. Secondly, heavy rainfall occurred during the period which overloaded the holding pond and resulted in overflows to the Gulf Power ash pond. Table 5-5 presents the results of the process water balance for this period.

Table 5-5

DECEMBER 24 - JANUARY 16 WATER BALANCE

Date	Evaporation in Flue Gas (gpm)[a]	Water With Gypsum to Stack (gpm)	Net Fresh Water in (gpm)	Rainfall (+)/ Evaporation (-) (gpm)	Total Excess Water Entering System (gpm)	Overflow (gpm)
12-24-78	14.8	1.0	16.5	13.5	14.2	(d)
12-25	15.4	1.0	16.5	13.5	13.6	(e)
12-26	15.6	1.0	16.5	13.4	13.3	(e)
12-27	18.9	1.0	16.5	-0.5	-3.9	(e)
12-28	18.2	1.0	16.5	-0.3	-3.0	(e)
12-29	15.9	1.0	16.5	-	0.4	(e)
12-30	18.0	1.0	16.5	3.3	0.8	(e)
12-31	16.4	1.0	16.5	3.3	2.4	(e)
1-1-79	16.2	1.0	16.5	3.3	2.6	(e)
1-2	18.0	1.0	16.5	3.3	0.8	(e)
1-3	19.5	1.0	27.1	-	6.6	(e)
1-4	19.4	1.0	27.1	-	6.7	(e)
1-5	17.2	1.0	27.1	-0.3	8.6	.6
1-6	16.3	1.0	27.1	-	9.8	1.0
1-7	15.9	1.0	27.1	-	10.2	
1-8	20.2	1.0	27.1	28.5	34.4	8.3
1-9	17.4	1.0	27.1	-0.4	8.3	5.3
1-10	17.4	1.0	27.1	-0.1	8.6	6.3
1-11	14.9	1.0	27.1	-0.4	10.8	6.3
1-12	13.3	1.0	27.1	2.2	15.0	17.4
1-13	16.6	1.0	27.1	2.2	11.7	
1-14	16.5	1.0	27.1	-	9.6	
1-15	19.8	1.0	27.1	5.2	11.5	54.9
1-16	21.6	1.0	27.1	-0.2	4.3	80.5[c]
					Average = 8.2	Average = 7.5

---

[a] Multiply by 3.785 to obtain liters/min

[b] Total Excess Water = Net fresh water in +Rainfall (-Evaporation) - Evaporation in flue gas - water with gypsum to stack.

[c] Pumped to fly ash pond over three day period (1-16 to 1-19), one day average.

[d] Overflow from the CT-121 pond to Gulf Power's pond occurred but was not measured.

[e] No overflow was observed on these days.

Since the CT-121 system's pond was full during the period, all of the excess water entering the system resulted in overflow to Gulf Power's ash pond. The average rate of excess water entering the system was 8.2 gpm (31 liters/min). About 280,000 gallons (1070 m^3) of excess water entered the system during the period. It was estimated by an independent method that approximately 260,000 gallons (980 m^3) left the system as overflow which agrees closely with the total excess water entering. On December 24, the pond reached the drain pipe level; on January 16, the pond was still at the December 24 level. Therefore, no net accumulation occurred during this time and all excess water above that required for FGD system operation exited via the pond overflow mechanism. At this point it was decided that a tighter control on the pond level would be initiated. The overflow pipe was sealed to prevent further losses during Phase II. Additionally, steps were taken to increase the amount of pond water used in the process during Phase II. For instance, pond return water was used for pump seal water and for spray water in the duct between the venturi and the JBR during portions of Phase II. The results of these changes are discussed in the Phase II water balance section.

PHASE II TEST RESULTS

The objective of Phase II testing was to determine the CT-121 system's response to a wider range of process conditions than was encountered during the two months of routine operation at fixed conditions (Phase I). The variables tested included: (1) perturbations in process conditions to simulate operator inattention or process upsets, and (2) site specific variables such as coal or limestone type.

The discussion of the Phase II results is organized to follow the specific tests conducted:

- Statistical test series - pH, ΔP, oxidation air rate, and limestone particle size
- Reduction in JBR slurry solids
- Reduction in oxidation air rates and simulated compressor failure
- Variable boiler load simulation
- High sulfur coal testing
- Chloride spiking
- Mixer failure and reversal of flow pattern
- Particulate and trace elements sampling
- Spiking with liquid SO_2

A summary of the important Phase II results is presented first. Following the summary, results of specific tests are discussed in chronological order (except for repeated tests). In addition to test results, the prescrubber operation and the overall water balance for Phase II of the evaluation program are also discussed in this section.

Summary of Phase II

Phase II testing provided a basis for evaluating the performance of the CT-121 prototype system over a wide range of operating conditions. The prototype system demonstrated an ability to function reliably under the conditions imposed, and no conditions were encountered which appeared to adversely affect long-term system performance.

The JBR's SO_2 removal capability was influenced by a number of process variables. The control variables, JBR overflow pH and JBR pressure drop, had the most substantial effect, while variations in inlet flue gas SO_2 concentration did not effect SO_2 removal efficiency significantly until the inlet SO_2 concentration exceeded 2200 ppm. The JBR pH, JBR gas-side pressure drop, and the inlet SO_2 concentration were included in a model to predict SO_2 removal efficiency over the range of operating conditions encountered in Phase II. The results of the modeling work are presented in Eqs. 5-4 and 5-5. It should be emphasized that these equations model the results of prototype testing during Phase II and will not necessarily model the performance of future commercial CT-121 systems.

$$\text{Fractional } SO_2 \text{ Removal } (SO_2 < 2200 \text{ ppm}) = \frac{1 - \exp\left[-3.49 \left(\frac{\Delta P}{15.4}\right)^{1.07}\right]}{1 + 56.9 \left(\frac{15.4}{\Delta P}\right)\left(10^{-pH}\right)\left(\frac{SO_2}{1000}\right)^{.11}}$$

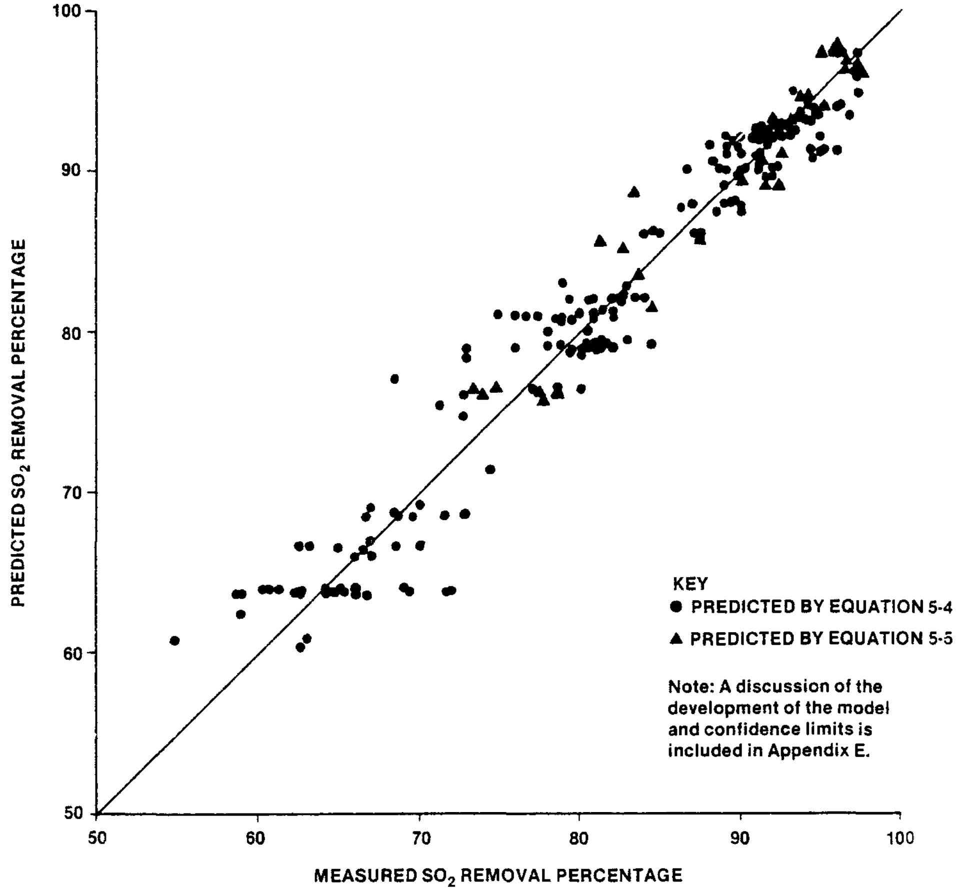
$$\text{Fractional } SO_2 \text{ Removal } (SO_2 \geq 2200 \text{ ppm}) = \frac{1 - \exp\left[-3.85 \left(\frac{\Delta P}{15.4}\right)^{1.44}\right]}{1 + 0.84 \left(\frac{15.4}{\Delta P}\right)\left(10^{-pH}\right)\left(\frac{SO_2}{1000}\right)^{5.26}}$$

In these equations, "ΔP" represents the pressure drop across the JBR in inches of water, "pH" represents the JBR overflow pH, and "SO_2" represents the inlet flue gas SO_2 concentration in ppm.

The theoretical form of this model had been developed by Chiyoda (10), although new constants were derived to fit the prototype results. The constants in Eq. 5-4 were determined from 200 data sets while constants in Eq. 5-5 were developed using 29 data sets. The model was divided into the two equations to account for the effect of high inlet SO_2 concentrations. An attempt to fit the data to a single equation resulted in fairly large deviations between predicted and measured SO_2 removal efficiencies for test conditions where the inlet SO_2 concentrations exceeded 2200 ppm. The development of Eqs. 5-4 and 5-5 and the confidence intervals about the equations is presented in Appendix E.

Examination of Eqs. 5-4 and 5-5 shows that an increase in JBR ΔP decreases the ΔP exponential term in the numerator (which increases the magnitude of the numerator) and decreases the denominator thereby increasing the predicted SO_2 removal. An increase in overflow pH decreases the 10^{-pH} term and the overall value of the denominator which also increases the predicted SO_2 removal. Comparison of Eqs. 5-4 and 5-5 shows that the effect of the inlet SO_2 concentration is much greater when the concentration exceeds 2200 ppm because the SO_2 term's exponent is much larger in Eq. 5-5. An increase in SO_2 content in Eq. 5-5 causes the denominator to increase substantially which results in a lower predicted SO_2 removal efficiency. Figure 5-10 shows the agreement between the model results and the measured SO_2 removal efficiencies for the Phase II results.

Two additional variables, oxidation air rate (O/SO_2 stoichiometry) and flue gas rate, also affected SO_2 removal somewhat, but these variables were not included in the SO_2 removal efficiency model since changes in O/SO_2 stoichiometry and flue gas rate did not have a measurable effect on system performance until substantial deviations from design conditions were tested. An O/SO_2 stoichiometry of 4 resulted in an SO_2 removal of about 77 percent compared to about 90 percent at a design O/SO_2 stoichiometry of 10. An O/SO_2 stoichiometry of 8 was tested in the initial statistical test matrix but had shown no effect. Changes in the flue gas flow rate also resulted in changes in the SO_2 removal efficiency. As was discussed in the Phase I results, the system exhibited about 94 percent removal at half load compared to about 90 percent at full load. While the difference was judged to be statistically significant at the 0.05 probability level, the effect was not nearly as large as that caused by relatively small changes in pH or ΔP, and flue gas flow rate was not included in the model.



Note: A discussion of the development of the model and confidence limits is included in Appendix E.

Figure 5-10
Predicted Versus Measured SO_2 Values for Phase II Data Using Equations 5-4 and 5-5

Two different limestones, one 90 percent less than 200 mesh and the other 90 percent less than 325 mesh, were tested in Phase II. Due to the relatively low operating pH in the JBR, no differences were noted in limestone utilization or SO_2 removal. There was also little difference noted in system performance during the chloride spiking tests when the JBR liquor contained 6000 mg/ℓ chloride.

Throughout Phase II, the gypsum solids settled and dewatered rapidly. The gypsum relative saturation required for the onset of scaling was never approached in the JBR. Only minimal scaling in the JBR was observed at the end of Phase II, and the scale that was present did not cause any operating problems. These results were encouraging since the tests were done over a range of JBR solids concentrations and SO_2 mass removal rates which could have resulted in process conditions conducive to scaling.

Particulate and trace element sampling showed that the venturi/JBR combination removed an average of 99.4 percent of the inlet particulates at a loading of 3.4 gr/scf. In addition, trace element balances showed that removal of 5 volatile trace elements (As, Sb, Cd, Hg, Se) from the flue gas was about 90 percent. Moreover, 99 percent removal was seen for 10 of the less volatile trace elements (Ca, Mg, Ti, Cr, Cu, Pb, Ni, Va, Be, Zn). Details of the particulate removal and trace element testing are presented in Section 6.

The system was operated open loop during January and February due to freezing, rainy weather. During March, April, and May, the system ran closed loop except for two periods when overflow occurred due to raising the gypsum stack.

Overall, the system responded extremely well to the variety of tests conducted. Unexpected downtime was less than 22 hours during Phase II. The majority of this time (21 hours) was due to two outages that resulted from problems with the limestone feed rotor and limestone powder consistency during the change to the second limestone.

Statistical Test Series

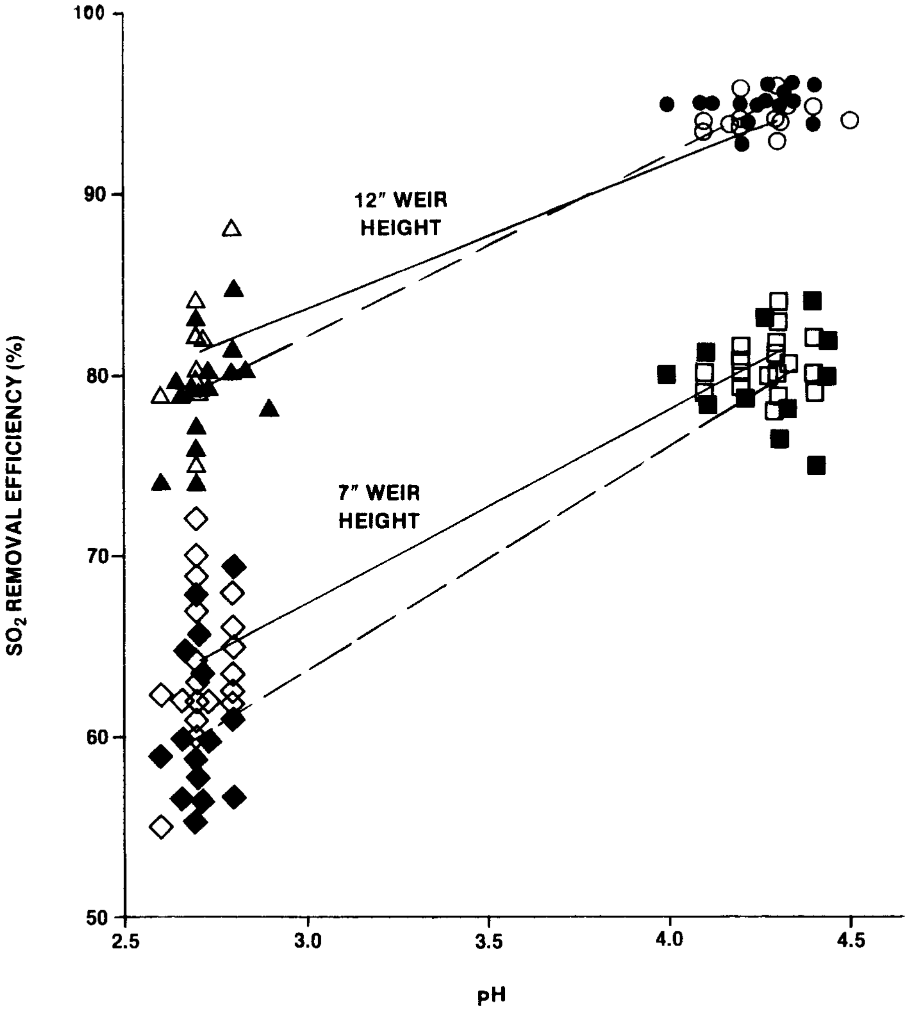
The first test series conducted in Phase II was designed to evaluate the CT-121 system response to changes in JBR pH, JBR pressure drop, oxidation air rate, and limestone particle size. Attention was focused primarily on the JBR operation in this test series because this vessel is the heart of the CT-121 system. Parameters monitored to measure system performance included: (1) SO_2 removal, (2) limestone utilization, and (3) gypsum scaling tendency and crystal structure.

Since the flue gas SO_2 concentrations were monitored continuously by on-line instrumentation, sufficient data concerning SO_2 removal were gathered to draw conclusions based on statistical analyses. As described in Section 4, a half factorial test matrix provided information concerning main variable effects as well as some information about two-factor interactions. A summary of the statistical calculations and data reduction is presented in Appendix E.

The pressure drop and pH had the most significant effects on SO_2 removal. The limestone grind and oxidation air rate had minimal effect on the SO_2 removal in the ranges examined in this test series. Increases in the pH or the pressure drop significantly increased SO_2 removal. In fact, these two variables had such an overriding effect on the performance of the JBR, that single variable tests were conducted later in Phase II. The results of these single variable tests are discussed in following subsections.

Figures 5-11 and 5-12 show the effects of pH, ΔP, and limestone particle size graphically. As shown in these figures, the SO_2 removal remained between 92 and 96 percent at the 4.3 pH and 12 inch (30 cm) weir setting with both limestones. Operation at both the 4.3 pH, 7 inch weir conditions and the 2.7 pH, 12 inch weir conditions resulted in about 80 percent SO_2 removal. Although the average removal with the finer limestone is about one percentage point less than with the coarser limestone, the actual difference is not judged to be of major significance due to the scatter in the data. One method of analysis in Appendix E shows that limestone size is statistically significant at a 10 percent probability of error level although its reference is overshadowed by the high significance levels of the ΔP and pH effects. The greatest difference in SO_2 removal for the different limestones was at the low pH, low weir setting. At these set points, the removal averaged 64 percent with the 200 mesh stone and only 60 percent with the 325 mesh stone.

Although the statistical analysis shows that a limestone grind of 90 percent less than 200 mesh yields slightly better SO_2 removal than a grind of 90 percent less than 325 mesh, there are other process variables which could have affected these results. One of the most significant may have been the weir setting. Exact duplication of weir setting was not possible because it was mechanically difficult to adjust. The flue gas flow rate also varied somewhat during the statistical tests. Although the gas flow generally remained between 46,000 and 54,000 scfm, the variable boiler load tests in Phase I indicate this could have had a small effect on the SO_2 removal. Also, the liquid flows to the JBR (prescrubber bleed, pond water return, and limestone feed) as well as changes in the underflow draw off rate can



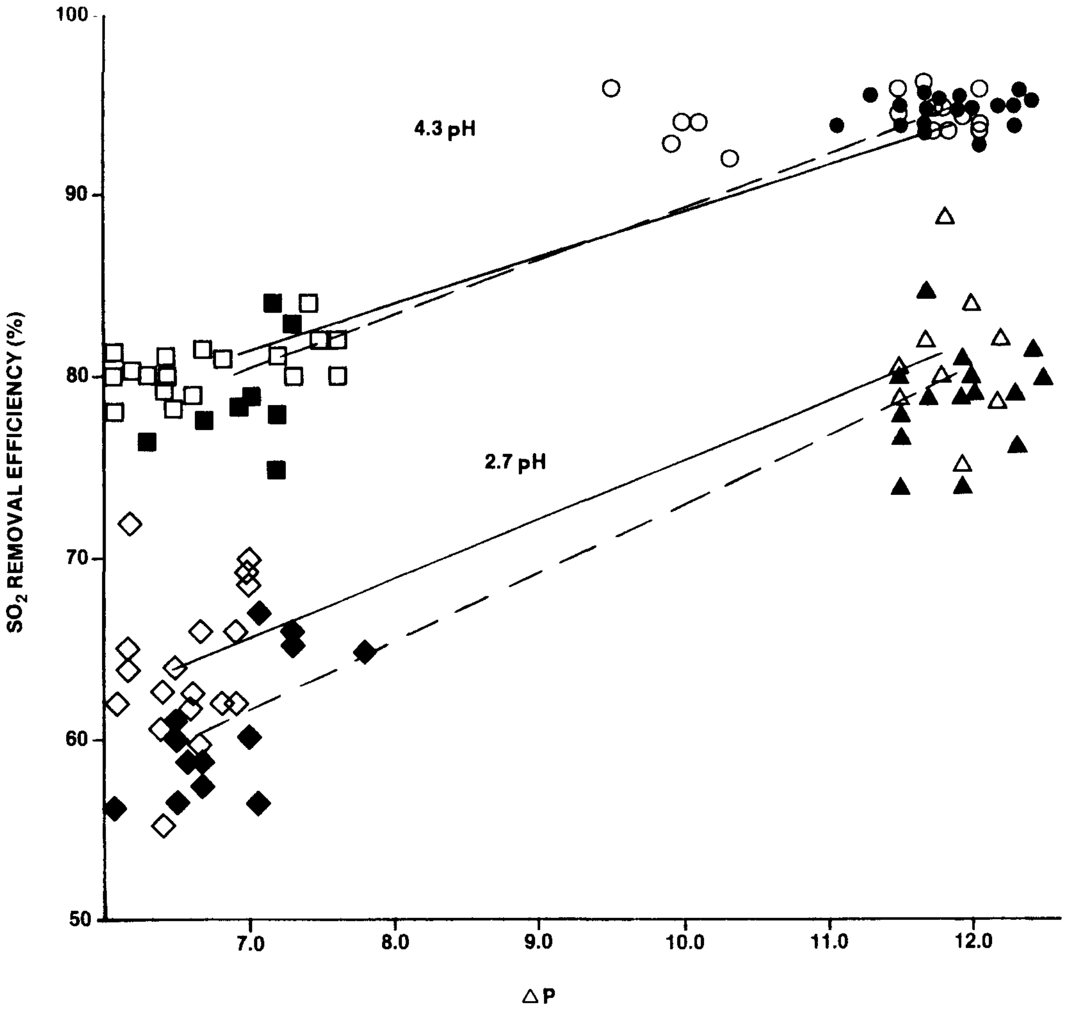
		VARIABLE SET POINTS			SO_2 REMOVAL EFFICIENCY (%)	
	pH	WEIR HEIGHT* (Inches)	AIR RATE (scfm)	LIMESTONE SIZE (90% less than)	AVERAGE MEASURED	PREDICTED BY EQ. 5-4
● TEST 1A	4.3	12	1050	325 mesh	95	92
▲ TEST 1B	2.7	12	1350	325 mesh	79	80
■ TEST 1C	4.3	7	1350	325 mesh	80	76
◆ TEST 1D	2.7	7	1050	325 mesh	60	61
○ TEST 1F	4.3	12	1350	200 mesh	94	92
△ TEST 1G	2.7	12	1050	200 mesh	81	80
□ TEST 1H	4.3	7	1050	200 mesh	80	76
◇ TEST 1I	2.7	7	1350	200 mesh	64	61

——— LIMESTONE 90% < 200 mesh

— — — LIMESTONE 90% < 325 mesh

*MULTIPLY BY 2.54 TO OBTAIN cm

Figure 5-11
Effect of pH on SO_2 Removal (Phase II Statistical Results)



	VARIABLE SET POINTS				SO$_2$ REMOVAL EFFICIENCY (%)	
	pH	WEIR HEIGHT* (inches)	AIR RATE (scfm)	LIMESTONE SIZE (90% less than)	AVERAGE MEASURED	PREDICTED BY EQ. 5-4
● TEST 1A	4.3	12	1050	325 mesh	95	92
▲ TEST 1B	2.7	12	1350	325 mesh	79	80
■ TEST 1C	4.3	7	1350	325 mesh	80	76
◆ TEST 1D	2.7	7	1050	325 mesh	60	61
○ TEST 1F	4.3	12	1350	200 mesh	94	92
△ TEST 1G	2.7	12	1050	200 mesh	81	80
□ TEST 1H	4.3	7	1050	200 mesh	80	76
◇ TEST 1I	2.7	7	1350	200 mesh	64	61

——————— LIMESTONE 90% < 200 mesh

— — — — LIMESTONE 90% < 325 mesh

*MULTIPLY BY 2.54 TO OBTAIN cm

Figure 5-12
Effect of ΔP on SO$_2$ Removal (Phase II Statistical Results)

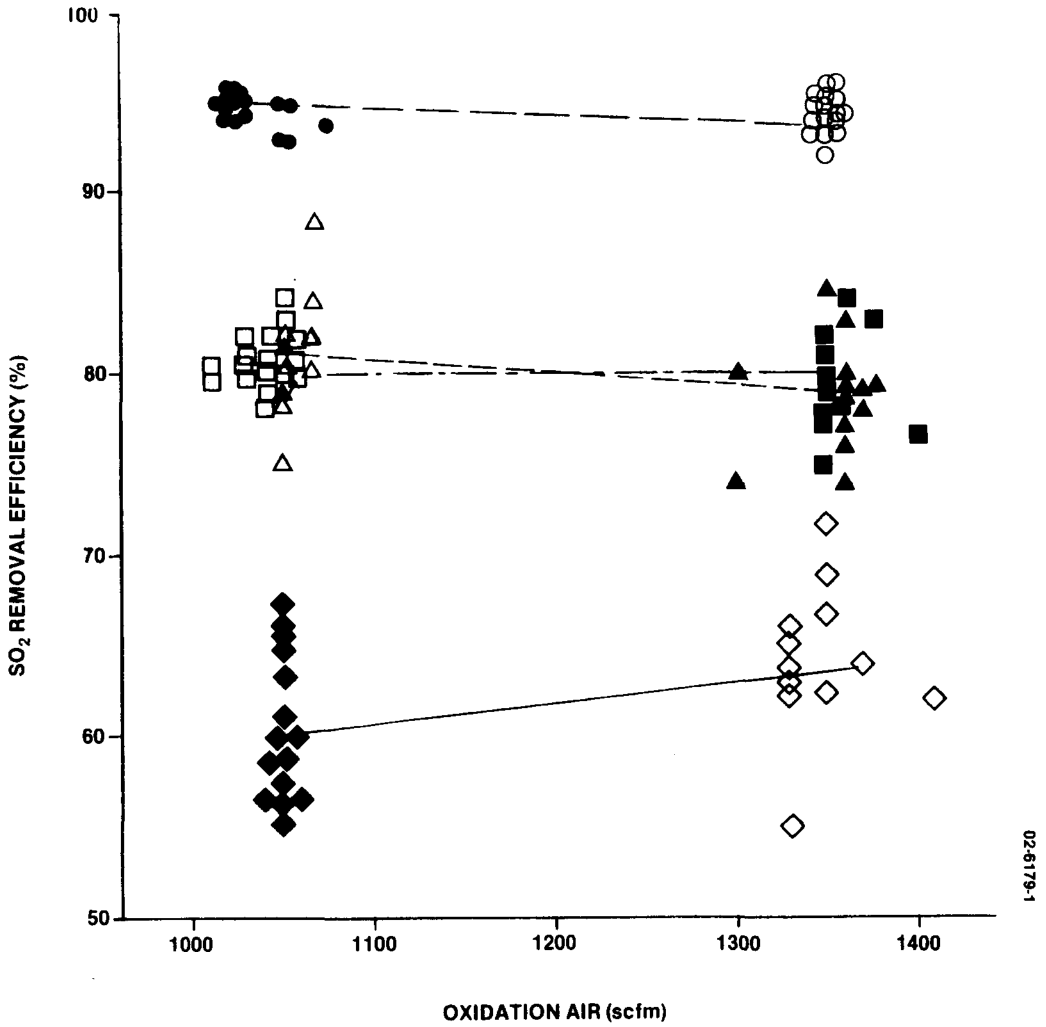
affect the instantaneous froth height in the JBR. This height affects the gas-liquid interfacial contact time and ΔP which influences the SO_2 removal. The effect of unaccounted for variations in JBR froth height would be most significant at the low weir height and could have caused the wider data scatter observed at the low weir settings. The impact of these uncontrolled variables could have had as significant an effect on the SO_2 removal as the limestone grind. As a result, the statistical analysis described in Appendix E indicated the effect of limestone grind to be statistically insignificant.

Comparing the slopes of the straight lines drawn on the plots in Figures 5-11 and 5-12 gives a visual indication of the interaction between pH and ΔP. For instance, if the 12 inch weir setting line were parallel to the 7 inch weir line in Figure 5-11, then there would be no interaction. Although the lines are not exactly parallel, the statistical analysis indicates that none of the two-factor interactions measured in this initial test matrix were of major statistical significance.

Figure 5-13 shows the results of changing the oxidation air rate during this test series. It is apparent from examining Figure 5-13 that the oxidation air rate did not have a major effect on SO_2 removal efficiency. The air stoichiometries tested in this series ranged from about 9 to 12. Based on these test results and the fact that the mixing efficiency in the JBR was not adversely affected, it was decided that lower air rates should be tested to define operability limits. Testing was performed later in Phase II at lower air rates.

Limestone Utilization. No statistically significant differences in limestone utilization were noted based on the initial Phase II test matrix results. The two variables which might be expected to influence the utilization were the JBR pH and the limestone particle size. The overflow pH set point ranged from 2.7 to 4.3 during the Phase II statistical tests. Table 5-6 compares the properties of the Georgia Marble and Southern Materials Company (SMC) limestones. The main difference noted between the two limestones was the finer grind of the Georgia Marble stone, but independent laboratory tests for limestone reactivity were not conducted.

Table 5-7 presents the limestone utilizations measured throughout Phase II. All of the utilizations were extremely high; most were above 98 percent (carbonate method, see Phase I Limestone Utilization Discussion). The average utilization for the Georgia Marble runs (Tests 1A-1 through 1D) was 98.6 percent while 97.8 percent was the average for the Southern Material Company (SMC) limestone tests (1F-1 through I-1). For the high pH set points in the text matrix (Tests 1A-1, 1A, 1C,



	VARIABLE SET POINTS				SO_2 REMOVAL EFFICIENCY (%)	
	pH	WEIR HEIGHT* (inches)	AIR RATE (scfm)	LIMESTONE SIZE (90% less than)	AVERAGE MEASURED	PREDICTED BY EQ. 5-4
● TEST 1A	4.3	12	1050	325 mesh	95	92
▲ TEST 1B	2.7	12	1350	325 mesh	79	80
■ TEST 1C	4.3	7	1350	325 mesh	80	76
◆ TEST 1D	2.7	7	1050	325 mesh	60	61
○ TEST 1F	4.3	12	1350	200 mesh	94	92
△ TEST 1G	2.7	12	1050	200 mesh	81	80
□ TEST 1H	4.3	7	1050	200 mesh	80	76
◇ TEST 1I	2.7	7	1350	200 mesh	64	61

◆————◇ low pH, low ΔP
● — — — ○ high pH, high ΔP
△- - - - -▲ low pH, high ΔP
□——·——■ high pH, low ΔP

* Multiply by 2.54 to obtain cm.

Figure 5-13
Effect of Oxidation Air Rate on SO_2 Removal (Phase II Statistical Results)

1F, and 1H), the average utilization was 97.6 percent. The average utilization for the low pH set points (Tests 1B, 1D, 1G, and 1I) was 99.1 percent. Overall during Phase II, the utilization averaged 98.3 percent, the same as during Phase I.

Table 5-6.

COMPOSITIONS AND PARTICLE SIZE DISTRIBUTION FOR LIMESTONES USED IN THE EVALUATION PROGRAM

	Georgia Marble (Sylacauga, AL)	Southern Materials Company (Ocala, FL)
Composition (%)		
$CaCO_3$	98.0	99.0
$MgCO_3$	1.7	0.8
Inerts	0.3	0.2
Size Distributions (%)		
<100 mesh	99.9	99.8
<200 mesh	99.8	91.8
<325 mesh	96.3	76.1

As stated previously, these differences in limestone utilization were not found to be statistically significant. Even at the high pH set points, the driving force for limestone dissolution was high enough that the effects of variations in limestone reactivity or slurry pH were minimized. The differences in utilization could have been due to several factors including: (1) fluctuations in the limestone reactivity (even for different deliveries of the same limestone), (2) variations in the immediate history of the JBR slurry (such as pH fluctuations) prior to the sampling time, and (3) measurement error.

Gypsum Crystal Structure and Scaling Tendency. One of the purposes of Phase II was to evaluate the impact of unplanned changes in operating conditions on gypsum crystal structure and gypsum scale formation. The data analysis did not indicate a significant relationship between operating conditions and gypsum relative saturation or crystal morphology.

The gypsum relative saturation ranged from about 1.0 to 1.15 during the statistical test series. However, the JBR underflow solids concentration varied between 18 and

Table 5-7

PHASE II LIMESTONE UTILIZATION - ANALYTICAL DATA

				JBR Underflow Stream						Gypsum Tank Effluent Stream					
					Solid Phase Analyses (mmole/g)			Utilization (%)			Solid Phase Analyses (mmole/g)			Utilization (%)	
	Test	Date	JBR Overflow pH	pH	Ca^{++}	$SO_4^=$	$CO_3^=$	Carbonate Data[a]	Sulfate Data[b]	pH	Ca^{++}	$SO_4^=$	$CO_3^=$	Carbonate Data[a]	Sulfate Data[b]
Georgia Marble Limestone	1A-1	1/25/79	4.1	4.9	5.49	5.57	0.094	98.3	101.5	7.1	5.37	5.54	0.355	93.4	103.2
	1A	1/28	4.3	4.9	5.55	5.67	0.052	99.1	102.2						
	1B	1/31	3.0	2.9	5.38	5.30	-	-	98.5	7.8	5.69	5.57	0.088	98.4	97.9
	1C	2/3	4.3	5.3	5.21	5.67	0.105	98.0	108.8						
	1D	2/6	2.9	3.0	5.82	5.59	0.058	99.0	96.0	6.5	5.77	5.38	0.489	91.5	93.2
	1E	2/9	3.8	4.3	5.93	5.69	-	-	96.0						
SMC Limestone	1F	2/16	4.3	4.5	5.68	-	0.269	95.3							
	1G	2/19	2.9	3.1	5.65	6.03	0.033	99.4	106.7	6.3	5.71	5.72	0.310	-	-
	1H	2/22	4.7	5.3	6.11	5.77	0.138	97.7	94.4	-	6.04	5.67	0.315	94.8	93.8
	1I	2/23	2.9	3.1	6.02	5.77	0.066	98.9	95.8	-	5.86	5.52	0.290	95.1	94.2
	1I-1	2/26	3.1	3.2	5.48	5.90	-	-	107.7	-	5.83	5.71	-		97.9
High Sulfur Coal		2/28	4.8	5.0	5.72	5.92	0.060	99.9	103.5	6.5	6.29	4.67	1.51	78.0	74.2
		3/15	3.1	2.9	5.88	5.89	0.070	98.8	100.2	-	5.73	5.84	0.100	98.3	101.9
		3/16	3.7	3.9	5.66	5.83	0.059	99.0	103.0	-	5.62	5.66	0.268	95.2	100.7
		3/23	4.6	5.2	5.77	5.89	0.108	98.1	102.1	6.0	5.75	5.39	0.54	98.4	93.7
		3/28	3.5	4.0						5.2	5.81	5.37	0.315	94.6	92.4
		3/29	4.2	4.7	5.81	5.52	0.120	97.9	95.0						
		3/30	3.6	3.9						-	5.65	5.69	0.275	95.1	100.7
		4/4	3.6	4.0	5.89	5.93	0.128	97.8	100.7	4.2	6.20	5.40	0.642	89.6	87.1
		4/9	2.6	2.8	5.67	5.57	0.049	99.1	98.2	-	5.70	5.53	0.416	92.7	97.0
		4/11	4.2	5.3	5.79	5.56	0.110	98.1	96.0	-	5.75	5.36	0.419	92.7	93.2
		4/16	4.0	5.2	5.80	5.62	0.100	98.3	97.7	6.5	5.93	5.40	0.590	90.0	91.1
		4/17	4.9	5.5	5.84	5.51	0.256	95.6	94.3	-					
Cl^- Spiking		4/24	3.6	4.0	5.91	5.71	0.033	99.4	96.6	2.2	5.36	5.58	0.004	99.9	104.1
		4/26	3.5	4.7	5.60	5.60	0.103	98.2	100.0	5.2	5.95	5.28	0.541	90.7	
SO_2 Spiking		5/16	3.4	4.4						-	6.17	6.15	0.280	95.5	99.7
		5/18								-	6.12	5.51	1.100	82.0	90.0
		5/21	3.7	4.7	6.04	6.19	0.113	98.1	102.5	-	6.17	6.09	0.159	97.4	98.7
								98.3 average	99.7 average					93.2 average	95.4 average

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[a] % Utilization = $100 \cdot [Ca^{++} - CO_3^=]/Ca^{++}$ (solid phase)

[b] % Utilization = $100 \cdot SO_4^=/Ca^{++}$ (solid phase)

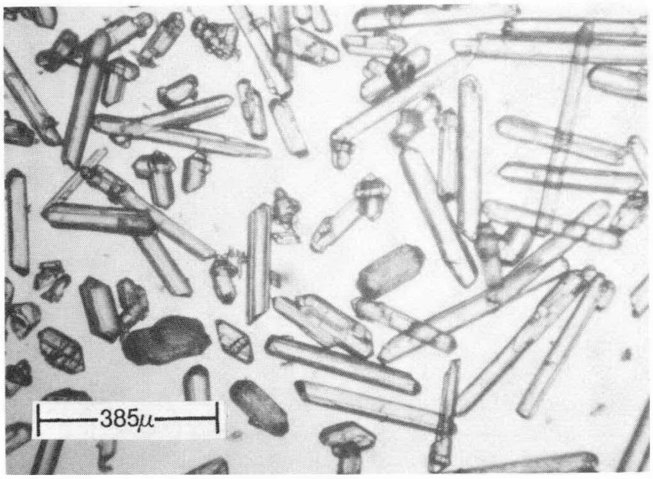
30 weight percent while the overflow solids content ranged from about 6 to 12 percent. This variation in the JBR solids inventory may have had as significant an impact on the relative saturation or crystal structure as any of the planned variable perturbations. Each of the tests in the matrix was conducted for three days (at least three solid-phase residence times). This should have been sufficient to approach a new solid phase steady-state condition for each test, but the fluctuations in the solids loadings complicate interpretation of the results. It is significant to note that the gypsum relative saturation did not approach the critical level of 1.3 in any of the tests.

The crystal structure and size were also similar throughout the Phase II statistical test matrix. This similarity may have been due to the compensating fluctuations in the solids concentration. It might be expected that the gypsum crystals would be smaller (i.e., larger surface area) under conditions where the SO_2 removal and gypsum production rates were higher (high pH, high ΔP). However, as shown in Figures 5-14 through 5-17, no significant crystal size differences can be seen in the photomicrographs taken of the solids during the initial Phase II tests. The size and shape of the crystals shown in Figures 5-14 through 5-17 are also similar to those observed during the Phase I testing (Figures 5-4 through 5-8). However, no dense media settling tests were conducted to analyze the particle size distributions.

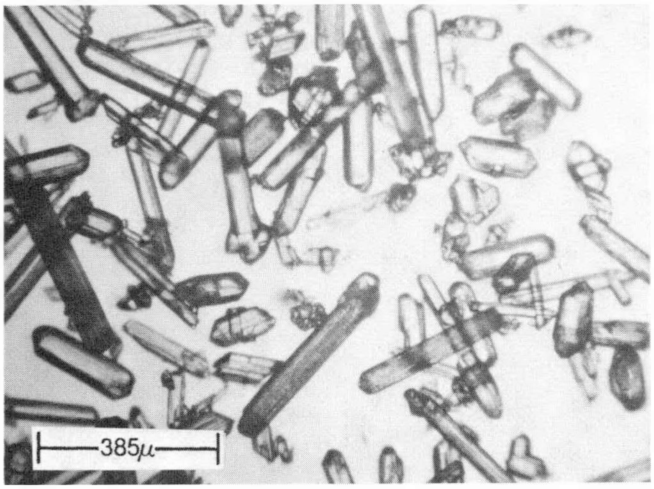
Reduction in JBR Slurry Solid Concentration

One of Chiyoda's main objectives in the development of the CT-121 process was the prevention of gypsum scaling within the JBR vessel. As part of the specified operating conditions, Chiyoda recommends that an adequate supply of gypsum seed crystals be maintained to minimize the chances of scale deposition on equipment. Perhaps the most critical zone of the JBR is the froth area where SO_2 removal is achieved and the solids concentration is lowest due to the rapid settling rate of the gypsum solids. The solids concentration in the froth layer is maintained by providing both air and mechanical agitation for mixing ensuring that a reasonably high level of solids exists in the reactor.

As a result of the procedures followed in the design and the recommended operation of the CT-121 system, Chiyoda does not anticipate that long-term operation at a low suspended solids level would occur in a commercial system. Recommended operating procedures require that the slurry solids be continuously monitored by an on-line density meter and checked with manual measurements every four hours so deviations from the solids concentration control set point would be quickly detected.

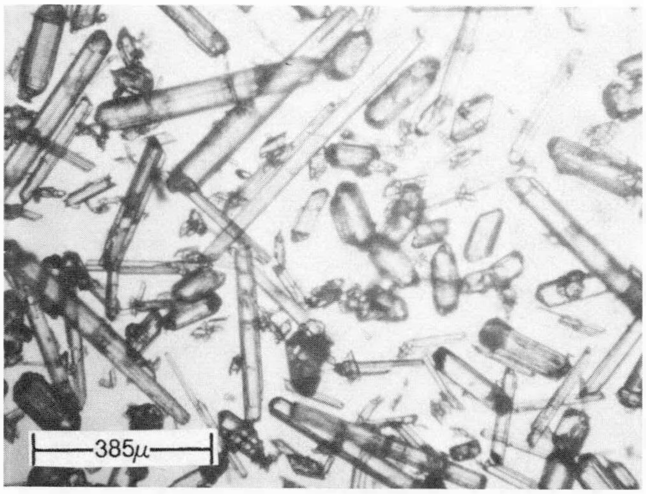


Test 1A 1/25/79
High ΔP, High pH, Low Air, Georgia Marble Limestone

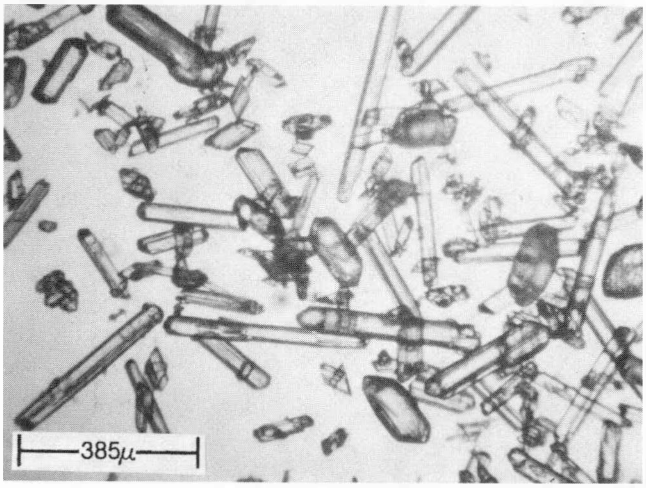


Test 1B 1/31/79
High ΔP, Low pH, High Air, Georgia Marble Limestone

Figure 5-14
Phase II JBR Underflow Solids
Test 1A Versus Test 1B

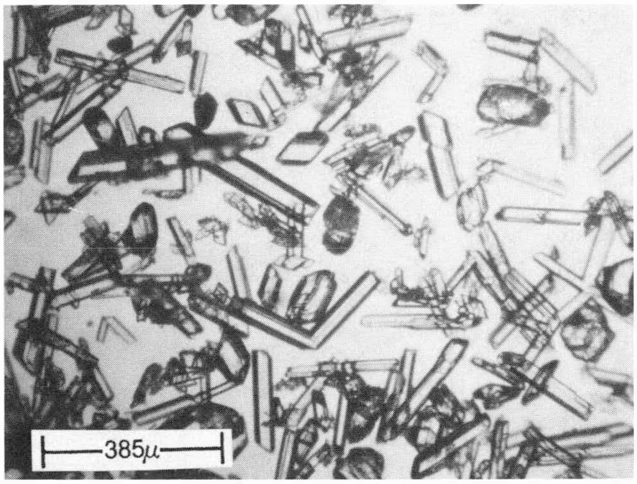


Test 1C 2/3/79
Low ΔP, High pH, High Air, Georgia Marble Limestone

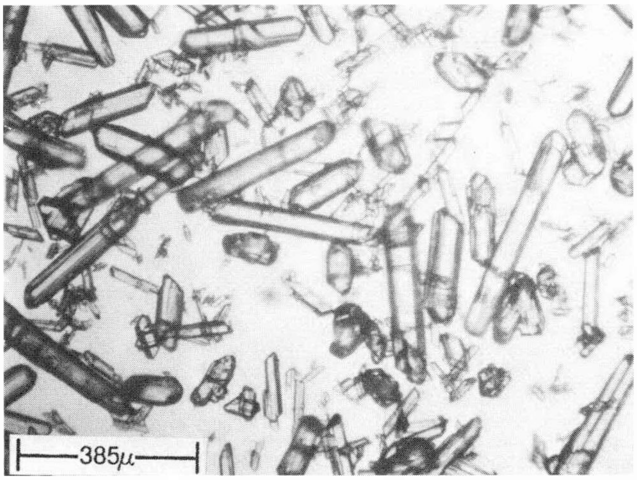


Test 1D 2/6/79
Low ΔP, Low pH, Low Air, Georgia Marble Limestone

Figure 5-15
Phase II JBR Underflow Solids
Test 1C Versus Test 1D

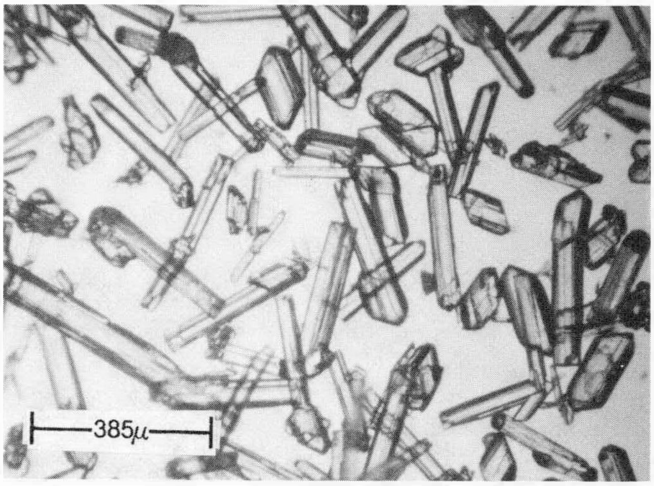


Test 1F 2/16/79
High∆P, High pH, High Air, SMC Limestone

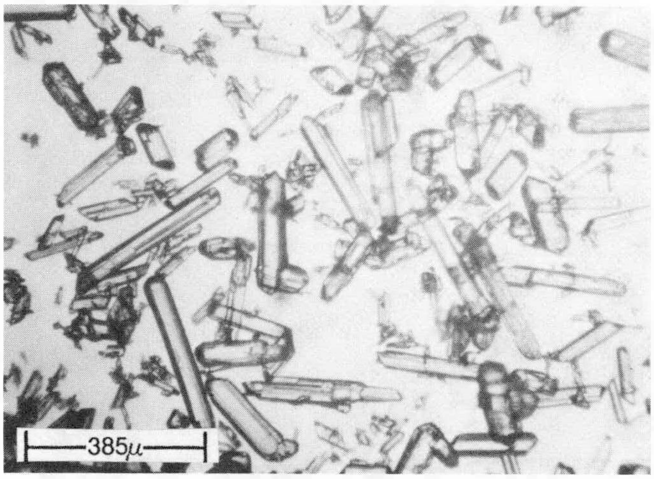


Test 1G 2/19/79
High∆P, Low pH, Low Air, SMC Limestone

Figure 5-16
Phase II JBR Underflow Solids
Test 1F Versus Test 1G



Test 1H 2/25/79
Low ΔP, High pH, Low Air, SMC Limestone



Test 1I 2/28/79
Low ΔP, High pH, Low Air, SMC Limestone

Figure 5-17
Phase II JBR Underflow Solids
Test 1H Versus Test 1I

Two short term (4-6 hour) tests were performed to observe the effect of lower solids concentration. Table 5-8 presents the results of these tests which were conducted on March 2 and March 5, 1979. Three sample points (the underflow and overflow streams and SC-3, a sample port on the side of the JBR near the froth zone) were monitored to determine if scaling conditions would occur as the JBR underflow solid concentration was lowered. As Table 5-8 shows, no conclusive trend relating gypsum relative saturation to slurry solids concentration was observed for either of the two tests when the solids concentration was lowered.

On March 2 (overflow pH set point of 3.5), the gypsum relative saturation in the underflow stream increased from 1.07 to 1.15 as the solids content was lowered from about 16 to 13 weight percent. Correspondingly, the relative saturation in stream SC-3 increased from 1.01 to 1.11 during this same period. It should be noted that the pH also varied significantly during the test (between 2.9 and 3.5 in SC-3 and from 3.0 to 4.0 in the underflow). Although no significant variations were noted in hourly process readings, these pH variations could have affected the instantaneous SO_2 removal rate and the required gypsum precipitation rate which would also have affected the gypsum relative saturation. Therefore, the reduction in solids concentration probably was not the only contributing factor to the increased gypsum relative saturation.

On March 5 (overflow pH set point of 4.3), the solids concentration was somewhat harder to control. Table 5-8 shows that the average solids concentration in each stream remained relatively constant even though the solids purge rate was increased. For four of the five samples taken, the solids in the underflow remained between 17 and 20 weight percent, and the solids loading in SC-3 remained between 5 and 6 percent. The composition, pH, and solids content of the overflow stream were close to those of SC-3 throughout the tests. The gypsum relative saturations also remained fairly constant during the March 5 tests, and no trend concerning solids loading was discernible, at least over the range of solids concentration tested.

Overall, no trend relating gypsum relative saturation (scaling tendency) to JBR suspended solids concentration was detected from the March 2 or March 5 results. This could be due to the conservative approach taken in reducing the solids concentration since avoiding gypsum scaling was also a desired outcome of these tests. The tests did show that the CT-121 prototype system could be operated over a fairly wide range of suspended solids concentrations in the JBR underflow without approaching gypsum relative saturations near the 1.3 critical level necessary for the onset of scaling. Although the tests were of short duration and visual inspections could

Table 5-8

RESULTS OF REDUCTION IN JBR UNDERFLOW SOLIDS ON GYPSUM RELATIVE SATURATION

			JBR Underflow			SC-3[b]				JBR Overflow		
Date	pH Set Point	Time (EST)	Weight Percent Solids[a]	pH	Computer Relative Saturation	Weight Percent Solids	pH	Computer Relative Saturation	Experimental Relative Saturation	Weight Percent Solids	pH	Computer Relative Saturation
3-2-79	3.5	0845	13.8, 13.3	4.5	1.05					6.2	3.8	.97
		1125	15.9, 14.6	3.0	1.07	7.6	2.9	1.01				
		1230	11.4, 12.8	4.0	1.15		3.5	1.11	1.17			
3-5-79	4.3	0945	18.5, 21.4	5.4	1.08	5.8	4.5	1.16	1.17	5.9		
		1120	17.6, 17.0	5.4	1.10	5.9	4.5	1.11		5.7	4.6	1.10
		1255	18.1, 17.3	4.6	1.05	5.6	4.2	1.09				
		1430	14.1, 14.7	5.3	1.09	4.6	4.5	1.13		4.8	4.6	1.10
		1545	18.8, 15.8	5.3	1.09	5.1	4.3	1.15	1.22			

---

[a] Duplicate weight percent solids samples

[b] Port located at side of JBR near the froth zone

not be made immediately following the tests, the JBR inspection at the end of Phase II did not reveal any significant scale buildup.

Reduced Oxidation Air Tests

Since the air flow rates tested during the statistical tests early in Phase II had little effect on system performance, additional tests at lower air rates were conducted on March 8, May 1 and May 2. The objectives of these tests were:

- to estimate the minimum O/SO_2 ratio required for complete oxidation and efficient SO_2 removal, and
- to determine if the JBR could operate over long periods with reduced SO_2 removal efficiency in the event of a partial or complete air compressor failure.

The second objective is important in projecting the reliability of a commercial CT-121 system and evaluating the possible need for redundant air compressors.

It was observed that the SO_2 removal did not begin decreasing until the oxygen/SO_2 stoichiometric ratio was reduced below a value of 4 to 5, provided the air was uniformly distributed throughout the JBR. Conventional forced oxidation limestone systems have operated at stoichiometric ratios as low as 2 to 1. However, in the CT-121 system, the slurry pH is so low that SO_2 removal would be negligible if the sulfite species were not quickly removed by oxidation. Therefore, the higher air stoichiometry is required so the oxidation reaction will not be rate limiting in the overall SO_2 removal sequence.

Based on the results of the compressor failure tests, it is apparent that a cone bottom JBR would plug with settled solids if no air was supplied to the reactor. Although the SO_2 removal was reduced, 20% of the usual air rate (an O/SO_2 stoichiometry ratio of approximately 2 was required to maintain the suspension of solids. A flat bottom JBR might not experience these operating problems in this circumstance if sufficient agitation power is supplied to the slurry by stirrers. This indicates, however, that multiple compressors could minimize reductions of SO_2 oxidation and removal in the event of a single compressor failure.

March 8 Test. The results from the March 8 reduced air tests are shown in Figure 5-18. Based on these tests, a reduction in air rate to 600 scfm (O/SO_2 stoichiometric ratio of 5.1:1) did not seem to significantly alter system operation. This reduction was accomplished by lowering the air sparge rate through both the inner

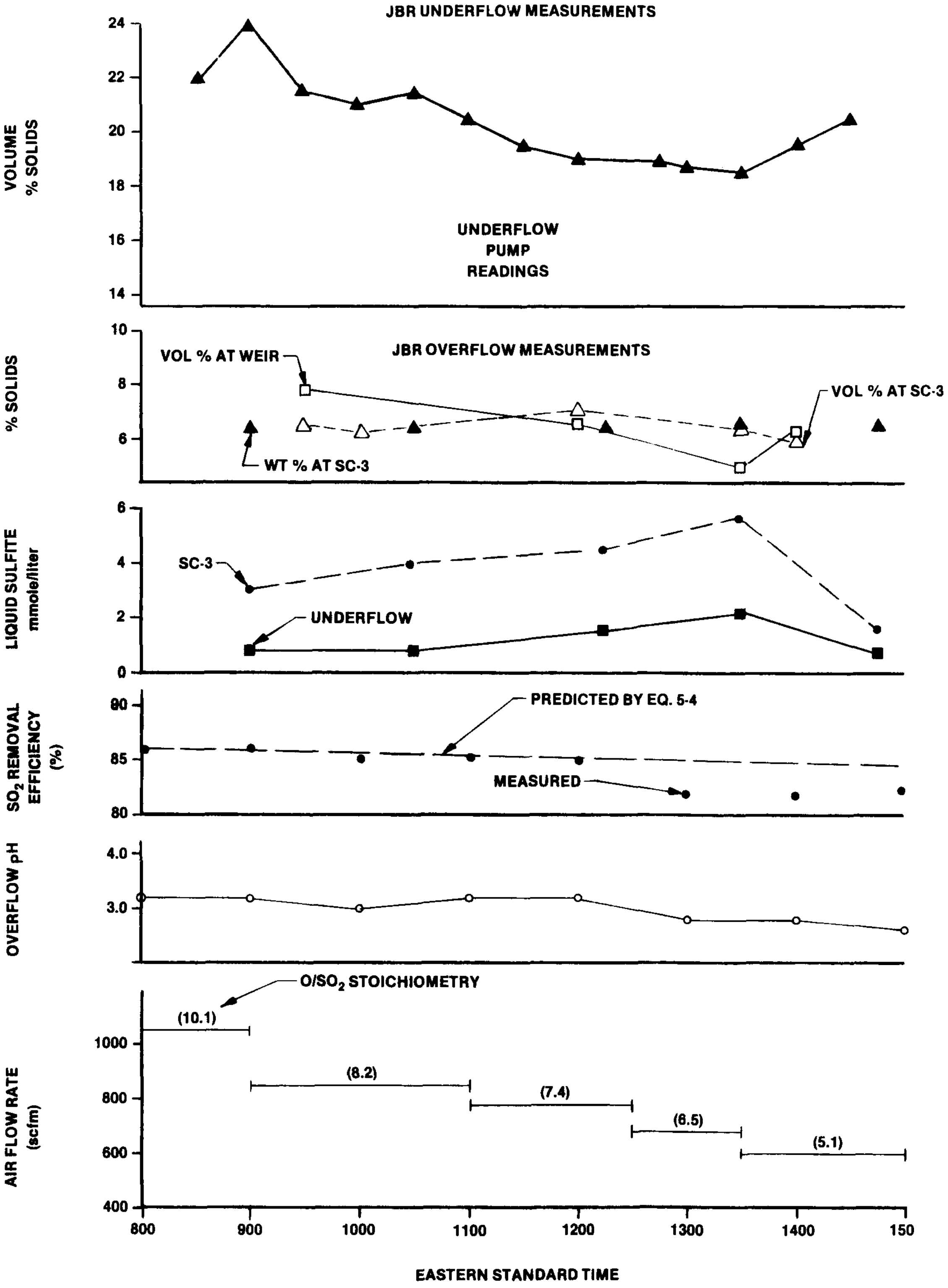


Figure 5-18
Results from Short Term Reduced Air Tests on 3-8-79

and outer sparger rings in the JBR. The sparger ring configuration is shown in Figure 5-19. Variables which were monitored during the test included:

- solids concentrations,
- liquid sulfite concentrations,
- SO_2 removal efficiencies, and
- pH.

As indicated in Figure 5-18 the solids concentration in the overflow did appear to decrease initially, but it increased during operation at the lowest air rate. This reduction may be partially explained by a general reduction in the solids concentration in the JBR as reflected by the underflow solids measurements. However, solids measurements at sample port SC-3 (in the top section of the JBR) did not change substantially during the tests. Some increase in the liquid sulfite level was noted, but again, this decreased at the lowest air flow rate. Since the tests were of such a short duration, it was impossible to monitor trends in oxidation by solids analyses, but no calcium sulfite solids would be expected at the low pH's involved. The measured SO_2 removal efficiency remained between 86 and 82 percent during the testing period. This was somewhat less than the removal measured earlier in Phase I due to a lower JBR pressure drop of approximately 9 inches (23 cm) H_2O. Removal efficiency did decrease with decreasing air rate, but fluctuations of this magnitude (3-4 percent) were common throughout the test program. It is also noted that the pH had decreased slightly when the lower SO_2 removal efficiencies were measured. The predicted SO_2 removals based on Eq. 5-4 are also shown in Figure 5-18. While the effect of pH in Eq. 5-4 does not account for the full amount of the observed decrease in SO_2 removal, the remaining variation in measured data is well within the 95 percent confidence limits of the predictive equation. Consequently, the lower pH may have had as much an effect on SO_2 removal as the lower air rate had.

May 1, 2 Tests. On May 1 and 2, additional tests were conducted to further define CT-121 system operation with low air flows. In these tests, the air flow was lowered by first reducing the flow to the outer sparger ring and then completely shutting off this flow. The air flow to the inner ring was then reduced and eventually shut off to simulate a short term air compressor failure.

On May 1, an attempt was made to determine the relationship between SO_2 removal and the oxidation air rate. The results were inconclusive. The SO_2 removal dropped a few percentage points as the air rate was lowered, however, the pressure

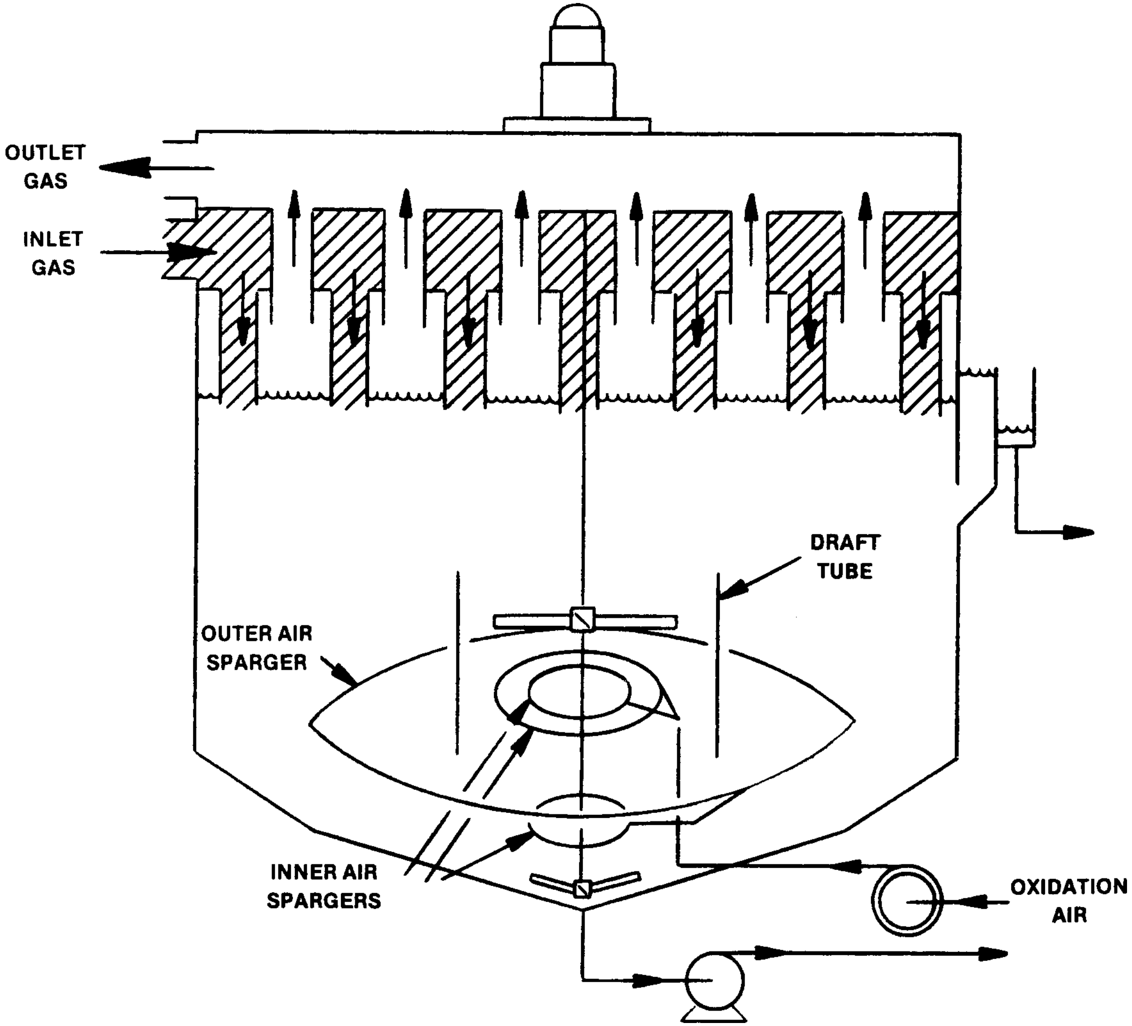


Figure 5-19
JBR Internal Configuration

drop across the JBR was 2 inches (50 mm) lower at the end of the test than at the beginning of the test. The lower pressure drop alone would have accounted for over 5 percent lower SO_2 removal based on Eq. 5-4.

Because the tests on May 1 were inconclusive, lower air rate tests were repeated on May 2 and provisions were made to maintain a constant JBR ΔP over the test period. Lower air rates resulted in a lower JBR pressure drop on May 1 for two reasons. First, less mixing air in the JBR resulted in less air void space in the gypsum slurry which lowered the level of air-gypsum slurry mixture in the JBR. This lower slurry level resulted in a lower gas side pressure drop through the froth zone. Secondly, lower air rates resulted in less agitation which increased the gypsum solids settling rate. The JBR underflow stream flow rate had to be increased to maintain a constant solids concentration to avoid plugging problems which also contributed to a lower slurry volume in the JBR on May 1. The water feed rate to the JBR was not sufficient to overcome the factors that lowered the slurry height. On May 2, an additional JBR feed liquor line was employed to maintain the slurry at a level which would result in a constant gas pressure drop.

Table 5-9 presents the results of the low air flow testing on May 2. The JBR operated for over 2 hours in a stable fashion at about 50 percent of the normal air flow rate (485 scfm or 770 Nm^3/hr). This air flow corresponds to an O/SO_2 absorbed stoichiometry of about 4. The SO_2 removal was somewhat lower than at full air flow (75 percent removal versus 90 percent), but no operational difficulties were observed. Even at 20 percent of the normal flow (O/SO_2 stoichiometry of 2.5) the system was still removing about 65 percent of the SO_2. The feasibility of continuous operation at this low flow was not determined.

Later in the day, the oxidation air was turned completely off to simulate an air compressor failure. Once the air was turned off, the underflow concentration began increasing drastically and the SO_2 removal dropped to about 40 percent. Within two minutes, the field operator was instructed to turn the air back on. In that short period of time, the underflow solids concentration doubled and it appeared that plugging was imminent. However, application of the air quickly dispersed the rapidly settling solids. Consequently, it appears that prolonged operation without air would have resulted in plugging the cone bottom of the prototype JBR. Redesign of the JBR to include a flat bottom and changing the direction of mixer rotation (see Mixer Tests and Reversed Agitation Tests on p. 5-65) could help.

Table 5-9

REDUCED OXIDATION AIR FLOW TEST RESULTS - 5/2/79

Time (CST)	In	Out	SO_2 Removal Efficiency Measured	SO_2 Removal Efficiency Predicted[a]	pH	JBR ΔP (inches)	Total Air (scfm)	Underflow[b] Percent Solids	Stoichiometric Ratio ($\frac{1}{2}O_2/SO_2$ sorbed)
1000	1450	105	92.6	88.1	3.6	10.7	1180	21	8.6
1100	1400	130	90.5	81.3	3.8	10.1	1180	20	9.2
1200	1400	420	69.7	81.1	4.3	8.0	480[c]	23	4.4
1300	1575	435	72.1	83.3	3.5	9.2	480	22	3.9
1400	1600	400	75.0	86.3	3.5	10.2	480	18-20	3.8
1415	1600	420	73.8	86.3	3.6	10.0	480	18-20	3.9
1430	1600	340	78.8	88.3	3.8	10.5	480	18-20	3.7
1435	1450	320	77.9	88.3	3.8	10.5	480	18-20	4.1
1440	1450	320	77.9	88.3	3.8	10.5	360	18.5	3.1
1445	1550	380	75.5	86.3	3.6	10.0	240	20	2.0
1455	1500	425	71.7	86.3	3.6	10.0	240	19.5	2.1
1500	1450	490	66.2	85.8	3.5	10.0	240	21	2.4
1506	1450	510	64.8	84.4	3.3	10.0	240	$\sim$20	2.5
1511	1450	>860	<40.0	81.1	3.2	9.3	0	Up to 38 Before Air On	2.5
1515	1500	460	69.3	86.2	3.4	10.4	520	20	4.8
1540	1600	460	71.3	78.1	2.8	10.4	960	12.5	8.1

---

[a] SO_2 removal predicted from Equation 5-4.

[b] Density meter reading.

[c] Air flow to outer air sparger ring cut off at 1200 hours.

The flat bottom design alternative has been suggested by Chiyoda and is discussed further in Section 7.

The lower SO_2 removal efficiency which resulted from the lower oxidation air rate on May 2 can be explained by examining the liquid phase sulfite concentration. With low air flow, the sulfite oxidation will be slower, leaving more sulfite present. This in turn raises the equilibrium SO_2 vapor pressure and decreases the driving force for SO_2 sorption. As shown in Table 5-10, samples taken at the overflow weir and from the underflow indicated that sulfite levels rose by a factor of at least three during the reduced air tests over those measured during other periods in Phase II when design oxidation air rates were employed.

Table 5-10

SULFITE CONCENTRATIONS MEASURED IN JBR SLURRY LIQUOR STREAMS DURING LOW OXIDATION AIR RATE TESTS

Sample	Time (CST)	pH	Dissolved Sulfite (mmole/liter)
SC-3 (froth level)	1300	3.25	3.2
Overflow	1300	3.6	3.6
Underflow	1300	4.1	2.4
Overflow	1500	3.5	3.2
Underflow	1500	4.3	3.1
Typical Phase II Values			
Overflow		3.5-4.0	0.1-1.0
Underflow		4.0-4.5	<0.2

Figure 5-20 graphically shows the effect of oxidation air on SO_2 removal for the May 2 and March 8 low air flow tests, and compares the SO_2 removal predicted by Eq. 5-4 at design air flow rates. Above an O/SO_2 stoichiometric ratio of about 4, the observed SO_2 removal corresponded fairly closely to the SO_2 removal predicted by Eq. 5-4. As the air flow was decreased the rates of oxidation and mixing both decreased. The result was an increase in the soluble sulfite concentration in the froth layer, a higher equilibrium back pressure of SO_2, and lower SO_2 removal. At stoichiometric ratios of from 1.5 to 4 the SO_2 removal efficiency was

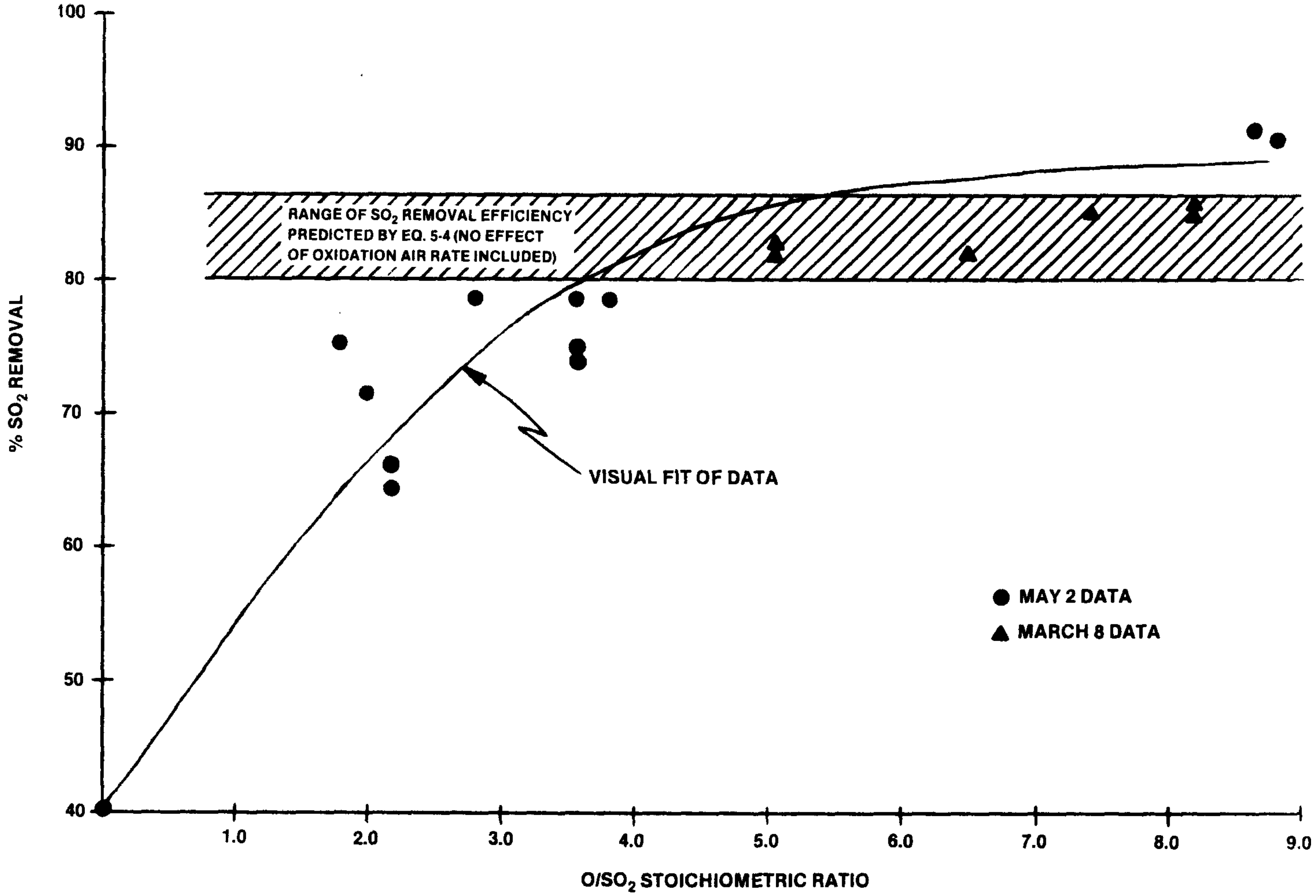


Figure 5-20
Low Oxidation Air Test Results - Phase II ($\Delta P = 9.0$ to 9.5″ H_2O;
$pH = 3.2$ to 3.8; Inlet $SO_2 = 1400 - 1600ppm$)

65 to 80 percent compared to 80 to 85 percent SO_2 removal predicted by Eq. 5-4 under similar operating conditions. Unfortunately, due to rapid changes in the test conditions, samples could not be taken to quantify the increase in sulfite concentration in the froth area at the time when the air was completely shut off. Under zero air flow conditions, the SO_2 removal efficiency dropped to 40 percent. The JBR ΔP also dropped at this time because of the reduced volume of the JBR slurry-air mixture under zero air flow conditions. The combination of higher dissolved sulfite and lower ΔP probably caused the reduction in SO_2 removal efficiency to less than 40 percent.

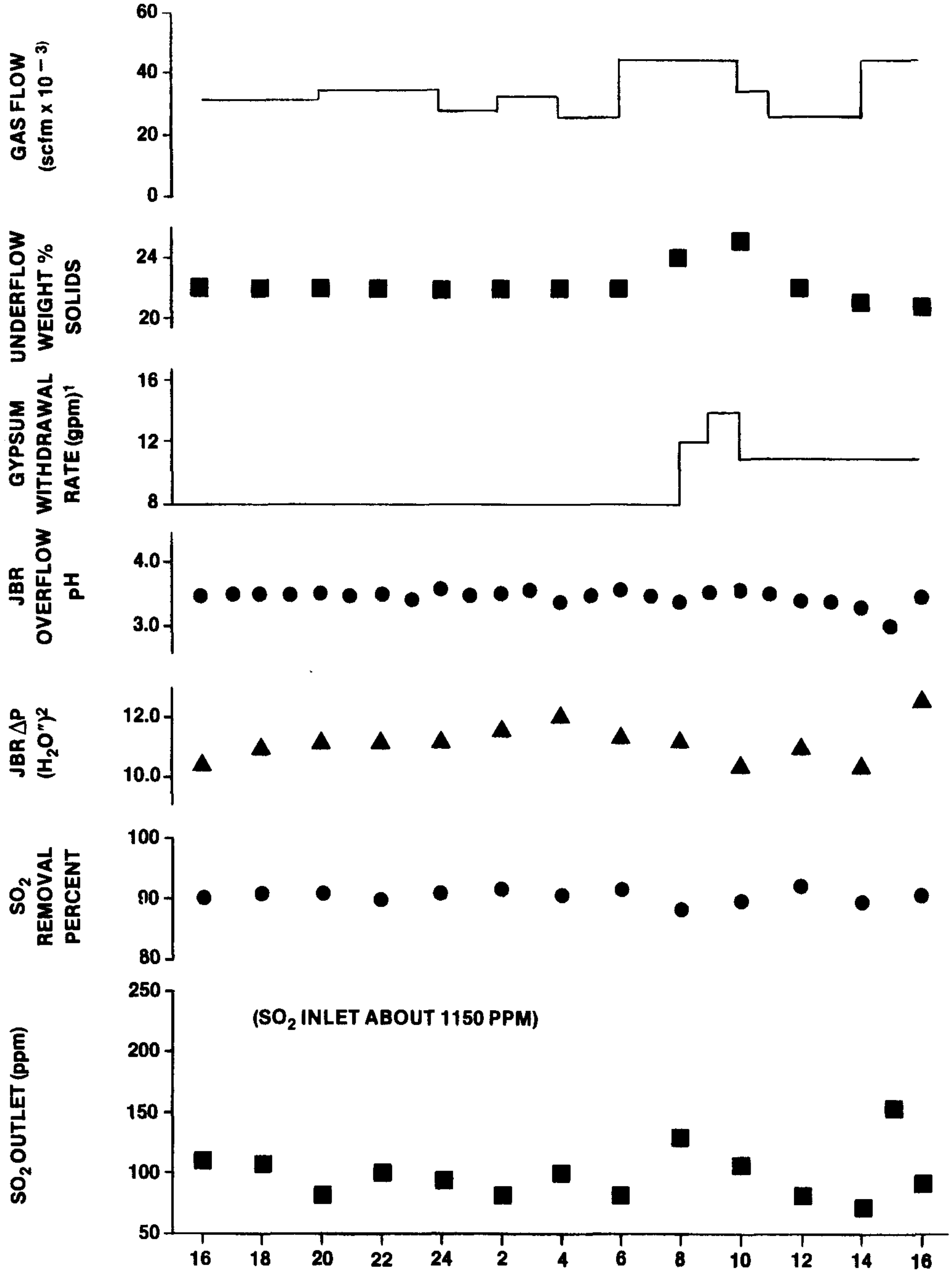
Simulated Variable Boiler Load Tests

On March 15 and 16 a second variable load test was conducted to verify the results from a similar test conducted in Phase I (discussed earlier in this section). From a pH control standpoint, the system responded quite favorably to changes in gas flow rate. The deviations from the pH set point were generally within ±0.2 pH units and the set point pH was re-established within about 5 minutes even with no advance warning of gas flow changes. Normal pH fluctuations were on the order of ±0.1 pH units throughout the program. Figure 5-21 summarizes the results of these simulated variable load tests.

During this test, the CT-121 system operators obtained the boiler load every two hours and adjusted the gas flow to the JBR accordingly. Once this change was made, the operators adjusted the limestone flow required to maintain a constant pH. This mode of operation required greater process responsiveness than did the Phase I variable load tests. The test results indicate that the CT-121 prototype system responded quickly even without the feedforward control used in Phase I.

High Sulfur Coal Testing

Gulf Power began burning higher sulfur coal from the Hallmark Mine (Jefferson Seam of the Black Warrior Basin near Sipsey, Alabama) on March 19 so that the CT-121 system response to higher SO_2 loadings could be evaluated. This coal contained between 3 and 3.5 percent sulfur, and combustion in the Scholz boilers resulted in flue gas SO_2 concentrations that ranged from 1700 to 2500 ppm. Removal of 90-95 percent of the SO_2 was easily accomplished in the CT-121 prototype by increasing the JBR pH and/or ΔP slightly. The relative saturation increased somewhat with the higher sulfate loading, but scaling conditions were not approached. The original test plan called for a second statistical test matrix to be conducted with the higher sulfur coal. However, the supply of high sulfur coal became intermixed with



[1] MULTIPLY BY 3.785 TO OBTAIN liters/min.

[2] MULTIPLY BY 2.54 TO OBTAIN cm.

Figure 5-21
Results of March 15-16 Simulated Variable Boiler Load Test

the other coal on the pile. The mixed coal feed thus produced widely varying SO_2 concentrations and as a result, several one-variable tests were performed instead.

Prior to beginning these tests, Chiyoda requested a two-week period to reoptimize the process control set points for the higher inlet SO_2 concentrations. Table 5-11 and Figure 5-22 summarize the results of this two-week optimization testing.

Table 5-11

CHIYODA TWO WEEK OPTIMIZATION RUN

Date	Weir Height (inches)[a]	Oxidation Air Rate (scfm)	JBR Overflow pH		Average SO_2 In (ppm)	Average Measured Percent SO_2 Removal
			Set Point	Actual		
3-19-79	13	1800	3.5	3.5	1760[b]	90.5
3-21	13	1800	4.0	3.8	1890[b]	93.0
3-22	13	1800	4.3	4.0	2030	94.8
3-23	13	1800	2.7	2.7	1960	82.5
3-26	13	1530	3.5	3.5	1930	91.0
3-27	13	1300		3.5	2020	92.2
3-28	13	1300	4.3	4.3	1820	95.1
3-28	13	1300		4.4	1060[c]	95.7
3-29	8	1530	3.5	3.5	1520	79.7
3-30	8	1530	2.7	2.6	2050	58.8
3-30	8	1530	4.3	4.3	2020	77.8

---

[a] Multiply by 2.54 to obtain cm.

[b] Leak in inlet sampling line, values presented are low by about 10 percent. The percent SO_2 removal for these days, therefore, are also slightly low.

[c] Switched boilers, low sulfur coal in bunkers.

Compared with the results of Phase I tests at 1000-1400 ppm inlet SO_2 levels, these tests show that higher SO_2 levels require slightly modified conditions to achieve 90 percent removal. In Phase I, the removal efficiency ranged from 90 to 94 percent with a pH of 3.5 and a ΔP of 11.5 inches (29 cm). With the higher sulfur coal, 90 to 94 percent removal was obtained at a pH of 3.4 to 3.9 and a ΔP of 13 inches (33 cm).

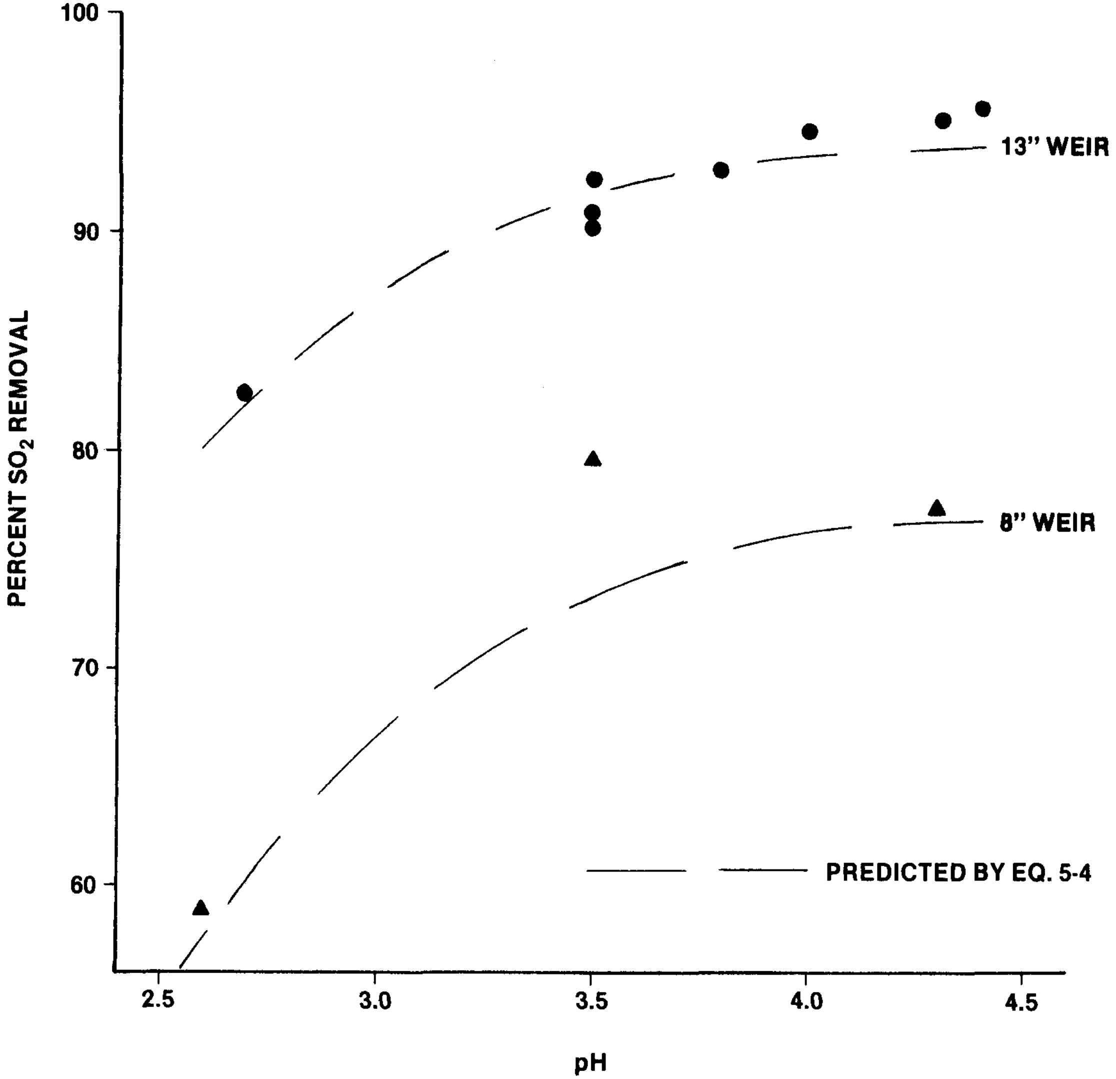


Figure 5-22
SO_2 Removal Versus pH-High Sulfur Coal Test Period

Oxidation air testing was not performed by Chiyoda during the two week optimization period. The lowest air rate (1300 scfm or 2100 Nm^3/hr) resulted in an O/SO_2 stoichiometric ratio of 6 to 7 which did not hinder the system's SO_2 removal capability.

Since the higher SO_2 removal rates result in higher precipitation rates and shorter solid phase residence time, the gypsum crystals were expected to be smaller during the high sulfur tests. This result is observed in the photomicrographs shown in Figure 5-23. The crystals are shorter and have a smaller length-to-diameter (L/D) ratio than the crystals grown in Phase I and earlier in Phase II (e.g., Figure 5-4 through 5-8, and Figures 5-14 through 5-18). The smaller L/D ratio results in a larger specific surface area. Crystals greater than 200 microns in length were typical of operation with lower SO_2 concentrations (in Phase I and earlier in Phase II). The crystals shown in Figure 5-23 are generally less than 100 microns in length while the diameter for a typical crystal remained between 20 and 50 microns for both high and low SO_2 operation. Although the crystals produced in the high sulfur coal tests were smaller than those produced in previous tests, no difference in handling properties was observed.

In addition to the smaller crystals, the gypsum relative saturation was also slightly higher during most of the high sulfur coal testing. Relative saturations of between 1.1 and 1.15 were measured routinely during late March and early April in the JBR overflow. These values are slightly higher than the 1.0 to 1.1 measured during Phase I. However, even during the high sulfur coal testing, the gypsum relative saturations were considerably lower than the 1.3 critical level necessary for the initiation of nucleation and scaling.

Steady State High SO_2 Testing. The purpose of the first test performed after the two week Chiyoda optimization period was to demonstrate the CT-121 system's capability to operate continuously at a steady state with 2000 ppm SO_2 in the inlet flue gas. The system was run at a constant set of conditions for four days to observe the effect of the higher mass loading of SO_2 on the process operability. Set points were specified by Chiyoda, and these are presented with the operating ranges and average conditions in Table 5-12. As can be seen, the SO_2 removal efficiency averaged 88.5 percent. The SO_2 pickup rate was about 105 gram moles per minute which was about twice as high as that observed during the low sulfur coal tests. The relative saturation in the JBR was measured between 1.1 and 1.15, which is about 50 percent higher than the values seen in Phase I.

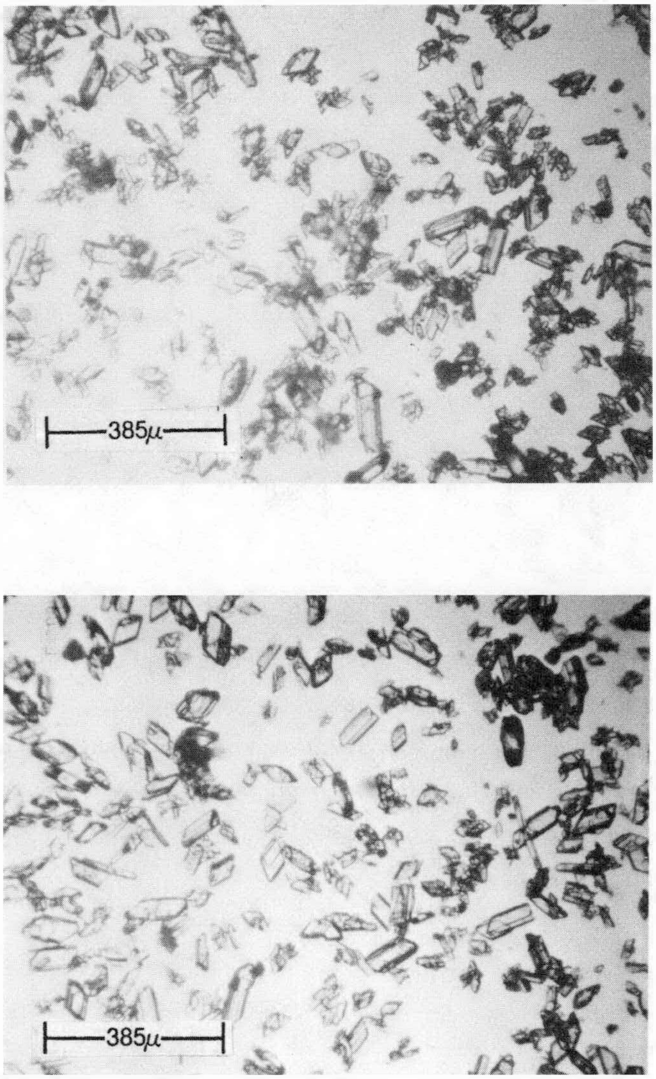


Figure 5-23
Phase II JBR Underflow Solids 3/29/79
Two-week Chiyoda Optimization Period with High Sulfur Coal

Table 5-12

STEADY STATE HIGH SO_2 REMOVAL TEST (APRIL 2-6)

	Process Conditions	
	Average	Operating Range
Gas Flow (scfm)	53,000[a]	(49,000-60,000)
SO_2 In (ppm)	2020	(1,700-2,500)
Percent SO_2 Removal	88.5	(83.9-90.7)
Gypsum Production (tons per day)	29	
JBR Overflow pH	3.5[a]	(3.4-3.7)
Weir Height (inches)[b]	12[a]	
Average ΔP (inches)[b]	11.8	(11.6-12.0)
Air Rate (scfm)	1530	
JBR Relative Saturation		(1.1-1.15)

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[a] Chiyoda specified control set points.

[b] Multiply by 2.54 to obtain cm.

Gypsum Relative Saturation Versus pH. During the statistical test series conducted at the beginning of Phase II, no dependence of gypsum relative saturation on pH was discernible over the pH range tested. Additional tests were conducted on April 9 and 11 to further investigate this relationship and Table 5-13 summarizes the results of these tests. As shown in Table 5-13, these results indicate that there is little dependence of relative saturation on pH. Difficulty in quantifying relatively small changes in saturation makes quantification of the relationship between relative saturation and SO_2 removal rate difficult. Fluctuations in JBR solids loadings, gypsum crystal structure, and inlet flue gas SO_2 concentrations also complicate the correlation effort. Thus, only a general trend of increasing gypsum relative saturation with SO_2 removal rate was noted during the evaluation program.

Table 5-13

JBR OVERFLOW RELATIVE SATURATION VERSUS pH AND SO_2 PICKUP RATE (during Phase II tests with mixed high and low sulfur coal[a])

Date	pH	Weir Height (inches)[b]	SO_2 Removal Rate (gmol/min)	Gypsum Relative Saturation
4-3-79	3.4	12	116	1.16
4-9	2.5	12	74	1.10
4-11	4.2	8	75	1.13

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[a] The mixing of high sulfur coal with Gulf Power's normal lower sulfur coal in the existing coal pile resulted in fluctuations in inlet flue gas SO_2 concentrations.

[b] Multiply by 2.54 to obtain cm.

JBR pH and ΔP Variation Tests. As stated earlier, it was originally planned to repeat the half factorial test matrix that was conducted during Phase I with the high sulfur coal. However, due to time constraints and variations in the inlet SO_2 concentration this was not practical. The results of the previous statistical test series showed that pH and pressure drop had the greatest influence on SO_2 removal at lower inlet SO_2 concentrations. Therefore, several tests were conducted at different weir levels (pressure drops). During system operation at each weir level, the pH was varied over a range of 2.5 to 4.5. One factor which complicated the analysis of the results was the variation in the inlet SO_2 concentration. It was felt that the majority of this problem was due to mixing of the recently delivered high sulfur coal on the existing pile of lower sulfur coal. Table 5-14 presents some of the data gathered during these tests. As this table shows, the SO_2 removal drops off substantially at the lower pressure drops. For a constant pressure drop, the pH has a strong effect on the SO_2 removal. Very good agreement between the measured removal and that predicted by Eq. 5-4 was obtained in this test series.

The differing SO_2 removal rates did cause some interesting variations in the gypsum crystal structure. A photomicrograph of the JBR underflow solids from April 13 is shown in Figure 5-24. There are a number of crystals which are rosette-like in structure. Rosettes are typically formed during operation with relatively high SO_2 removal rates which cause high gypsum precipitation rates and less orderly growth patterns. Since these solids are from a transition phase of high sulfur to lower

Table 5-14

RESULTS OF PRESSURE DROP, pH TESTING IN PHASE II

Weir Setting (inches)[a]	Average Inlet SO_2 (ppm)	JBR Overflow pH	Measured SO_2 Removal	Predicted[b] SO_2 Removal
15	1920	4.3	96.5	96.1
15	1490	4.3	96.5	96.1
15	1480	4.0	96.0	95.8
10.5	1500	2.7	74.5	76.0
10.5	1500	3.5	87.1	87.1
10.5	1450	4.3	91.8	89.2
8.5	1600	3.8	82.0	82.1
4.5	1400	4.4	60.0	60.0
3.2	1400	4.4	45.0	47.0

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[a] Multiply by 2.54 to obtain centimeters.

[b] Developed using equation 5-4.

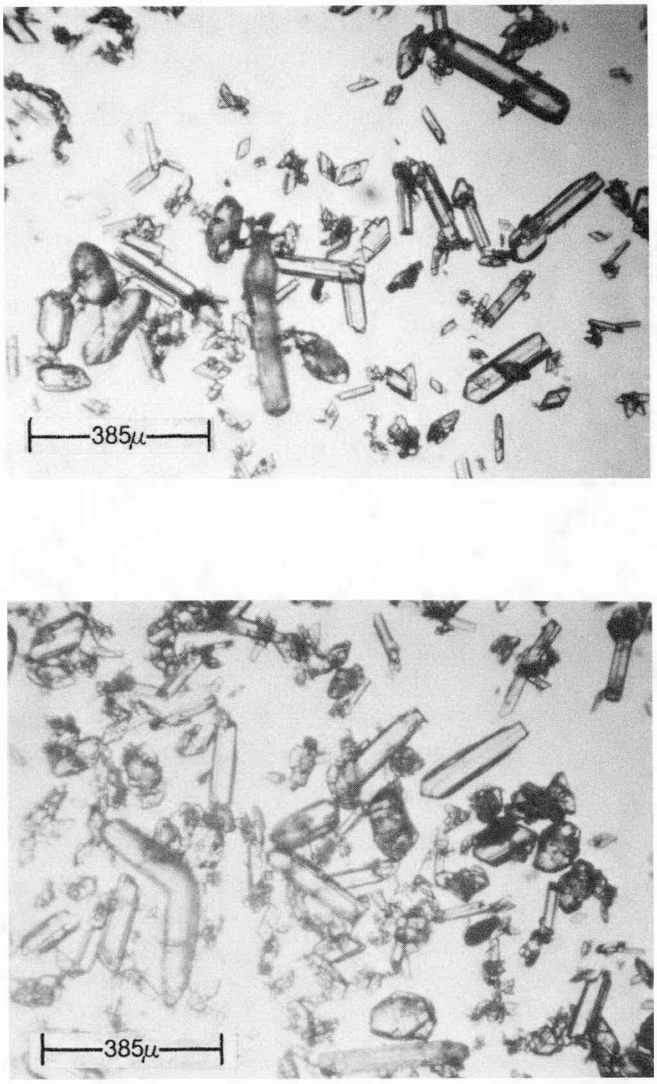

Figure 5-24
Phase II JBR Underflow Solids 4/13/79
Pressure Drop and pH Tests with Low and High Sulfur Mixed Coal

sulfur loadings, it is not surprising to see the small aggregates and some larger rod-shaped crystals which are indicative of slower precipitation rates.

Chloride Spiking

One site-specific condition that utilities have little control over is the chloride level in the coal. In wet FGD systems, the chloride is usually sorbed into the liquid phase. Since chloride is very water soluble, the chloride level can build up to very high concentrations, especially in closed loop systems. In addition to the obvious potential corrosion problem, the effects of higher chloride levels on the CT-121 process chemistry are also of concern. For example, the CT-121 system would have had a dissolved chloride concentration of about 20,000 mg/liter with the Hallmark coal if closed loop operation and a constant feed of Hallmark coal had been achieved for a sufficient period of time.

During the week of April 23-27, calcium chloride pellets were added to the JBR via the limestone slurry tank to simulate the effects of high chloride loading in the flue gas. However, since there were some concerns about performance of materials in the prototype system, the increase in chloride concentration was limited to about 6000 mg/liter. Consequently, a chloride level of 5600-6200 mg/liter was maintained in the JBR for over four days. On the weekend prior to chloride addition, SO_2 removal averaged 91.4 percent. During the last three days of addition, the removal averaged 90.8 percent. This difference was not judged to be statistically significant. Therefore, the increased chloride level from 1100 ppm to 6000 mg/liter had minimal effect on the SO_2 removal efficiency and process chemistry of the CT-121 system.

The most logical explanation for why no dependence was seen involves the mechanism of forced oxidation in the JBR. In most conventional natural oxidation lime/limestone scrubbers, the slurry contacts the gas and is then sent to a reaction tank. This contact with gaseous SO_2 results in sorption into the liquid phase and a lowering of pH due to the following reaction:

$$SO_2(g) \rightleftarrows SO_2(\ell) + H_2O \rightleftarrows H_2SO_3 \rightleftarrows HSO_3^- + H^+$$

In the reaction tank, the pH is raised by adding an alkali, resulting in supersaturation of calcium sulfite/sulfate salts and causing precipitation.

Under these conditions, alkaline species such as sulfite and carbonate can accept the hydrogen ion generated by SO_2 sorption. These species buffer the pH and increase the liquid phase alkalinity of the scrubbing liquor. If the total amount of anions in solution is increased by the addition of a very soluble anion such as chloride, the cations must also increase in concentration to maintain electrical neutrality. Therefore, in typical lime/limestone systems with limited magnesium or sodium concentrations,* the calcium level will normally increase. This higher calcium concentration decreases the sulfite and carbonate concentrations due to solubility constraints. Lower levels of carbonate and sulfite reduce the alkalinity available for sorption and consequently the SO_2 removal is reduced. Normally, the liquid-to-gas ratio (L/G) must be increased in order to offset the lower absorption capability.

However, in the normal operating pH range of 3.5-4.5 in the CT-121 system, there are few liquid species which can neutralize the sulfurous acid formed upon SO_2 sorption. If the sulfite species were not oxidized to sulfate, SO_2 removal would quickly be limited by a high equilibrium SO_2 vapor pressure in the liquid. This phenomenon is evident in the venturi-prescrubber where no SO_2 removal takes place due to saturation of the liquid with sulfurous acid.

The CT-121 system uses the oxidation reaction to maintain the mass transfer driving force for SO_2 sorption. This mechanism is presented in the following equation:

$$SO_2(\ell) + H_2O \rightleftarrows H_2SO_3 \rightleftarrows HSO_3^- + H^+ + \tfrac{1}{2}O_2 \rightarrow SO_4^= + 2H^+$$

As the sulfite is oxidized to sulfate, the SO_2 back pressure is lowered and the driving force is re-established. Oxidation of sulfite to sulfate is best accomplished at the acidic pH's where the CT-121 system operates. However, if there is insufficient oxidation air, the liquid phase alkalinity present is quickly consumed, and the capability for SO_2 removal is reduced because of insufficient sulfite oxidation rate.

As observed, addition of chloride did not significantly effect the SO_2 removal capability of the CT-121 system. This is because the chloride ion does not seem to affect the oxidation mechanism. An increase in calcium concentration and a decrease

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*This discussion assumes that highly soluble magnesium and sodium salts are not available for dissolution in the scrubber liquor in large amounts.

in sulfate concentration due to solubility constraints were observed during chloride spiking as expected. The sulfate values decreased from 3000 to 1400 ppm while the calcium values increased from 840 to 3000 ppm.

There were no discernible differences in either the gypsum crystal structure or the gypsum relative saturation observed during the chloride spiking. It should be reiterated that the chloride level tested was for a short period of time and at a level much lower than actual levels in some commercial systems currently being designed and operated.

Mixer Failure and Reversed Agitation Tests

Due to the rapid settling rate of the gypsum crystals, there is some concern about system performance in the event of an agitator failure. Additionally, Chiyoda was interested in observing the effect of reversing the agitator direction. Up to this time, the blades had turned counterclockwise, forcing the slurry up through the draft tube and then down the outer edge (see Figure 5-19).

In preparation for this test, the air rate was raised to 1800 scfm and solids were withdrawn for six hours at an accelerated rate. During the five minutes the agitator was off, the solids concentration increased rapidly. The nuclear density meter monitoring the underflow solids concentration was not working properly at this time. However, a grab sample showed 27 percent (volume) solids after two to three minutes without agitation. No decrease in SO_2 removal or pH was observed while the agitator was off which indicates the oxidation air agitation was sufficient to maintain both the mixing and oxidation required for efficient SO_2 removal at least for a short period of time. Upon restarting the agitator, the system worked well and the agitator continued to turn in the opposite (clockwise) direction for the remaining three weeks of Phase II.

As stated previously, system operation during the five-minute period when the agitator was off indicated that the system may have been able to continue operation for a short time in this condition. Some solids settling was observed, but it was not as pronounced as when the oxidation air was turned off. Based on these observations, it is unlikely that a cone bottom JBR similar in design to the prototype could keep running for a long period with either a complete air failure or agitator breakdown. It also appears that a failure of one agitator out of a set of three or four in a commercial system would probably not seriously affect a JBR's operation. The concept of a flat bottom JBR is discussed in Section 7, "Commercial Applications."

Particulate and Trace Elements Testing

During the week of May 7 through 14, tests were conducted to determine the fate of particulates and trace elements in the CT-121 system. The primary objective of this test was to provide EPRI with generic information about trace element distributions in the inlet and outlet streams in limestone FGD systems. The effect of this testing on the process performance is summarized here, while the detailed trace element balances are presented in Section 6, "Particulate and Trace Elements Sampling Results."

It is important to remember that the prototype system had a venturi prescrubber upstream of the JBR. The particulate removal results obtained with this configuration cannot be directly applied to different presaturator/JBR system designs.

The prototype system was very effective with respect to particulate removal. Particulate removal across the venturi-JBR system averaged 99.4 percent for an average inlet loading of 3.4 grains/dscf, with the majority of the trace elements present in the gas also effectively removed by the system.

For this test, all of the ESP sections on Unit #2 were deactivated so that the particulate loading in the flue gas would be more typical of a wet particulate removal system. The ash in the coal fed to the boiler was distributed as follows: (1) about 10 percent of the ash in the coal remained as bottom ash, (2) another 40 percent settled by gravity in the ESP hoppers, and (3) the remaining 50 percent was entrained in the flue gas exiting the ESP. The method used to determine this distribution is discussed in Section 6. The particulate loading in the flue gas to the prototype unit was about 3 to 4 grains/scf. The CT-121 system treated abqut 85 percent of the flue gas which was produced by Unit #2 during the week.

The performance of the JBR was not noticeably different during the high ash loading tests in spite of the higher fly ash concentration in the slurry. About 99 percent of the incoming particulate was removed from the flue gas in the venturi. Since the venturi bleed stream was routinely routed to the JBR, the increased fly ash loading effectively reduced the gypsum solids residence time in the JBR. The resulting JBR underflow slurry solids contained about 50 percent gypsum and 50 percent fly ash which should have decreased the available gypsum surface area and thus, increased the scaling tendency. However, because the flue gas SO_2 content dropped to about 1000 ppm during the first part of the test week, the gypsum relative saturation did not rise appreciably and values between 1.1 and 1.15 were reported during the particulate tests. Photomicrographs of the JBR underflow solids from

May 11, shown in Figure 5-25, indicate that these gypsum solids were similar to solids produced with the lower sulfur coal in Phase I and early in Phase II. As would be expected, a significant amount of fly ash was also present.

During this test, the JBR overflow pH was set at 3.5 and the weir was maintained at 11.5 inches (29 cm). Under these conditions, the removal from the 1000 ppm SO_2 flue gas averaged about 90 percent compared to 90.5 percent SO_2 removal predicted by Eq. 5-4 for these same conditions with low fly ash loadings. As expected, the increased fly ash loading did not inhibit the SO_2 removal efficiency in the JBR. During the last two days of particulate testing, the SO_2 concentration rose to about 1500 ppm while the SO_2 removal remained at 90 percent.

SO_2 Spiking Experiments

During the last week of Phase II testing, sulfur dioxide was used to spike the flue gas to SO_2 concentrations of 3000 ppm. This was intended to determine the CT-121 system's capability to treat a high sulfur coal flue gas. Numerous problems occurred with the rental vaporizer unit which was designed to vaporize liquid SO_2 prior to injection into the JBR inlet gas duct. The primary problem involved an undersized trim valve which could not deliver the desired flow rate continuously. Attempts were made to bypass the vaporizer, but the flow rates delivered were still erratic. As a result, the SO_2 concentration remained constant for only a few hours at a time during the entire week of SO_2 spiking tests.

The data gathered in the SO_2 spiking experiments are presented in Figures 5-26 and 5-27. It should be noted that the scatter in the data was probably caused to a large extent by the unsteady vaporizer operation. If the inlet SO_2 concentration is changing rapidly, corresponding steady-state pH and removal efficiency are more difficult to determine accurately.

Figure 5-26 shows a ΔP of 11.5 inches (29 cm H_2O) with varying pH's and removal percentages. Unlike the previous tests with lower SO_2 concentrations, this test shows that SO_2 content has a definite influence on removal efficiency. The pH required to achieve 90 percent SO_2 removal ranged between about 3.6 and 4.7 as the inlet SO_2 changed from 1700 to 3500 ppm.

Figure 5-27 shows the data gathered while operating at a ΔP of 15 inches (38 cm H_2O). Removal efficiencies of 95 percent were obtained with an inlet concentration of 3000 ppm at a ΔP of 15 inches and 4.5 pH. Notice also that the variation in removal efficiency due to variation in SO_2 loadings and JBR pH was reduced when the

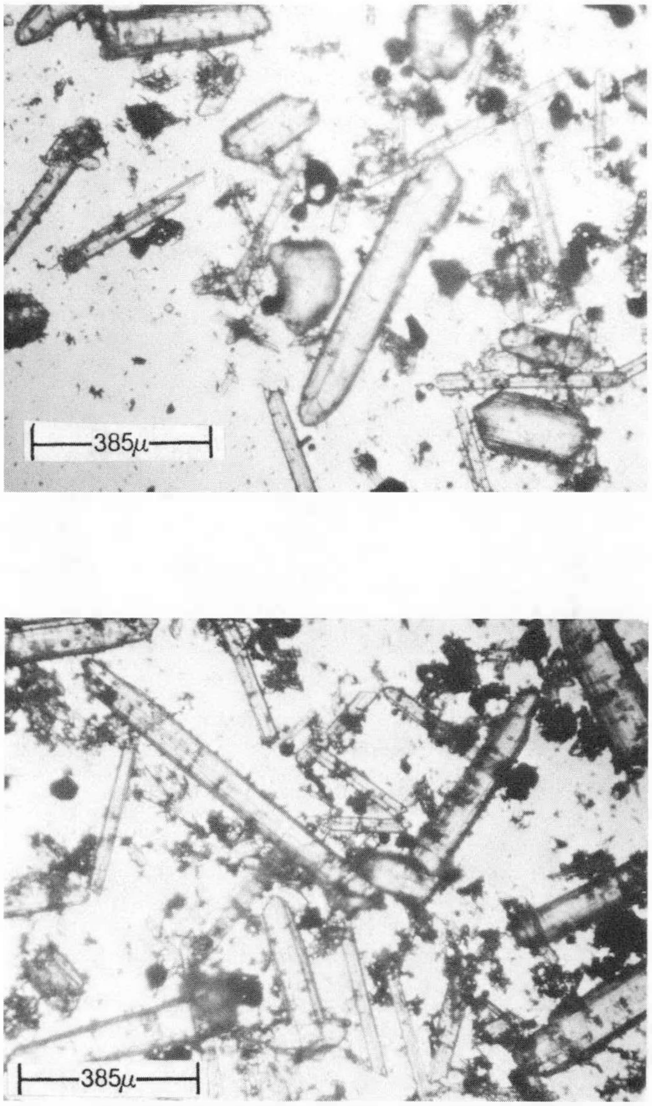

Figure 5-25
Phase II JBR Underflow Solids 5/11/79
Particulate Tests

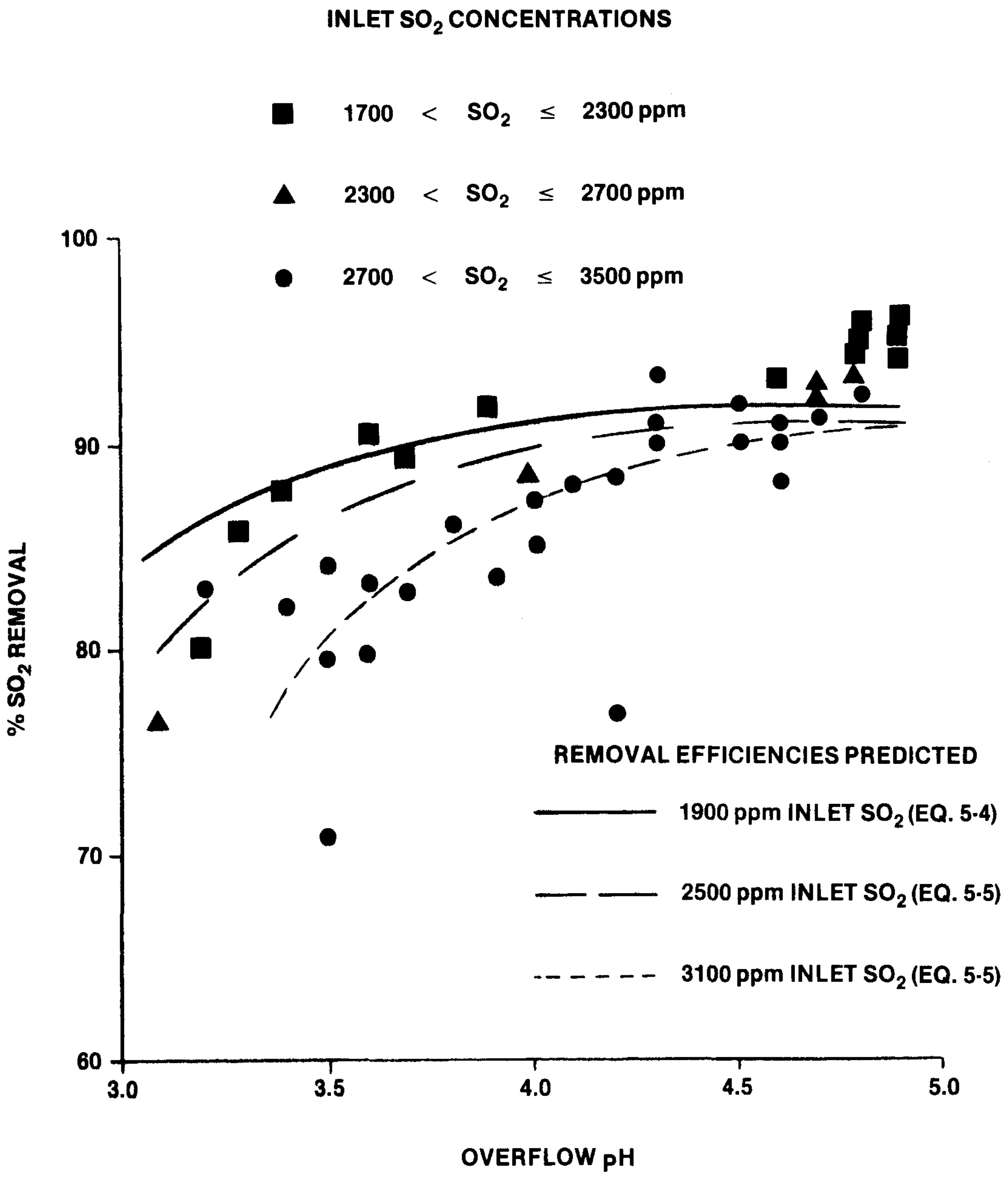

Figure 5-26
pH Versus Percent SO_2 Removal (11.5 Inch Weir Height, ΔP∿11.5″)
(Phase II - May 14 through May 22)

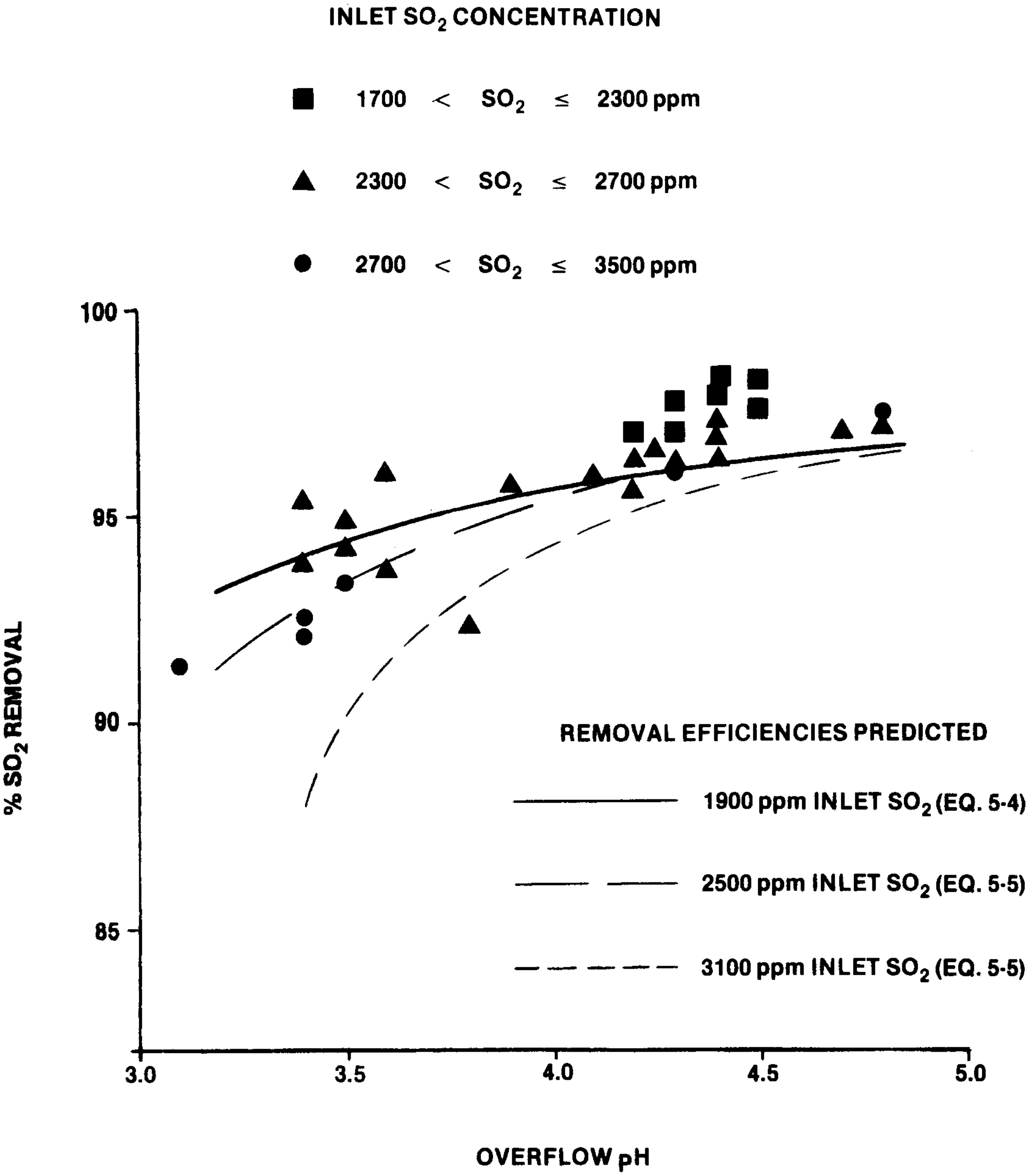

Figure 5-27
pH Versus Percent SO_2 Removal (15 Inch Weir Height, ΔP∿15")
(Phase II- May 14 through May 22)

system was operated at 15 inches ΔP. This is probably due to the increased gas-liquid contact efficiency and increased reaction time with a higher weir setting.

The gypsum relative saturations measured during the spiking experiments were higher than in other periods of testing. In the week of May 14-22, the JBR overflow gypsum relative saturation remained between 1.15 and 1.23 which was consistently higher than any other period in the test program. This would be expected since the SO_2 removal and gypsum precipitation rates were as much as 3 to 4 times higher than those measured in Phase I. The measured relative saturations were still less than that necessary for incipient gypsum nucleation. However, the relative saturation was not measured in the froth zone, and one week of intermittent operation at 3000 ppm inlet SO_2 is not sufficient operating time to determine what the long-term scaling potential might be.

Conservative design practice in the future should provide a safe operating margin for operating perturbations or gas-liquor-solid maldistributions. With this in mind, it appears that the maximum flue gas SO_2 level that the prototype unit at Scholz could safely scrub would be in the 3000 to 3500 ppm range, at full load gas flow.

The gypsum crystal structure should also be affected by the higher SO_2 levels. Figure 5-28 shows the JBR underflow solids from May 17. The gypsum crystals shown here exhibit characteristics representative of fairly rapid crystal growth. The crystals are shorter and more rosette-like in shape resulting in more specific crystal surface area. Although these crystals are smaller than those seen in Phase I and early in Phase II, they are not markedly different from those observed during the testing on April 13 with a mixture of high and low sulfur coal (Figure 5-24). No noticeable differences in gypsum handling properties were observed during any of the test program.

Phase II Water Balance

This section discusses the water balance for the last month of Phase II in detail along with an overview of the four month Phase II period. Detailed data such as the daily rainfall/evaporation totals and process water balance totals are presented in Appendix D.

Overview. Table 5-15 summarizes the monthly water balance results for Phase II. As Table 5-15 shows, the CT-121 prototype system did not operate in a closed loop

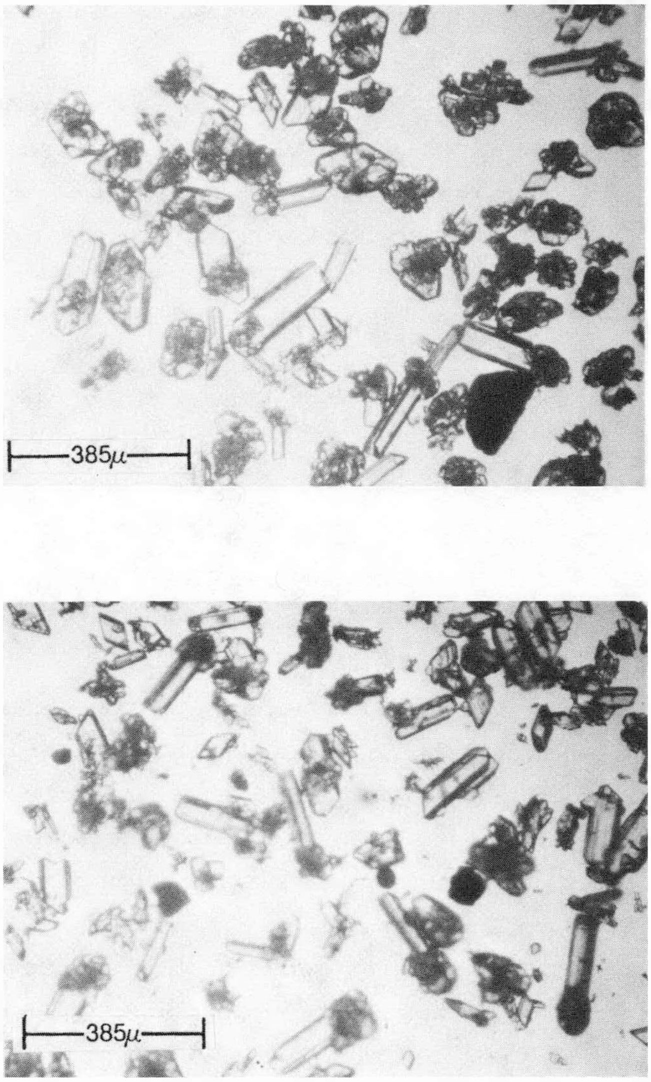

Figure 5-28
Phase II JBR Underflow Solids 5/17/79
SO_2 Spiking Experiments

manner during Phase II, and as a result the holding pond overflowed to Gulf Power's ash pond on a number of occasions.

Table 5-15

PHASE II MONTHLY POND WATER BALANCE TOTALS (GALLONS)[a]

Month	Rain (+)	Pond Evaporation (-)	Overflow (-)	Net Accumulation
January	120,000	7,000	260,000	-147,000
February	103,000	14,000	126,000	-37,000
March	44,000	39,000	31,000	-26,000
April	170,000	38,000	11,000	101,000
May	64,000	44,000	-	20,000
	501,000	162,000	428,000	-89,000

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[a] To convert from gallons to liters, multiply by 3.785.

Freezing weather and heavy rains were the primary causes of the open loop operation in January and February. Table 5-15 shows that the overflow was more than double the water that can be accounted for by rain. Excess process water added to the system to keep lines from freezing accounts for the additional overflow. Adequate freeze protection would have significantly reduced the overflow to the ash pond.

A concerted effort was made to reduce the overflow occurrences in March, April, and May. The pond return water usage in the venturi prescrubber loop and for pump seal water was increased in these months. The effect these changes had on equipment operation is discussed further in the process equipment subsection later in Section 5. During March and April, the only overflow from the pond resulted from raising the gypsum stack walls. Due to the design of the prototype stack at Scholz, the stack raising process required that both the liquor in the perimeter ditch around the stack and the slurry from the process be pumped to the holding pond during the stack raising periods. This created an excess of liquid in the holding pond which resulted in overflow to the ash pond. A commercial-scale gypsum stacking operation should include provisions for handling the excess water in the stack raising periods which will alleviate such overflow problems. No discharges to the ash pond were recorded in May.

May 4-22 Water Balance. During the last month of Phase II, the process was tested to determine the fate of trace elements and particulates in the CT-121 system. Because commercial CT-121 systems may be used for simultaneous SO_2 and particulate removal it was important to evaluate the system's ability to function in a closed loop mode during this test. Heavy rains such as occurred during the particulate testing will affect the water balance if ponding or stacking is employed as the disposal technique. Consequently, the system's behavior with respect to the water balance during this time is worth special note.

Table 5-16 presents the overall system water balance from May 4 to the end of Phase II, May 22. During this period, the pond water inventory was being reduced at an average rate of 1.6 gpm (6 liters/min). Rainfall/evaporation measurements indicated a 1 gpm (3.8 liters/min) addition of rainwater over the period so the amount of pond liquor which was substituted for fresh water as water makeup was actually 2.6 gpm (9.8 liters/min). As stated earlier, overflow from the holding pond to the Scholz fly ash pond was not observed during May, and the system clearly operated in a closed loop fashion over the last three weeks of operation.

During the week of May 7-13, the ESP's were de-energized for the particulate tests, and the amount of solids being pumped to the stack was about double the normal value due to the fly ash. During these seven test days, the pond accumulation averaged 3.9 gpm (14.7 liters/min). Heavy rains during this week contributed to this accumulation. This rainfall was estimated to be 3.9 gpm (14.7 liters/min) which indicates that the prototype system could possibly operate closed loop while removing particulates on a continual basis. At sites where gypsum is disposed of in a gypsum stack or a pond, the degree of closed loop operation will depend on the rainfall/evaporation rates for the various seasons of the year.

PHASE III RESULTS

Following the conclusion of the EPRI Evaluation Program, Chiyoda spent two weeks making internal modifications to the JBR in order to perform additional testing. EPRI was invited to observe this three week test block, which was patterned after the Phase II testing, but process conditions and test duration were specified by Chiyoda. Their objective was to determine whether possible capital cost reducing modifications to the JBR would give an acceptable performance.

Table 5-16

PHASE II SYSTEM WATER BALANCE MAY 4-22

Date	Evaporation in Gas (gpm)[a] (-)	Water in Gypsum to Stack (gpm) (-)	Net Fresh Water In (gpm) (+)	Rainfall/ Evaporation (gpm) (+/-)	Daily Accumulation[c] (gpm)
5-4-79	19.8	1.0	14.7	b	-6.1
5-5	21.6	1.0	14.7	b	-7.9
5-6	25.9	1.0	14.7	2.5	-9.7
5-7	20.7	1.0	14.7	16.0	9.0
5-8	18.8	1.0	21.5	1.9	3.6
5-9	19.9	1.0	21.5	1.2	1.8
5-10	19.9	1.0	21.5	5.1	5.7
5-11	20.2	1.0	21.5	2.7	3.0
5-12	19.0	1.0	21.5	-1.9	-0.4
5-13	19.6	1.0	21.5	2.5	3.4
5-14	21.1	1.0	21.5	-0.8	-1.4
5-15	21.4	1.0	21.5	-0.1	-1.0
5-16	23.5	1.0	18.3	-1.7	-7.9
5-17	18.8	1.0	18.3	-1.8	-3.3
5-18	19.8	1.0	18.3	-1.2	-3.7
5-19	20.4	1.0	18.3	b	-3.1
5-20	19.8	1.0	18.3	b	-2.5
5-21	20.5	1.0	18.3	-4.4	-7.6
5-22	19.9	1.0	18.3	-1.8	-4.4
Avg.	20.6	1.0	19.0	1.0	-1.6

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[a] To convert from gpm to liters/min multiply by 3.785.

[b] No measurement taken.

[c] Example Calculation.

Accumulation = Fresh water + rain - (pond evaporation + gas evaporation
+ gypsum water)

System Modifications

Internal modifications designed to reduce the complexity of the JBR internally were made during a two week period between Phases II and III. The agitator draft tube baffle was removed, 40 percent of the spargers were sealed, and 60 percent of the gas risers were blocked off. Since the same amount of flue gas was scrubbed as in Phase II, the resulting gas velocities through the sparger and risers were increased in Phase III. A few slurry lines were placed on the inlet gas deck to observe if irrigation would keep the inlet deck and sparger tubes free from solids buildup. Also, a Bird-Young vacuum filter was installed for filtering the slurry.

In addition to the effect of these modifications, a number of operating variables were also evaluated. Discussion of the Phase III results is divided into the following categories:

- Startup
- Baseline testing after modifications
- Reduction in the number of limestone feed lines (from two to one)
- Air sparger configuration test
- pH testing
- Low air testing
- Interim inspection
- Prescrubber pump tests
- Parametric studies
- Vacuum filter performance
- Final inspection

Startup. Following the two week modification period, the system was restarted with the JBR essentially empty of slurry. Only once before at the beginning of the shakedown period (Phase 0) was the system started without the benefit of a large volume of gypsum slurry. In both cases, gypsum seed crystals were added to the water in the JBR to prevent nucleation and scale growth on the internals. At the start of Phase 0, Chiyoda filled the JBR with fresh water and CT-101 gypsum for seed material. At the start of Phase III, pond water was used to fill the JBR and solids from the outlet gas deck were shoveled through the gas risers to produce about a 1 percent slurry of seed crystals in the JBR.

Chiyoda was fairly cautious with the process chemistry during the first startup in Phase 0. Once the gas and air flows were established, the pH was set at 2.5. At this low pH, the SO_2 removal was fairly low which kept the gypsum relative saturation below critical scaling levels. As more SO_2 was removed, oxidized and precipitated, the solids concentration began increasing to the normal set point. Only then was the pH, hence the SO_2 removal rate, increased.

During the startup in Phase III, the pH was raised to 4.0 within about 2 hours of establishing steady-state gas flow. The solids concentration increased to normal within 24 hours. Inspections after Phase III showed that some test conditions did promote scaling. This accelerated startup schedule could have been one source of higher relative saturations. However, since the slurry was not sampled during the early hours of operation, this theory cannot be verified.

Baseline Test After Modifications. Following the end of the original EPRI program, Chiyoda ran the scrubber for three more days before shutting down for modifications. This was done to obtain premodification baseline information. Following startup two weeks later, the same conditions were tested. No significant differences in operation were observed. Table 5-17 presents the operating conditions and summarizes the performance of the system for the operating periods both before and after the JBR modifications. As shown in Table 5-17, the SO_2 removal after the modifications (87.9 percent) was identical to that measured before the JBR internals were changed (87.9 percent). The SO_2 removal model derived from the Phase II data, Eq. 5-4, also predicts 87.9 percent under both sets of operating conditions.

Based on the similar performance of the system before and after the JBR modifications, the modifications seem to have had little effect on the prototype JBR SO_2 removal efficiency. However, the average inlet SO_2 concentration was about 1580 ppm on June 11 and 12 (after modifications) compared to 1940 ppm before the modifications. While such a difference in SO_2 concentration had very little effect on system performance in Phase II, changes in the SO_2 concentration in this range might be expected to have a more significant effect in Phase III because of the higher gas and SO_2 mass flow rates per flue gas sparger. Further investigation would have to be performed to identify the full effect of SO_2 concentration on system performance with the modified JBR configuration.

Table 5-17

PHASE III TEST CONDITIONS BEFORE AND AFTER JBR MODIFICATIONS

	Before	After
Date	May 23,24	June 11,12
Time Period (hours)	25	22
Gas Flow (scfm)	46,000	45,000
Average Inlet SO_2 (ppm)	1,940	1,580
Average Overflow pH	4.3	4.3
Weir Height (ΔP) (inches)[a]	10	10
Oxidation Air Flow (scfm)	1,300	1,300
Mean SO_2 Removal (percent)	87.9	87.9
Predicted SO_2 Removal[b] (percent)	87.9	87.9
Standard Deviation of Mean Removal	1.49	1.43

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[a] Multiply by 2.54 to get cm

[b] Predicted from Eq. 5-4 - Phase II predictive equation

The major effect observed during the initial Phase III test period was greater solids stratification in the JBR. The overflow varied from 3 to 6 weight percent solids, whereas the normal values in Phases I and II were about 8 percent or greater. Removing the draft tube probably "short circuited" the mixing pattern to some extent and allowed greater settling than in the previous mode of operation. The estimated gypsum relative saturation in the JBR overflow stream ranged from 1.15 to 1.3 during Phase III which is somewhat higher than the relative saturations measured in Phase II (1.23 was the maximum). The increased solids stratification in the absence of the draft tube did not cause underflow stream plugging problems.

Reduction in the Number of Limestone Feed Lines (from two to one). In this test, only one of the limestone feed pipes to the JBR was used instead of the usual two. The inlet flue gas average SO_2 concentration also increased to 2070 ppm during testing with one limestone feed line from 1580 ppm during testing with two limestone feed lines. Although the average SO_2 removal was lower (85.8 percent), the decrease in the number of limestone feed lines cannot be identified as the sole cause for the decrease in the SO_2 removal efficiency. This increase in inlet SO_2

concentration removal may also have had an effect on SO_2 efficiency due to the change in JBR configuration in Phase III. This possible effect has been discussed in the preceding subsection, "Baseline Test After Modifications."

Table 5-18 presents the results of the 22 hours prior to this test and the 22 hours after the limestone feed change. As shown in this table, the mean SO_2 removal during this test decreased from 87.9 percent to 85.8 percent. Based on the variance of each data set and the number of observations, a test showed that a statistically significant difference exists at the 5 percent probability of error level. This change could be due to either the limestone feed line change or the increased SO_2 concentration or both.

Table 5-18

REDUCTION IN LIMESTONE FEEDER PIPES

Number of pipes	2	1
Date	June 11,12	June 12,13
Time Period (hours)	22	22
JBR Weir Setting (inches)[a]	10	10
Average pH	4.3	4.3
Average SO_2 Inlet (ppm)	1580	2070
Predicted SO_2 Removal[b] (percent)	87.9	87.9
Mean SO_2 Removal (percent)	87.9	85.8
Standard Deviation of Mean Removal	1.43	2.31

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[a] Multiply by 2.54 to get cm

[b] Based on Equation 5-4

Note that the SO_2 removal predicted using Eq. 5-4 is 87.9 percent for both the two feed-pipe and the single feed-pipe tests. As mentioned in the baseline test discussion, the equation may not be representative of Phase III conditions (due to the high SO_2 loading per flue gas sparger in Phase III). A single limestone feed line was used for the remainder of Phase III.

Air Sparger Configuration Test. During the next test, all three of the inner oxidation air sparger rings were turned off. (Figure 5-19 shows the location of the oxidation air sparger rings.) The outer sparger air rate was increased to compensate for stopping the air to the inner rings. As a result, the total O/SO_2 stoichiometry only dropped from about 7 to 6. No statistically significant decrease in SO_2 removal was noted in this test, and the inner spargers were not used again during Phase III. Table 5-19 presents the range and average of the SO_2 removal observed with and without the inner air spargers.

Table 5-19

AIR SPARGER CONFIGURATION TEST

	With Inner Spargers	Without Inner Spargers
Date	June 12,13	June 13,14
Air Flow (scfm)	1300	1080
Inlet SO (ppm)	1800	2140
JBR Overflow pH	4.3	4.3
JBR Weir Height (inches)[a]	10	10
Approximate O/SO Ratio	7	6
Highest Measured Removal	90.1	89.3
Lowest Measured Removal	81.2	83.1
Mean Removal	86.4	86.3
Standard Deviation of Mean	2.49	2.28
Number of Observations	11	7

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[a] Multiply by 2.54 to obtain cm.

pH Testing. A pH variation test was performed in Phase III to observe the effect of pH on performance of the modified JBR. The maximum pH value obtained was 5.8, nearly a full pH unit higher than any test in Phase II. The weir setting was 10 inches (25 cm) and the SO_2 concentration was about 1800 ppm. The results of the test are plotted in Figure 5-29. As can be seen in this figure, Eq. 5-4 does not accurately predict the SO_2 removal of the Phase III JBR configuration below a pH of about 4.5. This may have been due to the higher SO_2 loading and higher flue gas

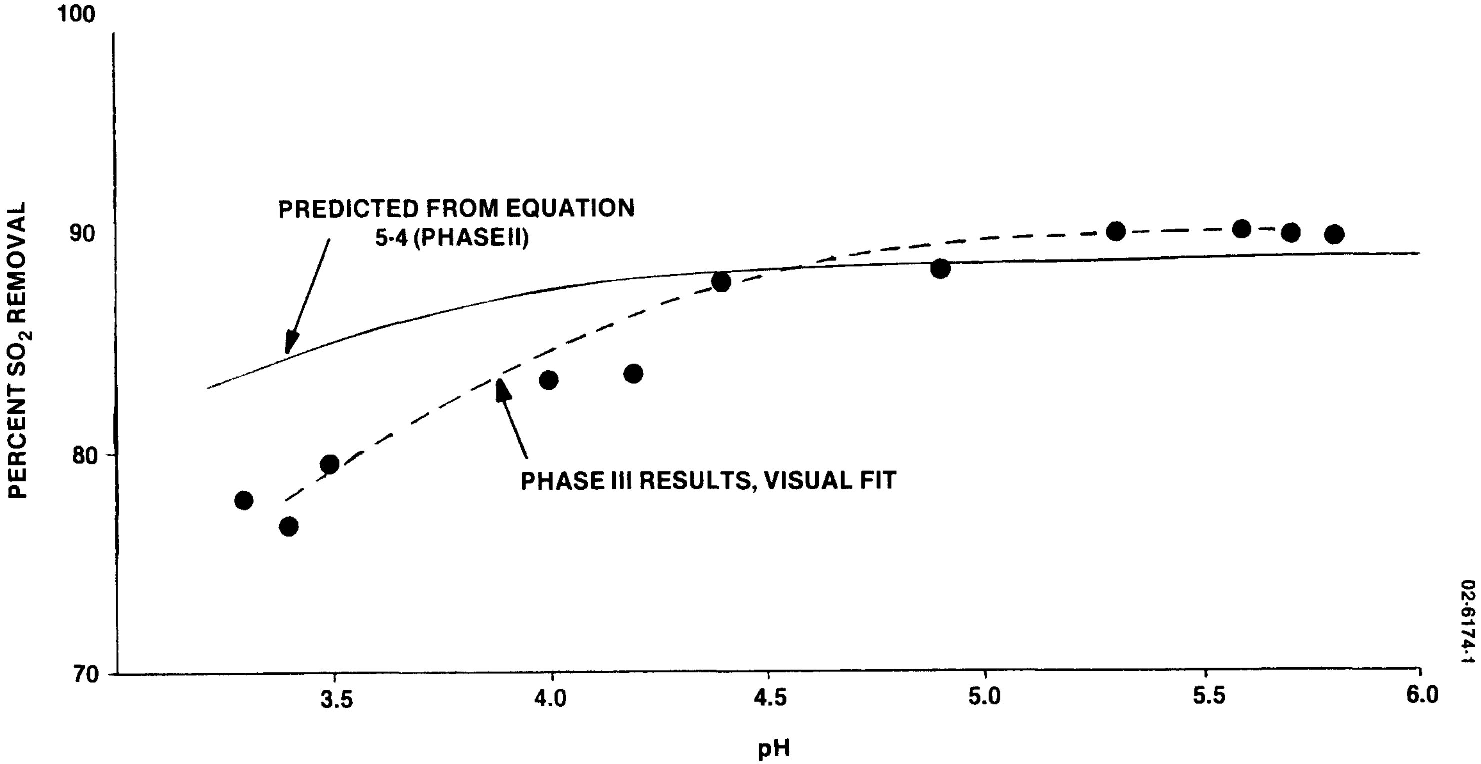

Figure 5-29
Effect of pH on SO_2 Removal - Phase III (SO_2∿1800 ppm, 10″ Weir Height)

velocity through each flue gas sparger. The higher SO_2 mass loading would have had more of an effect at conditions where the slurry alkalinity was less (i.e., lower pH's).

This test established the upper bound of the pH influence on SO_2 removal in the JBR. The pH of the JBR overflow was raised to 5.8 for several hours and only a slight increase in removal was observed as indicated in Figure 5-29. The excess of liquid and solid phase alkalinity at these test conditions appeared to have little effect on removal efficiency. Removal was apparently constrained by mass transfer limitations (i.e., contact time and efficiency) rather than alkalinity. With the overflow stream pH of 5.8, unreacted limestone in the overflow and bottoms stream was 13.5 and 10.8 percent by weight, respectively. Based on the underflow stream this corresponds to a limestone utilization of about 87 percent which represents an uneconomical mode of operation. The large excess of carbonate in the solids was indicated by the three hour period required for the pH to drop one unit without any limestone addition. The abundance of limestone particles during this test is evident in photomicrographs of the JBR overflow and underflow solids shown in Figures 5-30 and 5-31. In addition to the limestone reagent wasted, this increased unreacted limestone in the froth area could result in localized regions of high gypsum supersaturation which could contribute to scale formation on the flue gas sparger tubes.

Low Air Testing. Table 5-20 summarizes the results from the low air test performed June 18. The results are fairly consistent with the test results obtained during Phase II on May 2. During the May 2 test, an O/SO_2 stoichiometric ratio of 4 resulted in approximately 75 percent removal with an 11.5 inch weir setting while 90 percent removal was obtained at normal air flows. During the June 18 Phase III air test, 85 percent removal was obtained with the 10 inch weir at a stoichiometry of 6. At the lower O/SO_2 stoichiometry of 3.4, only 68 percent removal was observed. Although these tests were performed at different weir settings and internal JBR configurations, the effect of lower air rates is similar. Both the Phase II and III reduced oxidation air tests show that the oxidation reaction exerts a major influence in the overall reaction rate when the O/SO_2 stoichiometry has been reduced to less than 4. As a result of the lower O/SO_2 stoichiometry, the sulfite remaining in solution tends to limit the removal rate by increasing the SO_2 vapor pressure. Figure 5-32 summarizes the effect of air rate on SO_2 removal efficiency during Phase III.

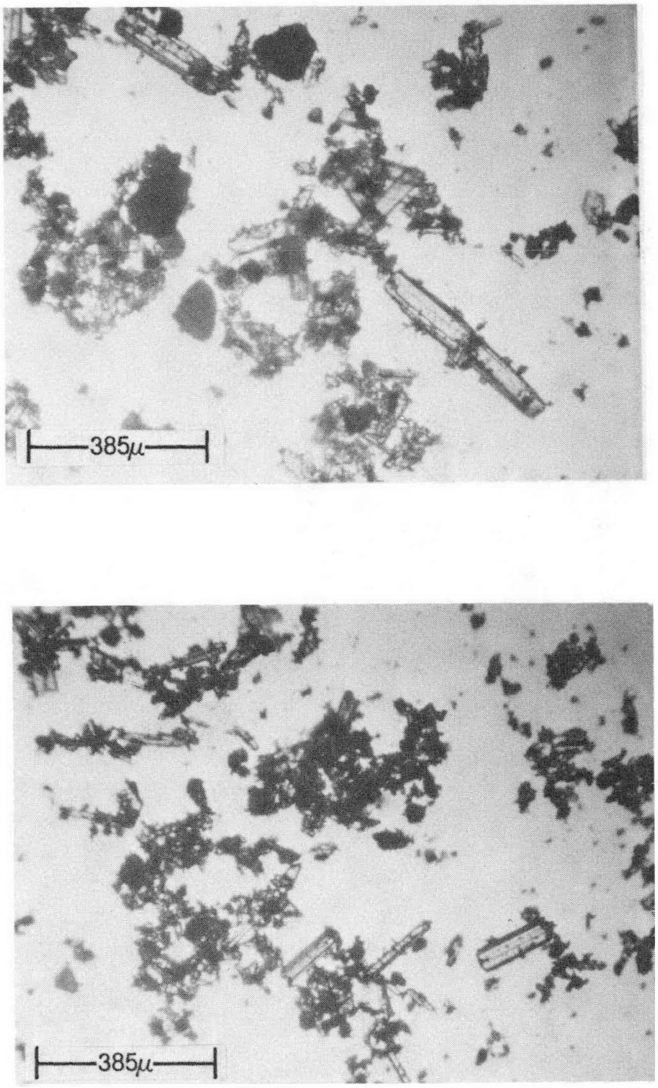

Figure 5-30
Phase III JBR Overflow Solids 6/15/79
High pH Test

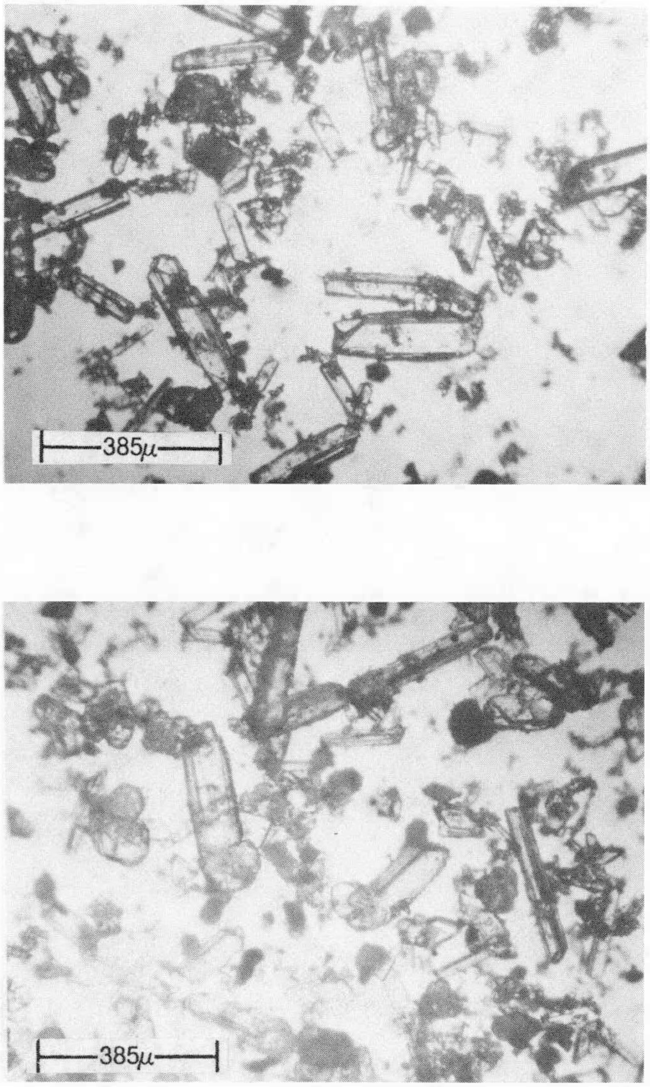

Figure 5-31
Phase III JBR Underflow Solids 6/15/79
High pH Test

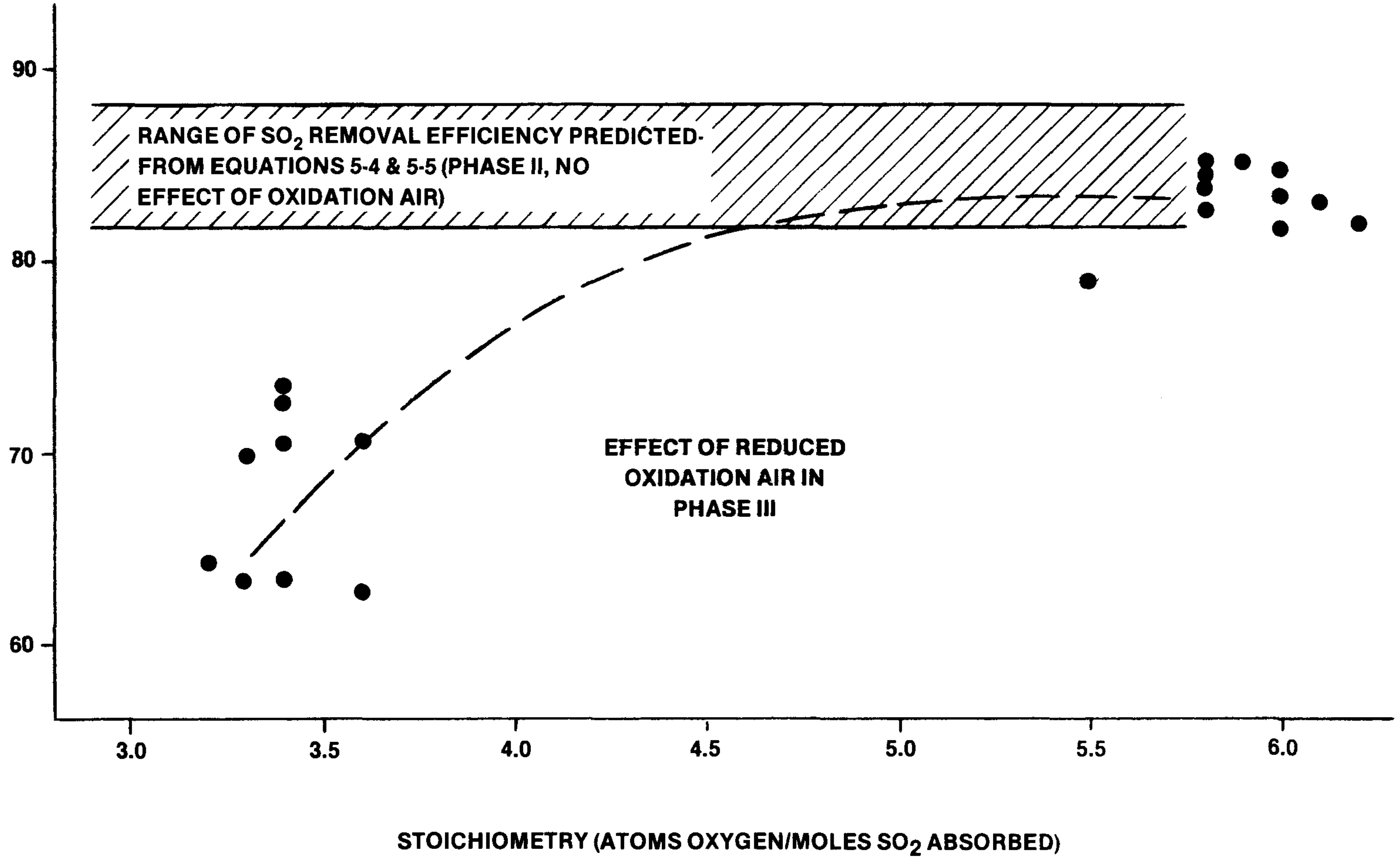

Figure 5-32
Effects of Oxygen/Sulfur Dioxide Stoichiometry on SO_2 Removal Efficiency (Phase III, June 17,18,19 - JBR $\Delta P = 9$ to 10 Inch, Inlet $SO_2 = 2000$ to 2450 ppm, JBR pH = 4 to 4.5)

Table 5-20

PHASE II LOW AIR TEST

Date	pH	Weir Setting[a] (inches)	Air Rate (scfm)	O/SO_2 Stoichiometric Ratio	Percent Removal
6-17-79	4.8	10	1080	6.3	85
6-18-79	4.8	10	540	3.4	68

[a] Multiply by 2.54 to obtain cm

All of the low air test results were obtained at one agitator speed. Since the agitator tip speed can affect both bulk mixing and the dispersion of air within the JBR, changes in the agitator shaft speed, the draft tube configuration, or the agitator blade design could all have an effect on oxidation efficiency.

Interim Inspection. Following the low air test, an inspection of the JBR was made. The inlet gas deck was clean, and the outlet deck was also fairly clean. However, because the outlet deck had not been examined closely by Radian after gypsum solids were shoveled through the gas risers prior to startup, it was not possible to determine whether Phase III operations caused an increase in solid carryout rate due to a faster gas velocity through the risers.

There where signs of increased scale around the flue gas sparger gas distribution openings for those spargers near the JBR walls.* The JBR was not drained so the internal spargers could not be examined.

Prescrubber Pump Tests. Two tests were performed on June 20-21 and on June 28 with the main recycle pump to the prescrubber venturi shut off. As a result, the gas entering the JBR was not completely saturated with water. The potential existed for slurry to dry inside the spargers at the wet-dry interface and cause plugging during these tests.

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*These peripheral spargers were sealed during the modification period, and without any gas flow or agitation on the inside, scale growth was expected.

The main recycle pump supplies about 600 gpm (2300 liters/min) of recycle water to the venturi throat. With the recycle pump off, the venturi was fed by 40 gpm (150 liters/min) of pond recycle water and about 15 gpm (57 liters/min) of fresh water. Although only 15-20 gpm (57-76 liters/min) of water was required to saturate the flue gas, the nozzles which deliver pond water and fresh water to the venturi were not adequately designed for this function. Consequently, the flue gas was only partially saturated and cooled to about 150°F (66°C) as compared to a saturated temperature of about 130°F (54°C). Total duration of these two tests was about 20 hours.

The results of these two tests indicated that complete flue gas saturation before entering the JBR is not required; however, a spray system above the inlet spargers should be used to provide rinse water for prevention of solids drying on the interior sparger walls. The maximum safe temperature above the saturated gas temperature was not well defined. If the flue gas is unsaturated in the spargers, it is conceivable that slurry could be dried on the interior of the spargers as it splashes. Enough of this drying could result in plugged spargers. In the prototype system, about one-third of the inlet gas deck was continually wetted with pond water makeup. The spargers in this region appeared to have fewer solid deposits than those in unwetted spargers.

Parametric Studies. In the last week of Phase III, Chiyoda attempted to conduct parametric studies but the results were inconclusive due to unsteady operation. The SO_2 vaporizer was used again in an attempt to maintain a 3000 ppm SO_2 level, the weir height was raised to 13 inches (33 cm), and the air rate was raised to 1600 scfm. Unfortunately, the limestone silo was nearly empty, and pH control was rather erratic. The process plots in Appendix A show that while 90 percent removal was reached at times, it could not be maintained continuously.

Vacuum Filter Performance. Chiyoda also tested a high-speed Bird-Young rotary vacuum, shown in Figure 5-33, during this week. This one square foot filter, rotating at 14 rpm, could process 3000-4000 pounds (∿1500 kg) per hour of gypsum which was twice the JBR solids production rate. The filter cake was typically 85 weight percent solids after about two seconds of filter operation and could easily be handled by a dump truck or front end loader if insufficient area was available for a gypsum stack. The filtrate liquor contained some suspended solids since a 40μ filter cloth was used. Also, sizing of the filter reservoir may be a critical factor in actual operation since the gypsum solids settle so quickly. Consequently, agitation

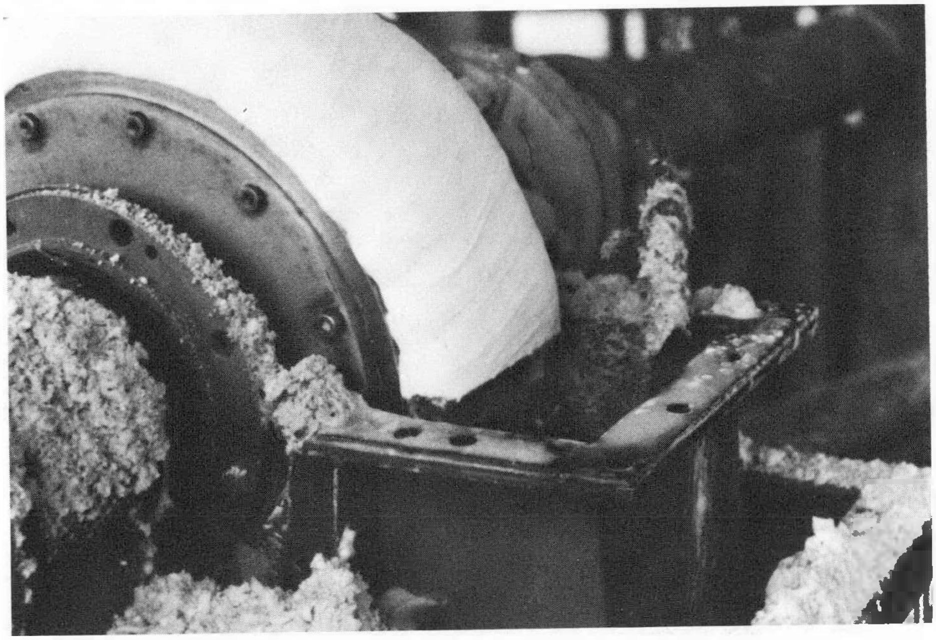


Figure 5-33
Testing Vacuum Filter on Gypsum Solids - Phase III

may be required in the reservoir if a long retention time is used. The test filter had about a half gallon (two liter) reservoir with a 20 gpm (76 liters/min) slurry flow rate. At this flow rate and the high rotary speed, no settling occurred.

Final Inspection. Inspection of the spargers at the end of Phase III showed greater scaling and plugging than noted in the inspection at the end of Phase II. However, so many tests were performed which could have caused these conditions that it is unlikely that any one upset would cause an immediate system outage. The plugging in some spargers suggested that slurry had splashed up and dried on the inside. Other spargers showed growth around the openings indicating that not enough gypsum crystals were present to prevent scaling. The spargers which had been sealed off also showed more scale than observed during the inspection prior to this test. It is probable that a combination of two factors, less gypsum seed crystals in the froth zone and incomplete saturation of the flue gas, were major contributors to the solids buildup on the flue gas spargers.

PERFORMANCE OF EQUIPMENT AND INSTRUMENTATION - PHASES I AND II

The performance of process equipment and instrumentation during Phases I and II is discussed in this section. Observations that were made during four inspection periods are summarized, and operation of key process equipment and instrumentation is described. Problems which forced system outages are presented, and the performance indicators commonly employed by EPA are discussed. Finally, the results of the coupon corrosion testing are summarized.

Inspections

Four planned inspections were conducted during the course of Phases I and II. The first was on January 19 at the conclusion of Phase I. The second was on March 12 just prior to the second variable load test. The third inspection was on April 23 just prior to the initiation of the chloride spiking experiment, and the fourth inspection was on May 25 at the conclusion of Phase II.

Phase I Inspection - January 19, 1979. A brief inspection was conducted on January 19, two days after the completion of Phase I testing. Since the JBR was not drained, comments cannot be made concerning the slurry zone within the JBR.

In general, the CT-121 prototype equipment was in good condition at the end of Phase I. The venturi disengaging chamber walls had a slight buildup of fly ash and gypsum. There was also an area where the venturi liner had to be repaired.

A dent on the outer metal surface showed probable construction damage which resulted in delamination and a crack in the lining immediately below one of the tangential nozzles in the venturi. The portions of the JBR which were visible were also in good condition. There were soft gypsum solids on the outer surface of the sparger tubes above the froth zone, apparently due to slurry splash-up during operation. The solids were easily removed by hand and did not pose an operating problem. There were also gypsum solids in the JBR gas outlet chamber and on the mist eliminator. It should be noted that Chiyoda had been requested to shut down the system without washing the mist eliminator. Inspections after mist eliminator indicated that essentially all of these solids were easily removed by spray washing. The solids in the outlet chamber were due to carryover from the froth zone and could also be easily removed. In a commercial system an efficient wash system could be employed to rinse these solids back into the JBR through the gas risers. In addition, this area would be a convenient location to store gypsum seed crystal in the event the system was drained and had to be restarted without a large solids inventory. Gypsum from the outlet deck was used for Phase III startup.

March 12 Inspection. On March 12 the system was shut down for inspection and maintenance prior to a second variable load test. At this time, a broken water nozzle above the venturi throat was replaced to insure adequate gas cooling at low flow rates. The venturi was in much the same condition as had been observed at the end of Phase I, but with no additional liner failures.

A complete inspection of the JBR was also made at this time since the slurry was drained. The inlet gas deck was slightly cleaner than in January with less accumulation of fly ash and gypsum. The outlet deck had a greater amount of solids carryover than observed in January, but again no scale was found on the mist eliminator.

Some scale was observed on the interior of the sparger tubes. However, since this was the first time they were inspected, the growth rate could not be determined. The patches of scale were fairly small and no scale was found in the sparger openings. Thus, scale did not cause any major restriction to the gas flow. Subsequent inspections revealed that the rate of scale deposition was slow enough, in fact, that no operating problems would be expected over a year's operating period. Additionally, since the majority of the scale was on the inside of the sparger tube, the solids could be easily removed by use of a reamer on an annual or even less frequent basis.

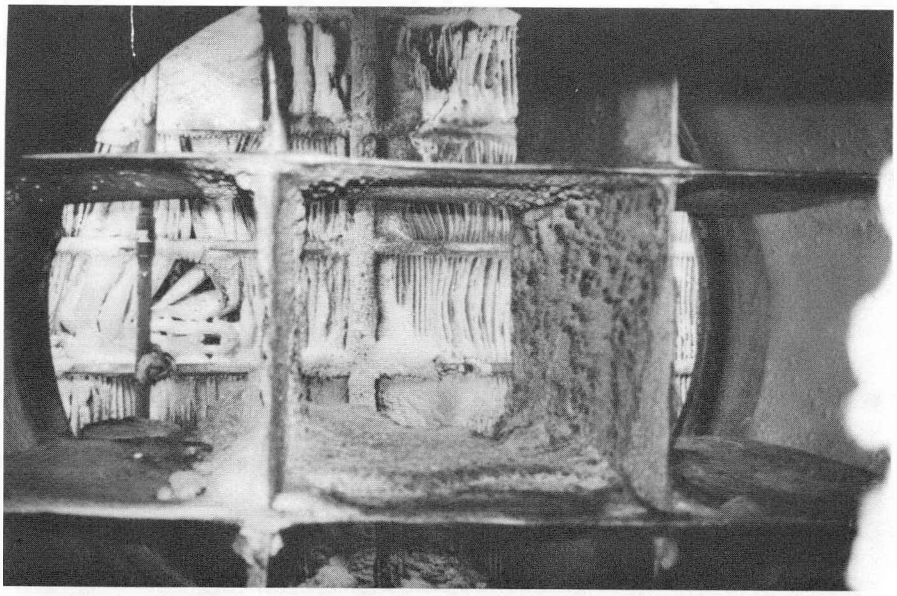
Formation of the scale on the interior of the spargers near the distribution openings could be caused by several related factors. Circulation and agitation in the lower region of the sparger are probably minimal and caused mainly by gas pressure surges. This reduced circulation and agitation could result in a stagnant region with a relatively low suspended solids concentration in the interior of sparger tubes. SO_2 sorption and natural oxidation could occur in this stagnant zone due to contact between the inlet flue gas and the liquor surface within the sparger. The newly formed sulfate would tend to precipitate on the sparger walls if insufficient seed crystals were present. Again, it should be restated that this growth was slow and did not hamper gas distribution or JBR performance.

April 23 Inspection. The system was shut down on April 23 in preparation for the chloride spiking test. The duplicate corrosion coupon sets were removed in order to isolate any effect of chlorides. A full inspection was not made at this time; however, the outlet gas deck revealed an increase in solids carryover from the previous inspection.

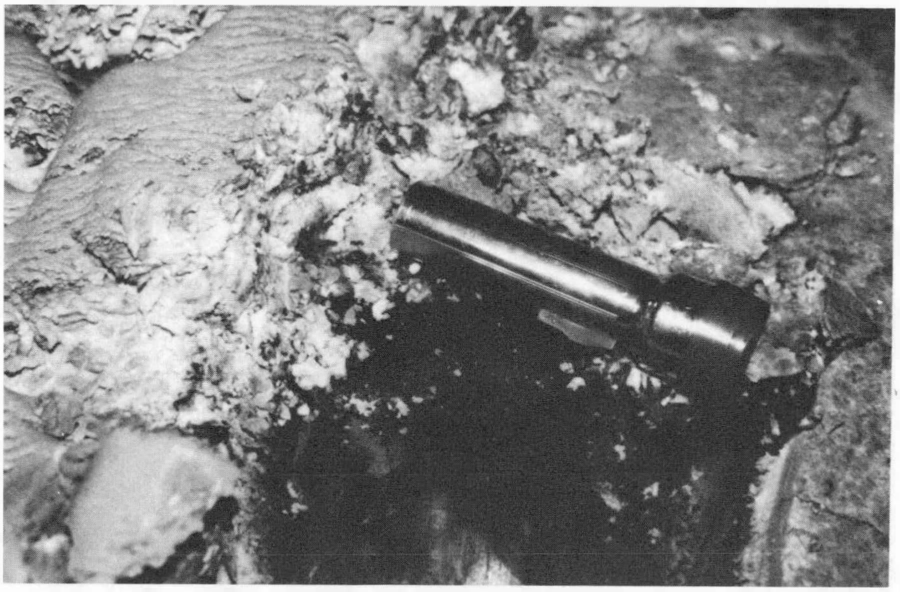
May 25 Inspection - End of Phase II. The EPRI program officially ended on May 22. Operation continued for two additional days to provide a baseline for comparison with further test results following Chiyoda JBR modifications, so the inspection at the conclusion of Phase II testing actually occurred on May 25.

For this inspection, all of the vessels were drained and opened. Overall, the JBR was in excellent condition. The condition of the inlet and outlet gas decks was similar to that noted in previous inspections with perhaps more solids on the outlet deck. The mist eliminator had soft gypsum solids on the first stage which were easily removed by hand. The second stage had light deposits on it, possibly due to the damaged sections in the front stage. Figure 5-34 shows the mist eliminator and JBR soft solids buildup while Figure 5-35 shows the mist eliminator before and after washing. Although Figure 5-35 shows the effect of washing after only three days of operation, the normal washing frequency was once every one to two weeks. Note that the cleaned blades were essentially free of solids. The reason for any residual solids is poor wash water distribution. Also note that the malformed plastic blades were due to a temperature excursion in the earlier CT-101 evaluation program and not this program (11).

The JBR reaction zone was thoroughly inspected at the end of Phase II. The spargers, side walls, draft tube, air pipes and agitator blade all showed patches of scale deposition, generally 1/16 of an inch (0.16 cm) or less in thickness.



Mist Eliminator After Two Weeks Without Washing
(Damaged Sections Due to CT-101 Program)



JBR Outlet Gas Deck - No Scale Present

Figure 5-34

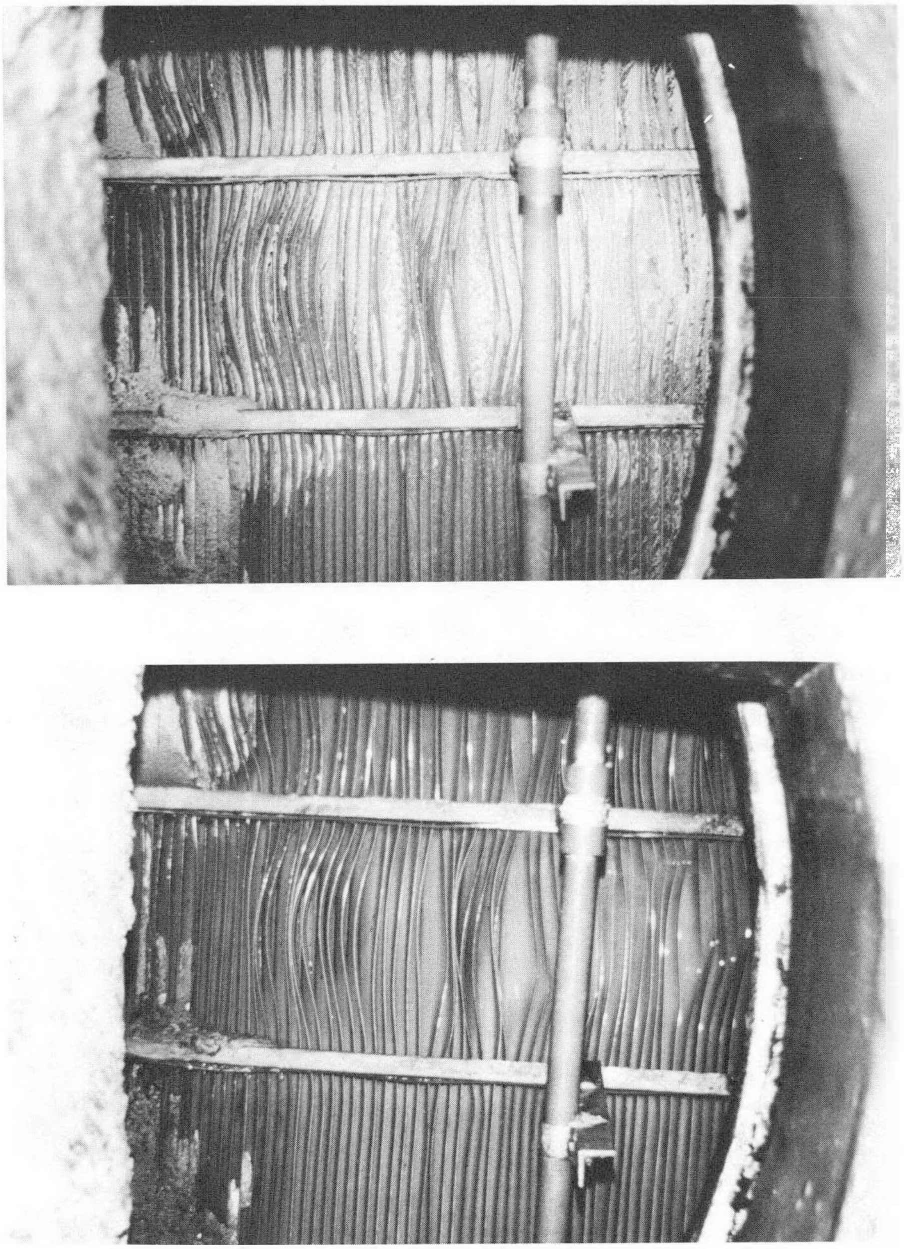


Figure 5-35
Before and After Washing Mist Eliminators (Three Days Since Previous Wash) (Damaged Sections Due to CT-101 Program)

Chiyoda had designed both FRP and stainless steel spargers to test material performance. The internal area of some of the FRP spargers had some scale growth below the distribution openings. However, scale was not observed in all of the FRP spargers and not observed in any stainless steel spargers. Most of the clean spargers were located under spray nozzles in the inlet gas deck. Pond water was introduced as makeup through these nozzles at a rate of 5-15 gpm (20-55 liters/min). Consequently, this continual rinsing probably prevented any solids deposition in these spargers. An annual cleaning of the spargers with a reamer could be done quite easily from the inlet gas deck without draining the JBR. Suitable maintenance precautions would allow thorough removal of the dislodged solids and prevent problems later.

A peculiar "rippled" deposit of scale from 1/8 to 1/4 inch (0.32 to 0.64 cm) thick was present on a section of wall on the south side of the JBR. No adequate explanation could be found for this deposit.

The oxidizing air spargers were in fairly good condition. About 40 percent of the holes on the inner air sparger rings were partially plugged or scaled. However, this could have resulted from variations in air flow during testing. The outer air ring had some deposits also, but its performance did not seem to be impaired.

Other vessels in the system were also inspected. The gypsum surge tank did not contain any scale, and the prescrubber was in acceptable condition and did not have any scale in the holding tank section. Loose gypsum solids from the mist eliminator wash stream had filled the pond return liquor tank to the intake level of the pump suction line. In the original design, the mist eliminator wash was to drain into the limestone feed tank, but due to a shortage of pipe during construction, it was routed back to the pond return liquor tank. The limestone slurry tank did not show any scale or corrosion which may be worthy of special note, since $CaCl_2$ was added directly into this tank in the chloride spiking test. The dissolved chloride level could have reached 15,000 to 20,000 mg/liter in the limestone tank during the week this spiking test was conducted.

To summarize the findings of the inspection, no major scale buildup or other problems were noted which might have necessitated a system shutdown. Although there was some gypsum scale noted in the JBR, the buildup was minor considering the nine months of operation which preceded this inspection and the many different operating conditions which were imposed. In fact, from a standpoint of scaling, the CT-121 system performed in a very reliable manner compared to many existing lime/limestone systems.

Process Equipment

A description of the pumps, blowers, and mixers used in the CT-121 demonstration is included in Appendix H. Downtime due to equipment malfunction was approximately 22 hours during Phases I, II, and III of the evaluation program. Of this, 17 hours were required to clean the limestone feeder rotor when it would not discharge powder. Performance of some of the major equipment is discussed below.

Venturi Prescrubber. Operation of the venturi was troublesome at times; however, this equipment never caused an emergency outage. Originally, the system had an automatic valve which was regulated by a level controller in the recycle tank. During all of Phase I and for the first month of Phase II, fresh and pond water addition was such that only 3-6 gpm of blowdown was required to keep a constant level. At this low rate, the total dissolved solids concentration in the purge liquor was relatively high and the pH was 1.9. The gypsum relative saturation of the prescrubber liquor typically remained in the 1.3 to 1.4 range where gypsum nucleation and scaling is likely to occur. Since the purge line was one inch in diameter and had many bends and elbows, the line and control valve eventually plugged. The solids in the line were a combination of fly ash, unburned coal, gypsum crystals and dirt. During the few days that were required to change the bleed line, the level in the venturi tank was controlled by dumping liquor to the trench which was then pumped to the gypsum tank with the sump pump.

In late February, a larger line was installed to feed pond liquor to the venturi and a larger purge line was installed that bypassed the automatic control valve. The blowdown rate was raised to 15-20 gpm which resulted in a prescrubber liquor pH of 2.5 while the relative saturation dropped to below 1.2 as a general rule. No further flow restriction in the prescrubber bleed line was noted until the experiment with reduced fresh water flow was conducted in May.

In early May, a test was conducted to determine the effect of decreasing the fresh water and increasing the pond water usage in the prescrubber. The fresh water rate was decreased from 12 to 7 gpm (45 to 26 liters/min). For about 24 hours, the prescrubber system operation remained stable with an increase in gypsum relative saturation to 1.25 to 1.3. These relative saturations are just below those indicating the onset of spontaneous nucleation.

During the next 12 hour period, the gas temperature rose requiring more liquor evaporation for complete gas saturation. This in turn lowered the blowdown rate and increased the cycles of concentration which caused a corresponding increase in gypsum relative saturation. A reduced flow through the purge pipe was the first indication of a problem. After gypsum crystals were found in a strainer the next day, the fresh water flow was increased back to 12 gpm and the purge line was removed and cut open. Gypsum crystals had grown on the pipe walls restricting the flow by as much as 30 percent. Although the higher gypsum relative saturations would certainly have contributed to rapid scale buildup, it cannot be stated with certainty that this incident caused the full restriction. This problem could have been avoided without increasing the fresh water makeup if the pond water flow rate to the prescrubber had been increased when the flue gas temperature began to rise. However, the pond water return pump system did not have sufficient capacity to supply the additional requirement. Moreover, the prescrubber control scheme was not designed to alter the pond water flow based on flue gas temperature.

The only other problem with the prescrubber involved failure of the quench nozzle above the venturi throat. On March 12, this fresh water nozzle was replaced during an inspection shutdown since it was not properly distributing the liquid. Under low gas flow conditions (poor distribution), the gas was not being saturated which may have contributed to the blistering of a portion of the venturi disengaging chamber liner during Phase I variable load tests. Once the nozzle was replaced no further trouble of this nature was reported.

Pump Service. In general, all of the process pumps performed well. One of the venturi recycle pumps seized once, but upon inspection no obstruction was found. The impeller clearance was readjusted before placing it back in service, after which there were no further problems.

In addition, the motor to the sump pump which emptied the trenches burned out May 7 and needed replacing. At the time, the venturi level was being controlled by draining to the trench. Consequently, some overflow from the trench occurred before the motor could be replaced.

The JBR underflow pumps and the pond water recycle recirculation pumps were run for over two months using pond water for seal water without any problems. The underflow slurry pumps' (50 gpm (190 liter/min) Allen-Sherman-Hoff frame AA-10-5 pumps) Centriseal system consisted of an expeller seal plus asbestos gland packing. The pond clear liquor, circulation pumps (45 gpm (170 liter/min) Gould Model 3196 pumps) were sealed by a Dura Type RO (Code EXSEFVV) mechanical seal and lip seal with water flush. Both types of pumps were sealed with about 0.2 gpm (0.76 liters/min) of sealing water. Since there were no noticeable pump performance problems, a detailed inspection of the seal mechanisms was not performed.

The only pumps that were undersized in the system were the pond water return pumps. As more pond water was used in the process in an effort to operate in a closed loop manner, it became necessary to operate these pumps continuously. Occasionally, it was also necessary to use additional fresh water as makeup because not enough pond water could be returned to the system. Installation of a larger line and rerouting of some of the piping to eliminate turns and bends helped alleviate this problem, but a pump with excess capacity would have been a better alternative and could have helped prevent the venturi prescrubber bleed line pluggage with gypsum scale which was discussed earlier in this Process Equipment Section. A higher capacity return pump would have allowed a higher prescrubber bleed rate which would have resulted in a lower relative saturation in the prescrubber liquor.

Mist Eliminator. The mist eliminator consisted of two banks (two passes/bank) of chevrons made of PVC mounted vertically in a horizontal duct which were left over from the CT-101 evaluation (12). As shown in Figure 5-35 some localized heat damage had occurred during the CT-101 evaluation from a reheater temperature excursion during a shutdown procedure, but the resulting warped blades caused no operational problems.

The mist eliminators showed no scale buildup or plugging problems throughout the program. In general, they were washed once every two weeks with pond water for about one minute which resulted in a total of about 300 gallons (1130 liters) of pond water rinsing the mist eliminators per wash cycle. Pressure drop across the two banks of chevrons ranged from two to four inches (7.6 to 15 cm) of water at full gas load. This pressure drop did not appear to be affected by solids buildup between mist eliminator washings. However, there is some question about operator consistancy in recording mist eliminator pressure drop.

Figures 5-34 and 5-35 were included in the inspections section and show pictures of the mist eliminators both before and after washing. The damaged area of the eliminator discussed earlier can be seen in these figures. At the end of the program a visual observation of mist eliminator washing was made. After 30 seconds, about 90 percent of the solids had been removed. After one minute, the wash was essentially complete. No scale was ever found on any chevron surface. The solids on the mist eliminator consisted of gypsum crystals carried over from the JBR.

The good reliability of the mist eliminators is probably due to the low (1 to 2 weight percent) concentration of $CaCO_3$ solids in the JBR slurry. Without deposition of calcium carbonate or calcium sulfite solids on the mist eliminator, SO_2 is not sorbed from the flue gas to cause gypsum scaling.

Limestone Feeder. The limestone feed system consisted of a limestone silo which was positioned above a rotary star feeder. The rate of rotation of the feeder determined the amount of limestone powder fed to the limestone slurry feed tank. Although this rotary feeder worked well initially when the finely ground Georgia marble stone was used, problems developed when the limestone source was changed to Southern Materials Company (SMC). The SMC stone appeared to be lighter in bulk density and coarser than the Georgia Marble stone. As a result, the solids adhered to the star feeder and flow from the limestone silo into the limestone slurry tank stopped.

As stated earlier, this was the equipment problem which caused almost all the system downtime during the program. The equipment was out of service for about 17 hours while air jets were added to the star feeder system. With the aid of this compressed air, the SMC limestone powder could be removed from the feeder, and the plugging problem was eliminated.

Forced Draft Fan. The forced draft fan was manufactured by Buffalo Forge Company and was the same one used in the CT-101 demonstration. Over 10,000 hours during 25 months of CT-101 operation had been logged prior to the CT-121 prototype system startup. During the CT-121 demonstration, the fan functioned well, and no corrosion was noted at the end of the program. During the earlier CT-101 program, fan corrosion had been a problem, but a purge system had been designed to flush the fan during outages to eliminate flue gas leakage and H_2SO_4 condensation problems. This purge and the high system reliability during CT-121 testing both had a positive effect on corrosion and fan reliability.

On nine occasions during the CT-121 evaluation program, F.D. fan outages were caused when protective circuitry tripped the fan as Gulf Power changed from one boiler to the other. The fan was off for a total of six minutes for this reason. The fan also developed hot bearings on May 24 and was out of service for about one hour after the official end of Phase II.

Oxidation Air Compressor. The air compressor supplying oxidation air to the system was a two-stage compressor manufactured by Gardner-Denver. This compressor performed well during the evaluation program with only one outage caused by a compressor malfunction. On this occasion in October during Phase O, the compressor developed bearing problems and had to be shut down for over a day. When the compressor was down, the JBR was drained while a spare diesel driven air compressor was employed to maintain agitation during the draining. Subsequent testing in Phase II indicated that the 425 scfm flow capacity of this spare compressor might have been able to keep the system operable at a reduced SO_2 removal efficiency. However, testing with the spare compressor was not conducted.

Instrumentation

Instrumentation problems only caused one outage during the evaluation program. The millivolt-milliamp converter in the temperature sensor circuit downstream of the venturi failed and shut off the fan through the automatic trip circuitry. This temperature sensor/fan shutoff mechanism was designed to protect the FRP ductwork from high temperatures. While no other instruments caused CT-121 system shutdown, the freezing weather did cause some problems particularly with the liquid level gauges. The performance of some of the major instrumentation is described in this section.

SO_2 Analyzers. The SO_2 sample conditioning system at Scholz was designed by SCS to give dry gas SO_2 concentrations at 40°F (4°C). Both the inlet and outlet flue gas samples were sent through heat traced teflon sample lines to a central analysis location where the samples were chilled to remove the moisture and then analyzed for SO_2 in a DuPont model 400 ultra violet photometric analyzer. A more detailed description of this system is given in Appendix I. Normally, the inlet and outlet DuPont SO_2 analyzers performance was excellent; values obtained for both inlet and outlet analyses were typically ±5 percent of those obtained by both Reich analysis and EPA method 6. When discrepancies of 10 percent or more occurred, the analysis was repeated for confirmation. If a discrepancy was verified, the continuous sampling system was checked for leaks and recalibrated. The sites of most leaks were unheated junctions in the tubing where brass fittings were used instead of stainless steel.

The stack probes were made of 316SS tubing with a shielded 2 inch by 8 inch sintered metal probe filter of five micron pore size. Once an hour a 30 second back purge of 100 psi air cleaned the filter and sample line. The DuPont 400 analyzers were equipped with an automatic re-zero which adjusts during this purge.

The analyzers were usually checked against reference span gases once a week. Calibration was rarely required and was done only if the indicator differed from the span gas value by five percent or more. Normal full-scale ranges were 0-4000 ppm for the inlet analyzer and 0-500 on the outlet. During some of the tests for the analyzers when the outlet was higher than 500 ppm, the gain was increased to a 0-1000 ppm range. No significant deviation from linear response was noted in the performance of the outlet analyzer with the higher gain (wider full-scale range). This was verified by manual SO_2 determinations since higher concentration span gas was not available.

The only major problem encountered with the SO_2 analyzers during the program involved the automatic re-zero function on the outlet gas analyzer. During much of Phase I, the potentiometer would not select a stable zero point. This malfunction caused a zero drift which had to be accounted for. Since the drift was in the zero function and did not affect the span, the proper SO_2 concentration could be calculated by adjusting the actual reading to account for the zero drift (subtracting the zero reading from the SO_2 measurement). Table 5-21 shows the results of span gas checks and the effect of the zero drift during Phase I. Note that the difference between the outlet span measurement and the calibrated span gas SO_2 concentration is usually very close to the magnitude of the zero drift. The adjusted DuPont SO_2 concentrations agreed with the manual SO_2 analyses reasonably well.

pH Meter. The pH meter and probe performed very well during the program. The dip-type probe was situated in the overflow stream at the weir. The probe was continuously cleaned by a hard neoprene ring which fit snugly around the probe and moved up and down to minimize any solids or stagnant film buildup. Electro-Fact electrodes (model 13SG/Z) were used with a Foxboro temperature compensating meter. Only one electrode failed in service although several were broken during calibration which was performed once a week. Although this calibration schedule may have been more frequent than necessary, it was desirable to ensure valid test results.

Kay-Ray Density Meter. A nuclear slurry density measurement system made by Kay-Ray Inc. was installed by Chiyoda to supply a continuous measurement of the suspended

Table 5-21

COMPARISON OF DUPONT SPAN CALIBRATION VERSUS ZERO DRIFT - PHASE I

	SO_2 Concentration (ppmv)					
	Inlet Analyzer			Outlet Analyzer		
Date	Zero	Instrument Reading with Span Gas Input[a]	Deviation In Span Gas SO_2 Measurements[b]	Zero	Instrument Reading with Span Gas Input[a]	Deviation In Span Gas SO_2 Measurements[b]
11-21-78	(?)	1960	(-70)	+45	457	(-5)
11-22	0	1980	(-50)	+15	470	(+14)
11-24	0	2000	(-30)	+17	487	(+25)
11-27	0	2000	(-30)	+1	459	(-3)
11-28	0	2020	(-10)	+8	465	(-3)
11-29	0	2010	(-20)	+15	471	(+9)
12-4	0	1960	(-70)	+36	485	(+23)
12-5	0	2010	(-20)	<0	437	(-25)
12-11	0	2010	(-20)	+10	472	(+10)
12-13	0	2020	(-10)	+20	475	(+13)
12-15	0	1980	(-50)	+23	482	(+20)
12-22	0	2000	(-30)	+22	445	(+20)
12-26	0	1960	(-70)	+45	468	(+43)
12-28	0	1975	(-55)	+30	450	(+25)
12-29	0	1950	(-80)	0	425	(0)
112-79	0	1950	(-70)	+38	468	(+43)
1-4	0	1950	(-80)	+12	440	(+15)
1-8	0	1920	(-110)	+5	425	(0)
1-10	0	1950	(-80)	+20	447	(+22)
1-12	0	1910	(-120)	+25	443	(+18)

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[a] During Phase I, the zero deviation was read and the instrument spanned before the zero was adjusted.

[b] SO_2 analyzer span gas value minus the manually calibrated span gas value.

solids concentration in the JBR underflow. The unit was mounted on a horizontal section of pipe before the control valve in the underflow slurry line.

The suspended solids concentration in the JBR is a key control variable because a low JBR solids inventory can lead to chemical scaling, and a sufficiently high suspended solids concentration can cause JBR underflow line plugging and solids handling problems. For this reason, the JBR underflow was sampled by the field operator every four hours to check the on-line instrumentation. This manual solids concentration measurement was conducted by measuring the volume of settled solids in a centrifuge tube. Figure 5-36 shows that this quick procedure for volume percent solids produced results that were consistent with the more accurate filtering/ drying method for determining weight percent suspended solids concentration.

The agreement between the manual and density meter solids measurements was generally good, although there could have been some improvements in density meter operating reliability. Mounting the sensor on a vertical section of pipe would have improved accuracy since, at times, the solids settled in the pipe causing incorrect readouts. Nearby lightning also seemed to affect the readout, and weather protection is also desirable to ensure accurate output.

Ultrasonic Flowmeter. One option of the program proposal was the testing of an ultrasonic flowmeter. A unit was leased from Polysonics Inc. (Model UFM-PD) of Houston to determine the applicability and accuracy of using such a device on slurry streams. This unit had a single transponder which was clamped onto a pipe with silicon sealer applied to ensure adequate contact. The transponder sends an ultrasonic signal through the pipe and fluid which bounces off the particles and returns. By measuring the Doppler shift in frequency due to the moving particles, a particle velocity is obtained. The volumetric flow is calculated from the cross-sectional area of the pipe assuming the particle velocity is equal to the stream velocity. The unit was easy to use and fairly accurate. Unfortunately, only one stream in the process, the slurry flow to the gypsum stack, could be isolated for independent flow rate measurements to verify the sonic flowmeter readings. This flow rate, which was obtained by timing level changes in a 25 gallon barrel, averaged 48 to 50 gpm. The flowmeter gave a velocity equivalent to 48 gpm.

Checking flows on other pipes gave reasonable values, but no independent method existed for checking them. The unit gave good readings on both fiberglass reinforced plastic and stainless steel pipes. As stated by the manufacturer, readings on clear liquor streams were not accurate.

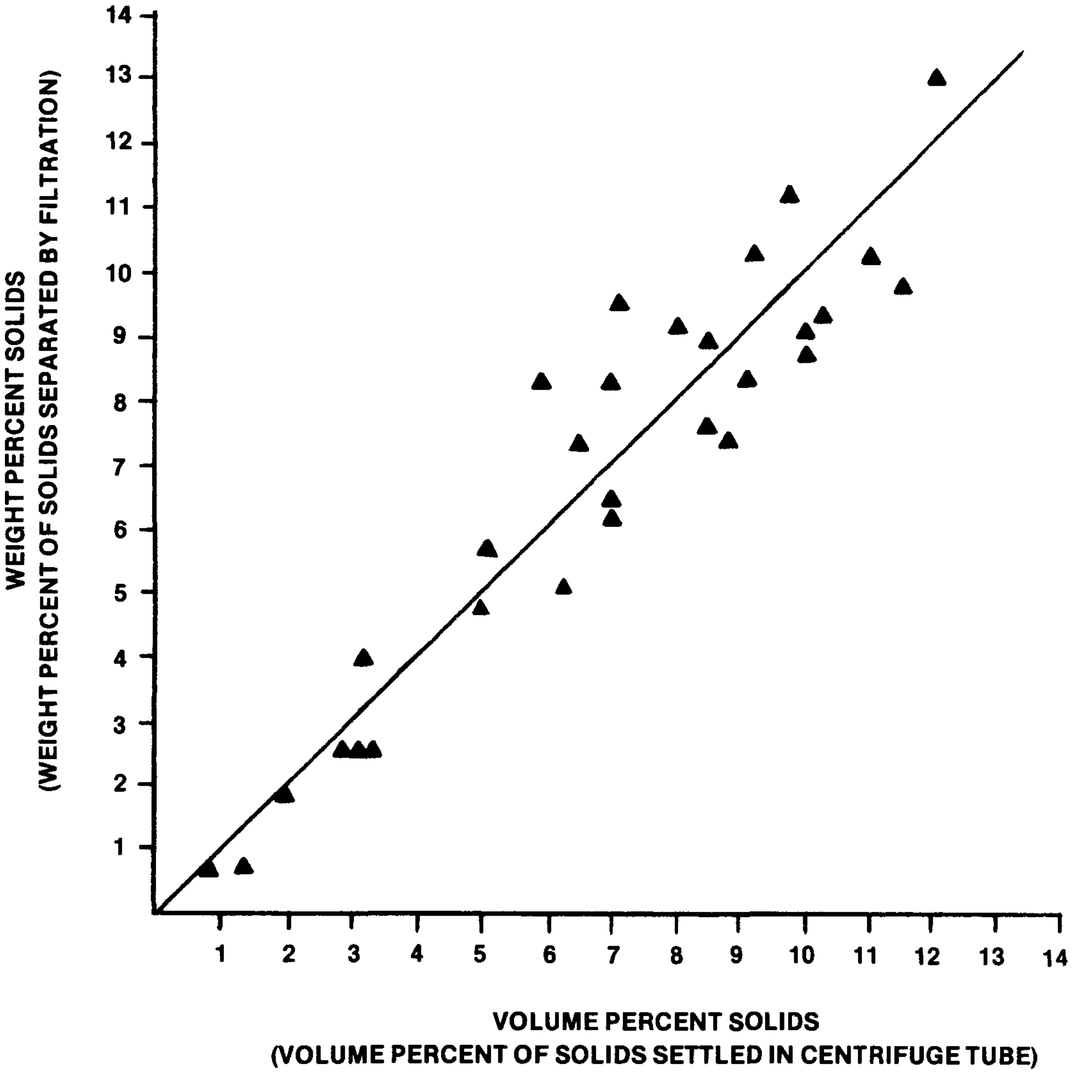

Figure 5-36
Volume Versus Weight Percent Solids for Gypsum Tank Effluent
(February-May 1979)

This ultrasonic flowmeter functioned well over the course of the program. Once calibrated, the instrument should perform well over a broad range of flow rates, 1 to 10,000 gpm (4 to 37,800 liters/minute). However, since the instrument was portable and was not mounted on one line throughout the program, no statements can be made concerning long-term reliability.

JBR ΔP Readings. Of all the instrument readings taken during the test program, the JBR ΔP readings were the most inaccurate and confusing. A differential pressure transducer was set up between the inlet and outlet gas decks, but was rarely calibrated. A water manometer between the two decks served as the reference by which the instrument, PdI-101, was corrected. Differences of ±2 inches (5 cm) were routinely encountered during the program. The comparison of the manometer readings and PdI-101 readings throughout the program is included in Appendix A. At times, PdI-101 was fairly consistent with the field manometer and at other times it was not. Possible reasons for these differences include different pressure fluctuation profiles between the taps, plugging of pressure tap lines, and incorrect calibration. As discussed in Section 3, the pressure drop depends on several factors; the most important is the weir height. Fluctuations in the gas flow, air rate, solids concentration, and overflow rate can change the ΔP value by ±10 percent. None of these factors can explain the difference observed between the instrument and the manometer, however.

Although the on-line pressure drop measurement (differential pressure cell) caused some initial confusion in comparing the Phase I and II test results, the manometer readings were judged to be accurate, and the evaluations were based on these manometer measurements. The relatively unreliable on-line ΔP measurements actually had no impact on system performance or control.

Annubar. An Ellison annubar (model 761-316SS) was used to monitor the inlet flue gas flow. The annubar used at first had been used in the CT-101 program. However, it was found to be corroded just before Phase 0 and was subsequently replaced on January 8, 1979 since it was giving incorrect readings. Once the new annubar was in service, it measured gas flow rates within 5 percent of the flows determined from pitot traverses. The reproducibility and accuracy of gas flow rate measurements were enhanced by over 100 feet (30 m) run of straight duct (∿14 L/D of straight duct) upstream from the annubar and pitot traverse ports. This allowed a flat velocity profile in the duct.

Performance Parameters

This section discusses the operating history of the CT-121 prototype plant during the EPRI evaluation program, Phases I and II, as well as Chiyoda testing in Phase 0 and Phase III. In an attempt to quantify the reliability of the process, four system viability parameters have been calculated. These indicators are used by EPA in periodically published status surveys to describe the performance of utility FGD systems (13).

The four parameters are labelled availability, reliability, operability, and utilization. The availability figure is derived from the hours the system was available for operation divided by the total hours in the period. The time the unit is considered available for operation includes downtime due to manpower or chemical shortages, inspections, or a decision to not use the scrubber. The reliability figure is obtained by dividing the FGD system operating hours by the hours the system was called upon to operate. However, this factor does not penalize the system for elected outages and supply shortages. The operability and utilization factors are very similar. Both use the hours the system actually operated divided by either the boiler hours or the total time, respectively. Moreover, they do penalize the system for elected outages such as inspections. During the CT-121 evaluation program, gas could be taken from either of two boilers. Consequently, the boiler operating hours and the total time in the period were equal because both boilers were never down simultaneously.

Table 5-22 shows the four system viability parameters for the CT-121 evaluation program. The availability and reliability parameters, which do not penalize the system for inspections and other elective outages, are high throughout the program. The availability factor remained above 99 percent for all phases and the average was 99.3 percent for the total program. The reliability factor was above 99 percent during all phases and the average was 99.2 percent for the entire program. The operability and utilization parameters which penalize elective outages were somewhat lower. Still, the overall program operability and utilization factors were 90 percent. As is shown in Table 5-22, these parameters were only 58.6 percent during Phase III because of a two week outage for JBR modifications prior to test initiation.

Table 5-22

CT-121 VIABILITY PARAMETERS

	Viability Parameters (percent)			
	Availability[a]	Reliability[b]	Operability[c]	Utilization[d]
Chiyoda Shakedown Phase (Phase O)	99.2	99.1	88.0	88.0
EPRI Evaluation Program (Phases I and II)	99.3	99.3	97.3	97.3
Extended Chiyoda Testing (Phase III)	99.5	99.1	58.6	58.6
Total Program Average	99.3	99.2	90.0	90.0

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[a] Availability - Hours the FGD system is available for operation (whether operated or not), divided by the hours in the period. Total Program = 7226/7276

[b] Reliability - Hours the FGD system was operated divided by the hours the FGD system was called upon to operate. Total Program = 6552/6602

[c] Operability - Hours the FGD was operated divided by the boiler operating hours in the period. Total Program = 6552/7276

[d] Utilization Factor - Hours that the FGD system operated divided by total hours in the period. Total Program = 6552/7276

A better understanding of the performance of the CT-121 prototype system can be gained by examining Table 5-23 which summarizes each outage during the evaluation program. Of the 724 outage hours, 674 hours were caused by scheduled shutdowns or inspections. As explained in the previous paragraph, almost 360 hours of these 674 hours were required for planned system modifications prior to Phase III testing.

The remaining outage time, about 50 hours, was caused by a variety of factors. However, none of the outages resulted from chemical scaling or process chemistry upset, even though the tests performed on the system at times simulated process upset conditions. The reliable operation during the evaluation program gives a measure of confidence to predictions about long-term CT-121 process performance. The greatest number of the unscheduled outages were caused by a circuit trip which put the forced draft fan out of service when Gulf Power switched the scrubber electricity supply from one boiler to the other. Overall, twelve fan outages accounted for about 15 hours of downtime. Two limestone feeder malfunctions also accounted for the longest unscheduled outages, about 21 hours of total outage time.

Table 5-23

PROTOTYPE SYSTEM OUTAGES DURING PHASES O, I, II, AND III

Date	Length of Outage (hours)	Explanation
Phase O		
8-30-78		1115 hours-Initial Startup
8-30	.5	Remove blind flange
9-6	.75	Repair FRP pipe
9-19	37.	Scheduled shutdown
9-29	.16	BL-101 kicked off
10-2	.08	BL-101 kicked off
10-3	13.5	Maintenance on air compressor
10-22	129.75	Scheduled shutdown
11-7	2.1	Inspection
11-13	37.5	Maintenance and winterization
Phase I		
11-15-78		0800-Start of Phase I
11-18	0.05	BL-101 kicked off
12-5	0.05	Maintenance kicked BL-101 off
12-6	0.01	BL-101 kicked off
12-12	0.03	BL-101 kicked off
1-17-79	83.13	Inspection, End of Phase I
Phase II		
1-20		1100-Start of Phase II
1-26	0.01	BL-101 kicked off
2-15	17.25	Limestone feed problems
2-28	0.62	Temperature indicator malfunction
2-28	0.01	BL-101 kicked off
3-12	7.0	Inspection
	8.0	Maintenance
4-13	0.01	BL-101 kicked off
4-23	4.00	Remove corrosion coupons
4-26	0.01	BL-101 kicked off
5-5	3.83	Limestone feed problems
5-12	0.01	BL-101 kicked off
5-22		1200-End of Phase II
Phase III		
5-24	1.0	Hot bearings on BL-101
5-24	359.42	Inspection and modifications
6-8		1040-Continuation of Phase III
6-19	14.22	Inspection
6-21	4.37	Out of limestone
6-29		1445-End of Testing

Note: BL-101 is the forced draft flue gas fan.

It should be emphasized that the 10-month test period is not long enough to serve as a basis for long-term performance predictions. However, the performance of this system was quite impressive and should lend optimism to chances of reliable operation for future full-scale systems. It should also be emphasized that Chiyoda hired and trained local manpower to operate the prototype system. Chiyoda supervisory personnel were usually on site for only one shift per day, and the system performed well without constant supervisory attendance.

During the 10-month program, 18,377 hours of operator labor were used. Each shift was composed of 2 men, a senior operator in charge of the control room and a field operator who adjusted the equipment as needed. Maintenance hours charged to the program totaled 2286 hours which is about one man per day shift.

Corrosion Test Results

Both stressed and unstressed coupons were exposed to process fluids in the CT-121 system to determine the corrosion resistance of potential metallic construction materials. Five unstressed spools (courtesy of International Nickel Company [INCO]) were placed in the following locations: prescrubber liquor, prescrubber outlet gas, JBR liquor, JBR outlet gas and the stack outlet. Radian-prepared spools containing stressed coupons were placed in the first four locations.

At the end of the program, the unstressed metal samples were returned to INCO for analysis. The stressed samples were analyzed at Radian. A summary of these results is presented in this subsection.

The INCO spools contained specimens of the metals listed in Table 5-24. The stressed coupons contained samples of the metals listed in Table 5-25. Two racks of stressed coupons were placed on each spool so that one rack could be pulled before the chloride test began for later comparison. Since the presence of high chlorides for even a short time can often lead to stress cracking, the use of duplicate specimens helped to identify chloride effects.

The stressed metals prepared by Radian were mechanically-bent, U-shaped coupons. Radian attempted to duplicate the metal types included in the INCO samples so nine of the sixteen metals in the unstressed sample sets were duplicated in the stressed sample sets. Three unstressed metals not on the INCO spools were also added to the stressed spools: Allegheny Ludlum 29-4 and 18-2 and Type 310 Stainless Steel. The corrosion results at each sample location are discussed below.

Table 5-24

INCO TEST METALS (UNSTRESSED)

Type 304 S.S.
Type 316L S.S.
Type 316 SS Sensitized
Type 317 S.S.
Carpenter alloy 20Cb-3
Incoloy alloy 825
Hastelloy alloy G
Inconel alloy 625
Hastelloy alloy C-276
Hastelloy alloy C-4
Uddeholm alloy 904L
Timet 50A (Titanium)
SS Cast Grade CD4MCU
IN-862 Cast SS
Illium Alloy PD

Table 5-25

RADIAN TEST METALS (STRESSED)

Type 304 S.S.
Type 310 S.S.
Type 316L S.S.
Carpenter alloy 20Cb-3
Incoloy alloy 825
Hastelloy alloy G
Inconel alloy 625
Hastelloy alloy C-276
Allegheny Ludlum 29-4
Allegheny Ludlum 18-2
Type 317L S.S.
Uddeholm Alloy 904L

JBR Liquor. Both Radian and INCO corrosion spools were placed in the JBR liquor. Originally, these spools were located in a trough through which the recycle underflow stream returned to the JBR. However, solids settled too quickly here preventing fresh liquor from contacting the metal surface. After about two months, the spools were moved to the weir where they were continually wetted by the overflow liquor. Some scale did form on the metal surfaces due to the wet-dry environment.

The unstressed spool was exposed for a total of 152 days including the chloride spiking test when the chloride concentration stayed at 6000 ppm for four days. The summary analysis by INCO is presented in Table 5-26. Table 5-27 is an explanation of the comment number code used throughout the INCO results. Type 304 and 316 sensitized stainless steels showed undesirable characteristics. Low carbon 316 and 317SS showed some crevice corrosion; however, the crevice could have been caused by the test spool. Other metals were unaffected.

Analyses of the stressed coupons are presented in Tables 5-28 and 5-29. No adverse effects were noted on any sample. The first set was not exposed to the high chloride level, the second one was.

Prescrubber Liquor. The samples exposed to prescrubber liquor were placed in a bypass section of pipe which had a fairly low flow through it. This low flow may have caused solids deposition which could result in some of the non-uniform corrosion seen.

The INCO coupons were exposed for a length of 151 days. Table 5-30 shows that corrosion in this location was fairly severe as the higher nickel alloys containing molybdenum were fairly resistant to general and local corrosion. Resistant cast alloys were CD-4MCU, IN-862 and Illium alloy PD. Resistant wrought alloys included Uddelholm 904L, Hastelloy G and C-276 and Inconel 625.

Radian analysis of the stressed coupons is presented in Tables 5-31 and 5-32. Only four metals were not affected by this liquor: Hastelloy C-276, Hastelloy G, Inconel 625, and Uddelholm Type 904L. All of the other metals experienced some type of attack. The puzzling observation is that most of the metals exposed for 34 days show more attack than those exposed for 151 days. It is suspected that the low flow through the test box may have caused solids to coat some of the coupons and help inhibit corrosion. Coupon set 4 was exposed to high fly ash loadings during the particulate tests. Additionally, the chloride level rose from about 1000 to 2000 ppm in the prescrubber loop during the chloride test period.

Table 5-26

INCO UNSTRESSED COUPON RESULTS - JBR LIQUID

Exposure - 152 days: Location - JBR Overflow Weir: Media - Weak acid, one week of 6000 mg/liter chloride exposure

Material	Sample Ident	Corr Rate (MPY)	Avg Corr Rate (MPY)	Max Pit Depth (MILS)	Avg Pit Depth (MILS)	Max Crev Corr (MILS)	Comments[a]
Inconel Alloy 625	NCM 961	.0					
	NCM 962	.0	.0				
Incoloy Alloy 825	FL 869	.0					
	FL 870	.0	.0				
Hastelloy Alloy C-276	HCN 367	.0					
	HCN 368	.0	.0				
IN-862 Cast SS	FJ 151	.0					
	FJ 152	.0	.0				
Hastelloy Alloy G	HJ 501	.0					
	HJ 502	.0	.0				
Hastelloy Alloy C-4	HCF 142	.0					
	HCF 143	.0	.0				
SS Cast Grade CD4MCU	CD 267	.0					
	CD 268	.0	.0				
Timet SOA (Titanium)	TM 63	.0					
	TM 64	.0	.0				
Carpenter 20 CB-3	RPH 305	.0					
	RPH 306	.0	.0			1	
Uddeholm 904L	PQ 87	.0					
	PQ 88	.0	.0				
Illium Alloy PD	IE 63	.0					
	IE 64	.0	.0				
SS Type 317	RMH 105	.0				8	
	RMH 106	.0	.0			Incip	
SS Type 316L	RML 62	.0	.0			9	
	RML 63	.0	.0			8	
SS Type 304	UL 489	.0				9	
	UL 490	.0	.0			8	
SS Type 316 Sensitized	RMS 890	.2	.2	2	1		5,9,24

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[a] See Table 5-27

Table 5-27

INCO CORROSION TEST DATA COMMENTS

The INCO corrosion test data have a column entitled "Comments." The numbers listed in this column refer to the corresponding numbered comment below.

1. Non-uniform general corrosion.
2. Single pit.
3. A few random pits. (To the depth indicated on the table.)
4. Profuse pinpoint pitting. (Numerous, small, shallow pits with large ratio of depth to diameter. Depth usually only about one mil.)
5. Profuse pitting. (Numerous pits to the depth indicated on the table.)
6. Broad pits. (With small ratio of depth to diameter. Depth indicated on the table.)
7. End-grain sttack.
8. Intergranular etch.
9. Intergranular corrosion.
10. Intergranular corrosion with "grain cropping."
11. Stress-corrosion cracking. (The corrosion specimens are not intended to detect this type of attack but it occasionally occurs in the cold-worked area of the identification stamp.)
12. Evidence of dealloying.
13. Partially corroded away.
14. Missing and believed to be corroded away. Actual corrosion rate therefore greater than the calculated value.
15. Missing but not believed to be corroded away. Actual corrosion rate unknown.
16. Weld spatter on specimen.
17. Graphitization.
18. Average corrosion rate not indicated because the corrosion rates on the duplicate samples differed by a factor of more than two.
19. Corrosion exhibited what appeared to be a "flow pattern."
20. Since the actual operating time was comparatively short and the time in test was much longer, these corrosion rates and pit depths may not be representative of continuous operation. The corrosion rates were calculated on the basis of operating time only.
21. Most of specimen uncorroded except for preferential corrosive attack in one, or a few areas. Therefore, the corrosion rate which was calculated on the basis of all of the exposed area is low and not representative of the higher rate in the "active" area.
22. The crevice corrosion reported occurred immediately adjacent to the crevice.
23. Stress-corrosion cracking was observed in the crevice region formed by the spacer. There are residual stresses in this region because of the "punched" hole in the center of the coupon.
24. "Tunnelling" type of pitting observed in which major portions of the pits were concealed beneath the surface.
25. Exfoliation type of attack.
26. Specimen showed slight weight gain.
27. Specimen showed signs of mechanical damage.
28. Crevice corrosion beneath deposit.
29. Specimens rotated on test spool, resulting in loss of metal from center hole because of mechanical wear. Therefore, calculated corrosion rates are higher than actual rates.

Table 5-28

STRESSED COUPON SET 1

Media - JBR Liquid

Exposure Length - 123 days

	Metal	Comments
Stressed Coupons	Type 304 Stainless Steel	No effect
	Type 310 Stainless Steel	No effect
	Type 316L Stainless Steel	No effect
	Hastelloy C-276	No effect
	Hastelloy G	No effect
	Inconel 625	No effect
	Incoloy 825	No effect
	Carpenter 20 Cb-3	No effect
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	No effect
	Type 317L Stainless Steel	No effect
Unstressed Coupons	Type 310 Stainless Steel	No effect
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	No effect

Table 5-29

STRESSED COUPON SET 2

Media - JBR Liquid (Including 1 week of 6000 ppm chloride exposure)

Exposure Length - 152 days

	Metal	Comments
Stressed Coupons	Type 304 Stainless Steel	No effect
	Type 310 Stainless Steel	No effect
	Type 316L Stainless Steel	No effect
	Hastelloy C-276	No effect
	Hastelloy G	No effect
	Inconel 625	No effect
	Incoloy 825	No effect
	Carpenter 20 CB-3	No effect
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	No effect
	Uddeholm Type 904L	No effect
Unstressed Coupons	Type 310 Stainless Steel	No effect
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	No effect

Note: Sufficient coupons were not available to include 317L stainless and Uddeholm 904L in both coupon sets listed in Tables 5-28 and 5-29.

Table 5-30

INCO UNSTRESSED COUPON RESULTS - PRESCRUBBER LIQUOR

Exposure - 151 days: Location - Prescrubber Bleed Liquor: Media - 1.9 to 2.5 pH, 2000 mg/liter chloride exposure

	Sample Ident	Corr Rate (MPY)	Avg Corr Rate (MPY)	Max Pit Depth (MILS)	Avg Pit Depth (MILS)	Max Crev Corr (MILS)	Comments[a]
SS Cast Grade CD4MCU	CD 275	.0					
	CD 276	.0	.0				
IN-862 Cast SS	FJ 159	.0					
	FJ 160	.0	.0				
Illium Alloy PD	IE 69	.0	.0				
Uddeholm 904L	PQ 95	.0					
	PQ 96	.0	.0				
Hastelloy Alloy G	HJ 509	.0					
	HF 510	.0	.0				
Hastelloy Alloy C-276	HCN 375	.0					
	HCN 376	.0	.0				
Inconel Alloy 625	NCM 969	.0					
	NCM 970	.1	.0			Incip	22
Hastelloy Alloy C-4	HCF 150	.1				1	
	HCF 151	.1	.1			Incip	
Incoloy Alloy 825	FL 877	.2		5	3	5	5,7,22
	FL 878	.2	.2	5	3	5	5,7,22
Carpenter 20 CB-3	RPH 313	6.3					
	RPH 314	6.4	6.3				
SS Type 317	RMH 113	14.9					
	RMH 114	15.8	15.3				
SS Type 316L	RML 70	22.4					
	RML 71	18.3	20.4				
Timet 50A (Titanium)	TM 71	>41.5					14
	TM 72	>41.8	>41.7				14
SS Type 316 Sensitized	RMS 894	>43.1	>43.1				14
SS Type 304	UL 497	>56.5					14
	UL 498	>56.5	>56.5				14

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[a] See Table 5-27

Table 5-31

STRESSED COUPON SET 3

Media - Prescrubber Liquor

Exposure Length - 34 days

	Metal	Comments
Stressed Coupons	Type 304 Stainless Steel	Destroyed, completely dissolved
	Type 310 Stainless Steel	Uniform weight loss, etched surface, superficial pitting
	Type 316L Stainless Steel	Uniform weight loss, crevice attack
	Hastelloy C-276	No effect
	Hastelloy G	No effect
	Inconel 625	No effect
	Incoloy 825	Puddle attack in bend
	Carpenter 20 Cb-3	Etched surface, weight loss
	Allegheny Ludlum 29-4	Etched surface
	Allegheny Ludlum 18-2	Nearly destroyed, 90 percent weight loss
	Type 317L Stainless Steel	Slight uniform weight loss
Unstressed Coupons	Type 310 Stainless Steel	No effect
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	Nearly destroyed, 90 percent weight loss

Table 5-32

STRESSED COUPON SET 4

Media - Prescrubber Liquor (Fly Ash)

Exposure Length - 151 days

	Metal	Comments
Stressed Coupons	Type 304 Stainless Steel	Destroyed, completely dissolved
	Type 310 Stainless Steel	Etched surface
	Type 316L Stainless Steel	Uniform weight loss - 20 percent
	Hastelloy C-276	No effect
	Hastelloy G	No effect
	Inconel 625	No effect
	Incoloy 825	Slight crevice attack
	Carpenter 20 Cb-3	Superficial pitting
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	Nearly destroyed, 90 percent weight loss
	Uddeholm Type 904L	No effect
Unstressed Coupons	Type 310 Stainless Steel	No effect
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	No effect

Note: Sufficient coupons were not available to include 317L stainless and Uddeholm 904L in both coupon sets listed in Tables 5-31 and 5-32.

Prescrubber Outlet Gas. Samples in this location were placed in the fiberglass duct between the venturi and the JBR. The flue gas stream at this location was saturated and contained about 1000-3000 ppm of SO_2. The stream may have also contained sulfuric acid mist and liquor carryover from the venturi containing dissolved chloride.

The unstressed INCO coupons were exposed for 125 days including the particulate testing period. These coupons experienced severe localized attack on all alloys except Inconel 625, Hastelloy alloys, G, C-4, and C-276. Table 5-33 presents the INCO analysis.

The Radian stressed coupon analyses are presented in Tables 5-34 and 5-35. Only four metals showed acceptable service: Hastelloy C-276, Hastelloy G, Inconel 625, and Allegheny Ludlum 29-4. The unstressed samples of Allegheny Ludlum 29-4 and 18-2 also showed no adverse effects. Set 6, which shows more attack than Set 5, was exposed to fly ash not removed by the venturi during the particulate test and also to an increase in chloride level from about 1000 to 2000 ppm of chloride in the prescrubber liquor. It is unknown how much of this liquor was carried over from the venturi due to poor mist elimination. However, Set 6 appears to have more evidence of crevice attack on the stressed coupons than Set 5. This is indicative of stress corrosion caused by higher chloride levels.

JBR Outlet Gas. Coupons in contact with the outlet gas were placed on the upper deck of the JBR upstream of the mist eliminators. These were often found with a coating of solids during inspections.

The INCO coupons were exposed for a total of 125 days including the high chloride levels. Type 304 and sensitized 316 stainless steel exhibited some attack as shown in Table 5-36. The other coupons were unaffected.

Analyses of the stressed coupons are shown in Tables 5-37 and 5-38. As can be seen, the set exposed to the high chloride level shows a few incidences of pitting.

Stack Gas. One INCO spool was placed inside the fiberglass stack for 136 days. The gas was saturated at 115-125°F. The analyses from this location indicate some minor corrosion on the 304 and 316 stainless steels as shown in Table 5-39.

Table 5-33

INCO UNSTRESSED COUPON RESULTS - PRESCRUBBER OUTLET GAS

Exposure - 122 days: Location - Duct Between Prescrubber and JBR: Media - Saturated Flue Gas

Material	Sample Ident	Corr Rate (MPY)	Avg Corr Rate (MPY)	Max Pit Depth (MILS)	Avg Pit Depth (MILS)	Max Crev Corr (MILS)	Comments[a]
Inconel Alloy 625	NCM 963	.0					
	NCM 964	.0	.0				
Titanium	TM 65	.1					
	TM 66	.0	.0				
Hastelloy Alloy G	HJ 503	.0					
	HJ 504	.1	.0				
Hastelloy Alloy C-4	HCF 144	.1					
	HCF 145	.1	.1				
Hastelloy Alloy C-276	HCN 369	.1					
	HCN 370	.1	.1				
Incoloy Alloy 825	FL 871	.5		PERF 52	15	28	3,7,21
	FL 872	1.3		PERF 52	35	41	3,21,24
SS Uddeholm 904L	PQ 89	1.4		PERF 58	33	16	3,21,24
	PQ 90	.9	1.2	48	40	22	3
IN-862 Cast SS	FJ 153	2.1		22	14	37	3
	FJ 154	2.4	2.2	36	5	64	3
SS Type 317	RMH 107	1.8		24	15	34	3,7
	RMH 108	3.3	2.5	46	25	37	3,7
Carpenter 20 CB-3	RPH 307	2.7		PERF 44	25	PERF 44	3,7,24
	RPH 308	3.7	3.2	PERF 44	44	PERF 44	3,21,24
SS Cast Grade CD4MCU	CD 269	2.0		37	20	33	3,7,24
	CD 270	4.5		40	15	21	3,7
Illium Alloy PD	IE 65	3.8		29	10	14	3
	IE 66	3.8	3.8	20	10	20	3
SS Type 316L	RML 64	3.3		PERF 35	20	PERF 35	5,7
	RML 65	5.9	4.6	PERF 35	15	PERF 35	5,7
SS Type 316 Sensitized	RMS 891	11.9	11.9	PERF 36	20	PERF 36	5,7,9
SS Type 304	UL 491	36.2		PERF 49	49	PERF 49	5,13
	UL 492	19.1	27.6	PERF 49	20	15	5

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[a] See Table 5-27

Table 5-34

STRESSED COUPON SET 5

Media - Prescrubber Outlet Gas

Exposure Length - 93 days

	Metal	Comments
Stressed Coupons	Type 304 Stainless Steel	Severe pitting and crevice attack, nearly penetrated
	Type 310 Stainless Steel	Severe pitting and crevice attack, nearly penetrated
	Type 316L Stainless Steel	Moderate crevice pitting
	Hastelloy C-276	No effect
	Hastelloy G	No effect
	Inconel 625	No effect
	Incoloy 825	No effect
	Carpenter 20 Cb-3	No effect
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	No effect
	Type 317L Stainless Steel	Slight crevice crack
Unstressed Coupons	Type 310 Stainless Steel	Severe pitting, nearly penetrated
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	No effect

Table 5-35

STRESSED COUPON SET 6

Media - Prescrubbed Outlet Gas

Exposure Length - 125 days

	Metal	Comments
Stressed Coupons	Type 304 Stainless Steel	Severe pitting and crevice attack
	Type 310 Stainless Steel	Severe pitting and crevice attack, penetrated
	Type 316L Stainless Steel	Localized severe pitting
	Hastelloy C-276	No effect
	Hastelloy G	No effect
	Inconel 625	One pit
	Incoloy 825	Slight pitting and crevice attack
	Carpenter 20 Cb-3	Moderate pitting and crevice attack, nearly penetrated
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	Minor crevice attack
	Uddeholm Type 904L	Minor pitting
Unstressed Coupons	Type 310 Stainless Steel	Severe pitting
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	No effect

Note: Sufficient coupons were not available to include 317L stainless and Uddeholm 904L in both coupon sets listed in Tables 5-34 and 5-35.

Table 5-36

INCO UNSTRESSED COUPON RESULTS - JBR OUTLET GAS

Exposure - 122 days: Location - Outlet Gas Deck of JBR: Media - Scrubbed Flue Gas

	Sample Ident	Corr Rate (MPY)	Avg Corr Rate (MPY)	Max Pit Depth (MILS)	Avg Pit Depth (MILS)	Max Crev Corr (MILS)	Comments[a]
S.S. Uddelhom 904L	PQ 91	.0					
	PQ 92	.0	.0				
Incoloy Alloy 825	FL 873	.0					
	FL 874	.0	.0				
SS Cast Grade CD4MCU	CD 271	.0					
	CD 272	.0	.0				
Hastelloy Alloy C-4	HCF 146	.0					
	HCF 147	.0	.0				
Inconel Alloy 625	NCM 965	.0					
	NCM 966	.0	.0				
Carpenter 20 CB-3	RPH 309	.0					
	RPH 310	.0	.0				
SS Type 317	RMH 109	.0					
	RMH 110	.0	.0				
Hastelloy Alloy G	HJ						
	HJ 506	.0	.0				
Illium Alloy PD	IE 67	.0	.0				
Titanium	TM 67	.0					
	TM 68	.0	.0				
IN-862 Cast SS	FJ 155	.0					
	FJ 156	.0	.0				
Hastelloy Alloy C-276	HCN 371	.0					
	HCN 372	.0	.0				
SS Type 316L	RML 66	.0				Incip	
	RML 67	.0	.0				
SS Type 304	UL 493	.2	.1	24	10	7	3,7,24
	UL 494	.0				Incip	
SS Type 316 Sensitized	RMS 892	.6	.6				9

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[a] See Table 5-27

Table 5-37

STRESSED COUPON SET 7

Media - JBR Outlet Gas (High Chloride) Exposure Length - 125 days

	Metal	Comments
Stressed Coupons	Type 304 Stainless Steel	One pit
	Type 310 Stainless Steel	No effect
	Type 316L Stainless Steel	Several minor pits
	Hastelloy C-276	No effect
	Hastelloy G	No effect
	Inconel 625	No effect
	Incoloy 825	No effect
	Carpenter 20 Cb-3	Possible small crack
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	No effect
Unstressed Coupons	Type 310 Stainless Steel	One pit
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	No effect

Table 5-38

STRESSED COUPON SET 8

Media - JBR Outlet Gas Exposure Length - 93 days

	Metal	Comments
Stressed Coupons	Type 304 Stainless Steel	No effect
	Type 310 Stainless Steel	No effect
	Type 316L Stainless Steel	No effect
	Hastelloy C-276	No effect
	Hastelloy G	No effect
	Inconel 625	No effect
	Incoloy 825	No effect
	Carpenter 20 Cb-3	No effect
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	No effect
Unstressed Coupons	Type 310 Stainless Steel	No effect
	Allegheny Ludlum 29-4	No effect
	Allegheny Ludlum 18-2	No effect

Note: Sufficient coupons were not available to include 317L stainless and Uddeholm 904L in both coupon sets listed in Tables 5-37 and 5-38.

Table 5-39

INCO UNSTRESSED COUPON RESULTS - STACK GAS

Exposure - 122 days: Location - Stack: Media - Scrubbed Flue Gas

	Sample Ident	Corr Rate (MPY)	Avg Corr Rate (MPY)	Max Pit Depth (MILS)	Avg Pit Depth (MILS)	Max Crev Corr (MILS)	Comments[a]
Incoloy Alloy 825	FL 875	.0					
	FL 876	.0	.0				
SS Uddeholm 904L	PQ 93	.0					
	PQ 94	.0	.0				
SS Type 304	UL 495	.0					
	UL 496	.0	.0			Incip	
Illium Alloy PD	IE 68	.0	.0				
Hastelloy Alloy C-4	HCF 148	.0					
	HCF 149	.0	.0				
Carpenter 20 CB-3	RPH 311	.0					
	RPH 312	.0	.0				
SS Type 316L	RML 68	.0					
	RML 69	.0	.0			Incip	
Inconel Alloy 625	NCM 967	.0					
	NCM 968	.0	.0				
IN-862 Cast SS	FJ 157	.0					
	FJ 158	.0	.0				8
Hastelloy Alloy C-276	HCN 373	.0					
	HCN 374	.0	.0				
Hastelloy Alloy G	HJ 507	.0					
	HJ 508	.0	.0				
SS Cast Grade CD4MCU	CD 273	.0					
	CD 274	.0	.0				
SS Type 317	RMH 111	.0					
	RMH 112	.0	.0				
SS Type 316 Sensitized	RMS 893	.0	.0				9
Titanium	TM 69	.0					
	TM 70	.0	.0				

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[a] See Table 5-27

Section 6

PARTICULATE AND TRACE ELEMENT SAMPLING RESULTS

This section presents the results of the particulate and trace element sampling performed on the prototype CT-121 system at Scholz. For a one week period of time the electrostatic precipitators on Unit #2 at Scholz were deenergized. Consequently, the prototype CT-121 system was tested for both SO_2 and particulates removal. Four topics related to this sampling effort are discussed here.

- Particulate removal capability of the system.
- Trace element balance around the scrubber.
- Chloride balance around the boiler.
- Summary of removal efficiencies.

The schedule for the particulate and trace element sampling is presented in Table 6-1. On May 8 and 9, samples were taken around the venturi and on May 10 and 11 around the JBR. Overall system sampling and the trace element sampling was conducted on May 12 and 13.

PARTICULATE REMOVAL CAPABILITY

The Phase II system set points during the particulate sampling were identical to Phase I operating conditions. Significant findings based on the results of the particulate sampling were:

- The venturi prescrubber removed 99.3 percent of the particulate entering the scrubber system. The JBR removed 34 percent of the remaining particulate matter. The entire system (prescrubber and JBR) had a particulate removal efficiency of 99.6 percent based on average inlet and outlet loadings of 3.4 and 0.015 grains per dry standard cubic foot respectively.

- Comparison of the mass of particulate per size fraction in the inlet/outlet flue gas of the scrubber (JBR) indicates a reduction in particulate matter for fractions less than 4 microns in diameter. An increase in mass for fractions greater than 4 microns was observed in the flue gas indicating the generation of large particles by the scrubber. This increase in mass affects the overall particulate removal efficiency on a total weight basis by less than one-half percent.

Table 6-1

SAMPLING SCHEDULE FOR PARTICULATE AND TRACE ELEMENT TESTS

Location	Type of Sample	5/7	5/8	5/9	5/10	5/11	5/12	5/13	5/14
Venturi Inlet	EPA-5 Grain loading		†	†			†	†	
	Andersen		††	††			††	††	†[a]
	SO_2		†	†				†††	
	Cl	†	†	†			††††	††††	
	WEP						†	†	
Venturi Outlet	EPA-5 Grain loading		†	†	†	†[b]			
	Andersen		†	†	†	†			
	SO_2		†	†	†	†			
	Velocity		†	†	†	†			
Outlet Stack	EPA-5 Grain loading				†	†	†	†	
	Andersen				†	†	†	†	†[a]
	SO_2				†	†		†††	
	Cl						†††		
	Velocity				†	†	††††	††††	
	WEP						†	†	
Mist Eliminator Inlet	EPA-5 Grain loading					†			
	SO_2					†			
Unit #2 Boiler	Bottom Ash						..	..	
	Preheater Ash						..	..	
	Economizer Ash						..	..	
	Front ESP Hopper Ash						..	..	
	Back ESP Hopper Ash						..	..	
	Coal (composite)						....	....	
CT-121 Process Streams	Pond Water						...	...	
	Makeup Water						...	...	
	Limestone						.	.	
	Limestone Slurry						....	....	
	Scrubber Overflow Liquor						....	....	
	Gypsum Tank Effluent						....	....	

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[a] Blank Andersens performed on this day.

[b] Particulates not toally collected on filter because of improper filter placement. Grain loading not valid.

† Sample taken

. Grab sample.

The remainder of this subsection discusses the total particulate loading and the particle size distribution found at the three sampling locations.

Total Particulate Loading

Measurements of the total particulate loading were taken at three points in the CT-121 prototype system. These measurements were done isokinetically in accordance with the EPA method 5 sampling technique which is discussed in Appendix C.

Table 6-2 presents the results of the total particulate sampling. The three major sampling points were the venturi inlet, the venturi outlet (JBR inlet), and the stack (JBR outlet) downstream of the mist eliminator. Additionally, one sample was taken before the mist eliminator in order to determine particulate concentration. The gas flow rates presented were determined during the sampling. Flows at the venturi inlet and outlet are in good agreement with those normally measured by an annubar positioned in the venturi inlet ducting which was used for flow rate determination during the rest of the CT-121 evaluation program. The gas flow at the stack outlet is about 15 percent higher than it should be theoretically. This is possibly due to poor distribution or turbulence in the stack. The sample ports on the stack were about 2½ diameters downstream of a 90° bend and only 2 diameters upstream of the stack outlet. Consequently, the flow profile did not have an opportunity to flatten out. For purposes of calculating the mass flow rate, the outlet gas rate was assumed to be equal to the inlet flow plus the 1000 dscfm of air injected in the JBR for oxidation.

Table 6-3 summarizes the particulate removal measured across the vessels. Removal across the venturi was 99.3 percent, removal across the entire system was slightly higher, and removal across the JBR was about 34 percent. The mist eliminator grain loading was higher than the loading to the JBR indicating that the scrubber was generating some particulate matter which was carried out by the scrubbed gas. However, this measurement was obtained at a single point, not in a duct traverse and could thus bias the result. This subject is discussed further in the next subsection.

The venturi outlet loading was very low (.026 gr/dscf) resulting in a low removal efficiency across the JBR. Because the system was built with the existing CT-101 equipment, it was not possible to quantitatively assess the removal capability of the JBR alone. Discussions before this sampling effort considered the possibility

Table 6-2

TOTAL PARTICULATE SAMPLING RESULTS

Date	Sampling Location	Time (EST)	Gas Flow (dscfm)[a]	Total Particulate Loading (grains/dscf)	Total Particulate Loading (lbs/10^6 Btu)[d]	Mass Flow Rate (lbs/hour)	Percent Isokinetic
5-8-79	Venturi Inlet	1643-1805	48,000	3.55	6.25	1450	95
	Venturi Outlet	1542-1655	46,000	0.024	.042	9.8	84
5-9	Venturi Inlet	1501-1620	49,000	3.39	6.08	1410	99
	Venturi Outlet	1503-1620	46,000	0.025	.046	10.6	92
5-10	Venturi Outlet	1452-1557	41,000	0.029	.045	10.4	85
	Stack	1446-1552	55,000[b]	0.019	.029	6.8	95
5-11	Mist Eliminator Inlet	1017-1117	38,000[c]	0.039	.069	16.1	97
	Stack	1418-1529	56,000[b]	0.013	.024	5.5	96
5-12	Venturi Inlet	1130-1662	48,000	2.4	4.31	1000	93
	Stack	1130-1662	56,000[b]	0.013	.024	5.6	94
5-13	Venturi Inlet	1107-1335	47,000	4.2	7.24	1680	86
	Stack	1117-1335	56,000[b]	0.016	.029	6.7	97

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[a] dscf - Based on 60°F, 1 atm.

[b] Cyclonic Flow - Flow used for calculations = Venturi Inlet + 1000 dscfm air.

[c] Only one sample point was used in an expanding duct section, 48,000 scfm used for mass flow rate.

[d] Heat input of 232×10^6 Btu/hr = $12{,}300\ \frac{\text{Btu}}{\text{lb}} \times \frac{\text{270 tons}}{\text{day}} \times \frac{\text{1 day}}{\text{24 hr}} \times \frac{\text{2000 lbs}}{\text{ton}} \times \frac{\text{21 MW scrubbed}}{\text{25 MW generated}}$

of turning off the recirculation pump on the venturi and operating it as a quench tower. However, it was decided that results from this quench tower configuration would not accurately model any possible commercial configuration since the potential would exist for fly ash agglomeration resulting in "abnormal" size distributions of the fly ash particles. For these reasons, the system was tested as it was normally operated.

Table 6-3

SUMMARY OF TOTAL PARTICULATE REMOVAL

	Particulate Concentration (grains/dscf)				
Date	Venturi Inlet	Venturi Outlet	Mist Eliminator Inlet[a]	Stack Outlet[b]	Percent Removal
5-8-79	3.6	.024			99.3
5-9	3.4	.025			99.3
5-10		.029		.019	34.5
5-11			.039	.013	
5-12	2.4			.013	99.4
5-13	4.2			.016	99.6
Average	3.4	.026	-	.015	-

---

[a] Mist eliminator inlet data was obtained at a single point in the duct as opposed to traversing. This data was gathered in order to determine the effect of the mist eliminator on the system. This value is not used in the percent removal calculations.

[b] Measured value was increased by 3 percent in order to compensate for air injection when the flow rate was used in the percent removal calculation.

However, all of the effluent from the venturi was sent to the JBR to determine both the chemical and physical effects of the fly ash on the JBR performance. It was assumed that the ash was uniformly distributed throughout the JBR, including the froth layer. However, a significant difficulty exists in predicting the JBR's particulate removal capability even though very little particulate matter escaped the prototype system. If the JBR is used as a primary particulate removal device (no venturi or ESP), the particles will be suspended in the gas upon entering the froth zone and not suspended in the liquid phase. It is quite possible that the froth bubbles impact enough liquid to ensure adequate removal; however, this theory was not proven during this sampling effort due to the previously mentioned equipment constraints. Re-entraining particulates from the froth layer is accomplished by a different physical mechanism than that employed for removal of particulates from a gas stream. Consequently, the low loadings seen after the JBR do not prove that the prototype JBR would be an effective particulate control device.

Particle Size Distribution

Particulate samples were taken with an Andersen Mark III cascade impactor at the venturi inlet and outlet and the stack outlet to determine the particle size distributions at these points. The Andersen impactor classifies particles with respect to their aerodynamic size and collects them on a series of impaction surfaces. The impactors used had eight stages followed by a filter to catch the particulate mass penetrating the last stage (nominal <5 μm).

Figure 6-1 is an averaged differential plot of the grain loading (per impactor stage) for the three gas streams. The area under any part of a curve is representative of the mass concentration in that size interval. Figure 6-1 shows that the stack outlet has a higher concentration of particles larger than 4 microns than the venturi outlet. This indicates that particulate generation is occurring in the JBR. It should be emphasized that the mist eliminators were damaged and could be responsible for this increase in larger particles by not adequately removing entrained slurry. Consequently, the results obtained here may not be directly applicable to the particulate emissions of a commercial CT-121 system.

Particulate size distributions usually fit a log normal distribution and they can, therefore, be described by the particle diameter and the geometric standard deviation. Table 6-4 expresses the measured distributions in this fashion. Because of the bimodal nature of the stack outlet sample, two sets of particle diameter and standard deviation values are required to describe the stack outlet distribution. The small particle mode in the stack sample represents primary particulate which has penetrated both the venturi and JBR. The large particle mode probably results from mass associated with entrained scrubber liquor droplets.

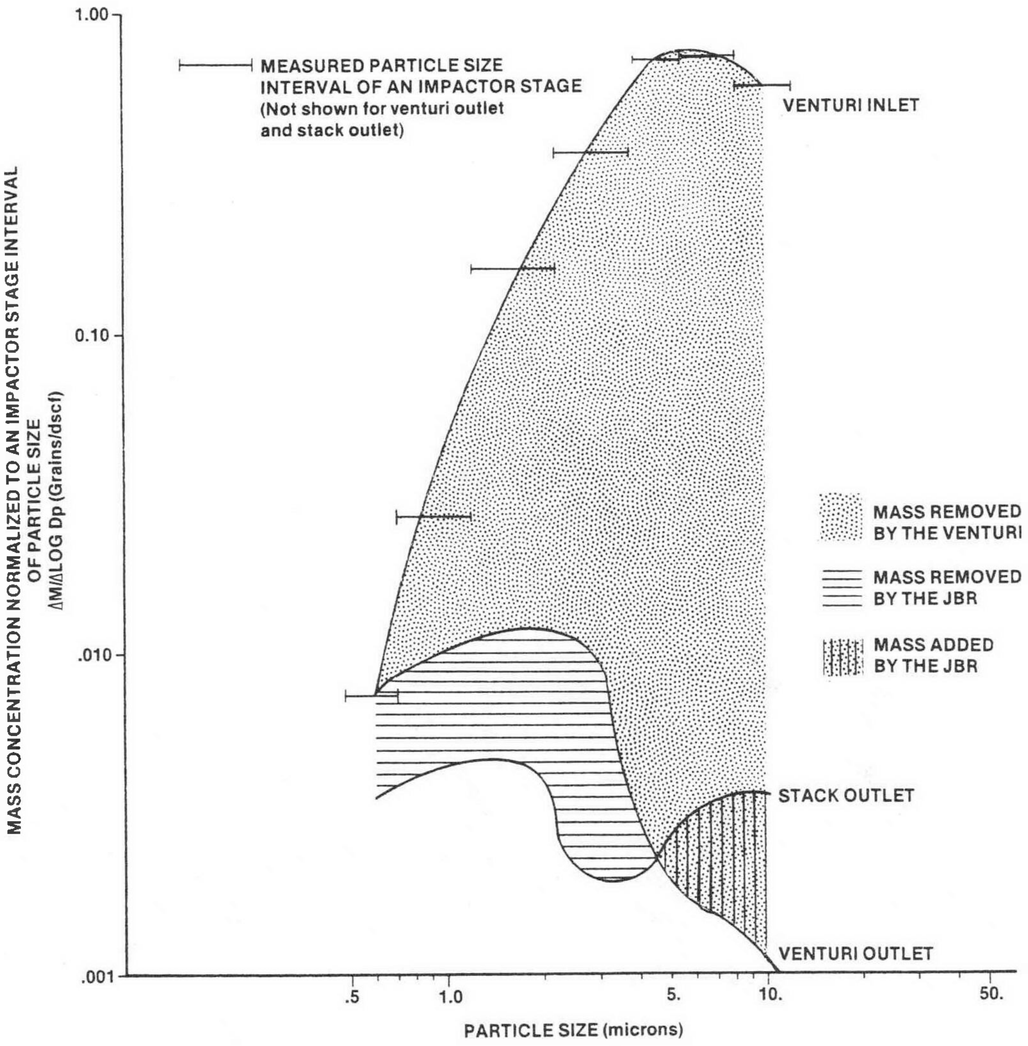

Figure 6-1
Average Differential Particle Size Distribution at the Venturi Inlet, Venturi Outlet, and Stack Outlet During Characterization Studies of the CT-121 Process

Table 6-4

MEAN DIAMETER AND GEOMETRIC STANDARD DEVIATION OF PARTICLE SIZE DISTRIBUTIONS

Sample	Particle Size Distributions Mean Diameter (microns)	 Geometric Standard Deviation
Venturi Inlet	5.8	1.6
Venturi Outlet	1.6	2.3
Stack (small particle mode)	1.5	2.3
Stack (large particle mode)	1.0	2.1

Figure 6-2 is a plot of the cumulative mass fraction as a function of particle size. Only one percent of the venturi inlet particulate mass is less than 2 microns in diameter, while the venturi outlet and stack fine particle fraction (less than 2 microns) comprises 80 and 65 percent respectively of the total mass emissions.

Figure 6-3 presents plots of the particulate removal efficiency (fractional efficiency curve) for the venturi and the CT-121 system as a function of particle size. In the submicron region the JBR significantly increases particulate removal. However, at about 10 microns the curves are seen to cross, reflecting the mass added to the gas stream by the larger particulates generated in the JBR. This increase in mass due to large particles affects the overall particulate removal by less than one-half of a percent.

MAJOR ELEMENT AND TRACE ELEMENT BALANCE

A mass balance around the scrubbing system (venturi and JBR) was performed to determine the fate of 19 elements. This task was performed in response to the Electric Power Research Institute's interest in the disposition of trace elements in lime and limestone FGD systems. The majority of these elements are present in the fly ash particulate matter rather than the flue gas. However, due to the established relationship of trace element concentration with particle size for fly ash (14) and the variability of control devices to remove different ash size fractions at different efficiencies (15), a simple understanding of particulate removal does not necessarily define the removal efficiency of trace elements.

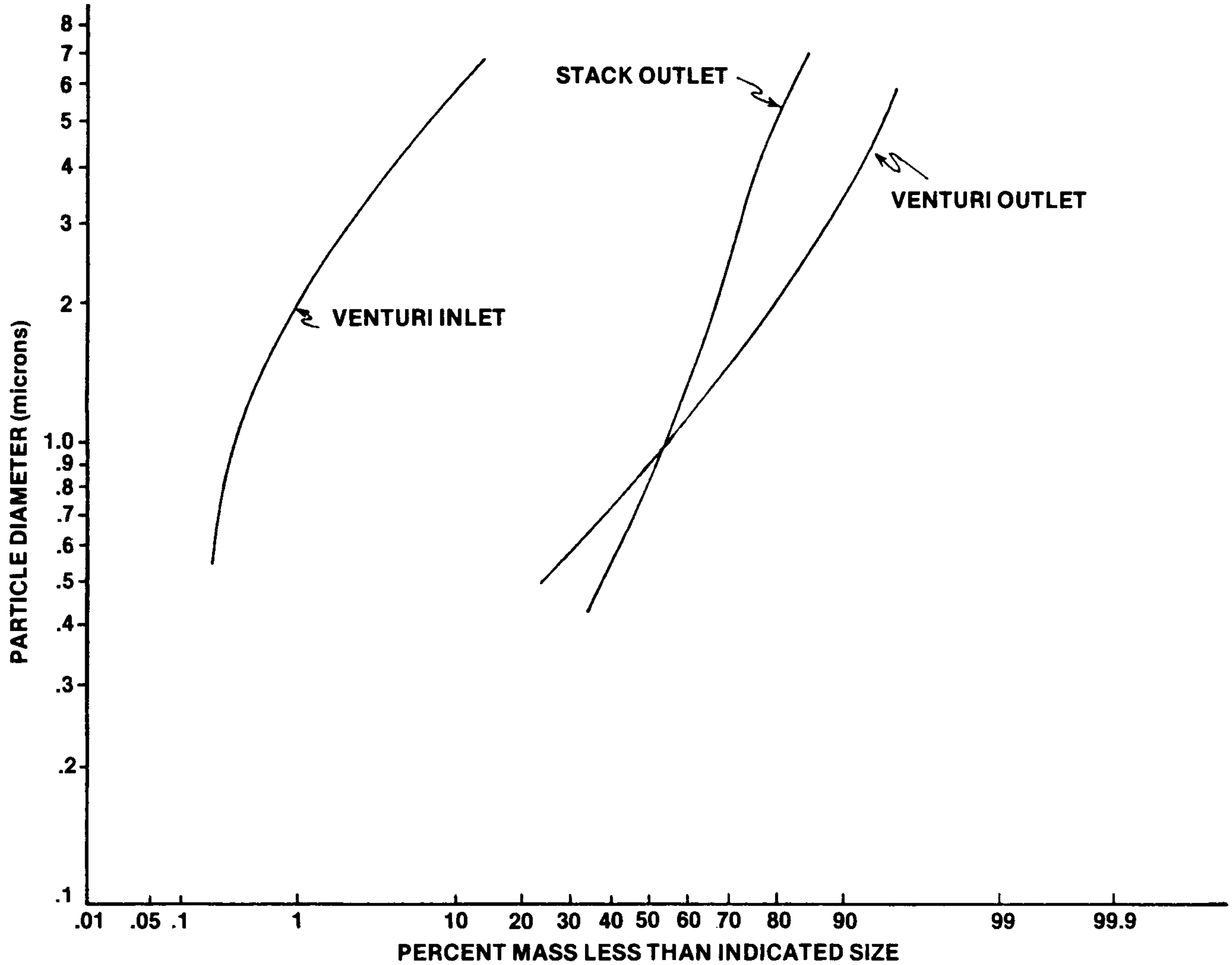

Figure 6-2
Average Cumulative Particle Size Distribution at the Venturi Inlet,
Venturi Outlet, and Stack Outlet During Characterization Studies of the
CT-121 Process

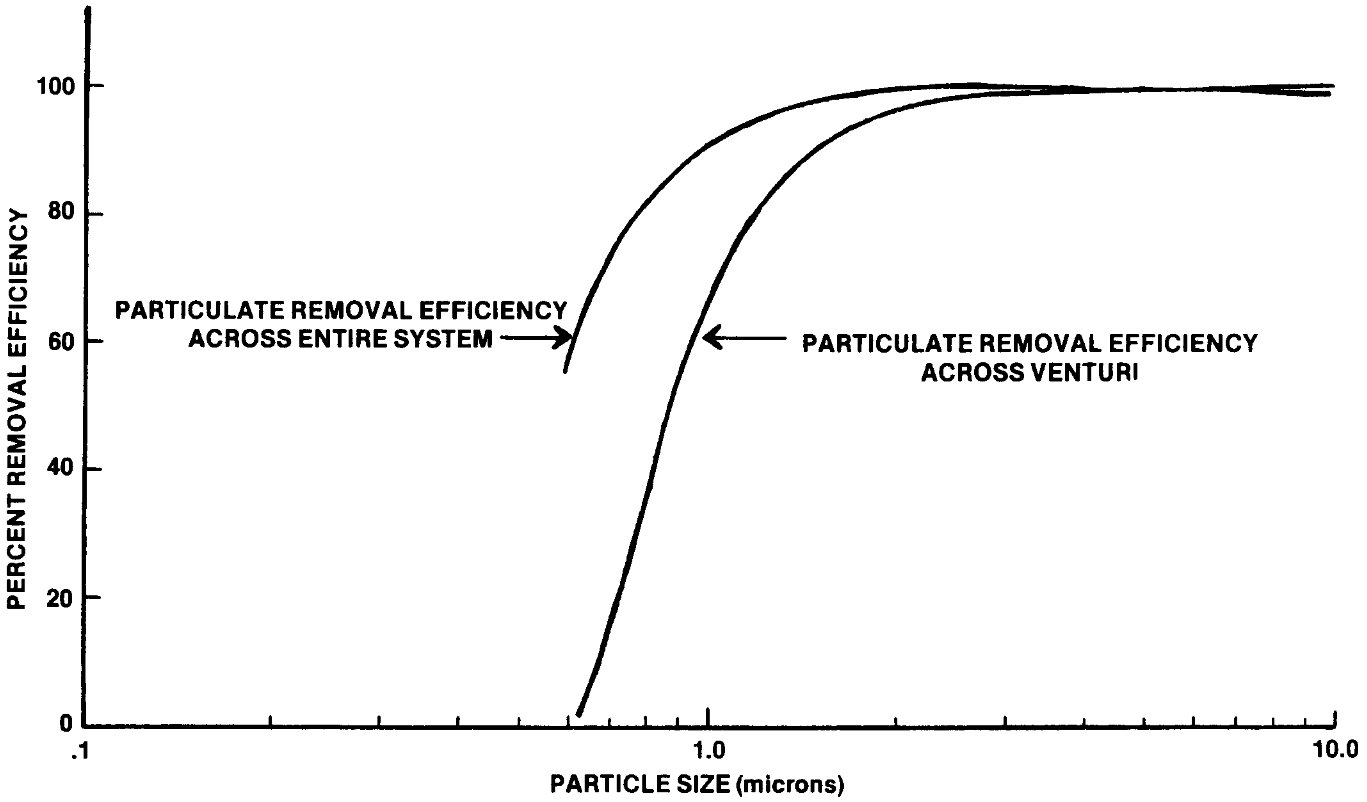

Figure 6-3
Venturi Prescrubber and the CT-121 Overall Particulate Removal Efficiency Curves

Trace element sampling was performed with a high particulate loading in the flue gas entering the CT-121 prototype system. The trace element sampling was conducted after the particulate sizing and concentration tests were completed in order to allow the scrubbing system (not including the gypsum stack and pond) to reach a steady-state with regard to the elemental distribution. Steady-state conditions increase the confidence in the mass balance and also simplify the required calculations.

The nineteen (19) elements selected for analysis were: antimony, arsenic, beryllium, cadmium, calcium, chloride, chromium, copper, lead, magnesium, mercury, nickel, selenium, silver, sulfur, thallium, titanium, vanadium, and zinc. Calcium, magnesium and sulfur were selected because they are major elements in the scrubber solids and liquor. Chloride was selected because of EPRI's desire to complete a chloride mass balance around the boiler. Titanium was selected to help judge the closure of the material balances since titanium is relatively nonvolatile and is associated entirely with the ash rather than the flue gas. Acceptable closure of the titanium balance indicates the process measurements for the inlet and outlet streams containing ash are not significantly in error. The remaining fourteen elements were selected based upon their suspected environmental activity. The remainder of this section presents the results of sampling conducted on May 12-13, 1979.

Elemental mass balances indicated closure for 14 elements: antimony, arsenic, beryllium, calcium, chloride, copper, magnesium, mercury, nickel, selenium, sulfur, titanium, vanadium, and zinc. The balance for chromium was considered marginal (i.e., within the assumed error limits but not in the range of acceptable mass closure). Balance results for cadmium, lead, and silver were poor. The low concentration of thallium in process streams prevented quantification and, therefore, no balance was calculated. Moreover, low concentrations of cadmium, lead, and silver have probably resulted in a higher error in their determination.

The following subsections present flow rate determinations, an analysis of the potential error propagation, and mass balance results.

Flow Rate Determination

Streams included in the balance around the CT-121 system were:

- limestone,
- makeup water,
- pond water,
- inlet flue gas and particulate,
- gypsum tank effluent, and
- outlet flue gas and particulate.

Figure 6-4 indicates the flow rates calculated for each stream. The limestone could not be sampled due to the closed feed system. Therefore, samples were collected from each shipment received for the previous twenty days. Attempts to monitor the addition rate directly were also not successful. The addition rate was, therefore, determined based upon the equivalent molar SO_2 removal rate observed during the sampling, and the effective limestone utilization.

The flow for the makeup water was determined by a flow totalizer and pond water flow was monitored with a rotameter. Three grab samples of each stream were collected on two successive days.

The inlet flue gas flow rate was determined by monitoring the gas velocity profile each day prior to sampling as previously discussed. Due to the turbulent flow pattern at the sampling point of the CT-121 stack, it was difficult to accurately measure the outlet flow rate. Therefore, the outlet rate was estimated to be three percent greater than the inlet rate to account for oxidation air added to the JBR.

The gypsum tank effluent flow was determined by monitoring the pump outlet pressure. A flow versus pressure calibration was previously performed using the ultrasonic flowmeter. Details of the sampling and chemical analyses are presented in Appendices C and F.

Trace Element Material Balance Results

The results of the material balances are presented in Table 6-5. The mass rates for the first six elements (arsenic through titanium) are presented in pounds per hour (lb/hr). The remaining thirteen elements are listed as $lb/10^3$ hr for convenience in presentation. The uncertainty value associated with the total mass in and out provides a mechanism to define the closure of the balance under the defined uncertainties of flow rate and concentration.

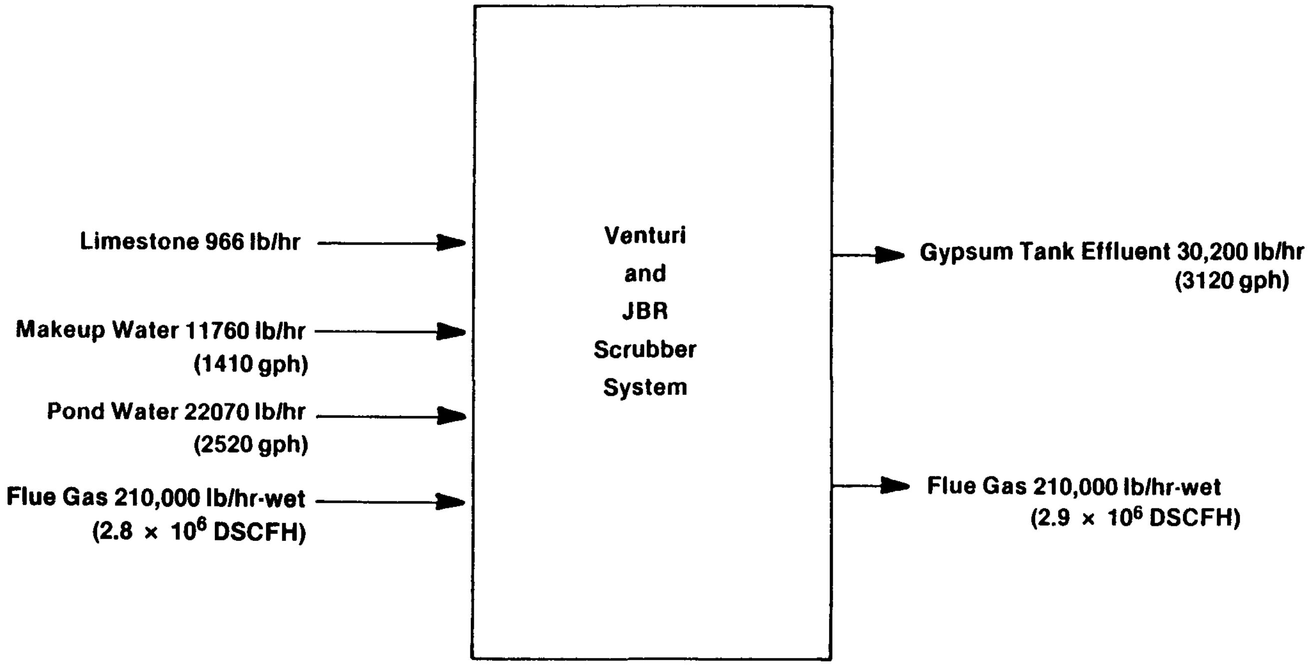

Figure 6-4
Stream Flow Rates Around the CT-121 Process

Table 6-5

MATERIAL BALANCE FOR THE CT-121 PROTOTYPE SCRUBBER

	Inlet Streams					Outlet Streams			
Element	Limestone	Pond Overflow	Makeup Water	Inlet Flue Gas	Total In	Gypsum Tank Effluent	Outlet Flue Gas	Total Out	Ratio Out/In
Arsenic (lb/hr)	<0.001	0.003	<0.00006	1.0	1.0 ± 0.1	0.81	0.093	0.90 ± 0.1	0.90
Calcium (lb/hr)	390	27	0.50	8.9	430 ± 40	470	0.17	470 ± 70	1.09
Chloride (lb/hr)	<0.05	40	0.47	4.7	45 ± 5	45	0.36	45 ± 6	1.0
Magnesium (lb/hr)	2.3	14	0.25	6.7	23 ± 2	23	0.04	23 ± 3	1.0
Sulfur (lb/hr)	<0.3	19	<0.06	384	400 ± 50	360	40	400 ± 50	1.0
Titanium (lb/hr)	0.039	0.001	<0.0001	6.2	6.2 ± 0.9	7.2	0.023	7.2 ± 1	1.16
Antimony (lb/10^3 hr)	<1.0	0.23	<0.06	9.7	10 ± 1	9.4	1.2	11 ± 1	1.1
Beryllium (lb/10^3 hr)	0.14	0.44	<0.02	17	18 ± 2	18	<0.5	18 ± 3	1.0
Cadmium (lb/10^3 hr)	<0.1	<0.04	<0.02	4.0	4.0 ± 0.7	0.47	0.30	0.77 ± 0.1	0.19
Chromium (lb/10^3 hr)	5.3	4.6	0.072	180	190 ± 30	140	1.4	140 ± 20	0.74
Copper (lb/10^3 hr)	3.9	<0.1	<0.06	260	260 ± 40	290	<0.1	290 ± 40	1.12
Lead (lb/10^3 hr)	<0.5	<0.04	<0.02	100	100 ± 10	47	0.88	48 ± 9	0.48
Mercury (lb/10^3 hr)	<0.01	0.32	<0.01	10.6^c	11 ± 2	5.2	4.2^a	9.4 ± 2	0.85
Nickel (lb/10^3 hr)	42	20	<0.06	160	220 ± 20	230	0.31	230 ± 30	1.05
Selenium (lb/10^3 hr)	<0.5	4.2	<0.02	15	19 ± 2	20	2.1	22 ± 3	1.16
Silver (lb/10^3 hr)	<0.09	0.03	<0.06	0.95	0.98 ± 0.2	0.47	0.05	0.52 ± 0.07	0.53
Thallium (lb/10^3 hr)	0.077	<0.02	<0.01	<2.0	<2.0	<1.0	<0.05	<2.0	--
Vanadium (lb/10^3 hr)	27	23	0.60	360	410 ± 50	390	3.0	390 ± 60	0.95
Zinc (lb/10^3 hr)	2.4	14	0.12	280	300 ± 40	250	8.2	260 ± 40	0.87

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[a] Sampled 30 minutes per hour for 3 hour period.

[b] 8 hour continuous sample.

[c] Value reflects the amount of mercury collected on the gold plugs during sampling.

A ratio of the outlet mass to the inlet mass of an element around the scrubber system provides a convenient criteria for evaluating closure. Radian considers ratios between 0.75 and 1.25 to represent acceptable closure. Elements with ratios outside this range but with overlap of the inlet and outlet mass rates when the uncertainties are considered, are deemed to have marginal closure. Balance values that lie outside both these constraints are considered poor. The marginal balance for chromium can be used as an example. Here, the out/in ratio is 0.74 which is outside the acceptable closure limit, but the bounds of the inlet and outlet mass rates overlap. The lower bound of this inlet flow is .19 - .03 or .16 lbs/hr and the upper bound of the outlet flow is .14 + .02 or .16 lbs/hr. Therefore, considering the uncertainties associated with flow rate and concentration measurements, the balance is deemed marginal. Cadmium, lead, and silver are seen to have poor closure.

Error Propagation

An error propagation analysis was performed on the mass balances for each element to account for the uncertainty or variance in the determination of both flow rate and concentration of each stream. The uncertainty assumed for each flow rate and concentration is presented in Table 6-6. Equation 6-1 was derived from a standard result of the propagation of errors analysis (16) and was used to calculate the uncertainty in each elemental mass balance at the 95% confidence level.

$$\text{uncertainty} = 2s = \sum_{i}^{n} 2\sqrt{M_i^2\left[\left(\frac{x_1}{2}\right)^2 + \left(\frac{x_2}{2}\right)^2\right]} \qquad (6\text{-}1)$$

where

M_i = mass loading of a specific element in stream i (lbs/hr)

x_1 = estimated error in the flow rate

x_2 = estimated error in the concentration

The uncertainty at the 95 percent confidence level was summed for the inlet and for the outlet mass flows for each element in Table 6-5.

Table 6-6

ESTIMATION OF ERROR IN MEASUREMENTS[a]
(95% Confidence Level)

	Limestone	Pond Overflow	Makeup Water	Inlet Flue Gas	Gypsum Tank Effluent	Outlet Flue Gas
Flow Rate	10	5	5	10	10	20
Element[b]						
As	100	25	100	10	10	10
Ca	5	10	10	10	10	10
Cl	100	10	10	10	10	20
Mg	10	10	10	10	10	10
S	100	10	20	7	10	5
Ti	15	15	100	10	10	15
Sb	100	10	100	10	10	10
Be	15	10	100	10	10	100
Cd	100	100	100	15	15	20
Cr	10	10	100	10	10	10
Cu	10	100	100	10	10	100
Pb	100	100	100	10	15	10
Hg	100	15	100	20	15	20
Ni	10	10	100	10	10	50
Se	100	10	100	10	10	10
Ag	100	10	100	15	15	15
Tl	50	100	100	100	100	100
V	10	10	10	10	10	10
Zn	10	10	15	10	10	10

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[a] Error expressed in percent.

[b] The estimated analytical errors are a function of the analytical procedure and the concentration of the analyte.

CHLORIDE BALANCE AROUND BOILER

Acceptable balance closure was observed for chloride around the boiler. Samples of the coal, various ash streams and flue gas were collected to determine the fate of chloride during combustion. Figure 6-5 presents a process schematic with flow rates for the various streams. Since only 82 percent of the flue gas was cycled to the JBR, Gulf Power's stack is also shown to identify the total chloride flow. The composition of the flue gas to Gulf Power's stack is assumed equivalent to the venturi inlet gas. The total gas rate was determined by a combustion calculation using the coal feed rate and oxygen content of the flue gas. The flow rate of flue gas to the Gulf stack was determined by differences in the total gas and the gas directed to the scrubber.

The ash flow rates were determined by estimation and calculation. Total ash flow was obtained using the ash percentage of the coal and the coal firing rate. Bottom ash production was visually estimated by the increase in volume in the bottom of the boiler over a 12 hour period. This estimate was made twice. The ash in the flue gas to the CT-121 system was measured by EPA Method 5. The difference in the fly ash rate exiting the boiler and that entering the CT-121 system was then accounted for. Assuming the gas leaving via the Gulf stack was identical in composition to the CT-121 inlet, the remaining ash was distributed among the various hoppers. At the Scholz plant, an automatic vacuum pneumatic system is used to empty the ash hoppers daily. The time required to empty each hopper was measured, and the remaining ash mass prorated to the various sets of hoppers based on these terms. Coal and gas flow rates were averaged over a two day period to allow an adequate time period to define ash flow rates.

The coal, each individual ash stream, and the flue gas were analyzed for chloride content. Table 6-7 presents the results of these analyses. Ash samples were collected twice daily by Radian while coal samples from the coal feeders were collected by site personnel every four hours. The individual coal samples were combined and the composite received by Radian. Analysis of the three flue gas samples for chloride are reproducible to ±11 percent at the low gas concentrations. Analysis of duplicate fractions of the coal indicate a ±7 percent reproducibility. Analysis of the ash samples indicate a ±20% reproducibility. Estimated error in measuring the coal and flue gas flow rates was ±10% while the assumed error in estimating the ash flow rates was ±30%.

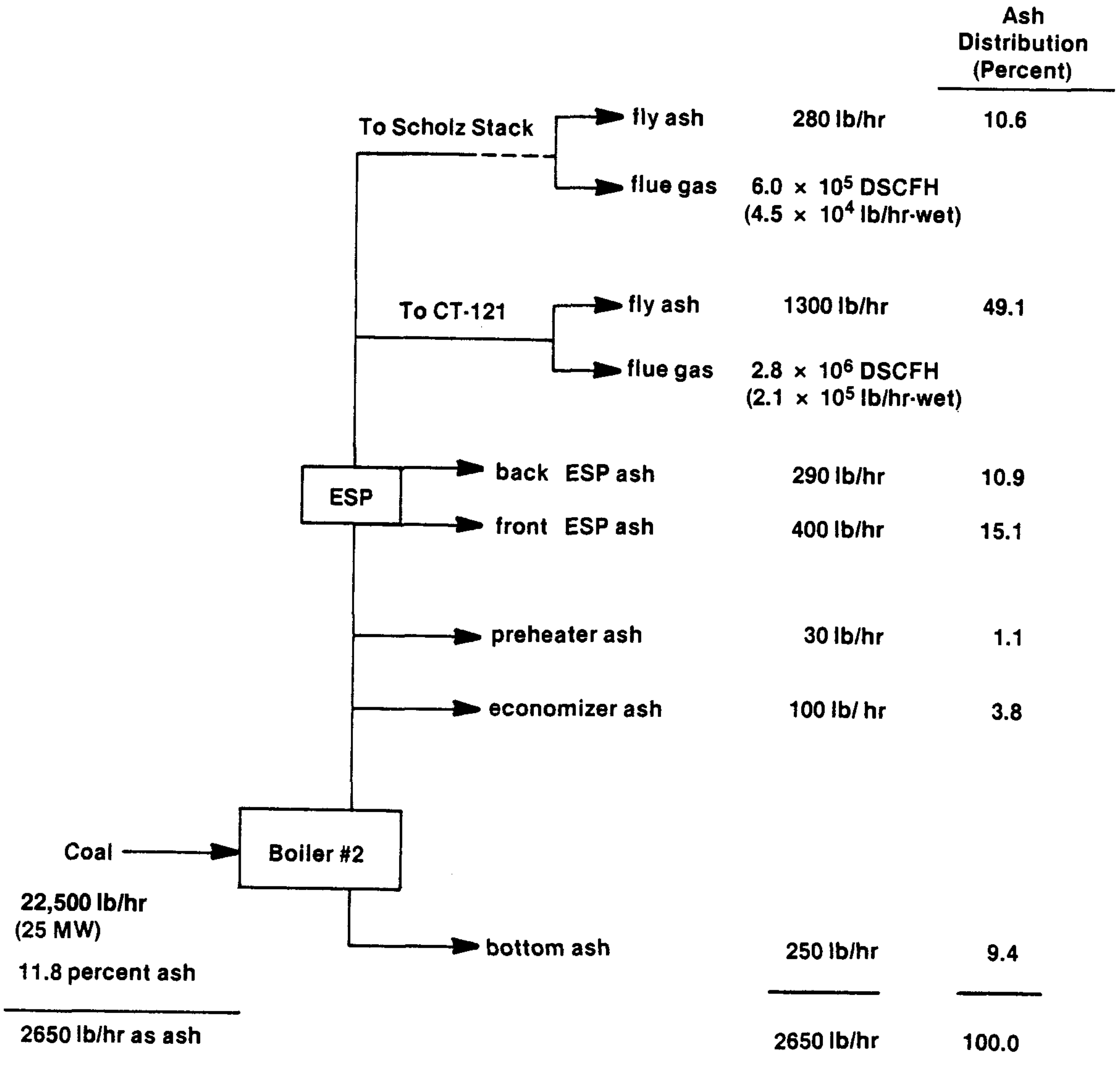

Figure 6-5
Unit #2 Overall Ash Material Balance

Table 6-7

SCHOLZ UNIT #2 CHLORIDE BALANCE
(May 12-13, 1979)

	(lbs/hr)
Inlet	
Coal	7.2 ± 0.9
Total In	7.2 ± 0.9
Outlet	±
Bottom Ash	0.014 ± 0.005
Economizer Ash	0.006 ± 0.002
Preheater Ash	0.002 ± 0.001
Front ESP Ash	0.022 ± 0.008
Back ESP Ash	0.014 ± 0.005
Fly Ash to CT-121	0.064 ± 0.023
Fly Ash to Gulf Stack	0.014 ± 0.005
Flue Gas to CT-121	4.7 ± 1.0
Flue Gas to Gulf Stack	1.0 ± 0.22
Total Out	5.8 ± 1.2

Out/In = 0.81

The mass balance for chloride around the Scholz unit #2 boiler is acceptable as indicated by the out/in ratio of 0.81. This result is within the error estimated for the inlet and outlet chloride mass.

SCRUBBER REMOVAL EFFICIENCY

During the two day intensive sampling period May 12-13, 1979, samples of the inlet and outlet flue gas were collected for analysis. The removal efficiency of the CT-121 process for particulate matter, SO_2, Cl, major elements, and trace elements across the CT-121 prototype system are given in Table 6-8.

Greater than 99 percent of the total inlet particulate matter to the venturi was removed. Assuming each element is uniformly associated with the particulate matter regardless of particle size, similar removal for each element would be expected. This is true for eleven of the sixteen elements present in the flue gas as particulates. Five of the more volatile elements (arsenic, antimony, cadmium, mercury, and selenium) do not follow this trend with the removal for these elements ranging from 60 to 92 percent while the concentration of one element (thallium) was too low to allow quantification of a removal efficiency.

Table 6-8

REMOVAL EFFICIENCY OF THE CT-121 PROCESS

Component	Inlet Flow (lb/hr)	Outlet Flow (lb/hr)	Percent Removal Efficiency	Uncertainty Range
SO_2	740 ± 100	77 ± 10	89.6	99.6 - 99.4
Chloride	7.4 ± .7	0.35 ± .05	92	94.4 - 90.0
Total Particulates	1300 ± 180	6.1 ± .9	99.5	99.6 - 99.4
Arsenic	1.0 ± .1	0.093 ± .01	91	92.5 - 88.6
Calcium	8.9 ± .1	0.17 ± .02	98.1	98.5 - 97.6
Magnesium	6.7 ± .9	0.04 ± .006	99.4	99.6 - 99.2
Titanium	6.2 ± .9	0.023 ± .003	99.6	99.7 - 99.5
	Inlet Flow (lb/10^3 hr)	Outlet Flow (lb/10^3 hr)		
Antimony	9.7 ± .1	1.2 ± .2	88	90.6 - 83.9
Beryllium	17 ± 2	<0.5	<96.7	
Cadmium	4.0 ± .6	0.30 ± .04	92	93.9 - 90.0
Chromium	180 ± 30	1.4 ± .2	99.2	99.4 - 98.9
Copper	260 ± 40	<0.1	>99.9	
Lead	100 ± 10	0.88 ± .1	99.1	99.2 - 98.9
Mercury	10.6 ± 1.0	4.2 ± .6	60	70.0 - 50.0
Nickel	160 ± 20	0.31 ± .04	99.8	99.9 - 99.8
Selenium	15 ± 2	2.1 ± .3	86	89.4 - 81.5
Silver	0.95 ± .1	0.05 ± .007	95	95.9 - 93.3
Thallium	<2.0	<0.05	ND	
Vanadium	360 ± 50	3.0 ± .4	99.2	99.4 - 98.9
Zinc	280 ± 40	8.2 ± 1.0	97	97.8 - 96.2

ND = Not Determined

Section 7

COMMERCIAL APPLICATIONS

Since the CT-121 prototype at Scholz was to a large extent constructed by modifying the existing CT-101 demonstration equipment, there will be some design concepts used in a commercial CT-121 system that were not tested in this evaluation. This section describes designs which Chiyoda has considered for incorporation in commercial systems and which were identified in the evaluation program as possibly affecting the process operation. Figure 7-1 reflects one possible configuration which Chiyoda is considering for commercial applications (17).

The topics discussed in this section include:

- Power requirements
- Scale up criteria
- Slurry mixing and solids stratification
- Limestone slurry system
- Quench and wash systems
- Fan design and performance
- Gypsum disposal

POWER REQUIREMENTS

The power consumed by the prototype CT-121 system during the evaluation program is recorded in Appendix A, Process and Operating Data. The average power consumption during the evaluation was about 550 kilowatts. The prototype system treated an average gas flow equivalent of about 21 megawatts based on a gas flow of 50,000 scfm and a 2,400 scfm/MW_e factor determined during the particulate testing. Thus, the power consumed as a percentage of the plant output is estimated to be

$$550 \text{ kW}/21\text{x}10^3 \text{ kW} = 0.026 \text{ or } 2.6 \text{ percent} \qquad (7\text{-}1)$$

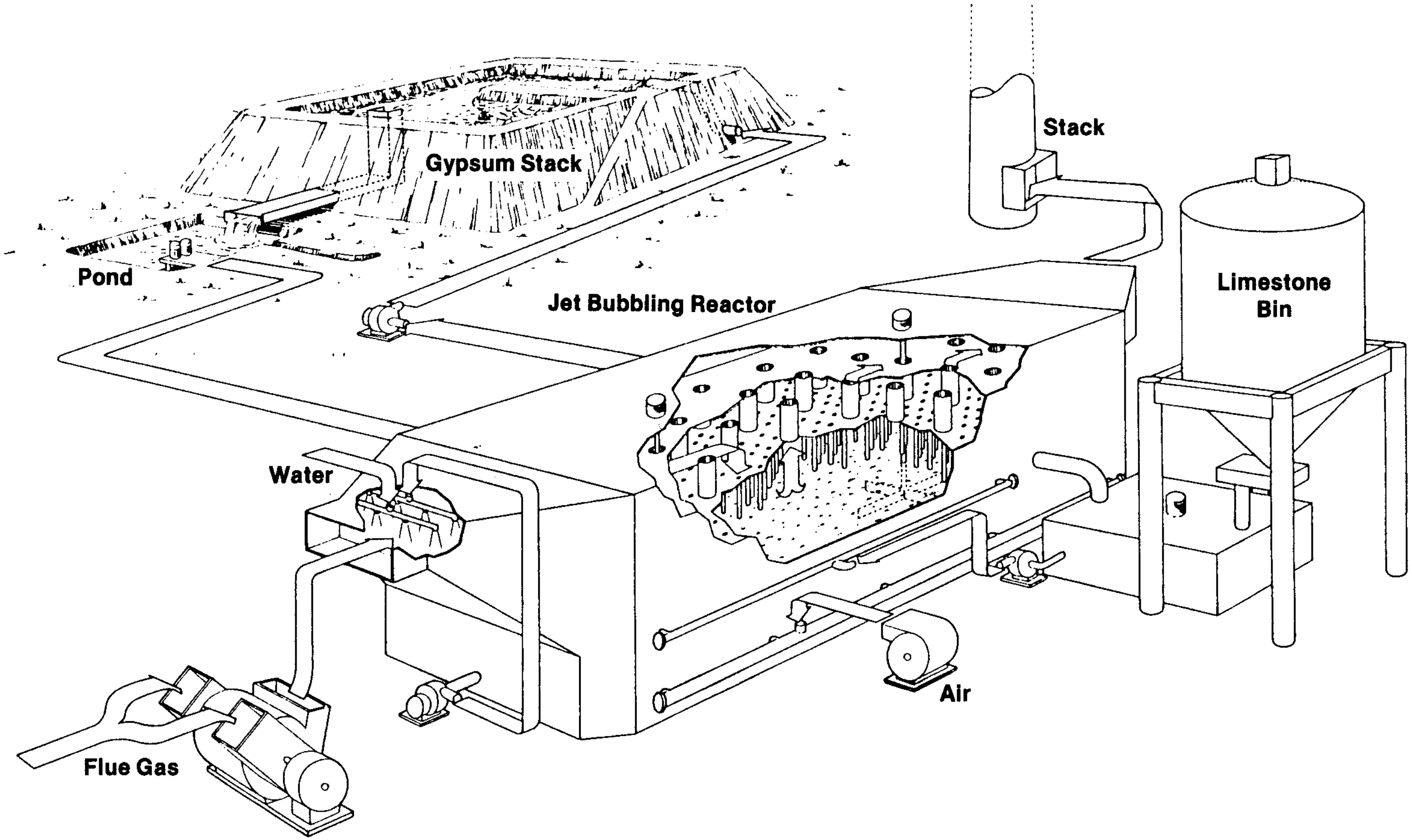

Figure 7-1
Chiyoda Thoroughbred 121 Flue Gas Desulfurization System With Gypsum Stack

It is emphasized that this figure is specific to the prototype unit and should not be used as a basis for estimating power requirements for a commercial unit. For example, large, new bituminous coal-fired boilers operating at or near sea level typically produce 2100 scfm of flue gas per MW_e generated. The two largest consumers of power in the prototype CT-121 system were the oxidation air compressor and the forced draft fan. The compressor and fan used in the CT-121 prototype were part of the original CT-101 demonstration unit and, as such, were not specifically tailored for the requirements of the CT-121 prototype unit.

Air Compressor

The two-stage air compressor, as discussed in Section 3, was designed for use with the CT-101 process. The adiabatic compression power requirement for a new compressor with a discharge pressure equivalent to 7.3 psig and with a capacity of 1000 scfm can be calculated from Eq. 7-2 (18).

$$\text{Adiabatic h.p.} = 0.00436\ Q_1 P_1 \left(\frac{K}{K-1}\right)\left[\left(\frac{P_2}{P_1}\right)^{\frac{(K-1)}{K}} -1\right] \qquad (7\text{-}2)$$

where

Q_1 = inlet gas flow rate = 1000 scfm (1600 Nm^3/hr)

P_1 = inlet pressure = 14.7 psia (0.1 MPa)

P_2 = discharge pressure = 22.0 psia (0.15 MPa)

K = ratio of C_p/C_v = 1.4 for air

The adiabatic power required by the new compressor would have been about 27 horsepower or 20 kilowatts. If a compressor efficiency of 60 percent is assumed, the actual power requirement would be about 33 kilowatts.

The measured compressor power consumption during the program was about 182 horsepower or 135 kilowatts. This excess power requirement was due to two factors. First, the compressor was oversized with 300-500 scfm of excess compressed air being vented to the atmosphere. Secondly, the output pressure of the first stage was higher than that required by the process. Consequently, the second stage of the compressor was used to throttle the pressure and the actual energy consumption was much higher than for a compressor designed for the CT-121 system. Thus, a decrease in compressor power consumption of about 78 percent might be expected in a commercial system which had a 7.3 psig output requirement from the compressor and air stoichiometries similar to those employed in the test program.

Forced Draft Fan

In Section 5, Table 5-4 indicates the total pressure drop for the prototype system was about 26 inches water gauge (66 cm H_2O) at 48,000 scfm flue gas flow. Of this, 3.4 inches (8.6 cm H_2O) was attributed to the mist eliminator, 12.4 inches (31.8 cm H_2O) pressure drop occurred across the JBR, and the remaining 10.2 inches (25.9 cm H_2O) was attributed to venturi and duct losses by difference. If the JBR pressure drop is assumed to be constant with minor increases in gas flow, the total system pressure drop would be about 27 inches (68.6 cm H_2O) at a flue gas flow of 50,000 scfm. Since the inlet pressure to the fan was about atmospheric, the power requirement was calculated to be about 410 horsepower (305 kW) using Eq. 7-3 (19).

$$\text{Shaft Power (h.p.)} = 0.000157 \frac{Q\Delta P}{\eta} \qquad (7\text{-}3)$$

where

Q = gas flow (acfm) = 73,000 acfm @ 300°F, 14.7 psia

ΔP = increase in pressure across the fan (inches water gauge) = 27

η = efficiency = 0.75

As shown in Figure 7-1, one of Chiyoda's commercial design concepts involves the use of a spray quench section instead of the venturi which was included in the prototype system. If the quench and duct losses could be reduced to 4 inches (10.2 cm H_2O) by using a spray quench, the fan power requirement could be reduced to about 314 horsepower (234 kW) since the total system pressure drop would be about 20 inches (51 cm H_2O). This represents a power savings of about 30 percent in the operation of the fan.

Summary of Overall Power Requirements

There are other areas where the power requirements for a newly designed and constructed system might differ from those observed with the prototype unit. For example, a spray quench would require a lower L/G and, therefore, a smaller horsepower pump than the venturi in the prototype. Furthermore, an agitation system designed for the prototype would require a smaller motor and the gypsum tank and mixer could have been eliminated. The overall potential power savings are presented in Table 7-1.

Table 7-1

SUMMARY OF POTENTIAL POWER SAVINGS

	Power Consumption (kW)	
	Actual	New Equipment
FD Fan	305	234
Air Compressor	135	33
Spray Quench Rather Than Venturi	30	11
JBR Mixer	22	7
Gypsum Tank Mixer	5	0
Other	53	53
Total	550	338

As shown in the above table, power savings of as much as 38 percent might have been realized for a newly designed and constructed prototype unit. The power consumption in this case might then be reduced to about 1.6 percent of the boiler output.

$$338 \text{ kW}/21 \times 10^3 \text{ kW} = 0.016 \text{ or } 1.6 \text{ percent} \qquad (7\text{-}4)$$

Limestone grinding is one area where the power requirements were not quantified during this demonstration. Since grinding facilities were not on site, limestone was purchased as a powder. Commercial limestone FGD units generally include limestone grinding, however.

It should be emphasized that the potential power savings itemized above are simply estimated for the prototype and are not intended for extrapolation to a commercial unit. Numerous factors including the duct work configuration, various motor efficiencies, the method for controlling gas flow, the method of solid waste dewatering and disposal, etc. must be considered in determining overall power requirements for a commercial unit.

SCALE UP CRITERIA

Chiyoda proposed to scale up the size of the prototype JBR according to the following two principal criteria:

- cross sectional area (number of spargers) - based on flue gas flow rate, and
- depth (or total volume) - based on inlet SO_2 concentration and removal rate.

Chiyoda plans to use the same proprietary flue gas sparger system in commercial units as that demonstrated at Scholz. The number of spargers will be adjusted based on the design gas flow rate so that the gas velocity through the sparger openings is comparable to that in the prototype unit. The data regarding sparger operation at Scholz should therefore be applicable to the scale-up to a commercial design with the diameter (or cross-sectional area) of the JBR dependent on the design flue gas flow rate. Chiyoda currently anticipates treating up to 200 MW of flue gas in a single JBR.

The JBR depth, and therefore total JBR slurry volume, are based on the removal rate of SO_2. Sufficient solid phase residence time will be allowed for gypsum crystal growth and prevention of the high relative saturations which can lead to scaling. It should be noted that Chiyoda has built 13 commercial CT-101 systems in Japan. This process involves the neutralization of sulfuric acid with limestone and subsequent gypsum production, which is similar to the precipitation of gypsum in the JBR in the CT-121 system.

From conversations with Chiyoda personnel, it is apparent that Chiyoda feels that the CT-121 system can be designed to operate successfully without spare modules. This has been their experience with the CT-101 system (20). From the evaluation program, it appears that design of such a system is possible from a process chemistry standpoint. Sufficient spare compressor, mixer, and pump capacity can reduce the chances of mechanical failures which could cause a reduction in the FGD system reliability. For instance, installation of multiple compressors for one module or for several modules could allow the CT-121 system to function with reduced SO_2 removal efficiency in the event of a compressor failure. Complete air failure, however, would force the module to be shut down. However, the recently promulgated NSPS regulations require a spare module for units over 125 MW if the owner wishes to bypass flue gas under strictly defined emergency conditions (21).

SLURRY MIXING AND SOLIDS STRATIFICATION

The cone bottom crystallizer from the CT-101 demonstration unit was modified for use as the prototype JBR at Scholz. The rapid gypsum settling rate and the cone bottom of the JBR necessitated close monitoring of the JBR underflow solids concentration to ensure that: 1) the solids inventory would not decrease to the point where scaling could occur in the froth zone, and 2) the underflow line would not plug. As is indicated in Figure 7-1, Chiyoda's current plans include a flat or gently sloping bottom rather than a cone bottom for the JBR. This approach should improve the solids mixing without increasing the agitator power requirement.

LIMESTONE SLURRY SYSTEM

Some changes may be made in the limestone slurry system. The use of JBR overflow as limestone slurry liquor worked quite well during the program, but this practice may not be included in all designs. The limestone may be instead slurried with pond return water in which case the overflow could still be collected in a surge tank to ensure both water balance and solids inventory are maintained. Alternately, a level activated pump could be used to control the JBR pressure drop at the desired setting by withdrawing excess liquid in the JBR.

In addition, in a commercial unit the limestone will probably be ground on site in a ball mill rather than purchased as a powder. Because of the low operating pH of the CT-121 process, high limestone utilization would be expected over a wide range of limestone particle sizes.

QUENCH AND WASH SYSTEMS

Chiyoda has designed and offered commercially a spray quench system rather than specifying a venturi as was used in the prototype unit. The advantages from a power consumption standpoint were discussed previously in this section (Forced Draft Fan discussion). However, the spray quench for a CT-121 system is a design consept which should be examined closely. The potential exists for solids buildup on the inside of the flue gas sparger tubes and a resultant restriction of gas flow if a wet-dry interface between the flue gas and the JBR gypsum slurry occurs. A quench system should be designed to ensure adequate gas cooling or an inlet chamber wash system should be included to keep the interior of the sparger tubes wet at all times.

A quench system which can use pond water would also be attractive especially if a gypsum stack is employed for solids disposal in a wet climate. If significant amounts of pond water are to be used, then the quench liquor flow must be sufficient to control the increased gypsum relative saturation due to evaporative concentration and/or to SO_2 sorption from the flue gas.

An alternate system could involve quenching with either JBR underflow or overflow. Sufficient flow would have to be maintained to ensure that gypsum scaling would not be a problem in the sparger tubes due to evaporation. While the slurry would include gypsum seed crystals which would assist in scale control, the solids build-up in the quench area may be more severe and washing the inlet gas chamber could require more attention. This approach is being examined by Chiyoda at their pilot unit in Japan.

FAN DESIGN AND PERFORMANCE

As with most FGD systems, there are two configurations for fan placement that might be used in a commercial design of the CT-121 system: 1) the forced draft configuration which was tested in the prototype evaluation program, and 2) the induced draft configuration.

Forced Draft Configuration

One aspect of operation with the forced draft configuration which merits further discussion is the response of the system to boiler load changes. The prototype system's response to simulated variable loads was good with respect to pH and SO_2 removal, but the response was somewhat sluggish with respect to liquid level changes, particularly for a partial load to full load increase. As discussed in Section 5 (Phase I results), the increased pressure in the outlet gas chamber caused by higher gas flows tends to force slurry over the weir until a new equilibrium pressure is established. As a result, the pressure drop across the prototype JBR rose on the order of one inch H_2O (2.5 cm H_2O) for a period of several minutes following an increase in flue gas flow from half load to full load (from 10 to 20 megawatts over 15 minutes). However, this change had little effect on prototype system performance (slightly higher power requirement and slightly higher SO_2 removal efficiency as a result of the increased pressure drop), and a commercial system could be designed to be more responsive to flue gas flow changes. One method of making the system more responsive would be to increase the width of the weir so that more rapid changes in the JBR slurry volume would be possible. Another solution might be to employ an alternate level control scheme where the slurry from the JBR froth zone is withdrawn through a pump via signals from a level sensor.

Control of JBR pressure drop in commercial systems will probably be simpler since increased flue gas flow (due to boiler load increases) will be distributed among several operating modules.

Induced Fan Configuration

Operation of the JBR in the induced draft fan configuration will be somewhat different than for the forced draft configuration. The effects of sparger pressure drop and slurry level are not compensating in the induced draft fan mode of operation as they are in the forced draft configuration (discussed in Section 5.0-Phase I, Variable Boiler Load Operation). Figure 7-2 will assist in this discussion.

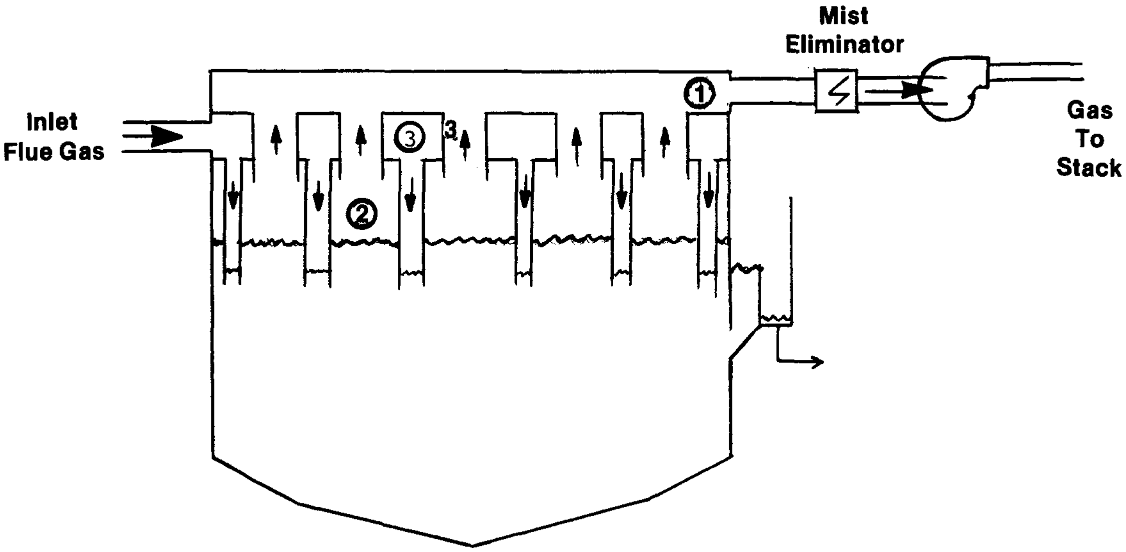

Figure 7-2
Effect of Induced Draft Fan on Effective JBR Slurry Levels

First, note that the liquid level in the JBR is higher than the weir setting since there is a negative gauge pressure in the JBR during operation in the induced draft configuration. Some surge capacity will therefore have to be provided in such a system during shutdowns. However, since such a surge tank is currently in Chiyoda's plans, providing the correct capacity will not present a problem. Also, during startup, additional liquor or slurry may have to be added to the JBR to quickly establish the working slurry height.

The differences in operation at high and low flue gas flow are perhaps more significant. If Figure 7-2 is examined, it is seen that the pressure at points 1 and 2 will be lower (more negative) at higher gas flows. Thus, the effective liquid level will be higher at higher gas flows. Since the pressure drop through the spargers is also higher at high gas flows, the pressure drop across the JBR will be substantially higher at high gas flows. The induced draft mode was not tested during the evaluation program. However, with the induced draft design, SO_2 removal efficiency at low gas flow conditions may not be as high as at high gas flows since there is no compensating effect between gas-liquid mixing and gas residence time. Unfortunately, the exact effect of the induced draft configuration on system performance cannot be predicted based on the results of this evaluation program.

Chiyoda has proposed using an automatic weir height control arrangement to respond to changes on the gas flow and SO_2 removal requirements. This approach would help alleviate the effect of gas flow on SO_2 removal for the induced draft configuration or could also be applied in a forced draft configuration to minimize the fan operating costs.

GYPSUM DISPOSAL

A number of solid-liquid separation and by-product gypsum disposal options exist for the CT-121 process. Gypsum produced by the CT-121 prototype unit was disposed of in a gypsum stack which was designed and constructed by Ardaman and Associates, Inc. based on experience gained in the phosphate industry. The results of the evaluation at Scholz indicate this disposal technique is feasible for a commercial unit. Vacuum filtration also appears to be a feasible alternative based on limited testing of a high speed rotary vacuum filter by Chiyoda. During these tests, JBR underflow was fed directly to the filter without any additional dewatering to produce a filter cake of 85 percent solids. Other disposal equipment or options such as centrifuging or simple ponding could also be used.

Chiyoda also conducted wallboard and cement utilization studies using the gypsum produced in the evaluation program. The conclusion of these tests was that the CT-121 gypsum is suitable for wallboard or cement manufacture. Furthermore, very little differences were said to exist between natural and the CT-121 gypsum (see Appendix J).

The principal statement that can be made concerning gypsum disposal at a commercial unit is that the CT-121 system produces a high quality gypsum that settles and dewaters extremely well and that numerous options are available for disposal. As a result maximum flexibility is afforded the commercial user to satisfy his site specific requirements.

Section 8

GYPSUM STACKING AND GROUNDWATER MONITORING

Two aspects of the test program encompassed the entire evaluation period rather than any particular phase of testing. These were the gypsum stacking experiment and the groundwater monitoring around the gypsum stack. The topics discussed in this section are also discussed in more detail in another EPRI report by Ardaman & Associates, Inc. (22).

GYPSUM STACK

Stacking of gypsum produced as a by-product in the phosphate fertilizer industry is a standard method of disposal. The application of this technique to calcium FGD sulfite sludges from systems has never previously been attempted due to the poor handling characteristics which result in part from the small particle size and the subsequent poor dewatering of the material. Gypsum produced by oxidation of the calcium sulfite settles and dewaters quickly, however, and will support a considerable load as it settles to about 70 percent solids in the stacking pond.

The actual gypsum stack is a fairly simple structure. Slurry is fed to a central area which generally has a decant pipe or perimeter pond to remove the supernatant liquor. Once this inner area is filled with solids, a dragline is used to dredge the material onto the dike walls. The solids are placed on the sidewalls of the stack which raises the height of the structure. This process is repeated as additional gypsum is added. Stacks over one hundred feet high have been constructed in the phosphate fertilizer industry.

At the beginning of the stack construction at Scholz, a pond was dug about seven feet deep which had an earthen divider dike separating the two halves. A vertical riser type of decant pipe was laid to transfer the liquid to the holding pond before it was pumped back to the CT-121 process. Figure 8-1 shows the stack in early November, 1978. Gypsum can be seen on the left side of the pond. Filling of the starter pond continued from December to February as seen in Figures 8-2 and 8-3.

Figure 8-1
Stacking Pond at Start of Program 11/15/78

Figure 8-2
Stack Being Walked On 12/15/78

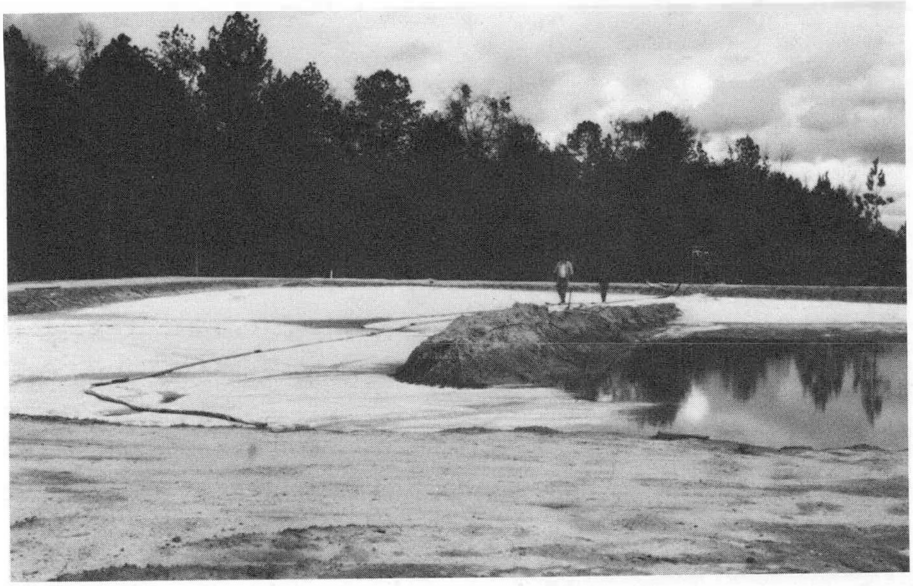

Figure 8-3
Starter Pond Nearly Full 2/3/79

Figure 8-4
Dragline in Operation 3/21/79

During the middle of March the pond was filled with gypsum and work on the stack began. Figure 8-4 shows the dragline positioned at the edge of the pond during the early stages of stack construction. Slurry below the water level was rather sloppy, requiring the center area to be pumped out to facilitate handling and stacking. Figure 8-5 presents the before and after configuration of the stack. The stack was made smaller than originally planned because of less than design rates of gypsum production due to a lower sulfur concentration in the coal than expected. The dike walls started to take shape as seen in Figure 8-6; groundwater monitoring wells are seen in the foreground. Figure 8-7 shows the final polishing of the stack as the top was leveled during the first raising. As can be seen, the dike supports the weight of a small grader easily. During the subsequent work, the dragline also operated from both the east and west dikes.

Prior to raising the stack a second time, the gypsum was allowed to drain for a few days by routing the fresh slurry to the perimeter pond. This made handling significantly easier. Figure 8-8 shows the full stack prior to the second raising. After excavation, the interior of the stack was ready to be refilled, as seen in Figure 8-9.

Sloughing of the outer walls of the stack occurred at this time due to several causes. First, the slope of the walls was fairly steep and secondly, the base of the dike was not very thick. The difference in head (about 10 feet) between the stack water level and the perimeter pond was causing water to flow through the walls. Flow was noticed at the base of the stack as seen in Figure 8-10. The effects of this flow on the north is shown in Figure 8-11.

During the second raising, the slope of the walls was decreased and the base widened. These changes in the stack design seemed to alleviate the sloughing problem. Gypsum produced during the particulate testing period was stacked on the south wall in order to keep it separated from the rest. The wet fly ash-sludge mixture was not very structurally stable and did not dewater well. Once it was raised above the water level and drained, however, it became solid. Figure 8-12 shows the stack at the end of Phase II prior to the final raising. Figures 8-13, 8-14, and 8-15 show the east, west, and north walls at the end of the EPRI portion of the program. Sloughing is much less than previously observed.

At the end of Phase III, the stack was again full. However, this time it was not raised. Pond water was recirculated over it for a two month aging period and then stopped. The stack will be analyzed after one year to determine is structural

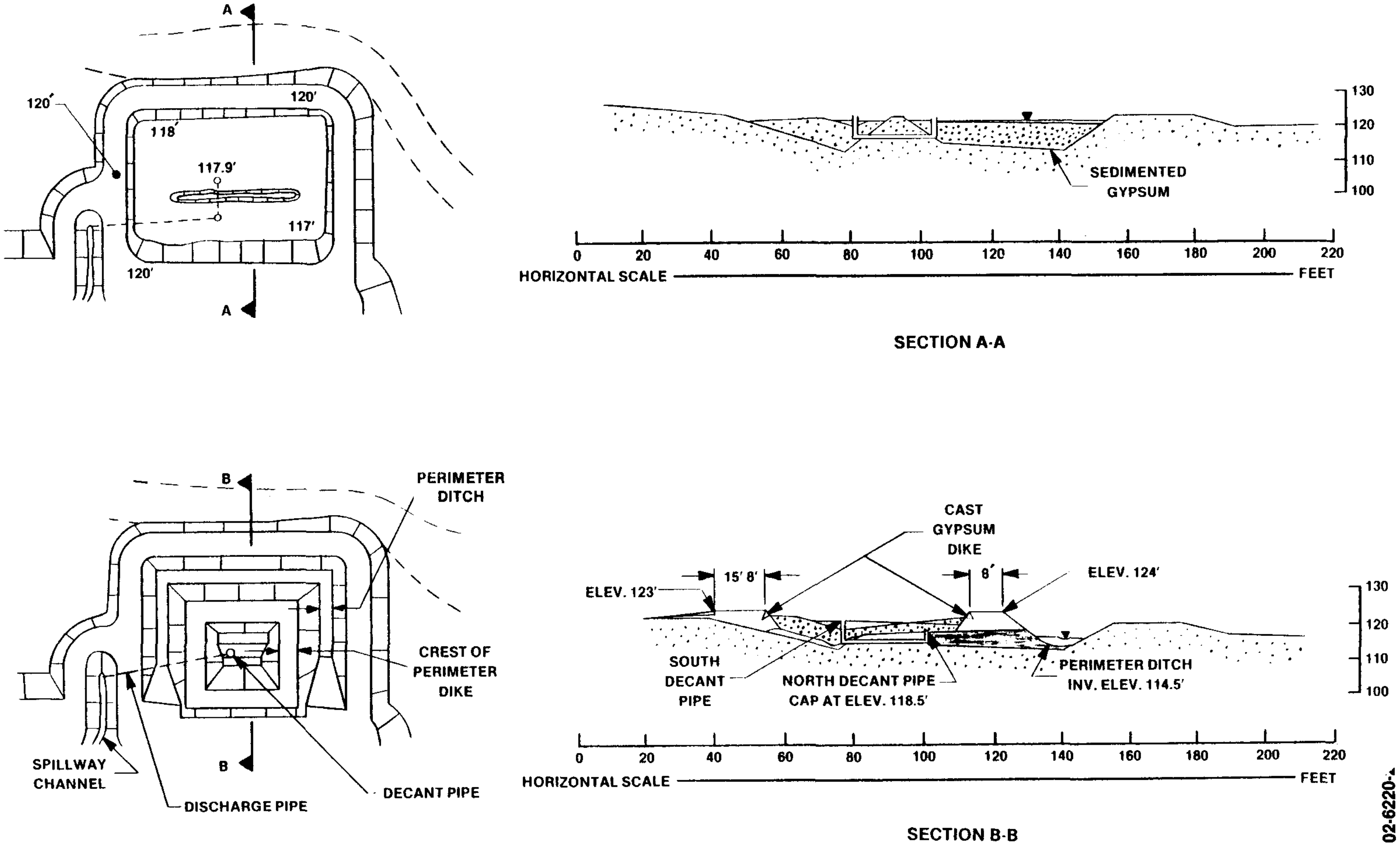

Figure 8-5
Gypsum Stack Site Plan and Cross-Section Before and After Raising Perimeter Dike

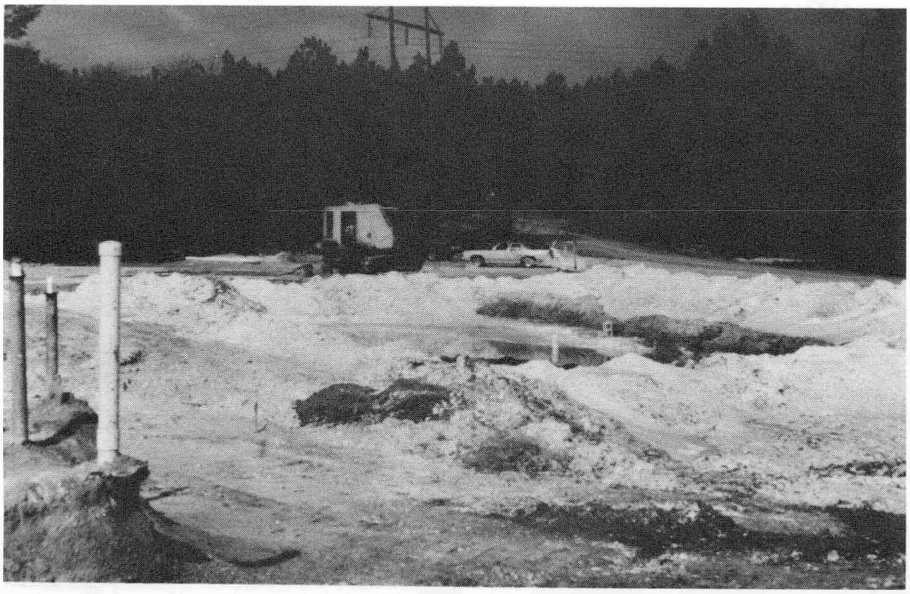

Figure 8-6
Forming Walls of Stack 3/22/79

Figure 8-7
Leveling Top of the Stack 3/27/79

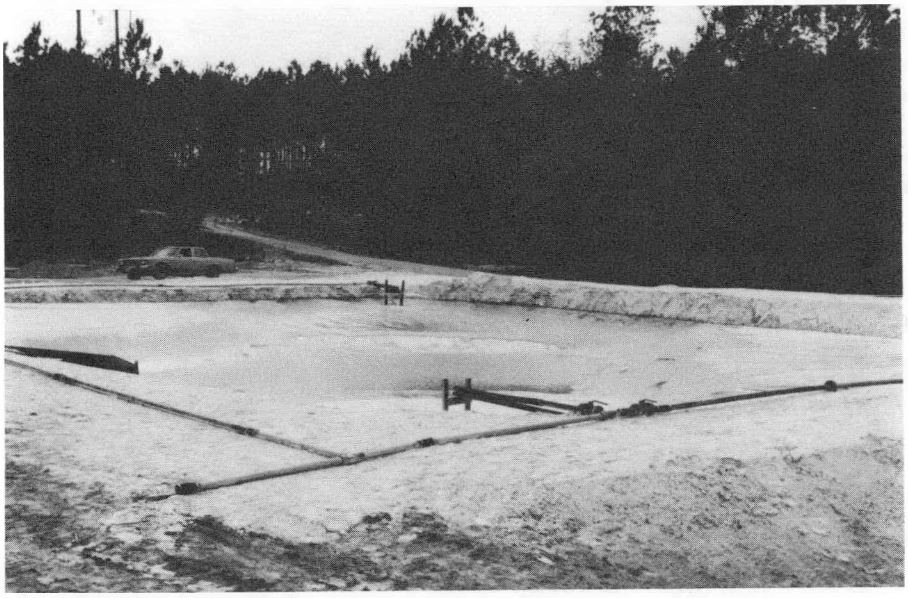

Figure 8-8
Prior to Second Stack Raising 4/13/79

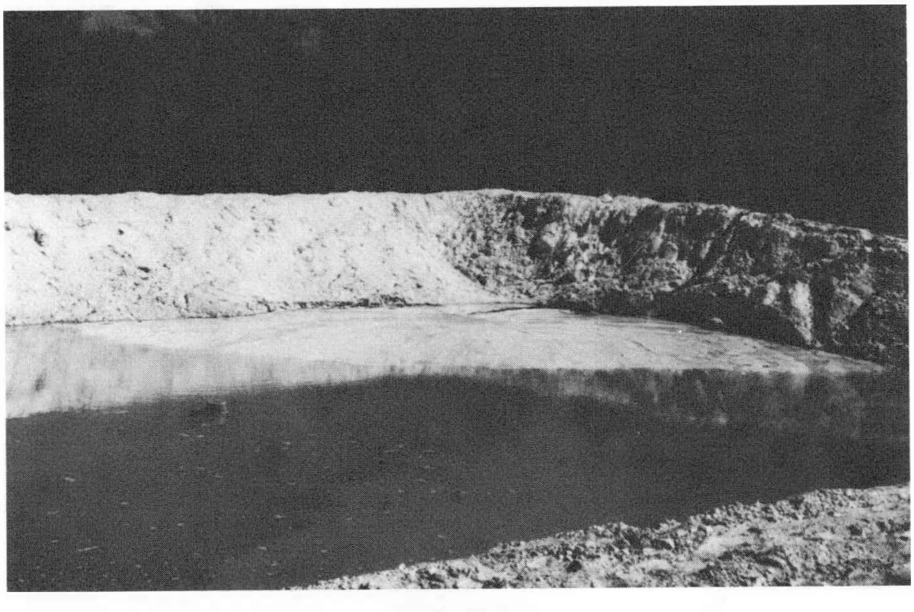

Figure 8-9
Filling Stack After Raising Walls 4/20/79

Figure 8-10
East Wall Sloughing At Water Line 4/27/79

Figure 8-11
North Wall Sloughing 4/27/79

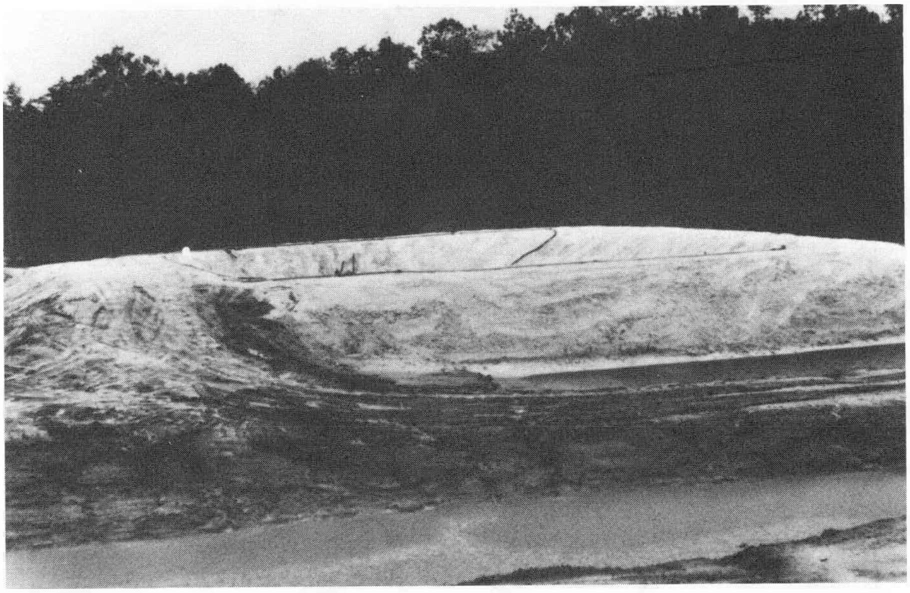

Figure 8-12
Filled Stack

Figure 8-13
East Wall 5/22/79

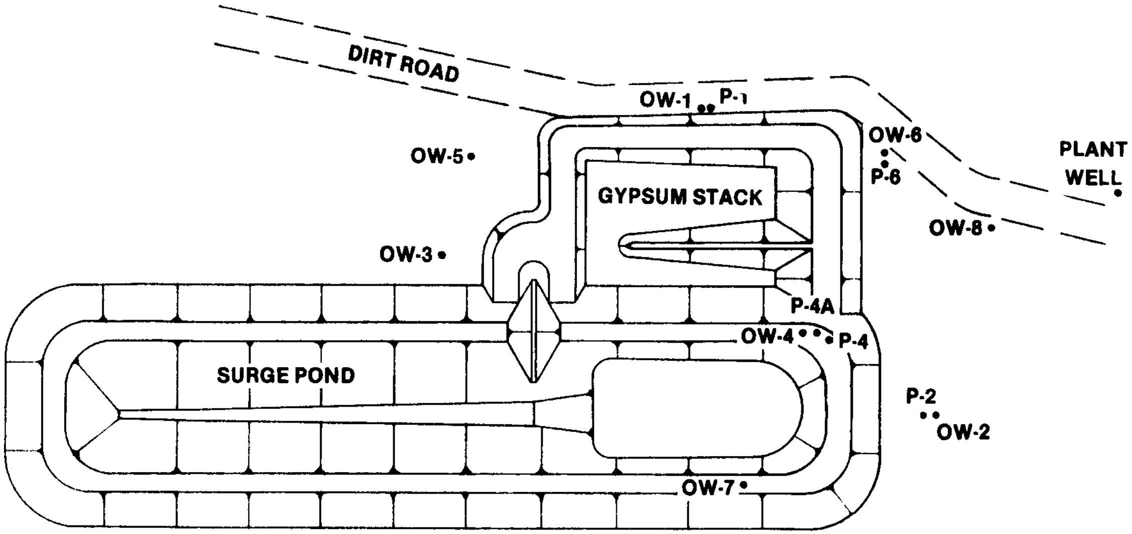

Figure 8-16
Groundwater Monitoring Wells Locations

However, four wells downstream of the stack have shown increases in calcium, sulfate, and total dissolved solids with time. These wells are OW-2, OW-6, P-4A, and P-6. Figure 8-17 shows the results of these three analyses for well OW-6 over the course of the program. Plots for all the wells, major species analyses and trace element values are given in Appendix G. Additional sampling of these wells during the one year aging period for the stack is planned. Further discussion of the groundwater flow and infiltration of the process water is given in the Ardaman report.

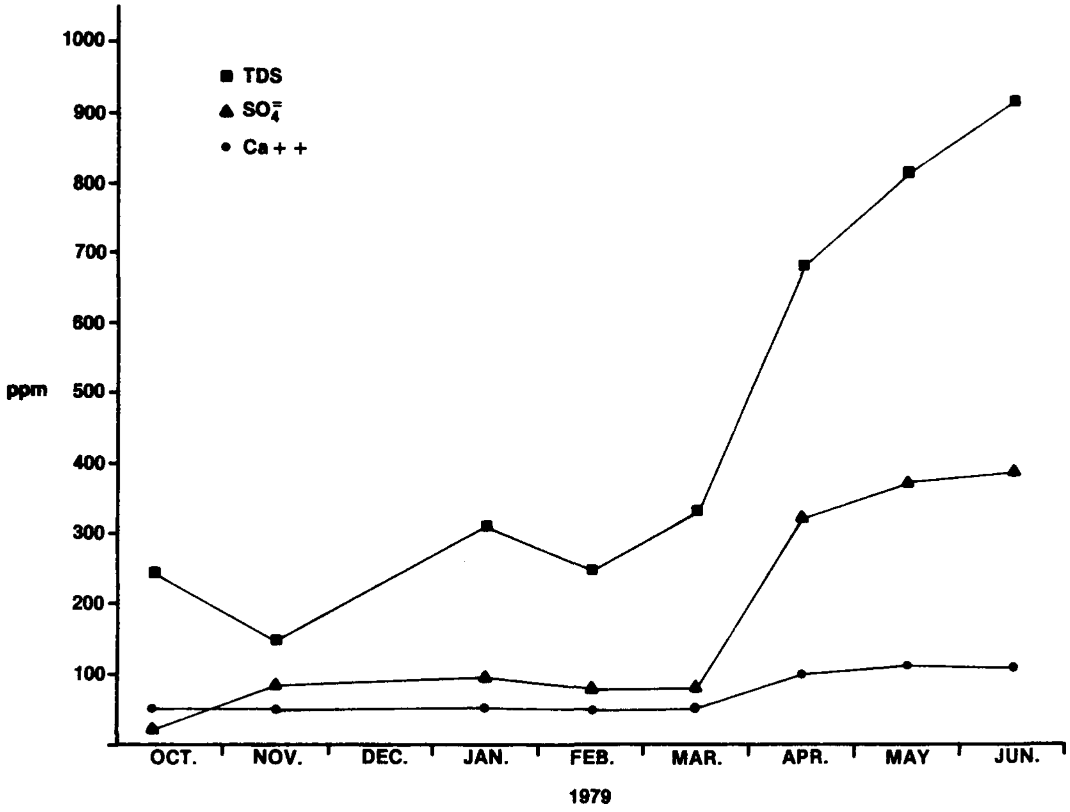

Figure 8-17
Ca, SO_4 & TDS Concentrations For Observation Well 6
During The Evaluation Program

Section 9

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