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LIME/LIMESTONE SCRUBBING FOR SO_2 AND PARTICULATE REMOVAL IN A MARBLE BED SCRUBBER

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LIME/LIMESTONE SCRUBBING FOR SO_2 AND PARTICULATE REMOVAL IN A MARBLE BED SCRUBBER

by

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ABSTRACT

The Environmental Protection Agency (EPA) awarded a contract to Combustion Engineering, Inc. (C-E) to conduct research and development work on SO_2 scrubber systems using the C-E test equipment and facilities.

Sixteen once-through soluble system tests using sodium carbonate scrubbing solution were conducted. The results showed that the marble bed scrubber is a very good liquid-gas contacting device for SO_2 removal from flue gases with an overall efficiency of 90 to 95 percent. Liquid to gas ratio and scrubber liquid composition significantly affected the SO_2 removal while other variables had little or no effect on SO_2 removal.

Six limestone furnace injection systems tests were conducted using boiler calcined limestone and flyash mixture. The results also showed that solids concentration in the spray slurry and liquid to gas ratio significantly affected the SO_2 removal.

Six limestone tail-end system tests were conducted using commercial limestone in a dual marble bed scrubber. It was determined that the SO_2 removal efficiencies of the low and upper beds are the same, based on the SO_2 concentrations entering the respective beds.

It was demonstrated that scale-free operation of both the furnace injection and tail-end systems can be achieved in a closed loop system without employing the liquid blowdown by maintaining 8 to 10% solids in the spray slurry.

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SECTION 1

PROGRAM OVERVIEW

1.1 INTRODUCTION

Combustion Engineering (C-E) has developed an Air Pollution Control System (APCS) employing lime/limestone wet scrubbing. At the time of contract negotiations between C-E and EPA in 1970, the C-E APC systems at Union Electric (St. Louis) and Kansas Power and Light (Lawrence) were experiencing calcium sulfite and sulfate scaling problems.

The purpose of the contract was to analyze the previous C-E APCS data and to conduct research and development on small pilot scale (KDL pilot plant), large pilot scale (KDL prototype), and full plant scale versions of C-E lime/limestone wet scrubbing process (limestone furnace injection system with single marble bed scrubbers) in order to accelerate its commercial development by solving the calcium sulfite and sulfate scaling problems. The original purpose of the contract was later revised to include the following:

(1) Confirm the adequacy of the methods developed by C-E to control calcium sulfate and sulfite scaling in the system.

(2) Obtain the vapor-liquid and solid-liquid mass transfer rate data that could be used in the design of the APCS.

(3) Predict two marble bed scrubber system performance from the performance of a single marble bed scrubber system.

Experimental work under the contract was carried out on the prototype scrubber system at the Kreisinger Development Laboratory (KDL) of Combustion Engineering in Windsor. Three kinds of systems were studied: (1) once through Soluble System using sodium carbonate scrubbing solution, (2) Limestone Furnace Injection System using boiler calcined limestone and flyash mixture as the additive, and (3) Limestone Tail-End System.

The Soluble System tests were run to obtain data pertaining to the absorption characteristics of the marble bed scrubber. Since no solids were present in the system, material balances could be made more accurately for the marble bed and overall system. This information was then used to calculate the stage efficiency of the marble bed for various test conditions.

In order to develop a better understanding of the Limestone Furnace Injection System and Limestone Tail-End System, detailed material balances were carried out for all of the tests run. These material balances permitted the calculation of dissolution and precipitation rates for important chemical species in the marble bed and associated equipment. Supersaturation of sulfur compounds was also investigated using these test data and the equilibrium computer program.

1.2 SUMMARY OF RESULTS AND CONCLUSIONS

1.2.1 Previous C-E APCS Data

EPA was supplied with the technical information generated by C-E in previous and current APCS development work. This information consisted of reports covering the work on the KDL Prototype and the field units at Detroit Edison Company, Union Electric Company, and Kansas Power and Light Company. An oral presentation was made on October 13, 1971 in Windsor by C-E personnel to EPA and Radian Corporation personnel covering C-E's experience with Air Pollution Control Systems both in the field and in the laboratory.

The objective was to analyze previous C-E APCS data and use this data in the development of a test program to be carried out on the KDL Prototype. The purpose of this program was to determine a set of optimum operating conditions for improving the operation of C-E APCS field units. Radian and EPA concluded that the previous C-E APCS data were incomplete and could not be used in the development of the KDL Prototype test program.

1.2.2 Collection and Storage of Boiler Calcined Material

A mixture of boiler calcined limestone and flyash was used in six tests conducted on the KDL prototype. Considerable effort and funds were expended in the collection and storage of the boiler calcined material. The boiler calcined material and flyash were collected from unit No. 2 of the Meramec plant of Union Electric Company, St. Louis. About 30 tons of boiler calcined limestone and flyash mixture, 65 tons of boiler calcined dolomite and flyash mixture, and 50 tons of flyash was stored in 50 lb bags in the warehouse of Pozament Corporation in Milford, Connecticut. About 135 tons of boiler calcined limestone and flyash mixture was initially stored in North Haven, Connecticut for six months in a silo rented from Guyott Co. (owned by

Connecticut Highway Equipment Co.) and was later transferred to Pozament Corporation. Only a small fraction of this boiler calcined material was used and the leftover material was disposed of as instructed by EPA personnel.

1.2.3 Soluble System Tests

Soluble System experiments were performed to determine the vapor-liquid mass transfer characteristics (overall tray efficiency) of the marble bed scrubber using once-through sodium carbonate scrubbing solution. These tests showed that:

(1) The marble bed scrubber is a good liquid-gas contacting device with an overall tray efficiency of 90 to 95 percent.

(2) The SO_2 removal in the marble bed scrubber is limited by the vapor-liquid equilibrium.

Liquid to gas ratio (L/G) and the scrubber liquor composition strongly influence the SO_2 removal. For example, increasing L/G from 15 to 20 GPM per 1000 CFM raised SO_2 removal from 60% to 77%. Increasing the sodium carbonate concentration in the scrubber from 25 to 120 millimoles per liter raised the SO_2 removal from 64% to 95%. Variables such as gas and liquid temperatures, scrubber feed location (above or below the bed) and gas flow do not seem to affect the SO_2 removal. No NO_x removal can be obtained with sodium carbonate scrubbing solution.

1.2.4 Limestone Furnace Injection System Tests

Limestone Furnace Injection System experiments were performed to determine the system performance and the solid-liquid mass transfer characteristics in the marble bed scrubber and the hold tank (reaction tank) using boiler calcined limestone and flyash mixture as the additive.

These tests showed that the major parameters influencing the SO_2 removal of the system are liquid to gas ratio and the solids content of the spray slurry. An increase in L/G from 20 to 35 GPM/1000 CFM improved SO_2 removal from 60 percent to 70 percent with other factors held constant. SO_2 removal was improved from 36 percent to 68 percent by increasing the solids content of the spray slurry from 0.7 percent to 3.5 percent. Further increases in slurry concentration up to 8 percent did not result in additional improvement in SO_2 removal.

Calcium sulfate scaling in the Furnace Injection System can be prevented by maintaining the relative supersaturation of this material below 1.3. This was achieved in a closed loop system with no liquid blowdown by maintaining 8 percent total solids (including flyash) in the spray slurry. Calcium sulfite scaling, on the other hand, occurs in the scrubber when the spray slurry pH reaches 11 with CaO or $Ca(OH)_2$ solids entering the scrubber.

1.2.5 Limestone Tail-End System Tests

The Limestone Tail-End System tests were performed in order to determine whether two marble bed scrubber performance (SO_2 removal and scaling) can be predicted by extrapolating the single marble bed scrubber performance of the C-E scrubber at Shawnee (EPA test facility). Information concerning the solid-liquid mass transfer characteristics in the marble bed scrubber and the hold tank was also desired.

The tests revealed that the SO_2 removal efficiency and scaling tendencies of a scrubber with two marble beds can be predicted by extrapolating single bed test results at Shawnee. The SO_2 removal efficiencies of the lower and upper beds appear to be the same based on the SO_2 concentrations entering the respective beds. SO_2 removal can be improved significantly (from 76 percent removal to 87 percent removal) by increasing L/G from 15 to 25 GPM/1000 CFM with other factors held constant. Limestone feed rates above 100% stoichiometry have little or no effect on SO_2 removal efficiency in high solids systems. In these tests more than half the additive dissolution occurs in the marble bed in spite of the short residence time there.

Calcium sulfate scaling can be controlled in the system by maintaining the relative supersaturation level below 1.7. This can be achieved in a closed loop system without employing liquid blowdown by maintaining 8 to 10 percent solids (excluding flyash) in the spray slurry.

1.3 TEST EQUIPMENT

1.3.1 General Description

The Prototype is located at Kreisinger Development Laboratory of Combustion Engineering, Inc. in Windsor, Connecticut. A schematic of the system is shown in Figure 1-1. The system consists of all components of the C-E field units.

The flue gas from an oil fired boiler (30,000 to 40,000 pounds of steam per hour) passes through a heat extractor in which the gas can be cooled down to any desired temperature between 150 and 300°F before entering the scrubber. The flue gas from the heat extractor passes through the scrubber inlet section, marble beds, demister, and reheater before entering the stack. The scrubber inlet section is about 8 ft. long and converges towards the scrubber. Provisions are made for introducing either flyash or additive or both into the inlet either to simulate coal firing or furnace injection. The inlet is kept from plugging with deposits by the periodic operation of a soot blower.

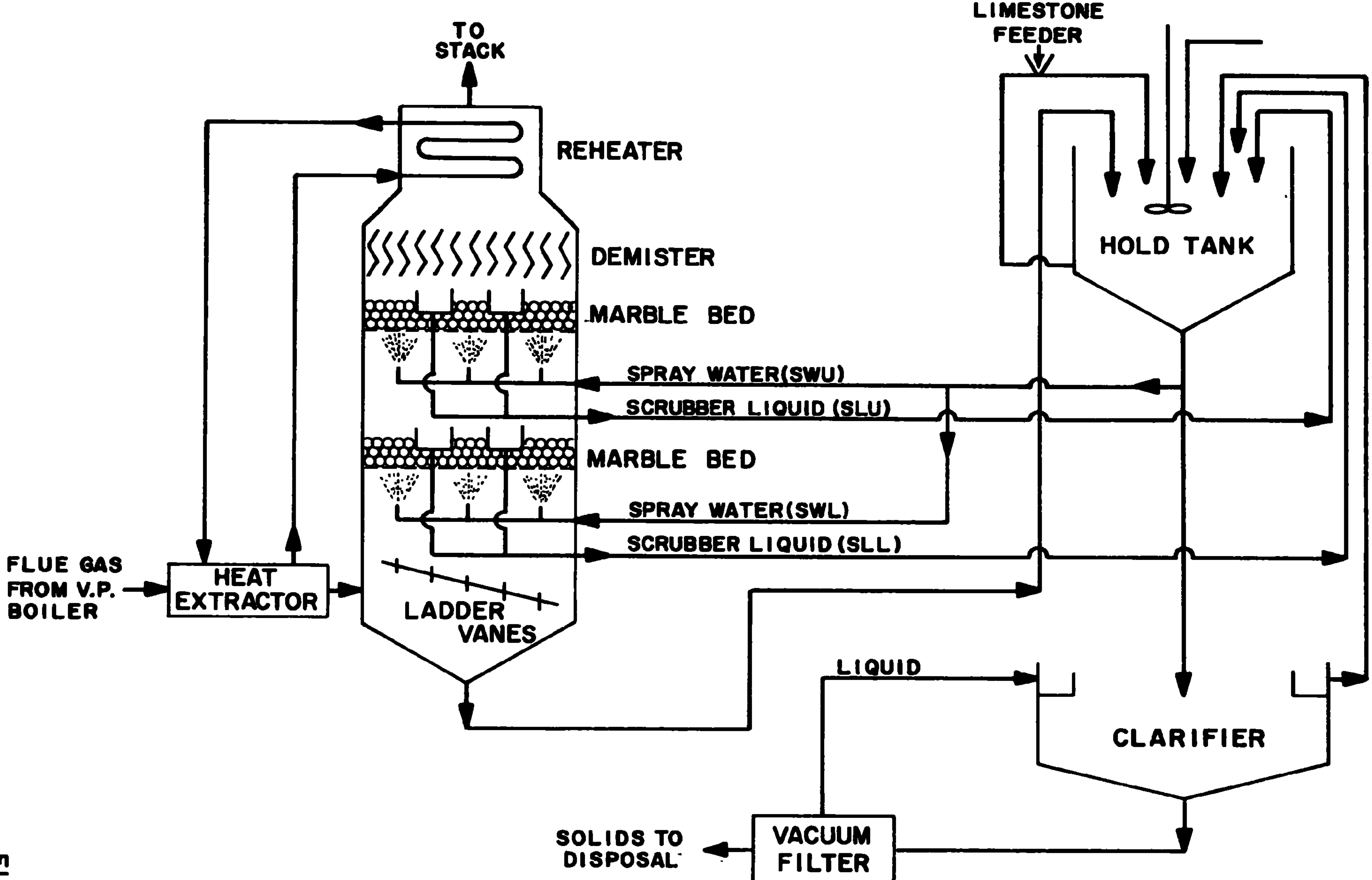

FIGURE 1-1

CE AQCS PROTOTYPE

The marble bed consists of a 5 ft. by 5 ft. perforated, stainless steel plate supporting 3/4 inch diameter glass spheres (marbles) 3 inches deep; five overflow pots of 10 inch diameter; and five downcomers of 3 inch pipe. The overflow and pot height controls the turbulent layer height and is usually set at 9 inches from the perforated plate, but can be varied by making some minor changes. A stainless steel perforated plate with 3/8 inch holes and 35 percent open area supports the marbles. There are 36 commercial spray nozzles under the bed and 8 nozzles consisting of 1 inch pipes with splash plates above the bed. The spray slurry or spray liquid can be introduced either under or above the bed or both. There are two marble beds in the scrubber. The upper bed can be removed from the scrubber when it is not needed.

The chevron type demister made of stainless steel separates the entrained liquid from the gas and prevents the reheater from plugging. The gas leaving the scrubber is heated 25 to 50°F in the reheater to protect the I.D. fan.

Clarified liquid from the clarifier or the reaction tank (hold tank) effluent can be used as spray water or spray slurry. Make-up water and additive for the soluble and tail-end systems are added to the hold tank.

1.4.2 Flow Measurement

Liquid flow in the system is measured by magnetic flow meters which are calibrated both electrically and by manually measuring the flow. For the manual calibration, the hold tank is filled with water and the flow through the flow meter is set at a particular value. Water levels in the hold tank at the beginning and end of the calibration procedure are noted and the flow meter reading is checked against the flow rate obtained from the difference in water level in the hold tank.

Additive feed rate is controlled by using Wallace & Tiernan feeders. These feeders are calibrated both by using the calibration weights and by weighing a collected sample from the feeder. The manual sample is checked against the feeder reading.

Gas flow is measured with a pitot tube located at the center of the duct in the stack after the I.D. fan. The single point pitot tube gas flow measuring technique was checked against the multiple point pitot tube traverse and the SO_2 tracer gas method. The gas flow check is given in detail in Appendix A.

SO_2 concentrations were measured using both the manual method and the Dupont 400 Photometric Analyzer. The manual method consists of absorbing SO_2 gas into 3 weight percent H_2O_2 solution and titrating with 0.1N (for the inlet sample) and 0.01N (for the outlet sample) NaOH solution. The Dupont Analyzer was calibrated with SO_2 gas from standard gas cylinders. The gas cylinder concentrations were also verified by the manual method described.

SECTION 2

ONCE-THROUGH SOLUBLE SYSTEM TESTS

2.1 TEST DESCRIPTION

The objective of the once-through soluble system tests was to determine the vapor-liquid mass transfer characteristics (overall tray efficiency) of the marble bed scrubber using sodium carbonate scrubbing solution.

The operation of the KDL Prototype for the once-through soluble system tests is schematically represented in Figure 2-1. Flue gas from the package boiler (burning oil) entered the scrubber after it passed through a heat extractor. The flue gas was cooled to any desired temperature between 150 and 300°F in the heat extractor. Sulfur dioxide (SO_2) gas was added to the flue gas in order to increase the scrubber inlet SO_2 concentration to approximately 2,000 PPM (0.2 mole %). The flue gas passed through the marble bed and the turbulent layer where it was in contact with the scrubbing liquor. The flue gas left the system after passing through a demister and a reheater.

Scrubbing liquor was prepared by mixing solid sodium carbonate (Na_2CO_3) and well water in the hold tank. The hold tank of approximately 6,000 gallon capacity represented an average residence time of 30 to 40 minutes for most of the soluble system tests. Thus, fluctuations in the scrubber liquor composition due to minor fluctuations in the solid Na_2CO_3 feed to the hold tank could be assumed negligible. Scrubber liquor (Na_2CO_3 solution) was introduced into the scrubber through 36 spray nozzles under the bed and/or through eight pipes with splash plates at the end above the bed. The bed reject was drained through the scrubber bottom while the liquid from the turbulent layer was drained through the overflow pot-downcomer arrangement.

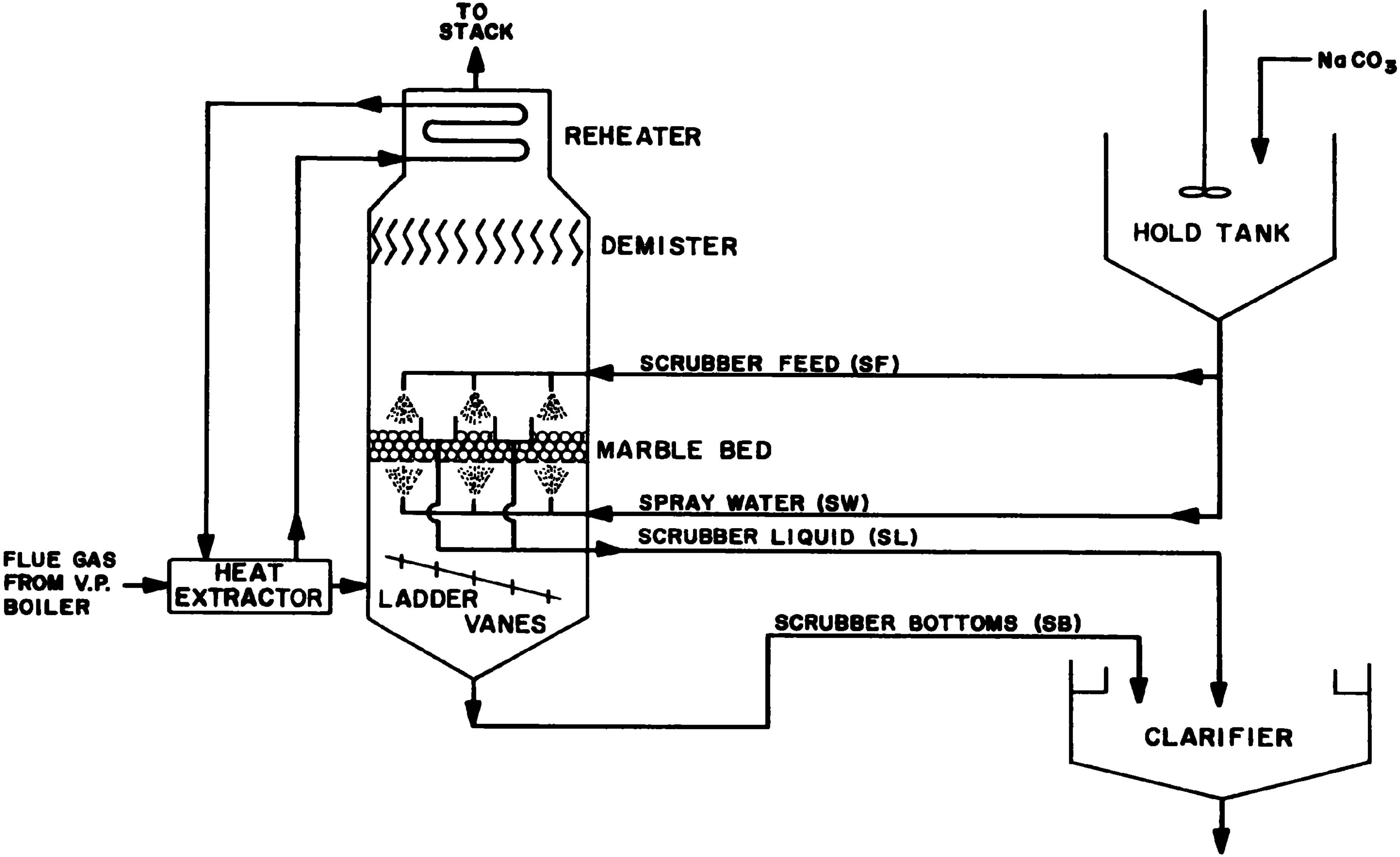

FIGURE 2-1

ONCE THROUGH SOLUBLE SYSTEM

Liquid from the downcomers and the scrubber bottoms was pumped out of the system through the clarifier which was used as a liquid disposal tank during the once-through soluble system tests. Scrubber bed height or turbulent layer height was varied by varying the overflow pot height.

The test program for the soluble system tests was designed to study the effect of operating parameters such as gas flow rate, liquid flow rate, liquid to gas ratio, scrubbing liquor composition and temperature, scrubber inlet gas temperature and scrubber bed height on the vapor-liquid mass transfer characteristics of the marble bed scrubber. The proposed test program is shown in Table 2-1. Actual test conditions and test data are given in detail in Appendix B and are very nearly the same as the proposed test conditions given in Table 2-1.

2.2 DATA EVALUATION

2.2.1 System Performance

The test data and results are given in detail in Appendix B. Several runs were repeated because the total sulfur material balance did not close within ± 10%. The data and results of the runs for which the material balance did not close within ± 10% are not given in this report. Gas flow checks, as described in Appendix A, and liquid flow calibration checks were made periodically.

In all the runs except run 10R the overflow pot height was set at 9 inches from the perforated plate. At this setting the bed drained normally with most of the water draining through the overflow pots and downcomers, and with very little water draining through the bed itself. But, in run 10R, the overflow pot height was set at 15 inches from the perforated plate. Seepage through the bed was excessive; about 95% of the water drained through the bed while only 5% drained through the overflow pots. This was

TABLE 2-1. TEST PARAMETERS
FOR THE SOLUBLE SYSTEM

Experiment Number	Comments	FG Rate (ACFM)	SF Rate (GPM)	SF Composition M Moles/Lit.	SW Rate (GPM)	SW Composition M Moles/Lit.	Inlet Gas Temperature (°F)	Scrubber Bed Height (inches)	Hold Tank Temp. (°F)
1R	Low Gas Temp.	11,000	55	25	110	25	225	9	110
2R	SF Only	11,000	165	25	0	25	300	9	110
3R	SW Only Amb. Liq. Temp.	11,000	0	25	165	25	300	9	70
4R	SW Only	11,000	0	25	165	25	300	9	110
5R	High Gas Flow	13,000	55	25	110	25	300	9	110
6R	Low Gas Flow	9,000	55	25	110	25	300	9	110
7R	High L/G	11,000	70	25	150	25	300	9	110
8R	Low L/G	11,000	35	25	75	25	300	9	110
9R	Base Cond.	11,000	55	25	110	25	300	9	110
10R	High Bed Ht.	11,000	55	25	110	25	300	15	110
11R	SW Only Amb. Liq. Temp.	11,000	0	120	165	120	300	9	70
12R	Base Cond.	11,000	55	120	110	120	300	9	110
13R	Base Cond.	11,000	55	35	110	35	300	9	110
14R	Low L/G	11,000	35	35	75	35	300	9	110
15R	High Gas Flow	13,000	55	35	110	35	300	9	110
16R	Low Gas Flow	11,000	55	35	110	35	225	9	110

Note: Inlet SO_2 is 2000 PPM

because the gas could not support a high enough turbulent layer to facilitate bed drainage through the overflow pots. Also, it was observed that the seepage through the bed increased when the scrubbing liquor was introduced into the scrubber above the marble bed rather than under the marble bed.

The results show that liquid to gas ratio (L/G) and scrubber liquor composition significantly affect the SO_2 removal in the scrubber. For example in experiments 4R and 7R while keeping other conditions the same, an increase in L/G from 15 to 20 GPM/1000 CFM resulted in SO_2 removal increase from 60 to 77%. Furthermore, an increase in liquor composition from 25 to 120 m moles/lit result in an increase in SO_2 removal from 64 to 95%. The other variables such as gas and scrubbing liquor temperatures, gas flow and feed location do not seem to have significant effect on SO_2 removal in the marble bed scrubber. The inlet and outlet NOx concentrations given in Appendix B are approximately the same within the accuracy of the experimental measurements. Therefore, it can be concluded that no NOx removal can be obtained with sodium carbonate scrubbing solution.

2.2.2 Sampling and Analytical Methods

The pH measurements were made with a SS-3 Zeromatic Beckman pH meter, which was carefully standardized and temperature compensated. The pH meter was always located 1 to 2 feet away from the sample points for better pH representation of the sample. The sample temperatures were measured with a mercury thermometer during sampling.

Samples were pumped through a Millipore filter holder (142 mm in diameter) and filtered through a 1μ Millipore membrane. The filtering equipment was set up 4 to 5 feet away from the sampling point to minimize the transport time between the sample point and filtration. The greater the transport time the greater the chance for oxidation of sulfite to sulfate. A screw type pump was used to transport the sample isokinetically.

The analytical methods are given in detail in Appendix D. The analytical procedures used by Combustion Engineering (C-E) and Radian Corporation are different. At the instructions of the EPA project officer, the sulfite analysis was made using Radian's procedure although it is more laborious and time consuming than C-E's method. Sodium and total sulfur analyses were made using C-E's method. In a few runs, sulfite analysis was made using both the C-E and the Radian methods to compare the accuracy of the two methods. The liquid phase analytical results given in Appendix C show that the C-E and Radian methods are comparable in results.

2.2.3 Analytical Results

The liquid phase analytical results and pH's are given in Appendix C. The preliminary tests showed that the marble bed liquor composition was not uniform over the entire cross-section of the marble bed. This probably resulted from non-uniform gas distribution to the marble bed.

The scrubber liquor discharges through three downcomers as shown in Figure 2-2. In order to determine which downcomers should be sampled to get a reasonable value for the concentration of sulfite ($SO_3^=$ + HSO_3^-) in the bed, all the three downcomers were sampled for a few runs. Based on the results of these runs, it was decided to sample the downcomers from both sides of the bed for sulfite and average the results to obtain the values for the concentration of sulfite in the bed. All other analyses for the bed liquor composition were made on pump discharge from the surge tank. The pump discharge is a good average of the three downcomers, since all three downcomers discharge into the surge tank, from which liquor is pumped to the clarifier tank for disposal.

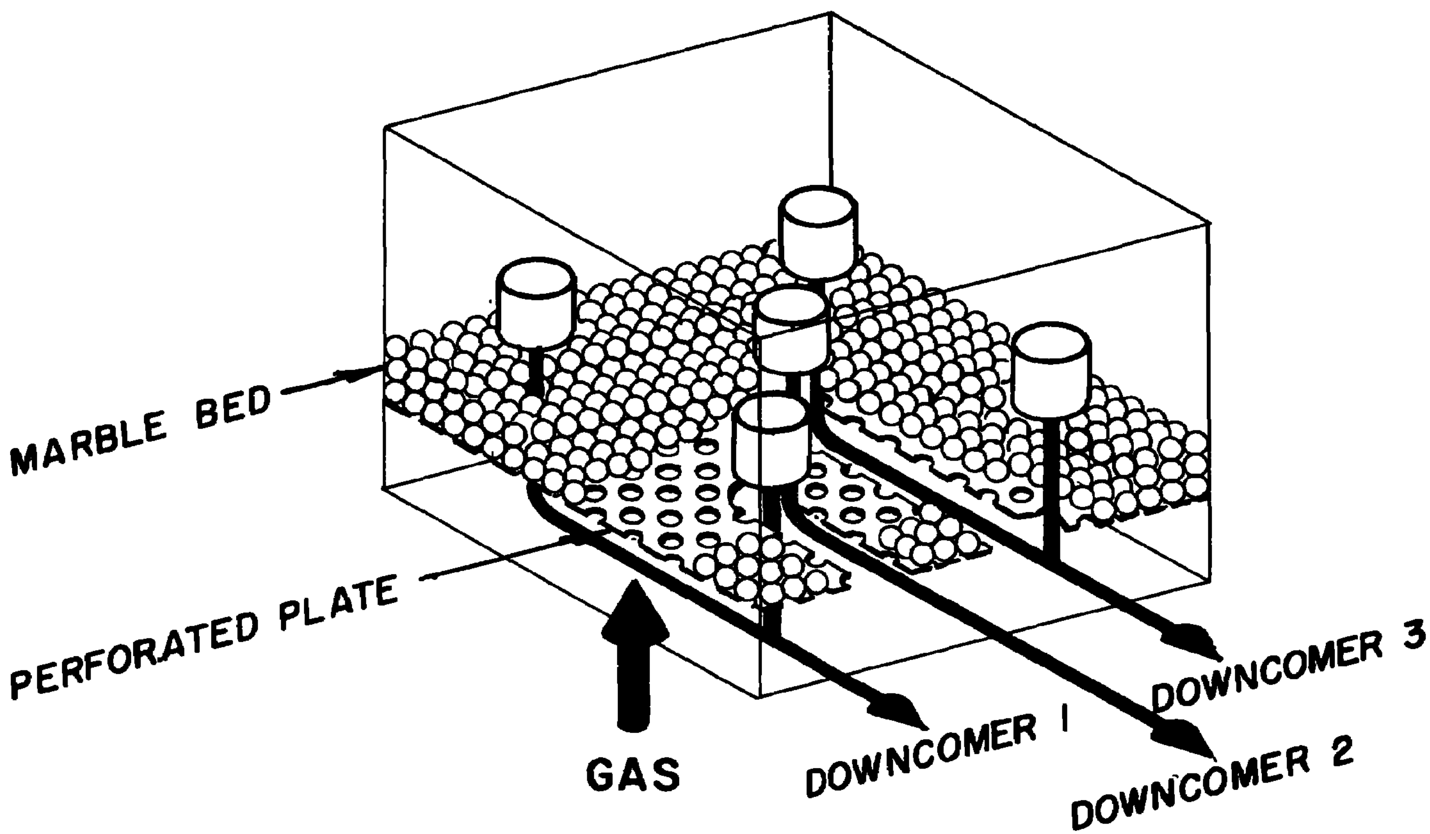

FIGURE 2-2

OVERFLOW POT AND DOWNCOMER ARRANGEMENT

2.2.4 Material Balance

The results of the total sulfur material balance for the scrubber are shown in Table 2-2. The sulfur removed from the gas ΔS_G, and the sulfur absorbed by the liquid, ΔS_L, are calculated, for all the liquid streams entering and leaving the scrubber, from the following relationships:

$$\Delta S_G = \text{(Gas Flow Rate X } SO_2 \text{ concentration) in} - \text{(Gas Flow Rate X } SO_2 \text{ concentration) out}$$

$$\Delta S_L = \Sigma \text{ (Flow X Total Sulfur Concentration) out} - \Sigma \text{ (Flow X Total Sulfur Concentration) in}$$

The inlet gas flow rates were calculated from the measured outlet gas flow rates by correcting for liquid evaporated or condensed in the scrubber and for the 6.7% air leakage[1] into the system between the inlet and outlet sampling points.

The results are within the accuracy of the experimental errors indicating adequacy of the flow measurements, sampling and analytical techniques.

2.3 CALCULATION OF STAGE EFFICIENCIES

Of the sixteen experiments run with sodium carbonate as the additive on the KDL APCS Prototype, five were chosen from which to calculate stage efficiencies based on maximum theoretical absorption of SO_2. Experiments 1R, 5R, 8R, 12R, and 14R were evaluated since they represented variations in L/G, stoichiometry, inlet SO_2, and other operating parameters.

The theoretical maximum amount of SO_2 which could have been absorbed in each experiment was determined by the following method. Soluble analyses from the marble bed effluent were the input to an equilibrium

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1. Determined by Orsat measurement of oxygen in flue gas entering and leaving scrubber.

TABLE 2-2. TOTAL SULFUR MATERIAL BALANCE

Experiment Number	Date	Gas Flow (CFM) (@ 130°F)	Liquor Flow (GPM) Below/Above	SO_2 Concentration (PPM) In	SO_2 Concentration (PPM) Out	% SO_2 Removal	Sulfur Removed From Gas ΔS_G (g Moles/Min)	Sulfur Absorbed By the Liquid ΔS_L (g Moles/Min)	$\frac{\Delta S_G - \Delta S_L}{\Delta S_G} \times 100$
1R Set 1	10/29/71	10,960	107/54	2,018	880	61.4	11.92	12.63	- 6.0
Set 2	10/29/71	10,960	107/54	2,018	860	62.3	11.92	12.38	- 3.9
2R Set 1	10/27/71	10,750	165/0	2,050	750	63.5	12.78	13.23	- 3.5
Set 2	10/27/71	10,800	165/0	2,050	750	63.5	12.57	13.18	- 3.1
3R Set 1	10/14/71	11,200	170/0	2,095	860	59.0	14.18	14.73	- 3.9
Set 2	10/14/71	11,200	170/0	2,095	860	59.0	14.18	14.45	- 1.9
4R Set 1	10/28/71	10,800	170/0	2,030	800	60.7	12.10	12.21	- 0.9
Set 2	10/28/71	10,800	170/0	2,030	790	61.2	12.21	12.10	+ 0.9
5R Set 1	11/ 2/71	12,980	106/55	2,275*	1,020*	55.2	14.72	14.35	2.5
Set 2	11/ 2/71	12,980	107/55	2,290*	1,048*	54.3	-	-	-
6R Set 1	11/ 2/71	9,180	110/55	-	-	-	-	-	-
Set 2	11/ 2/71	9,180	110/55	2,050	480	76.5	14.06	13.84	- 1.6
7R Set 1	11/ 3/71	11,240	152/69	2,000	450	77.5	16.28	16.58	- 1.8
Set 2	11/ 3/71	11,240	152/69	2,000	460	77.0	16.16	16.61	- 2.8
8R Set 1	11/ 3/71	11,200	73/36	-	-	-	-	-	-
Set 2	11/ 3/71	11,190	73/36	1,782*	829*	53.5	9.39	9.65	- 2.8
9R Set 1	10/29/71	11,000	116/54	2,050	700	65.9	13.76	14.38	- 4.5
Set 2	10/29/71	10,910	116/54	2,010	732	63.7	12.96	14.27	-10.1
10R Set 1	11/ 9/71	10,680	112/53	1,980	540	72.6	14.22	14.08	1.3
Set 2	11/ 9/71	10,690	112/53	1,960	520	73.5	14.32	14.36	- 0.3
11R Set 1	10/14/71	11,500	165/0	1,980	120	94.0	22.25	22.40	- 0.7
Set 2	10/14/71	11,400	169/0	1,980	120	94.0	22.06	24.75	- 7.7
12R Set 1	11/ 9/71	11,210	110/53	2,020	80	94.4	20.61	20.10	2.5
Set 2	11/ 9/71	11,200	110/53	1,980	100	94.3	20.15	19.35	4.0
13R Set 1	11/ 4/71	11,330	110/54	2,000	420	81.5	17.78	18.06	- 7.6
Set 2	11/ 4/71	11,400	110/54	1,980	320	86.3	19.11	18.23	- 3.0
14R Set 1	11/ 5/71	11,300	75/36	2,070	780	62.4	13.20	12.93	2.0
Set 2	11/ 5/71	11,360	75/36	2,040	780	61.7	12.91	12.80	0.9
15R Set 1	11/ 5/71	12,980	110/55	2,040	500	75.6	18.97	18.85	0.6
Set 2	11/ 5/71	12,980	110/55	2,040	500	75.6	18.97	18.79	1.0
16R Set 1	11/ 5/71	11,500	110/55.5	2,010	350	82.5	18.03	17.86	1.1
Set 2	11/ 5/71	11,500	110/55.5	2,020	350	83.2	18.14	17.90	1.3

*Manual SO_2 Readings

computer program (obtained from EPA and modified by C-E) which calculated the partial pressure of SO_2 in equilibrium with the downcomer liquid at the scrubber operating conditions. To obtain an equilibrium line, the computer calculation was repeated for incremental amounts of total SO_2 ($SO_3^=$ and HSO_3^-) added to the liquid over what was actually present in the analysis. For Experiment 1R - Set 1 (Figure 2-3) two variations in this approach were tried: in the first case, the amount of total SO_2 which had oxidized in the liquid to sulfate was held constant as additional amounts of total SO_2 (liquid) were input to the computer program, while in the second case the ratio of sulfate to total SO_2 in the actual analysis was held constant as additional sulfur was added to the liquid. As can be seen in Figure 2-3, keeping the ratio constant caused only a small change in the equilibrium line and subsequently only a very small change in the stage efficiency calculation. For this reason, the equilibrium line for the other experiments was obtained by the first method described above.

Following construction of the equilibrium line on axes of mole fraction SO_2 in the gas versus mole fraction total sulfur in the liquid, an operating line was derived for each experiment and plotted on the same diagram. This operating line was obtained from the material balance equation

$$L\ (X_{out} - X_{in}) = G\ (Y_{in} - Y_{out})$$

where L = liquid flow rate entering and leaving stage

G = gas flow rate

X_{out} = liquid composition leaving stage

X_{in} = liquid composition entering stage

Y_{out} = gas composition leaving stage

Y_{in} = gas composition entering stage

rearranged to

$$Y_{out} = (-L/G)\ X_{out} + [(L/G)\ X_{in} + Y_{in}]$$

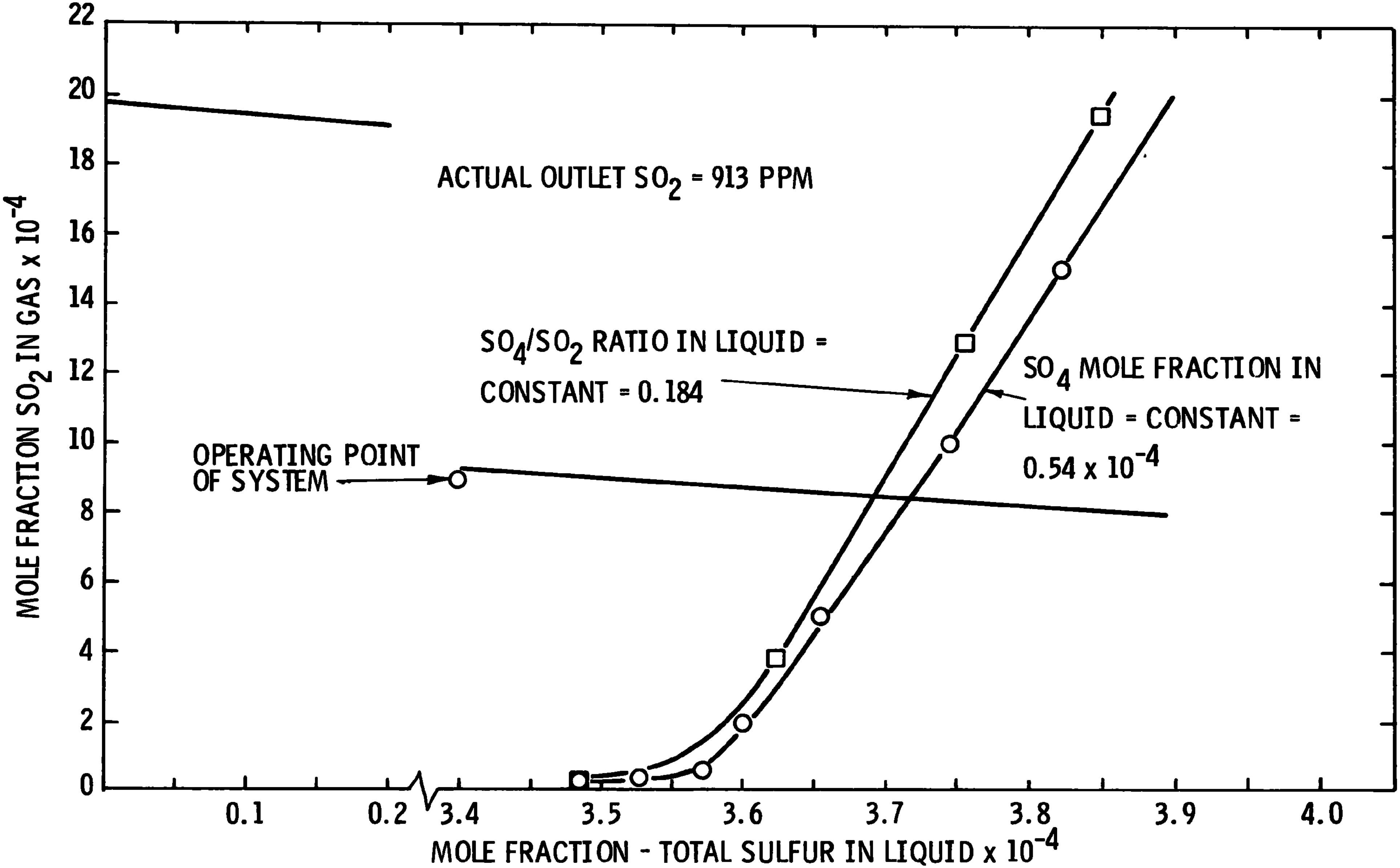

Figure 2-3

SODIUM CARBONATE SYSTEM - STAGE EFFICIENCY DETERMINATION

Corrections in SO_2 concentrations and gas flow rates were made for air leakage and changes in humidity across the marble bed. The point of maximum theoretical SO_2 absorption was obtained from the intersection of the operating and equilibrium lines.

The diagrams for the other experiments done are presented in Appendix E. Efficiencies were obtained from

$$\frac{\text{Inlet } SO_2 - \text{Outlet } SO_2 \text{ (Actual)}}{\text{Inlet } SO_2 - \text{Outlet } SO_2 \text{ (Theoretical)}}$$

and the results tabulated along with operating parameters in Table 2-3.

The actual operating point of the marble bed for experiment 1R Set 1 was plotted in Figure 2-3 by averaging the analysis of the downcomer and bottoms streams and using the corrected SO_2 outlet concentration. If the material balance for this experiment had closed completely, the point would have fallen on the operating line. As can be seen, some deviation exists and causes a small error in the efficiency calculation. In the other experiments, the point fell either slightly above or below the operating line causing a maximum $\pm$ 5% error to be introduced into the efficiency calculation.

The values for the stage efficiencies in Table 2-3 are very close for all of the experiments except 8R. This low value is caused by errors in material balance and analysis and is not due to any operating condition. In fact, no conclusions can be made regarding which film, gas or liquid, controls mass transfer based on these test data since too many conditions are varied from test to test.

In general, the data indicates that the marble bed is an efficient SO_2 contractor and that SO_2 removal was limited by vapor-liquid equilibria in the test run. Assuming that the bed is well-mixed, the rate of mass transfer is controlled by the composition of the bulk liquid which determines the rate of product and reactant diffusion through the liquid film.

TABLE 2-3. SUMMARY OF STAGE EFFICIENCY CALCULATIONS

Experiment Number/ Set Number	L/G	Moles Na_2CO_3 / Moles SO_2	Inlet* SO_2	Outlet* SO_2	Equilibrium Outlet SO_2	Stage Efficiency
1R/Set 1	15.2	0.284	1980	913	850	94.5
1R/Set 2	15.2	0.291	1980	902	840	94.5
5R/Set 1	12.8	0.255	2175	1055	1010	96
8R/Set 2	10.0	0.295	1680	857	690	83
12R/Set 1	15.2	1.89	1920	83	0	95.5
14R/Set 1	10.1	0.307	1940	805	720	93

*Inlet and outlet SO_2 values represent concentrations immediately before and after the marble bed, not at the points where they were actually measured. Corrections for humidity were made for both inlet and outlet values while corrections for leakage were made for inlet but not outlet values.

Calculation of gas-phase mass transfer coefficients ($K_g a$) for the experiments run was not attempted because of the difficulty in determining the gas phase driving force. By examining the plot of Experiment 1R in Figure 2-3 it can be seen that small errors in the scrubber effluent analysis can cause large errors in the calculated SO_2 partial pressure of the sample. For example, if the actual mole fraction of total sulfur in the liquid is 3.65×10^{-4} corresponding to partial pressure of 500 ppm SO_2, an error of $\pm$ 3% in the analysis would cause the calculated SO_2 partial pressure to fluctuate from 100 to 1000 ppm SO_2.

If we use the relationship

$$\frac{G}{K_g a} \times N_{og} \text{ T.U.} = \text{constant}$$

to calculate $K_g a$;

where G = gas flow rate

$K_g a$ = gas phase mass transfer coefficient

N_{og} T.U. = number of gas phase transfer units

N_{og} T.U. is determined from

$$N_{og} \text{ T.U.} = \frac{Y_{SO_2 \text{ in}} - Y_{SO_2 \text{ out}}}{(Y - Y^*) \text{ lm}}$$

which reduces to

$$N_{og} \text{ T.U.} = \ln \frac{Y_{SO_2 \text{ in}} - Y^*}{Y_{SO_2 \text{ out}} - Y^*}$$

for a well-mixed reactor where Y^* is the SO_2 partial pressure over the liquid. From these equations it can be seen that determination of SO_2 partial pressure over the liquid is an important step in obtaining $K_g a$'s and any error in partial pressure calculations would be reflected in the $K_g a$ values.

SECTION 3

LIMESTONE FURNACE INJECTION SYSTEM TESTS

3.1 SYSTEM CHEMISTRY

The process of removing SO_2 from the flue gas using boiler calcined limestone (CaO) as the additive in the limestone furnace injection system consists of the following reactions:

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (1)$$

$$Ca(OH)_2 + 2SO_2 + H_2O \rightarrow Ca(HSO_3)_2 + H_2O \quad (2)$$

$$CaSO_3 + SO_2 + H_2O \rightarrow Ca(HSO_3)_2 \quad (3)$$

$$Ca(HSO_3)_2 + Ca(OH)_2 \rightarrow 2CaSO_3 + 2H_2O \quad (4)$$

$$CaSO_3 + 1/2\ O_2 \rightarrow CaSO_4 \quad (5)$$

The CaO coming from the furnace is first hydrated as shown in reaction 1. Removal of SO_2 in the limestone furnace injection system depends upon the formation of calcium bisulfite by reaction of suspended calcium sulfite (reaction 3) and calcium hydroxide (reaction 2) with sulfur dioxide and water.

The reactions in which soluble bisulfite is converted to insoluble calcium sulfite (reaction 4) and sulfite is oxidized to sulfate (reaction 5) account for the water products as well as the regeneration of the solid calcium sulfite reactant that is recirculated to the scrubber.

3.2 TEST DESCRIPTION

The purpose of the furnace injection test series was to determine the solid-liquid mass transfer characteristics in the scrubber and the hold tank, and to define a range of satisfactory operating conditions for application to the field units. In addition the following information was determined because of its importance in designing furnace injection SO_2 scrubbing systems:

(1) Rate of hydration and dissolution of calcined limestone. This determines the alkalinity in the scrubber bed and the size of the reaction tank. This rate can be determined either using a material balance or using equilibrium methods.

(2) Rate of precipitation of calcium sulfate, calcium sulfite and calcium carbonate. These rates assist in designing the reaction tank so that the exiting stream will be close enough to saturation to prevent calcium sulfate scaling in the scrubber.

(3) Rate of oxidation to sulfate. This determines the incremental increase in supersaturation of calcium sulfate in the marble bed and determines the liquid to gas ratio (L/G) and the limit on supersaturation entering the scrubber needed to prevent calcium sulfate scaling in the scrubber system.

(4) A correlation between the reactivity of the calcined limestone and its rate of hydration and dissolution. The design of the SO_2 scrubbing system will not only depend on the above measurements but will very strongly depend on the reactivity of the additive entering the system. The reactivity in turn usually depends on the following variables: type of limestone, temperature of calcination and place of injection in the furnace.

Figure 3-1 is the flow arrangement for experiment 17R and Figure 3-2 is for experiments 18R, 19R, 20R, 21R and 22R. The test conditions are shown in Table 3-1. In these tests, the furnace injection APC System was simulated by blowing a mixture of boiler calcined limestone and flyash mixture into the scrubber inlet gas stream. Liquid SO_2 was vaporized using steam and then injected into the flue gas, FG (generated from an oil fired boiler) to increase the SO_2 concentration to 0.15 to 0.2 mole percent, depending on the test requirement. In Experiment 17R, the slurry from the marble bed turbulent

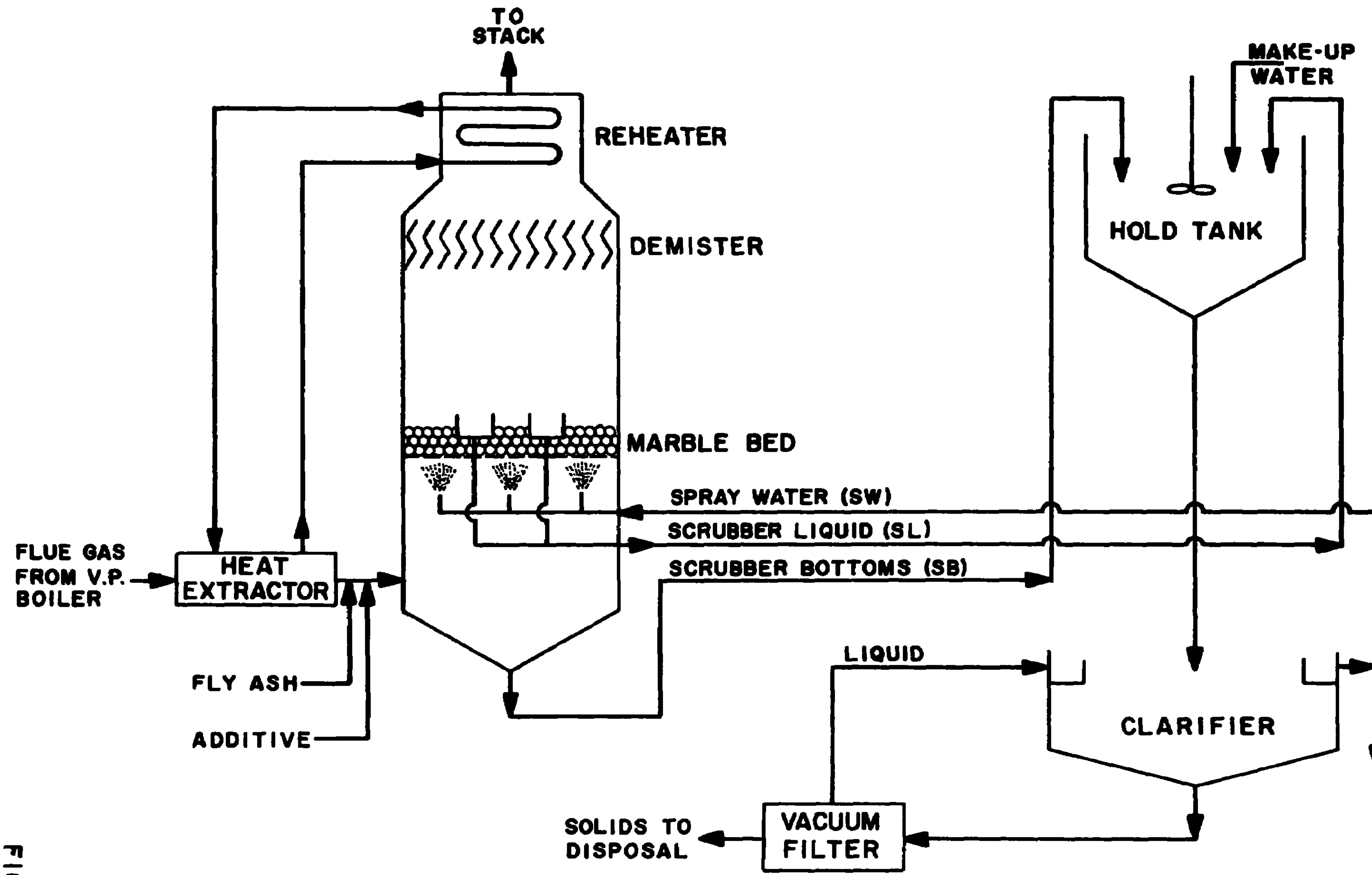

FIGURE 3-1

LIMESTONE FURNACE INJECTION SYSTEM–NO RECYCLE

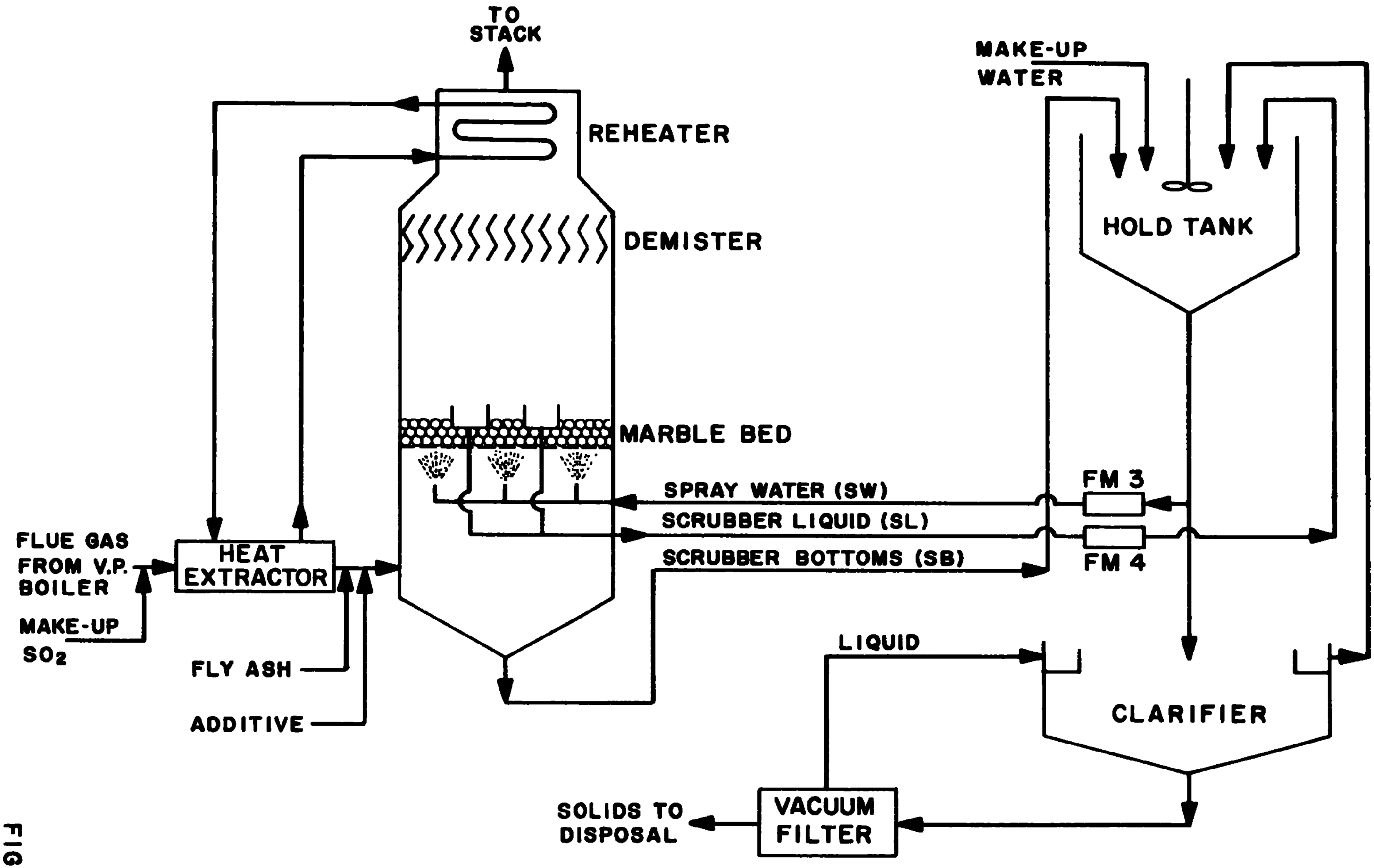

FIGURE 3-2

LIMESTONE FURNACE INJECTION SYSTEM-WITH RECYCLE

TABLE 3-1. TEST PARAMETERS FOR THE LIMESTONE FURNACE INJECTION SYSTEM

Test No.	17R	18R	19R	20R	21R	22R
Gas Flow Rate, ACFM @ 120°F	11,000	11,000	10,000	10,000	10,000	10,000
Inlet SO_2, PPM	1,500	1,500	2,000	2,000	2,000	2,000
Additive (Flyash & calcined limestone) feed rate (% of stoichiometry)	75	75	75	75	75-100	75-100
Underbed Slurry (GPM)	110	198	205	205	200	350
Liquid to Gas Ratio, L/G (GPM/1000 CFM)	10	18	20	20	20	35
Overbed Spray, GPM	0	0	0	0	0	0
Excess O_2 %	5	5	-	-	8	5
Inlet Gas Temp (°F)	300	300	300	300	300	300
Liquid Blowdown (GPM)	55	0	-	-	0	0
Clarifier Liquid (GPM)	0	25	-	-	15	15
Hold Tank, Tank Capacity (GAL)	6,000	6,000	6,000	6,000	3,000	5,200
Hold Tank Stirring	Max.	Max.	Max.	Max.	Max.	Max.
Make up Water (GPM)	55	5	-	-	5	5
Solid Concentration in Spray Slurry (%)	0	3	2	1	8	8

layer (SL) left the scrubber through the overflow pots into the downcomers and then discharged into the hold tank. The turbulent layer provided gas liquid contacting for SO_2 absorption. The scrubber bottom slurry (SB), which is rejected spray water, flyash and additive, was also discharged into the hold tank. The hold tank provides good solid liquid contacting and thus allows for hydrolysis and subsequent dissolution of calcined limestone. The slurry entering the hold tank had a pH of 4-6; the slurry leaving had a pH of 10-11. The hold tank effluent was discharged into the clarifier where the solids were settled, and the clarifier underflow was sent to the vacuum filter where the solids were further concentrated and then sent to disposal. Most of the clear liquid (165 gallons per minute) was carried to the scrubber as spray water (pH - 10.5 -11) and the remaining clarifier liquid of about 50 gallons per minute was blowdown.

In experiments 18R, 21R and 22R, part of the hold tank effluent was used as spray water, while the rest was sent to the clarifier, and the liquid returned to the hold tank. In these tests the solid concentration in the slurry was maintained between 3 and 8 percent (30% to 60% flyash, see Table F-7).

In experiments 19R and 20R, the solid concentration in the slurry was about 1 and 2 percent, and therefore a larger portion of the hold tank effluent was sent to the clarifier. Part of the clarifier liquid separated in the clarifier was removed from the system as "blowdown" and the rest was returned to the hold tank.

The flow rates for all the streams in experiments 17R to 22R are shown in Table F-1 in Appendix F.

To determine when the system reached steady state, samples were taken from the spray water (SW), and the clarifier liquid (CL) and analyzed for calcium, sulfite and sulfate. Steady state in these tests was defined as the point when the calcium and total sulfur concentration in the filtrate of the clarifier liquid (CL) and the spray water (SW) were reasonably close. Depending upon the test conditions, steady state was usually reached after 6-20 hours of operation. These analyses of the samples to determine steady state are shown in Tables F-2 to F-4 in Appendix F.

Spot checks of the liquid and gas flowmeters were made on a regular basis before every test. These checks showed that the original calibration curves prepared during the soluble tests were still valid. A listing of these procedures is available in the soluble system section and in Appendix A. Major mechanical modifications which were made between experiments are listed in Appendix G.

3.3 DATA EVALUATION

3.3.1 System Performance

Table 3-2 summarizes the limestone furnace injection results. In experiments 21R and 22R, while holding other conditions the same, the SO_2 removal efficiency increased from 59 percent to 72 percent with an increase of L/G from 20 to 36 GPM/1000 CFM. Therefore, the SO_2 removal efficiency tends to increase with liquid to gas ratio. In experiments 20R, 19R and 18R, as the solids concentration in the slurry increased from 0.7 to 3.5 the SO_2 removal efficiency increased from 36 to 68 percent, while in experiments 18R and 21R no further increase in the SO_2 removal efficiency was observed as the solid concentration in the slurry was increased from 3.5 to 7.4 percent. Therefore, it can be concluded that no improvement in SO_2 removal efficiency can be obtained by increasing the solid concentration in the spray water

TABLE 3-2. SUMMARY OF LIMESTONE FURNACE INJECTION TESTS PERFORMANCE RESULTS

Experiment No.*	17R	20R	19R	18R	21R	22R
Gas Flow ACFM @ 130°F	11,000	10,020	10,000	11,000	9,800	9,900
L/G, GPM/100 CFM	10.0	20.3	20.2	18.6	20.4	36
Inlet SO_2 Conc. (PPM)	1,456	1,950	1,882	1,471	1,992	2,020
Solid in Underbed Slurry (%)	0	0.7	1.3	3.5	7.4	8.9
Solid Recycle (%)	0	72	85	89	95	95
Spray Water pH	11.2	5.8	5.5	10.6	8.6	6.0
Stoichiometry (%)	71.0	85.5	89.1	72.8	90.1	88.1
SO_2 Removal Efficiency (%)	43.0	35.7	43.6	67.6	59.2	72.5
Liquid Blowdown to Control Calcium Sulfate Scale	Yes	Yes	Yes	No	No	No
Calcium Sulfate Scaling	No	Yes	Yes	Yes	No	No
Calcium Sulfite Scaling	Yes	No	No	No	No	No

* The listing of experiments is based on the order in which they were conducted.

beyond 3.5 percent for this system. Table 3-2 also shows that the solid recycle increase is accompanied by an increase in spray water pH and SO_2 removal efficiency. This is believed to be the result of increased retention time of the solids in the system, which allows the hydration and dissolution of CaO to near completion and thus provide greater alkalinity and consequently results in greater pH and SO_2 removal efficiency.

In experiment 17R the spray water pH was about 11 and minor calcium sulfite scaling resulted. Calcium sulfate scaling did not occur anywhere above a solids concentration in the slurry of about 8 percent, but did occur at solids concentrations below 3.5 percent. This leads to the conclusion that liquid blowdown is not needed to control calcium sulfate scaling when high solid concentration in the slurry is utilized.

The problems associated with the furnace injection system test are listed in Appendix G.

3.3.2 Analytical Results and Sampling Methods

A solid-liquid separation device consisting of a Millipore filter and filter holder was used to obtain solid and liquid samples. The samples were drawn such that the residence time in the sampling system was much smaller than in the vessel from which the sample was drawn. Since the marble bed slurry discharge had to flow a long distance before entering the hold tank, samples from both the marble bed and the scrubber liquid at the hold tank were taken to determine if any change had taken place while flowing in the pipe. The same technique was used with the scrubber bottom, where samples were taken at both the scrubber and the hold tank.

Since Radian Corp. was performing most of the solid and liquid chemical analyses, C-E decided to analyze the liquid samples for soluble calcium, sulfite and sulfate mainly for control purposes. In experiments 17R and 18R, C-E used the same method used by Radian for the sulfite analysis, namely the Arsenite method. In experiments 21R and 22R, C-E used the sodium thiosulfate back titration method, while in experiments 19R and 22R, no analyses were made by C-E.

A summary of each analytical procedure is given in Appendix D. The C-E and Radian Analytical results in experiments 17R, 18R, 21R, and 22R are within 10 percent of each other, except for the marble bed samples from experiments 21R and 22R which differed by about 40 percent. The difference between the C-E and Radian results in the marble bed is attributed to difficulties in sampling.

Results of the individual liquid and solid analysis made by C-E and Radian are listed in tables F-5 through F-16 in Appendix F. The chemical analysis of the additive is listed in Tables F-17 and F-18 in Appendix F.

3.3.3 Total Sulfur Material Balance

Detailed calculations of the total sulfur material balances of the limestone furnace injection experiments are listed in Table H-1 through H-4 in Appendix H. The results showed unexpectedly good material balance closure. The purpose of performing sulfur material balances was to check the reliability of the flow measurements and the analytical results and as a criterion for determining the reliability of the tests. Of the experiments with high solid concentration in the slurries, only experiment 18R was used to perform a total sulfur material balance. The closure errors between the total sulfur in entering and leaving streams were relatively low within 9 percent in the hold tank and within 13 percent in the marble bed.

3.3.4 Rate Calculations with Slurries of Low Solid Concentrations

It was found that in order to successfully and completely characterize the streams in the system, only slurries with low solids concentration could be used. This is because in the case of high solid slurries, a difference in the calculated rates resulting from a slight change in solid concentration was masked by that resulting from the error in solid concentration measurement. For example, when the error involved in the solid concentration measurement is $\pm 5\%$, then a change in solid concentration of $\pm 2\%$ due to precipitation or dissolution will be completely masked by that error. With zero or low solid concentration in the slurry, the rates of formation, dissolution and oxidation were successfully calculated without making any significant assumptions. These calculations which are listed in Table H-5 to H-7 in Appendix H were made for experiments 17R, 19R and 20R. While experiment 17R gave consistent results, experiments 19R and 20R gave very inconsistent results.

3.3.5 Rate Calculations With Slurries of High Solid Concentrations

As mentioned in the previous section, a detailed species material balance cannot be performed successfully in experiments with high solids concentrations due to high experimental errors. Therefore a slightly different approach had to be taken in calculating the rate of precipitation, dissolution and oxidation. Based on the results obtained in the experiment with low solids concentration (17R), the following assumptions were made:

(1) All of the oxidation in the system occurred in the marble bed.

(2) Total oxidation in the system is the ratio of the total sulfate to total sulfur in both the solid and liquid streams leaving the system.

$$\text{Oxidation} = \frac{(SO_4^{=})\text{ Liquid} + (SO_4^{=})\text{ Solid}}{\text{Total Sulfur}}$$

(3) Formation of $CaCO_3$ in the scrubber is negligible.

(4) The amount of CO_2 transferred to the hold tank from the atmosphere is negligible.

These assumptions were applied to data from experiments 17R, 19R and 20R, as well as to experiments 18R, 21R and 22R. The rate calculations using a liquid material balance and the above assumptions are shown in Table H-8 to H-13 in Appendix H.

Tables 3-3a and 3-3b summarize all the rate results obtained for all the experiments. The following criteria were used to determine the reliability of the results:

(1) Total calcium hydroxide dissolution rate in the system should not exceed the total calcium feed rate to the system with the additive.

(2) The rate of SO_2 removal from the gas should always be greather than the calcium sulfite and calcium sulfate precipitation rates in the whole system.

(3) The rate of SO_2 oxidation anywhere in the system cannot be negative.

(4) The rate of $Ca(OH)_2$ dissolution anywhere in the system cannot be negative.

(5) The error in the total sulfur material balance around both the hold tank and the marble bed should not exceed 10 percent.

Table 3-4 lists these criteria for all the furnace injection experiments, and indicates whether or not each of these crtieria is satisfied. Calculated rate data for the following tests are considered reliable:

17R, (17R), 18R, (19R), (20R)

TABLE 3-3a. SUMMARY OF RATE RESULTS FROM LIMESTONE FURNACE INJECTION TEST

Location	Experiment 17R				Experiment 19R				Experiment 20R			
	Marble Bed		Hold Tank		Marble Bed		Hold Tank		Marble Bed		Hold Tank	
	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2
Outlet Flue Gas Flow (CFM @ 130°F)	11,000	11,000			10,000	9,940			10,020	10,020		
Liquid to Gas Ratio - (GPM/1000 CFM)	10	10			20	20			20	20		
CaO Feed Rate (M Moles/Min)	11,306	11,306			15,750	15,750			15,750	15,750		
Stoichiometry based on inlet SO_2 (%)	71.0	71.0			88.0	89.5			85.0	86.0		
SO_2 Removal Eff. (%)	43.0	43.0			43.7	43.6			36.1	35.3		
Solid Conc. in Spray Slurry (wt. %)	NONE	NONE			1.14	1.46			0.69	0.7		
ΔS_G (Amount of SO_2 absorbed (M Moles/Min)	7,077	7,077			5,766	5,368			6,616	6,400		
$Ca(OH)_2$ Dissolution (M Moles/Min)	2,196 (5,007)	2,698 (5,358)	1,900 (1,151)	1,488 (717)	3,006 (268)	7,844 (1,965)	3,687 (2,579)	3,006 (2,577)	6,138 (3,865)	2,600 (3,726)	3,136 (867)	3,127 (494)
Sulfite Oxidation (M Moles/Min)	3,130 (3,107)	4,305 (2,951)	224 -	281 -	- 600 (3,775)	-2,994 (3,275)	530 -	508 -	557 (3,652)	1,339 (3,488)	- 133 -	260 -
$CaSO_3 \cdot 1/2\ H_2O$ formation (M Moles/Min)	1,307 (1,355)	791 (2,144)	1,848 (2,083)	1,960 (2,193)	-1,021 (-4,550)	1,358 (-4,200)	5,329 (5,858)	4,804 (5,312)	1,209 (-1,887)	395 (-1,741)	3,707 (2,811)	2,681 (2,941)
$CaSO_4 \cdot 2\ H_2O$ formation (M Moles/Min)	- 955 (1,592)	- 539 (784)	331 (6)	- 57 (- 549)	- 899 (- 105)	- 550 (- 273)	2,198 (383)	1,223 (186)	- 725 (- 480)	-2,024 (544)	1,133 (- 433)	1,392 (-1,360)
$CaCO_3$ formation (M Moles/Min)	- 216	16	790 (226)	577 (158)	- 985	565	142 (320)	- 32 (68)	- 612	- 660	- 34 (159)	210 (170)
Error in Total Sulfur Material balance $(\frac{In - Out}{In}) \times 100$ (%)	- 10.7	- 12.4	1.5	- 2.1	6.0	9.0	5.0	2.3	5.2	- 0.7	3.6	5.2

TABLE 3-3b. SUMMARY OF RATE RESULTS FROM LIMESTONE FURNACE INJECTION TESTS

Location	Experiment 18R				Experiment 21R				Experiment 22R			
	Marble Bed		Hold Tank		Marble Bed		Hold Tank		Marble Bed		Hold Tank	
	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2
Outlet Flue Gas Flow (CFM @ 130°F)	11,000	11,000			9,670	10,000			9,940	9,900		
Liquid to Gas Ratio - (GPM/1000 CFM)	18.6	18.6			20.6	20			36	35.5		
CaO Feed Rate (M Moles/Min)	11,503	11,503			16,599	16,599			16,599			
Stoichiometry based on inlet SO_2 (%)	72.8	72.8			91.5	88.8			87.8	88.4		
SO_2 Removal Eff. (%)	67.6	67.6			57.7	60.7			70.8	74.2		
Solid Conc. in Spray Slurry (wt. %)	3.67	3.35			8.02	6.67			8.58			
ΔS_G (Amount of SO_2 absorbed) (M Moles/Min)	10,717	10,717			13,917	14,703			16,760			
$Ca(OH)_2$ Dissolution (M Mole/Min)	6,137	6,868	3,387	3,286	5,179	9,422	-10,894	- 6,564	14,745		15,167	
Sulfite Oxidation (M Moles/Min)	2,990	3,097			4,968	3,910			5,799			
$CaSO_3 \cdot 1/2\ H_2O$ formation (M Moles/Min)	5,943	5,027	1,435	1,849	2,563	4,380	- 280	556	4,664	17,265		
$CaSO_4 \cdot 2\ H_2O$ formation (M Moles/Min)	- 1,339	- 560	1,711	1,069	1,150	459	- 1,391	- 3,985	4,664		9,442	
$CaCO_3$ formation (M Moles/Min)							- 72	594			398	
Error in Total Sulfur Material balance $(\frac{In - Out}{In}) \times 100$ (%)	13.5	12.2	0.3	- 9.2								

TABLE 3.4. CRTIERIA FOR DETERMINATION OF LIMESTONE FURNACE INJECTION TEST RELIABILITY

Test No.	$Ca(OH)_2$ Dissolution ≥ Ca++ in Additive		$\Delta S_G \geq CaSO_2 \cdot 1/2H_2O + CaSO_4 \cdot 2H_2O$		Oxidation Anywhere > 0		$Ca(OH)_2$ Dissolution in Hold Tank and Marble Bed ≥ 0		Error in Total Sulfur Material Balance ≥ 10%	
	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2
17R	X	X	X	X	X	X	X	X	X	*
(17R)	X	X	X	X	X	X	X	X	X	*
18R	X	X	X	X	X	X	X	X	X	X
19R	X	X	X	X	*	*	X	X	X	X
(19R)	X	X	X	X	X	X	X	X	X	X
20R	X	X	X	X	X	X	X	X	X	X
(20R)	X	X	X	X	X	X	X	X	X	X
21R	X	X	X	X	X	X	*	*	-	-
22R	*	-	X	-	X	-	X	-	-	-

KEY: ( ) Calculated by assuming all the oxidation occurs in marble bed
X Good
* Bad
- No Data

The parentheses indicate that the rate calculations for the high solid slurry experiments were determined assuming all the oxidation occurred in the marble bed.

Table 3-3a and 3-3b summarize the rates of $CaSO_3 \cdot 1/2H_2O$ and $CaSO_4 \cdot 2H_2O$ precipitation, sulfite oxidation and $Ca(OH)_2$ dissolution. In the low slurry solid concentration experiments, most of the $CaSO_3 \cdot 1/2H_2O$ precipitation occurred in the hold tank, while in the high solid concentration experiments, most of the calcium sulfite precipitated in the marble bed. Calcium sulfate precipitation rate data were inconsistent, and therefore it was almost impossible to detect the trend and location of its precipitation. The dissolution rate of $Ca(OH)_2$ in the marble bed was always greater than 50 percent of the total dissolution except in experiment 19R, where it was 30 percent.

This leads to the conclusion that most of the additive dissolves in the marble bed. It is important however, to point out that the percent of total dissolution in the marble bed should be controlled so that calcium sulfite scaling will not occur.

It should also be noted that in most experiments the rate of $CaCO_3$ formation was negligible in both the marble bed and the hold tank. In addition, out of the total SO_2 absorbed in the system, the fraction that underwent oxidation was higher (40-55 percent) in the low solid slurry experiments than in the high solid slurry experiments (25-35 percent).

3.3.7 Calculation of Additive Dissolution Rate From Equilibrium Data

Based on the results of the stage efficiency calculations for the soluble system tests, additive dissolution rates were determined for the furnace injection tests by using vapor-liquid equilibria. Two major assumptions were made in these calculations:

(1) Stage efficiency remained constant at 90% (from the soluble system tests).

(2) The marble bed operated as a well mixed reactor and additive dissolved at a fixed rate to maintain a constant partial pressure of SO_2 exerted by the liquid in the bed.

Figure 3-3 is an operating and equilibrium line diagram of experiment 17R. The equilibrium line on the diagram represents the soluble portion of the scrubber feed. The abscissa is constructed so that the total sulfur concentration in the liquid entering the scrubber is represented by the vertical line at the far left of the graph. The point on the abscissa corresponding to the actual SO_2 removal is the total sulfur concentration in the liquid leaving the scrubber. This concentration does not exist in the actual data taken but is equal to the weighted average of the downcomers and scrubber bottoms concentrations assuming no precipitation of sulfur compounds in the scrubber.

If no additive dissolution had occurred, the SO_2 outlet concentration could have been no lower than 1260 ppm as represented by the intersection of the operating and equilibrium lines. Since the actual SO_2 outlet concentration obtained during the test was 770 ppm, some additive dissolution had to occur. Assuming the stage to be 90% efficient for 770 ppm outlet SO_2, the outlet SO_2 equivalent to 100 percent stage efficiency would be 680 ppm (according to the previously stated assumption, the rate of additive dissolution should be sufficient to maintain 680 ppm SO_2 partial pressure over the liquid). Even if the stage efficiency is less than 100 percent, the rate of additive dissolution would be the same. In order to calculate the dissolution, the simplest method would be to determine what quantity was necessary to maintain 680 ppm SO_2 over the liquid if SO_2 removal equal to 100 percent stage efficiency was obtained.

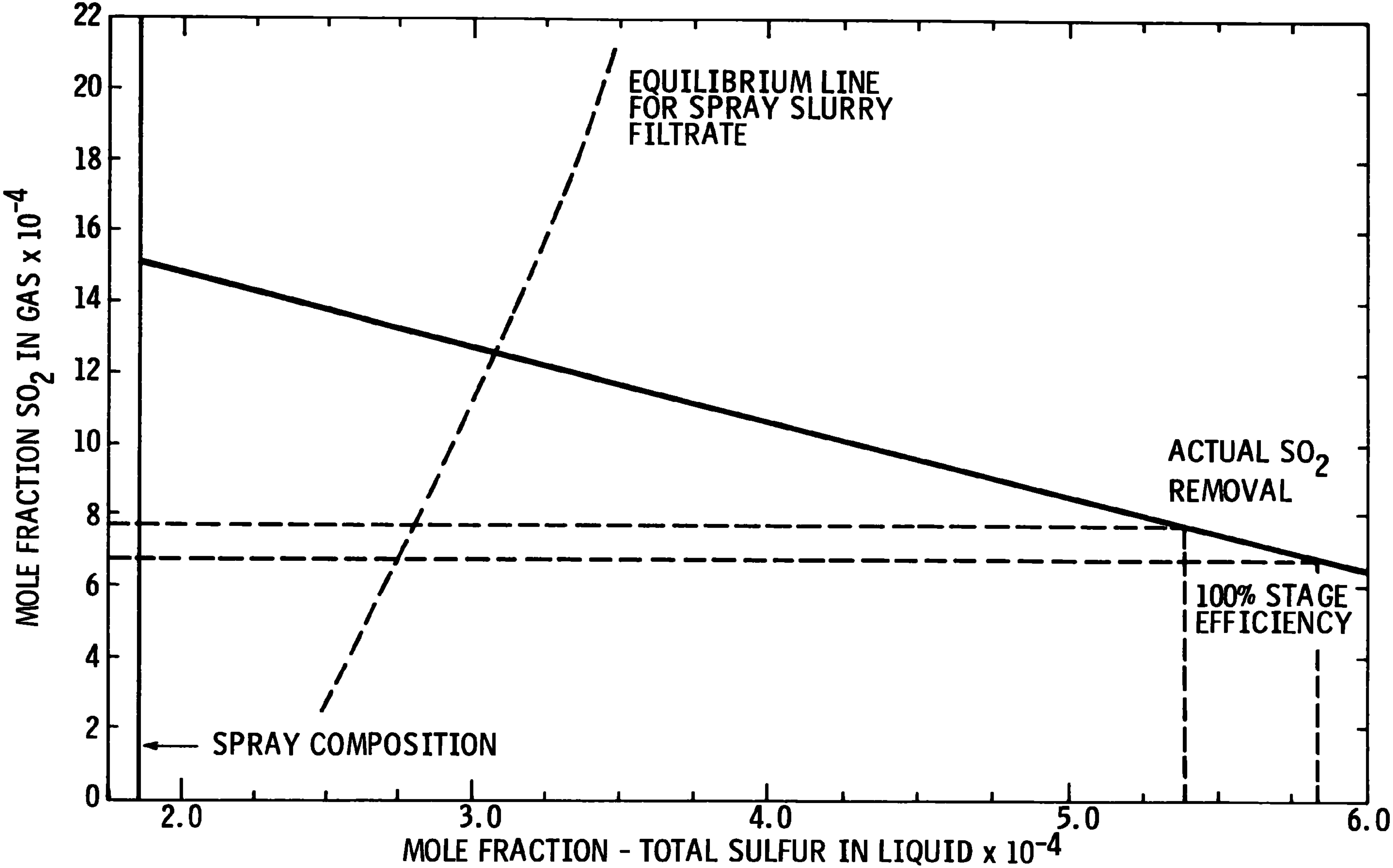

Figure 3-3

PLOT OF OPERATING LINE FOR EXPERIMENT 17R

To quantitatively determine the additive dissolution, varying amounts of calcium were input to the computer equilibrium program along with most of the spray water composition. Only soluble carbon dioxide values were taken from the downcomer analysis, and sulfite and sulfate were those derived from Figure 3-3 for 100% stage efficiency. Total system oxidation was used to determine the ratio of sulfate and sulfite at this point. Partial pressure of SO_2 over the liquid for varying amounts of soluble calcium is plotted for experiment 17R in Figure 3-4. The concentration of calcium producing a partial pressure of 680 ppm SO_2 was found to be 24.45 $\frac{\text{m moles}}{\text{liter}}$. By subtracting the amount of soluble calcium entering the scrubber from this value and multiplying the difference by the flow rate, a dissolution rate of 4950 $\frac{\text{m moles}}{\text{min}}$ was obtained. This procedure was carried out for experiments 18R to 22R; the graphs are presented in Appendix I. Table 3-5 contains a summary of these results along with the results obtained by material balance methods.

Agreement of the dissolution rates obtained by equilibrium data with those done by liquid species material balance is reasonable in most cases. Experiments 18R and 22R exhibit the most deviation. Comparing the dissolution rates to the SO_2 absorption rates indicates that additive dissolution is responsible for an average of two-thirds of the SO_2 removal.

3.3.8 Supersaturation of Calcium Sulfate and Sulfite

Using the soluble chemical analyses from marble bed samples and the equilibrium computer program, supersaturation values of calcium sulfate (ratio of the activity product to solubility product) were calculated for experiments 17R through 22R. Table 3-6 contains these results along with an indication of any calcium sulfate scaling which occurred during the tests. A supersaturation value of approximately 1.3 appears to be the threshold for calcium sulfate scaling in these tests.

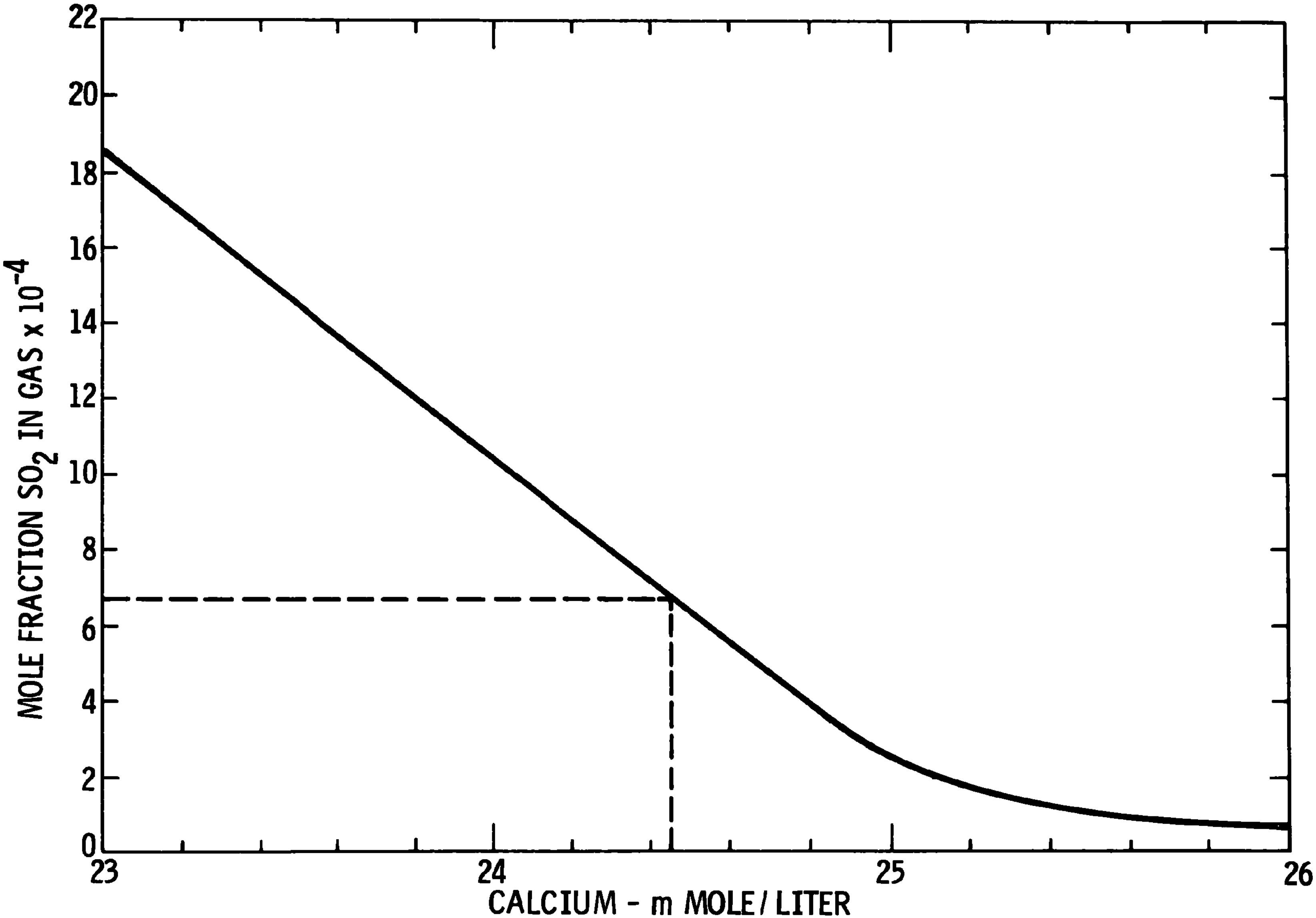

Figure 3-4

PLOT OF CALCIUM vs PARTIAL PRESSURE OF SO_2 FOR SCRUBBER EFFLUENT - EXPERIMENT 17R

TABLE 3-5. SUMMARY OF CALCIUM HYDROXIDE DISSOLUTION CALCULATIONS FOR MARBLE BED

All values are in $\frac{\text{M Moles}}{\text{Min.}}$

Experiment No.	Set No.	Liquid Species Material Balance Using Assumed Oxidation*	Solids Species Material Balance	Results From Equilibrium Diagrams	Amount of SO_2 absorbed
17R	1	5000	2200	5000	7100
	2	5400	2700		7100
18R	1	6100		2800	10700
	2	6900			10700
19R	1	3000	300		5800
	2	7800	2000	5200	5400
20R	1	6100	3900		6600
	2	2600	3700	4200	6400
21R	1	5200		8200	13900
	2	9400			14700
22R	1	14700		8800	16800

* Oxidation value obtained for entire system was assumed to occur only in marble bed.

TABLE 3-6. COMPARISON OF CALCIUM SULFATE SUPERSATURATION AND SCRUBBER PERFORMANCE

Test No.	Relative Supersaturation Of Calcium Sulfate*	Did Calcium Sulfate Scaling Occur?
17R	0.97	No
18R	1.33	Yes
19R	1.84	Yes
20R	2.03	Yes
21R	1.18	No
22R	1.32	No

* Defined by: $$\frac{[\text{Ca activity in marble bed}]\ [\text{SO}_4\ \text{activity in marble bed}]}{K_{sp}\ \text{of}\ CaSO_4\ \text{at}\ T°}\ \text{at}\ T°$$

Values of supersaturation for calcium sulfite in the marble bed were not calculated because of the large fluctuations with pH. Although a supersaturation value can be obtained for the marble bed samples, this probably does not represent the actual value in the bed itself. Any dissolution of additive while the sample was being taken would raise the pH and increase the calcium sulfite supersaturation.

3.4 CONCLUSIONS

In summary, the following conclusions can be drawn from the limestone furnace injection system tests.

(1) SO_2 removal can be improved significantly (8 to 10 percentage points) by increasing the liquid to gas ratio from approximately 20 to 35 GPM/1000 CFM.

(2) SO_2 removal can be improved significantly by increasing the solids concentration in the spray slurry from 0 to 3.5%.

(3) No improvement in SO_2 removal could be obtained by increasing the solids in the spray slurry beyond 3.5%.

(4) Calcium sulfate scaling was controlled in a closed loop system without employing liquid blowdown by maintaining 8% total solids (30%-60% flyash) in the spray slurry. (Based on a maximum continuous run time of 10 hours).

(5) Calcium sulfate scaling can be controlled by maintaining the supersaturation level below 1.3.

(6) Calcium sulfite scaling in the scrubber can be controlled by maintaining the spray slurry pH below 11 to insure that no CaO or $Ca(OH)_2$ solids enter the scrubber.

(7) More than half the additive dissolves in the scrubber bed in spite of the short residence time in the bed.

SECTION 4

LIMESTONE TAIL-END SYSTEM TESTS

4.1 SYSTEM CHEMISTRY

The process of removing SO_2 from the flue gas using limestone in the limestone tail-end system consists of the following reactions:

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca(HCO_3)_2 \quad (1)$$

$$2SO_2 + Ca(HCO_3)_2 \rightarrow Ca(HSO_3)_2 + 2CO_2 \quad (2)$$

$$CaSO_3 + SO_2 + H_2O \rightarrow Ca(HSO_3)_2 \quad (3)$$

$$Ca(HSO_3)_2 + CaCO_3 \rightarrow CaSO_3 + Ca(HCO_3)_2 \quad (4)$$

$$CaSO_3 + 1/2\ O_2 \rightarrow CaSO_4 \quad (5)$$

Reactions 1, 2 and 3 are the principal absorption reactions. Sulfur dioxide reacts with relatively soluble bicarbonate to form calcium bisulfite. In addition, solid calcium sulfite recycled from the reaction tank or hold tank reacts with SO_2 to form calcium bisulfite.

The reactions in which sulfite is oxidized to sulfate (reaction 5) and soluble bisulfite is converted to insoluble calcium sulfite (reaction 4) account for the waste products as well as the regeneration of the solid calcium sulfite reactant that is recirculated to the scrubber. The ratio of calcium sulfite to calcium sulfate found in the APCS solid waste depends upon the extent to which these reactions go to completion.

4.2 TEST DESCRIPTION

The C-E scrubber at EPA's alkali Scrubbing Test Facility (at TVA's Shawnee steam plant) has only one marble bed, while current commercially offered C-E scrubbers have two marble beds. On the other hand, the other two scrubbers at the facility are similar to current commercially offered designs. Therefore, it was felt that comparing the performance of the C-E scrubber with the other two test scrubbers at Shawnee might be difficult. Therefore, the one and two marble bed tail-end limestone tests using the KDL prototype were designed to assist EPA in extrapolating the single marble bed results from Shawnee to predict the performance of the C-E scrubber with two marble beds. The tests also provided data for determining the solid-liquid mass transfer rates in the scrubber and the hold tanks. In addition, the following information was sought which would greatly assist in designing a limestone tail-end system for scrubbing SO_2:

(1) Rate of dissolution of limestone ($CaCO_3$). This would determine the alkalinity in the scrubber bed and the proper size of the reaction tank. The rate can be determined either using a material balance or using equilibrium methods.

(2) Rate of precipitation of calcium sulfate and calcium sulfite. The rates would assist in designing the reaction tank such that the exiting stream will be close enough to saturation to prevent calcium sulfate scaling in the scrubber.

(3) Rate of oxidation to sulfate. This would determine the incremental increase in supersaturation of calcium sulfate in the marble bed and therefore would determine both the liquid to gas ratio (L/G) and the limit on supersaturation entering the scrubber needed to prevent calcium sulfate scaling in the scrubber system.

Contrary to the furnace injection tests where the additive was introduced into the scrubber along with the flue gas, the additive in the tail-end system was introduced into the hold tank as shown in Figure 4-1. Liquid SO_2 was vaporized using steam and then injected into the flue gas (FG) in order to increase its SO_2 concentration to about 0.25 mole percent. The slurry (SL) from the marble beds' turbulent layers (pH of

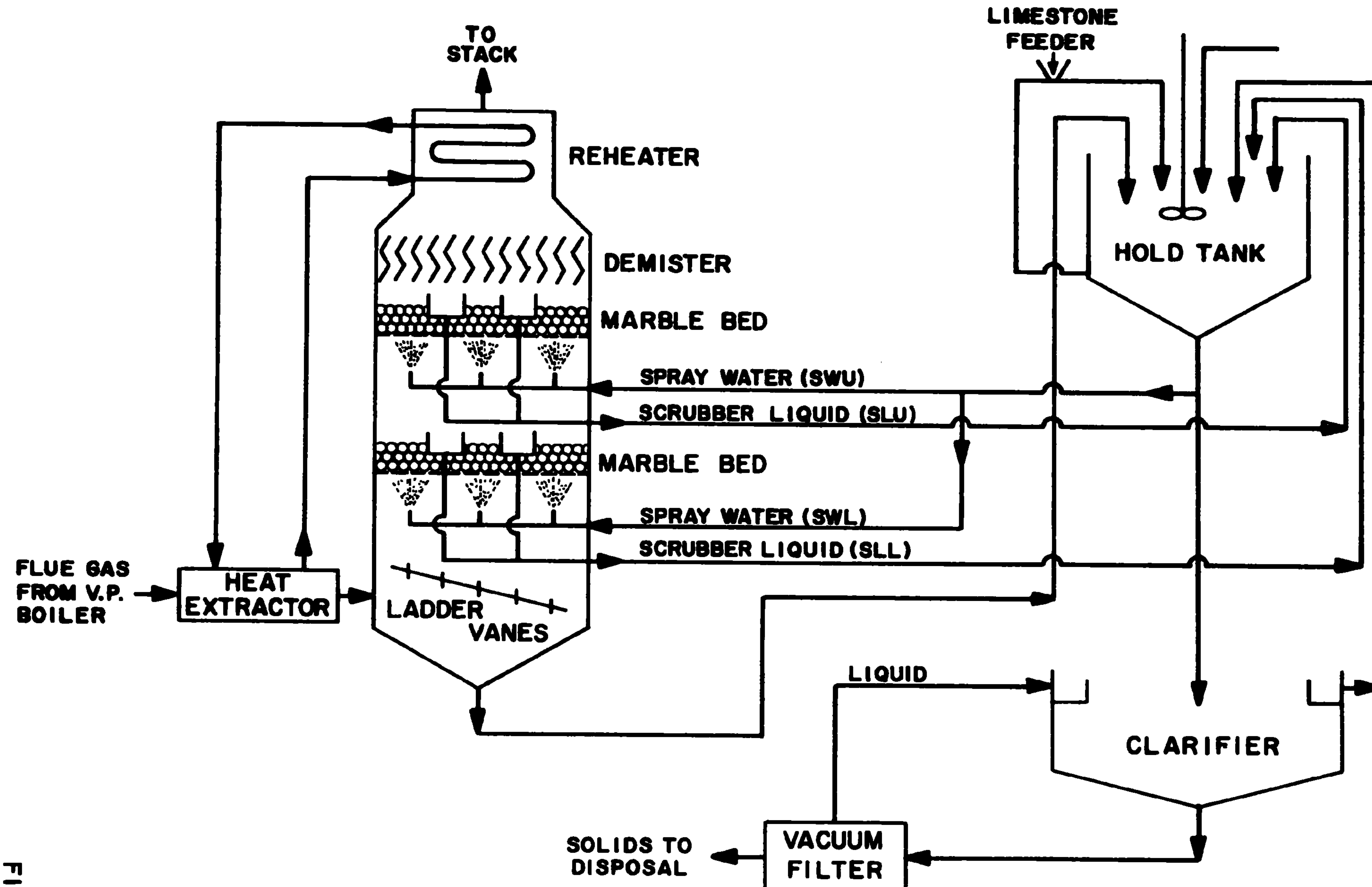

FIGURE 4-1

LIMESTONE TAIL-END SYSTEM

5-5.5) left the scrubber through the overflow pots into the downcomers and was then discharged into the hold tank (10 feet diameter by 10 feet high). The scrubber bottom slurry (SB) which was rejected spray water was also discharged into the hold tank. The hold tank provided good solid liquid contacting and allowed for the limestone dissolution. The test conditions for the six tests are listed in Table 4-1 and the operating data is given in Table J-1 in Appendix J.

In experiments 25R, 26R and 27R, only one marble bed was used, while in experiments 28R, 29R and 30R, two marble beds were used. Most of the slurry leaving the hold tank was introduced under the marble bed through the spray nozzles. The spray water pH varied between 6.0 and 6.5. The marble bed together with the turbulent layer the volume of which is about 20 cubic feet, provided good mixing where the absorption of SO_2 took place. A portion of the hold tank effluent was pumped to the clarifier to maintain about 8 percent solid concentration in the slurry. The solids were settled in the clarifier and the clarified liquid (CL) was returned to the hold tank. The hold tank was maintained at full capacity of about 6000 gallons at all times. The reaction tank residence time at a 500 gpm pumping rate is about 12 minutes.

To determine when the system reached steady state, samples taken from the spray water (SW) and the clarifier liquid (CL) were analyzed for calcium, sulfite and sulfate. Steady state in these tests is defined as the point when the calcium and total sulfur concentration in the filtrate of the clarified liquid (CL) and the spray water (SW) were reasonably close. The analyses of the samples used to determine steady state are shown in Table J-2 in Appendix J.

TABLE 4-1. TEST PARAMETERS FOR THE LIMESTONE TAIL-END SYSTEM

Experiment No.	25R	26R	27R	28R	29R	30R
Number of beds	1	1	1	2	2	2
Gas Flow Rate						
ACFM @ 120°F	10,000	10,000	10,000	10,000	10,000	10,000
ft/Min	450	450	450	450	450	450
Inlet SO_2, PPM	2,400	2,400	2,400	2,400	2,400	2,400
Limestone Feed Rate (% Stoichiometry)	100	150	150	150	150	100
Fly Ash Feed Rate (Gr/SCFM)	0	0	0	0	0	0
Underbed Slurry						
GPM/bed	250	250	150	150	250	250
L/G, GPM/1000 CFM	25	25	15	15	25	25
Overbed Spray, GPM/bed	0	0	0	0	0	0
Solid Conc. in Slurry, wt. %	8	8	8	8	8	8

4.3 DATA EVALUATION

4.3.1 System Performance

The results of the tail-end tests are summarized in Table 4-2. While holding all other conditions the same in single bed experiments 26R and 27R, the SO_2 removal efficiency increased by 8 percentage points when the liquid to gas ratio (L/G) was increased from 15 to 25 GPM/1000 CFM. In double bed experiments 28R and 29R, the overall SO_2 removal increased by 11 percentage points when the L/G was increased from 15 to 25 GPM/1000 CFM per bed. It can be concluded therefore, that the liquid to gas ratio has a significant effect on the SO_2 removal efficiency.

The overall SO_2 removal efficiency remained unchanged in both single and double marble bed tests while the additive feed rate was increased from about 100 to 150 percent stoichiometry with all the other conditions kept the same. This leads to the conclusion that in high solids systems when the additive feed rate is increased beyond 100 percent, the SO_2 removal efficiency remains unchanged and as a result, the additive utilization tends to decrease.

While the solid concentration in the slurry in all tail-end experiments was maintained between 6.5 and 8.5 percent, no calcium sulfite or calcium sulfate scaling was observed. Liquid blowdown was not used during these tests to control calcium sulfate scaling. Therefore, it can be concluded that calcium sulfate scaling in a limestone tail-end system can be controlled by maintaining a solid concentration in the slurry of about 8 percent (excluding fly ash).

The SO_2 removal efficiency in the upper and the lower marble beds based on the SO_2 concentrations in the gas entering the respective marble beds, was the same. For example, in experiment 27R, the lower marble bed removed about 50 percent of about 2400 ppm SO_2 entering

TABLE 4-2. SUMMARY OF LIMESTONE TAIL-END TESTS

PERFORMANCE RESULTS

Experiment No.	25R	26R	27R	28R	29R	30R
No. of Marble Beds Used	1	1	1	2	2	2
L/G (GPM/1000 CFM) - Lower Bed	24.5	24.0	15.0	16.0	24.5	25.0
L/G (GPM/1000 CFM) - Upper Bed	-	-	-	15.0	22.5	23.5
Solids in Spray water (%)	7.4	6.5	7.5	6.7	8.6	-
Inlet SO_2 (PPM)	2345	2505	2315	2420	2435	2380
Solid Recycle - (%)	96	94	92	95	97	96
Stoichiometry (%)	98	145	156	152	148	94
SO_2 removal efficiency (%)*	55.5	57	49	76	87	86
Additive Utilization - %	57	39	31	50	59	91
Calcium Sulfite Scale	None	None	None	None	None	None
Calcium Sulfate Scale	None	None	None	None	None	None
Liquid Blowdown	None	None	None	None	None	None

*Corrected for Air leakage

The gas flow was maintained at about 10,000 CFM @ 130°F, 1 atm in all tests.

it, and in experiment 28R, both marble beds removed about 75 percent of the SO_2 (2400 ppm) entering the lower bed. This means that the lower bed removed 50% of the 2400 ppm SO_2 entering it while the upper bed removed another 50% of the remaining 1200 ppm SO_2 entering the upper bed. This resulted in an overall removal of 75%. Therefore, it can be concluded that single marble bed SO_2 removal efficiency for the range of inlet SO_2 concentration studied can be extrapolated to predict two marble bed SO_2 removal efficiency.

4.3.2 Analytical Results and Sampling Methods

The furnace injection sampling method was also used in the tail-end tests, and the corresponding samples from the upper marble bed were added to the list of samples used in the furnace injection tests. C-E, however, did not perform chemical analysis on any of the tail-end test series in order not to duplicate Radian Corporation's effort. The results of the solid analyses are listed in Tables J-3 through J-8, and those of the liquid analysis are listed in Tables J-9 through J-14, in Appendix J. In their July, 1972 Progress Report to EPA, Radian indicated a significant error in the liquid sulfite analysis in experiment 25R. This caused an error in the sulfate results, since sulfate is obtained by the difference between total sulfur and sulfite. The remainder of the analyses were fairly accurate except for the marble bed sulfite and sulfate results which are slightly in error due to a relatively large residence time in the sampling lines thus allowing further time for reaction and oxidation. The samples for obtaining solid concentration in the slurry in experiment 30R were accidentally discarded, thus preventing total sulfur material balance calculation for that test.

4.3.3 Total Sulfur Material Balance

Detailed calculations of the total sulfur material balance of the limestone tail-end experiments are summarized in Tables K-1 through K-5 in Appendix K, and the results are summarized in Tables 4-3a and 4-3b. The results show low errors considering the analytical and sampling problems, and the inaccurancy in sampling for high solid concentration in the slurry. In arriving at the amount of total sulfur in the slurry streams, the specific gravity of the slurry used was assumed to be 1.0 in order to convert the slurry flow rate from GPM to pounds per minute.

4.3.4 Rate Calculations

Since the solid concentration in all of the limestone tail-end tests was high, a material balance calculation to determine the rates was not feasible without making certain assumptions. In the case of high solid slurries, a difference in a rate resulting from a slight change in solid concentration was masked by that resulting from the error in the solid concentration measurement. Therefore, in order to obtain the rates of precipitation and dissolution, the following assumptions and observations were used:

(1) All of the oxidation in the system occurred in the marble bed. (From experiment 17R, furnace injection.)

(2) Total oxidation in the system is the ratio of the total sulfate to total sulfur in both the solid and liquid streams leaving the systems.

$$\text{Oxidation} = \frac{(SO_4^{=})\ \text{Liquid} + (SO_4^{=})\ \text{Solid}}{\text{Total Sulfur}}$$

(3) The amount of CO_2 transferred to the hold tank from the atmosphere is negligible.

TABLE 4-3a. SUMMARY OF RATE RESULTS FROM LIMESTONE TAIL END TESTS

Location	Experiment 25R Marble Bed Set #1	Experiment 25R Marble Bed Set #2	Experiment 25R Syst. Remainder Set #1	Experiment 25R Syst. Remainder Set #2	Experiment 26R Marble Bed Set #1	Experiment 26R Marble Bed Set #2	Experiment 26R Syst. Remainder Set #1	Experiment 26R Syst. Remainder Set #2	Experiment 27R Marble Bed Set #1	Experiment 27R Marble Bed Set #2	Experiment 27R Syst. Remainder Set #1	Experiment 27R Syst. Remainder Set #2
Inlet Blue Gas Flow (CFM @130°F)	9,950	9,900			10,060	10,100		10,250	10,180			
Liquid to Gas Ratio per Bed (GPM/1000 CFM) - Upper	-	-	-	-	-	-	-	-	-	-	-	-
Liquid to Gas Ratio per Bed (GPM/1000 CFM) - Lower	24.1	25.2			24.3	23.3		14.6	14.7			
Additive Feed Rate (M Moles/Min)			24,062	24,062			38,590	38,590			39,044	39,044
Stoichiometry based on inlet SO_2(%)	98.5	97.6			144.5	.46.1		156.7	156.6			
SO_2 Removal Eff. (%)	56.2	54.7			56.5	57.0		48.2	49.4			
Solid Conc. in Spray Slurry (wt. %)	7.55	-			-	6.57		7.18	7.69			
ΔS_G (Amount of SO_2 absorbed) (M Moles/Min)	12,770	13,501			14,081	11,911		11,237	11,438			
Sulfite Oxid. (%)	25.0	23.4			26.1	23.8		26.4	24.9			
Sulfite Oxidation (M Moles/Min)	3,192	3,159			3,675	2,834		2,966	2,848			
$CaSO_3 \cdot 1/2\ H_2O$ formation (M Moles/Min)	745		10,497	10,127	-3,122	-1,146	13,769	13,098	-2,907	247	11,279	8,255
$CaSO_4 \cdot 2\ H_2O$ formation (M Moles/Min)	4,997		1,233	-2,201	2,898	-274	1,568	3,000	3,160	885	-742	1,854
$CaCO_3$ dissolution (M Moles/Min)	4,832		5,586	4,281	6,769	5,413	6,801	7,647	5,092	6,954	5,937	7,565
Error in Total Sulfur material balance $(\frac{In - Out}{In}) \times 100$	-3.1		-0.2	-0.5		-20.7		3.7	-9.2	-13.1	-3.3	-1.9

*System remainder includes hold tank, surge tanks and clarifier.

TABLE 4-3b. SUMMARY OF RATE RESULTS FROM LIMESTONE TAIL END TESTS

Location	Experiment 28R				Experiment 29R				Experiment 30R			
	Marble Bed		Syst. Remainder*		Marble Bed		Syst. Remainder*		Marble Bed		Syst. Remainder*	
	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2	Set #1	Set #2
Inlet Flue Gas Flow (CFM @ 130°F)	10,160	10,400			10,200	10,400		10,280	10,280			
Liquid to Gas Ratio - Upper per Bed (GPM/1000 CFM) - Lower	14.8 15.5	14.4 15.3			22.0 24.0	21.6 23.5		22.8 24.3	22.8 24.3			
Additive Feed Rate (M Moles/Min)			39,044	39,044			39,044	39,044			24,213	24,213
Stoichiometry based on inlet SO_2(%)	152.4	151.7			147.8	147.5		97.1	90.0			
SO_2 Removal Eff. (%)	75.5	76.0			87.1	87.6		84.4	87.3			
Solid Conc. in Spray Slurry (wt.%)	6.40	6.71			8.41	8.72		-	-			
ΔS_G (Amount of SO_2 absorbed) (M Moles/Min)	17,002	18,057			21,489	21,050		19,643	20,463			
Sulfite Oxid. (%)	24.4	25.9			27.9	28.4		30.0	30.5			
Sulfite Oxidation (M Moles/Min)	4,150	4,680			5,995	5,978		5,893	6,241			
$CaSO_3 \cdot 1/2\ H_2O$ formation (M Moles/Min)	1,319	10	13,009	12,991	2,825	3,076	11,687	11,562	-3,306	-5,086	23,284	19,592
$CaSO_4 \cdot 2\ H_2O$ formation (M Moles/Min)	1,430	1,721	3,695	3,346	-676	-262	6,839	6,373	161	1,120	6,154	2,205
$CaCO_3$ dissolution (M Moles/Min)	9,503	10,102	7,893	7,744	12,601	12,152	7,782	9,124	9,861	9,394	15,975	8.199
Error in Total Sulfur material balance $(\frac{In - Out}{In}) \times 100$	-14.8	-3.9	-5.6	2.2	-16.0	-20.9	-31.2	-4.5				

*System remainder includes hold tank, surge tanks and clarifier

A summary of the rate calculations are shown in Tables K-6 through K-11 in Appendix K. Tables 4-3a and 4-3b summarize the rate results obtained from the limestone tail-end tests. In order to determine the reliability of rate data from these experiments, the following criteria were used:

(1) The rate of SO_2 removal from the gas should always be greater than the sum of calcium sulfite and calcium sulfate precipitation rates in the system (marble bed and system remainder).

(2) The rate of SO_2 removal from the gas should be equal to the rate of limestone dissolution in the system (marble bed and system remainder).

(3) The sulfite analysis should be reliable (discussed in section 4.3.2).

Table 4-4 lists these criteria for the limestone tail-end experiments and indicates whether or not each criterion is satisfied. The following tests were considered reliable:

26R(1), 27R(1, 2), 28R(2), 29R(1, 2), 30R(2).

The parentheses indicate the set number. The negative calcium sulfite and calcium sulfate precipitation rates in the marble bed and the hold tank could be attributed to one or both of the following:

(1) Errors resulting from the liquid sulfite analysis and/or liquid sampling techniques.

(2) The assumption that all of the oxidation in the system occurred in the marble bed may not be true. The calculation of the rate of limestone dissolution, however, should not be affected by the calcium sulfite and calcium sulfate precipitation rates, since the rate of limestone dissolution depends on the total sulfur analysis which in this case is relatively accurate.

TABLE 4-4. CRITERIA FOR DETERMINATION RELIABILITY OF LIMESTONE TAIL-END TEST

Test No.	$\Delta S_G >$ $CaSO_3 \cdot 1/2H_2O + CaSO_4 \cdot 2H_2O$		$\Delta S_G = CaCO_3$ Dissolution		Sulfite Analysis	
	Set 1	Set 2	Set 1	Set 2	Set 1	Set 2
25R	*	-	*	-	*	X
26R	X	*	X	X	X	X
27R	X	X	X	X	X	X
28R	*	X	X	X	X	X
29R	X	X	X	X	X	X
30R	*	X	*	X	X	X

X - Good

* - Bad

- - No Data

In all the limestone tail-end experiments, most of the calcium sulfite precipitation occurred in the hold tank. The fraction of total precipitation occurring in the marble bed could not be determined due to the error involved in the determination of sulfite concentration in the liquid.

Most of the calcium sulfate precipitation occurred in the hold tank when two marble beds were used. However, when one marble bed was used, the calculated precipitation rates fluctuated appreciably. This inconsistency prevented drawing any conclusions regarding where most of the calcium sulfate precipitation took place. The calcium sulfate precipitation rates, like the calcium sulfite precipitation rates, were in error for the reasons discussed above.

During the experiments with one marble bed, the rates of limestone dissolution in the marble bed and the hold tank were approximately equal. The dissolution rates in the marble bed basically did not change with the liquid to gas ratio. When two marble beds were employed, the fractional rate of dissolution of limestone in the marble bed increased from 50 percent to about 60 percent. This was expected since it was accompanied by an increase in SO_2 removal efficiency.

4.3.5 Calculation of Additive Dissolution Rate From Equilibrium Data

The dissolution rate of calcium carbonate in the marble bed was calculated from an equilibrium approach in the same manner as described in the furnace injection tests. For the first single bed calcium carbonate test, 25R, the operating line is plotted in Figure 4-2. As was determined in the soluble system tests, a stage efficiency of 90% was used in making dissolution rate calculations. The amount of calcium needed in solution in the marble bed to maintain the partial pressure corresponding to 100% stage efficiency was determined for experiment 25R from Figure 4-3.* To calculate the dissolution rate, the concentration of soluble calcium in the scrubber feed was subtracted from the calcium concentration determined above and the difference was multiplied by the inlet liquor flow rate. These results are summarized in Table 4-5.

Calculation of dissolution rates for the tests with two marble beds presented one major problem: no measured sulfur dioxide concentration between the first and second beds. If liquid analyses were used, corrections would have been necessary to account for amounts of calcium sulfite and sulfate precipitated in the scrubber or in the lines before the sample was taken. Since gas-side analysis is needed to determine the amounts of calcium sulfate and sulfite precipitated, a value for the amount of sulfur dioxide removed in the first bed could not be obtained from liquid analyses either. For these reasons, assumptions for the amount of sulfur dioxide removed in the first bed were made based on results from the single bed tests. These values were correlated to the single bed tests according to the L/G in each test; included in the L/G for the bottom bed in the two bed tests was the amount of slurry rejected from the top bed. These calculated sulfur dioxide values are presented in Table 4-6.

Figure 4-4 is the operating line diagram for the upper bed in experiment 28R; the diagram for the determination of calcium concentration is shown in Figure 4-5. Appendix L contains the diagrams for tests 29R and 30R. The rates for dissolution of calcium carbonate for the upper bed are listed in Table 4-5 along with a total dissolution rate for both beds using average dissolution values from the single-bed tests. Calcium carbonate dissolution values by material balance are also listed in Table 4-5.

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*All diagrams for experiments 26R and 27R are given in Appendix L.

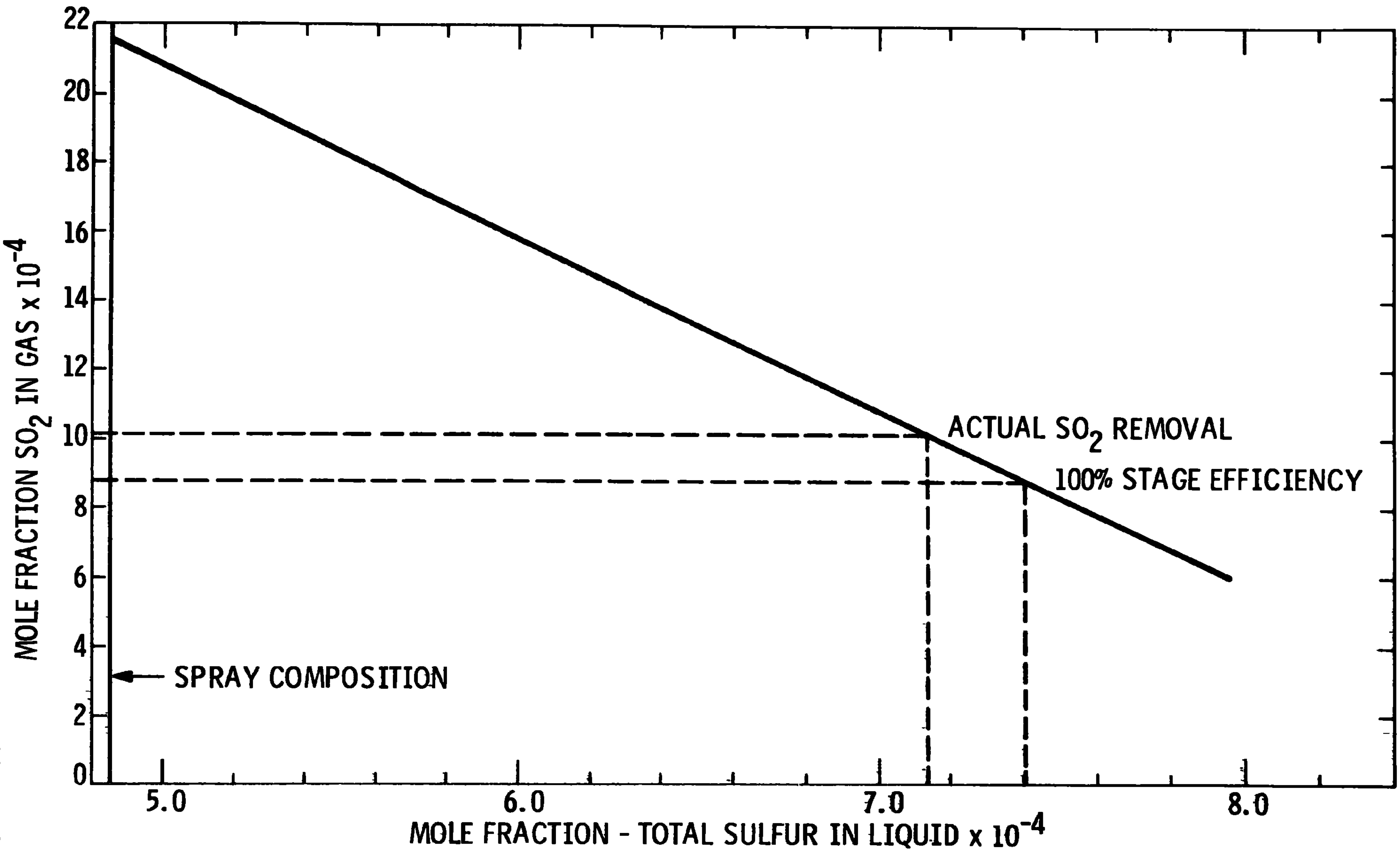


Figure 4-2

PLOT OF OPERATING LINE FOR EXPERIMENT 25R

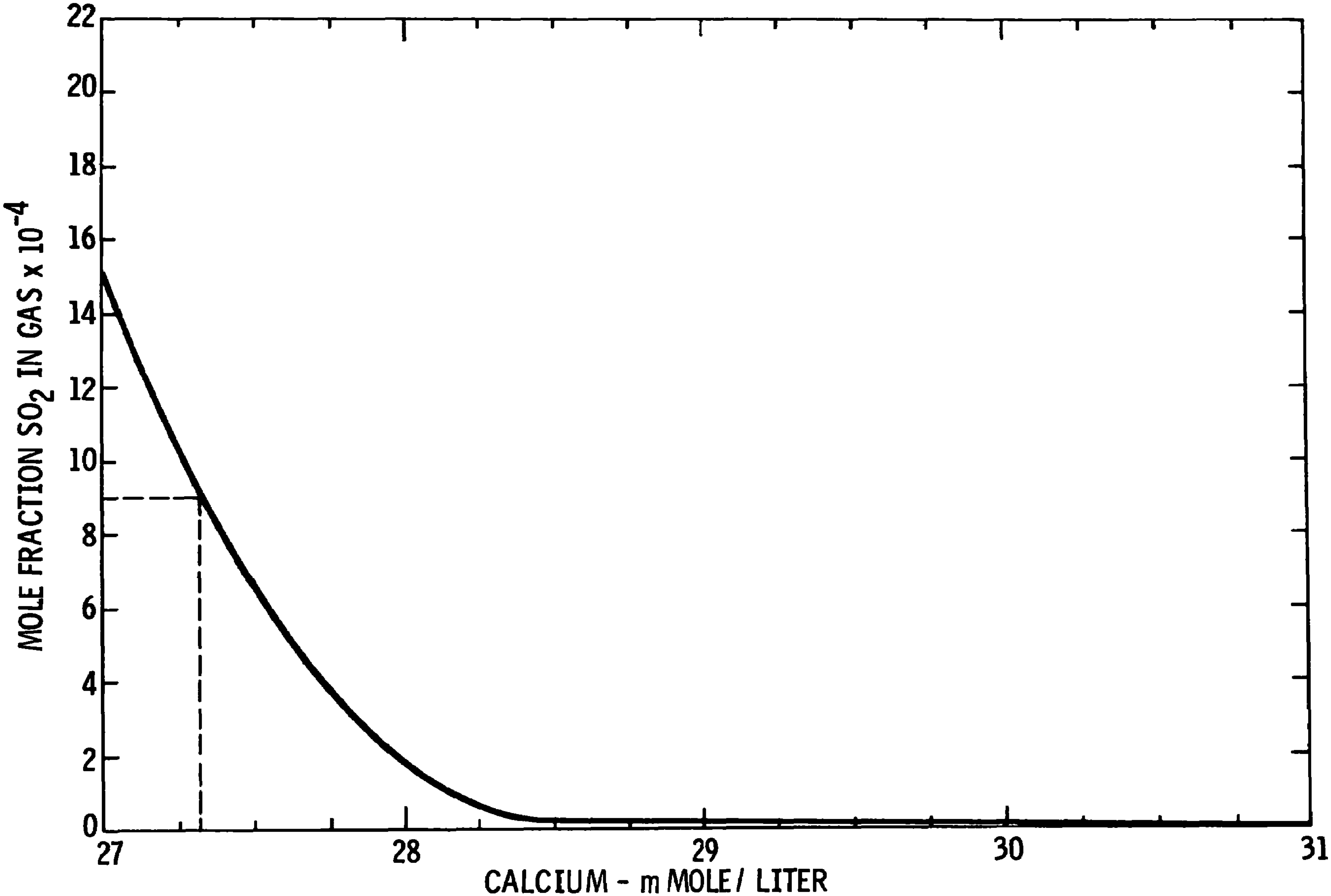


Figure 4-3

PLOT OF CALCIUM vs PARTIAL PRESSURE OF SO_2 FOR SCRUBBER EFFLUENT - EXPERIMENT 25R

TABLE 4-5. SUMMARY OF CALCIUM CARBONATE DISSOLUTION CALCULATIONS

All values are in $\frac{\text{M Moles}}{\text{Min.}}$

Experiment	Rate From Equilibrium Method: Bottom Bed	Top Bed	Total for Both Beds	Rate From Material Balance: Bottom Bed	Total for Both Beds	Amount of SO_2 absorbed
25R	3030			4832		12770
26R	6880			6769		14081
27R	5700			5092		11237
28R	5700	2380	8080		9503	17002
29R	6880	2520	9400		12601	21489
30R	6880	3080	9960		9861	19643

TABLE 4-6. ASSUMED SO_2 REMOVAL FOR LOWER BED IN TWO-BED CALCIUM CARBONATE TESTS

Experiment	28R	29R	30R
SO_2 entering lower bed	2223	2248	2240
SO_2 leaving lower bed	1091	943	940
SO_2 leaving top bed	563	299	377

SO_2 values are corrected for humidity and air leakage.

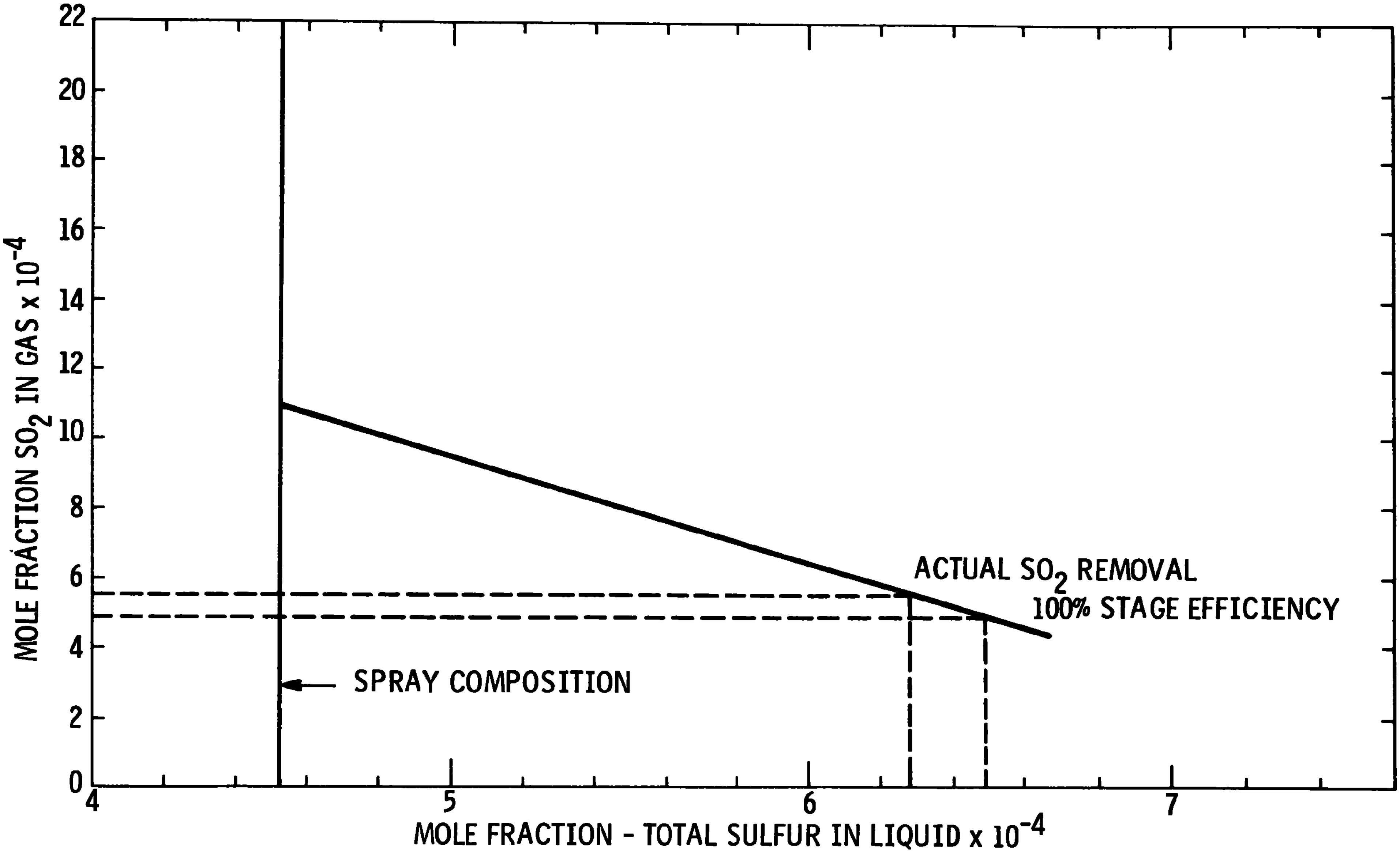


Figure 4-4

PLOT OF OPERATING LINE FOR EXPERIMENT 28R

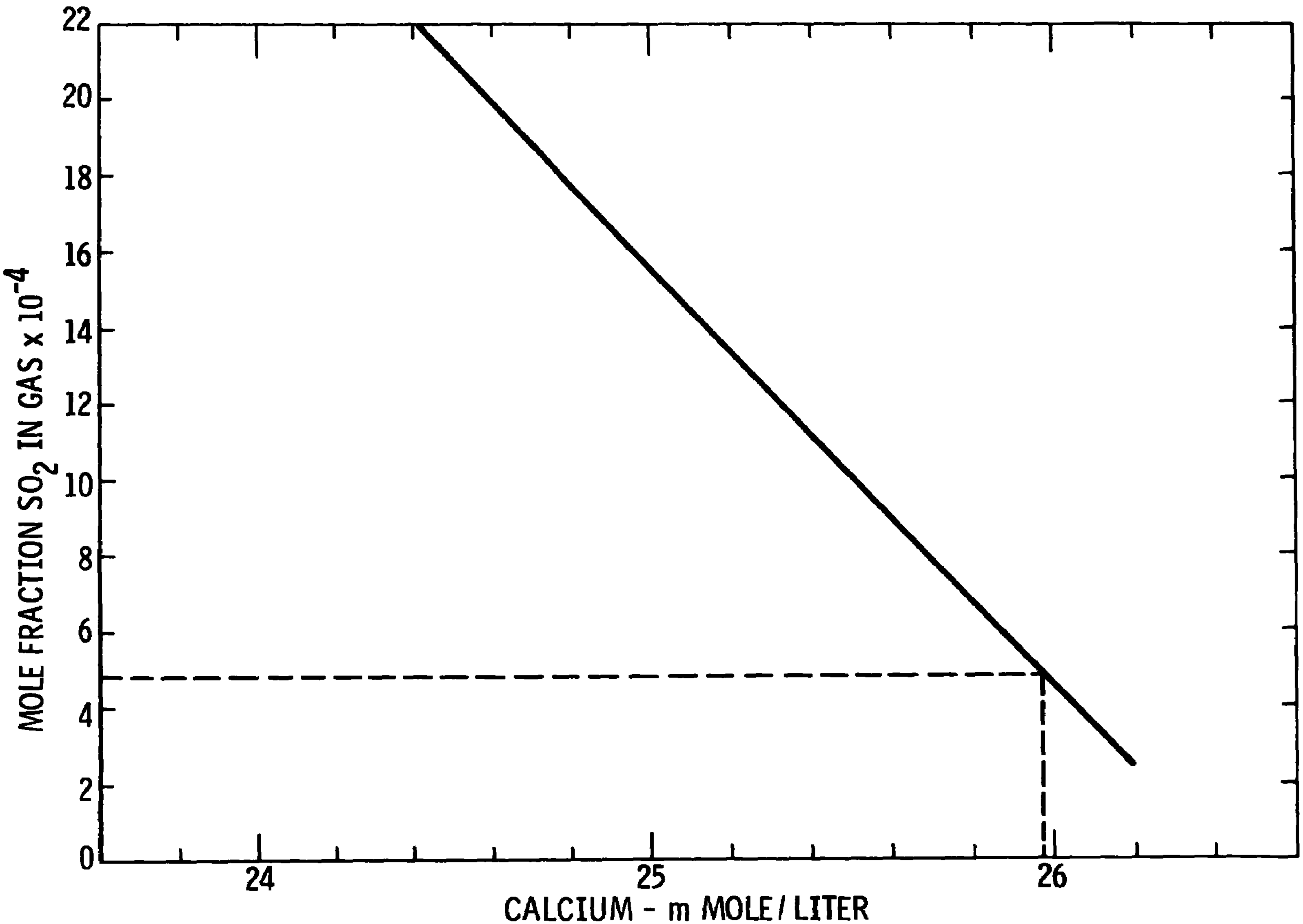


Figure 4-5

PLOT OF CALCIUM vs PARTIAL PRESSURE OF SO_2 FOR SCRUBBER EFFLUENT - EXPERIMENT 28R

Overall, the agreement between the two methods of calculation is very good. Due to the inaccurate sulfite analyses in experiment 25R, the dissolution rates obtained are probably not reliable. In general, one half of the total system dissolution took place in the marble bed, indicating that half of the SO_2 removal was because of additive dissolution and half by the soluble alkali in the scrubber feed.

4.3.6 Supersaturation of Calcium Sulfate and Sulfite

Values for the degree of supersaturation of calcium sulfate in the marble bed were calculated for Tests 25R-30R. The soluble analyses from the marble bed samples were input to a computer equilibrium program to determine the activities of calcium and sulfates. Table 4-7 presents the results of these calculations.

No calcium sulfate scaling was observed for any of the six tests, although supersaturation values are higher than the threshold values of 1.3 obtained in the furnace injection tests. No definite explanation can be given at this time for the fact that supersaturation values as high as 1.7 did not cause calcium sulfate scaling in the calcium carbonate tests.

Values of supersaturation for calcium sulfite were not calculated for the same reasons as given in Section 3.3.8 (Furnace Injection Tests). No calcium sulfite scaling was observed during the tests.

4.4 CONCLUSIONS

The following conclusions can be drawn from the tail-end limestone system tests:

(1) The performance (SO_2 removal efficiency and scaling) of the scrubber with two marble beds can be predicted by extrapolating the single marble bed test results of the C-E scrubber at Shawnee (EPA

TABLE 4-7. CALCIUM SULFATE SUPERSATURATION

Experiment No.	Bed	Temp(°C)	Relative Supersaturation	
				RADIAN*
25R	Bottom	49	0.92	0.87
26R	Bottom	48	1.62	1.51
27R	Bottom	47	1.40	1.32
28R	Bottom	44	1.73	1.34
	Top	47	1.70	1.44
29R	Bottom	46	1.53	1.40
	Top	46	1.61	1.40
30R	Bottom	43	1.54	1.37
	Top	47	1.57	1.37

*Determined by Radian Corporation under EPA Contract 68-02-0023 test facility). The SO_2 removal efficiencies of the lower and upper beds appear to be the same based on the SO_2 concentrations entering the respective beds.

(2) Above 100% stoichiometry, limestone feed rate has little or no effect on SO_2 removal efficiency in high solids systems.

(3) Calcium sulfate scale can be controlled in a closed loop system without employing liquid blowdown by maintaining 8 to 10% solids (excluding flyash) in the spray slurry. (Based on a maximum continuous run time of 10 hours).

(4) SO_2 removal can be improved significantly (8 to 10 percentage points) by increasing the liquid to gas ratio from approximately 15 to 25 GPM/1000 CFM.

(5) Calcium sulfate scaling can be controlled by maintaining the supersaturation below 1.7.

(6) More than half the additive dissolution occurs in the marble bed in spite of the short residence time in the bed.

APPENDIX A

GAS FLOW CHECK

APPENDIX A

GAS FLOW CHECK

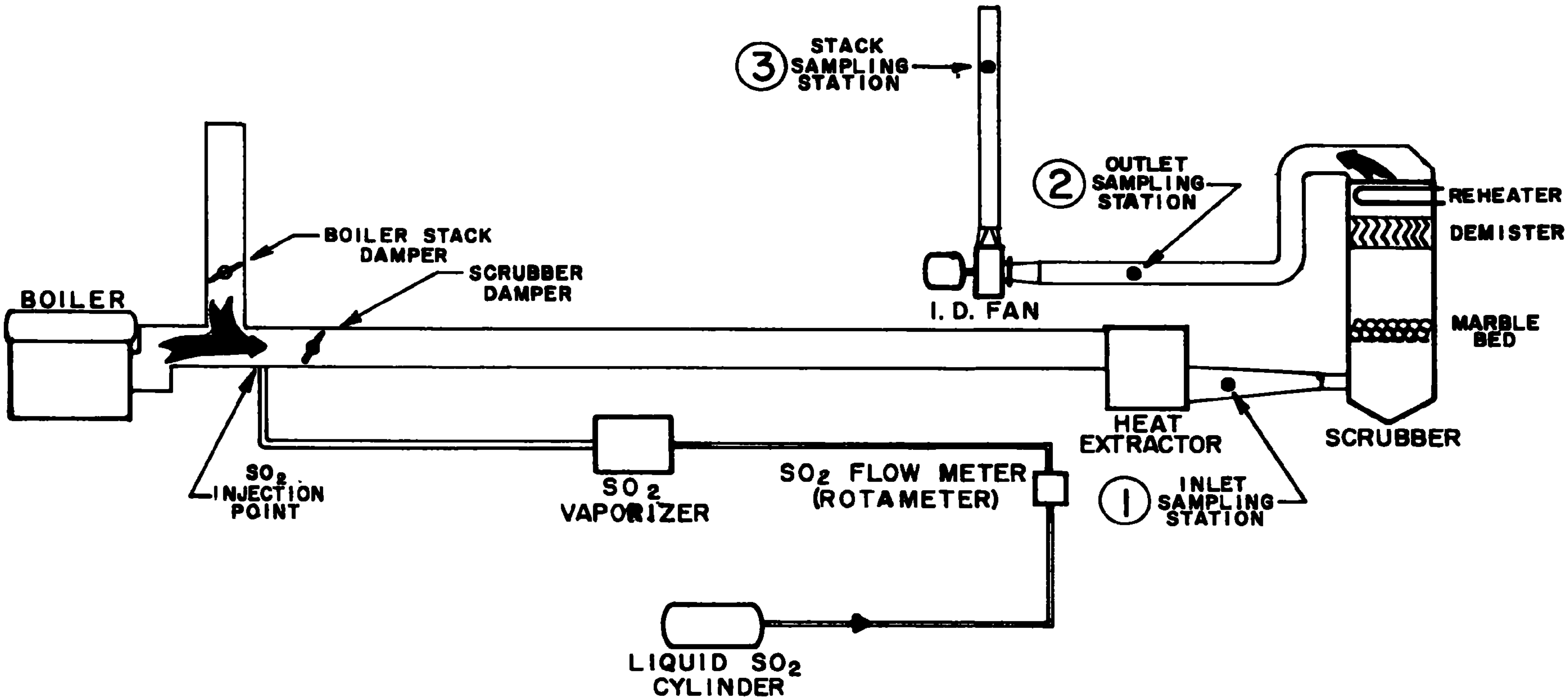
The gas flow check was divided into two parts.

a. Determination of the duct coefficient which is defined as the ratio of the average velocity to the center line velocity.

b. Comparison of gas flows obtained by using the pitot tube located at the center of the duct and the SO_2 tracer gas method.

The flow arrangement used for gas flow check is shown in Figure A-1. The gas flow was set at approximately 12,500 CFM at 130°F and 1 atmosphere. Six sets of pitot tube traverses were taken in two perpendicular directions using a standard pitot tube and the equal area method. These results are shown in Table A-1. The duct coefficient is defined as the ratio of the average velocity obtained by multiple point pitot tube traverse to the center line velocity. Once the duct coefficient is determined, the need for a multiple point velocity traverse is eliminated. The center line velocity obtained by using the pitot tube fixed at the center of the duct could be converted to the average velocity that could have been obtained with the multiple point pitot tube traverse by multiplying the center line velocity by the average duct coefficient. The average duct coefficient was found to be 0.932.

A measured quantity of gaseous SO_2 was introduced into the duct right after the boiler and long before it gets to the scrubber. The SO_2 concentrations at the inlet, outlet and stack sampling stations measured simultaneously with the center line velocity taken at the stack sampling station were used to calculate the gas flow rate and the leakage into the system. The center line velocity was converted to the average velocity of



CE AQCS PROTOTYPE — GAS FLOW CHECK

FIGURE A-1

TABLE A-1. C-E APCS - GAS FLOW CHECK
DUCT COEFFICIENT* - VELOCITY TRAVERSE

Pitot Tube Location	Set No. 1 Velocity, Ft/Sec.		Set No. 2 Velocity, Ft/Sec.		Set No. 3 Velocity, Ft/Sec.	
	N-W Direction	S-W Direction	N-W Direction	S-W Direction	N-W Direction	S-W Direction
1	63.8	69.6	62.9	67.4	62.5	69.0
2	70.7	73.7	71.9	74.8	71.1	74.7
3	74.7	75.8	74.8	76.8	74.6	75.6
4	77.5	77.7	76.9	77.3	77.3	77.3
5	76.8	74.9	77.4	74.9	77.6	76.6
6	74.9	70.8	74.9	69.6	74.9	69.7
7	67.7	64.9	67.5	64.0	70.3	63.5
Average	71.7	71.8	71.9	71.6	71.8	71.7
Duct* Coefficient	0.925	0.925	0.935	0.925	0.93	0.927

	Set No. 4		Set No. 5		Set No. 6	
1	61.7	60.9	63.3	59.6	63.3	59.6
2	69.1	67.3	68.0	66.4	68.7	66.4
3	70.6	70.2	70.6	68.7	71.0	68.7
4	71.0	70.2	71.0	71.0	70.6	69.5
5	69.1	68.7	69.1	69.1	68.7	68.4
6	66.4	65.3	66.9	65.7	66.1	65.7
7	61.3	60.5	61.3	59.6	59.6	61.3
Average	66.3	65.6	66.4	66.5	66.2	65.1
Duct* Coefficient	0.934	0.935	0.936	0.936	0.936	0.936

Average Duct Coefficient = 0.932

*Duct Coefficient = Average velocity/center line velocity the multiple point velocity traverse by multiplying it with the average duct coefficient. No liquid was introduced into the scrubber. A mixture of air and flue gas from the boiler, to which gaseous SO_2 was added, passed through the scrubber. The boiler was operated on natural gas so that the SO_2 added to the duct at the SO_2 injection point shown in Figure A-1 was the only source of SO_2. The boiler operation was necessary to provide the steam needed to vaporize SO_2 in the SO_2 vaporizer. Liquid SO_2 taken from the SO_2 cylinder was measured using a rotameter before it reached the SO_2 vaporizer. Manual SO_2 method was used to measure the SO_2 concentrations at the inlet, outlet and stack sampling stations, because the DuPont SO_2 analyzer cannot measure SO_2 concentration at more than one location at any given time. The results shown in Table A-2 show that there is very good agreement in gas flow obtained using pitot tube and SO_2 tracer gas methods. Since the gas flow measured with the pitot tube checked very well with that obtained using SO_2 as tracer gas, an independent method, it could be concluded that pitot tube is a reasonably good instrument to measure gas flow on the KDL prototype scrubber.

SO_2 concentrations at the stack sampling station should be less than or equal to those at the outlet sampling station depending upon whether or not there is leakage into the system between the stack and the outlet sampling stations. Slightly higher SO_2 concentrations at the stack compared to the outlet shown in Table A-2 are within the accuracy limits ($\pm$ 4.25%) of the manual SO_2 method. Since the leakage into the system given in Table A-2 is calculated from the SO_2 concentrations at the inlet, outlet and stack, the leakage between the inlet and outlet sampling stations appears to be slightly higher than the leakage between the inlet and stack sampling stations. The air leakage into the system was found to be 5 to 8 percent of the gas flow measured at the stack sampling station.

TABLE A-2. COMPARISON OF PITOT TUBE AND SO_2 TRACER GAS METHODS

Date of Run	10/8/71	10/8/71	10/11/71	11/1/71	11/11/71
Gas Flow, CFM @ 1 atm. and 130°F					
Center Line Velocity Converted to Multiple Point Pitot Tube Traverse using Duct Coefficient Measured at the Stack Sampling Station	11,950	11,900	11,510	11,900	12,285
SO_2 as Tracer Gas - Measured at the Stack Sampling Station	12,150	12,010	11,540	-	-
SO_2 as Tracer Gas - Measured at the Outlet Sampling Station	-	-	-	12,590	12,315
SO_2 Concentration in the Gas, PPM					
Inlet Sampling Station	1,659	2,241	2,930	2,182	1,704
Outlet Sampling Station	1,548	2,122	2,710	2,013	1,561
Stack Sampling Station	1,581	2,121	2,770	-	-
Leakage into the System, % of Gas Flow Measured at the Stack Sampling Station					
Between Inlet and Stack Sampling Stations	5.0	5.3	5.5	-	-
Between Inlet and Outlet Sampling Stations	7.2	5.3	7.5	7.8	8.4

APPENDIX B

SOLUBLE SYSTEM TEST DATA

AND RESULTS

APPENDIX B

SOLUBLE SYSTEM TEST DATA AND RESULTS

Experiment No.	1R		2R	
Date of Run	10/29/71		10/27/71	
Set No.	1	2	1	2
FG Rate (CFM @ 130°F)	10,960	10,960	10,750	10,800
Feed Composition	Dilute	Dilute	Dilute	Dilute
SW Rate (GPM)	107	107	0	0
SF Rate (GPM)	54	54	165	165
SL Rate (GPM)	149	149	88	85
SB Rate (GPM)	20	20	77	80
SW, SF Temp. (°F)	111	111	112	111
SL Temp. (°F)	121	121	129	129
SB Temp. (°F)	120	120	129	129
Inlet Gas Dew Point (°F)	117	117	118	118
Outlet Gas Dew Point (°F)	112	112	123	123
H. Extractor Outlet Gas Temp. (°F)	231	231	294	292
Reheater Inlet Gas Temp. (°F)	124	124	130	130
Overflow Pot Height (inches)	9	9	9	9
Inlet SO_2, ppm - Manual	2,138	2,090	2,025	2,045
Inlet SO_2, ppm - Analyzer	2,018	2,018	2,050	2,050
Outlet SO_2, ppm - Manual	960	936	796	830
Outlet SO_2, ppm - Analyzer	880	860	750	750
% SO_2 Removal	61.4	62.3	63.5	63.5
% Stoichiometry	30.8	30.8	40.4	40.6
Sulfur removed from Flue Gas ΔS_G, gmole/min.	11.92	11.92	12.78	12.57
Sulfur absorbed by Na_2CO_3 ΔS_L, gmole/min.	12.63	12.38	13.23	13.18
$\frac{\Delta S_G - \Delta S_L}{\Delta S_G} \times 100$	-6.0	-3.9	-3.5	-3.1

	1R	2R
O_2 in the Flue Gas, %		
Boiler Outlet	-	3.9
Scrubber Inlet	3.7	3.1
Scrubber Outlet	5.4	5.0
CO_2 in the Flue Gas, %		
Scrubber Inlet	12.1	12.7
Scrubber Outlet	11.5	12.4
NO_x, ppm		
Inlet	-	-
Outlet	-	-

Experiment No.	3R		4R	
Date of Run	10/14/71		10/28/71	
Set No.	1	2	1	2
FG Rate (CFM @ 130°F)	11,200	11,200	10,800	10,800
Feed Composition	Dilute	Dilute	Dilute	Dilute
SW Rate (GPM)	170	170	170	170
SF Rate (GPM)	0	0	0	0
SL Rate (GPM)	160	160	152.5	150
SB Rate (GPM)	15.0	15.0	15.5	15.5
SW, SF Temp. (°F)	52	52	114	117
SL Temp. (°F)	105	105	128	129
SB Temp. (°F)	102	102	126	126
Inlet Gas Dew Point (°F)	112	112	118	118
Outlet Gas Dew Point (°F)	91	91	121	121
H. Extractor Outlet Gas Temp. (°F)	318	318	306	309
Reheater Inlet Gas Temp. (°F)	108	108	130	130
Overflow Pot Height (inches)	9	9	9	9
Inlet SO_2, ppm - Manual	2,215	2,215	2,080	2,080
Inlet SO_2, ppm - Analyzer	2,095	2,095	2,030	2,030
Outlet SO_2, ppm - Manual	880	880	875	875
Outlet SO_2, ppm - Analyzer	860	860	800	790
% SO_2 Removal	59.0	59.0	60.7	61.2
% Stoichiometry	35.6	33.4	36.9	36.9
Sulfur removed from Flue Gas ΔS_G, gmole/min.	14.18	14.18	12.10	12.21
Sulfur absorbed by Na_2CO_3 ΔS_L, gmole/min.	14.73	14.45	12.21	12.10
$\frac{\Delta S_G - \Delta S_L}{\Delta S_G} \times 100$	-3.9	-1.9	-0.9	+0.9

	3R	4R
O_2 in the Flue Gas, %		
Boiler Outlet	-	3.8
Scrubber Inlet	-	3.6
Scrubber Outlet	-	5.1
CO_2 in the Flue Gas, %		
Scrubber Inlet	-	13.1
Scrubber Outlet	-	12.7
NO_x, ppm		
Inlet	-	-
Outlet	-	-

Experiment No. Date of Run	5R 11/2/71		6R 11/2/71	
Set No.	1	2	1	2
FG Rate (CFM @ 130°F)	12,980	12,980	9,180	9,180
Feed Composition	Dilute	Dilute	Dilute	Dilute
SW Rate (GPM)	106	107	110	110
SF Rate (GPM)	55	55	55	55
SL Rate (GPM)	150	145	135	135
SB Rate (GPM)	14	14	29	24
SW, SF Temp. (°F)	102	102	115	115
SL Temp. (°F)	120	120	125	125
SB Temp. (°F)	125	125	125	125
Inlet Gas Dew Point (°F)	117	117	122	122
Outlet Gas Dew Point (°F)	120	120	121	121
H. Extractor Outlet Gas Temp. (°F)	298	299	303	304
Reheater Inlet Gas Temp. (°F)	122	122	127	127
Overflow Pot Height (inches)	9	9	9	9
Inlet SO_2, ppm - Manual	2,275	2,290	-	2,110
Inlet SO_2, ppm - Analyzer	*	*	*	2,050
Outlet SO_2, ppm - Manual	1,020	1,048	-	450
Outlet SO_2, ppm - Analyzer	*	*	*	480
% SO_2 Removal	55.2	54.3	-	76.5
% Stoichiometry	26.0	26.0	-	52.3
Sulfur removed from Flue Gas ΔS_G, gmole/min.	14.72	-	-	14.06
Sulfur absorbed by Na_2CO_3 ΔS_L, gmole/min.	14.35	-	-	13.84
$\frac{\Delta S_G - \Delta S_L}{\Delta S_G} \times 100$	2.5	-	-	-1.6

	5R	6R
O_2 in the Flue Gas, %		
Boiler Outlet	3.6	3.8
Scrubber Inlet	-	3.1
Scrubber Outlet	-	4.5
CO_2 in the Flue Gas, %		
Scrubber Inlet	-	6.4
Scrubber Outlet	-	6.8
NO_x, ppm		
Inlet	143	162
Outlet	159	170

Experiment No.	7R		8R	
Date of Run	11/3/71		11/3/71	
Set No.	1	2	1	2
FG Rate (CFM @ 130°F)	11,240	11,240	11,200	11,190
Feed Composition	Dilute	Dilute	Dilute	Dilute
SW Rate (GPM)	152	152	73	73
SF Rate (GPM)	69	69	36	36
SL Rate (GPM)	185	185	93	90
SB Rate (GPM)	34.5	34.5	15	15.5
SW, SF Temp. (°F)	112	112	109	110
SL Temp. (°F)	120	121	121	125
SB Temp. (°F)	122	123	124	125
Inlet Gas Dew Point (°F)	116	116	116	116
Outlet Gas Dew Point (°F)	123	123	123	123
H. Extractor Outlet Gas Temp. (°F)	291	298	312	300
Reheater Inlet Gas Temp. (°F)	122	122	125	125
Overflow Pot Height (inches)	9	9	9	9
Inlet SO_2, ppm - Manual	1,815	1,770	*	1,782
Inlet SO_2, ppm - Analyzer	2,000	2,000	-	-
Outlet SO_2, ppm - Manual	310	670	*	829
Outlet SO_2, ppm - Analyzer	450	460	-	-
% SO_2 Removal	77.5	77.0	-	53.5
% Stoichiometry	51.3	52.4	-	34.9
Sulfur removed from Flue Gas ΔS_G, gmole/min.	16.28	16.16	-	9.39
Sulfur absorbed by Na_2CO_3 ΔS_L, gmole/min.	16.58	16.61	-	9.65
$\frac{\Delta S_G - \Delta S_L}{\Delta S_G} \times 100$	-1.8	-2.8	-	-2.8
O_2 in the Flue Gas, %				
Boiler Outlet	3.9		4.1	
Scrubber Inlet	6.3		5.2	
Scrubber Outlet	7.3		7.0	
CO_2 in the Flue Gas, %				
Scrubber Inlet	10.4		11.2	
Scrubber Outlet	10.3		10.0	
NO_x, ppm				
Inlet	178		-	
Outlet	194		-	

Experiment No.	9R		10R	
Date of Run	10/29/71		11/9/71	
Set No.	1	2	1	2
FG Rate (CFM @ 130°F)	11,000	10,910	10,680	10,690
Feed Composition	Dilute	Dilute	Dilute	Dilute
SW Rate (GPM)	116	116	112	112
SF Rate (GPM)	54	54	53	53
SL Rate (GPM)	155	155	154	153
SB Rate (GPM)	14.5	14.5	9.9	10.7
SW, SF Temp. (°F)	110	110	110	111
SL Temp. (°F)	121	121	120	120
SB Temp. (°F)	120	120	120	121
Inlet Gas Dew Point (°F)	115	115	114	114
Outlet Gas Dew Point (°F)	119	119	120	120
H. Extractor Outlet Gas Temp. (°F)	292	295	302	304
Reheater Inlet Gas Temp. (°F)	124	124	120	121
Overflow Pot Height (inches)	9	9	15	15
Inlet SO_2, ppm - Manual	-	-	2,040	2,070
Inlet SO_2, ppm - Analyzer	2,050	2,010	1,980	1,960
Outlet SO_2, ppm - Manual	-	-	620	615
Outlet SO_2, ppm - Analyzer	700	732	540	520
% SO_2 Removal	65.9	63.7	72.6	73.5
% Stoichiometry	35.7	36.5	41.2	41.4
Sulfur removed from Flue Gas ΔS_G, gmole/min.	13.76	12.96	14.22	14.32
Sulfur absorbed by Na_2CO_3 ΔS_L, gmole/min.	14.38	14.27	14.08	14.36
$\frac{\Delta S_G - \Delta S_L}{\Delta S_G} \times 100$	-4.5	-10.1	1.3	-0.3

	9R	10R
O_2 in the Flue Gas, %		
Boiler Outlet	4.1	3.9
Scrubber Inlet	3.9	3.7
Scrubber Outlet	5.0	5.0
CO_2 in the Flue Gas, %		
Scrubber Inlet	13.5	12.1
Scrubber Outlet	12.1	11.6
NO_x, ppm		
Inlet	-	159
Outlet	-	153

Experiment No.	11R		12R	
Date of Run	10/14/71		11/9/71	
Set No.	1	2	1	2
FG Rate (CFM @ 130°F)	11,500	11,400	11,210	11,200
Feed Composition	CONCENTRATED		CONCENTRATED	
SW Rate (GPM)	165	169	110	110
SF Rate (GPM)	0	0	53	53
SL Rate (GPM)	155	160	150	150
SB Rate (GPM)	14	13	17	17
SW, SF Temp. (°F)	52	52	110	110
SL Temp. (°F)	105	105	121	121
SB Temp. (°F)	100	105	122	123
Inlet Gas Dew Point (°F)	113	113	114	114
Outlet Gas Dew Point (°F)	90	90	118	118
H. Extractor Outlet Gas Temp. (°F)	288	289	295	296
Reheater Inlet Gas Temp. (°F)	108	108	122	122
Overflow Pot Height (inches)	9	9	9	9
Inlet SO_2, ppm - Manual	2,084	2,084	2,090	2,080
Inlet SO_2, ppm - Analyzer	1,980	1,980	2,020	1,980
Outlet SO_2, ppm - Manual	118	118	113	113
Outlet SO_2, ppm - Analyzer	120	120	80	100
% SO_2 Removal	94.0	94.0	94.4	94.3
% Stoichiometry	146	155	184	192
Sulfur removed from Flue Gas ΔS_G, gmole/min.	22.25	22.06	20.61	20.15
Sulfur absorbed by Na_2CO_3 ΔS_L, gmole/min.	22.40	24.75	20.10	19.35
$\frac{\Delta S_G - \Delta S_L}{\Delta S_G}$ X 100	-0.7	-7.7	2.5	4.0

	11R	12R
O_2 in the Flue Gas, %		
Boiler Outlet	-	3.9
Scrubber Inlet	-	4.1
Scrubber Outlet	-	5.3
CO_2 in the Flue Gas, %		
Scrubber Inlet	-	11.0
Scrubber Outlet	-	10.6
NO_x, ppm		
Inlet	-	-
Outlet	-	-

Experiment No.	13R		14R	
Date of Run	11/4/71		11/5/71	
Set No.	1	2	1	2
FG Rate (CFM @ 130°F)	11,330	11,400	11,300	11,360
Feed Composition	INTERMEDIATE		INTERMEDIATE	
SW Rate (GPM)	110	110	75	75
SF Rate (GPM)	54	54	36	36
SL Rate (GPM)	153	153	95	95
SB Rate (GPM)	54	54	15	14
SW, SF Temp. (°F)	110	110	115	115
SL Temp. (°F)	120	119	122	122
SB Temp. (°F)	120	120	122	122
Inlet Gas Dew Point (°F)	116	116	113	113
Outlet Gas Dew Point (°F)	123	123	122	122
H. Extractor Outlet Gas Temp. (°F)	298	298	300	299
Reheater Inlet Gas Temp. (°F)	122	122	129	129
Overflow Pot Height (inches)	9	9	9	9
Inlet SO_2, ppm - Manual	2,050	2,040	2,100	2,070
Inlet SO_2, ppm - Analyzer	2,000	1,980	2,070	2,040
Outlet SO_2, ppm - Manual	380	280	-	775
Outlet SO_2, ppm - Analyzer	420	320	780	780
% SO_2 Removal	81.5	86.3	62.4	61.7
% Stoichiometry	46.5	46.5	31.5	32.8
Sulfur removed from Flue Gas ΔS_G, gmole/min.	17.78	19.11	13.20	12.91
Sulfur absorbed by Na_2CO_3 ΔS_L, gmole/min.	18.06	18.23	12.93	12.80
$\frac{\Delta S_G - \Delta S_L}{\Delta S_G} \times 100$	-7.6	-3.0	2.0	0.9

	13R	14R
O_2 in the Flue Gas, %		
Boiler Outlet	4.2	4.2
Scrubber Inlet	3.7	4.4
Scrubber Outlet	4.3	5.3
CO_2 in the Flue Gas, %		
Scrubber Inlet	14.2	12.8
Scrubber Outlet	12.8	12.8
NO_x, ppm		
Inlet	152	-
Outlet	148	-

Experiment No.	15R		16R	
Date of Run	11/5/71		11/5/71	
Set No.	1	2	1	2
FG Rate (CFM @ 130°F)	12,980	12,980	11,500	11,500
Feed Composition	INTERMEDIATE		INTERMEDIATE	
SW Rate (GPM)	110	110	110	110
SF Rate (GPM)	55	55	55.5	55.5
SL Rate (GPM)	145	145	145	145
SB Rate (GPM)	16.5	16.5	20	20
SW, SF Temp. (°F)	110	110	110	110
SL Temp. (°F)	120	120	115	114
SB Temp. (°F)	120	120	116	115
Inlet Gas Dew Point (°F)	115	115	111	111
Outlet Gas Dew Point (°F)	118	118	118	118
H. Extractor Outlet Gas Temp. (°F)	302	299	223	222
Reheater Inlet Gas Temp. (°F)	120	121	116	115
Overflow Pot Height (inches)	9	9	9	9
Inlet SO_2, ppm - Manual	2,100	2,090	2,042	2,052
Inlet SO_2, ppm - Analyzer	2,040	2,040	2,010	2,020
Outlet SO_2, ppm - Manual	528	540	-	389
Outlet SO_2, ppm - Analyzer	500	500	350	350
% SO_2 Removal	75.6	75.6	82.5	83.2
% Stoichiometry	43.7	43.5	48.6	48.6
Sulfur removed from Flue Gas ΔS_G, gmole/min.	18.97	18.97	18.03	18.14
Sulfur absorbed by Na_2CO_3 ΔS_L, gmole/min.	18.85	18.79	17.86	17.90
$\frac{\Delta S_G - \Delta S_L}{\Delta S_G} \times 100$	0.6	1.0	1.1	1.3

	15R	16R
O_2 in the Flue Gas, %		
Boiler Outlet	3.8	4.0
Scrubber Inlet	4.1	4.4
Scrubber Outlet	5.1	5.5
CO_2 in the Flue Gas, %		
Scrubber Inlet	12.8	12.8
Scrubber Outlet	12.8	12.8
NO_x, ppm		
Inlet	-	-
Outlet	-	-

APPENDIX C

SOLUBLE TESTS - ANALYTICAL RESULTS

APPENDIX C

SOLUBLE TESTS - ANALYTICAL RESULTS

M Mole/Liter

10/29/71 Experiment No. 1R	Downcomer 1 SL	Downcomer 2 SL	Downcomer 3 SL	Pump Discharge SL	Scrubber Feed (SW, SF)	Scrubber Bottom SB
Set 1						
Time	1052	1055	1058	1100	1110	1106
Total Sulfur as $SO_4^=$	-	-	-	20.3	0.3	18.0
1)* $SO_3^= + HSO_3^-$	15.5	14.4	14.8	15.0	0.12	13.0
2) $SO_3^= + HSO_3^-$	16.7	16.3	16.4	16.2	-	15.8
Na+	-	-	-	21.1	21.0	21.0
pH, initial	5.2	5.5	5.5	5.38	10.3	5.65
pH, final	4.5	5.4	5.35	5.1	-	-
Set 2						
Time	1115	1117	1120	1125	1117	1130
Total Sulfur as $SO_4^=$	-	-	-	19.7	0.3	18.4
1) $SO_3^= + HSO_3^-$	15.1	14.0	14.8	14.8	-	13.4
2) $SO_3^= + HSO_3^-$	16.0	16.2	15.2	16.7	-	15.8
Na+	-	-	-	21.1	21.0	21.1
pH, initial	5.28	5.42	5.1	5.1	10.30	5.92
pH, final	5.19	5.35	5.02	5.02	-	6.0

10/27/71 Experiment No. 2R						
Set 1						
Time	1400	1409	1411	1416	1418	1414
Total Sulfur as $SO_4^=$	21.8	22.7	22.9	20.6	0.3	22.3
1) $SO_3^= + HSO_3^-$	17.7	13.3	16.9	15.2	0.12	15.8
2) $SO_3^= + HSO_3^-$	15.4	13.2	15.7	15.3	-	14.6
Na+	28.6	28.6	27.8	27.8	27.6	27.8
pH, initial	5.95	6.30	6.05	6.05	10.45	6.05
pH, final	5.9	6.20	5.95	5.95	-	5.95
Set 2						
Time	1420	1422	1424	1429	1430	1428
Total Sulfur as $SO_4^=$	21.8	22.3	22.9	20.9	0.3	21.8
1) $SO_3^= + HSO_3^-$	17.0	13.5	16.3	14.4	0.12	15.5
2) $SO_3^= + HSO_3^-$	15.5	12.6	13.1	-	-	-
Na+	27.8	27.8	27.8	27.6	27.3	27.6
pH, initial	6.0	6.3	6.05	6.05	10.45	5.95
pH, final	5.95	6.25	6.00	6.00	-	5.90

*1) C-E Method
2) Radian Method

	Downcomer 1 SL	Downcomer 2 SL	Downcomer 3 SL	Pump Discharge SL	Scrubber Feed (SW, SF)	Scrubber Bottom SB
	M Mole/Liter					
10/14/71						
Experiment No. 3R						
Set 1						
Time	1200				1200	1200
Total Sulfur as $SO_4^=$	22.91				0.34	18.75
$SO_3^= + HSO_3^-$	22.70				-	18.70
Na^+	26.96				26.96	26.08
pH, initial	4.65				10.93	6.00
pH, final	4.40				-	5.75
Set 2						
Time	1200				1200	1200
Total Sulfur as $SO_4^=$	22.59				0.34	19.27
$SO_3^= + HSO_3^-$	21.80				-	18.90
Na^+	25.21				25.21	25.65
pH, initial	4.0				10.9	5.9
pH, final	3.68				-	5.62
10/28/71						
Experiment No. 4R						
Set 1						
Time	1215	1216	1218	1219	-	1220
Total Sulfur as $SO_4^=$	20.6	19.7	20.5	19.7	0.3	17.1
$SO_3^= + HSO_3^-$	17.6	15.5	16.0	16.8	0.12	13.70
Na^+	18.6	16.9	17.7	17.3	-	15.1
pH, initial	24.5	24.7	24.5	24.5	24.3	24.5
pH, final	3.75	5.20	5.29	4.38	-	5.90
Set 2						
Time	1221	1222	1223	1224	1227	1225
Total Sulfur as $SO_4^=$	20.8	20.3	19.7	20.3	0.3	16.6
$SO_3^= + HSO_3^-$	17.5	15.4	16.2	16.5	0.12	13.7
Na^+	18.0	16.6	17.8	18.2	-	14.8
pH, initial	25.2	25.0	25.0	25.0	24.1	25.0
pH, final	3.93	5.35	5.36	4.50	-	6.02

11/2/71 Experiment No. 5R	Downcomer 1 SL	Downcomer 3 SL	M Mole/Liter Pump Discharge SL	Scrubber Feed (SW, SF)	Scrubber Bottom SB
Set 1					
Time	1548	1551	1553	-	1554
Total Sulfur as $SO_4^=$	-	-	23.75	0.28	19.79
$SO_3^= + HSO_3^-$	20.72	19.28	-	0	21.38
Na^+	-	-	25.00	24.56	24.56
pH, initial	5.48	5.55	5.57	10.37	5.82
pH, final	5.32	5.54	5.48	-	5.85
Set 2					
Time	1601	1603	1604	-	-
Total Sulfur as $SO_4^=$	-	-	23.95	0.28	19.79
$SO_3^= + HSO_3^-$	21.01	19.37	-	0	21.36
Na^+	-	-	24.34	24.34	24.34
pH, initial	5.30	5.55	5.58	10.38	5.85
pH, final	5.35	5.52	5.43	-	5.85
11/2/71 Experiment No. 6R					
Set 1					
Time	1320	1322	1324	1332	1330
Total Sulfur as $SO_4^=$	-	-	24.01	0.28	18.75
$SO_3^= + HSO_3^-$	21.02	20.40	-	0	14.92
Na^+	-	-	26.95	26.95	26.95
pH, initial	5.95	6.05	6.12	10.35	6.44
pH, final	5.92	-	6.08	-	6.32
Set 2					
Time	1348	1351	1356	1353	1359
Total Sulfur as $SO_4^=$	-	-	24.06	0.28	18.95
$SO_3^= + HSO_3^-$	20.41	20.51	-	0	16.67
Na^+	-	-	26.72	26.86	26.60
pH, initial	5.95	6.08	6.12	10.35	6.43
pH, final	5.88	5.99	6.02	-	6.38

11/3/71 Experiment No. 7R	Downcomer 1 SL	Downcomer 3 SL	M Mole/Liter Pump Discharge SL	Scrubber Feed (SW, SF)	Scrubber Bottom SB
Set 1					
Time	1200	1201	1204	1207	1205
Total Sulfur as $SO_4^=$	-	-	20.20	0.28	20.31
$SO_3^= + HSO_3^-$	20.13	19.55	-	0	18.55
Na^+	-	-	27.17	27.17	26.95
pH, initial	6.15	6.31	6.40	10.70	6.20
pH, final	6.05	6.25	6.21	-	6.15
Set 2					
Time	1210	1212	1220	1227	1225
Total Sulfur as $SO_4^=$	-	-	20.31	0.28	20.20
$SO_3^= + HSO_3^-$	18.43	16.91	-	0	18.60
Na^+	-	-	26.73	26.52	26.52
pH, initial	6.20	6.35	6.22	10.68	6.18
pH, final	6.06	6.326	6.20	-	6.06
11/3/71 Experiment No. 8R					
Set 1					
Time	1527	1529	1532	1536	1533
Total Sulfur as $SO_4^=$	-	-	27.60	0.27	20.05
$SO_3^= + HSO_3^-$	20.75	25.05	-	0	17.62
Na^+	-	-	33.04	32.39	31.52
pH, initial	6.00	5.87	5.92	10.46	6.48
pH, final	5.87	5.78	5.84	-	6.52
Set 2					
Time	1645	1647	1650	1654	1652
Total Sulfur as $SO_4^=$	-	-	25.52	0.27	19.27
$SO_3^= + HSO_3^-$	21.63	22.04	-	0	18.49
Na^+	-	-	29.13	29.13	29.34
pH, initial	5.64	5.65	5.62	10.38	6.38
pH, final	5.56	5.55	5.62	-	6.37

10/29/71 Experiment No. 9R	Downcomer 1 SL	Downcomer 2 SL	Downcomer 3 SL	Pump Discharge SL	Scrubber Feed (SW, SF)	Scrubber Bottom SB
			M Mole/Liter			
Set 1						
Time	1602	1607	1610	1613	1610	1615
Total Sulfur as $SO_4^=$	-	-	-	23.1	0.3	20.1
1)* $SO_3^= + HSO_3^-$	18.4	16.0	17.0	16.8	0.12	15.4
2) $SO_3^= + HSO_3^-$	18.4	16.9	18.2	17.7	-	18.2
Na+	-	-	-	24.3	24.3	24.3
pH, initial	5.65	5.95	5.90	5.82	-	6.02
pH, final	5.69	5.97	5.85	5.75	-	6.00
Set 2						
Time	1621	1625	1627	1628	1625	1633
Total Sulfur as $SO_4^=$	-	-	-	22.8	0.3	20.1
1) $SO_3^= + HSO_3^-$	18.0	15.6	16.4	16.7	0.12	15.1
2) $SO_3^= + HSO_3^-$	19.4	16.3	16.9	17.8	-	18.7
Na+	-	-	-	23.9	24.1	23.9
pH, initial	5.45	5.87	5.84	5.71	10.38	5.97
pH, final	5.52	5.92	5.79	5.72	-	5.98

*1) C-E Method
2) Radian Method

11/9/71 Experiment No. 10R	Downcomer 1 SL	Downcomer 3 SL	M Mole/Liter Pump Discharge SL	Scrubber Feed (SW, SF)	Scrubber Bottom SB
Set 1					
Time	1305	1308	1312	1314	1311
Total Sulfur as $SO_4^=$	-	-	22.91	0.27	24.06
$SO_3^= + HSO_3^-$	20.78	19.41	-	0	20.44
Na^+	-	-	26.52	26.73	26.73
pH, initial	5.62	5.62	5.80	10.38	6.04
pH, final	5.62	5.55	5.73	10.35	5.88
Set 2					
Time	1316	1318	1321	1322	1320
Total Sulfur as $SO_4^=$	-	-	23.43	0.27	23.95
$SO_3^= + HSO_3^-$	20.53	18.73	-	0	19.88
Na^+	-	-	26.73	26.73	26.73
pH, initial	5.75	5.85	5.85	10.37	6.08
pH, final	5.65	5.62	5.77	10.32	5.95
10/14/71 Experiment No. 11R					
Set 1					
Time	1430			1430	1430
Total Sulfur as $SO_4^=$	34.37			0.44	41.66
$SO_3^= + HSO_3^-$	34.25			0.13	34.75
Na^+	109.56			110.86	110.43
pH, initial	7.4			11.5	7.8
pH, final	7.2			-	7.55
Set 2					
Time	1430			1430	1430
Total Sulfur as $SO_4^=$	38.02			0.51	42.18
$SO_3^= + HSO_3^-$	33.25			0.38	34.85
Na^+	114.78			115.65	114.78
pH, initial	7.5			11.44	7.5
pH, final	7.28			-	7.25

M Mole/Liter

11/9/71 Experiment No. 12R	Downcomer 1 SL	Downcomer 3 SL	Pump Discharge SL	Scrubber Feed (SW, SF)	Scrubber Bottom SB
Set 1					
Time	1510	1512	1513	1517	1515
Total Sulfur as $SO_4^=$	-	-	31.66	0.39	37.29
$SO_3^= + HSO_3^-$	30.10	27.23	-	0	34.15
Na^+	-	-	130.43	130.43	130.43
pH, initial	7.85	8.00	8.02	10.80	7.75
pH, final	7.78	7.95	7.95	10.75	7.62
Set 2					
Time	1520	1522	1523	1526	1525
Total Sulfur as $SO_4^=$	-	-	30.46	0.39	35.62
$SO_3^= + HSO_3^-$	29.15	26.97	-	0	32.86
Na^+	-	-	133.91	133.47	133.91
pH, initial	8.00	8.15	8.12	10.80	7.95
pH, final	7.97	8.12	8.05	10.70	7.82
11/4/71 Experiment No. 13R					
Set 1					
Time	1218	1220	1223	1225	1224
Total Sulfur as $SO_4^=$	-	-	28.64	0.27	26.56
$SO_3^= + HSO_3^-$	24.88	23.51	-	0	22.05
Na^+	-	-	33.91	34.13	34.34
pH, initial	6.05	6.18	6.22	10.48	6.42
pH, final	5.95	6.13	6.12	-	6.38
Set 2					
Time	1228	1230	1237	1234	1233
Total Sulfur as $SO_4^=$	-	-	28.90	0.27	26.82
$SO_3^= + HSO_3^-$	25.65	24.30	-	0	23.10
Na^+	-	-	36.30	36.73	36.30
pH, initial	6.18	6.35	6.35	10.52	6.45
pH, final	6.08	6.22	6.10	-	6.42

Experiment No.	Downcomer 1 SL	Downcomer 3 SL	M Mole/Liter Pump Discharge SL	Scrubber Feed (SW, SF)	Scrubber Bottom SB
Set 1					
Time	1511	1513	1514	1518	1516
Total Sulfur as $SO_4^=$	-	-	32.70	0.27	22.91
$SO_3^= + HSO_3^-$	26.79	26.50	-	0	21.23
Na^+	-	-	33.47	33.69	33.47
pH, initial	5.87	5.75	5.87	10.37	6.55
pH, final	5.75	5.63	5.77	-	6.48
Set 2					
Time	1521	1523	1524	1527	1526
Total Sulfur as $SO_4^=$	-	-	32.50	0.27	23.17
$SO_3^= + HSO_3^-$	25.73	25.45	-	0	20.18
Na^+	-	-	33.04	32.60	32.60
pH, initial	5.78	5.75	5.81	10.45	6.53
pH, final	5.78	5.72	5.72	10.37	6.47
11/5/71					
Experiment No. 15R					
Set 1					
Time	1324	1326	1327	1330	1329
Total Sulfur as $SO_4^=$	-	-	31.25	0.27	30.00
$SO_3^= + HSO_3^-$	26.38	25.91	-	0	25.72
Na^+	-	-	36.08	36.08	36.30
pH, initial	5.97	6.18	6.18	10.38	6.35
pH, final	5.42	6.04	6.08	-	6.32
Set 2					
Time	1335	1337	1338	1341	1340
Total Sulfur as $SO_4^=$	-	-	31.14	0.27	29.89
$SO_3^= + HSO_3^-$	26.58	25.10	-	0	25.40
Na^+	-	-	36.08	35.86	35.86
pH, initial	6.08	6.05	6.25	10.38	6.25
pH, final	5.96	6.08	6.08	-	6.22

11/5/71 Experiment No. 16R	Downcomer 1 SL	Downcomer 3 SL	M Mole/Liter Pump Discharge SL	Scrubber Feed (SW, SF)	Scrubber Bottom SB
Set 1					
Time	1137	1139	1141	1144	1143
Total Sulfur as $SO_4^=$	-	-	29.58	0.27	26.30
$SO_3^= + HSO_3^-$	25.30	24.57	-	0	18.81
Na^+	-	-	35.24	35.43	34.95
pH, initial	6.05	6.35	6.42	10.38	6.45
pH, final	6.03	6.22	6.28	-	6.37
Set 2					
Time	1148	1149	1151	1153	1154
Total Sulfur as $SO_4^=$	-	-	29.39	0.27	26.22
$SO_3^= + HSO_3^-$	27.14	22.99	-	0	22.49
Na^+	-	-	35.21	35.52	35.21
pH, initial	6.05	6.32	6.35	10.38	6.55
pH, final	6.02	6.18	6.25	-	6.44

APPENDIX D

ANALYTICAL PROCEDURES

FOR APCS SAMPLES

APPENDIX D

ANALYTICAL PROCEDURES FOR APCS SAMPLES

The procedures for quantitatively analyzing solutions containing sulfite, sulfate, calcium, magnesium and sodium used in the APCS testing follow. These methods are time-tested and generally follow currently accepted analytical practices. It should be stressed that the instability of scrubber samples produces obvious variations and that sampling techniques are extremely important. The methods referred to are for control testing and in the hands of a good analyst produce results within 5% of the actual concentration.

APCS SULFITE*

Analysis (Liquid)

1. Transfer 20 ml of standard potassium iodide-iodate (0.0125 N = 0.5 mg SO_3/ml) to a 150 ml beaker.

Note: If sample contains solids it must be pressure filtered at the point of sampling prior to Step 2. The sample bottle (250 ml or less) should be filled to the top and capped immediately. A nitrogen purge can be maintained on samples during titration where sulfite values are below 200 ppm and precision is necessary. Samples must be analyzed within 10 minutes from time of sampling.

2. Pipet a sample volume (freshly taken-middle of sample bottle) containing less than 10 mg SO_3 beneath the surface of the KI-KIO_3 (if a 5 ml sample volume is used, procedure is good to 2000 ppm).

3. To the 150 ml beaker containing the sample and KI-KIO_3 add 1 ml of 1 + 1 HCL, and 1 ml of starch solution. Stir gently and immediately back titrate to a colorless end point with 0.100 N sodium thiosulfate.

Calculations:

$$(\text{ml of KI-KIO}_3)\ (\text{Normality}) - (\text{ml of Na}_2\text{S}_2\text{O}_3)\ (\text{Normality}) = \text{meq SO}_3/\text{sample}$$

$$\text{meq SO}_3 \times \frac{1000}{\text{Sample Vol}} \times 40 = \text{ppm SO}_3$$

$$\text{SO}_3 \times 0.800 = \text{SO}_2$$

*The EPA Arsenite method was used for comparison. This method fixes the sulfite at the point of sampling. It may be slightly more precise but requires considerably more time in preparation.

APCS SULFATE

Analyses (Soluble $SO_4^=$)

INTRODUCTION

This procedure is for total sulfur as SO_4. All sulfite is oxidized to sulfate in this method.

1. Pipet a filtered sample volume (see note) into a 1 liter volumetric flask containing 2 ml of 1 + 1 HCl, 1 ml of 30% H_2O_2 and approximately 300 ml of D. I. water. Stir on magnetic stirrer and dilute to 1 liter mark.

NOTE: For best sulfate results when using turbidmetric method, the diluted volume should contain between 20 and 80 ppm. Run at least two standards near level expected and check curve routinely.

2. ASTM 516-68 modified sulfate method:

A. Pipet 25 ml of sample into four separate beakers.

B. Place beakers on magnetic stirrers and insert plastic magnets. Adjust to reasonable mixing speed.

C. Add simultaneously to all beakers 10 ml glycerol and 5 ml of sodium chloride solution.

D. Add 0.3g of barium chloride dihydrate crystals to only three samples. (Triplicate analyses) Leave one sample as reagent blank.

E. Begin timing. Stir all solutions for 1 minute and then remove beakers.

F. Fill a 2 cm cell with reagent (blank) not containing barium chloride and prepare spectrophotometer as shown below.

Model DU

Wavelength - 400 nm   Sensitivity - 2

Slit - 0.1   Phototube - Blue

G. Let solutions containing barium chloride stand for 4 minutes ± 30 seconds and return to stirrer for 15 seconds.

H. Set spectrophotometer at zero absorbance on the reagent blank not containing the barium chloride. Then read.

CALCULATIONS

I. Record optical density of triplicate samples. If O. D. varies on any one sample more than 0.007 units, repeat analyses.

J. Run at least two standards in area of expected concentration to determine slope of curve. Whenever new reagents are made or if the room temperature varies more than 2°F, check curve with standards before running samples.

REAGENTS: Barium Chloride - Crystals of barium chloride ($BaCl_2$ $2H_2O$ screened to 20 to 30-mesh).

Glycerol Solution - (1 + 1) - Mix 1 volume of glycerol with 1 volume of water.

Sodium Chloride Solution (240 g per liter) - Dissolve 240g of sodium chloride (NaCl) in water containing 20 ml of concentrated hydrochloric acid (HCl, sp gr 1.19), and dilute to 1-liter with water. Filter the solution if turbid.

Sulfate, Standard Solution (ml = 0.100 mg SO_4--). Dissolve 0.1479 g of anhydrous sodium sulfate (Na_2SO_4) in water, and dilute with water to 1 liter in a volumetric flask. Standardize by the procedure prescribed in Section 2.

APCS SODIUM ANALYSIS

1. Take the diluted sample used in the sulfate determination and determine the sodium concentration by flame emission.

2. Prepare the necessary calibration curves using the following settings:

MODEL B		0 - 10 ppm	10 - 25 ppm	20 - 50 ppm
λ = 589 nm	Photomultiplier	D	D	C
H_2 = 3.5 psi	Sensitivity	2	1	1
O_2 = 10.5 psi				

3. In the concentration range expected adjust the slit to approximately 50% transmittance with the maximum curve standard. Peak out wavelength for optimum sensitivity and then readjust slit opening to 100% t.

4. Continually flush distilled water through aspirator when not running sample.

5. When reading sample or standard allow 30 seconds for meter reading to stabilize. Record transmittance of sample and read from graph.

6. Routinely check the transmittance of at least two standards during sample analyses.

REFERENCE: ASTM D 1428

REAGENTS: Sodium Chloride (0.2542 g per liter). Dry sodium chloride (NaCl) to constant weight at 105 C. Dissolve 0.2542 g of NaCl in water and dilute to 1 liter with water. Dilute 10 ml of this solution to 1 liter and store in polyethylene or equally alkali-metal-free containers. The latter solution contains 1000 ppb sodium. This solution can be further diluted to provide a known standard of any sodium concentration less than 1000 ppb Na+.

APCS CALCIUM

Analysis (Liquid)

1. Take a portion of the diluted sample prepared under the sulfate determination and read on atomic absorption. Dilute sample so that % absorption falls between 15 and 75% (absorbance 0.070 to 0.600).

2. With A/A warmed up and set properly according to P. E. book run at least three standards of a similar matrix salt to prepare a calibration curve. (5, 10 and 15 ppm with 3 slot burner should be adequate). Use 422.7 nm wave length.

Calculations:

Read off curve or set up ratio of absorbance to nearest standard. Then multiply by dilution factor to obtain ppm of Ca.

Ca X 1.40 = CaO

X-RAY METHOD FOR CALCIUM SULFATE SOLUTIONS ANALYSIS

The x-ray fluorescence method is advantageous when rapidity of analysis is an important factor. Analytical results in most cases are comparable and in some cases superior to those attainable by "wet chemical" methods.

Presently the technique has been applied to the analysis of sulfur (40 ppm and greater) and calcium (2 ppm and greater) in solutions.

1. Procedure

a) Dilute 10 ml of unknown 1:1 with 10% HNO_3 (by volume) spiked with H_2O_2 prepared from conc. HNO_3 (sp. gr. = 1.42).

b) Transfer 5 ml of sample to specimen cup and obtain count at S K α (1) and Ca Kα (1) peaks. Correct count for background.

APCS MAGNESIUM

Analysis (Liquid)

1. Take a portion of the diluted sample prepared under the sulfate determination and read on atomic absorption. Dilute sample so that % absorption falls between 15 and 75% (absorbance 0.070 to 0.600).

2. With A/A warmed up and set properly according to P. E. book run at least three standards of a similar matrix salt to prepare a calibration curve. (0.5, 1.0, 2.0 ppm with 3 slot burner should be adequate). Use 285.2 nm wave length.

Calculations:

Read off curve or set up ratio of absorbance to nearest standard. Then multiply by dilution factor to obtain ppm of Mg.

Mg X 1.646 = MgO

PROCEDURE FOR THE DETERMINATION OF TOTAL SO_2 IN AQUEOUS SOLUTIONS

Introduction

This method is intended to give an accurate determination of total SO_2 in aqueous solutions taken from limestone injection - wet scrubbing processes and containing interfering substances such as nitrite ion. The sample is added to an excess of buffered iodine solution. The iodine remaining after the stoichiometric SO_2 oxidation is titrated with standard sodium arsenite solution using an amperometric dead-stop method for endpoint detection.

The iodine solution is generated as needed for each determination using standard iodate solution and excess iodide ion at low pH (∿1-2). This method is more convenient and reliable than using standard iodine solutions. The iodine solution is buffered to pH 6.0-6.2 to inhibit sulfite-nitrite and nitrite-iodine (iodide) reactions. This also inhibits the air oxidation of iodide. Arsenite solutions give more accurate results than thiosulfate solutions in the presence of nitrite and are also more stable under ordinary conditions. The deadstop end-point detection method gives more reliable and accurate results than starch indicators, etc. In practice, the deadstop method is also convenient and simple.

In this method the order of addition of reagents and other procedures are critical and the procedure given should be followed closely.

Apparatus

1) 50 ml burette (preferably an automatic burette)
2) magnetic stirrer

3) pipets (including 2 ml and 20 ml sizes) and bulb pipet fillers

4) 400 ml beakers (preferably graduated)

5) deadstop apparatus:

a) two platinum electrodes

b) 1.5 volt dry cell battery (a #735 "hobby battery works fine)

c) electrometer or 0-15 or 20 μA microammeter

d) voltage divider: 1.5 v to 0.1 v

Connect one electrode to one terminal of the voltage divider output (0.1 volt). Place the meter in series with the second electrode and the other voltage divider terminal.

Reagents and Solutions

Use distilled water and reagent grade chemicals for all solutions.

CAUTION: Arsenic is toxic and care should be taken when preparing and handling these solutions.

1) Sodium arsenite stock solution (0.100 mole/liter) - Weigh out accurately 9.893g arsenic trioxide (As_2O_3, primary standard, 99.99%) and dissolve in about 100 ml 2M NaOH (8g NaOH/100 ml) with stirring. Adjust the pH to about 7 to 8 with first concentrated, then 1N HCl. Add about 1g $NaHCO_3$, transfer the solution quantitatively to a 1 liter volumetric flask and dilute to the mark with distilled water. This solution will be used to make up the standard solution for iodine titration.

2) Sodium arsenite standard solution (0.0100 mole/liter) - Pipet 100.0 ml of the 0.100 mole/l sodium arsenite solution prepared in 1) into a 1 liter volumetric flask and dilute to the mark with distilled water. This solution is most conveniently and safely handled in an automatic burette assembly.

3) Potassium iodide (50 f/liter) - Dissolve 50g of iodate free KI and 0.5g of $NaHCO_3$ in freshly boiled and cooled distilled water and dilute to one liter. Alternatively, 45g of iodate-free NaI may be used in place of the KI. The water is boiled or otherwise deaerated to remove dissolved oxygen which might oxidize iodide to iodine causing errors in the determination.

4) Potassium iodate standard solution (0.0833) mole/liter)- Dissolve 8.917g of potassium iodate (KIO_3), dried at 120°C, and 0.5g of sodium bicarbonate ($NaHCO_3$) in distilled water and dilute to 500 ml in a volumetric flask.

5) 1N HCl - Dilute 86 ml of concentrated reagent grade hydrochloric acid (36%) to 1 liter with distilled water.

6) pH 6.0 buffer (1 mole/liter sodium acetate, 0.05 mole/ liter acetic acid) - This solution should contain 82 g/liter anhydrous sodium acetate (or 136 g/liter of the trihydrate) and 2.9 ml/liter glacial acetic acid. It is convenient to prepare several liters of this solution at a time since about 175 ml is used for each determination. The water used to prepare this solution should be deaerated by boiling or bubbling nitrogen through it.

Procedure

The iodine-buffer solution should be prepared just prior to addition of the sample. The order of the following steps is important and should be maintained.

a) Place 20 ml of KI solution (3) in a 400 ml beaker containing a magnetic stirring bar.

b) Accurately pipet 2.00 ml of the KIO_3 solution (4) into the beaker.

c) Add 2.0 ml 1N HCl and swirl the beaker for about 10-15 seconds to ensure complete mixing and reaction.

d) Immediately add about 175 ml pH 6.0 buffer (6) being careful not to lose any solution due to splashing. Stir the solution with the magnetic stirrer at low speed.

e) Place the platinum electrodes in the solution and hook up the deadstop equipment (see apparatus). The current should be about 10-15 microamps.

f) Accurately pipet a volume of sample containing between 5×10^{-5} and 5×10^{-4} mole total SO_2 into the iodine-buffer solution. For the in-house test about 10 ml of sample should probably be used (also see j).

g) Increase the stirrer speed and begin the titration with the 0.01 mole/liter sodium arsenite solution (2) using a 50 ml burette. The color of the solution may be used as a rough guide to the approach of the end point. The iodine-red color changes to yellow about 10 ml before the end point. When the solution becomes light yellow the titration should be continued dropwise. The solution usually becomes colorless a few drops before the end point. The current will decrease about 0.2 to 1 microamp immediately before the end point and then decrease about 8-9 microamp at the end point.

h) When the large current drop described above occurs stop the titration and record the ml of sodium arsenite used. Rinse the electrodes with distilled water after removing them from the solution.

i) Run blanks each day using the above procedure without the addition of a sample. Two blanks should agree within 0.1 ml. Record the volume of titrant used in the blanks (it should be about 50 ml).

j) If the iodine color is completely discharged (the solution becomes colorless) when the sample is added, prepare a fresh iodine-buffer solution and use a smaller sample volume (5 ml). If the volume of titrant taken for the blank and sample are within 5 ml of each other, repeat the determination, using a correspondingly larger sample. If very low SO_2 concentrations are encountered modify the reagent concentrations for the determination.

Calculation and Accuracy

The concentration of total SO_2 in the sample can be calculated using the following equation.

$$C = \frac{(B-S)M}{V}$$

where:

C = concentration of total SO_2 (mole/liter)

B = volume in milliliters of arsenite solution needed to titrate the blank

S = volume in milliliters of arsenite solution needed to titrate the sample

M = molarity of the arsenite solution, mole/liter (normally 0.0100)

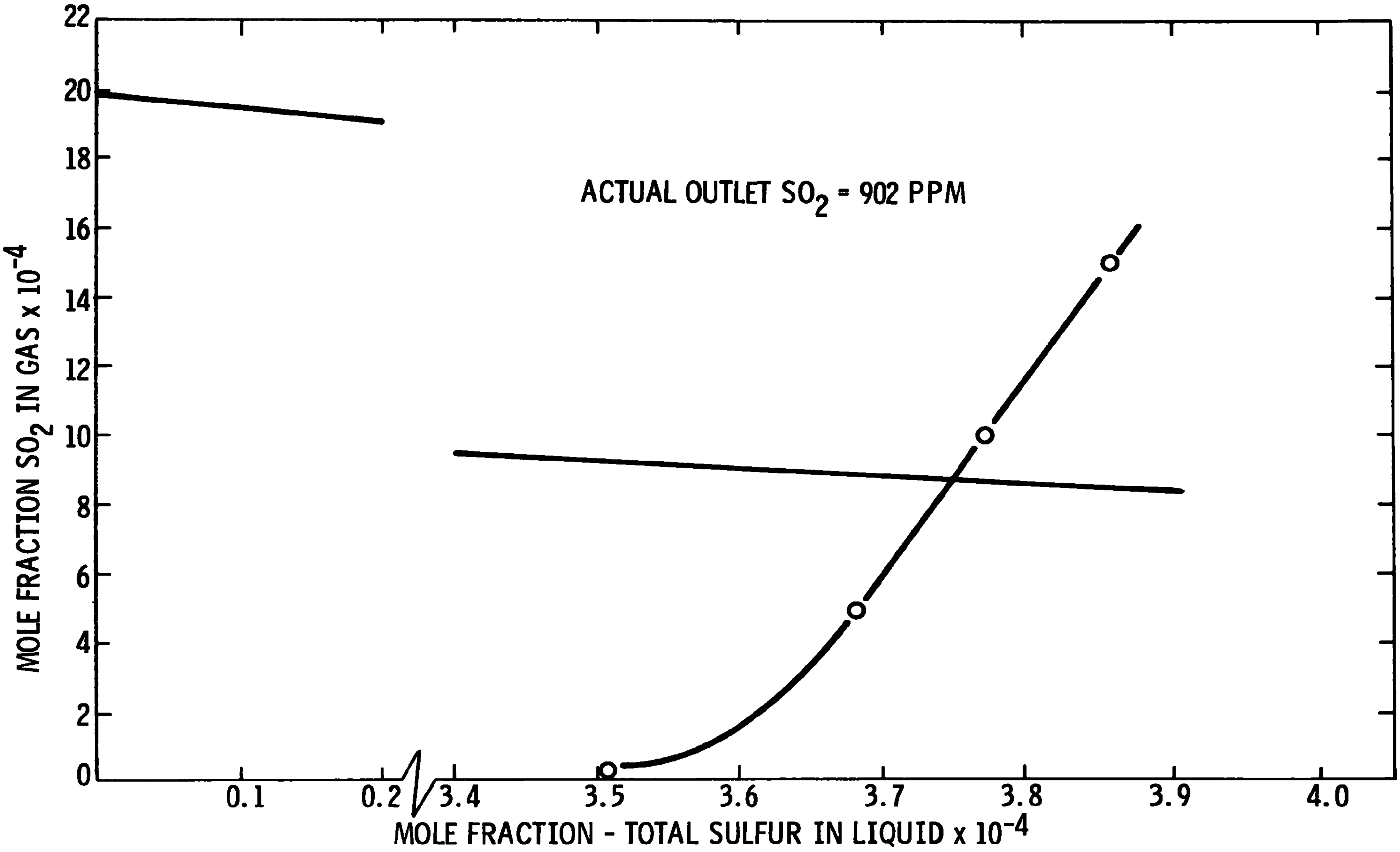
V = volume of sample used, milliliters.

Using a $NO_2^-:SO_2$ mole ratio of 50:1 the SO_2 determination has been made with a 1-3% error using this procedure. Five determinations of K_2SO_3 without nitrite added gave a relative deviation of 0.25%.

APPENDIX E

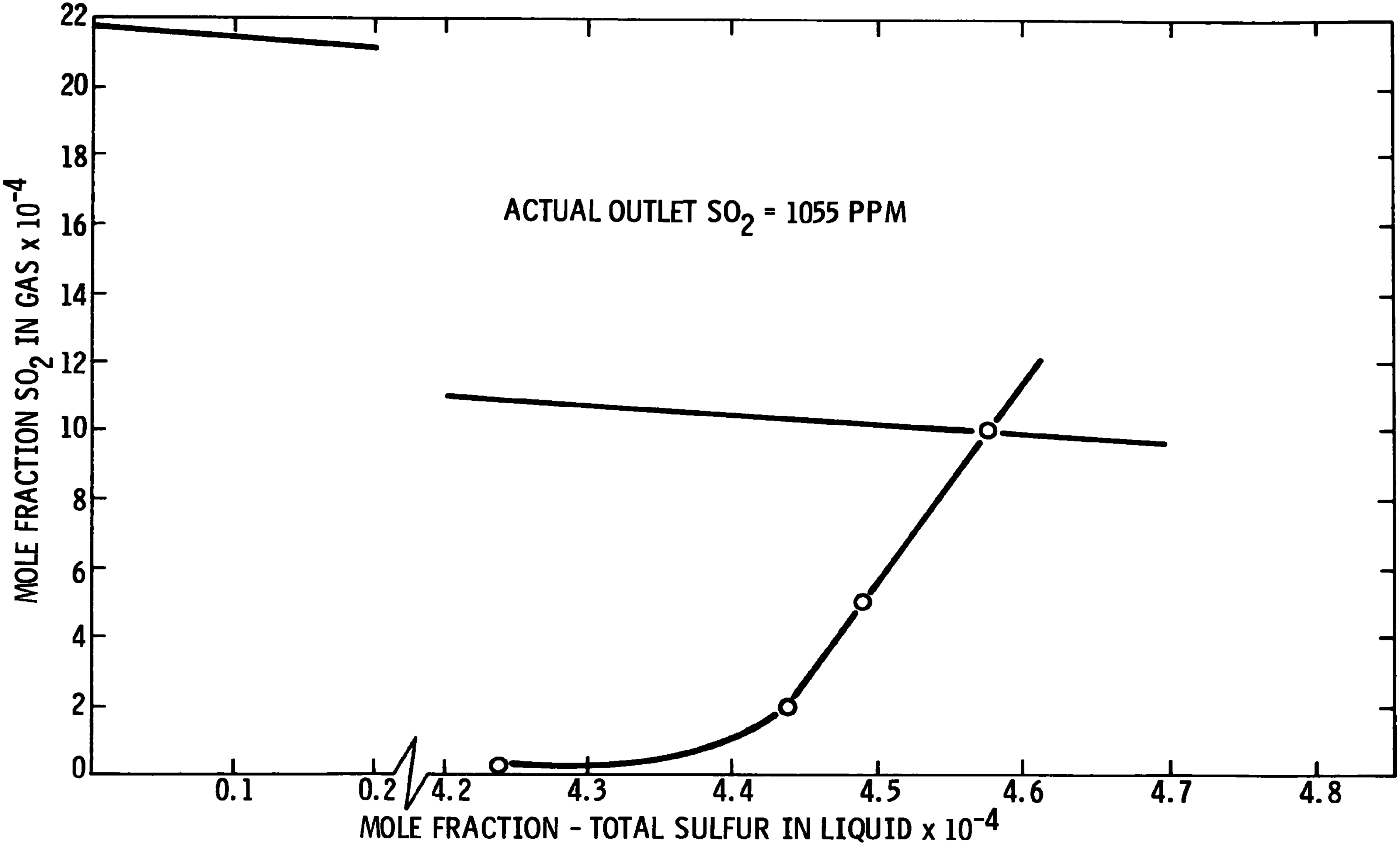
SOLUBLE SYSTEM

STAGE EFFICIENCY CALCULATION DIAGRAMS



SODIUM CARBONATE SYSTEM - EXPERIMENT 1 R-SET 2

Figure E-1



SODIUM CARBONATE SYSTEM - EXPERIMENT 5 R-SET 1

Figure E-2

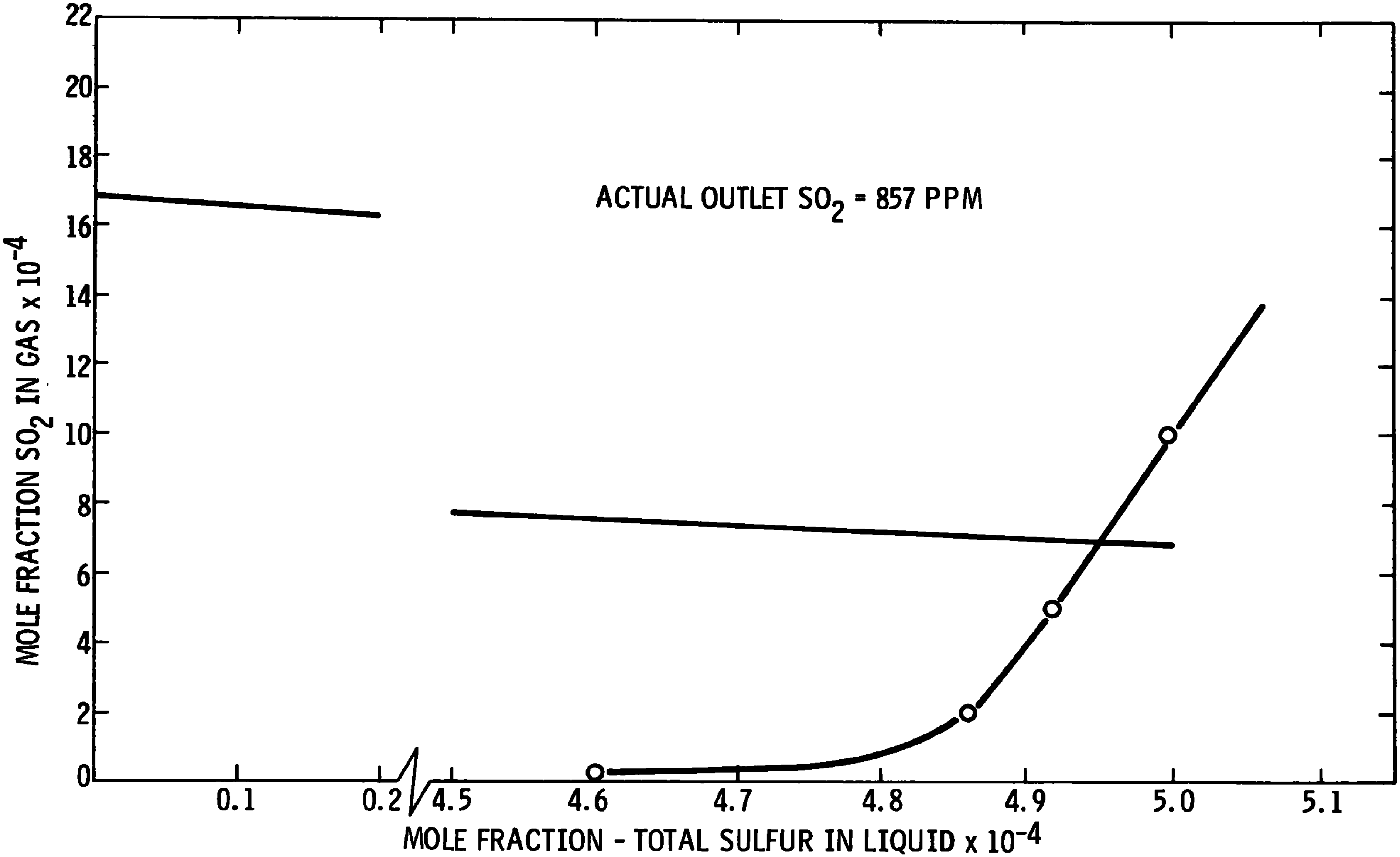
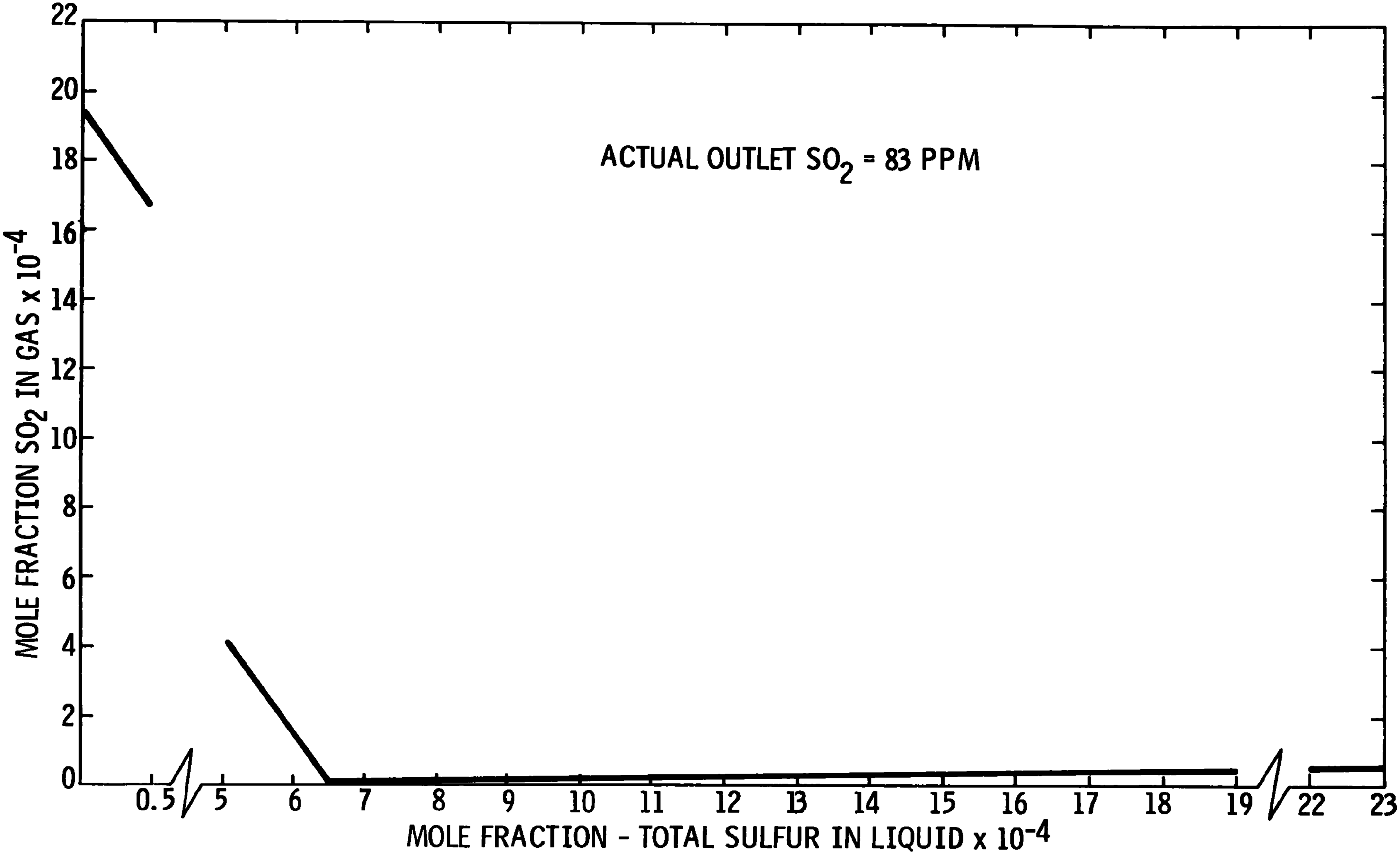


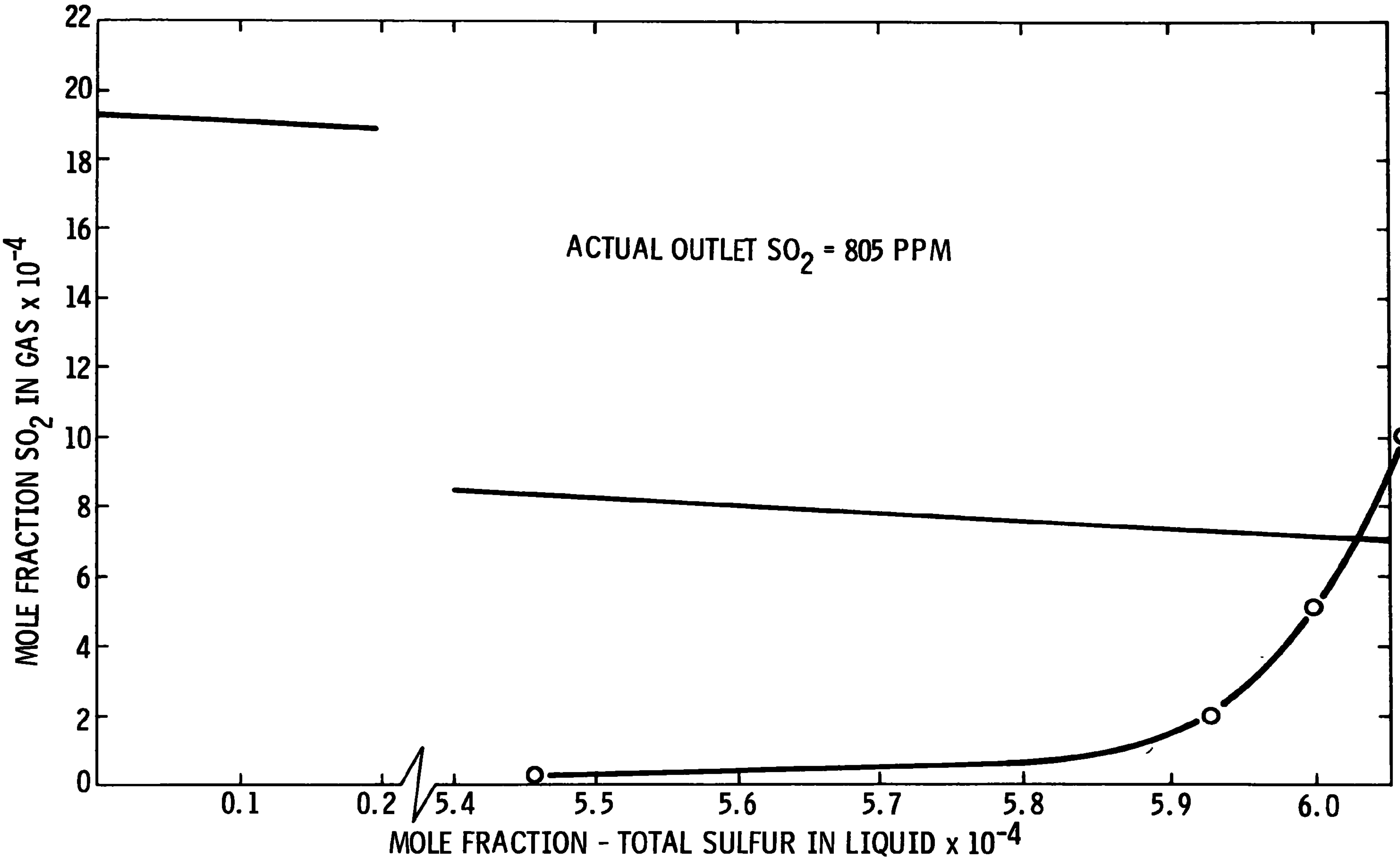
Figure E-3

SODIUM CARBONATE SYSTEM - EXPERIMENT 8 R-SET 2



SODIUM CARBONATE SYSTEM - EXPERIMENT 12 R-SET 1

Figure E-4



SODIUM CARBONATE SYSTEM - EXPERIMENT 14 R-SET 1

Figure E-5

APPENDIX F

LIMESTONE FURNACE INJECTION SYSTEM

OPERATING DATA

AND

ANALYTICAL RESULTS

TABLE F-1. C-E APCS PROTOTYPE
FURNACE INJECTION TESTS

Experiment No.	17R		18R		19R	
Date of Run	12/28/71		3/8/72		4/21/72	
Set No.	1	2	1	2	1	2
Time	1320-1405	1550-1650	1800-1900	1900-2030	1130-1200	1250
Flue Gas (FG) Rate (CFM @ 130°F)	11,000	11,000	11,000	11,000	10,000	9,940
Fly Ash + Additive Feed Rate (lb/hr.)	270	270	270	270	370	370
Spray Water SW (gpm)	110	110	205	205	201	201
Scrubber Liquid SL (gpm)	89	87	178	182	175	175
Scrubber Bottom SB (gpm)	25	28	30	30	20	20
Clarifier Liquid CL (gpm)	165	165	20	20	0	0
Liquid Blowdown LB (gpm)	55	55	0	0	35	35
Clarifier Feed CF (gpm)	165	165	25	25	35	35
Clarifier Bottom CB (gpm)	4	4	3	3	3	3
Filter Liquid FL (gpm)	4	4	3	3	2	2
Spray Water SW (°F)	100	100	120	120	106	108
Scrubber Liquid SL (°F)	123	121	122	123	115	115
Scrubber Bottom SB (°F)	121	119	122	123	116	118
Inlet Gas Dew Point (°F)	127	126	122	122	112	-
Outlet Gas Dew Point (°F)	122	121	121	121	106	-
Reheater Inlet Gas Temp. (°F)	128	124	125	125	112	112
Heat Extractor Outlet Gas Temp. (°F)	304	305	285	285	293	289
Inlet SO_2 (ppm)	1,456	1,456	1,471	1,471	1,883	1,881
Outlet SO_2 (ppm)*	764	764	447	447	925	925
Inlet O_2 (%)	5.6	5.6	4.5	4.5	10.7	-
Outlet O_2 (%)	6.1	6.1	5.8	5.8	12.0	-
Inlet CO_2 (%)	9.3	9.3	6.2	6.2	7.0	-
Outlet CO_2 (%)	7.8	7.8	6.2	6.2	6.0	-
SO_2 Removal Efficiency (%)	43.0	43.0	67.6	67.6	43.7	43.6
Stoichiometry (%)	71.0	71.0	72.8	72.8	88.8	89.5
Solid Concentration in Spray Water (%.)	-	-	3.67	3.35	1.14	1.46
Average Air Leakage (%)**	6.7	6.7	6.7	6.7	15.0	15.0
Dust Loading on the Outlet (gr./SCFM)	0.033	0.033			0.002	0.003

+High soot concnetration due to low O_2 conc. in the boiler
*Uncorrected for air leakage.
**Average air leakage.

TABLE F-1. C-E APCS PROTOTYPE
FURNACE INJECTION TESTS (Continued)

Experiment No.	20R		21R		22R	
Date of Run	4/20/72		4/26/72		4/28/72	
Set No.	1	2	1	2	1	2
Time	1035-1130	1245-1345	1330-1345	1530-1420	1315-1630	1515-1600
Flue Gas (FG) Rate (CFM @ 130°F)	10,020	10,020	9,670	10,000	9,940	9,900
Fly Ash + Additive Feed Rate (lb/hr.)	370	370	390	390	390	390
Spray Water SW (gpm)	204	205	200	200	358	355
Scrubber Liquid SL (gpm)	180	180	180	180	258	260
Scrubber Bottom SB (gpm)	20	20	20	20	100	95
Clarifier Liquid CL (gpm)	40	40	10	10	10	10
Liquid Blowdown LB (gpm)	40	40	0	0	0	0
Clarifier Feed CF (gpm)	80	80	10	10	10	10
Clarifier Bottom CB (gpm)	-	-	3	3	3	3
Filter Liquid FL (gpm)	-	-	2	2	-	-
Spray Water SW (°F)	108	109	120	120	116	119
Scrubber Liquid SL (°F)	120	119	125	123	117	120
Scrubber Bottom SB (°F)	120	119	125	123	116	119
Inlet Gas Dew Point (°F)	104.5	104.5	110	-	108.2	107.5
Outlet Gas Dew Point (°F)	113.2	113	114.5	-	112.5	117
Reheater Inlet Gas Temp. (°F)	114	114	121	120	117	119
Heat Extractor Outlet Gas Temp. (°F)	300	299	342	342	291	299
Inlet SO_2 (ppm)	1,962	1,939	2,000	1,985	2,022	2,019
Outlet SO_2 (ppm)*	1,091	1,090	735	677	514	453
Inlet O_2 (%)	-	10.5	10.4	-	10.4	-
Outlet O_2 (%)	-	11,9	12.0	-	11.9	-
Inlet CO_2 (%)	-	7.0	7.0	-	6.9	-
Outlet CO_2 (%)	-	6.0	6.0	-	6.0	-
SO_2 Removal Efficiency (%)	36.1	35.1	57.7	60.7	70.8	74.2
Stoichiometry (%)	85.0	86.0	91.5	88.8	87.8	88.4
Solid Concentration in Spray Water (%.)	0.69	0.70	8.02	6.67	8.58	-
Average Air Leakage (%)**	15.0	15.0	15.00	15.00	15.00	15.00
Dust Loading on the Outlet (gr./SCFM)	0.002	0.003	0.005	0.025+	-	-

+High soot concnetration due to low O_2 conc. in the boiler
*Uncorrected for air leakage.
**Average air leakage.

TABLE F-2. ANALYSIS OF FILTRATE SAMPLES FOR STEADY STATE DETERMINATION EXPERIMENT 17R

12-27-71

				EB					SL							
Time	#	Ca	Na	Mg	Cl	SO_4	Ca	Na	Mg	Cl	SO_4	Ca	Na	Mg	Cl	SO_4
0920	1	909		<1		1699	1140		17		2982	1078		<1		1986
1145	2	650		16		1516	761		17		2230	540		3		1566
1315	3	603		3		1434	768		10		2322	525		<1		1132
1430	4	568		6		1208	747		12		2175	569		<1		1192
1540	5	567				1033	831				2200	632				1161

12-28-71

0820	6	628		<1		1628						490		<1		1700
0930	7	513	18	<1	90	1160	752	19	13	110	2193	588	18	<1	100	1172
1030	8	504	18	<1	90	1100	828	18	21	100	2041	579	18	<1	90	1128
1250	9	549				1051	824				2154	610				1020
1400	10	528				1007	734				1872	560				1036
1750	11	485				1012	759				2071	517				974
1835	12	424				919	608				1745	513				915
1915	13	408	14		70	969	623	14		70	1693	479	14		60	1019
2015	14	420				1066	598				1718	473				990

EB - Hold Tank Effluent
SR - Scrubber Liquid
SW - Spray Water Feed

TABLE F-3. ANALYSIS OF FILTRATE SAMPLES FOR STEADY STATE DETERMINATION EXPERIMENT 18R

		Cl (ppm)				SL (ppm)				SW (ppm)			
Time	#	Ca++	$SO_3^=$	$SO_4^=$	pH	Ca++	$SO_3^=$	$SO_4^=$	pH	Ca++	$SO_3^=$	$SO_4^=$	pH
						2-1-72							
1305	1	524	-	1170	7.20	1469	1232	1461	5.45	908	0	1820	5.75
						2-2-72							
0848	2	520	140	1172	7.28	741	-	-	-	-	-	-	-
1030	3	566	20	1346	8.62	1209	1352	2217	5.51	756	100	1960	8.32
1130	4	598	44	1477	7.38	1221	1232	3021	5.45	830	160	2348	6.78
1200	5	599	32	1271	8.43	922	800	2260	5.65	807	56	2232	8.52
1230	6	613	40	1342	9.31	1151	796	2564	5.82	914	56	2422	9.49
1300	7	636	52	1407	9.25	1136	712	2425	6.21	929	40	2312	9.73
1330	8	664	40	1472	9.38	917	320	2066	8.29	909	48	2142	10.01
						2-3-72							
1130	9	700	60	1538	10.87	-	60	-	11.48	1052	56	1312	12.01
1300	10	736	60	1508	11.16	800	60	1658	8.11	1000	60	1528	11.65
1500	11	790	40	1682	10.91	826	192	1999	6.52	926	56	1922	10.95
1530	12	632	32	1475	11.22	660	232	1677	6.49	748	56	1598	10.92
1600	13	740	40	1510	11.18	794	256	1862	9.75	912	32	1679	10.88
1630	14	794	32	1553	11.22	816	12	1755	6.39	850	32	1741	11.19
1700	15	792	34	1557	11.18	828	252	1753	6.24	918	32	1679	10.98

TABLE F-4. FILTRATE ANALYSIS AND SOLID CONCENTRATION VALUES FOR STEADY STATE DETERMINATION

		CL					SW					
Experiment No.	Time	Ca++ (PPM)	$SO_3^=$ (PPM)	Total Sulfur As $SO_4^=$ PPM	$SO_4^=$ (PPM)	pH	Ca++ (PPM)	$SO_3^=$ (PPM)	Total Sulfur As $SO_4^=$ PPM	$SO_4^=$ (PPM)	pH	Percent Solids
			4-18-72						4-18-72			
20R	1100	594	352	1860	1437	6.2	660	644	2130	1357	5.8	0.4
20R	1600	659	412	1920	1420	6.0	784	552	2150	1487	5.7	0.3
			4-19-72						4-19-72			
20R	1200	792	380	2290	1834		882	592	2540	1829	6.7	0.5
20R	1300	663	552	1950	1287		790	132	2230	2071		0.5
20R	1400	811	320	2340	1956	6.0	878	376	2470	2018	6.3	0.6
20R	1500	800	316	2230	1850	6.1	879	324	2390	2001	6.3	0.8
20R	1600	823	304	2260	1859		855	268	2200	1878		1.1
			4-20-72						4-20-72			
20R	0700	745	252	2040	1737	6.25	902	180	2140	1924	9.00	1.1
20R	0730	894	240	2280	1992	6.2	952	440	2630	2102	6.4	1.1
20R	0830	893	312	2550	2175	6.3	886	356	2370	1942	5.8	1.1
20R	0900	857	336	2440	2036	6.3	829	352	2440	2017	5.8	0.9
20R	0930	877	380	2650	2194		813	300	2340	1980	5.8	0.7
20R	1000		432					320				
			4-21-72						4-21-72			
19R	-	904	460	2850	2298		1034	72	2100	2013		0.8
19R	0800	892	444	2760	2227	5.7	983	472	3050	2483	5.7	1.6
19R	0830	890	452	3000	2457		978	632	3340	2581		2.4
19R	0900	906	472	2890	2323	4.8	965	700	3420	2580	5.4	1.5
19R	0930	900	444	2940	2407	4.9	875	572	2890	2203	5.7	1.7
19R	1000	876	452	2710	2167		841	624	2730	1981		1.4
19R	1030	880	452	2690	2147		830	632	2790	2031		1.7
19R	1100	855	448	2660	2122	5.0	836	612	2820	2085	5.5	2.2

TABLE F-4. FILTRATE ANALYSIS AND SOLID CONCENTRATION VALUES FOR STEADY STATE DETERMINATION (Continued)

		CL					SW					
Experiment No.	Time	Ca++ (PPM)	$SO_3^=$ (PPM)	Total Sulfur As $SO_4^=$ PPM	$SO_4^=$ (PPM)	pH	Ca++ (PPM)	$SO_3^=$ (PPM)	Total Sulfur As $SO_4^=$ PPM	$SO_4^=$ (PPM)	pH	Percent Solids
		4-25-72					4-25-72					
21R	1300						778	900	3450	2370		4.4
21R	1400						679	240	2580	2292	6.1	6.1
21R	1500						733	120	2590	2446	7.0	7.9
21R	1530						744	-	2720	-	7.3	
21R	1600						712	120	2870	2726		8.5
		4-26-72					4-26-72					
21R	0630	789	20	1960	1936		1297	140	1470	1302		13.5
21R	0700	808	60	1940	1868		1297	40	1550	1502		10.3
21R	0730	818	60	2190	2118		686	120	2280	2136		9.1
21R	0830	849	80	2030	1934		791	112	2260	2125		9.7
21R	0900	853	80	2110	3014		721	80	2640	2544		6.8
21R	1000	844	92	2150	2039		825	128	2550	2396	6.7	6.8
21R	1100	833	64	2140	2063		853	140	2820	2652	6.2	7.8
21R	1200						866	108	2700	2570	6.2	6.3
21R	1300	846	120	2190	2046		776	88	2780	2674	9.15	5.4
		4-28-72					4-28-72					
22R	0750						791	44	2060	2067	9.4	6.5
22R	0830						857	60	2290	2218	7.4	7.1
22R	0900						913	40	2320	2272		10.2
22R	0930						848	52	2250	2187		10.5
22R	1000						817	64	2440	2363	6.7	9.0
22R	1110						756	336	3340	2936		8.4
22R	1210						729	124	3960	2811		9.5
22R	1315	860	56	1990	1992		719	40	3020	2972	9.5	8.6

TABLE F-5. RESULTS OF SOLID PHASES ANALYSES
EXPERIMENT 17R

Sample Location	Date	Wt % Solids in Slurry	Composition in Millimole/Gram Solid: Total S	Ca	Mg	SO_2	SO_3	CO_2	Weight % Undissolved
Set 1									
Marble Bed Front	12/28/71	0.211	0.869	3.22	.522	0.80	0.07	0.220	51.3
Marble Bed Back	12/28/71	0.316							
Scrubber Bottom "S"	12/28/71	1.02	0.677	5.68	.402	0.59	0.09	0.362	35.5
Spray	12/28/71	.0078							
Hold Tank Effluent	12/28/71	0.327	1.74	4.57	0.479	1.51	0.23	0.650	41.4
Set 2									
Scrubber Liquid "T" 1	12/28/71	0.274	0.939	3.40	.448	0.52	0.42	0.227	49.6
Scrubber Liquid "T" 2	12/28/71	0.251	1.002	3.68	.488	0.55	0.45	0.236	53.7
Scrubber Liquid "T" 3	12/28/71	0.269	0.914	3.57	.506	0.49	0.42	0.224	51.7
Scrubber Bottom "T" 1	12/28/71	0.850	1.012	5.52	.430	0.88	0.13	0.566	41.9
Scrubber Bottom "T" 2	12/28/71	0.904	1.012	5.59	.435	0.78	0.23	0.554	41.5
Hold Tank Effluent	12/28/71	0.327	1.74	4.56	.479	1.51	0.23	0.650	41.4
Marble Bed Front	12/28/71	0.163	0.765	3.28	.498	0.30	0.46	0.296	55.7
Marble Bed Back	12/28/71	0.293							
Scrubber Bottom "S"	12/28/71	1.11	0.692	5.80	.416	0.50	0.14	0.511	41.2
Spray	12/28/71	0.0103							
Clarifier Bottom	12/28/71	1.11	2.10	3.87	.516	1.76	0.34	0.755	40.5
Filter Liquid	12/28/71	0.0139							
Filter Solid	12/28/71	79.6	0.538	4.15	.868	0.45	0.09	0.595	40.5

TABLE F-6. RESULTS OF SOLID PHASES ANALYSES
EXPERIMENT 18R

Sample Location	Date	Wt % Solids in Slurry	Composition in Millimole/Gram Solid						Weight % Undissolved
			Total S	Ca	Mg	SO_2	SO_3	CO_2	
Set 1									
Scrubber Liquid: T1	2/ 3/72	4.45	3.15	4.50	0.34	2.26	0.87	0.58	34.6
2		4.46	3.10	4.57	0.34	2.27	0.83	0.55	32.1
3		5.28	3.04	4.60	0.34	2.18	0.86	0.50	34.8
Scrubber Bottoms: T1	2/ 3/72	5.83	2.50	4.81	0.41	1.57	0.93	0.52	35.1
2		6.00	2.62	4.62	0.41	1.63	0.99	0.61	35.9
3		6.15	2.60	4.69	0.40	1.73	0.87	0.73	36.0
Clarifier Liquid	2/ 3/72	.017							
Hold Tank Effluent	2/ 3/72	4.50	3.08	4.47	0.40	2.22	0.86	0.63	34.1
Marble Bed: Front	2/ 3/72	4.17	3.33	4.56	0.31	2.31	1.02	0.59	33.3
Back	2/ 3/72	4.10	3.34	4.52	0.32	2.34	1.00	0.60	34.2
Scrubber Bottoms S	2/ 3/72	5.39	2.51	4.85	0.41	1.73	0.785	0.49	36.0
Scrubber Spray	2/ 3/72	3.67	3.01	4.59	0.41	2.17	0.84	0.58	34.9
Additive	2/ 3/72		0.51	5.97	0.50	0.06	0.45	0.39	46.3
Set 2									
Scrubber Liquid: T1	2/ 3/72	4.07	3.28	4.59	0.33	2.26	1.02	0.51	34.0
2		4.12	3.16	4.54	0.33	2.32	0.84	0.54	34.5
3		3.93	3.20	4.49	0.33	2.36	0.84	0.58	34.6
Scrubber Bottoms: T1	2/ 3/72	5.26	2.36	4.80	0.41	1.63	0.73	0.62	36.3
2		5.61	2.42	4.85	0.41	1.67	0175	0.63	36.5
3		5.79	2.66	4.64	0.41	1.89	0.77	0.63	36.3
Hold Tank Effluent	2/ 3/72	3.66	2.98	4.57	0.41	2.12	0.865	0.64	34.0
Marble Bed: Front	2/ 3/72	4.10	3.18	4.50	0.32	2.32	0.86	0.49	33.2
Back		3.91	3.19	4.54	0.32	2.36	0.83	0.52	34.6
Scrubber Bottoms S		4.99	2.43	4.93	0.40	1.69	0.745	0.59	35.1
Scrubber Spray	2/ 3/72	3.35	3.08	4.47	0.40	2.20	0.88	0.54	34.6
Clarifier Bottoms	2/ 3/72		2.98	4.33	0.43	2.13	0.85	0.54	35.3

TABLE F-7. RESULTS OF SOLID PHASES ANALYSES
EXPERIMENT 19R

Sample Location	Date	Wt % Solids in Slurry	Composition in Millimole/Gram Solid: Total S	Ca	Mg	SO_2	SO_3	CO_2	Weight % Undissolved
Set 1									
Scrubber Liquid Tk 1	4/21/72	1.22	1.96	3.30	0.224	1.32	0.64	0.175	53.0
Scrubber Liquid Tk 2	4/21/72	1.22	1.90	3.31	0.222	1.29	0.61	0.166	50.2
Scrubber Liquid Tk 3	4/21/72	1.23	1.95	3.45	0.228	1.34	0.61	0.177	50.5
Scrubber Bottoms Tk 1	4/21/72	2.61	2.06	4.10	0.329	1.57	0.49	0.271	44.5
Scrubber Bottoms Tk 2	4/21/72	2.73	1.64	4.93	0.321	1.28	0.36	0.240	42.3
Scrubber Bottoms Tk 3	4/21/72	3.28	1.88	4.53	0.330	1.52	0.36	0.237	45.1
Hold Tank Effluent	4/21/72	1.39	2.26	3.85	0.200	1.60	0.66	0.172	47.7
Marble Bed: Front	4/21/72	1.50	1.83	3.68	0.244	1.24	0.59	0.171	51.1
Marble Bed: Back	4/21/72	1.38	1.90	3.47	0.221	1.28	0.62	0.171	51.7
Scrubber Bottoms S	4/21/72	3.21	1.53	4.88	0.341	1.47	0.06	0.280	45.1
Scrubber Spray	4/21/72	1.14	2.21	3.73	0.197	1.62	0.59	0.215	45.6
Set 2									
Scrubber Liquid Tk 1	4/21/72	1.21	1.85	3.39	0.240	1.22	0.63	0.161	51.1
Scrubber Liquid Tk 2	4/21/72	1.35	1.84	3.52	0.243	1.23	0.61	0.209	51.9
Scrubber Liquid Tk 3	4/21/72	1.34	1.77	3.50	0.235	1.15	0.62	0.201	50.5
Scrubber Bottoms Tk 1	4/21/72	3.27	2.13	4.19	0.336	1.58	0.55	0.333	44.0
Scrubber Bottoms Tk 2	4/21/72	3.54	1.85	4.72	0.334	1.37	0.48	0.349	42.0
Scrubber Bottoms Tk 3	4/21/72	3.10	1.90	4.16	0.334	1.45	0.45	0.335	43.4
Hold Tank Effluent	4/21/72	1.49	2.05	3.84	0.215	1.45	0.60	0.189	45.5
Marble Bed: Front	4/21/72	1.67	1.66	3.98	0.265	1.18	0.48	0.198	48.6
Marble Bed: Back	4/21/72	1.52	1.79	3.89	0.255	1.15	0.64	0.243	48.9
Scrubber Bottoms S	4/21/72	4.19	1.42	5.01	0.350	1.33	0.09	0.402	42.4
Scrubber Spray	4/21/72	1.46	2.01	4.01	0.224	1.41	0.60	0.180	45.4
Fly Ash and Lime			0.45	5.81	0.500			0.455	45.8
Fly Ash and Lime			0.54	5.78	0.498				47.6

TABLE F-8. RESULTS OF SOLID PHASES ANALYSES
EXPERIMENT 20R

Sample Location	Date	Wt % Solids in Slurry	Composition in Millimole/Gram Solid: Total S	Ca	Mg	SO_2	SO_3	CO_2	Weight % Undissolved
Set 1									
Scrubber Liquid Tk 1	4/20/72	0.735	1.67	3.18	0.300	0.98	0.69	0.205	50.3
Scrubber Liquid Tk 2	4/20/72	0.743	1.57	3.34	0.307	0.98	0.59	0.209	51.2
Scrubber Liquid Tk 3	4/20/72	0.691	1.58	3.79	0.370	1.03	0.55	0.172	52.2
Scrubber Bottoms Tk 1	4/20/72	2.67	1.72	4.61	0.483	1.37	0.35	0.384	40.8
Scrubber Bottoms Tk 2	4/20/72	1.87	1.98	4.73	0.578	1.53	0.45	0.199	42.2
Scrubber Bottoms Tk 3	4/20/72	2.27	1.83	4.41	0.482	1.51	0.32	0.327	44.1
Clarifier Liquid	4/20/72	0.013				0.93			
Hold Tank Effluent	4/20/72	0.738	2.05	3.73	0.241	1.44	0.61	0.201	41.9
Marble Bed: Front	4/20/72	0.983	1.53	3.67	0.315	1.05	0.48	0.210	51.4
Marble Bed: Back	4/20/72	0.868	1.47	3.40	0.290	0.97	0.50	0.150	54.1
Scrubber Bottoms S	4/20/72	2.53	1.36	4.87	0.364	1.20	0.16	0.249	44.3
Scrubber Spray	4/20/72	0.694	2.00	3.77	0.251	1.42	0.58	0.181	48.8
Set 2									
Scrubber Liquid Tk 1	4/20/72	0.72	1.46	2.72	0.251	0.93	0.53	0.163	55.4
Scrubber Liquid Tk 2	4/20/72	0.703	1.42	3.08	0.290	0.95	0.47	0.204	58.3
Scrubber Liquid Tk 3	4.20/72	0.697	1.41	4.46	0.366	0.94	0.47	0.158	58.8
Scrubber Bottoms Tk 1	4/20/72	2.03	1.79	3.05	0.287	1.26	0.53	0.278	45.2
Scrubber Bottoms Tk 2	4/20/72	2.06	1.73	4.53	0.367	1.44	0.29	0.310	45.2
Scrubber Bottoms Tk 3	4/20/72	2.06	1.59	4.28	0.362	1.24	0.35	0.346	44.0
Hold Tank Effluent	4/20/72	0.665	1.93	3.61	0.249	1.30	0.63	0.217	47.9
Marble Bed: Front	4/20/72	0.843	1.26	3.70	0.318	1.03	0.23	0.223	54.2
Marble Bed: Back	4/20/72	0.756	1.21	3.21	0.320	0.88	0.33	0.192	55.7
Scrubber Bottoms S	4/20/72	2.26	1.21	4.86	3.84	1.16	0.05	0.299	49.1
Scrubber Spray	4/20/72	0.699	1.79	3.70	0.250	1.28	0.51	0.192	49.1

TABLE F-9. RESULTS OF SOLID PHASES ANALYSES
EXPERIMENT 21R

Sample Location	Date	Wt % Solids in Slurry	Composition in Millimole/Gram Solid: Total S	Ca	Mg	SO_2	SO_3	CO_2	Weight % Undissolved
Set 1									
Hold Tank Effluent	4/26/72	8.02	3.53	4.37	.245	2.27	1.26	0.250	36.2
Marble Bed: Front	4/26/72	8.09	3.46	4.46	.216	2.26	1.20	0.235	36.7
Marble Bed: Back	4/26/72	9.10	3.65	4.50	.200	2.40	1.25	0.227	34.7
Clarifier Bottoms	4/26/72		2.65	4.21	.295	1.66	0.99	0.394	32.9
Set 2									
Hold Tank Effluent	4/26/72	6.67	3.20	4.11	.186	2.35	0.85	0.200	35.9
Marble Bed: Front	4/26/72	7.65	3.38	4.11	.184	2.28	1.10	0.241	36.5
Marble Bed: Back	4/26/72	7.83	3.35	4.51	.194	2.22	1.13	0.211	36.0

TABLE F-10. RESULTS OF SOLID PHASES ANALYSES
EXPERIMENT 22R

Sample Location	Date	Wt % Solids in Slurry	Composition in Millimole/Gram Solid: Total S	Ca	Mg	SO_2	SO_3	CO_2	Weight % Undissolved
Set 1									
Hold Tank Effluent	4/28/72	8.58	3.55	4.37	.190	2.32	1.23	0.205	35.3
Marble Bed: Front	4/28/72	7.84	3.61	4.44	.200	2.35	1.26	0.196	35.7
Marble Bed: Back	4/28/72	8.51	3.83	4.52	.188	2.52	1.31	0.243	35.1
Set 2									
Marble Bed: Front	4/28/72	9.18	3.75	4.44	.172	2.40	1.35	0.146	34.9
Marble Bed: Back	4/28/72	9.82	3.85	4.53	.155	2.51	1.34	0.133	34.6
Additive			0.50	6.09	.483	0.08	0.42	0.469	47.4

TABLE F-11. LIQUID CHEMICAL ANALYSIS AT STEADY STATE EXPERIMENT 17R

Concentration in m moles/liter

Set No.	Time	Sampling Point	Ca^{++} RAD.	Ca^{++} C-E	Mg^{++}	Na^{+}	$CO_3^{=}$	Total S RAD.	Total S C-E	$SO_3^{=}$ RAD.	$SO_3^{=}$ C-E	Cl^{-}	Tot. N	pH Low / High	Temp °C
1	1331	Marble Bed Back	18.6	19.3				25.5	25.84	8.57	8.9				
1	1322	Marble Bed Front	22.0	18.8	0.20	0.76	1.10	22.2	21.98	8.95	9.0	2.65	0.73	4.55/ 5.5	49.5
1	1347	Scrubber Bottoms (Scrubber)	16.8	16.8			0.27	12.9	12.61	1.26	1.0	2.81	0.73	10.6/ 10.8	47.0
1	1400	Spraywater	12.6	13.7	0.01	0.74	0.13	10.3	11.27	0.84	1.0	2.13		11.18	37.5
1	1445	Scrubber Liquid at Tank		19.9					23.75		8.9			5.78/ 5.86	
1	1457	Scrubber Bottom at Tank		17.4					11.30		1.0			11.15/11.22	
1	1537	Hold Tank Effluent	12.6	11.7	0.07	0.68	0.26	10.0	10.90	1.30	1.5	2.06		10.75	37.5
1		Make Up Water	1.08			0.45									
2	1701	Marble Bed Back	21.45	20.0		0.75		25.2	24.06	9.23	8.6			4.45/ 4.75	47.5
2	1650	Marble Bed Front	19.0	18.2	0.27	0.68	0.87	21.6	21.08	7.57	5.8	2.29		4.52/ 5.08	46.5
2	1712	Scrubber Bottom (Scrubber)	16.0	16.3		0.74	0.20	12.6	13.00	1.30	1.7	2.39		9.9/ 10.5	46.5
2	1725	Spray Water	13.5	12.8	0.02	0.68	0.10	9.6	10.68	0.89	1.3	11.02			37.0
2	1505	Scrubber Liquid at Tank	19.8	19.6	0.35	0.77	0.96	22.3	21.95	8.06	9.2	2.63		5.78/ 5.86	50.5
2	1517	Scrubber Bottoms at Tank	17.5	17.6	0.01	0.77	0.06	10.7	12.74	1.00	1.1	2.81		11.15/11.22	48.0
2	1537	Hold Tank Effluent	12.6	11.7	0.07	0.68	0.26	10.0	10.90	1.30	1.5	2.06		10.75	36.5
2	1605	Clarifier Bottoms	16.2	17.2		0.66	0.12	8.5	10.00	0.58	0	0.73		11.85	25.0
2		Make Up Water	1.08			0.45									

TABLE F-12. LIQUID CHEMICAL ANALYSIS AT STEADY STATE EXPERIMENT 18R

Concentration in m moles/liter

Set No.	Time	Sampling Point	Ca^{++} RAD.	Ca^{++} C-E	Mg^{++}	Na^{+}	$CO_3^{=}$	$SO_4^{=}$ RAD.	$SO_4^{=}$ C-E	$SO_3^{=}$ RAD.	$SO_3^{=}$ C-E	Cl^{-}	Tot. N	pH Low / High	Temp °C
1	1905	Marble Bed Back	24.4	24.80	3.60	1.10		19.47	24.64	7.43	3.85			5.75	45.0
1	1854	Marble Bed Front	22.8	24.10	3.70	1.05		21.25	24.04	2.55	2.06	6.44		6.23	43.0
1	1913	Scrubber Bottoms (Scrubber)	25.7	24.42		1.14		17.41	19.09	0.74	0.45	6.89		10.6	47.0
1	1923	Spray Water	23.5	22.52		1.10		17.56	18.15	0.64	0.35	6.11		10.75	46.0
1	1757	Scrubber Liquid at Tank	20.6	21.25	3.41	1.10		18.56	19.98	3.64	2.57	6.33		6.45	47.9
1	1805	Scrubber Bottom at Tank	33.2	32.72		1.11		17.20	17.20	1.10	0.89	6.91		11.4	47.9
1	1838	Hold Tank Effluent	23.3	22.97		1.06		17.5	17.35	0.80	0.53	6.17		10.75	46.0
1	1833	Clarifier Liquid	20.9	20.60		0.93		16.38	16.49	0.57	0.56	3.91		11.05	37.5
2	2022	Marble Bed Back	24.7	26.12	3.40	1.11		22.26	22.33	5.14	5.75			6.0	45.0
2	2030	Marble Bed Front	26.0	26.87	3.42	1.13		22.73	27.97	7.47	2.60	6.49		6.05	45.0
2	2040	Scrubber Bottoms (Scrubber)	25.5	24.95		1.17		18.60	19.02	0.92	0.42			10.45	47.0
2	2050	Spray Water	23.2	23.25		1.09		18.6	19.67	0.68	0.38			10.4	47.0
2	1933	Scrubber Liquid at Tank	21.8	22.17	3.40	1.12		19.78	20.46	4.92	3.25	6.45		5.90	47.8
2	1939	Scrubber Bottom at Tank	34.30	34.30		1.14		17.69	18.51	0.91	0.72	7.15		11.46	47.5
2	2011	Hold Tank Effluent	23.9	24.20		1.11		19.0	18.68	1.31	0.55	6.28		10.6	46.0
2	2067	Clarifier Liquid	22.0	22.35		0.94		17.1	16.96	0.73	0.40	4.40		11.2	37.9

TABLE F-13. LIQUID CHEMICAL ANALYSIS AT STEADY STATE
EXPERIMENT 19R

Concentration in m moles/liter

Set No.	Time	Sampling Point	Ca^{++} RAD.	Ca^{++} C-E	Mg^{++}	Na^{+}	$CO_3^{=}$	$SO_4^{=}$ RAD.	$SO_4^{=}$ C-E	$SO_3^{=}$ RAD.	$SO_3^{=}$ C-E	Cl^{-}	Tot. N	pH Low / High	Temp °C
1	1215	Marble Bed Rock	34.4		4.52		1.83	26.8		26.6				4.5	41.5
1	1208	Marble Bed Front	34.4		4.49		1.86	26.1		27.1		2.32		4.7	41.0
1	1225	Scrubber Bottoms (Scrubber)	27.7		4.20		0.83	24.45		14.75		3.24		5.6	44
1	1230	Spray Water	25.7		4.67		1.12	20.35		15.55		2.13		5.5	39
1	1125-1145	Scrubber Liquid at Tank	35.3		4.50			25.1		28.6		1.33		4.98	43.4
1	1130-1152	Scrubber Bottom at Tank	23.8		4.38		0.75	22.5		7.9		3.36		5.88	43.8
1	1200	Hold Tank Effluent	24.5		4.30		1.10	20.6		15.7		2.10		5.43	39.0
1	1157	Clarifier Liquid	22.5		3.41		0.24	23.1		6.0		2.00		5.30	23.5
1		Make Up Water	1.08			.45									
2	1340	Marble Bed Back	34.8		4.37		1.97	27.45		25.45				4.65	42.0
2	1330	Marble Bed Front	34.5		4.40		1.83	25.55		26.35		2.30		4.90	41.50
2	1345	Scrubber Bottom (Scrubber)	276		4.24		0.83	23.65		13.65		3.25		5.6	44.0
2	1325	Spray Water	25.2		4.23		1.00	21.45		15.15		2.08		5.5	37.0
2	1243-1305	Scrubber Liquid at Tank	35.3		4.41		1.36	25.2		27.31		2.26		5.02	44
2	1248-1310	Scrubber Bottom at Tank	22.2		4.07		0.17	21.9		4.5		3.17		6.15	44
2	1320	Hold Tank Effluent	25.5		4.23		0.97	20.85		15.05		2.03		5.50	39
2	1315	Clarifier Liquid	22.6		3.45		0.22	22.85		5.95		2.03		5.60	23.5

TABLE F-14. LIQUID CHEMICAL ANALYSIS AT STEADY STATE
EXPERIMENT 20R

Concentration in m moles/liter

Set No.	Time	Sampling Point	Ca^{++} RAD.	Ca^{++} C-E	Mg^{++}	Na^{+}	$CO_3^{=}$	$SO_4^{=}$ RAD.	$SO_4^{=}$ C-E	$SO_3^{=}$ RAD.	$SO_3^{=}$ C-E	Cl^{-}	Tot. N	pH Low / High	Temp °C
1	1105	Marble Bed Back	32.5		3.59		1.69	31.25		15.25				4.53	42
1	1140	Marble Bed Front	32.0		3.44	0.40	1.49	30.15		14.75		2.23		4.7	42.5
1	1200	Scrubber Bottom at Scrubber	26.1		3.32		1.38	25.3		8.1		3.01		5.93	44
1	1208	Scrubber Spray	23.4		3.18		0.93	24.7		7.9		1.89		5.72	39.0
1	1036-1105	Scrubber Liquid at Tank	31.6		3.20	0.38		30.1		15.6				5.21	44
1	1048-1110	Scrubber Bottom at Tank	21.6		3.30		0.06	18.9		1.01		3.11		10.9	45.3
1	1125	Hold Tank Effluent	23.6		3.24	0.38	0.95	24.45		7.45		2.03		5.75	40
1		Make Up Water	1.08			.45									
2	1340	Marble Bed Back	33.8		3.73		1.27	29.15		17.05				4.55	42.5
2	1350	Marble Bed Front	33.1		3.80		1.74	30.25		16.65		2.38		4.70	40
2	1357	Scrubber Bottom at Scrubber	30.0		3.62		0.70	26.6		12.0		3.13		5.70	42.5
2	1330	Scrubber Spray	26.6				0.98	25.5		10.2		2.03		5.87	44.5
2	1232-1300	Scrubber Liquid at Tank	33.9		3.65		1.42	29.1		18.3		2.04		5.10	43.5
2	1240-1307	Scrubber Bottom at Tank	24.7		3.58		0.48	23.3		2.85		3.12		6.30	44.5
2	1323	Hold Tank Effluent	25.9		3.57		0.87	24.65		10.25		2.13		5.70	40.0
2	1320	Clarifier Liquid	22.9		3.28		0.57	20.9		7.4		1.95		5.80	39.0

TABLE F-15. LIQUID CHEMICAL ANALYSIS AT STEADY STATE
EXPERIMENT 21R

Concentration in m moles/liter

Set No.	Time	Sampling Point	Ca++ RAD.	Ca++ C-E	Mg++	Na+	$CO_3^=$	$SO_4^=$ RAD.	$SO_4^=$ C-E	$SO_3^=$ RAD.	$SO_3^=$ C-E	Cl-	Tot. N	pH Low / High	Temp °C
1	1430	Marble Bed Back	22.6	24.91	16.0		1.94	33.6	31.15	7.60	10.9			5.48	46.0
1	1422	Marble Bed Front	23.6	23.05	16.8		1.98	27.8	29.30	6.70	9.50	9.22		5.69	44.0
1	1440	Scrubber Bottom at Scrubber	20.0	21.75	10.5			25.9			1.60			8.18	47.5
1	1500	Scrubber Spray	16.8	21.79	13.9		0.23	28.1	24.82	1.28	0.90	8.70		8.30	45.5
1	1320-1350	Scrubber Liquid at Tank	24.7	30.20	16.0	1.11	0.18	27.4	25.50	5.05	0.70	9.19		6.01	46.8
1	1327-1355	Scrubber Bottom at Tank	24.3	28.75	1.29		0.23	21.6	21.30	0.9	1.00	10.7		9.77	45.0
1	1405	Hold Tank Effluent	18.1		11.7	1.06	0.28	26.7		1.10		8.85		8.52	45.0
1	1400	Clarifier Liquid	19.4	20.8	4.30		0.3	21.3	22.40	0.85	1.10	3.94		9.85	29.0
2	1642	Marble Bed Back	23.6	25.45	16.6		2.04	34.4	32.50	1.20	11.65			5.38	46.5
2	1633	Marble Bed Front	20.5	24.72	16.8		1.89	26.8	29.40	1.29	9.14	9.13		5.50	44.0
2	1652	Scrubber Bottom at Scrubber	19.4	20.90	12.0		0.52	27.9	25.60	1.12	1.25	10.0		6.42	47.8
2	1700	Scrubber Spray	16.9	18.59	13.9		0.15	27.8	25.82	1.32	1.00	8.56		8.90	46.0
2	1528-1605	Scrubber Liquid at Tank	19.8	21.17	17.3		1.42	34.4	24.70	7.6	2.60	9.00		5.37	47.2
2	1535-1610	Scrubber Bottom at Tank	21.1	25.80	9.8		0.19	27.8	16.33	1.2	1.35	10.3		9.48	46.0
2	1623	Hold Tank Effluent	16.9		15.1	1.09	0.50	28.8		1.73		8.73	0.3	7.03	45.0
2	1618	Clarifier Liquid	17.6	20.7	4.72		0.29	20.8	22.35	0.98	1.50	4.60		9.90	29.9

TABLE F-16. LIQUID CHEMICAL ANALYSIS AT STEADY STATE
EXPERIMENT 22R

Concentration in m moles/liter

Set No.	Time	Sampling Point	Ca^{++} RAD.	Ca^{++} C-E	Mg^{++}	Na^{+}	$CO_3^{=}$	$SO_4^{=}$ RAD.	$SO_4^{=}$ C-E	$SO_3^{=}$ RAD.	$SO_3^{=}$ C-E	Cl^{-}	Tot. N	pH Low	pH High	Temp °C
1	1605	Marble Bed Back		22.10	19.9		0.90		35.05		8.05			5.44		42.5
1	1555	Marble Bed Front		21.75	19.9		1.44		32.10		9.64	9.81		5.35		44.0
1	1610	Scrubber Bottom at Scrubber		22.05	19.0		2.09		27.6		7.19	10.4		5.67		45.5
1	1620	Scrubber Spray		17.98	19.8		0.62		31.10		3.75	9.75		6.05		45.0
1	1335	Scrubber Liquid at Tank		27.20	18.5		0.79		39.50		18.55	9.30		5.27		46.0
1	1330	Scrubber Bottom at Tank		19.58	15.5		1.38		30.43		4.75	9.92		6.50		46.5
1		Hold Tank Effluent		16.4	17.9	1.15	0.65		29.77		1.93	9.56	0.3	6.81		45.5
1	1340	Clarifier Liquid		21.10	5.20		0.23	22.55	21.50		0.75	5.58		8.88		28.0

TABLE F-17. CHEMICAL ANALYSIS OF CANNED SAMPLES OF ADDITIVE FROM ST. LOUIS (Wt%)

Sample #	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	SO_3
				Boiler Calcined Limestone and Flyash					
LF1	29.1	10.3	9.0	39.2	0.6	0.3	1.1	0.5	4.6
LF2	31.6	11.8	10.0	29.6	2.8	0.7	1.6	1.1	5.0
LF3	33.9	11.3	9.3	34.6	3.0	0.5	1.4	0.5	3.6
LF4	31.4	10.5	8.3	36.1	3.0	0.5	1.1	1.3	4.0
LF5	27.4	10.1	8.0	36.6	3.1	0.7	1.1	0.9	4.4
LF6	15.8	7.4	7.5	44.9	2.8	0.4	0.9	0.7	4.4
LF7	20.8	10.4	7.4	37.2	3.6	0.8	1.2	0.7	4.6
				Boiler Calcined Dolomite and Flyash*					
DF1	52.0	24.8	6.4	1.5	1.5	0.3	3.0	1.3	0.3
DF2	39.1	17.8	10.5	3.8	1.0	0.3	1.9	1.1	1.2
DF3	50.2	25.8	6.4	1.9	1.4	0.5	2.7	1.8	0.4
DF4	28.4	16.0	6.6	25.7	7.4	0.6	2.0	0.8	2.3
				Flyash					
F1	50.9	23.3	7.0	4.9	1.5	0.4	2.5	11.3	1.1
F2	48.1	24.4	6.1	3.5	1.6	0.4	2.7	1.2	0.8

* Although these samples were marked as Boiler Calcined Dolomite and Flyash, there appears to be very little dolomite in DF1, DF2, and DF3.

These samples were taken randomly and the sample numbers are for C-E's use only.

TABLE F-17 (Continued). CHEMICAL ANALYSIS OF BAGGED BOILER CALCINED ADDITIVE AND FLYASH (Wt%)

Sample #	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	SO_3	TiO_5
04012	33.6	2.6	26.1	14.3	6.9	0.3	trace	0.4
04009	31.9	3.3	20.0	13.0	7.7	0.7	3.6	0.6
05011	31.2	2.4						
05012	30.9	2.5						
05013	29.7	2.3						
05014	30.9	2.5						
05015	30.9	2.4						
05016	31.8	2.4						
05017	32.4	2.4						

TABLE F-18. CHEMICAL ANALYSIS OF ADDITIVE SAMPLES FROM UNION ELECTRIC

Canned Boiler Calcined Limestone and Flyash
(m mole/g)

Sample Number	CaO	SO_3
LF1	7.00	0.58
LF2	5.29	0.625
LF3	6.18	0.45
LF4	6.45	0.50
LF5	6.54	0.55
LF6	8.02	0.55
LF7	6.64	0.54

Bagged Boiler Calcined Limestone and Flyash
(m mole/g)

04012	6.00	-
04009	5.70	0.45
05011	5.57	-
05012	5.52	-
05013	5.30	-
05014	5.52	-
05015	5.52	-
05016	5.68	-
05017	5.79	-

APPENDIX G

LIMESTONE FURNACE INJECTION SYSTEM TESTS

PROBLEMS AND MODIFICATIONS

APPENDIX G

LIMESTONE FURNACE INJECTION SYSTEM TESTS -- PROBLEMS AND MODIFICATIONS

Mechanical Performance: During the furnace injection tests several problems were encountered, resulting in lost down and correction time. The following summarizes these problems:

Additive Injection System: The additive feed into the system could not be maintained initially due to constant tripping of the fan motor used to blow the additive into the inlet gas stream. Since there was a vacuum being pulled on the discharge side of the blower, a high gas flow resulted which overloaded the motor. The problem was solved by installing an orifice on the suction side of the blower.

Scrubber Bottom Tank: The outlet line was frequently plugged as a result of solids settling due to low flow rate and lack of mixing. The problem was solved by installing a mixer and a recycle line to increase the flow rate.

SO_2 Analyzer: Dust from the gas inlet leaked into the SO_2 analyzing system despite the availability of a filter. This problem was corrected first by introducing the sampling probes ahead of the point of additive injection, and then by shielding it with a piece of pipe with the pipe cross-sectional area perpendicular to the gas flow.

Nozzle Erosion and Plugging: Nozzle erosion was an operating problem since the nozzle material (brass) was not a good erosion resistant material. Nozzle erosion resulted in a change in the spray pattern, and therefore a disruption of liquid distribution. This problem was corrected by replacing the eroded nozzles.

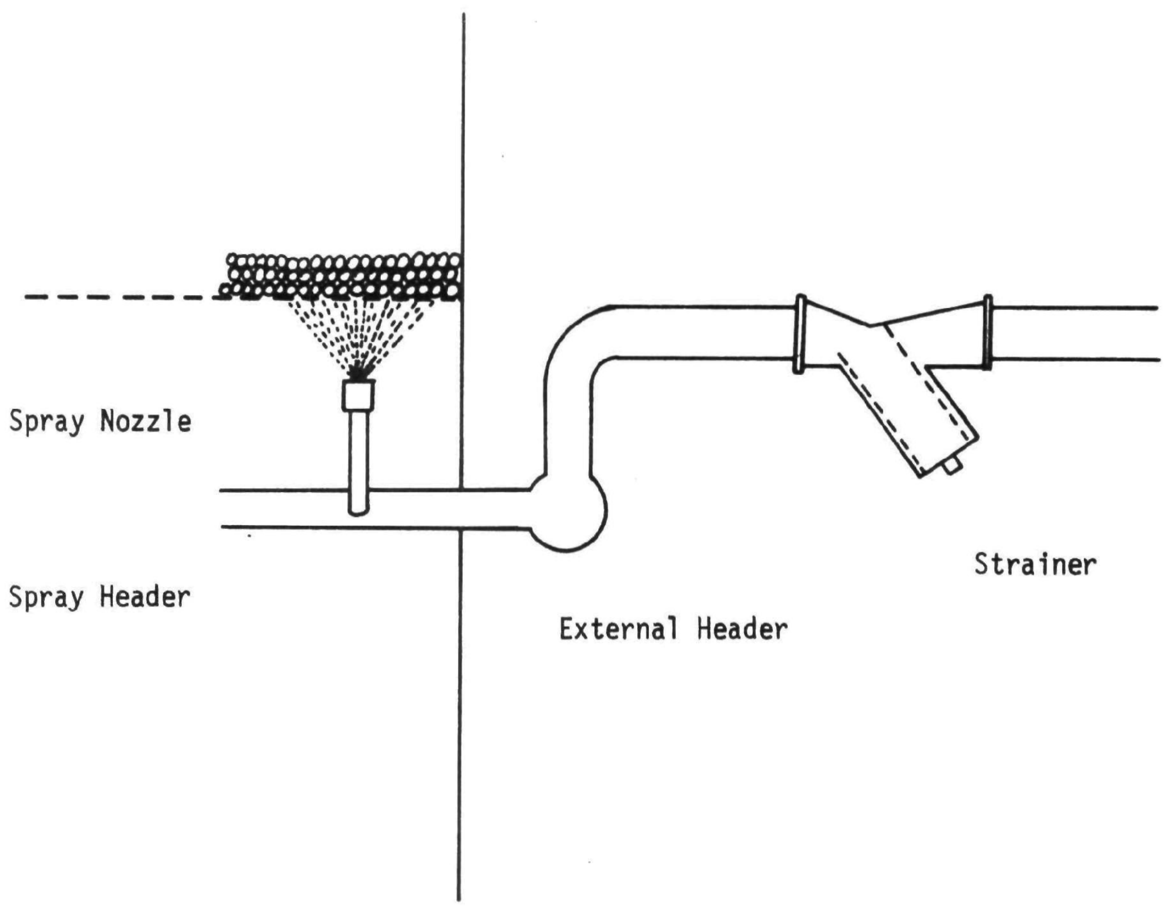
Spray nozzle plugging was a persistent problem during the last test (18R) with boiler calcined limestone. This nozzle plugging was suspected to be the result of either or both of the following:

a. Presence of particles larger than the nozzle orifice diameter.

b. Maldistribution of fine particles in the three spray headers.

The first type of plugging was caused by particles with sizes larger than the spray nozzle orifice diameter (1/8"). When the nozzles were blocked with large particles, subsequent buildup of fine particles resulted. The source of large particles was suspected to be the additive itself, and chips peeling off both the Hold Tank and pipe walls and then carried to the nozzles in the slurry. A screen was installed on the outlet of the additive feeder to prevent the large particles in the additive from getting into the system. The second source was eliminated by installing a strainer in the slurry feedline to the scrubber as shown in Figure G-1. The strainer prevented large particles from the peeling of previous scale in both the Tank and pipes from reaching the spray nozzles.

The second type of nozzle plugging was a result of maldistribution of fine additive particles in the three headers. As the feed slurry, a, in the main external header turned 90° to enter spray header No. 1 (shown in Figure G-2), a centrifugal force would pull some of the solids toward spray headers No. II and III and hence increase the solid concentration in Stream b.



Large Particle Eliminator in the Spray Water

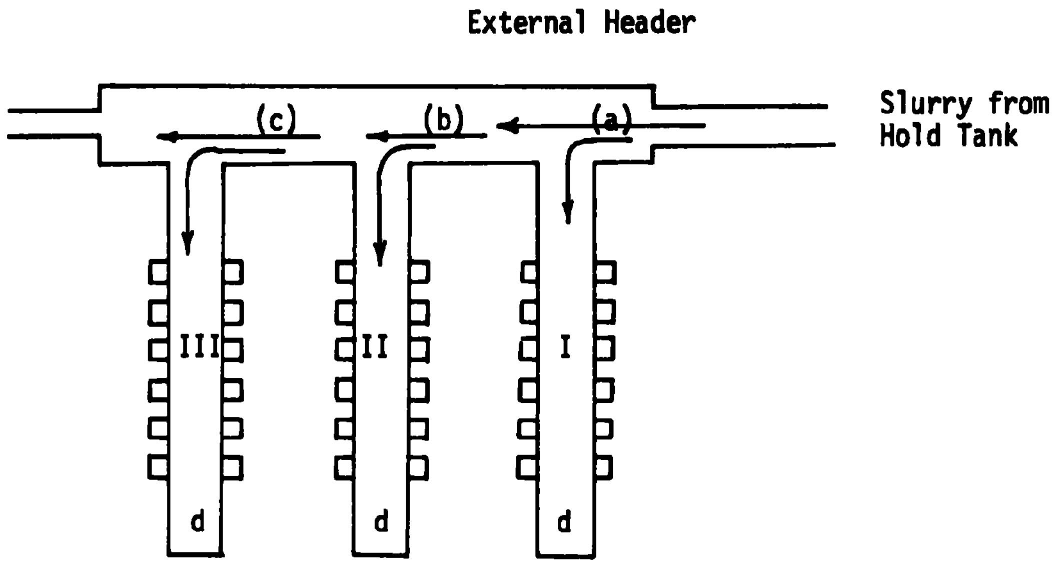
FIGURE G-1

By the same token Stream c was higher in solid concentration than b and c. Thus the solid concentration in spray header III was greater than II, which in turn was greater than I. This was evident in the nozzle plugging pattern. To eliminate this maldistribution in the headers, the external spray header was modified to receive the slurry feed in two locations rather than one as shown in Figure G2. This improved the solids distribution in the three spray headers, and eliminated plugging. Also the dead space labeled (d) in Figure G-2 at the end of each spray header was removed to avoid buildup which eventually would plug the nozzles.

Heat Extractor Plugging: After the last EPA test series, deposit formation was noticed on the gas and liquid sides of the heat extractor tubes. The deposit on the gas side was mechanical (oil ash) in nature, and was cleaned by means of high pressure water. The deposit on the water side was chemical in nature and was cleaned using dilute acid. The heat Extractor and the duct cleanup was made as part of a maintenance repair to keep the equipment in good enough condition to carry out test work.

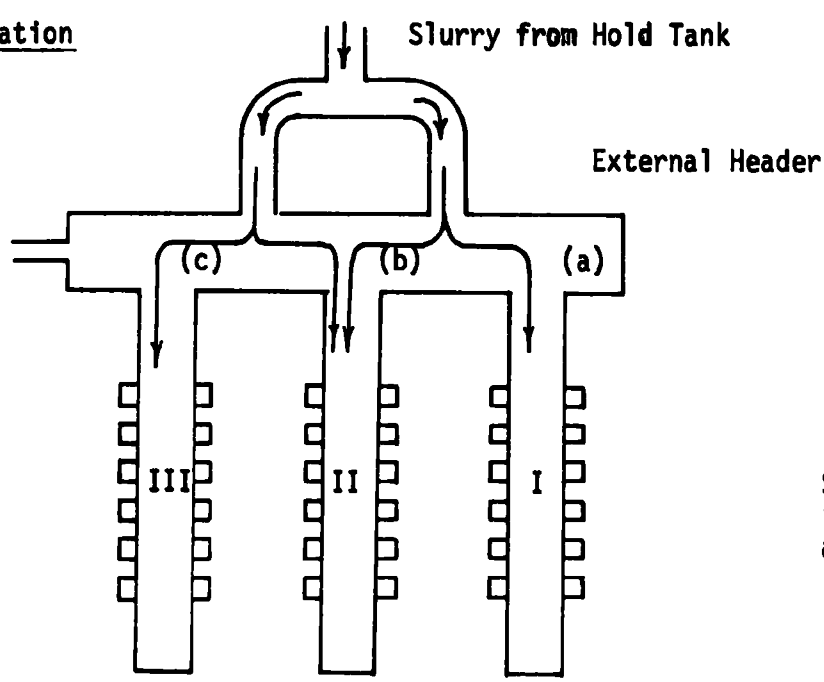
Air Leakage Due the Additive Injection System: The O_2 concentration at the scrubber inlet is considerably higher than at the boiler because of the air leakage into the system between the scrubber and the boiler. Thus, with a minimum excess O_2 of 5% in the boiler, the O_2 concentration in the scrubber inlet was about 10%. Therefore, under these conditions, Test 21R had to be eliminated since it called for 5 percent O_2 in the flue gas at the scrubber inlet.

Before Modification



Dead Zone Accumulating
Fine Particles
Solids Concentration in I<II<III

After Modification



Solids concentration in three headers is approximately equal.

I≈II≈III

Dead Zone Eliminated

System Modification to Eliminate Fine Particle Nozzle Plugging

FIGURE G-2

APPENDIX H

LIMESTONE FURNACE INJECTION SYSTEM

MATERIAL BALANCE

AND

RATE CALCULATIONS

TABLE H-1. TOTAL SULFUR MATERIAL BALANCE

Experiment 17R

		Flow Rate	Solid Content	Total S in Solid (m mole/g)	Total S in Liquid (m mole/l)	Total S in Gas (ppm)	Total S (m mole/ min)
Marble Bed (Set #1)							
Entering Streams	Spray Water	406 l/min	0		11.27		4,576
	Additive	2,010 g/min		0.55			1,106
	Gas In	10,950 g mole/min				1,456	15,943
Leaving Streams	Gas Out	11,605 g mole/min				764	8,866
	Scrubber Liquid	329 l/min	2.635	0.869	23.41		8,455
	Scrubber Bottom	102 l/min	10.2	0.677	12.61		1,991
		Total Sulfur In = 21,625 - Total Sulfur Out = 19,312					
Marble Bed (Set #2)							
Entering Streams	Spray Water	431 l/min	0		10.68		4,603
	Additive	2,010 g/min		0.55			1,106
	Gas In	10,950 g mole/min				1,456	15,943
Leaving Streams	Gas Out	11,605 g mole/min				764	8,866
	Scrubber Liquid	329 l/min	2.28	0.765	22.57		7,999
	Scrubber Bottom	102 l/min	11.1	0.692	13.0		2,109
		Total Sulfur In = 21,652 - Total Sulfur Out = 18,974					
Hold Tank (Set #1)							
Entering Streams	Scrubber Liquid	329 l/min	2,635	0.869	23.75		8,567
	Scrubber Bottom	102 l/min	10.20	0.677	11.3		1,857
	Make Up Water	208 l/min					
Leaving Streams	Hold Tank Eff.	639 l/min	3.27	1.73	10.9		10,580
		Total Sulfur In = 10,424 - Total Sulfur Out = 10,580					
Hold Tank (Set #2)							
Entering Streams	Scrubber Liquid	329 l/min	2.65	0.95	21.95		8,050
	Scrubber Bottom	102 l/min	8.77	1.012	12.74		2,205
	Make Up Water	208 l/min					
Leaving Streams	Hold Tank	631 l/min	3.27	1.74	10.9		10,468
		Total Sulfur In = 10,255 - Total Sulfur Out = 10,468					

TABLE H-2. TOTAL SULFUR MATERIAL BALANCE

Experiment 18R

		Flow Rate	Solid Content g/l	Total S in Solid (m mole/g)	Total S in Liquid (m mole/l)	Total S in Gas (ppm)	Total S (m mole/min)
Hold Tank (Set #1)							
Entering Streams	Scrubber Liquid	682 l/min	47.3	3.09	22.55		115,058
	Scrubber Bottom	114 l/min	60.0	2.57	18.09		19,641
	Clarifier Liquid	76 l/min	0.17	-	17.05		1,295
Leaving Streams	Hold Tank Eff.	872 l/min	45.0	3.08	17.88		136,450
		Total Sulfur In = 135,994 - Total Sulfur Out = 136,450					
Hold Tank (Set #2)							
Entering Streams	Scrubber Liquid	682 l/min	40.4	3.21	23.71		104,614
	Scrubber Bottom	114 l/min	55.5	2.49	19.23		17,946
	Clarifier Liquid	76 l/min			17.36		1,319
Leaving Streams	Hold Tank Eff.	872 l/min	36.6	2.98	19.99		112,538
		Total Sulfur In = 123,879 - Total Sulfur Out = 112,538					
Marble Bed (Set #1)							
Entering Streams	Inlet Gas	10,820 g mole/min				1,471	15,920
	Scrubber Spray	796 l/min	36.7	3.01	18.50		102,658
	Additive	2,045 g/min		0.51			1,043
Leaving Streams	Outlet Gas	11,630 g mole/min				447	5,200
	Scrubber Liquid*	682 l/min	41.4	3.34	27.30		112,923
	Scrubber Bottom	114 l/min	53.9	2.51	19.54		17,650
		Total Sulfur In = 119,621 - Total Sulfur Out = 135,773					
Marble Bed (Set #2)							
Entering Streams	Inlet Gas	10,820 g mole/min				1,471	15,916
	Scrubber Spray	796 l/min	33.5	3.08	20.05		98,091
	Additive	2,045 g/min		0.51			1,042
Leaving Streams	Outlet Gas	11,630 g mole/min				447	5,198
	Scrubber Liquid	682 l/min	40.5	3.18	29.30		107,817
	Scrubber Bottom	114 l/min	49.9	2.435	19.44		16,067
		Total Sulfur In = 115,049 - Total Sulfur Out = 129,082					

*Average of Back and Front Marble Bed

TABLE H-3. TOTAL SULFUR MATERIAL BALANCE

Experiment 19R

		Flow Rate	Solid Content g/l	Total S in Solid (m mole/g)	Total S in Liquid (m mole/l)	Total S in Gas (ppm)	Total S (m mole/min)
Marble Bed (Set #1)							
Entering Streams	Gas In	9,200 g mole/min				1,883	17,324
	Scrubber Spray	738 l/min	13.9	2.21	35.90		40,165
	Additive	2,800 g/min		0.55			1,540
Leaving Streams	Gas Out	10,555 g mole/min				1,095	11,558
	Scrubber Liquid	662 l/min	14.4	1.87	53.30		53,111
	Scrubber Bottom	76 l/min	32.10	1.83	39.20		7,444
Total Sulfur In = 68,029 - Total Sulfur Out = 72,113							
Marble Bed (Set #2)							
Entering Streams	Gas In	9,120 g mole/min				1,881	17,155
	Scrubber Spray	738 l/min	14.60	2.0	36.60		48,560
	Additive	2,800 g/min		0.55			1,540
Leaving Streams	Gas Out	10,487 g mole/min				1,124	11,787
	Scrubber Liquid	662 l/min	15.90	1.73	52.40		52,898
	Scrubber Bottom	76 l/min	41.90	1.82	37.30		8,630
Total Sulfur In = 67,255 - Total Sulfur Out = 73,315							
Hold Tank (Set #1)							
Entering Streams	Scrubber Liquid	662 l/min	12.20	1.68	53.7		49,118
	Scrubber Bottom	76 l/min	28.70	2.17	30.4		7,044
	Make Up Water	133 l/min					
Leaving Streams	Hold Tank Eff.	871 l/min	13.90	2.26	36.3		58,979
Total Sulfur In = 56,162 - Total Sulfur Out = 58,979							
Hold Tank (Set #2)							
Entering Streams	Scrubber Liquid	662 l/min	13.0	1.69	52.51		49,306
	Scrubber Bottom	76 l/min	33.0	2.09	26.4		7,248
	Make Up Water	133 l/min					
Leaving Streams	Hold Tank Eff.	871 l/min	14.90	2.05	35.90		57,873
Total Sulfur In = 56,554 - Total Sulfur Out = 57,873							

TABLE H-4. TOTAL SULFUR MATERIAL BALANCE

Experiment 20R

		Flow Rate	Solid Content g/l	Total S in Solid (m mole/g)	Total S in Liquid (m mole/l)	Total S in Gas (ppm)	Total S (m mole/min)
Marble Bed (Set #1)							
Entering Streams	Gas In	9,400 g mole/min				1,962	18,443
	Scrubber Spray	757 l/min	6.94	2.0	32.6		35,185
	Additive	2,800 g/min		0.50			1,400
Leaving Streams	Scrubber Liquid	681 l/min	9.25	1.50	45.7		40,571
	Scrubber Bottom	76 l/min	25.3	1.53	33.4		5,480
	Gas Out	10,850 g mole/min				1,090	11,827
Total Sulfur In = 55,028 - Total Sulfur Out = 57,878							
Marble Bed (Set #2)							
Entering Streams	Gas In	9,400 g mole/min				1,939	18,227
	Scrubber Spray	757 l/min	6.99	1.78	35.7		36,444
	Additive	2,800 g/min		.50			1,400
Leaving Streams	Gas Out	10,850 g mole/min				1,090	11,827
	Scrubber Liquid	681 l/min	8.00	1.23	46.55		38,402
	Scrubber Bottom	76 l/min	22.6	1.48	38.60		5,476
Total Sulfur In = 56,071 - Total Sulfur Out = 55,705							
Hold Tank (Set #1)							
Entering Streams	Scrubber Liquid	681 l/min	7.33	1.61	45.7		39,158
	Scrubber Bottom	76 l/min	22.7	1.80	19.9		4,618
	Clarifier Liquid	151 l/min	0.13				
	Make Up Water	151 l/min			28.40		4,288
Leaving Streams	Hold Tank Eff.	1,059 l/min	7.38	2.05	31.90		49,804
Total Sulfur In = 48,064 - Total Sulfur Out = 49,804							
Hold Tank (Set #2)							
Entering Streams	Scrubber Liquid	681 l/min	7.07	1.43	47.4		39,164
	Scrubber Bottom	76 l/min	20.5	1.69	26.1		4,617
	Clarifier Liquid	151 l/min					
	Make Up Water	151 l/min			28.3		4,273
Leaving Streams	Hold Tank Eff.	1,059 l/min	6.65	1.93	34.90		50,551
Total Sulfur In = 48,054 - Total Sulfur Out = 50,551							

TABLE H-5. RATE CALCULATION USING SOLID MATERIAL BALANCE

Experiment 17R

Marble Bed (Set #1)

1. $CaSO_3$ 1/2 H_2O Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams		-	-	-	-	-	-
Leaving Streams	Scrubber Liquid*	329 l/min	2.635	0.80			693
	Scrubber Bottom	102 l/min	10.200	0.59			614

Rate of $CaSO_3$ 1/2 H_2O Formation = $CaSO_3$ 1/2 H_2O (Out) - $CaSO_3$ 1/2 H_2O (In)

= 693 + 614 = 1307 m mole/min.

2. SO_2 Oxidation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Inlet Flue Gas	10,950 g mole/min				1,456	15,943
	Scrubber Spray	406 l/min			1.0		406
Leaving Streams	Outlet Flue Gas	11,605 g mole/min				764	8,866
	Scrubber Liquid*	329 l/min			8.95		2,944
	Scrubber Bottom	102 l/min			1.0		102

Rate of SO_2 Oxidation = SO_2 (In) - SO_2 (Out) - $CaSO_3$ 1/2 H_2O Formation Rate

= 16,349 - 11,912 - 1,307 = 3,130 m mole/min.

3. Ca SO_4 2 H_2O Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	(Additive)	2,010 g/min		0.55			1,105
Leaving Streams	Scrubber Liquid*	329 l/min	2.635	0.069			59.8
	Scrubber Bottom	102 l/min	10.2	0.087			90.5

Rate of Ca SO_4 2 H_2O Formation = $CaSO_4$ 2 H_2O (Out) - $CaSO_4$ $2H_2O$ (In)

= 90.5 + 59.8 - 1,105 = 150 - 1,105

= -955 m mole/min

4. $CaCO_3$ Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	(Additive)	2,010 g/min		0.39**			784.0
Leaving Streams	Scrubber Liquid	329 l/min	2.635	0.220			191
	Scrubber Bottom	102 l/min	10.2	0.362			377

Rate of $CaCO_3$ Formation = $CaCO_3$ (Out) - $CaCO_3$ (In)

= 191 + 377 - 784 = -216 m mole/min

5. $Ca(OH)_2$ Dissolution

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Scrubber Spray	431 l/min+			13.7		5,905
Leaving Streams	Scrubber Liquid	329 l/min			19.0		6,251
	Scrubber Bottom	102 l/min			16.8		1,714

Rate of $Ca(OH)_2$ Dissolution = Ca(liq.) Out - Ca(liq.) In + $CaCO_3$ + $CaSO_4$ 2 H_2O + $CaSO_3$1/2 H_2O Form

= 6.251 + 1.714 - 5,905 + (1.307 - 955 - 216)

- 2,196 m moles/min.

*Average of marble bed front and back
**From Radian Corp.
+Subtotal of Scrubber Bottom + Scrubber Liquid

TABLE H-5. RATE CALCULATION USING SOLID MATERIAL BALANCE (Continued)

Hold Tank (Set #1)

1. $CaSO_3$ 1/2 H_2O Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Scrubber Liquid	329 l/min	2.635	0.80			693
	Scrubber Bottom	102 l/min	10.20	0.59			614
	Make Up Water	208 l/min	-	-			
Leaving Streams	Hold Tank Eff.°	639 l/min+	3.27	1.51			3,155

Rate of Ca SO_3 1/2 H_2O Formation = $CaSO_3$ 1/2 H_2O (Out) - $CaSO_3$ 1/2 H_2O (In)

= 3,155 - 693 - 614

= 1,848 m moles/min.

2. SO_2 Oxidation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Scrubber Liquid	329 l/min			8.9		2,928
	Scrubber Bottom	102 l/min			1.0		102
	Make Up Water	208 l/min					
Leaving Streams	Hold Tank Eff.°	639 l/min+			1.5		958

Rate of SO_2 Oxidation = SO_2 (liq.) In - SO_2 (liq.) Out - $CASO_3$ 1/2 H_2O Formation Rate

= 2,928 + 102 - 958 - 1,848

= 224 m mole/min.

3. $CaSO_4$ $2H_2O$ Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Scrubber Liquid	329 l/min	2.635	0.069			60
	Scrubber Bottom	102 l/min	10.2	0.087			90
	Make Up Water	208 l/min	-	-			
Leaving Stream	Hold Tank Eff.	639 l/min	3.27	0.23			481

Rate of $CaSO_4$ $2H_2O$ Formation = $CaSO_4$ $2H_2O$ (Out) - $CaSO_4$ $2H_2O$ In

= 481 - 90 - 60 = 331 m mole/min.

4. $CaCO_3$ Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Scrubber Liquid	329 l/min	2.635	0.220			191
	Scrubber Bottom	102 l/min	10.2	0.362			377
	Make Up Water	208 l/min					
Leaving Stream	Hold Tank Eff.	639 l/min	3.27	0.650			1,358

Rate of $CaCO_3$ Formation = $CaCO_3$ (Out) - $CaCO_3$ (In)

= 1,358 - 377 - 191 = 790 m mole/min.

5. $Ca(OH)_2$ Dissolution

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Scrubber Liquid	329 l/min			19.9		6,547
	Scrubber Bottom	102 l/min			17.4		1,774
	Make Up Water	208 l/min			1.08		224
Leaving Stream	Hold Tank Eff.	639 l/min			11.7		7,476

Rate of $Ca(OH)_2$ Dissolution = Ca(liq.) Out - Ca(liq.) In + $CaCO_3$ + $CaSO_4$ $2H_2O$ + $CaSO_3$ 1/2 H_2O

= 7,476 - 6,547 - 1,774 - 224 + 1,848 + 331 + 790

= 1,900 m moles/min

+Subtotal of Scrubber Bottom + Scrubber Liquid
°Stream characterization is assumed to be the same as in Set 2 since the sample was taken in between the two sets.

TABLE H-5. RATE CALCULATION USING SOLID MATERIAL BALANCE (Continued)

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Marble Bed (Set #2)							
1. $CaSO_3$ 1/2 H_2O Formation							
Entering Stream		-	-	-			
Leaving Streams	Scrubber Liquid	329 l/min	2.28	0.30			225
	Scrubber Bottom	102 l/min	11.10	0.50			566

Rate of $CaSO_3$ 1/2 H_2O Formation = $CaSO_3$ 1/2 H_2O (Out) - $CaSO_3$ 1/2 H_2O (In)

= 791 m mole/min

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
2. SO_2 Oxidation							
Entering Stream	Inlet Flue Gas	10,950 g moles/min				1,456	15,943
	Scrubber Spray	431 l/min			1.3		560
	Outlet Flue Gas	11,605 moles/min				764	8,866
	Scrubber Liquid	329 l/min			7.2		2,368
	Scrubber Bottom	102 l/min			1.7		173

Rate of SO_2 Oxidation = SO_2 (In) - SO_2 (Out) - $CaSO_3$ 1/2 H_2O Formation Rate

= 15,943 + 560 - 8,866 - 2,368 - 173 - 791 = 4,305 m mole/min

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
3. $CaSO_4$ $2H_2O$ Formation							
Entering Stream	Additive	2,010 g/min		0.55			1,105
Leaving Streams	Scrubber Liquid	329 l/min	2.28	0.465			349
	Scrubber Bottoms	102 l/min	11.1	0.192			217

Rate of $CaSO_4$ $2H_2O$ Formation = $CaSO_4$ $2H_2O$ (Out) - $CaSO_4$ $2H_2O$ (In)

= 217 + 349 - 1,105 = - 539 m mole/min

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
4. $CaCO_3$ Formation							
Entering Stream	Additive	2,010 g/min		0.39			784
Leaving Stream	Scrubber Liquid	329 l/min	2.28	0.296			222
	Scrubber Bottom	102 l/min	11.1	0.511			578

Rate of $CaCO_3$ Formation = $CaCO_3$ (Out) $CaCO_3$ (In)

= 222 + 578 - 784 = 16 m mole/min

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
5. $Ca(OH)_2$ Dissolution							
Entering Stream	Scrubber Spray	431 l/min			12.8		5,516
Leaving Stream	Scrubber Liquid	329 l/min			19.1		628
	Scrubber Bottom	102 l/min			16.3		1,662

Rate of $Ca(OH)_2$ Dissolution = Ca(liq.) Out - Ca(liq.) In = $CaCO_3$ + $CaSO_4$ $2H_2O$ + $CaSO_3$ 1/2 H_2O

= 6,284 + 1,662 - 5,516 + 791 - 539 + 16

= 2,698 m mole/min

TABLE H-5. RATE CALCULATION USING SOLID MATERIAL BALANCE (Continued)

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Hold Tank (Set #2)							
1. $CaSO_3$ 1/2 H_2O Formation							
Entering Stream	Scrubber Liquid	329 l/min	2.65	0.52			453
	Scrubber Bottom	102 l/min	8.77	0.83			742
	Make Up Water	208 l/min	-	-			-
Leaving Streams	Hold Tank Eff.°	639 l/min	3.27	1.51			3,155
	Rate of $CaSO_3$ 1/2 H_2O Formation = $CaSO_3$ 1/2 H_2O (Out) - $CaSO_3$ 1/2 H_2O (In) = 3,155 - 453 - 742 = 1,960 m mole/min						
2. SO_2 Oxidation							
Entering Stream	Scrubber Liquid	329 l/min			9.2		3,026
	Scrubber Bottom	102 l/min			1.7		173
	Make Up Water	208 l/min			-		-
Leaving Stream	Hold Tank Eff.	639 l/min			1.5		958
	Rate of SO_2 Oxidation = SO_2 (liq) In - SO_2 (liq) Out - $CaSO_3$ 1/2 H_2O Formation Rate = 3,026 + 173 - 958 - 1,960 = 281.00 m mole/min						
3. $CaSO_4$ $2H_2O$ Formation							
Entering Streams	Scrubber Liquid	329 l/min	2.65	0.43			375
	Scrubber Bottom	102 l/min	8.77	0.182			163
	Make Up Water	208 l/min	-	-			
Leaving Stream	Hold Tank Eff.	639 l/min	3.27	0.23			481
	Rate of $CaSO_4$ $2H_2O$ Formation = $CaSO_4$ $2H_2O$ (In) = 481 - 375 - 163 = 57 m mole/min						
4. $CaCO_3$ Formation							
Entering Streams	Scrubber Liquid	329 l/min	2.635	0.229			198
	Scrubber Bottom	102 l/min	10.2	0.560			583
	Make Up Water	208 l/min					
Leaving Streams	Hold Tank Eff	639 l/min	3.27	0.650			1,358
	Rate of $CaCO_3$ Formation = $CaCO_3$ (Out) - $CaCO_3$ (In) = 1,358 - 198 - 583 = 577 m mole/min						
5. $Ca(OH)_2$ Dissolution							
Entering Streams	Scrubber Liquid	329 l/min			19.6		6,448
	Scrubber Bottom	102 l/min			17.6		1,795
	Make Up Water	208 l/min			1.08		225
Leaving Streams	Hold Tank Eff.	639 l/min			11.7		7,476
	Rate of Ca(OH) Dissolution = Ca (liq.) Out - Ca (liq.) In + $CaCO_3$ + $CaSO_4$ $2H_2O$ + $CaSO_3$ 1/2 H_2O = 7,476 - 6,448 - 1,795 - 225 + 1,960 - 57 + 577 = 1,488 m mole/min						

Experiment 19R

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min

Marble Bed (Set #1)

1. $CaSO_3$ 1/2 H_2O Formation

Entering Streams	Scrubber Spray	738 l/min	13.9Δ	1.62			16,618
Leaving Streams	Scrubber Liquid*	662 l/min	14.4	1.26			12,011
	Scrubber Bottom	76 l/min	32.10	1.47			3,586

Rate of Ca SO_3 1/2 H_2O Formation = $CaSO_3$ 1/2 H_2O (Out) - $CaSO_3$ 1/2 H_2O (In)

= (12,011 + 3,586) - 16,618

= 15,597 - 16,618

= -1,021 m mole/min

2. SO_2 Oxidation

Entering Streams	Inlet Flue Gas	9,200 g mole/min				1,883	17,324
	Scrubber Spray	738 l/min			15.55		11,476
Leaving Streams	Outlet Flue Gas	10,555 g mole/min				1,095	11,558
	Scrubber Liquid*	662 l/min			26.8		17,742
	Scrubber Bottom	76 l/min			14.75		1,121

Rate of SO_2 Oxidation = SO_2 (In) - SO_2 (Out) - $CaSO_3$ 1/2 H_2O Formation Rate

= 28,800 - 30,421 + 1,021 = -600 m mole/min

3. $CaSO_4$ 2 H_2O Formation

Entering Streams	(Additive)	2,800 g/min		.55			1,540
	Spray Water	738 l/min	13.9	.59			6,052
Leaving Streams	Scrubber Liquid*	662 l/min	14.4	.61			5,815
	Scrubber Bottom	76 l/min	32.1	.36			878

Rate of $CaSO_4$ $2H_2O$ Formation = $CaSO_4$ $2H_2O$ (Out) - $CaSO_4$ $2H_2O$ (In)

= 6,693 - 7,592

= -899 m mole/min

4. $CaCO_3$ Formation

Entering Streams	(Additive)	2,800 g/min		.39			1,092
	Spray Water	738 l/min	13.9	.215			2,206
Leaving Streams	Scrubber Liquid*	662 l/min	14.4	.171			1,630
	Scrubber Bottom	76 l/min	32.1	.280			683

Rate of $CaCO_3$ Formation = $CaCO_3$ (Out) - $CaCO_3$ (In)

= 2,313 - 3,298

= -985 m mole/min

5. $Ca(OH)_2$ Dissolution

Entering Stream	Spray Water+	738 l/min			25.7		18,967
Leaving Streams	Scrubber Liquid*	662 l/min			34.4		22,773
	Scrubber Bottom	76 l/min			27.7		2,105

Rate of $Ca(OH)_2$ Dissolution = Ca(liq) Out - Ca(liq) In + $CaCO_3$ + $CaSO_4$ $2H_2O$ + $CaSO_3$ 1/2 H_2O Form

= 24,878 - 18,967 + -985 - 899 - 1,021

= 3,006 m mole/min

*Average of Marble bed front and back
ΔSame as the hold tank effluent
+Subtotal of scrubber bottom and scrubber liquid

TABLE H-6. RATE CALCULATION USING SOLID MATERIAL BALANCE (Continued)

Hold Tank (Set #1)

1. $CaSO_3$ 1/2 H_2O Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Liquid	Scrubber Liquid	662 l/min	12.20	1.32			10,661
	Make Up Water	133 l/min	-	-			
	Scrubber Bottom	76 l/min	28.70	1.55			3,381
Leaving Streams	Hold Tank Eff.	871 l/min	13.9	1.60			19,371

Rate of $CaSO_3$ 1/2 H_2O Formation = $CaSO_3$ 1/2 H_2O (Out) - $CaSO_3$ 1/2 H_2O (In)

= 19,371 - 14,042

= 5,329 m moles/min

2. SO_2 Oxidation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Scrubber Liquid	662 l/min			28.6		18,933
	Scrubber Bottom	76 l/min			7.9		600
	Make Up Water	133 l/min			-		
Leaving Streams	Hold Tank Eff.	871 l/min			15.7		13,674

Rate of SO_2 Oxidation = SO_2 (liq.) In - SO_2 (liq.) Out - $CaSO_3$ 1/2 H_2O Formation Rate

= 19,533 - 13,674 - 5,329

= 530 m moles/min

3. $CaSO_4$ $2H_2O$ Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Scrubber Bottom T	76 l/min	28.70	.36			785
	Scrubber Liquid T	662 l/min	12.20	.62			5,008
	Make-Up Water	133 l/min	-	-			
Leaving Streams	Hold Tank Eff.	871 l/min	13.90	.66			7,991

Rate of $CaSO_4$ $2H_2O$ Formation = $CaSO_4$ $2H_2O$ (Out) $CaSO_4$ $2H_2O$ (In)

= 7,991 - 5,793

= 2,198 m mole/min

4. $CaCO_3$ Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Scrubber Bottom T	76 l/min	28.70	.249			543
	Scrubber Liquid T	662 l/min	12.20	.173			1,397
	Make Up Water	133 l/min	-	-			
Leaving Streams	Hold Tank Eff.	871 l/min	13.90	.172			2,082

Rate of $CaCO_3$ Formation = $CaCO_3$ (Out) $CaCO_3$ (In)

= 2,082 - 1,940

= 142 m mole/min

5. $Ca(OH)_2$ Dissolution

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Scrubber Bottom T	76 l/min			23.8		1,809
	Scrubber Liquid T	662 l/min			35.3		23,369
	Make Up Water	133 l/min			1.08		144
Leaving Streams	Hold Tank Eff.	871 l/min			24.5		21,340

Rate of $Ca(OH)_2$ Dissolution = Ca(liq.) Out - Ca(liq.) In + ($CaCO_3$ + $CaSO_4$ $2H_2O$ + $CaSO_3$ 1/2 H_2O)

= 21,340 - 25,322 + (142 + 2,198 + 5,329)

= 21,340 - 25,322 + (7,669)

= 3,687 m moles/min

TABLE H-6. RATE CALCULATION USING SOLID MATERIAL BALANCE (Continued)

Marble Bed (Set #2)

1. $CaSO_3$ 1/2 H_2O Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Scrubber Spray	738 l/min	14.60	1.41			15,192
Leaving Streams	Scrubber Liquid*	662 l/min	15.9	1.17			12,315
	Scrubber Bottom	76 l/min	41.90	1.33			4,235

Rate of $CaSO_3$ 1/2 Formation = $CaSO_3$ 1/2 H_2O (Out) - $CaSO_3$ 1/2 H_2O (In)

= 16,550 - 15,192

= 1,358 m mole/min

2. SO_2 Oxidation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Inlet Flue Gas	9,120 g mole/min				1,881	17,154
	Scrubber Spray	738 l/min			15.15		11,180
Leaving Streams	Outlet Flue Gas	10,487 g mole/min				1,124	11,787
	Scrubber Liquid*	662 l/min			25.90		17,146
	Scrubber Bottom	76 l/min			13.65		1,037

Rate of SO_2 Oxidation = SO_2 (In) - SO_2 (Out) - $CaSO_3$ 1/2 H_2O Formation Rate

= 28,334 - 29,970 - 1,358

= -2,994 m mole/min

3. $CaSO_4$ $2H_2O$ Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Additive	2,800			0.55		1,540
	Spray Water	738 l/min	14.60		.60		6,464
Leaving Streams	Scrubber Liquid*	662 l/min	15.90		.56		5,894
	Scrubber Bottom	76 l/min	41.90		.49°		1,560

Rate of $CaSO_4$ $2H_2O$ Formation = $CaSO_4$ $2H_2O$ (Out) - $CaSO_4$ $2H_2O$ (In)

= 7,454 - 8,004

= - 550 m mole/min

4. $CaCO_3$ Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Additive	2,800 g/min		.39			1,092
	Spray Water	738 l/min	14.60	.18			1,939
Leaving Streams	Scrubber Liquid*	662 l/min	15.90	.22			2,316
	Scrubber Bottom	76 l/min	41.90	.402			1,280

Rate of $CaCO_3$ Formation = $CaCO_3$ (Out) - $CaCO_3$ (In)

= 3,596 - 3,031

= 565 m mole/min

5. $Ca(OH)_2$ Dissolution

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Spray Water	738 l/min			25.2		18,598
Leaving Stream	Scrubber Liquid*	662 l/m			34.7		22,971
	Scrubber Bottom	76 l/min			27.6		2,098

Rate of $Ca(OH)_2$ Dissolution = Ca(liq.) Out - Ca(liq.) In + $CaCO_3$ + $CaSO_4$ $2H_2O$ + $CaSO_3$ 1/2 H_2O Form

= 25,069 - 18,598 + (565 - 550 + 1,358)

= 25,069 - 18,598 + (1,373)

= 7,844 m mole/min

°Same as scrubber bottom at tank

TABLE H-6. RATE CALCULATION USING SOLID MATERIAL BALANCE (Continued)

Hold Tank (Set #2)

1. $CaSO_3$ 1/2 H_2O Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Scrubber Liq. T	662 l/min	13.0	1.20			10,327
	Scrubber Bottom	76 l/min	33.0	1.47			3,687
	Make Up Water	133 l/min	-	-			
Leaving Streams	Hold Tank Eff.	871 l/min	14.90	1.45			18,818

Rate of $CaSO_3$ 1/2 H_2O Formation = $CaSO_3$ 1/2 H_2O (Out) - $CaSO_3$ 1/2 H_2O (In)

= 18,818 - 14,014

= 4,804 m mole/min

2. SO_2 Oxidation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Scrubber Liquid T	662 l/min			27.31		18,079
	Scrubber Bottom T	76 l/min			4.5		342
	Make Up H_2O	133 l/min			-		
Leaving Streams	Hold Tank Eff.	871 l/min			15.05		13,109

Rate of SO_2 Oxidation = SO_2 (liq) In - SO_2 (liq) Out - $CaSO_3$ 1/2 H_2O Form Rate

= 18,421 - 13,109 - 4,804

= 508 m mole/min

3. $CaSO_4$ $2H_2O$ Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Scrubber Bottom T	76 l/min	33.0	.49			1,228
	Scrubber Liq. T	662 l/min	13.0	.62			5,336
	Make Up Water	133 l/min	-	-			
Leaving Streams	Hold Tank Eff	871 l/min	14.90	.60			7,787

Rate of $CaSO_4$ $2H_2O$ Formation = $CaSO_4$ $2H_2O$ (Out) - $CaSO_4$ $2H_2O$ (In)

= 7,787 - 6,564

= 1,223 m mole/min

4. $CaCO_3$ Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Scrubber Bottom	76 l/min	33.0	.339			850
	Scrubber Liquid	662 l/min	13.0	.19			1,635
	Make Up Water	133 l/min	-				
Leaving Streams	Hold Tank Eff.	871 l/min	14.9	.189			2,453

Rate of $CaCO_3$ Formation = $CaCO_3$ (Out) - $CaCO_3$ (In)

= 2,453 - 2,485

= - 32 m mole/min

5. $Ca(OH)_2$ Dissolution

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Streams	Scrubber Liq T	662 l/min			35.3		23,369
	Scrubber Bottom T	76 l/min			22.2		1,687
	Make Up Water	133 l/min			1.08		144
Leaving Streams	Hold Tank Eff.	871 l/min			25.5		22,211

Rate of $Ca(OH)_2$ Dissolution = Ca(liq) Out - Ca(liq) In + ($CaCO_3$ + $CaSO_4$ $2H_2O$ + $CaSO_3$ 1/2 H_2O)

= 22,211 - 25,200 + (-32 + 1,223 + 4,804)

= 3,006 m mole/min

TABLE H-7. RATE CALCULATION USING SOLID MATERIAL BALANCE

Experiment 20R

Marble Bed (Set #1)

1. $CaSO_3$ 1/2 H_2O Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Scrubber Spray	757 l/min	6.94	1.42			7,460
Leaving Stream	Scrubber Spray	681 l/min	9.25	1.01			6,362
	Scrubber Bottom	76 l/min	25.3	1.20			2,307

Rate of $CaSO_3$ 1/2 H_2O Formation = $CaSO_3$ 1/2 H_2O (Out) - $CaSO_3$ 1/2 H_2O (In)

= 8669 - 7460

= 1209 m mole/min

2. SO_2 Oxidation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Inlet Flue Gas	9,400 g mole/min				1,962	18,443
	Scrubber Spray	757 l/min			7.9		5,980
Leaving Stream	Outlet Flue Gas	10,850 g mole/min				1,090	11,826
	Scrubber Liquid	681 l/min			15.00		10,215
	Scrubber Bottom	76 l/min			8.1		616

Rate of Oxidation of SO_2 = SO_2 (In) - SO_2 (Out) - $CaSO_3$ 1/2 H_2O Formation Rate

= 24,423 - 22,657 - 1,209

= 557 m mole/min

3. $CaSO_4$ 2 H_2O Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Additive	2,800 g/min		0.5			1,400
	Scrubber Spray	757 l/min	6.94	0.58			3,047
Leaving Stream	Scrubber Liquid	681 l/min	9.25	0.49			3,087
	Scrubber Bottom	76 l/min	25.3	0.33			635

Rate of $CaSO_4$ 2 H_2O Formation = $CaSO_4$ 2 H_2O (Out) - $CaSO_4$ 2 H_2O (In)

= 3,721 - 4,447

= - 725 m mole/min

4. $CaCO_3$ Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Additive	2,800 g/min		0.455			1,274
	Scrubber Spray	757 l/min	6.94	0.181			951
Leaving Stream	Scrubber Liquid	681 l/min	9.25	0.180			1,134
	Scrubber Bottom	76 l/min	25.3	0.249			479

Rate of $CaCO_3$ Formation = $CaCO_3$ (Out) - $CaCO_3$ (In)

= 1,613 - 2,225

= - 612 m mole/min

5. Ca(OH) Dissolution

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Scrubber Spray	757 l/min			23.4		17,714
Leaving Stream	Scrubber Liquid	681 l/min			32.3		21,996
	Scrubber Bottom	76 l/min			26.1		1,984

Rate of $Ca(OH)_2$ Dissolution = Ca(liq) Out - Ca(liq) In + ($CaCO_3$ + $CaSO_4$ 2 H_2O + $CaSO_3$ 1/2 H_2O)

= 23,980 - 17,714 + - 612 + - 725 + 1209

= 6,138 m moles/min

TABLE H-7. RATE CALCULATION USING SOLID MATERIAL BALANCE (Continued)

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Hold Tank (Set #1)							
1. $CaSO_3$ 1/2H_2O							
Entering Stream	Scrubber Liquid	681 l/min	7.33	1.00			4,992
	Scrubber Bottom	76 l/min	22.7	1.47			2,536
	Clarifier Liquid	151 l/min	0.13	0.93			19
	Makeup Water	151 l/min					
Leaving Stream	Hold Tank Eff.	1,059 l/min	7.38	1.44			11,254

Rate of $CaSO_3$ 1/2 Formation = $CaSO_3$ 1/2 H_2O (Out) - $CaSO_3$ 1/2 H_2O (In)

= 11,254 - 7,547

= 3,707 m mole/min

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
2. SO_2 Oxidation							
Entering Stream	Scrubber Liquid	681 l/min			15.6		10,624
	Scrubber Bottom	76 l/min			1.01		77
	Clarifier Liquid	151 l/min			5.05		763
	Makeup Water	151 l/min					
Leaving Stream	Hold Tank Effluent	1,059 l/min			7.45		7,890

Rate of SO_2 Oxidation = SO_2 (In) - SO_2 (Out) - $CaSO_3$ 1/2 H_2O Form Rate

= 11,464 - 7,890 - 3,707

= - 133 m mole/min

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
3. $CaSO_4$ 2 H_2O Formation							
Entering Stream	Scrubber Liquid	681 l/min	7.33	0.61			3,045
	Scrubber Bottom	76 l/min	22.7	.33			569
	Clarifier Liquid	151 l/min	0.13				20
	Makeup Water	151 l/min					
Leaving Stream	Hold Tank Effluent	1,059 l/min	7.38	0.61			4,767

Rate of $CaSO_4$ 2 H_2O Formation = $CaSO_4$ 2 H_2O (Out) - $CaSO_4$ 2 H_2O (In)

= 4,767 - 3,634

= 1,133 m mole/min

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
4. $CaCO_3$ Formation							
Entering Streams	Scrubber Liquid	681 l/min	7.33	0.195			973
	Scrubber Bottom	76 l/min	22.7	0.355			612
	Clarifier Liquid	151 l/min	0.13				20
	Makeup Water	151 l/min					
Leaving Stream	Hold Tank Effluent	1,059 l/min	7.38	0.201			1,571

Rate of $CaCO_3$ Formation = $CaCO_3$ (Out) - $CaCO_3$ (In)

= 1,571 - 1,605

= -34 m mole/min

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
5. $Ca(OH)_2$ Dissolution							
Entering Stream	Scrubber Liquid	681 l/min			31.6		21,520
	Scrubber Bottom	76 l/min			21.6		1,642
	Clarifier Liquid	151 l/min			22.1		3,337
	Makeup Water	151 l/min			1.08		163
Leaving Stream	Hold Tank Effluent	1,059 l/min			23.6		24,992

Rate of $Ca(OH)_2$ Dissolution = Ca(liq) Out - Ca(liq) In + ($CaSO_4$ 2 H_2O + $CaCO_3$ + $CaSO_3$ 1/2 H_2O)

= 24,992 - 26,662 + 1,133 - 34 + 3,707

= 3,136 m mole/min

TABLE H-7. RATE CALCULATION USING SOLID MATERIAL BALANCE (Continued)

Marble Bed (Set #2)

1. $CaSO_3$ 1/2 H_2O Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Scrubber Spray	757 l/min	6.99	1.28			6,773
Leaving Stream	Scrubber Liquid	681 l/min	8.00	0.95			5,176
	Scrubber Bottom	76 l/min	22.6	1.16			1,992

Rate of $CaSO_3$ 1/2 H_2O Formation = $CaSO_3$ 1/2 H_2O (Out) - $CaSO_3$ 1/2 H_2O (In)

= 7,168 - 6,773

= 395 m mole/min

2. SO_2 Oxidation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Inlet Flue Gas	9,400 g mole/min				1,939	18,227
	Scrubber Spray	757 l/min			10.2		7,721
Leaving Stream	Outlet Flue Gas	10,850 g mole/min				1,090	11,827
	Scrubber Liquid	681 l/min			16.85		11,475
	Scrubber Bottom	76 l/min			12.00		912

Rate of SO_2 Oxidation = SO_2 liq (In) - SO_2 liq (Out) - $CaSO_3$ 1/2 H_2O Formation

= 25,948 - 24,214 - 395

= 1,339 m mole/min

3. $CaSO_4$ 2 H_2O Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Additive	2,800 g/min		0.50			1,400
	Scrubbing	757 l/min	6.99	0.51			2,699
Leaving Stream	Scrubber Liquid	681 l/min	8.00	0.28			1,525
	Scrubber Bottom	76 l/min	22.6	0.32°			550

Rate of $CaSO_4$ 2 H_2O Formation = $CaSO_4$ 2 H_2O (Out) - $CaSO_4$ 2 H_2O (In)

= 2,075 - 4,099

= - 2,024 m mole/min

4. $CaCO_3$ Formation

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Additive	2,800 g/min		0.455			1,274
	Scrubber Spray	757 l/min	6.99	0.192			1,016
Leaving Stream	Scrubber Liquid	681 l/min	8.00	0.205			1,116
	Scrubber Bottom	76 l/min	22.6	0.299			514

Rate of $CaCO_3$ Formation = $CaCO_3$ (Out) - $CaCO_3$ (In)

= 1,630 - 2,290

= - 660 m moles/min

5. $Ca(OH)_2$ Dissolution

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Entering Stream	Scrubber Spray	757		26.6			20,136
Leaving Stream	Scrubber Liquid	681		33.4			22,745
	Scrubber Bottom	76		30.0			2,280

Rate of $Ca(OH)_2$ Dissolution = Ca(liq) Out - Ca(liq) In + ($CaCO_3$ + $CaSO_3$ /1/2 H_2O + $CaSO_4$ 2 H_2O)

= 25,025 - 20,136 + - 660 + 395 + - 2,024

= 2,600 m moles/min

°Scrubber bottom of tank was used

TABLE H-7. RATE CALCULATION USING SOLID MATERIAL BALANCE (Continued)

		Stream Flow Rate	Slurry Solid Cont. (g/l)	Concen. In Solid (m mole/g)	Concen. In Liquid (m mole/l)	Concen. In Gas (PPM)	Total Species Flow Rate m mole/min
Hold Tank (Set #2)							
1. $CaSO_3$ 1/2 H_2O Formation							
Entering Streams	Scrubber Liquid	681 l/min	7.07	0.94			4,526
	Scrubber Bottom	76 l/min	20.5	1.25			1,948
	Clarifier Liquid	151 l/min					
	Makeup Water	151 l/min					
Leaving System	Hold Tank Effluent	1,059 l/min	6.65	1.30			9,155
	Rate of $CaSO_3$ 1/2 H_2O Formation = $CaSO_3$ (Out) - $CaSO_3$ In						
	= 9,155 - 6,474						
	= 2,681 m mole/min						
2. SO_2 Oxidation							
Entering Streams	Scrubber Liquid	681 l/min			18.3		12,462
	Scrubber Bottom	76 l/min			2.85		217
	Clarifier Liquid	151 l/min			7.4		1,117
	Makeup Water	151 l/min					
Leaving Stream	Hold Tank Effluent	1,059 l/min			10.25		10,855
	Rate of SO_2 Oxidation = SO_2 (liq) In - SO_2 (liq) Out - $CaSO_3$ 1/2 H_2O Formation						
	= 13,796 - 10,855 - 2,681						
	= 260 m mole/min						
3. $CaSO_4$ 2 H_2O Formation							
Entering Streams	Scrubber Liquid	681 l/min	7.07	.49			2,359
	Scrubber Bottom	76 l/min	20.5	.44			685
Leaving Stream	Hold Tank Effluent	1,059 l/min	6.65	.63			4,436
	Rate of $CaSO_4$ .2 H_2O Formation = $CaSO_4$ .2 H_2O (Out) - $CaSO_4$ .2 H_2O (In)						
	= 4,436 - 3,044						
	= 1,392 m mole/min						
4. $CaCO_3$ Formation							
Entering Stream	Scrubber Liquid	681 l/min	7.07	.173			833
	Scrubber Bottom	76 l/min	20.5	.311			485
	Clarifier Liquid	151 l/min					
	Makeup Water	151 l/min					
Leaving Stream	Hold Tank Effluent	1,059 l/min	6.65	0.217			1,528
	Rate of $CaCO_3$ Formation = $CaCO_3$ (Out) - $CaCO_3$ (In)						
	= 1,528 - 1,318						
	= 210 m moles/min						
5. $Ca(OH)_2$ Dissolution							
Entering Stream	Scrubber Liquid	681 l/min			33.9		23,086
	Scrubber Bottom	76 l/min			24.7		1,877
	Clarifier Liquid	151 l/min			22.9		3,458
	Makeup Water	151 l/min			1.08		163
Leaving Stream	Hold Tank Effluent	1,059 l/min			25.9		27,428
	Rate of $Ca(OH)_2$ Dissolution = Ca(liq) Out - Ca(liq) In + $CaCO_3$ + $CaSO_4$ .2 H_2O + $CaSO_3$ .1/2 H_2O						
	= 27,428 - 28,584 + 210 + 1,392 + 2,681						
	= 3,127 m mole/min						

TABLE H-8. RATE CALCULATIONS USING LIQUID MATERIAL BALANCE
Experiment 17R

Marble Bed (Set #1)

1. $CaSO_3 \cdot 1/2\ H_2O$

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Inlet Flue Gas	10,950 g mole/min		1,456	15,943
	Scrubber Spray	431 l/min	1.0		431
Leaving Streams	Outlet Flue Gas	11,605 g mole/min		764	8,866
	Scrubber Liquid*	329 l/min	8.95		2,944
	Scrubber Bottoms	102 l/min	1.0		102

Rate of $CaSO_3$ 1/2 H_2O = SO_2 IN - SO_2 OUT - Oxidation Rate

= 15,943 + 431 - 8,866 - 2,944 - .439 (15,943 - 8.866) - 102

= 4,462 - 3,107

= 1,355 m mole/min

2. $CaSO_4$ 2 H_2O

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Scrubber Spray	431 l/min	10.27		4,426
Leaving Streams	Scrubber Liquid*	329 l/min	14.46		4,757
	Scrubber Bottom	102 l/min	11.61		1,184

Rate of $CaSO_4$ 2 H_2O = SO_4 (Liq.) IN - SO_4 (Liq.) OUT + Oxidation Rate

= 4,426 - 5,941 + 3,107

= 1,592 m mole/min

3. $Ca(OH)_2$ Dissolution

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Scrubber Spray	431 l/min	13.7		5,905
Leaving Streams	Scrubber Liquid*	329 l/min	19.0		6,251
	Scrubber Bottom	102 l/min	16.8		1,714

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rate

= 7,965 - 5,905 + 2,947

= 5,007 m mole/min

*Ave. of Marble Bed Front and Back

TABLE H-8. RATE CALCULATIONS USING LIQUID MATERIAL BALANCE (Continued)

Hold Tank

1. $CaSO_3$ 1/2 H_2O

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Scrubber Liquid	329 l/min	8.9		2,928
	Scrubber Bottom	102 l/min	1.0		102
	Make Up H_2O	208 l/min	-		
Leaving Streams	Hold Tank Eff.	631 l/min	1.5		947

Rate of $CaSO_3$ 1/2 H_2O = SO_2 IN - SO_2 OUT

= 3,030 - 947

= 2,083 m mole/min

2. $CaSO_4$ $2H_2O$

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Scrubber Liquid	329 l/min	14.85		4,886
	Scrubber Bottom	102 l/min	10.3		1,051
	Make Up H_2O	208 l/min	-		
Leaving Streams	Hold Tank Eff.	631 l/min	9.4		5,931

Rate of $CaSO_4$ $2H_2O$ = SO_4 (IN) - SO_4 (OUT)

= 5,937 - 5,931

= 6 m mole/min

3. $CaCO_3$

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Scrubber Liquid+	329 l/min	1.1		362
	Scrubber Bottom++	102 l/min	.27		28
	Make Up H_2O	208 l/min	-		
Leaving Streams	Hold Tank Eff.	631 l/min	.26		164

Rate of $CaCO_3$ = CO_3 IN - CO_3 OUT

= 390 - 164

= 226 m mole/min

4. $Ca(OH)_2$ Dissolution

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Scrubber Liquid	329 l/min	19.9		6,547
	Scrubber Bottom	102 l/min	17.4		1,775
	Make Up H_2O	208 l/min	1.08		225
Leaving Streams	Hold Tank Eff.	631 l/min	11.7		7,383

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rate

= 7,383 - 8,547 + (226 + 6 + 2,083)

= 1,151 m mole/min

+Values from Marble Bed Front and Back
++Values from Scrubber Bottom at Scrubber

TABLE H-8. RATE CALCULATIONS USING LIQUID MATERIAL BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set #2)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	10,950 g mole/min		1,456	15,943
	Scrubber Spray	431 l/min	1.3		560
Leaving Streams	Outlet Flue Gas	11,605 g mole/min		764	8,866
	Scrubber Liquid	329 l/min	7.2		2,369
	Scrubber Bottom	102 l/min	1.7		173

Rate of $CaSO_3$ 1/2 H_2O = SO_2 IN - SO_2 OUT - OXID. Rate

= 16,503 - 11,408 - .417 (7,077)

= 16,503 - 11,408 - 2,951

= 2,144 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ $2H_2O$					
Entering Streams	Scrubber Spray	431 l/min	9.38		4,043
Leaving Streams	Scrubber Liquid	329 l/min	15.37		5,057
	Scrubber Bottom	102 l/min	11.3		1,153

Rate of $CaSO_4$ $2H_2O$ = SO_4 IN - SO_4 OUT + OXID. Rate

= 4,043 - 6,210 + 2,951

= 784 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Spray	431 l/min	12.8		5,517
Leaving Streams	Scrubber Liquid	329 l/min	19.1		6,284
	Scrubber Bottom	102 l/min	16.3		1,663

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rate

= 7,947 - 5,517 + (784 + 2,144)

= 5,358 m mole/min

TABLE H-8. RATE CALCULATIONS USING LIQUID MATERIAL BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Hold Tank					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid	329 l/min	9.2		3,027
	Scrubber Bottom	102 l/min	1.1		112
	Make Up H_2O	208 l/min			
Leaving Streams	Hold Tank Eff.	631 l/min	1.5		946
	Rate of $CaSO_3$ 1/2 H_2O = SO_2 IN - SO_2 OUT				
	= 3,139 - 946				
	= 2,193 m mole/min				
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid	329 l/min	12.75		4,195
	Scrubber Bottom	102 l/min	11.64		1,187
	Make Up H_2O	208 l/min			
Leaving Streams	Hold Tank Eff.	631 l/min	9.4		5,931
	Rate of $CaSO_4$ 2 H_2O = SO_4 IN - SO_4 OUT				
	= 5,382 - 5,931				
	= - 549 m mole/min				
3. $CaCO_3$					
Entering Streams	Scrubber Liquid	329 l/min	.96		316
	Scrubber Bottom	102 l/min	.06		6
	Make Up H_2O	208 l/min			
Leaving Streams	Hold Tank Eff.	631 l/min	.26		164
	Rate of $CaCO_3$ = CO_2 IN - CO_2 OUT				
	= 322 - 164				
	= 158 m mole/min				
4. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Liquid	329 l/min	19.6		6,448
	Scrubber Bottom	102 l/min	17.6		1,795
	Make Up H_2O	208 l/min	1.08		225
Leaving Streams	Hold Tank Eff.	631 l/min	11.7		7,383
	Rate of $Ca(OH)_2$ Dissolution = Ca OUT Ca IN + Ca Prec. Rates				
	= 7,383 - 8,468 + (158 - 549 + 2,193)				
	= 717 m mole/min				

TABLE H-9. RATE CALCULATIONS USING LIQUID BALANCE

Experiment 18R

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set #1)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	10,820 g mole/min		1,471	15,916
	Scrubber Spray	796 l/min	.35		279
Leaving Streams	Scrubber Liquid*	682 l/min	2.95		2,012
	Scrubber Bottom	114 l/min	.45		51
	Outlet Flue Gas	11,630 g mole/min		447	5,199

Rate of $CaSO_3$ 1/2 H_2O = SO_2 IN - SO_2 OUT - Oxidation Rate

= 16,195 - 7,262 - .279 (15,916 - 5,199)

= 8,933 - 2,990 -

= 5,943 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ $2H_2O$					
Entering Streams	Scrubber Spray	796 l/min	18.15		14,447
Leaving Streams	Scrubber Liquid*	682 l/min	24.34		16,600
	Scrubber Bottom	114 l/min	19.09		2,176

Rate of $CaSO_4$ $2H_2O$ = SO_4 IN - SO_4 OUT + Oxidation Rate

= 14,447 - 18,776 + 2,990

= -1,339 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Spray	796 l/min	22.52		17,926
Leaving Streams	Scrubber Liquid*	682 l/min	24.45		16,675
	Scrubber Bottom	114 l/min	24.42		2,784

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rates

= 19,459 - 17,926 + (-1,339 + 5,943)

= 6,137 m mole/min

*Ave. of Marble Bed Front and Back

TABLE H-9. RATE CALCULATIONS USING LIQUID BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Hold Tank					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid	682 l/min	2.57		1,753
	Scrubber Bottom	114 l/min	.89		101
	Clarified Liquid	76 l/min	.56		43
Leaving Streams	Hold Tank Eff.	872 l/min	.53		462

Rate of $CaSO_3$ 1/2 H_2O Form = SO_2 IN - SO_2 OUT

= 1,897 - 462

= 1,435 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ $2H_2O$					
Entering Streams	Scrubber Liquid	682 l/min	19.98		13,626
	Scrubber Bottom	114 l/min	17.20		1,961
	Clarified Liquid	76 l/min	16.49		1,253
Leaving Streams	Hold Tank Eff.	872 l/min	17.35		15,129

Rate of $CaSO_4$ $2H_2O$ = SO_4 IN - SO_4 OUT

= 16,840 - 15,129

= 1,711 m mole/min

3. $CaCO_3$ (No CO_2 Data are Available)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
4. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Liquid	682 l/min	21.25		14,493
	Scrubber Bottom	114 l/min	32.72		3,730
	Clarified Liquid	76 l/min	20.6		1,566
Leaving Streams	Hold Tank Eff.	872 l/min	22.97		20,030

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rates

= 20,030 - 19,789 + (3,146)

= 3,387 m mole/min

TABLE H-9. RATE CALCULATIONS USING LIQUID BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set 2)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	10,820 g mole/min		1,471	15,916
	Scrubber Spray	796 l/min	.38		302
Leaving Streams	Outlet Flue Gas	11,630 g mole/min		447	5,199
	Scrubber Liquid	682 l/min	4.175		2,847
	Scrubber Bottom	114 l/min	.42		48

Rate of $CaSO_3$ 1/2 H_2O = SO_2 IN - SO_2 OUT - Oxidation Rate

= 16,218 - 8,094 - .289 (10,717)

= 16,218 - 8,094 - 3,097

= 5,027 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ $2H_2O$					
Entering Streams	Scrubber Spray	796 l/min	19.67		15,657
Leaving Streams	Scrubber Liquid*	682 l/min	25.15		17,152
	Scrubber Bottom	114 l/min	19.02		2,168

Rate of $CaSO_4$ $2H_2O$ = SO_4 IN - SO_4 OUT + Oxidation Rate

= 15,657 - 19,320 + 3,097

= -566 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Spray	796 l/min	23.25		18,507
Leaving Streams	Scrubber Liquid*	682 l/min	26.495		18,070
	Scrubber Bottom	114 l/min	24.95		2,844

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rate

= 20,914 - 18,507 + (4461)

= 6,868 m mole/min

*Ave. of Marble Bed Front and Back

TABLE H-9. RATE CALCULATIONS USING LIQUID BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Hold Tank					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid	682 l/min	3.25		2,217
	Scrubber Bottom	114 l/min	.72		82
	Clarified Liquid	76 l/min	.40		30
Leaving Streams	Hold Tank Eff.	872 l/min	.55		480

Rate of $CaSO_3$ 1/2 H_2O Form = SO_2 IN - SO_2 OUT

= 2,329 - 480

= 1,849 m mole/min

2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid	682 l/min	20.46		13,954
	Scrubber Bottom	114 l/min	18.51		2,110
	Clarified Liquid	76 l/min	16.96		1,289
Leaving Streams	Hold Tank Eff.	872 l/min	18.68		16,289

Rate of $CaSO_4$ $2H_2O$ Form = SO_4 IN - SO_4 OUT

= 17,353 - 16,289

= 1,064 m mole/min

3. $CaCO_3$ (No CO_2 Data Was Available)

4. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Liquid	682 l/min	22.17		15,120
	Scrubber Bottom	114 l/min	34.30		3,910
	Clarified Liquid	76 l/min	22.35		1,699
Leaving Streams	Hold Tank Eff.	872 l/min	24.20		21,102

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rates

= 21,102 - 20,729 + 2,913

= 3,286 m mole/min

TABLE H-10. RATE CALCULATIONS USING LIQUID BALANCE

Experiment 19R

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set #1)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	9,200 g mole/min		1,884	17,333
	Scrubber Spray	738 l/min	15.55		11,476
Leaving Streams	Outlet Flue Gas	10,555 g mole/min		1,060	11,188
	Scrubber Liquid*	662 l/min	26.85		17,775
	Scrubber Bottom	76 l/min	14.75		1,121

Rate of $CaSO_3 \cdot$ 1/2 H_2O = SO_2 IN - SO_2 OUT - OXID. Rate

= 28,809 - 30,084 - .533 (17,333 - 11,188)

= - 4,550 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Spray	738 l/min	20.35		15,018
Leaving Streams	Scrubber Liquid*	662 l/min	26.45		17,510
	Scrubber Bottom	76 l/min	24.45		1,858

Rate of $CaSO_4$ = SO_4 IN - SO_4 OUT + OXID. Rate

= 15,018 - 19,368 + 3,275

= - 1,075 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Spray	738 l/min	25.7		18,967
Leaving Streams	Scrubber Liquid*	662 l/min	34.4		22,773
	Scrubber Bottom	76 l/min	27.7		2,105

Rate of $Ca(OH)_2$ Dissolution = CA OUT - Ca IN + Ca Prec. Rates

= 24,878 - 18,967 + - 4,550 - 1,075

= 286 m mole/min

*Ave. of Marble Bed Front and Back

TABLE H-10. RATE CALCULATIONS USING LIQUID BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Hold Tank					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid	662 l/min	28.6		
	Scrubber Bottom	76 l/min	7.9		18,933
	Make Up H_2O	133 l/min			600
Leaving Streams	Hold Tank Eff.	871 l/min	15.7		13,675

Rate of $CaSO_3$ 1/2 H_2O = SO_2 IN - SO_2 OUT

= 19,533 - 13,675

= 5,858 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid	662 l/min	25.1		16,616
	Scrubber Bottom	76 l/min	22.5		1,710
	Make Up H_2O	133 l/min			
Leaving Streams	Hold Tank Eff.	871 l/min	20.6		17,943

Rate $CaSO_4$ 2 H_2O = SO_4 IN - SO_4 OUT

= 18,326 - 17,943

= 383 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$					
Entering Streams	Scrubber Liquid	662 l/min	1.845		1,221
	Scrubber Bottom	76 l/min	.75		57
	Make Up H_2O	133 l/min			
Leaving Streams	Hold Tank Eff.	871 l/min	1.10		958

Rate of $CaCO_3$ = CO_2 IN - CO_2 OUT

= 1278 - 958

= 320 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
4. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Liquid	662 l/min	35.3		23,369
	Scrubber Bottom	76 l/min	23.8		1,809
	Make Up H_2O	133 l/min	1.08		144
Leaving Streams	Hold Tank Eff.	871 l/min	24.5		21,340

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rate

= 21,340 - 25,322 + (320 + 383 + 5,858)

= 2,579 m mole/min

TABLE H-10. RATE CALCULATIONS USING LIQUID BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set 2)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	9,120 g mole/min		1,881	17,155
	Scrubber Spray	738 l/min	15.15		11,181
Leaving Streams	Outlet Flue Gas	10,487 g mole/min		1,060	11,116
	Scrubber Liquid*	662 l/min	25.9		17,146
	Scrubber Bottom	76 l/min	13.65		1,037

Rate of $CaSO_3$ = SO_2 IN - SO_2 OUT - OXID. Rate

= 28,336 - 29,299 - .536 (17,155 - 11,116)

= 28,336 - 29,299 - .536 (6,039)

= 28,336 - 29,299 - 3,237

= -4,200 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Spray	738 l/min	21.45		15,830
Leaving Streams	Scrubber Liquid*	662 l/min	26.5		17,543
	Scrubber Bottom	76 l/min	23.65		1,797

Rate of $CaSO_4$ 2 H_2O = SO_4 IN - SO_4 OUT + OXID. Rate

= 15,830 - 19,340 + 3,237

= -273 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Spray	738 l/min	25.2		18,598
Leaving Streams	Scrubber Liquid*	662 l/min	34.65		22,938
	Scrubber Bottom	76 l/min	27.6		2,098

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rate

= 25,036 - 18,598 + (- 273 - 4,200)

= 25,036 - 18,598 + -4,473

= 1,965 m mole/min

TABLE H-10. RATE CALCULATIONS USING LIQUID BALANCE (Continued)

Hold Tank

1. $CaSO_3$ 1/2 H_2O

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Scrubber Liquid	662 l/min	27.31		18,079
	Scrubber Bottom	76 l/min	4.5		342
	Make Up H_2O	133 l/min			
Leaving Streams	Hold Tank Eff.	871 l/min	15.05		13,109

Rate of $CaSO_3$ 1/2 H_2O = SO_2 (IN) - SO_2 (OUT)

= 18,421 - 13,109

= 5,312 m mole/min

2. $CaSO_4$ 2 H_2O

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Scrubber Liquid	662 l/min	25.2		16,682
	Scrubber Bottom	76 l/min	21.9		1,664
	Make Up H_2O	133 l/min			
Leaving Streams	Hold Tank Eff.	871 l/min	20.85		18,160

Rate of $CaSO_4$ 2 H_2O = SO_4 (IN) - SO_4 (OUT)

= 18,346 - 18,160

= 186 m mole/min

3. $CaCO_3$

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Scrubber Liquid	662 l/min	1.36		900
	Scrubber Bottom	133 l/min	0.17		13
	Make Up H_2O				
Leaving Streams	Hold Tank Eff.	871 l/min	0.97		845

Rate of $CaCO_3$ = CO_2 (IN) - CO_2 (OUT)

= 913 - 845

= 68 m mole/min

4. $Ca(OH)_2$ Dissolution

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Scrubber Liquid	662 l/min	35.3		23,369
	Scrubber Bottom	76 l/min	22.2		1,687
	Make Up H_2O	133 l/min	1.08		144
Leaving Streams	Hold Tank Eff.	871 l/min	25.5		22,211

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rates

= 22,211 - 25,200 + (5,566)

= 2,577 m mole/min

TABLE H-11. RATE CALCULATIONS USING LIQUID BALANCE

Experiment 20R

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set #1)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	9,400 g mole/min		1,962	18,443
	Scrubber Spray	757 l/min	7.9		5,980
Leaving Streams	Outlet Flue Gas	10,850 g mole/min		1,090	11,827
	Scrubber Liquid*	681 l/min	15.0		10,215
	Scrubber Bottom	76 l/min	8.1		616

Rate of $CaSO_3$ 1/2 H_2O = SO_2 (IN) - SO_2 (OUT) - Oxidation Rate

= 24,423 - 22,658 - .552 (18,443 - 11,827)

= 24,423 - 22,658 - .552 (6,616)

= 24,423 - 22,658 - 3,652

= -1,887 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ $2H_2O$					
Entering Streams	Scrubber Spray	757 l/min	24.7		18,698
Leaving Streams	Scrubber Liquid*	681 l/min	30.7		20,907
	Scrubber Bottom	76 l/min	25.3		1,923

Rate of $CaSO_4$ = SO_4 (IN) - SO_4 (OUT) + Oxidation Rate

= 18,698 - 22,830 + 3,652

= - 480 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Spray	757 l/min	23.4		17,714
Leaving Streams	Scrubber Liquid*	681 l/min	32.25		21,962
	Scrubber Bottom	76 l/min	26.1		1,984

Rate of $Ca(OH)_2$ Dissolution = Ca (OUT) - Ca (IN) + Ca Prec. Rate

= 23,946 - 17,714 + (-542 - 1,769)

= 23,946 - 17,714 + (-2,367)

= 3,865 m mole/min

TABLE H-11. RATE CALCULATIONS USING LIQUID BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Hold Tank					
1. $CaSO_3$ 1/2 H_2O					
Entering Liquid	Scrubber Liquid	681 l/min	15.6		10,624
	Scrubber Bottom	76 l/min	1.01		77
	Make Up H_2O	151 l/min	-		-
	Clarified Liquid	151 l/min	5.05		763
Leaving Streams	Hold Tank Eff.	1,059 l/min	7.45		7,890

Rate of $CaSO_3$ 1/2 H_2O = SO_2 IN - SO_2 (OUT)

= 10,701 - 7,890

= 2,811 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Liquid	Scrubber Liquid	681 l/min	30.1		20,498
	Scrubber Bottom	76 l/min	18.9		1,436
	Make-Up H_2O	151 l/min	-		
	Clarified Liq.	151 l/min	23.35		3,526
Leaving Streams	Hold Tank Eff.	1,059 l/min	24.45		25,893

Rate of $CaSO_4$ $2H_2O$ = SO_4 IN - SO_4 OUT

= 25,460 - 25,893

= -433 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$					
Entering Liquid	Scrubber Liquid	681 l/min	1.59Δ		1,083
	Scrubber Bottom	76 l/min	.06		5
	Make-Up H_2O	151 l/min	-		
	Clarified Liquid	151 l/min	.51		77
Leaving Streams	Hold Tank Eff.	1,059 l/min	.95		1,006

Rate of $CaCO_3$ = CO_2 IN - CO_2 OUT

= 1,165 - 1,006

= 159 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
4. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Liquid	681 l/min	31.6		21,520
	Scrubber Bottom	76 l/min	21.6		1,642
	Make-Up H_2O	151 l/min	1.08		163
	Clarified Liquid	151 l/min	22.1		3,337
Leaving Streams	Hold Tank Eff.	1,059 l/min	23.6		24,992

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rate

= 24,992 - 26,662 + (2,811 - 433 + 159)

= 24,992 - 26,662 + 2,537

= 867 m mole/min

ΔFrom marble bed front and back

TABLE H-11. RATE CALCULATIONS USING LIQUID BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set 2)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	9,400 g mole/min		1,939	18,227
	Scrubber Spray	751 l/min	10.2		7,721
Leaving Streams	Outlet Flue Gas	10,850 g mole/min		1,090	11,827
	Scrubber Liquid*	681 l/min	16.85		11,475
	Scrubber Bottom	76 l/min	12.0		912

Rate $CaSO_3$ 1/2 H_2O Form = SO_2 IN - SO_2 OUT - OXID. Rate

= 25,948 - 24,214 - .543 (18,227 - 11,827)

= 1,734 - 3,475

= -1,711 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ $2H_2O$					
Entering Stream	Scrubber Spray	757 l/min	25.5		19,304
Leaving Streams	Scrubber Liquid*	681 l/min	29.7		20,226
	Scrubber Bottom	76 l/min	26.6		2,022

Rate of $CaSO_4$ $2H_2O$ = SO_4 IN - SO_4 OUT + OXID. Rate

= 19,304 - 22,248 + 3,488

= 544 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Spray	757 l/min	26.6		20,136
Leaving Streams	Scrubber Liquid*	681 l/min	33.45		22,779
	Scrubber Bottom	76 l/min	30.0		2,280

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Pre. Rate

= 25,059 - 20,136 + (544 - 1,741)

= 25,059 - 20,136 + (-1,197)

= 3,726 m mole/min

TABLE H-11. RATE CALCULATIONS USING LIQUID BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Hold Tank					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid	681 l/min	18.3		12,462
	Scrubber Bottom	76 l/min	2.85		217
	Make Up H_2O	151 l/min	-		
	Clarified Liquid	151 l/min	7.4		1,117
Leaving Streams	Hold Tank Eff.	1,059 l/min	10.25		10,855

Rate of $CaSO_3$ 1/2 H_2O = SO_2 IN - SO_2 OUT

= 13,796 - 10,855

= 2,941 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid	681 l/min	29.1		19,817
	Scrubber Bottom	76 l/min	23.3		1,771
	Make Up H_2O	151 l/min	-		
	Clarified Liquid	151 l/min	20.9		3,156
Leaving Streams	Hold Tank Eff.	1,059 l/min	24.65		26,104

Rate of $CaSO_4$ $2H_2O$ = SO_4 IN - SO_4 OUT

= 24,744 - 26,104

= - 1,360 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$					
Entering Streams	Scrubber Liquid	681 l/min	1.42		967
	Scrubber Bottom	76 l/min	.48		36
	Make Up H_2O	155 l/min	-		
	Clarified Liquid	155 l/min	.57		88
Leaving Streams	Hold Tank Eff.	1,059 l/min	.87		921

Rate of $CaCO_3$ = CO_2 IN - CO_2 OUT

= 1,091 - 921

= 170 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
4. $Ca(OH)_2$ Dissolution					
Entering Liquid	Scrubber Liquid	681 l/min	33.9		23,086
	Scrubber Bottom	76 l/min	24.7		1,877
	Make Up H_2O	155 l/min	1.08		167
	Clarified Liquid	155 l/min	22.9		3,550
Leaving Streams	Hold Tank Eff.	1,059 l/min	25.9		27,428

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rates

= 27,428 - 28,680 + 1,751

= 499 m mole/min

*Ave. of Marble Bed Front and Back

TABLE H-12. RATE CALCULATIONS USING LIQUID BALANCE

Experiment 21R

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set #1)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	10,200 g mole/min		2,000	20,400
	Scrubber Spray	758 l/min	.9		682
Leaving Streams	Outlet Flue Gas	8,820 g mole/min		735	6,483
	Scrubber Liquid*	681 l/min	10.2		6,946
	Scrubber Bottom	76 l/min	1.6		122

Rate of $CaSO_3$ 1/2 H_2O Form = SO_2 IN - SO_2 OUT - Oxid. Rate

= 21,082 - 13,551 - .357 (20,400 - 6,483)

= 21,082 - 13,551 - 4,968

= 2,563 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ $2H_2O$					
Entering Streams	Scrubber Spray	758 l/min	24.82		18,814
Leaving Streams	Scrubber Liquid*	681 l/min	30.27		20,614
	Scrubber Bottom	76 l/min	26.55		2,018

Rate of $CaSO_4$ $2H_2O$ Form = SO_4 IN - SO_4 OUT - Oxid. Rate

= 18,814 - 22,632 + 4,968

= 1,150 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Spray	758 l/min	21.79		16,517
Leaving Streams	Scrubber Liquid*	681 l/min	23.98		16,330
	Scrubber Bottom	76 l/min	21.75		1,653

Rate of $Ca(OH)_2$ Dissolution = Ca (OUT) - Ca (IN) + Ca Prec. Rate

= 17,983 - 16,517 + (2,563 + 1,150)

= + 5,179 m mole/min

*Average of marble bed front and back

TABLE H-12. RATE CALCULATIONS USING LIQUID BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Hold Tank					
1. $CaSO_3$ 1/2 H_2O					
Entering Steams	Scrubber Liquid	681 l/min	.7		477
	Scrubber Bottom	76 l/min	1.0		76
	Clarified Liquid	38 l/min	1.10		42
Leaving Streams	Hold Tank Eff.	795 l/min	1.10		875
	Rate of $CaSO_3$ 1/2 H_2O = SO_2 IN - SO_2 OUT				
	= 595 - 875				
	= -280 m mole/min				
2. $CaSO_4$ $2H_2O$					
Entering Streams	Scrubber Liquid	681 l/min	25.5		17,366
	Scrubber Bottom	76 l/min	21.3		1.619
	Clarified Liquid	38 l/min	22.4		851
Leaving Streams	Hold Tank Eff.	795 l/min	26.7		21,227
	Rate of $CaSO_4$ $2H_2O$ Form = SO_4 IN - SO_4 OUT				
	= 19,836 - 21,227				
	= - 1,391 m mole/min				
3. $CaCO_3$					
Entering Streams	Scrubber Liquid	681 l/min	.18		123
	Scrubber Bottom	76 l/min	.23		17
	Clarified Liquid	38 l/min	.3		11
Leaving Streams	Hold Tank Eff.	795 l/min	.28		223
	Rate of $CaCO_3$ Form = CO_2 IN - CO_2 OUT				
	= 151 - 223				
	= 72 m mole/min				
4. $Ca(OH_2)$ Dissolution					
Set #1 Marble Bed					
Entering Streams	Scrubber Liquid	681 l/min	30.2		20,566
	Scrubber Bottom	76 l/min	28.75		2,185
	Clarified Liquid	38 l/min	20.8		790
Leaving Stream	Hold Tank Eff.	795 l/min	18.1		14.390
	Rate of $Ca(OH_2)$ Dissolution = Ca OUT + Ca IN + Ca Prec. Rate				
	= 14,390 - 23,541 + (-72 -1391 -280)				
	= - 10,894 m mole/min				

TABLE H-12. RATE CALCULATIONS USING LIQUID BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Set #2 Marble Bed					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	10,550 g mole/min		1,985	20,941
	Scrubber Spray	758 l/min	1.00		758
Leaving Streams	Outlet Flue Gas	9,200 g mole/min		678	6,238
	Scrubber Liquid*	681 l/min	10.39		7,076
	Scrubber Bottom	76 l/min	1.25		95

Rate of $CaSO_3$ 1/2 H_2O Form = SO_2 IN - SO_2 (OUT) - Oxid. Rate

= 21,699 - 13,409 - 0.266 (14,703)

= 4,380 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ $2H_2O$					
Entering Streams	Scrubber Spray	758 l/min	25.82		19,572
Leaving Streams	Scrubber Liquid*	681 l/min	30.95		21,077
	Scrubber Bottom	76 l/min	25.6		1,946

Rate of $CaSO_4$ $2H_2O$ = SO_4 IN - SO_4 OUT + Oxd. Rate

= 19,572 - 23,023 + 3,910

= 459 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Spray	758 l/min	18.59		14,091
Leaving Streams	Scrubber Liquid*	681 l/min	25.09		17,086
	Scrubber Bottom	76 l/min	20.9		1,588

Rate of Ca $(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rate

= 18,674 - 14,091 + (459 + 4,380)

= 9,422 m mole/min

*Average of marble bed front and back

TABLE H-12. RATE CALCULATIONS USING LIQUID BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Hold Tank					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid	681 l/min	2.6		1,771
	Scrubber Bottom	76 l/min	1.35		103
	Clarified Liquid	38 l/min	1.50		57
Leaving Streams	Hold Tank Eff.	795 l/min	1.73		1,375

Rate of $CaSO_3$ 1/2 H_2O Form = SO_2 IN - SO_2 OUT

= 1,931 - 1,375

= 556 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ $2H_2O$					
Entering Streams	Scrubber Liquid	681 l/min	24.7		16,821
	Scrubber Bottom	76 l/min	16.33		1,241
	Clarified Liquid	38 l/min	22.35		849
Leaving Streams	Hold Tank Eff.	795 l/min	28.8		22,896

Rate of $CaSO_4$ $2H_2O$ = SO_4 IN - SO_4 OUT

= 18,911 - 22,896

= -3,985 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$					
Entering Stream	Scrubber Liquid	681 l/min	1.42		967
	Scrubber Bottom	76 l/min	.19		14
	Clarified Liquid	38 l/min	.29		11
Leaving Streams	Hold Tank Eff.	795 l/min	.50		398

Rate of $CaCO_3$ = CO_2 IN - CO_2 OUT

= 992 - 398

= 594 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
4. $Ca(OH)_2$ Dissolution					
Entering Stream	Scrubber Liquid	681 l/min	21.17		14,417
	Scrubber Bottom	76 l/min	25.80		1,961
	Clarified Liquid	38 l/min	20.7		787
Leaving Streams	Hold Tank Eff.	795 l/min	16.9		13,436

Rate of $Ca(OH_2)$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rate

= 13,436 - 17,165 - 2,835

= -6,564 m mole/min

TABLE H-13. RATE CALCULATIONS USING LIQUID BALANCE

Experiment 22R

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	10,466 g mole/min		2,021	21,152
	Scrubber Spray	1,355 l/min	3.75		5,081
Leaving Streams	Outlet Flue Gas	9,075 g mole/min		484	4,392
	Scrubber Bottom	380 l/min	7.19		2,732
	Scrubber Liquid*	977 l/min	8.85		8,646

Rate of $CaSO_3$ 1/2 H_2O = SO_2 IN - SO_2 OUT - OXID. Rate

= 26,233 - 15,770 - .346 (21,152 - 4,392)

= 26,233 - 15,770 - .346 (16,760)

= 26,233 - 15,770 - 5,799

= 4,664 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Spray	1,355 l/min	31.10		42,140
Leaving Streams	Scrubber Liquid*	977 l/min	33.58		32,807
	Scrubber Bottom	380 l/min	27.6		10,488

Rate of $CaSO_4$ 2 H_2O = SO_4 IN - SO_4 OUT + OXID. Rate

= 42,140 - 43,295 + 5,799

= 4,644 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Spray	1,355 l/min	17.98		24,362
Leaving Streams	Scrubber Liquid*	977 l/min	21.925		21,420
	Scrubber Bottom	380 l/min	22.05		8,379

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rates

= 29,799 - 24,362 + (4,664 + 4,644)

= 14,745 m mole/min

*Ave. of Marble Bed Front and Back

TABLE H-13. RATE CALCULATIONS USING LIQUID BALANCE (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Hold Tank					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Clarified Liquid	38 l/min	.75		29
	Scrubber Liquid	977 l/min	18.55		18,123
	Scrubber Bottom	380 l/min	4.75		1,805
Leaving Streams	Hold Tank Eff.	1,395 l/min	1.93		2,692

Rate of $CaSO_3$ 1/2 H_2O = SO_2 IN - SO_2 OUT

= 19,957 - 2,692

= 17,265 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid	977 l/min	39.5		38,591
	Scrubber Bottom	380 l/min	30.43		11,563
	Clarified Liquid	38 l/min	21.5		817
Leaving Streams	Hold Tank Eff.	1,395 l/min	29.77		41,529

Rate of $CaSO_4$ 2 H_2O = SO_4 IN - SO_4 OUT

= 50,971 - 41,529

= 9,442 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$					
Entering Streams	Scrubber Liquid	977 l/min	.79		772
	Scrubber Bottom	380 l/min	1.38		524
	Clarified Liquid	38 l/min	.23		9
Leaving Streams	Hold Tank Eff.	1,395 l/min	.65		907

Rate of $CaCO_3$ = CO_2 IN - CO_2 OUT

= 1,305 - 907

= 398 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
4. $Ca(OH)_2$ Dissolution					
Entering Streams	Scrubber Liquid	977 l/min	27.2		26,574
	Scrubber Bottom	380 l/min	19.58		7,440
	Clarified Liquid	38 l/min	21.1		802
Leaving Streams	Hold Tank Eff.	1,395 l/min	16.4		22,878

Rate of $Ca(OH)_2$ Dissolution = Ca OUT - Ca IN + Ca Prec. Rate

= 22,878 - 34,816 + (17,265 + 9,442 + 398)

= 15,167 m mole/min

APPENDIX I

LIMESTONE FURNACE INJECTION SYSTEM

ADDITIVE DISSOLUTION RATE DETERMINATION DIAGRAMS

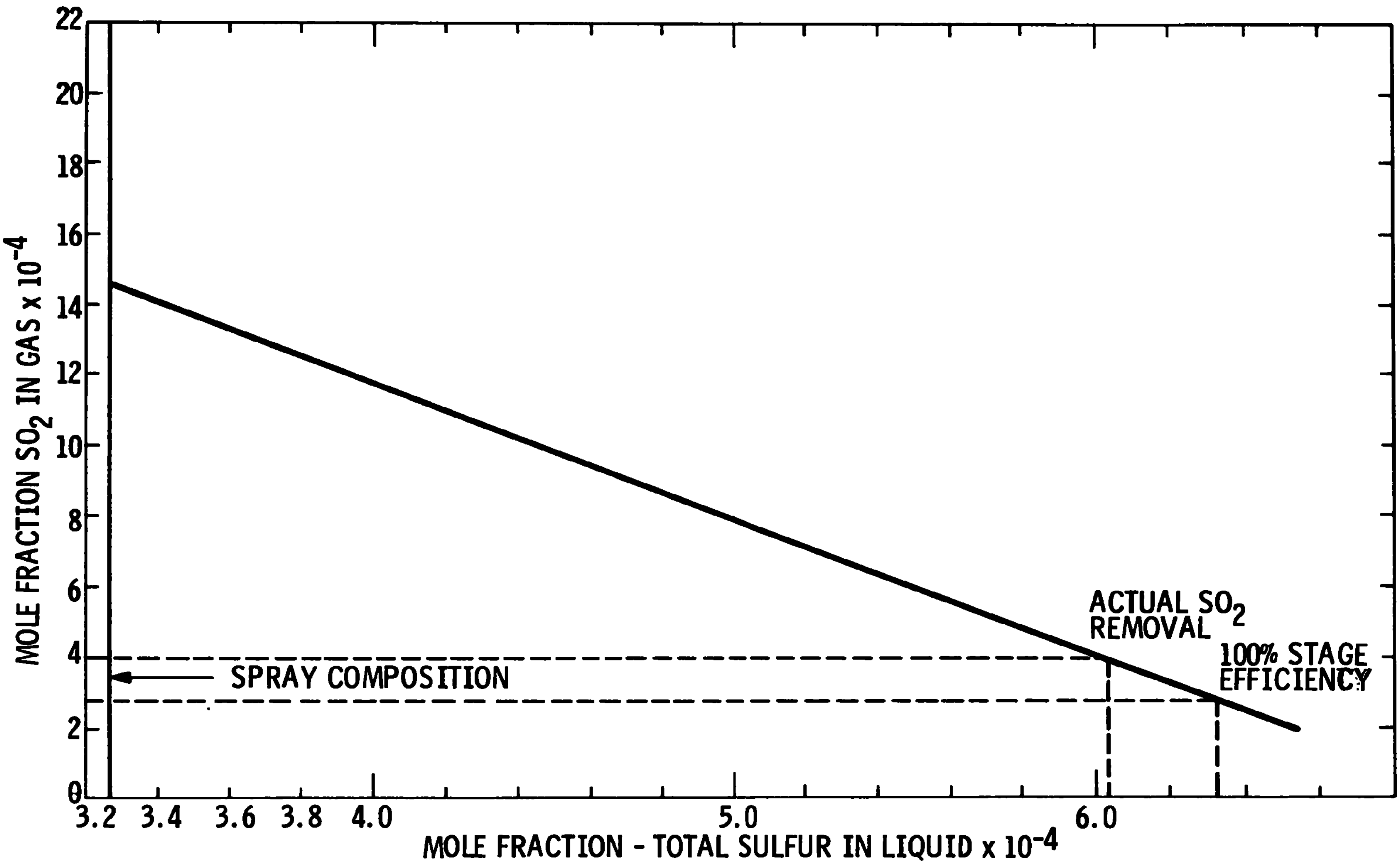


Figure I-1

PLOT OF OPERATING LIME FOR EXPERIMENT 18R

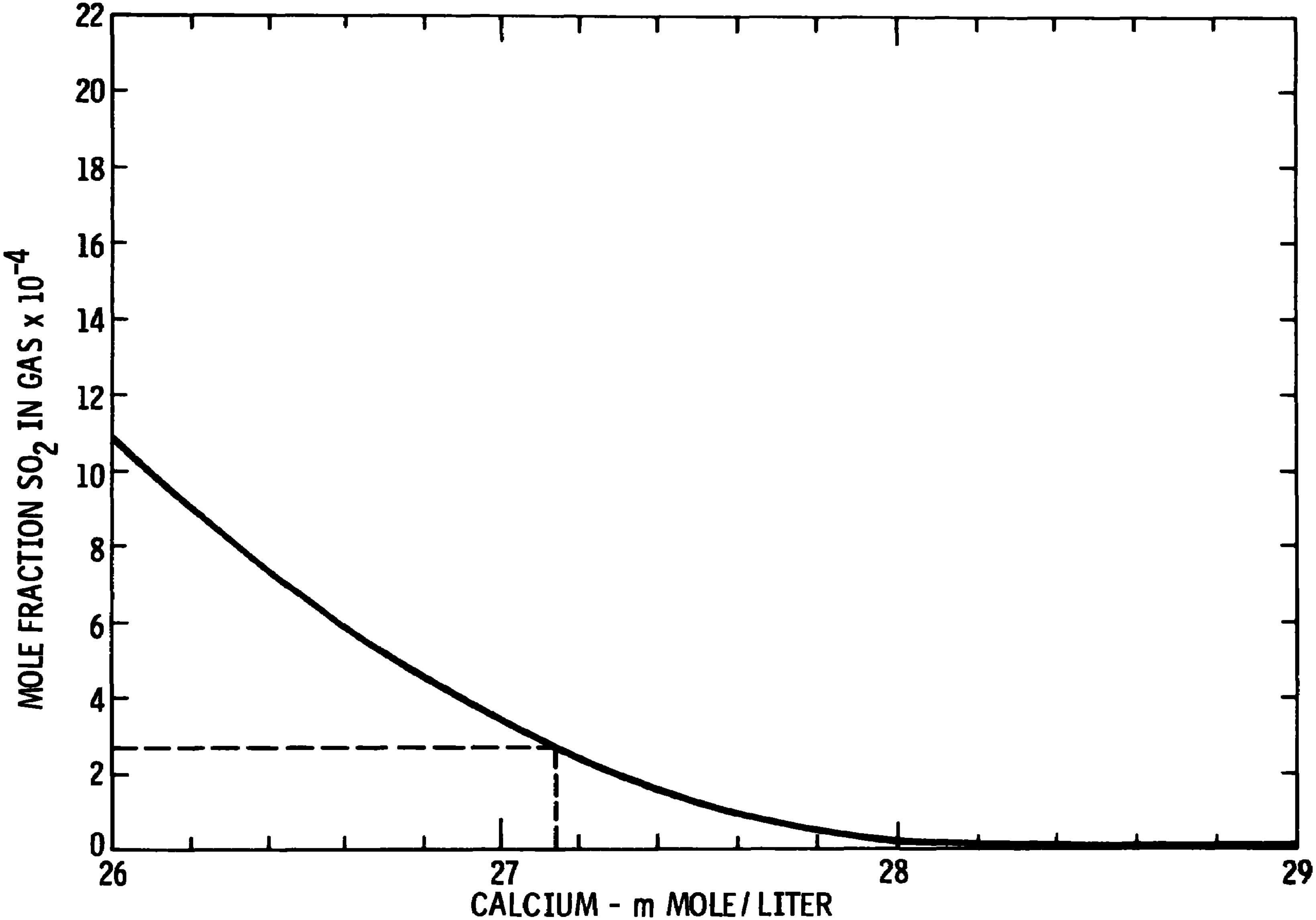
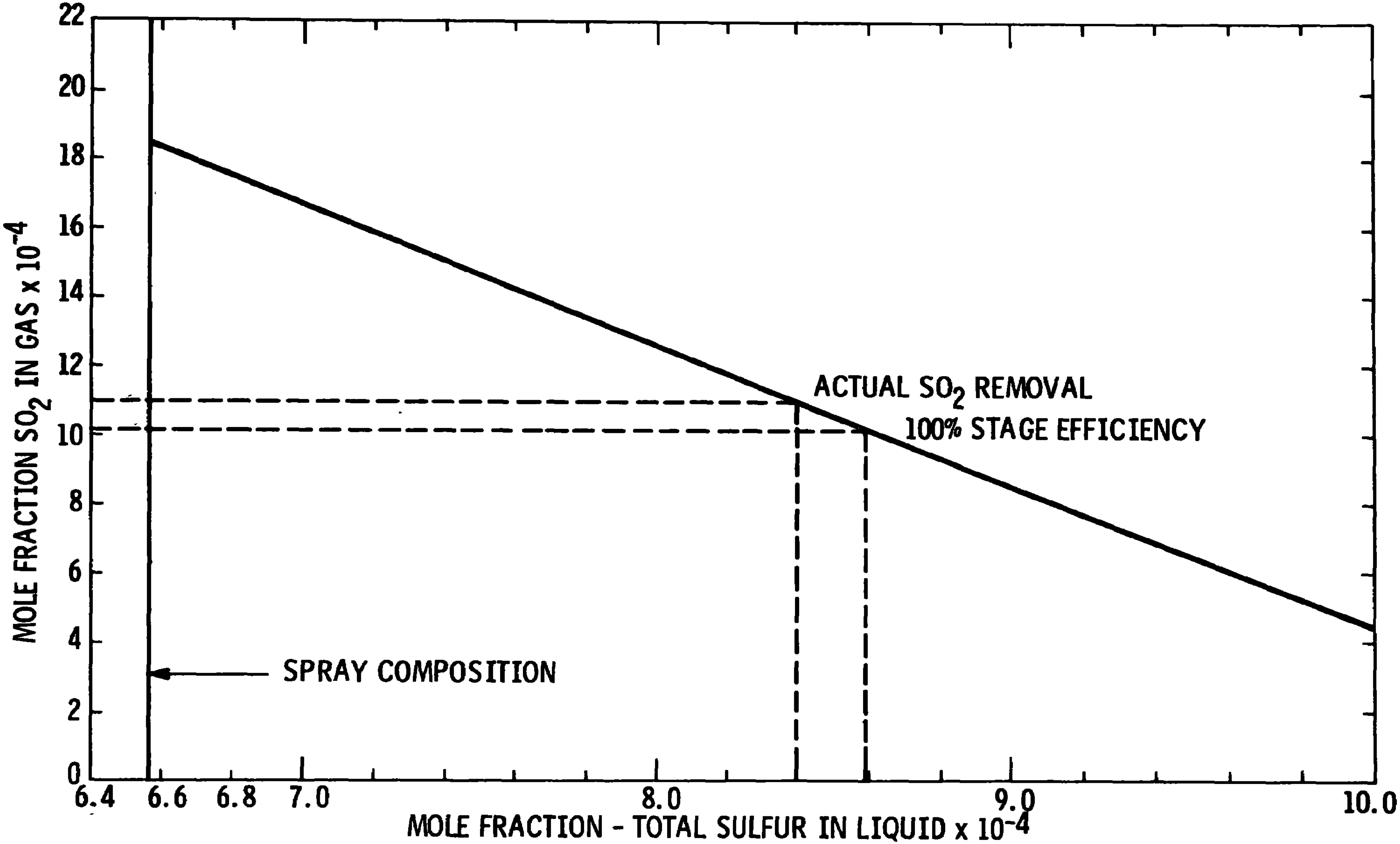


Figure I-2

PLOT OF CALCIUM vs PARTIAL PRESSURE OF SO_2 FOR SCRUBBER EFFLUENT - EXPERIMENT 18R



PLOT OF OPERATING LINE FOR EXPERIMENT 19R

Figure I-3

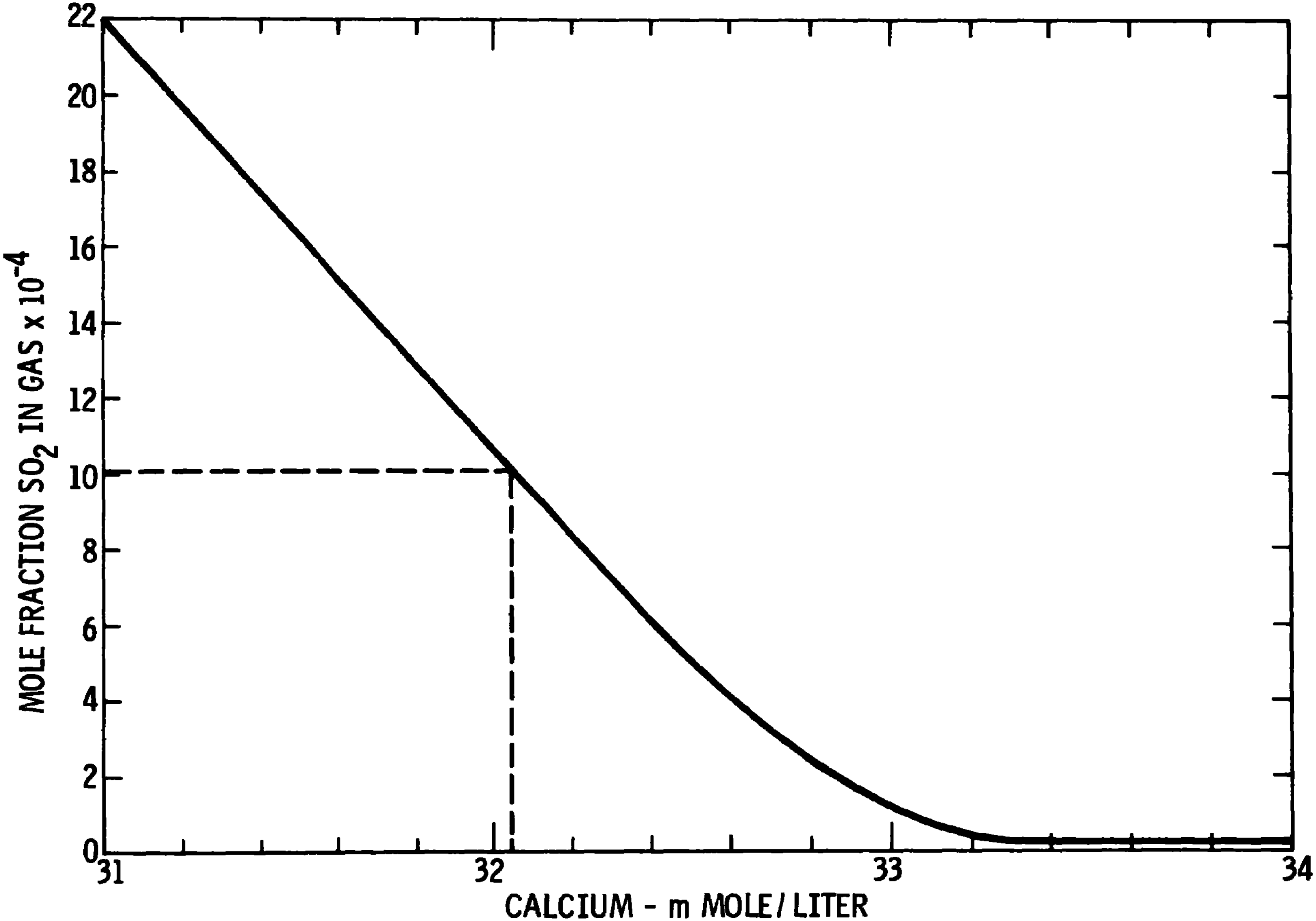


Figure I-4

PLOT OF CALCIUM vs PARTIAL PRESSURE OF SO_2 FOR SCRUBBER EFFLUENT - EXPERIMENT 19R

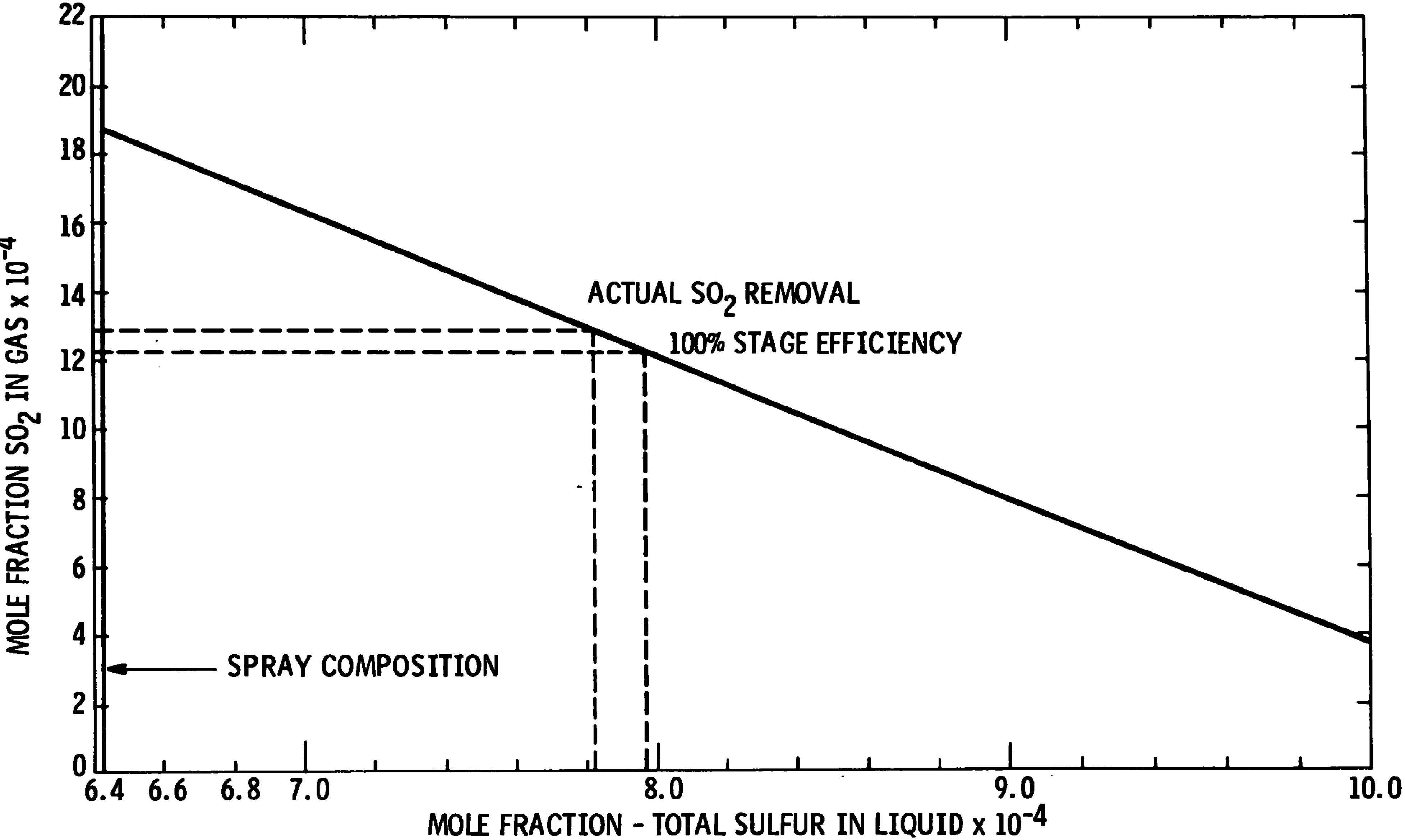


Figure I-5

PLOT OF OPERATING LIN FOR EXPERIMENT 20R

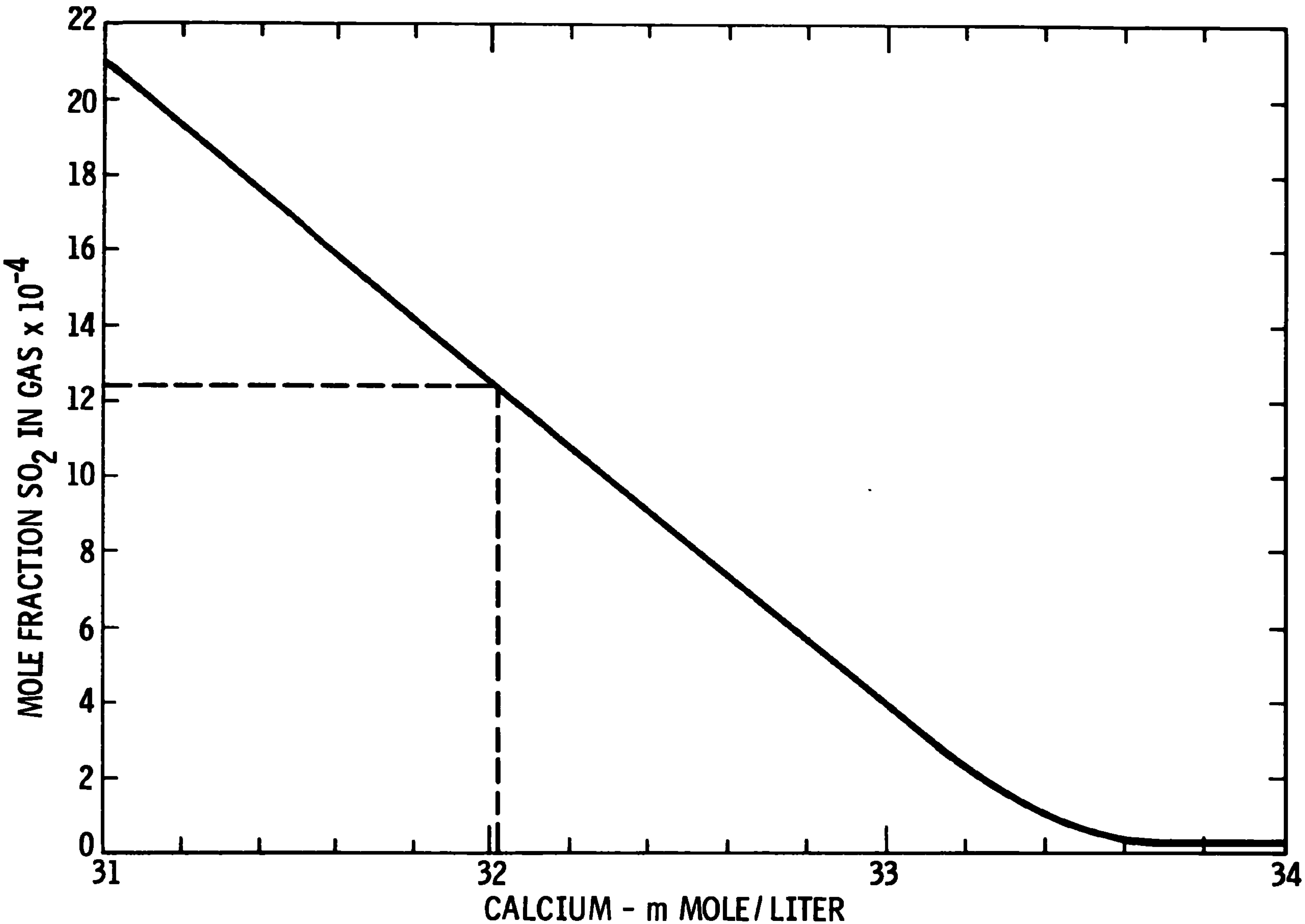


Figure I-6

PLOT OF CALCIUM vs PARTIAL PRESSURE OF SO_2 FOR SCRUBBER EFFLUENT - EXPERIMENT 20R

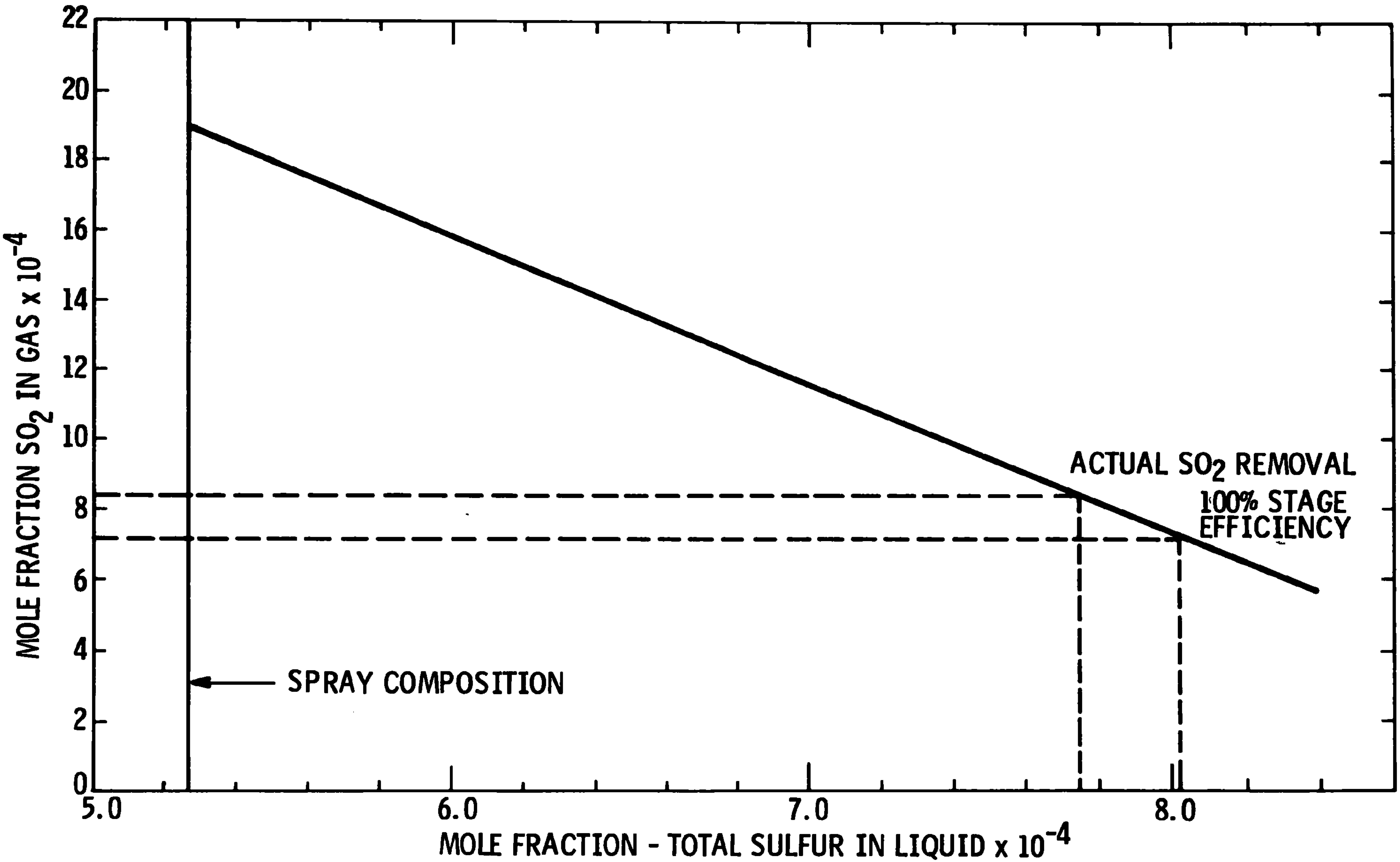


Figure I-7

PLOT OF OPERATING LINE FOR EXPERIMENT 21R

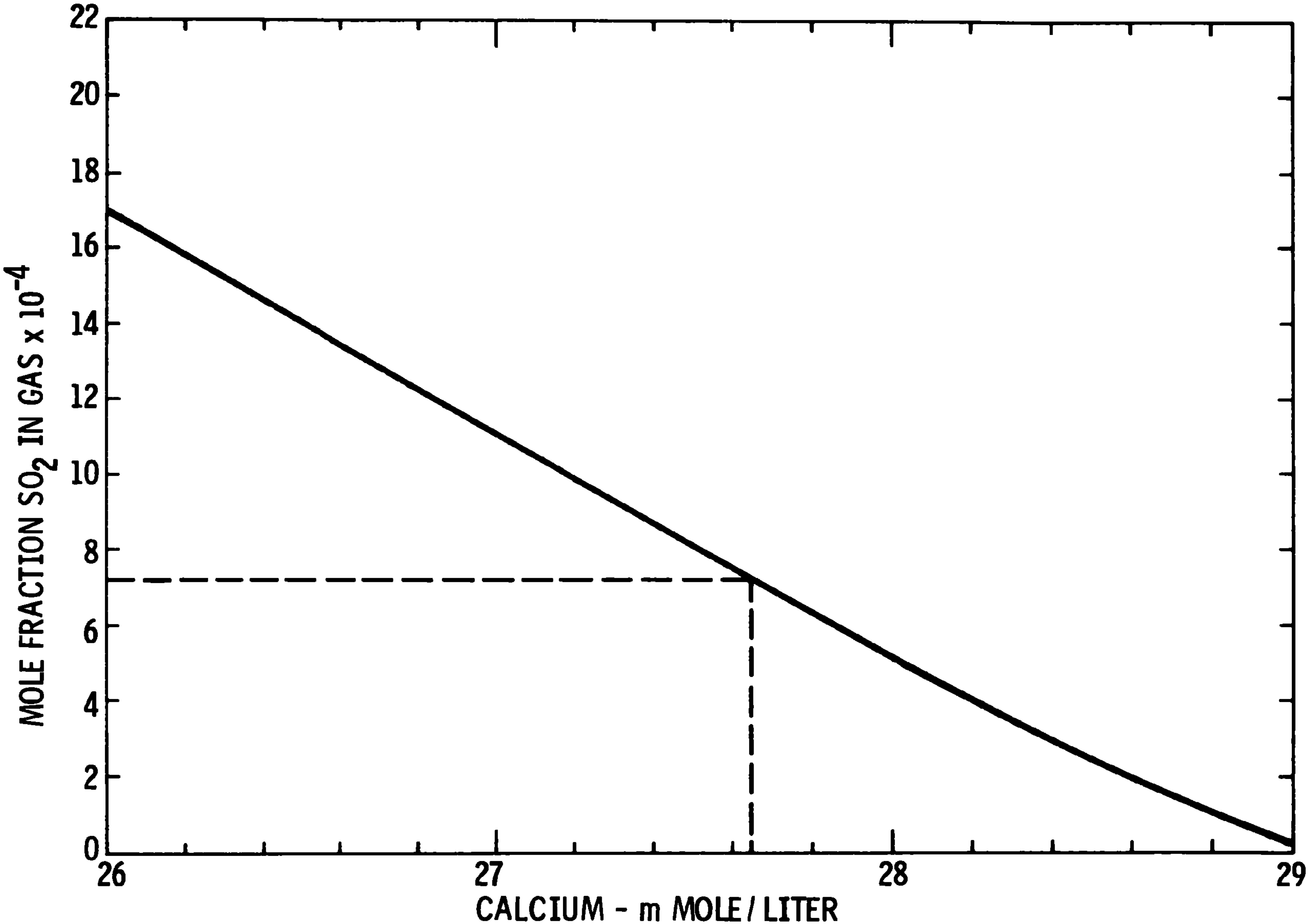


Figure I-8

PLOT OF CALCIUM vs PARTIAL PRESSURE OF SO_2 FOR SCRUBBER EFFLUENT - EXPERIMENT 21R

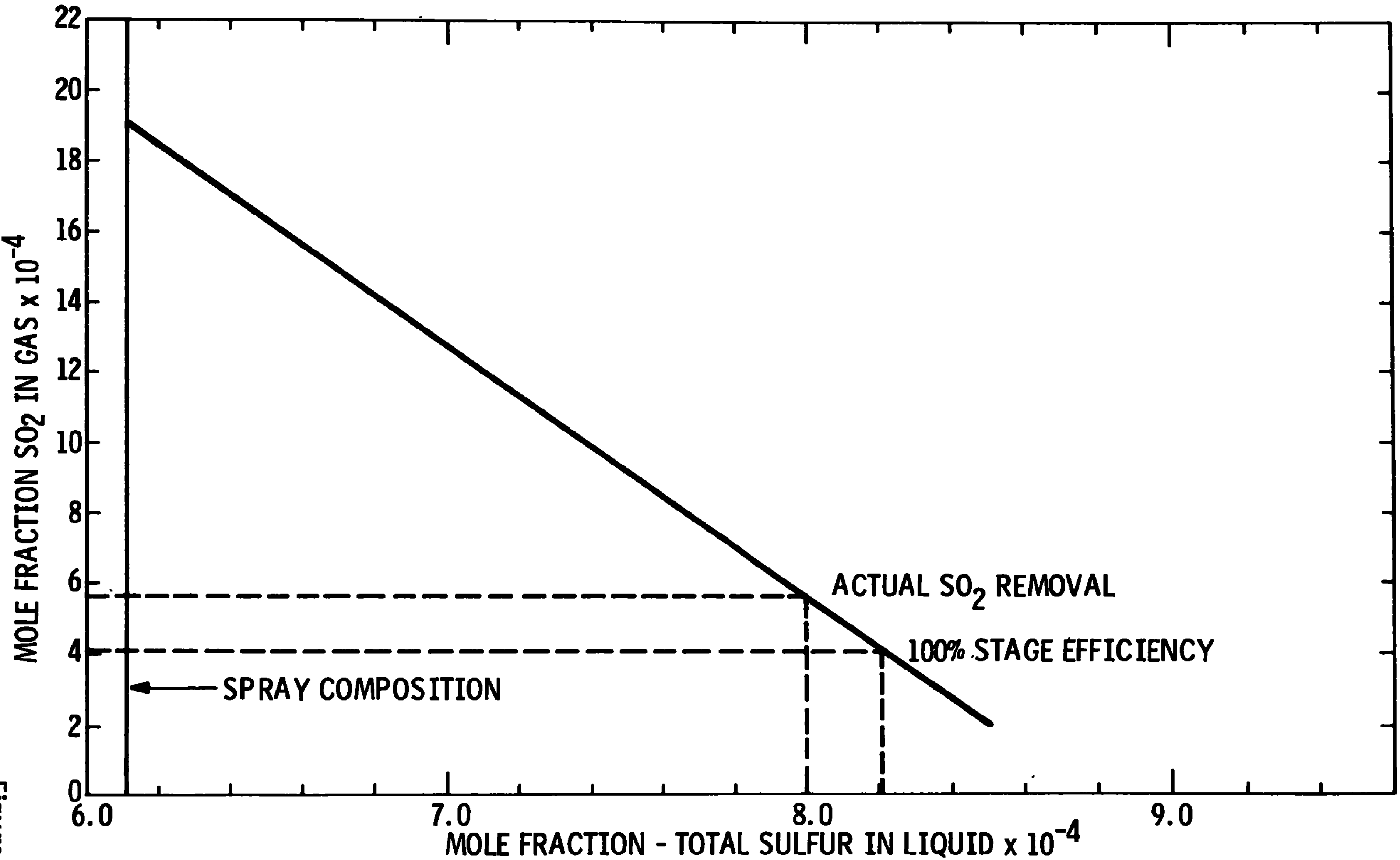


Figure I-9

PLOT OF OPERATING LINE FOR EXPERIMENT 22R

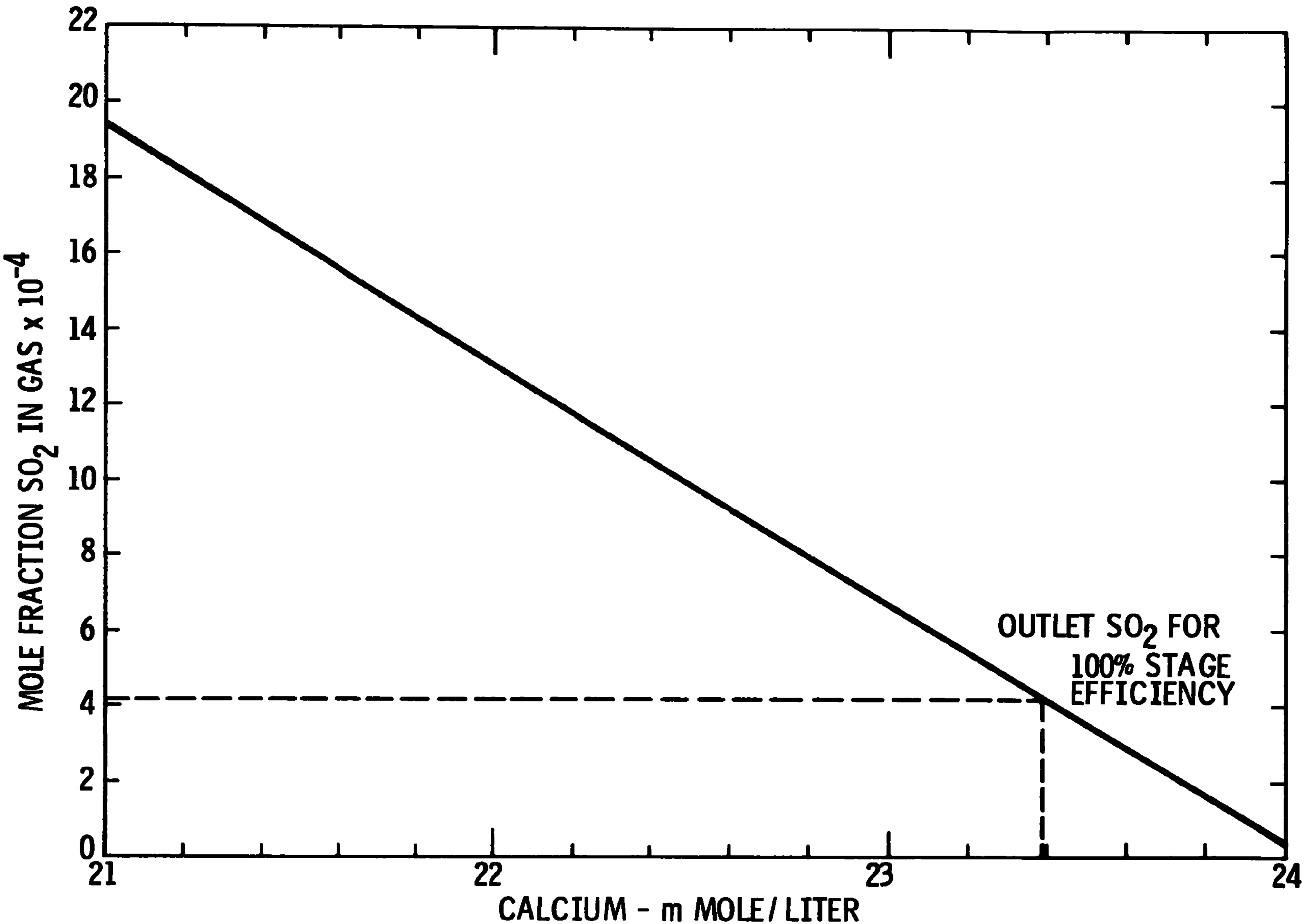


Figure I-10

PLOT OF CALCIUM vs PARTIAL PRESSURE OF SO_2 FOR SCRUBBER EFFLUENT - EXPERIMENT 22R

APPENDIX J

LIMESTONE TAIL-END SYSTEM

OPERATING DATA

AND

ANALYTICAL RESULTS

TABLE J-1. C-E APCS PROTOTYPE
TAIL-END LIMESTONE TESTS

Experiment No.	25R		26R		27R	
Date of Run	7/7/72		7/10/72		7/11/72	
Set Number	1	2	1	2	1	2
Time	1045-1200	1230-1315	1400-1500	1515-1600	0920-1030	1030-1130
Flue Gas (FG) Rate (cfm @ 130°F)	9,950	9,900	10,060	10,100	10,250	10,180
Additive Feed Rate (lb/hr)	318	318	510	510	516	516
Spray Water Lower (SWL) Rate (gpm)	240	250	245	235	150	150
Spray Water Upper (SWU) Rate (gpm)	-	-	-	-	-	-
Scrubber Liquid Lower (SLL) Rate (gpm)	180	195	180	178	135	135
Scrubber Liquid Upper (SLU) Rate (gpm)	-	-	-	-	-	-
Scrubber Bottom (SB) Rate (gpm)	60	55	65	58	15	15
Clarifier Liquid (CL) Rate (gpm)	10	10	15	15	12	12
Liquid Blowdown (LB) Rate (gpm)	0	0	0	0	0	0
Clarifier Feed (CF) Rate (gpm)	10	10	15	15	12	12
Clarifier Bottom (CB) Rate (gpm)	-	-	3	3	-	-
Filter Liquid (FL) Rate (gpm)	-	-	-	-	-	-
Spray Water (SW) Temp. (°F)	122	121	120	120	120	120
Scrubber Liquid (SL) Temp. (°F)	122	121	122	122	121	121
Scrubber Bottom (SB) Temp. (°F)	134	135	131	135	131	131
Inlet Gas Dew Point (°F)	114	114	113	113	104.5	104.5
Outlet Gas Dew Point (°F)	121.5	121.5	119	119	117.5	117.5
Reheater Inlet Gas Temp. (°F)	125	124	121	122	122	122
Heat Extractor Outlet Gas Temp. (°F)	295	298	315	315	298	305
Inlet SO_2 (ppm)	2,329	2,362	2,519	2,490	2,306	2,323
Outlet SO_2 (ppm)	956	997	1,023	999	1,114	1,099
Inlet O_2 (%)*	10.6	10.6	9.8	9.8	10.0	10.0
Outlet O_2 (%)	-	-	10.3	10.3	10.6	10.6
Inlet CO_2 (%)*	8.0	8.0	8.2	8.2	8.4	8.4
Outlet CO_2 (%)	-	-	7.8	7.8	7.5	7.5
Outlet SO_2 corrected for air leakage (ppm)	1,022	1,070	1,097	1,072	1,195	1,177
SO_2 Removal Efficiency (%)	56.2	54.7	56.5	57.0	48.2	49.4
Stoichiometry (%)	98.5	97.6	114.5	146.1	156.7	156.6
Solid Concentration in Spray Water	7.56	7.14	-	6.57	7.18	7.69

* Average Air Leakage 7.2%

TABLE J-1. (Continued)

Experiment No.	28R		29R		30R	
Date of Run	7/12/72		7/13/72		7/14/72	
Set Number	1	2	1	2	1	2
Time	1445-1545	1605-1705	1100-1200	1245-1315	0950-1050	1125-1225
Flue Gas (FG) Rate (cfm @ 130°F)	10,160	10,400	10,200	10,400	10,280	10,280
Additive Feed Rate (lb/hr)	516	516	516	516	320	320
Spray Water Lower (SWL) Rate (gpm)	158	160	245	245	250	250
Spray Water Upper (SWU) Rate (gpm)	150	150	225	225	235	235
Scrubber Liquid Lower (SLL) Rate (gpm)	168	170	210	200	215	215
Scrubber Liquid Upper (SLU) Rate (gpm)	112	110	170	180	180	180
Scrubber Bottom (SB) Rate (gpm)	28	30	90	90	90	90
Clarifier Liquid (CL) Rate (gpm)	15	15	15	15	10	10
Liquid Blowdown (LB) Rate (gpm)	0	15	0	0	0	0
Clarifier Feed (CF) Rate (gpm)	15	15	15	15	10	10
Clarifier Bottom (CB) Rate (gpm)	-	-	-	-	-	-
Filter Liquid (FL) Rate (gpm)	-	-	-	-	-	-
Spray Water (SW) Temp. (°F)	125	126	126	125	124	123
Scrubber Liquid (SL) Temp. (°F)	125	121	137	134	130	136
Scrubber Bottom (SB) Temp. (°F)	125	132	127	126	125	125
Inlet Gas Dew Point (°F)	119.3	119.3	114	114	115	115
Outlet Gas Dew Point (°F)	125	125	125.5	125.5	122	122
Reheater Inlet Gas Temp. (°F)	125	126	125	125	125	125
Heat Extractor Outlet Gas Temp. (°F)	308	312	315	305	340	340
Inlet SO_2 (ppm)	2,392	2,432	2,456	2,415	2,300	2,457
Outlet SO_2 (ppm)	546	543	297	280	334	405
Inlet O_2 (%)*	9.3	9.3	10.6	10.6	-	-
Outlet O_2 (%)	9.8	9.8	11.6	11.6	-	-
Inlet CO_2 (%)*	8.4	8.4	7.4	7.4	-	-
Outlet CO_2 (%)	8.1	8.1	6.7	6.7	-	-
Outlet SO_2 corrected for air leakage (ppm)	585	582	318	300	358	434
SO_2 Removal Efficiency (%)	75.5	76.0	87.0	87.6	84.4	87.3
Stoichiometry (%)	152.4	151.7	147.8	147.5	97.1	90.94
Solid Concentration in Spray Water	6.39	6.97	8.40	8.75	-	-

* Average Air Leakage 7.2%

TABLE J-2. SPRAY WATER FILTRATE ANALYSIS AND SOLIDS CONCENTRATION DATA FOR STEADY STATE DETERMINATION

Data	Test No.	Sample No.	Time	Ca++ (ppm)	$SO_3^=$ (ppm)	Total Sulfur as $SO_4^=$ (ppm)	$SO_4^=$ (ppm)	pH	Solid Conc. (%)
7/5/72	25R	1	1200	1272	952	4460	3317		1.3
"	"	2	1300	1287	852	4700	3677		1.8
"	"	3	1340	962	524	3080	2451		2.6
7/6/72	25R	4	0900	755	376	2450	1998		3.3
"	"	5	1000	524	376	1740	1317		4.3
"	"	6	1100	793	412	2540	2045		4.7
"	"	7	1200	760	404	2400	1915	6.15	5.2
"	"	8	1300	799	412	2550	2055	6.05	5.8
"	"	9	1400	754	392	2650	2179	6.05	7.4
"	"	10	1500	737	404	2680	2195	6.13	7.9
"	"	11	1600	701	352	2350	1927	6.19	7.5
"	"	12	1700	753	360	2390	1958	6.18	7.4
"	"	13	1800	758	412	2490	1995		7.2
"	"	14	1900	776	404	2430	1945		7.3
7/7/72	"	15	0730	786	104	2620	2495	6.20	7.0
"	"	16	0800	761	352	2580	2157	6.20	6.4
"	"	17	0900	758	372	2620	2173		6.8
"			1000					6.10	6.9
				Sampling for Test 25R					
7/7/72	26R	18	1330	777	396	2790	2314	6.10	7.2
"	"	19	1400	741	376	2410	1958		7.5
"	"	20	1500	525	328	1780	1386	6.10	7.0
"	"	21	1600	787	408	2740	2250	6.10	6.4
"	"	22	1700	750	112	2560	2425		6.4
7/10/72	"	23	0800	796	272	2780	2453		6.2
"	"	24	1000	756	92	2510	2399		6.5
"	"	25	1030	780	220	2780	2516	6.0	6.0
"	"	26	1100	700	192	2690	2459	6.02	6.6
"	"	27	1200	761	188	2640	2414		7.3
"	"	28	1300	780	192	2680	2449	6.10	6.9
"	"		1630						5.5
"	"		1645						6.1
"	"		1700						6.8
				Sampling for Test 26R					

TABLE J-2. (Continued)

Data	Test No.	Sample No.	Time	Ca++ (ppm)	$SO_3^=$ (ppm)	Total Sulfur as $SO_4^=$ (ppm)	$SO_4^=$ (ppm)	pH	Solid Conc. (%)
7/11/72	27R	29	0800	823	272	3010	2683	6.1	5.9
"	"	30	0830	812	192	2770	2539		6.5
"	"	31	0900	802	184	2870	2649	6.1	6.0
			Sampling for Test 27R and Installing Upper Marble Bed						
7/12/72	28R	32	0900	784	232	2700	2421	6.61	6.0
"	"		0930						6.1
"	"	33	1000	882	212	3070	2815	6.50	6.1
"	"		1030						6.1
"	"	34	1100	845	192	2860	2629	6.40	6.8
"	"		1130						6.6
"	"	35	1200	824	216	3010	2750	6.50	6.9
"	"	36	1300	772	172	2880	2673	6.50	12.8
"	"		1330						6.6
"	"	37	1400	756	156	2840	2652	6.40	5.5
			Sampling for Test 28R						
7/13/72	29R	38	0800	781	252	2970	2667	6.1	6.3
"	"		0840						6.1
"	"	39	0900	806	268	3070	2748		6.2
"	"		0930						6.0
"	"		1000						9.6
"	"		1030						6.8
			Sampling for Test 29R						
7/14/72	30R	40	0645	716	292	3200	2849		7.4
"	"		0715						7.7
"	"	41	0745	655	196	2850	2614		7.4
"	"		0815						7.5
"	"	42	0845	718	196	3030	2794		6.9
			Sampling for Test 30R						

TABLE J-3. RESULTS OF SOLID PHASE ANALYSES
EXPERIMENT 25R

7/7/72

Sample Location	Time	Wt % Solids in Slurry	Composition in Millimoles/Gram: Total S	Ca	Mg	SO_2	SO_3	CO_2	Weight % Undissolved
Set 1									
Scrubber Liquid Tk	1055	7.13	4.74	7.29	0.030	3.57	1.17	2.70	1.64
Scrubber Bottoms Tk	1100	7.74	4.42	7.38	0.031	3.27	1.15	3.09	2.18
Hold Tank Effluent	1120	7.79	4.28	7.46	0.032	3.21	1.07	3.24	2.18
Marble Bed: Front	1130	7.32	4.64	7.22	0.029	3.50	1.14	2.73	1.90
Marble Bed: Back	1142	6.32	5.39	7.32	0.023	4.02	1.37	2.08	2.05
Scrubber Bottoms S	1155	7.90	4.61	7.40	0.030	3.42	1.19	2.94	2.07
Scrubber Spray	1203	7.55	4.36	7.39	0.032	3.32	1.04	3.05	2.50
Set 2									
Scrubber Liquid Tk	1235	7.04	4.85	7.31	0.027	3.70	1.16	2.69	1.73
Scrubber Bottoms Tk	1240	7.29	4.67	7.48	0.028	3.51	1.16	2.81	2.09
Hold Tank Effluent	1300	7.14	4.31	7.31	0.029	3.30	1.01	2.94	2.04
Lime Stone			0.002	9.50	0.13	-	0.002	9.24	2.60
Lime Stone			0.015	9.45	0.13	-	0.002	9.40	2.26

TABLE J-4. RESULTS OF SOLID PHASE ANALYSES
EXPERIMENT 26R

7/10/72

Sample Location	Time	Wt % Solids in Slurry	Composition in Millimoles/Gram: Total S	Ca	Mg	SO_2	SO_3	CO_2	Weight % Undissolved
Set 1									
Scrubber Liquid Tk	1400	-	4.94	7.73	0.04	3.69	1.25	2.87	1.59
Scrubber Bottoms Tk	1405	-	4.92	7.69	0.04	3.76	1.16	2.86	1.43
Hold Tank Effluent	1420	-	4.59	7.83	0.04	3.39	1.20	3.23	1.80
Marble Bed: Front	1435	-	5.02	7.72	0.04	3.76	1.26	2.75	1.53
Marble Bed: Back	1445	-	5.26	7.67	0.03	4.02	1.24	2.57	1.43
Scrubber Bottom S	1450	-	4.54	7.92	0.04	3.40	1.03	3.40	2.08
Scrubber Spray	1455	-	3.94	8.05	0.05	2.90	1.04	4.37	2.89
Set 2									
Scrubber Liquid Tk	1515	6.24	4.54	7.67	0.06	3.39	1.15	3.30	1.84
Scrubber Bottoms Tk	1525	6.34	4.38	7.84	0.05	3.30	1.08	3.40	1.97
Hold Tank Effluent	1547	6.43	4.12	7.71	0.06	3.14	0.98	3.61	1.93
Marble Bed: Front	1555	7.94	4.31	7.69	0.06	3.29	1.02	3.40	1.97
Marble Bed: Back	1602	6.65	4.45	7.60	0.05	3.38	1.07	3.38	1.95
Scrubber Bottoms S	1615	-	4.43	7.68	0.06	3.37	1.06	3.40	1.73
Scrubber Spray	1610	6.57	3.82	7.90	0.06	2.94	0.88	4.03	2.44

TABLE J-5. RESULTS OF SOLID PHASE ANALYSES
EXPERIMENT 27R

7/11/72

Sample Location	Time	Wt % Solids in Slurry	Composition in Millimoles/Gram: Total S	Ca	Mg	SO_2	SO_3	CO_2	Weight % Undissolved
Set 1									
Scrubber Liquid Tk	0935	6.70	4.02	8.04	0.5	3.05	0.97	3.82	2.37
Scrubber Bottoms Tk	0940	5.94	4.53	7.95	0.5	3.53	1.00	3.22	1.79
Hold Tank Effluent	0953	7.43	3.60	8.13	0.06	2.65	0.95	4.36	2.70
Marble Bed: Front	1000	6.46	4.22	7.84	0.06	3.26	0.96	3.81	2.24
Marble Bed: Back	1007	7.52	3.98	7.95	0.06	3.04	0.94	4.02	2.91
Scrubber Bottoms S	1015	6.92	4.07	7.93	0.06	3.17	0.90	3.79	1.64
Scrubber Spray	1020	7.18	3.57	8.08	0.07	2.70	0.87	4.54	3.16
Set 2									
Scrubber Liquid Tk	1040	6.80	3.91	8.00	0.06	2.94	0.98	4.00	2.03
Scrubber Bottoms Tk	1045	7.47	3.72	8.06	0.07	2.78	0.93	4.28	2.12
Hold Tank Effluent	1100	7.38	3.49	8.07	0.06	2.62	0.87	4.65	2.28
Marble Bed: Front	1110	7.08	4.24	8.01	0.06	3.23	1.01	3.79	1.96
Marble Bed: Back	1115	7.97	4.44	7.96	0.06	3.45	0.99	3.55	1.83
Scrubber Bottoms S	1122	7.49	3.69	8.12	0.06	2.76	0.93	4.50	2.72
Scrubber Spray	1128	7.69	3.53	8.08	0.06	2.74	0.79	4.45	2.58

TABLE J-6. RESULTS OF SOLID PHASE ANALYSES
EXPERIMENT 28R

7/11/72

Sample Location	Time	Wt % Solids in Slurry	Composition in Millimoles/Gram: Total S	Ca	Mg	SO_2	SO_3	CO_2	Weight % Undissolved
Set 1									
Scrubber Liquid Tk Lower	0250	6.04	4.74	7.82	0.06	3.19	1.05	3.65	2.11
Scrubber Liquid Tk Upper	0255	6.07	4.31	7.87	0.06	3.26	1.05	3.70	1.92
Scrubber Bottoms Tk	0300	6.60	4.09	7.94	0.07	3.07	1.02	3.70	1.93
Hold Tank Effluent	0312	6.17	4.02	7.88	0.07	3.04	0.98	3.74	2.12
Marble Bed: Front-Upper	0325	6.61	4.30	7.86	0.06	3.21	1.09	3.40	1.81
Marble Bed: Front-Lower	0345	8.45	4.07	7.95	0.07	3.00	1.07	3.79	2.12
Marble Bed: Back-Lower	0355	4.72	5.49	7.52	0.04	4.26	1.23	2.16	1.20
Scrubber Bottoms S	0330	6.93	4.16	7.90	0.07	3.14	1.02	3.67	2.02
Scrubber Spray	0337	6.40	3.84	8.01	0.07	2.86	0.98	3.91	1.99
Set 2									
Scrubber Liquid Tk Lower	0405	6.05	4.46	7.82	0.04	3.34	1.12	3.30	1.99
Scrubber Liquid Tk Upper	0410	6.17	4.52	7.83	0.05	3.36	1.16	3.20	1.80
Scrubber Bottoms Tk	0420	6.60	4.22	7.85	0.06	3.15	1.07	3.49	1.98
Hold Tank Effluent	0440	6.47	4.06	7.77	0.06	3.01	1.05	3.90	1.97
Marble Bed: Front-Upper	0512	6.13	5.07	7.67	0.04	3.90	1.17	2.88	1.02
Marble Bed: Front-Lower	0447	6.61	4.18	7.76	0.06	3.11	1.07	3.53	1.96
Marble Bed: Back-Lower	0455	4.46	5.90	7.45	0.03	4.71	1.19	1.87	0.83
Scrubber Bottoms S	0505	7.67	4.50	7.84	0.05	3.39	1.11	3.00	2.04
Scrubber Spray	0520	6.71	4.21	7.92	0.06	3.13	1.08	3.48	1.64

TABLE J-7. RESULTS OF SOLID PHASE ANALYSES
EXPERIMENT 29R

7/13/72

Sample Location	Time	Wt % Solids in Slurry	Composition in Millimoles/Gram: Total S	Ca	Mg	SO_2	SO_3	CO_2	Weight % Undissolved
Set 1									
Scrubber Liquid Tk Lower	1100	7.21	4.75	7.72	0.05	3.42	1.32	3.00	1.60
Scrubber Liquid Tk Upper	1105	7.32	4.69	7.85	0.05	3.40	1.28	2.95	1.44
Scrubber Bottoms Tk	1115	7.59	4.56	7.80	0.06	3.28	1.28	3.04	1.75
Hold Tank Effluent	1130	10.05	4.51	7.62	0.08	3.25	1.26	2.93	1.76
Marble Bed: Front-Upper	1203	11.31	5.32	7.36	0.06	3.88	1.44	2.13	1.14
Marble Bed: Front-Lower	1141	7.86	4.55	7.57	0.08	3.37	1.18	2.92	1.77
Marble Bed: Back-Lower	1155	6.18	6.09	7.19	0.05	4.54	1.55	1.32	0.66
Scrubber Bottoms S	1145	7.09	4.80	7.54	0.06	3.45	1.35	2.73	1.49
Scrubber Spray	1210	8.41	4.53	7.55	0.07	3.27	1.26	2.90	1.83
Set 2									
Scrubber Liquid Tk Lower	1225	7.21	5.04	7.45	0.07	3.59	1.45	2.59	1.47
Scrubber Liquid Tk Upper	1230	8.19	4.75	77	0.07	3.36	1.39	2.75	1.66
Scrubber Bottoms Tk	1235	10.27	4.65	7.54	0.07	3.33	1.32	2.85	1.75
Hold Tank Effluent	1256	8.85	4.61	7.47	0.07	3.30	1.31	2.93	1.68
Marble Bed: Front-Upper	0135	12.34	5.60	7.30	0.04	4.10	1.50	2.06	0.98
Marble Bed: Front-Lower	0110	8.99	4.68	7.46	0.06	3.32	1.36	2.97	1.79
Marble Bed: Back-Lower	0118	6.87	6.05	7.22	0.03	4.50	1.55	1.34	0.76
Scrubber Bottoms S	0130	9.17	5.07	7.43	0.05	3.58	1.49	2.40	1.42
Scrubber Spray	0140	8.72	5.00	7.46	0.05	3.63	1.37	2.67	1.62

TABLE J-8. RESULTS OF SOLID PHASE ANALYSES
EXPERIMENT 30R

7/14/72

Sample Location	Time	Wt % Solids in Slurry	Composition in Millimoles/Gram Total S	Ca	Mg	SO_2	SO_3	CO_2	Weight % Undissolved
Set 1									
Scrubber Liquid Tk-Lower	1000		5.79	7.10	0.05	4.08	1.71	1.45	1.10
Scrubber Liquid Tk-Upper	1005		5.67	7.09	0.06	4.00	1.68	1.59	1.35
Scrubber Bottoms Tk	1015		5.52	7.13	0.05	3.87	1.65	1.82	1.55
Hold Tank Effluent	1031		5.63	7.16	0.05	3.94	1.69	1.82	1.46
Marble Bed: Front-Upper	1052		6.10	7.10	0.04	4.30	1.80	1.19	1.00
Marble Bed: Front-Lower	1038		5.81	7.01	0.05	4.04	1.77	1.49	1.21
Marble Bed: Back-Lower	1045		6.46	7.04	0.03	4.62	1.84	0.87	0.64
Scrubber Bottoms S	1058		5.66	7.17	0.05	3.89	1.77	1.82	1.34
Scrubber Spray	1105		5.70	7.15	0.05	3.87	1.83	1.67	1.40
Set 2									
Scrubber Liquid Tk-Lower	1125		5.81	7.09	0.04	4.02	1.79	1.46	1.34
Scrubber Liquid Tk-Upper	1130		5.82	7.15	0.04	4.02	1.80	1.47	1.35
Scrubber Bottoms Tk 1	1135		5.64	7.15	0.05	3.89	1.75	1.59	1.59
Hold Tank Effluent	1150		5.67	7.14	0.05	3.94	1.73	1.64	1.51
Marble Bed: Front-Upper	1210		6.12	7.03	0.05	4.25	1.87	1.33	0.99
Marble Bed: Front-Lower	1200		5.88	7.10	0.05	4.06	1.82	1.27	1.26
Marble Bed: Back-Lower	1205		6.39	7.00	0.04	4.56	1.83	0.86	0.71
Scrubber Bottoms S	1218		5.95	7.09	0.04	4.17	1.78	1.27	1.22
Scrubber Spray	1227		5.63	7.13	0.06	3.91	1.72	1.68	1.85

TABLE J-9. LIQUID CHEMICAL ANALYSIS AT STEADY STATE
EXPERIMENT 25R
7/7/72
Concentration in m moles/liter

Set No.	Time	Sampling Point	Ca++	Mg++	Na+	$CO_3^=$	$SO_4^=$	$SO_3^=$	Cl-	Tot. N	pH	Temp. °C
1	1142	Marble Bed Back	24.67	3.32	0.72	2.14	13.82	21.0	1.38	0.3	5.29	-
1	1130	Marble Bed Front	25.85	3.29	0.70	1.48	-	45.6	1.43	0.3	5.31	-
1	1155	Scrubber Bottoms (Scrubber)	24.35	3.26	0.71	3.15	24.67	9.95	1.32	0.3	5.23	49.0
1	1203	Spray Water	24.03	3.14	0.83	5.35	18.52	8.51	1.31	0.3	6.02	-
1	1055	Scrubber Liquid at Tank	22.55	3.23	0.69	6.52	8.54	21.55	1.44	0.3	5.50	50.5
1	1100	Scrubber Bottom at Tank	20.58	3.20	0.68	6.08	8.94	18.56	1.44	0.3	5.59	49.8
1	1120	Hold Tank Effluent	17.94	3.11	0.69	6.56	15.1	6.57	1.39	0.3	6.05	49.0
1	1115	Clarifier Liquid	15.83	0.90	0.90	2.01	12.8	4.02	1.36	0.3	6.99	27.5
2		Marble Bed Back										
2		Marble Bed Front										
2		Scrubber Bottom (Scrubber)										
2		Spray Water										
2	1235	Scrubber Liquid at Tank	22.0	3.24	0.71	5.15	9.99	20.96	1.31	0.3	5.45	49.3
2	1240	Scrubber Bottom at Tank	21.32	3.21	0.70	5.29	8.95	19.90	1.30	0.30	5.56	49.0
2	1300	Hold Tank Effluent	17.80	3.18	0.69	6.36	12.05	9.62	1.32	0.3	6.02	48.5
2	1255	Clarifier Liquid	15.98	0.96	0.91	2.12	10.02	6.98	1.15	0.3	6.96	28.0

TABLE J-10. LIQUID CHEMICAL ANALYSIS AT STEADY STATE
EXPERIMENT 26R
7/10/72
Concentration in m moles/liter

Set No.	Time	Sampling Point	Ca++	Mg++	Na+	$CO_3^=$	$SO_4^=$	$SO_3^=$	Cl-	Tot. N	pH	Temp. °C
1	1445	Marble Bed Back	28.5	3.52	0.88	3.09	24.1	15.8	1.30	0.5	5.13	48.0
1	1435	Marble Bed Front	30.7	3.56	0.89	3.80	22.5	21.8	1.35	-	4.97	48.0
1	1450	Scrubber Bottoms (Scrubber)	27.5	3.54	0.88	3.41	19.3	17.0	1.33	-	5.32	48.5
1	1455	Spray Water	21.5	3.45	0.87	5.67	21.4	3.73	1.37	-	5.97	47.0
1	1400	Scrubber Liquid at Tank	24.8	3.57	0.87	6.43	24.50	12.30	1.34	0.5	5.30	49.0
1	1405	Scrubber Bottom at Tank	24.2	3.73	0.88	5.69	21.3	9.62	1.37	0.5	5.32	48.7
1	1420	Hold Tank Effluent	19.7	3.35	0.87	6.52	20.4	3.31	1.35	0.5	6.00	48.0
1	1425	Clarifier Liquid	17.5	1.84	0.98	3.39	18.0	0.74	1.14	0.5	7.19	31.0
2	1602	Marble Bed Back	29.4	3.52	0.88	3.93	23.8	18.6	1.18	-	5.24	47.0
2	1555	Marble Bed Front	32.1	3.60	0.87	3.59	24.3	19.5	1.28	-	5.19	46.0
2	1615	Scrubber Bottom (Scrubber)	27.9	3.54	0.87	3.68	23.8	15.5	1.22	0.5	6.05	47.0
2	1610	Spray Water	22.5	3.56	0.87	6.16	-	-	1.21	-	5.29	47.0
2	1515	Scrubber Liquid at Tank	25.3	3.54	0.86	6.48	21.86	12.60	1.30	0.5	5.39	49.0
2	1520	Scrubber Bottom at Tank	27.36	3.57	0.88	5.26	24.36	11.03	1.22	0.5	5.41	48.5
2	1547	Hold Tank Effluent	20.5	3.38	0.85	5.65	20.60	3.36	1.19	0.5	6.07	47.0
2	1542	Clarifier Liquid	17.7	1.95	0.97	4.26	18.2	0.76	1.12	0.5	7.15	31.5

TABLE J-11. LIQUID CHEMICAL ANALYSIS AT STEADY STATE
EXPERIMENT 27R
7/11/72
Concentration in m moles/liter

Set No.	Time	Sampling Point	Ca++	Mg++	Na+	$CO_3^=$	$SO_4^=$	$SO_3^=$	Cl-	Tot. N	pH	Temp. °C
1	1007	Marble Bed Back	27.70	4.04	0.88	3.01	20.00	22.60	1.30	-	5.28	47.4
1	1015	Scrubber Bottoms (Scrubber)	26.90	3.92	0.89	3.49	16.60	23.80	1.34	0.5	5.27	48.2
1	1020	Spray Water	19.10	3.80	0.88	7.77	20.00	3.04	1.29	0.5	6.10	47.7
1	0935	Scrubber Liquid at Tank	24.33	3.94	0.86	7.45	22.65	10.02	1.35	0.5	5.42	49.2
1	0940	Scrubber Bottom at Tank	22.06	3.92	0.88	6.60	21.62	7.17	1.43	0.5	5.68	48.3
1	0953	Hold Tank Effluent	19.40	3.86	0.86	6.63	20.80	2.65	1.33	0.5	6.05	48.0
1	0950	Clarifier Liquid	17.90	2.43	0.92	4.33	18.70	1.08	1.22	0.5	6.68	32.5
2	2022	Marble Bed Back	29.80	3.86	0.90	2.79	23.10	16.90	1.25	0.5	5.59	47.2
2	2030	Marble Bed Front	30.20	3.97	0.91	3.98	25.40	18.90	1.22	0.5	5.31	48.5
2	2040	Scrubber Bottoms (Scrubber)	28.50	3.92	0.92	3.20	24.30	16.20	1.26	0.5	5.49	47.7
2	2050	Spray Water	19.60	3.89	0.89	7.51	-	-	1.41	0.5	6.22	48.1
2	1040	Scrubber Liquid at Tank	24.46	4.10	0.86	7.65	22.96	10.44	1.40	0.5	5.52	49.8
2	1045	Scrubber Bottom at Tank	21.66	3.97	0.92	7.21	20.83	7.99	1.30	0.5	5.67	49.1
2	1100	Hold Tank Effluent	24.88	3.84	0.88	6.85	14.9	12.5	1.38	0.5	6.12	47.4
2	1056	Clarifier Liquid	17.60	2.45	0.95	5.34	18.4	1.12	1.24	0.5	6.81	33.9

TABLE J-12. LIQUID CHEMICAL ANALYSIS AT STEADY STATE
EXPERIMENT 28R
7/11/72
Concentration in m moles/liter

Set No.	Time	Sampling Point	Ca++	Mg++	Na+	$CO_3^=$	$SO_4^=$	$SO_3^=$	Cl-	Tot. N	pH	Temp. °C
1	0325	Marble Bed Front-Upper	27.22	4.53	0.65	2.85	25.15	11.40	1.24	0.5	5.76	46.6
1	0355	Marble Bed Back-Lower	26.41	4.48	0.65	2.75	21.38	16.12	1.17	0.5	5.61	50.0
1	0345	Marble Bed Front-Lower	28.86	4.72	0.64	3.86	25.49	16.14	1.22	0.5	5.66	44.2
1	0330	Scrubber Bottoms (Scrubber)	26.95	4.55	0.64	4.16	22.22	16.14	1.26	0.5	5.67	50.5
1	0377	Spray Water	21.80	4.51	0.62	7.66	21.18	3.98	1.20	0.5	6.42	50.0
1	0250	Scrubber Liquid at Tank-Lower	24.65	4.50	0.70	6.71	22.30	12.60	1.15	0.5	5.69	51.4
1	0255	Scrubber Liquid at Tank-Uper	22.55	4.34	0.70	6.90	21.62	8.19	1.11	0.5	5.96	51.1
1	0300	Scrubber Bottom at Tank	23.10	4.50	0.68	5.83	21.44	8.83	1.16	0.5	5.91	50.3
1	0312	Hold Tank Effluent	20.06	4.33	0.68	6.63	20.92	3.48	1.21	0.5	6.31	50.3
1	0309	Clarifier Liquid	19.68	3.19	0.90	4.59	19.61	2.12	1.19	0.5	7.02	37.0
2	0512	Marble Bed Front-Upper	26.90	4.84	0.70	3.79	26.07	11.25	1.22	0.5	5.95	47.5
2	0455	Marble Bed Back-Lower	26.35	4.83	0.68	3.32	24.90	12.68	1.25	0.5	5.80	49.0
2	0477	Marble Bed Front-Lower	28.23	4.82	0.70	2.91	21.41	18.88	1.28	-	5.81	46.0
2	0505	Scrubber Bottoms (Scrubber)	25.73	4.90	0.64	3.68	22.53	15.68	1.29	05	5.79	50.8
2	0520	Spray Water	20.03	4.75	0.65	6.87	21.65	3.06	1.27	0.5	6.49	50.8
2	0410	Scrubber Liquid at Tank-Lower	23.52	4.65	0.66	5.33	22.34	10.05	1.19	0.5	5.98	51.5
2	0415	Scrubber Liquid at Tank-Upper	24.25	4.72	0.67	5.38	22.87	10.41	1.20	0.5	5.96	51.4
2	0420	Scrubber Bottom at Tank	23.93	4.75	0.66	5.58	23.32	9.05	1.27	0.5	6.00	50.9
2	0440	Hold Tank Effluent	19.80	4.63	0.72	6.07	21.27	3.27	1.25	0.5	5.45	50.8
2	0436	Clarifier Liquid	18.85	3.37	0.88	4.57	20.04	1.21	1.22	0.5	7.10	38.0

TABLE J-13. LIQUID CHEMICAL ANALYSIS AT STEADY STATE
EXPERIMENT 29R
7/13/72
Concentration in m moles/liter

Set No.	Time	Sampling Point	Ca++	Mg++	Na+	$CO_3^=$	$SO_4^=$	$SO_3^=$	Cl-	Tot. N	pH	Temp. °C
1	1203	Marble Bed Front-Upper	23.97	5.84	0.68	4.34	26.62	5.81	1.34	0.5	5.81	45.5
1	1155	Marble Bed Back-Lower	25.80	5.94	0.66	4.05	27.43	9.91	1.35	0.5	5.40	48.5
1	1141	Marble Bed Front-Lower	26.66	5.84	0.66	3.65	23.74	15.32	1.36	0.5	5.36	46.0
1	1145	Scrubber Bottoms (Scrubber)	26.63	5.83	0.66	3.09	22.13	15.51	1.37	0.5	5.29	50.5
1	1210	Spray Water	19.60	5.89	0.66	3.09	21.53	3.58	1.36	0.5	6.02	50.5
1	1100	Scrubber Liquid at Tank-Lower	23.87	5.65	0.65	6.54	23.36	10.57	1.36	0.5	5.50	51.5
1	1105	Scrubber Liquid at Tank-Upper	21.99	5.51	0.66	3.74	24.02	6.04	1.33	0.5	5.79	51.5
1	1115	Scrubber Bottom at Tank	23.26	5.80	0.65	4.87	23.72	9.54	1.35	0.5	5.49	51.3
1	1130	Hold Tank Effluent	19.40	5.67	0.66	4.91	21.41	4.03	1.36	0.4	6.04	51.2
1	1125	Clarifier Liquid	18.28	3.67	0.82	3.69	20.64	0.88	1.20	0.5	6.80	35.5
2	0135	Marble Bed Front-Upper	23.85	6.13	0.70	3.34	26.48	6.50	1.35	0.5	5.68	46.0
2	0118	Marble Bed Back-Lower	24.57	6.07	0.68	3.28	26.79	9.96	1.36	0.5	5.45	45.8
2	0110	Marble Bed Front-Lower	25.85	6.25	0.70	3.75	24.48	12.87	1.33	0.5	5.59	43.0
2	0130	Scrubber Bottoms (Scrubber)	24.13	6.28	0.70	3.59	23.14	14.29	1.37	0.5	5.31	50.7
2	0140	Spray Water	19.22	6.23	0.66	5.40	21.96	3.34	1.37	0.5	6.10	50.00
2	1225	Scrubber Liquid at Tank-Lower	23.01	6.10	0.67	6.22	23.10	10.42	1.46	0.5	5.50	50.9
2	1230	Scrubber Liquid at Tank-Upper	22.10	6.06	0.68	4.20	22.76	8.43	1.26	0.5	5.70	50.9
2	1235	Scrubber Bottom at Tank	22.10	6.25	0.66	6.97	24.49	7.50	1.39	0.5	5.54	50.5
2	1256	Hold Tank Effluent	18.91	6.13	0.70	5.38	21.85	3.50	1.36	0.5	6.03	50.4
2	1252	Clarifier Liquid	18.45	3.79	0.82	3.81	20.85	0.90	1.21	0.5	7.00	35.5

TABLE J-14. LIQUID CHEMICAL ANALYSIS AT STEADY STATE
EXPERIMENT 30R
7/14/72
Concentration in m moles/liter

Set No.	Time	Sampling Point	Ca++	Mg++	Na+	$CO_3^=$	$SO_4^=$	$SO_3^=$	Cl-	Tot. N	pH	Temp. °C
1	1052	Marble Bed Front-Upper	24.09	6.62	0.55	2.52	26.44	8.04	1.31	0.5	5.60	47.0
1	1045	Marble Bed Back-Lower	26.59	6.92	0.60	2.81	26.27	14.66	1.37	0.5	5.09	49.3
1	1038	Marble Bed Front-Lower	27.18	6.53	0.60	2.89	24.24	17.28	1.36	0.5	5.50	43.0
1	1158	Scrubber Bottoms (Scrubber)	26.92	6.89	0.52	2.92	23.95	18.26	1.34	0.5	5.11	49.6
1	1105	Spray Water	18.78	6.86	0.55	5.91	22.34	4.18	1.37	0.5	5.90	50.0
1	1000	Scrubber Liquid at Tank-Lower*	23.57	6.67	0.58	5.45	23.61	12.50	1.34	0.5	5.36	50.7
1	1005	Scrubber Liquid at Tank-Upper*	22.39	6.46	0.57	3.85	23.90	9.02	1.31	0.5	5.58	50.5
1	1020	Scrubber Bottom at Tank*	25.21	6.71	0.58	3.58	25.24	11.74	1.37	0.5	5.30	50.0
1	1031	Hold Tank Effluent	18.53	6.45	0.56	4.77	22.06	4.40	1.33	0.5	5.91	50.0
1	1023	Clarifier Liquid	18.57	4.60	0.85	4.09	20.47	1.73	1.27	0.5	6.68	36.0
2	1210	Marble Bed Front-Upper	24.43	6.78	0.50	3.08	25.36	9.70	1.34	0.5	5.94	47.0
2	1205	Marble Bed Back-Lower	27.63	7.03	0.48	3.10	26.61	17.09	1.34	0.5	5.02	49.9
2	1200	Marble Bed Front-Lower	25.53	6.95	0.48	2.36	21.14	20.48	1.34	0.5	5.08	47.80
2	1218	Scrubber Bottoms (Scrubber)	26.98	7.09	0.45	2.90	23.55	20.03	1.35	0.5	5.09	50.00
2	1227	Spray Water	18.59	6.97	0.42	6.34	21.59	5.13	1.35	0.5	5.84	50.00
2	1125	Scrubber Liquid at Tank-Lower*	24.75	6.89	0.47	4.85	24.27	14.02	1.35	0.5	5.30	50.9
2	1130	Scrubber Liquid at Tank-Upper*	22.68	6.77	0.45	4.70	23.66	10.50	1.34	0.5	5.49	50.5
2	1135	Scrubber Bottom at Tank*	25.12	6.84	0.45	4.33	24.39	15.13	1.36	0.5	5.25	50.3
2	1150	Hold Tank Effluent	18.91	6.92	0.47	5.28	21.91	4.89	1.36	0.5	5.80	50.00
2	1145	Clarifier Liquid	18.26	4.70	0.90	4.75	20.38	2.16	1.25	0.5	6.60	37.0

APPENDIX K

LIMESTONE TAIL-END SYSTEM

MATERIAL BALANCES

AND

RATE CALCULATIONS

TABLE K-1. TOTAL SULFUR MATERIAL BALANCE

Experiment 25R

		Flow Rate	Solid Content	Total S in Solid (m mole/g)	Total S in Liquid (m mole/l)	Total S in Gas (ppm)	Total S (m mole/min)
Marble Bed (Set #1)							
Entering Streams	Spray Water	908 l/min	75.5 g/l	4.36	27.03		323,438
	Gas In	9,792 g mole/min				2,329	22,805
Leaving Streams	Gas Out*	10,497 g mole/min				956	10,035
	Scrubber Liquid	681 l/min	68.2 g/l	5.01	34.82		256,397
	Scrubber Bottom	227 l/min	79.0 g/l	4.61	34.62		90,529
	Total Sulfur In = 346,243 m mole/min - Total Sulfur Out = 356,961 m mole/min						
Hold Tank (Set #1)							
Entering Streams	Scrubber Liquid	681 l/min	71.3 g/l	4.74	30.09		250,643
	Scrubber Bottom	227 l/min	77.4 g/l	4.42	27.50		83,901
	Clarifier Liquid	38 l/min			16.82		693
Leaving Streams	Hold Tank Eff.	946 l/min	77.9 g/l	4.28	21.67		335,907
	Total Sulfur In = 335,237 m mole/min - Total Sulfur Out = 335,907 m mole/min						
Hold Tank (Set #2)							
Entering Streams	Scrubber Liquid	738 l/min	70.4 g/l	4.85	30.96		°260,680
	Scrubber Bottom	208 l/min	72.9 g/l	4.67	28.85		81,245
	Clarifier Liquid	38 l/min			17.00		676
Leaving Streams	Hold Tank	984 l/min	71.4 g/l	4.73	21.67		344,298
	Total Sulfur In = 342,401 - Total Sulfur Out = 344,298						

*Average of marble bed front and back
°From hold tank eff.

TABLE K-2. TOTAL SULFUR MATERIAL BALANCE

Experiment 26R

		Flow Rate	Solid Content	Total S in Solid (m mole/g)	Total S in Liquid (m mole/l)	Total S in Gas (ppm)	Total S (m mole/min)
Marble Bed (Set #1)							
Entering Streams	Spray Water						
	Gas In						
Leaving Streams	Gas Out						
	Scrubber Liquid						
	Scrubber Bottom						
Marble Bed (Set #2)							
Entering Streams	Spray Water	889 l/min	65.7	3.82	23.96		244,416
	Gas In	9,940 g mole/min				2,490	24,751
Leaving Streams	Gas Out	10,655 g mole/min				999	10,644
	Scrubber Liquid	674 l/min	72.9	4.38	43.10		244,258
	Scrubber Bottom	219 l/min	63.4Δ	4.43	39.20		70,094
	Total Sulfur In = 269,167 m mole/min - Total Sulfur Out = 324,995 m moles/min						
Hold Tank (Set #2)							
Entering Streams	Scrubber Liquid	674 l/min	62.4	4.54	34.5		214,194
	Scrubber Bottom	219 l/min	63.4	4.38	35.4		68,567
	Clarifier Liquid	57 l/min			19.0		1,083
Leaving Streams	Hold Tank	946 l/min	64.3	4.12	24.0		273,314
	Total Sulfur In = 283,844 - Total Sulfur Out = 273,314						

ΔScrubber bottom at tank

TABLE K-3. TOTAL SULFUR MATERIAL BALANCE

Experiment 27R

		Flow Rate	Solid Content	Total S in Solid (m mole/g)	Total S in Liquid (m mole/l)	Total S in Gas (ppm)	Total S (m mole/min)
Marble Bed (Set #1)							
Entering Streams	Spray Water	568 l/min	71.8	3.57	23.04		158,657
	Gas In	10,100 g mole/min				2,306	23,290
Leaving Streams	Gas Out	10,820 g mole/min				1,114	12,053
	Scrubber Liquid	511 l/min	69.9	4.1	42.6		168,216
	Scrubber Bottom	57 l/min	69.2	4.07	40.4		18,357
Total Sulfur In = 181,947 - Total Sulfur Out = 198,626							
Marble Bed (Set #2)							
Entering Streams	Spray Water	568 l/min	76.9	3.53	27.4*		169,750
	Gas In	10,000 g mole/min				2,323	23,230
Leaving Streams	Gas Out	10,730 g mole/min					11,792
	Scrubber Liquid	511 l/min	75.25	4.34	42.15	1,099	188,424
	Scrubber Bottom	57 l/min	74.9	3.69	40.5		18,062
Total Sulfur In = 192,980 - Total Sulfur Out = 218,278							
Hold Tank (Set #1)							
Entering Streams	Scrubber Liquid	511 l/min	67.0	4.02	33.6		154,802
	Scrubber Bottom	57 l/min	59.4	4.53	28.4		16,985
	Clarifier Liquid	45 l/min			19.8		891
Leaving Streams	Hold Tank Eff.	613 l/min	74.3	3.60	23.5		178,371
Total Sulfur In = 172,678 - Total Sulfur Out = 178,371							
Hold Tank (Set #2)							
Entering Streams	Scrubber Liquid	511 l/min	68.0	3.91	33.4		152,932
	Scrubber Bottom	57 l/min	74.8	3.72	28.8		17,502
	Clarifier Liquid	45 l/min			19.5		878
Leaving Streams	Hold Tank	613 l/min	73.8	3.49	27.1		174,498
Total Sulfur In = 171,312 - Total Sulfur Out = 174,498							

*Hold Tank Eff.

TABLE K-4. TOTAL SULFUR MATERIAL BALANCE

Experiment 28R

		Flow Rate	Solid Content	Total S in Solid (m mole/g)	Total S in Liquid (m mole/l)	Total S in Gas (ppm)	Total S (m mole/min)
Marble Bed (Set #1)							
Entering Streams	Spray Water-Lower Bed	613 l/min	64.00	3.84	25.16		166,074
	Spray Water-Upper Bed	583 l/min	64.00	3.84	25.16		157,946
	Gas In	9,950 g mole/min				2,392	23,800
Leaving Streams	Gas Out	10,700 g mole/min				546	5,842
	Scrubber Liquid-Lower	653 l/min	65.85	4.48	39.51		218,440
	Scrubber Liquid-Upper	435 l/min	66.10	4.30	36.55		139,539
	Scrubber Bottom	109 l/min	69.30	4.16	38.36		35,604
	Total Sulfur In = 347,820 m moles/min - Total Sulfur Out = 399,425 m moles/min						
Marble Bed (Set #2)							
Entering Streams	Spray Water-Lower Bed	622 l/min	67.1	4.21	24.71		191,079
	Spray Water-Upper Bed	583 l/min	67.1	4.21	24.71		179,098
	Gas In	9,870 g mole/min				2,432	24,004
Leaving Streams	Gas Out	10,950 g mole/min				543	5,946
	Scrubber Liquid-Lower	660 l/min	55.4	5.04	38.94		209,983
	Scrubber Liquid-Upper	427 l/min	61.30	5.07	37.32		148,643
	Scrubber Bottom	117 l/min	76.70	4.50	38.21		44,853
	Total Sulfur In = 394,181 m moles/min - Total Sulfur Out = 409,424 m moles/min						
Hold Tank (Set #1)							
Entering Streams	Scrubber Liquid-Lower	653 l/min	60.4	4.74	34.90		209,740
	Scrubber Liquid-Upper	435 l/min	60.7	4.31	29.81		126,770
	Scrubber Bottom	109 l/min	66.0	4.09	38.36		33,604
	Clarifier Liquid	58 l/min			21.73		1,260
Leaving Streams	Hold Tank Eff.	1,254 l/min	61.7	4.02	24.40		341,632
	Total Sulfur In = 371,374 m moles/min - Total Sulfur Out = 341,632 m moles/min						
Hold Tank (Set #2)							
Entering Streams	Scrubber Liquid-Lower	660 l/min	60.5	4.46	32.41		199,478
	Scrubber Liquid-Upper	427 l/min	61.7	4.52	33.28		133,294
	Scrubber Bottom	117 l/min	66.0	4.22	38.21		37,057
	Clarifier Liquid	58 l/min			21.25		1,232
Leaving Streams	Hold Tank Eff.	1,263 l/min	64.7	4.06	24.54		362,761
	Total Sulfur In = 371,061 m moles/min - Total Sulfur Out = 362,761 m moles/min						

TABLE K-5. TOTAL SULFUR MATERIAL BALANCE

Experiment 29R

		Flow Rate	Solid Content	Total S in Solid (m mole/g)	Total S in Liquid (m mole/l)	Total S in Gas (ppm)	Total S (m mole/min)
Marble Bed (Set #1)							
Entering Streams	Spray Water-Lower	927 l/min	84.1	4.53	25.11		376,439
	Spray Water-Upper	852 l/min	84.1	4.53	25.11		345,983
	Gas In	10,050 g moles/min				2,456	24,924
Leaving Streams	Gas Out	10,750 g moles/min				297	3,193
	Scrubber Liquid-Lower	794 l/min	70.2	5.32	38.20		326,861
	Scrubber Liquid-Upper	643 l/min	113.1	5.32	32.43		407,740
	Scrubber Bottom	341 l/min	70.9	4.80	37.64		128,884
	Total Sulfur In = 747,346 m moles/min - Total Sulfur Out = 866,678 m moles/min						
Marble Bed (Set #2)							
Entering Streams	Spray Water-Lower	927 l/min	87.2	5.00	25.40		427,717
	Spray Water-Upper	852 l/min	87.2	5.00	25.40		393,112
	Gas In	10,250 g moles/min				2,415	24,754
Leaving Streams	Gas Out	10,980 g moles/min				280	3,074
	Scrubber Liquid-Lower	757 l/min	79.8	5.36	37.05		351,836
	Scrubber Liquid-Upper	680 l/min	123.4	5.60	32.98		492,333
	Scrubber Bottom	341 l/min	91.7	5.07	37.43		171,301
	Total Sulfur In = 845,583 m moles/min - Total Sulfur Out = 1,018,544 m moles/min						
Hold Tank (Set #1)							
Entering Streams	Scrubber Liquid-Lower	794 l/min	72.1	4.75	33.93		298,865
	Scrubber Liquid-Upper	643 l/min	73.2	4.69	30.06		240,075
	Scrubber Bottom	341 l/min	75.9	4.56	33.26		129,363
	Clarifier Liquid	57 l/min			21.52		1,226
Leaving Streams	Hold Tank Eff.	1,836 l/min	100.5	4.51	25.44		878,884
	Total Sulfur In = 669,529 m moles/min - Total Sulfur Out = 878,884 m moles/min						
Hold Tank (Set #2)							
Entering Streams	Scrubber Liquid-Lower	757 l/min	72.1	5.04	33.52		300,456
	Scrubber Liquid-Upper	680 l/min	81.9	4.75	31.19		285,746
	Scrubber Bottom	341 l/min	102.7	4.65	31.99		173,745
	Clarifier Liquid	57 l/min			21.75		1,240
Leaving Streams	Hold Tank Eff.	1,836 l/min	88.5	6.61	25.35		795,603
	Total Sulfur In = 761,187 m moles/min - Total Sulfur Out = 795,603 m moles/min						

TABLE K-6. RATE CALCULATIONS

Experiment 25R

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set #1)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Flue Gas In	9,792 g mole/min		2,329	22,805
	Scrubber Spray	908 l/min	8.51		7,727
Leaving Streams	Flue Gas Out	10,497 g mole/min		956	10,035
	Scrubber Liquid	681 l/min	21.0*		14,301
	Scrubber Bottom	227 l/min	9.95		2,259

Rate of $CaSO_3$ 1/2 H_2O = SO_2 In - SO_2 Out - Oxid. Rate

= 30,532 - 26,595 - .25 (22,805 - 10,035)

= 30,532 - 26,595 - 3,192

= 745 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Spray	908 l/min	18.5		16,816
Leaving Streams	Scrubber Liquid	681 l/min	13.82*		9,411
	Scrubber Bottom	227 l/min	24.67		5,600

Rate of $CaSO_4$ 2 H_2O = ΣSO_4 In - ΣSO_4 Out + Oxid. Rate

= 16,816 - 15,011 + 3,192

= 4,997 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Scrubber Spray	908 l/min	24.03		21,819
Leaving Streams	Scrubber Liquid	681 l/min	25.26		17,202
	Scrubber Bottom	227 l/min	24.35		5,527

Rate of $CaCO_3$ Dissolution = ΣCa Out - ΣCa In + ΣCa Prec. Rates

= 21,819 - 22,729 + 4,997 + 745

= 4,832 m mole/min

*Value from marble bed back only

TABLE K-6. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
System Remainder (Hold Tank, Surge Tanks and Thickener)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid	681 l/min	21.00		14,301
	Scrubber Bottom	227 l/min	9.95		2,258
	Clarifier Liquid	38 l/min	4.02		153
Leaving Streams	Hold Tank Eff.	946 l/min	6.57		6,215

Rate of $CaSO_3$ 1/2 H_2O = SO_2 In - SO_2 Out

= 16,712 - 6,215

= 10,497 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid	681 l/min	13.82		9,411
	Scrubber Bottom	227 l/min	24.67		5,620
	Clarifier Liquid	38 l/min	12.8		486
Leaving Streams	Hold Tank Eff.	946 l/min	15.1		14,284

Rate of $CaSO_4$ 2 H_2O = ΣSO_4 In - ΣSO_4 Out

= 15,517 - 14,284

= 1,233 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Scrubber Liquid	681 l/min	25.26		17,202
	Scrubber Bottom	227 l/min	24.35		5,527
	Clarifier Liquid	38 l/min	15.83		601
Leaving Streams	Hold Tank Eff.	958 l/min	17.94		17,186

Rate of $CaCO_3$ = ΣCa Out - ΣCa In + ΣCa Formation Rates

= 17,186 - 23,330 + 10,497 + 1,233

= 5,586 m mole/min

TABLE K-6. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
System Remainder (Hold Tank, Surge Tanks and Thickener)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid	738 l/min	21.0		14,700
	Scrubber Bottom	208 l/min	19.9		4,378
	Clarifier Liquid	38 l/min	6.98		265
Leaving Streams	Hold Tank Eff.	984 l/min	9.62		9,216

Rate of $CaSO_3$ 1/2 H_2O = SO_2 In - SO_2 Out

= 19,343 - 9,216

= 10,127 m mole/min

2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid	738 l/min	9.99		6,993
	Scrubber Bottom	208 l/min	8.95		1,969
	Clarifier Liquid	38 l/min	10.02		381
Leaving Streams	Hold Tank Eff.	984 l/min	12.05		11,544

Rate of $CaSO_4$ 2 H_2O = ΣSO_4 In - ΣSO_4 Out

= 9,343 - 11,544

= -2,201 m mole/min

3. $CaCO_3$					
Entering Streams	Scrubber Liquid	738 l/min	22.0		15,400
	Scrubber Bottom	208 l/min	21.32		4,690
	Clarifier Liquid	38 l/min	15.98		607
Leaving Streams	Hold Tank Eff.	984 l/min	17.80		17,052

Rate of $CaCO_3$ = ΣCa In - ΣCa Out + ΣCa Formation Rate

= 17,052 - 20,697 + 10,127 - 2,201

= 4,281 m moles/min

TABLE K-7. RATE CALCULATIONS

Experiment 26R

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set #1)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	9,900 g mole/min		2,519	24,938
	Scrubber Spray	927 l/min	3.73		3,457
Leaving Streams	Outlet Flue Gas	10,613 g mole/min		1,023	10,857
	Scrubber Liquid*	681 l/min	18.8		12,803
	Scrubber Bottom	246 l/min	17.0		4,182

Rate of $CaSO_3$ 1/2 H_2O = SO_2 In - SO_2 Out - Oxid. Rate

= 28,395 - 27,842 - .261 (14,081)

= 28,395 - 27,842 - 3,675

= 3,122 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Spray	927 l/min	21.4		19,837
Leaving Streams	Scrubber Liquid*	681 l/min	23.3		15,867
	Scrubber Bottom	246 l/min	19.3		4,747

Rate of $CaSO_4$ 2 H_2O = ΣSO_4 In - ΣSO_4 Out + Oxidation Rate

= 19,837 - 20,614 + 3,675

= 2,898 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Scrubber Spray	927 l/min	21.5		19,930
Leaving Streams	Scrubber Liquid*	681 l/min	29.6		20,158
	Scrubber Bottom	246 l/min	27.5		6,765

Rate of $CaCO_3$ Dissolution = ΣCa Out - ΣCa In + ΣCa Prec. Rates

= 26,923 - 19,930 + (-3,122 + 2,898)

= 6,769 m mole/min

*Ave. of marble bed front and back

TABLE K-7. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
System Remainder (Hold Tank, Surge Tanks and Thickener)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid	681 l/min	18.8		12,802
	Scrubber Bottom	246 l/min	17.0		4,182
	Clarifier Liquid	57 l/min	.74		42
Leaving Streams	Hold Tank Eff.	984 l/min	3.31		3,257
	Rate of $CaSO_3$ 1/2 H_2O = SO_2 (In) - SO_2 (Out)				
	= 17,026 - 3,257				
	= 13,769 m mole/min				
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid	681 l/min	23.3		15,867
	Scrubber Bottom	246 l/min	19.3		4,748
	Clarifier Liquid	57 l/min	18.0		1,026
Leaving Streams	Hold Tank Eff.	984 l/min	20.4		20,073
	Rate of $CaSO_4$ 2 H_2O = ΣSO_4 In - ΣSO_4 Out				
	= 21,641 - 20,073				
	= 1,568 m mole/min				
3. $CaCO_3$ Dissolution					
Entering Streams	Scrubber Liquid	681 l/min	29.6		20,157
	Scrubber Bottom	246 l/min	27.5		6,765
	Clarifier Liquid	57 l/min	17.5		998
Leaving Streams	Hold Tank Eff.	984 l/min	19.7		19,384
	Rate of $CaCO_3$ Dissolution = ΣCa Out - ΣCa In + ΣCa Pres. Rates				
	= 19,384 - 27,920 + (13,769 + 1,568)				
	= 6,801 m mole/min				

TABLE K-7. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set #2)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	9,940 l/min		2,490	24,750
	Scrubber Spray	889 l/min	3.36+		2,987
Leaving Streams	Scrubber Liquid*	674 l/min	19.05		12,839
	Scrubber Bottom	219 l/min	15.5		3,394
	Outlet Flue Gas	10,655		999	10,644

Rate of $CaSO_3$ 1/2 H_2O = SO_2 In - SO_2 Out - Oxid. Rate

= 27,737 - 26,877 - .238 (24,750 - 12,839)

= 29,584 - 27,896 - 2,834

= - 1,146 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Spray	889 l/min	20.6+		18,313
Leaving Streams	Scrubber Liquid	674 l/min	24.05		16,209
	Scrubber Bottom	219 l/min	23.8		5,212

Rate of $CaSO_4$ 2 H_2O = ΣSO_4 In - ΣSO_4 Out + Oxid. Rate

= 18,313 - 21,421 + 2,834

= -274 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Scrubber Spray	889 l/min	22.5		20,002
Leaving Streams	Scrubber Liquid	674 l/min	30.75		20,725
	Scrubber Bottom	219 l/min	27.9		6,110

Rate of $CaCO_3$ Dissolution = ΣCa Out - ΣCa In + ΣCa Prec. Rates

= 26,835 - 20,002 + (-274 + - 1,146)

= 5,413 m mole/min

+Value taken from hold tank off

TABLE K-7. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
System Remainder (Hold Tank, Surge Tank and Thickener)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid	674 l/min	19.05		12,839
	Scrubber Bottom	219 l/min	15.5		3,394
	Clarifier Liquid	57 l/min	.76		43
Leaving Streams	Hold Tank Eff.	946 l/min	3.36		3,178
	Rate of $CaSO_3$ 1/2 H_2O = SO_2 In - SO_2 Out				
	= 16,276 - 3,178				
	= 13,098 m mole/min				
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid	674 l/min	24.05		16,209
	Scrubber Bottom	219 l/min	23.8		5,212
	Clarifier Liquid	57 l/min	18.2		1,037
Leaving Streams	Hold Tank Eff.	946 l/min	20.6		19,487
	Rate of $CaSO_4$ 2 H_2O = ΣSO_4 In - ΣSO_4 Out				
	= 22,458 - 19,487				
	= 3,000 m mole/min				
3. $CaCO_3$ Dissolution					
Entering Streams	Scrubber Liquid	674 l/min	30.75		20,725
	Scrubber Bottom	219 l/min	27.9		6,110
	Clarifier Liquid	57 l/min	17.7		1,009
Leaving Streams	Hold Tank Eff.	946 l/min	20.5		19,393
	Rate of $CaCO_3$ Dissolution = ΣCa Out - ΣCa In + ΣCa Prec. Rates				
	= 19,393 - 27,844 + (13,098 + 3,000)				
	= 7,647 m mole/min				

TABLE K-8. RATE CALCULATIONS

Experiment 27R

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set #1)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Flue Gas In	10,100 g mole/min		2,306	23,290
	Scrubber Spray	568 l/min	3.04		1,727
Leaving Streams	Flue Gas Out	10,820 g mole/min		1,114	12,053
	Scrubber Liquid*	511 l/min	22.60		11,548
	Scrubber Bottom	57 l/min	23.8		1,357

Rate of $CaSO_3$ 1/2 H_2O = SO_2 In - SO_2 Out - Oxid. Rate

= 25,017 - 24,958 - 0.269 (23,290 - 12,053)

= 25,017 - 24,958 - 2,966

= -2,907 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Spray	568 l/min	20.0		11,360
Leaving Streams	Scrubber Liquid	511 l/min	20.0		10,220
	Scrubber Bottom	57 l/min	16.6		946

Rate of $CaSO_4$ 2 H_2O = ΣSO_4 In - ΣSO_4 Out + Oxid. Rate

= 11,360 - 11,166 + 2,966

= 3,160 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Scrubber Spray	568 l/min	19.1		10,849
Leaving Streams	Scrubber Liquid*	511 l/min	27.7		14,155
	Scrubber Bottom	57 l/min	26.9		1,533

Rate of $CaCO_3$ Dissolution = ΣCa Out - ΣCa In + ΣCa Prec. Rates

= 15,688 - 10,849 + (3,160 - 2,907)

= 5,092 m mole/min

*Taken from marble bed back

TABLE K-8. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
System Remainder (Hold Tank, Surge Tanks and Thickener)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid	511 l/min	22.60		11,548
	Scrubber Bottom	57 l/min	23.8		1,356
	Clarifier Liquid	45 l/min	1.08		48
Leaving Streams	Hold Tank Eff.	613 l/min	2.65		1,625

Rate of $CaSO_3$ 1/2 H_2O = SO_2 In - SO_2 Out

= 12,904 - 1,625

= 11,279 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid	511 l/min	20.0		10,220
	Scrubber Bottom	57 l/min	16.6		946
	Clarifier Liquid	45 l/min	18.7		842
Leaving Streams	Hold Tank Eff.	613 l/min	20.8		12,750

Rate of $CaSO_4$ 2 H_2O = ΣSO_4 In - ΣSO_4 Out

= 12,008 - 12,750

= -742 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$					
Entering Stream	Scrubber Liquid	511 l/min	27.7		14,154
	Scrubber Bottom	57 l/min	26.9		1,533
	Clarifier Liquid	45 l/min	17.90		805
Leaving Streams	Hold Tank Eff.	613 l/min	19.40		11,892

Rate of $CaCO_3$ = ΣCa In - ΣCa Out + ΣCa Formation Rates

= 11,892 - 16,492 + 11,279 - 742

= 5,937 m mole/min

TABLE K-8. RATE CALCULATIONS (Continued)

Marble Bed (Set 2)

1. $CaSO_3$ 1/2 H_2O

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Inlet Flue Gas	10,000 g mole/min		2,323	23,230
	Scrubber Spray	568 l/min	3.04°		1,727
Leaving Streams	Outlet Flue Gas	10,730 g mole/min		1,099	11,792
	Scrubber Liquid	511 l/min	17.9		9,147
	Scrubber Bottom	57 l/min	16.2		923

Rate of $CaSO_3$ 1/2 H_2O = SO_2 In - SO_2 Out - Oxid. Rate

= 24,957 - 22,723 - (23,230 - 11,792) .249

= 24,957 - 22,723 - 2,848

= 247 m mole/min

2. $CaSO_4$ 2 H_2O

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Scrubber Spray	568 l/min	20.0°		11,814
Leaving Streams	Scrubber Liquid	511 l/min	24.25		12,392
	Scrubber Bottom	57 l/min	24.3		1,385

Rate of $CaSO_4$ 2 H_2O = ΣSO_4 In - ΣSO_4 Out + Oxid. Rate

= 11,814 - 13,777 + 2,848

= 885 m mole/min

3. $CaCO_3$ Dissolution

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Scrubber Spray	568 l/min	19.6		11,133
Leaving Streams	Scrubber Liquid$^{\Delta}$	511 l/min	30.0		15,330
	Scrubber Bottom	57 l/min	28.5		1,625

Rate of $CaCO_3$ Dissolution = ΣCa Out - ΣCa In + ΣCa Prec. Rate

= 16,955 - 11,133 + (247 + 885)

= 6,954 m mole/min

°Values taken from SS Set 1
ΔAverage of marble bed front and back

TABLE K-8. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
System Remainder (Hold Tank, Surge Tanks and Thickener)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid	511 l/min	17.9		9,146
	Scrubber Bottom	57 l/min	16.2		923
	Clarifier Liquid	45 l/min	1.12		50
Leaving Streams	Hold Tank Eff.	613 l/min	3.04°		1,864

Rate of $CaSO_3$ 1/2 H_2O = SO_2 In - SO_2 Out

= 10,119 - 1,864

= 8,255 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid	511 l/min	24.25		12,391
	Scrubber Bottom	57 l/min	24.3		1,385
	Clarifier Liquid	45 l/min	18.4		828
Leaving Streams	Hold Tank Eff.	613 l/min	20.8°		12,750

Rate of $CaSO_4$ 2 H_2O = ΣSO_4 In - ΣSO_4 Out

= 14,604 - 12,750

= 1,854 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Scrubber Liquid	511 l/min	30.00		15,330
	Scrubber Bottom	57 l/min	28.5		1,624
	Clarifier Liquid	45 l/min	17.6		792
Leaving Streams	Hold Tank Eff.	613 l/min	24.8		15,202

Rate of $CaCO_3$ Dissolution = ΣCa Out - ΣCa In + Ca Prec. Rates

= 15,202 - 17,746 + (8,255 + 1,854)

= 7,565 m mole/min

TABLE K-9. RATE CALCULATIONS

Experiment 28R

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set #1)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Gas Inlet	9,950 g mole/min		2.392	23,800
	Spray Water-Lower	613 l/min	3.98		2,439
	Spray Water-Upper	583 l/min	3.98		2,320
Leaving Streams	Gas Outlet	10,700 g mole/min		546	5,840
	Scrubber Liquid-Lower	653 l/min	16.13		10,532
	Scrubber Liquid-Upper	435 l/min	11.40		4,959
	Scrubber Bottom	109 l/min	16.14		1,759

Rate of $CaSO_3$ 1/2 H_2O Formation = ΣSO_3(liq.) In - ΣSO_3(liq.) Out - Oxid. Rate

= 28,559 - 23,090 - 0.24 (17,002)

= 1,319 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Spray Water-Lower	613 l/min	21.8		13,363
	Spray Water-Upper	583 l/min	21.8		12,709
Leaving Streams	Scrubber Liquid-Lower	653 l/min	23.63		15,430
	Scrubber Liquid-Upper	435 l/min	25.15		10,940
	Scrubber Bottom	109 l/min	22.22		2,422

Rate of $CaSO_4$ 2 H_2O Formation = ΣSO_4(liq.) In - ΣSO_4(liq.) Out + Oxid. Rate

= 26,072 - 28,792 + 4,150

= 1,430 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Spray Water-Lower	613 l/min	21.80		13,363
	Spray Water-Upper	583 l/min	21.80		12,709
Leaving Streams	Scrubber Liquid-Lower	653 l/min	27.64		18,048
	Scrubber Liquid-Upper	435 l/min	27.22		11,841
	Scrubber Bottom	109 l/min	26.95		2,937

Rate of $CaCO_3$ Dissolution = ΣCa(liq.) Out - ΣCa(liq.) In + ΣCa Formation Rates

= 32,826 - 26,072 + 1,134 + 1,615

= 9,503 m mole/min

TABLE K-9. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
System Remainder (Hold Tank, Surge Tanks and Thickener)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid-Lower	653 l/min	16.13		10,532
	Scrubber Liquid-Upper	435 l/min	11.40		4,959
	Scrubber Bottom	109 l/min	16.14		1,759
	Clarifier Liquid	58 l/min	2.12		123
Leaving Stream	Hold Tank Eff.	1,254 l/min	3.48		4,364

Rate of $CaSO_3$ 1/2 H_2O Formation = ΣSO_3(liq.) In - ΣSO_3(liq.) Out

= 17,373 - 4,364

= 13,009 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid-Lower	653 l/min	23.63		15,430
	Scrubber Liquid-Upper	435 l/min	25.15		10,940
	Scrubber Bottom	109 l/min	22.22		2,421
	Clarifier Liquid	58 l/min	19.61		1,137
Leaving Stream	Hold Tank Eff.	1,254 l/min	20.92		26,233

Rate of $CaSO_4$ 2 H_2O Formation = ΣSO_4(liq.) In - ΣSO_4(liq.) Out

= 29,928 - 26,233

= 3,695 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$					
Entering Streams	Scrubber Liquid-Lower	653 l/min	27.64		18,048
	Scrubber Liquid-Upper	435 l/min	27.22		11,840
	Scrubber Bottom	109 l/min	26.95		2,937
	Clarifier Liquid	58 l/min	19.68		1,141
Leaving Streams	Hold Tank Eff.	1,254 l/min	20.06		25,155

Rate of $CaCO_3$ Dissolution = ΣCa(liq.) Out - ΣCa(liq.) In + ΣCa Formation

= 25,155 - 33,966 + 13,009 + 3,695

= 7,893 m mole/min

TABLE K-9. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set 2)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Gas Inlet	9,870 g mole/min		2,432	24,003
	Spray Water-Lower	622 l/min	3.06		1,903
	Spray Water-Upper	583 l/min	3.06		1,784
Leaving Streams	Gas Outlet	10,950 g mole/min		543	5,946
	Scrubber Liquid-Lower	660 l/min	15.78		10,415
	Scrubber Liquid-Upper	427 l/min	11.25		4,804
	Scrubber Bottom	117 l/min	15.68		1,835

Rate of $CaSO_3$ 1/2 H_2O Formation = ΣSO_3(liq.) In - ΣSO_3(liq.) Out - Oxid. Rate

= 27,690 - 23,000 - 0.259 (24,003-5,946)

= 10 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Spray Water-Lower	622 l/min	21.65		13,466
	Spray Water-Upper	583 l/min	21.65		12,622
Leaving Streams	Scrubber Liquid-Lower	660 l/min	23.15		15,279
	Scrubber Liquid-Upper	427 l/min	26.07		11,132
	Scrubber Bottom	117 l/min	22.53		2,636

Rate of $CaSO_4$ 2 H_2O Formation = ΣSO_3(liq.) In - ΣSO_3(liq.) Out + Oxid. Rate

= 26,088 - 29,047 + 4,680

= 1,721 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Spray Water-Lower	622 l/min	20.03		12,459
	Spray Water-Upper	583 l/min	20.03		11,677
Leaving Streams	Scrubber Liquid-Lower	660 l/min	27.29		18,011
	Scrubber Liquid-Upper	427 l/min	26.90		11,486
	Scrubber Bottom	117 l/min	25.73		3,010

Rate of $CaCO_3$ Dissolution = ΣCa(liq.) Out - ΣCa(liq.) In + ΣCa Formation Rates

= 32,507 - 24,136 + 50 + 1,681

= 10,102 m mole/min

TABLE K-9. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
System Remainder (Hold Tank, Surge Tanks and Thickener)					
1. $CaSO_3 \cdot 1/2\ H_2O$					
Entering Streams	Scrubber Liquid-Lower	660 l/min	15.78		10,414
	Scrubber Liquid-Upper	427 l/min	11.25		4,803
	Scrubber Bottom	117 l/min	15.68		1,834
	Clarifier Liquid	58 l/min	1.21		70
Leaving Streams	Hold Tank Eff.	1,263 l/min	3.27		4,130
	Rate of $CaSO_3 \cdot 1/2\ H_2O$ Formation = ΣSO_3(liq.) In - ΣSO_3(liq.) Out = 17,121 - 4,130 = 12,991 m mole/min				
2. $CaSO_4 \cdot 2\ H_2O$					
Entering Streams	Scrubber Liquid-Lower	660 l/min	23.15		15,279
	Scrubber Liquid-Upper	427 l/min	26.07		11,131
	Scrubber Bottom	117 l/min	22.53		2,636
	Clarifier Liquid	58 l/min	20.04		1,162
Leaving Streams	Hold Tank Eff.	1,263 l/min	21.27		26,864
	Rate of $CaSO_4 \cdot 2\ H_2O$ Formation = ΣSO_4(liq.) In - ΣSO_4 (liq.) Out = 30,208 - 26,864 = 3,346 m mole/min				
3. $CaCO_3$					
Entering Streams	Scrubber Liquid-Lower	660 l/min	27.29		18,011
	Scrubber Liquid-Upper	427 l/min	26.90		11,486
	Scrubber Bottom	117 l/min	25.73		3,010
	Clarifier Liquid	58 l/min	18.85		1,093
Leaving Streams	Hold Tank Eff.	1,263 l/min	19.80		25,007
	Rate of $CaCO_3$ Dissolution = ΣCa(liq.) Out - ΣCa(liq.) In + ΣCa Formation = 25,007 - 33,600 + 12,991 + 3,346 = 7,744 m mole/min				

TABLE K-10. RATE CALCULATIONS

Experiment 29R

Marble Bed (Set #1)

1. $CaSO_3$ 1/2 H_2O

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Gas Inlet	10,050 g mole/min		2,456	24,682
	Spray Water-Lower	927 l/min	3.58		3,318
	Spray Water-Upper	852 l/min	3.58		3,050
Leaving Streams	Gas Outlet	10,750 g mole/min		297	3,193
	Scrubber Liquid-Lower	794 l/min	12.61		10,012
	Scrubber Liquid-Upper	643 l/min	5.81		3,736
	Scrubber Bottom	341 l/min	15.51		5,289

Rate of $CaSO_3$ 1/2 H_2O Formation = ΣSO_3(liq.) In - ΣSO_3(liq.) Out - Oxid. Rate

= 31,050 - 22,230 - 0.279 (24,682 - 3,193)

= 2,825 m mole/min

2. $CaSO_4$ 2 H_2O

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Spray Water-Lower	927 l/min	21.53		19,958
	Spray Water-Upper	852 l/min	21.53		18,344
Leaving Streams	Scrubber Liquid-Lower	794 l/min	25.58		20,310
	Scrubber liquid-Upper	643 l/min	26.62		17,117
	Scrubber Bottom	341 l/min	22.13		7,546

Rate of Ca SO_4 2 H_2O Formation = ΣSO_4(liq.) In - ΣSO_4(liq.) Out + Oxid. Rate

= 38,302 - 44,973 + 5,995

= -676 m mole/min

3. $CaCO_3$ Dissolution

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Entering Streams	Spray Water-Lower	927 l/min	19.60		18,169
	Spray Water-Upper	852 l/min	19.60		16,699
Leaving Streams	Scrubber Liquid-Lower	794 l/min	26.23		20,827
	Scrubber Liquid-Upper	643 l/min	23.97		15,412
	Scrubber Bottom	341 l/min	26.63		9,081

Rate of $CaCO_3$ Dissolution = ΣCa(liq.) Out - ΣCa(liq.) In + ΣCa Formation Rates

= 45,320 - 34,868 + 2,825 - 676

TABLE K-10. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
System Remainder (Hold Tank, Surge Tanks and Thickener)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid-Lower	794 l/min	12.61		10,012
	Scrubber Liquid-Upper	643 l/min	5.81		3,735
	Scrubber Bottom	341 l/min	15.51		5,289
	Clarifier Liquid	57 l/min	0.88		50
Leaving Streams	Hold Tank Eff.	1,836 l/min	4.03		7,399

Rate of $CaSO_3$ 1/2 H_2O Formation = ΣSO_3(liq.) In - ΣSO_3(liq.) Out

= 19,086 - 7,399

= 11,687 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid-Lower	794 l/min	25.58		20,310
	Scrubber Liquid-Upper	643 l/min	26.62		17,116
	Scrubber Bottom	341 l/min	22.13		7,546
	Clarifier Liquid	57 l/min	20.64		1,176
Leaving Streams	Hold Tank Eff.	1,836 l/min	21.41		39,309

Rate of $CaSO_4$ 2 H_2O Formation = ΣSO_4(liq.) In - ΣSO_4(liq.) Out

= 46,148 - 39,309

= 6,839 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$					
Entering Streams	Scrubber Liquid-Lower	794 l/min	26.23		20,826
	Scrubber Liquid-Upper	643 l/min	23.97		15,413
	Scrubber Bottom	341 l/min	26.63		9,081
	Clarifier Liquid	57 l/min	18.28		1,042
Leaving Streams	Hold Tank Eff.	1,836 l/min	19.40		35,618

Rate of $CaCO_3$ Dissolution = ΣCa(liq.) Out - ΣCa(liq.) In + ΣCa Formation Rates

= 35,618 - 46,362 + 11,687 + 6,839

= 7,782 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set 2)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Gas Inlet	10,250 g mole/min		2,415	24,754
	Spray Water-Lower	927 l/min	3.34		3,096
	Spray Water-Upper	852 l/min	3.34		2,846
Leaving Streams	Gas Outlet	10,980 g mole/min		280	3,704
	Scrubber Liquid-Lower	757 l/min	11.42		8,645
	Scrubber Liquid-Upper	680 l/min	6.50		4,420
	Scrubber Bottom	341 l/min	14.29		4,873

Rate of $CaSO_3$ 1/2 H_2O Formation = ΣSO_3(liq.) In - ΣSO_3(liq.) Out - Oxid. Rate

= 30,696 - 21,642 - 0.284 (24,754-3,704)

= 30,696 - 21,642 - 5,978

= 3,076 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Spray Water-Lower	927 l/min	21.96		20,356
	Spray Water-Upper	852 l/min	21.96		18,710
Leaving Streams	Scrubber Liquid-Lower	757 l/min	25.64		19,409
	Scrubber Liquid-Upper	680 l/min	26.48		18,006
	Scrubber Bottom	341 l/min	23.14		7,891

Rate of $CaSO_4$ 2 H_2O Formation = ΣSO_4(liq.) In - ΣSO_4(liq.) Out + Oxid. Rate

= 39,066 - 45,306 + 5,978

= -262 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Spray Water-Lower	927 l/min	19.22		17,817
	Spray Water-Upper	852 l/min	19.22		16,375
Leaving Streams	Scrubber Liquid-Lower	757 l/min	25.21		19,084
	Scrubber Liquid-Upper	680 l/min	23.85		16,218
	Scrubber Bottom	341 l/min	24.13		8,228

Rate of $CaCO_3$ Dissolution = ΣCa(liq.) Out - ΣCa(liq.) In + ΣCa Formation Rate

= 43,530 - 34,192 + 3,076 - 262

= 12,152 m mole/min

TABLE K-10. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
System Remainder (Hold Tank, Surge Tanks, and Thickener)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid-Lower	757 l/min	11.42		8,644
	Scrubber Liquid-Upper	680 l/min	6.50		4,420
	Scrubber Bottom	341 l/min	14.29		4,873
	Clarifier Liquid	57 l/min	0.90		51
Leaving Streams	Hold Tank Eff.	1,836 l/min	3.50		6,426

Rate of $CaSO_3$ 1/2 H_2O Formation = ΣSO_3(liq.) In - ΣSO_3(liq.) Out

= 17,988 - 6,426

= 11,562 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid-Lower	757 l/min	25.64		19,409
	Scrubber Liquid-Upper	680 l/min	26.48		18,006
	Scrubber Bottom	341 l/min	23.14		7,890
	Clarifier Liquid	57 l/min	20.85		1,188
Leaving Streams	Hold Tank Eff.	1,836 l/min	21.85		40,116

Rate of $CaSO_4$ 2 H_2O = ΣSO_4(liq.) In - ΣSO_4(liq.) Out

= 46,489 - 40,116

= 6,373 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Scrubber Liquid-Lower	757 l/min	25.21		19,083
	Scrubber Liquid-Upper	680 l/min	23.85		16,218
	Scrubber Bottom	341 l/min	24.13		8,228
	Clarifier Liquid	57 l/min	18.45		1,051
Leaving Streams	Hold Tank Eff.	1,836 l/min	18.91		34,718

Rate of $CaCO_3$ Dissolution = ΣCa(liq.) Out - ΣCa(liq.) In + ΣCa Formation Rate

= 34,718 - 43,529 + 11,562 + 6,373

= 9,124 m moles/min

TABLE K-11. RATE CALCULATIONS

Experiment 30R

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set #1)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	10,116 g mole/min		2,300	23,267
	Scrubber Spray-Lower	946 l/min	4.18		3,954
	Scrubber Spray-Upper	889 l/min	4.18		3,716
Leaving Streams	Outlet Flue Gas	10,845 g mole/min		334	3,624
	Scrubber Liquid*-Lower	814 l/min	15.97		13,000
	Scrubber Liquid*-Upper	681 l/min	8.04		5,499
	Scrubber Bottom	341 l/min	18.26		6,227

Rate of $CaSO_3$ 1/2 H_2O = ΣSO_3 (liq.) IN - ΣSO_3 (liq.) OUT - Oxidation Rate

Precipitation = 30,937 - 28,350 - 0.3 (19,643)

= -3,306 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Spray-Lower	946 l/min	22.34		21,134
	Scrubber Spray-Upper	889 l/min	22.34		19,860
Leaving Streams	Scrubber Liquid*-Lower	814 l/min	25.25		20,553
	Scrubber Liquid*-Upper	681 l/min	26.44		18,006
	Scrubber Bottom	341 l/min	23.95		8,167

Rate of $CaSO_4$ 2 H_2O = ΣSO_4 (liq.) IN - ΣSO_3 (liq.) OUT + Oxidation Rate

Precipitation = 40,994 - 46,726 + 5,893

= 161 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Scrubber Spray-Lower	946 l/min	18.78		17,766
	Scrubber Spray-Upper	889 l/min	18.78		16,695
Leaving Streams	Scrubber Liquid*-Lower	814 l/min	26.88		21,880
	Scrubber Liquid*-Upper	681 l/min	24.09		16,405
	Scrubber Bottom	341 l/min	26.92		9,180

Rate of $CaCO_3$ Dissolution - ΣCa (liq.) OUT - ΣCa (liq.) IN + ΣCa Formation Rates

= 47,465 - 34,461 - 3,145

= 9,861 m moles/min

*Average of Marble Bed Front and Back

TABLE K-11. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
System Remainder (Hold Tank, Surge Tanks, and Thickener)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid-Lower	814 l/min	15.97		12,999
	Scrubber Liquid-Upper	681 l/min	8.04		5,480
	Scrubber Bottom	341 l/min	18.26		6,226
	Clarifier Liquid	57 l/min	1.73		99
Leaving Streams	Hold Tank Eff.	1,892 l/min	4.40		8,325

Rate of $CaSO_3$ 1/2 H_2O = ΣSO_3 (liq.) IN - ΣSO_3 (liq.) OUT

Precipitation = 24,804 - 8,325

= 16,479 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid-Lower	814 l/min	25.25		20,553
	Scrubber Liquid-Upper	681 l/min	26.44		18,005
	Scrubber Bottom	341 l/min	23.95		8,166
	Clarifier Liquid	57 l/min	20.47		1,167
Leaving Streams	Hold Tank Eff.	1,892 l/min	22.06		41,737

Rate of $CaSO_4$ 2 H_2O = ΣSO_4 (liq.) IN - ΣSO_4 (liq.) OUT

Precipitation = 47,891 - 41,737

= 6,154 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Scrubber Liquid-Lower	814 l/min	26.88		21,880
	Scrubber Liquid-Upper	681 l/min	24.09		16,405
	Scrubber Bottom	341 l/min	26.92		9,179
	Clarifier Liquid	57 l/min	18.57		1,058
Leaving Streams	Hold Tank Eff.	1,892 l/min	18.53		35,059

Rate of $CaCO_3$ Dissolution = ΣCa (liq.) OUT - ΣCa (liq.) IN + ΣCa Formation Rates

= 35,059 - 48,522 + 16,479 + 6,154

= 9,170 m mole/min

TABLE K-11. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
Marble Bed (Set #2)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Inlet Flue Gas	10,116 g mole/min		2,457	24,855
	Scrubber Spray-Lower	946 l/min	5.13		4,853
	Scrubber Spray-Upper	889 l/min	5.13		4,561
Leaving Streams	Outlet Flue Gas	10,845 g mole/min		405	4,392
	Scrubber Liquid-Lower	814 l/min	18.78		15,286
	Scrubber Liquid-Upper	681 l/min	9.70		6,606
	Scrubber Bottom	341 l/min	20.03		6,830

Rate of $CaSO_3$ 1/2 H_2O Precipitation = ΣSO_3 (liq.) IN - ΣSO_3 (liq.) OUT - Oxidation Rate

= 34,269 - 33,114 - 0.305 (24,855 - 4,392)

= -5,086 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Spray-Lower	946 l/min	21.59		20,424
	Scrubber Spray-Upper	889 l/min	21.59		19,193
Leaving Streams	Scrubber Liquid-Lower	814 l/min	23.88		19,438
	Scrubber Liquid-Upper	681 l/min	25.36		17,270
	Scrubber Bottom	341 l/min	23.55		8,030

Rate of $CaSO_4$ 2 H_2O Precipitation = ΣSO_4 (liq.) IN - ΣSO_4 (liq.) OUT + Oxidation Rate

= 39,617 - 44,738 + 6,241

= 1,120 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Scrubber Spray-Lower	946 l/min	18.59		17,586
	Scrubber Spray-Upper	889 l/min	18.59		16,526
Leaving Streams	Scrubber Liquid-Lower	814 l/min	26.58		21,636
	Scrubber Liquid-Upper	681 l/min	24.43		16,636
	Scrubber Bottom	341 l/min	26.98		9,200

Rate of $CaCO_3$ Dissolution = ΣCa (liq.) OUT - ΣCa (liq.) IN + ΣCa Formation Rate

= 47,472 - 34,112 - 3,966

= 9,394 m mole/min

TABLE K-11. RATE CALCULATIONS (Continued)

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
System Remainder (Hold Tank, Surge Tanks and Thickener)					
1. $CaSO_3$ 1/2 H_2O					
Entering Streams	Scrubber Liquid-Lower	814 l/min	18.78		15,286
	Scrubber Liquid-Upper	681 l/min	9.70		6,605
	Scrubber Bottom	341 l/min	20.03		6,830
	Clarifier Liquid	57 l/min	2.16		123
Leaving Streams	Hold Tank Eff.	1,892 l/min	4.89		9,252

Rate of $CaSO_3$ 1/2 H_2O = ΣSO_3 (liq.) IN - ΣSO_3 (liq.) OUT

Precipitation = 28,844 - 9,252

= 19,592 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
2. $CaSO_4$ 2 H_2O					
Entering Streams	Scrubber Liquid-Lower	814 l/min	23.88		14,438
	Scrubber Liquid-Upper	681 l/min	25.36		17,270
	Scrubber Bottom	341 l/min	23.55		8,030
	Clarifier Liquid	57 l/min	20.38		1,167
Leaving Streams	Hold Tank Eff.	1,892 l/min	21.91		43,700

Rate of $CaSO_4$ 2 H_2O = ΣSO_4 (liq.) IN - ΣSO_4 (liq.) OUT

Precipitation = 45,905 - 43,700

= 2,205 m mole/min

		Stream Flow Rate	Species Conc. in Liq. (m mole/l)	Species Conc. in Gas (ppm)	Species Flow Rate (m mole/min)
3. $CaCO_3$ Dissolution					
Entering Streams	Scrubber Liquid-Lower	814 l/min	26.58		21,636
	Scrubber Liquid-Upper	681 l/min	24.43		16,636
	Scrubber Bottom	341 l/min	26.98		9,200
	Clarifier Liquid	57 l/min	18.26		1,041
Leaving Streams	Hold Tank Eff.	1,892 l/min	18.19		34,415

Rate of $CaCO_3$ Dissolution = ΣCa (liq.) OUT - ΣCa (liq.) IN + ΣCa Formation Rate

= 34,415 - 48,013 + 19,592 + 2,205

= 8,199 m moles/min

APPENDIX L

LIMESTONE TAIL-END SYSTEM

DISSOLUTION RATE DETERMINATION

DIAGRAMS

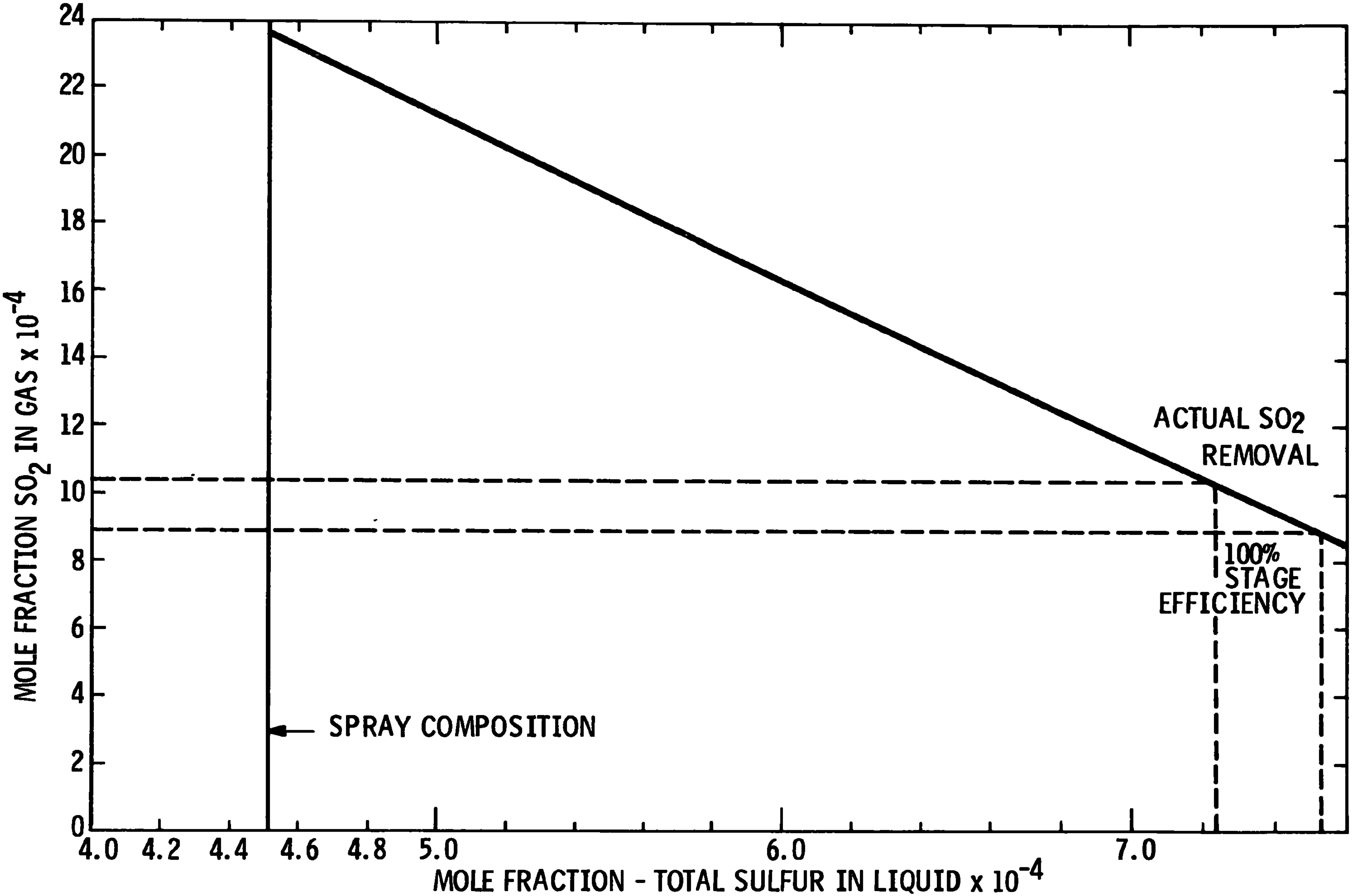


Figure L-1

PLOT OF OPERATING LINE FOR EXPERIMENT 26R

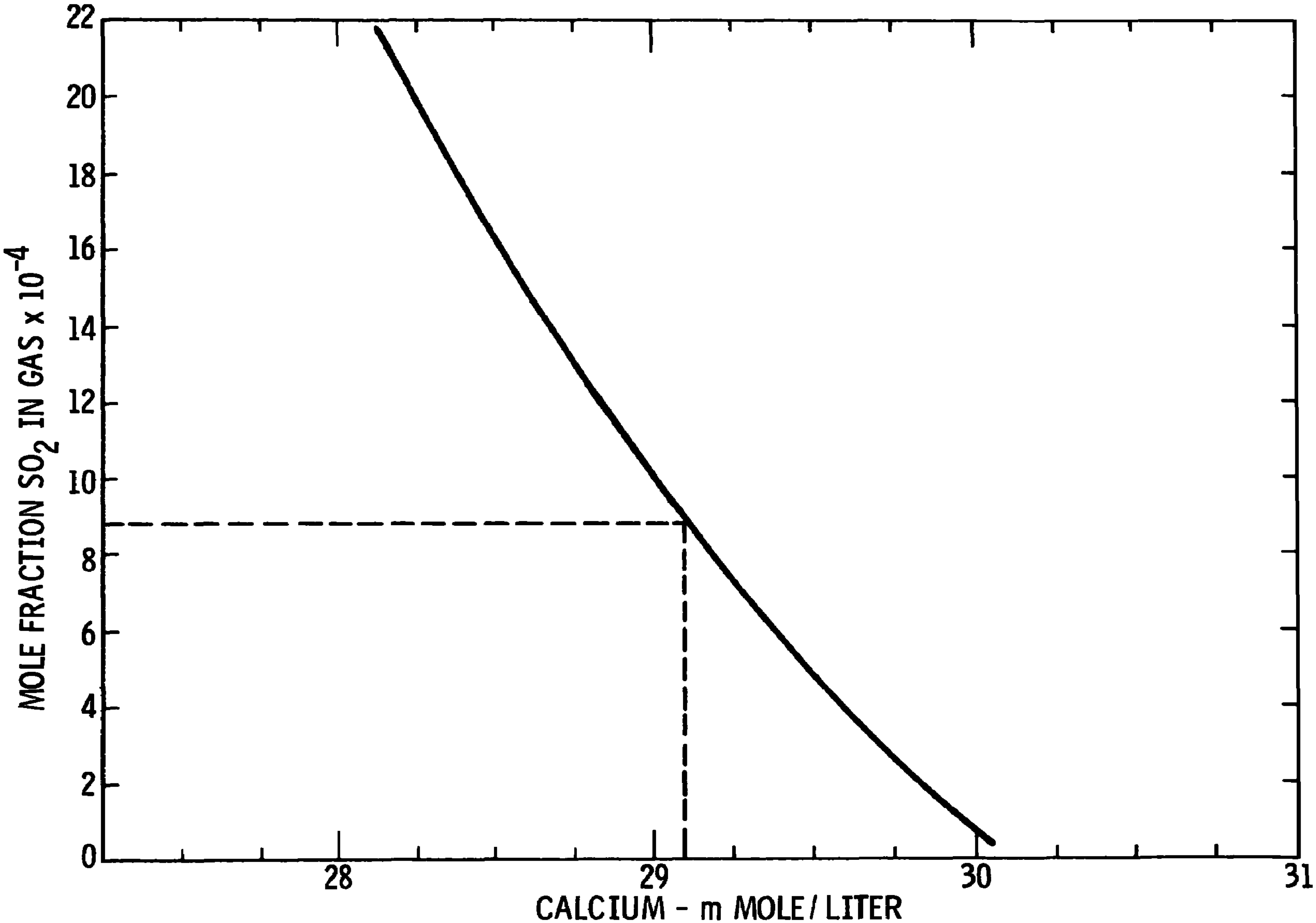
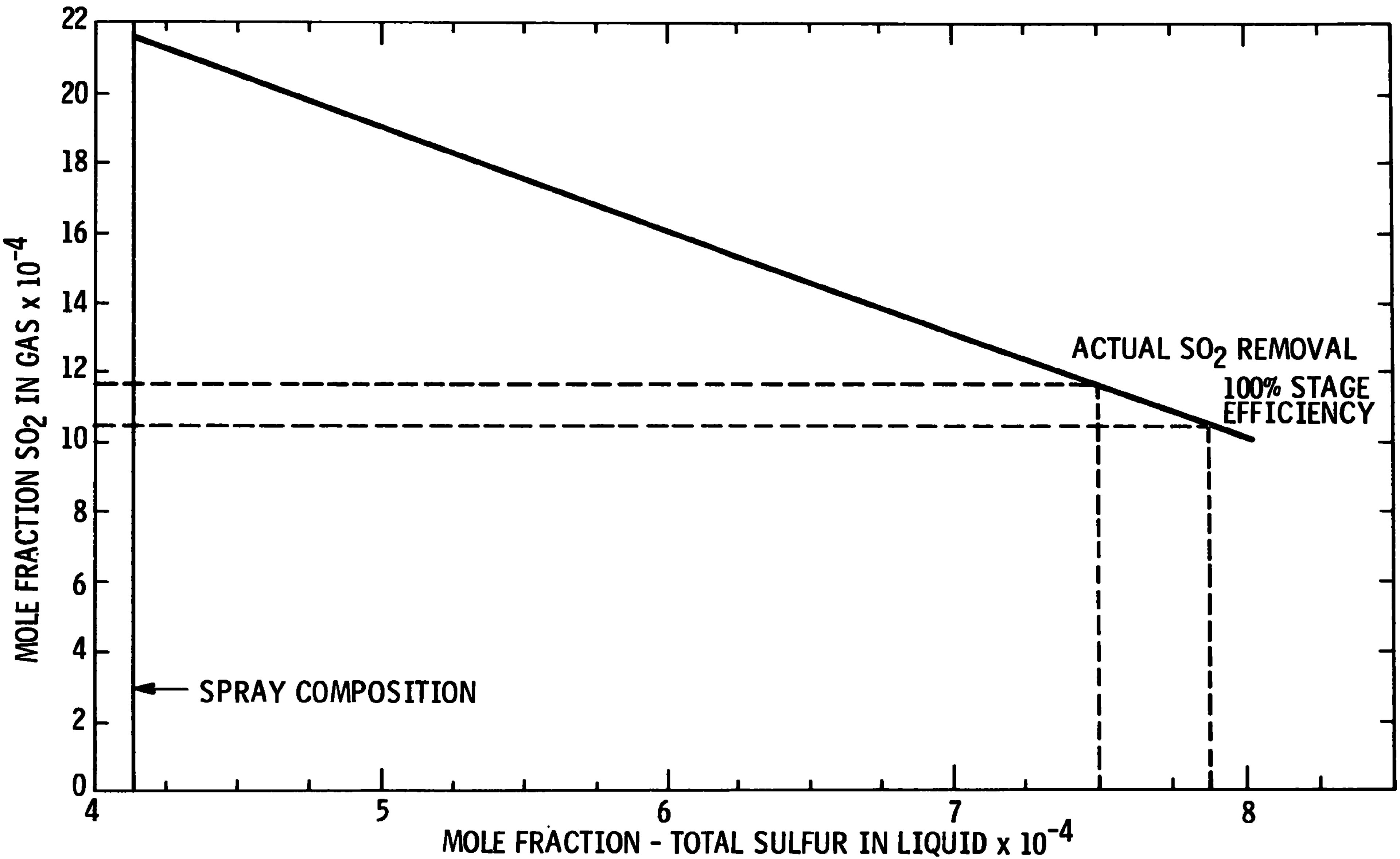


Figure L-2

PLOT OF CALCIUM vs PARTIAL PRESSURE OF SO_2 FOR SCRUBBER EFFLUENT - EXPERIMENT 26R



PLOT OF OPERATING LINE FOR EXPERIMENT 27R

Figure L-3

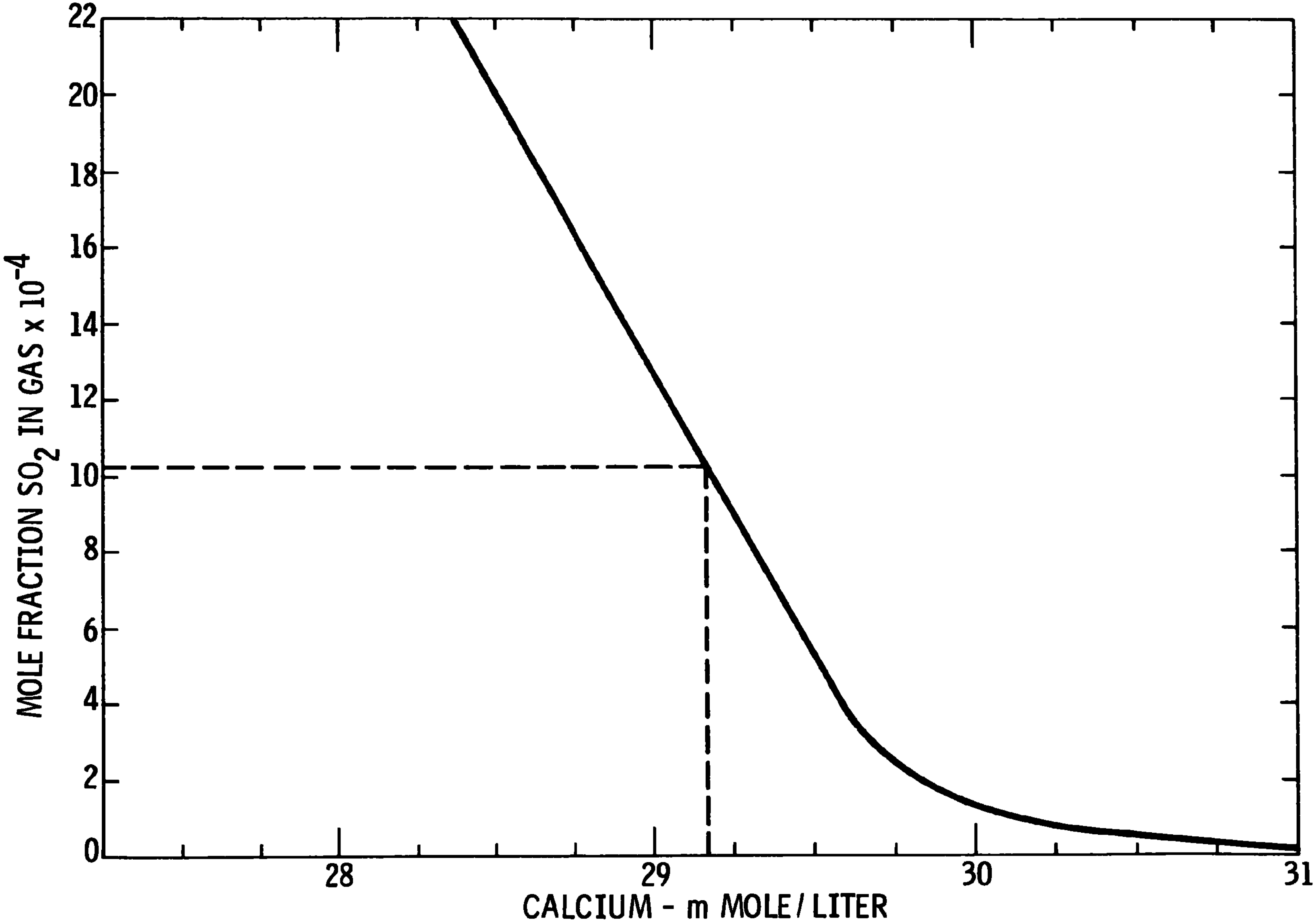
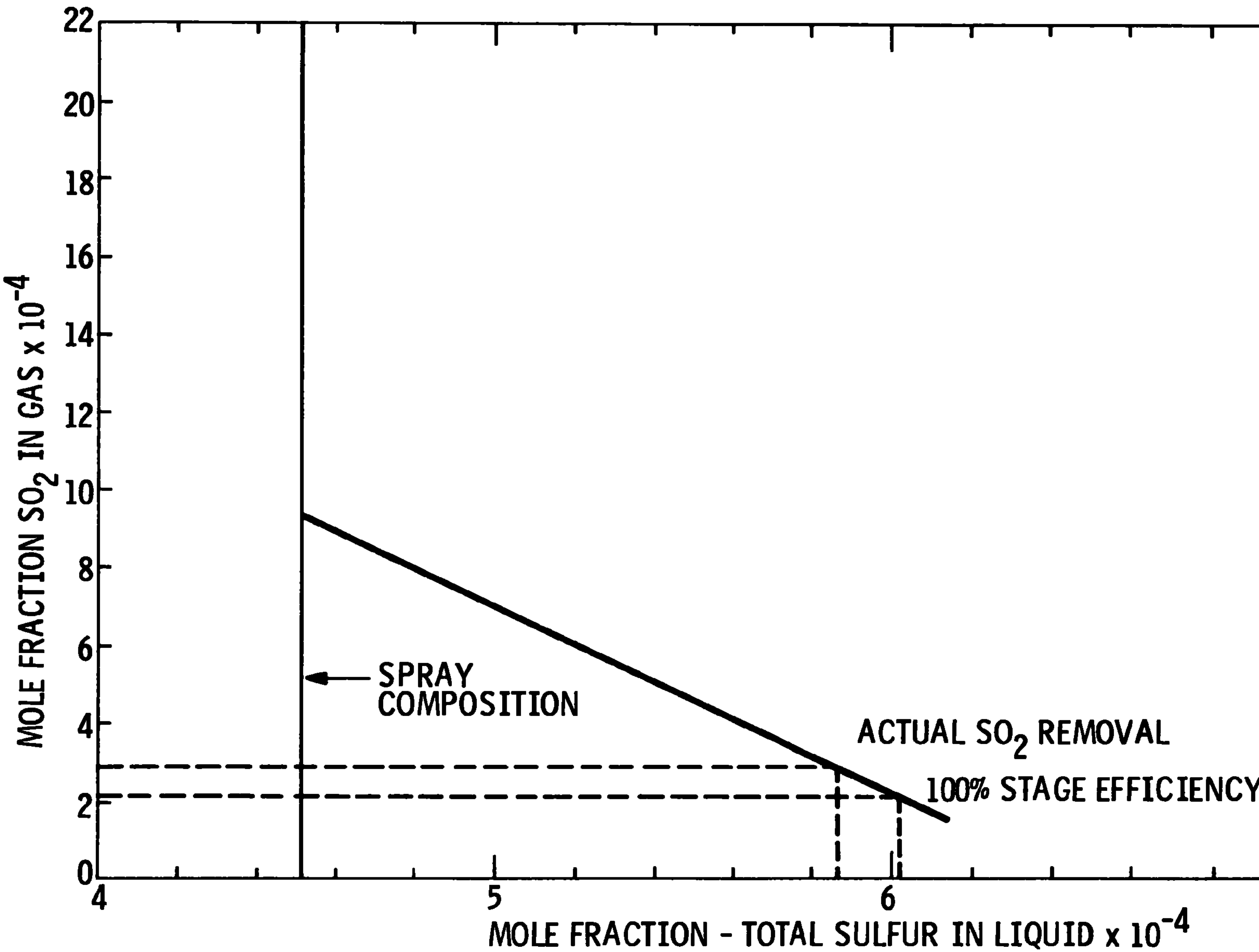


Figure L-4

PLOT OF CALCIUM vs PARTIAL PRESSURE OF SO_2 FOR SCRUBBER EFFLUENT - EXPERIMENT 27R



PLOT OF OPERATING LINE FOR EXPERIMENT 29R

Figure L-5

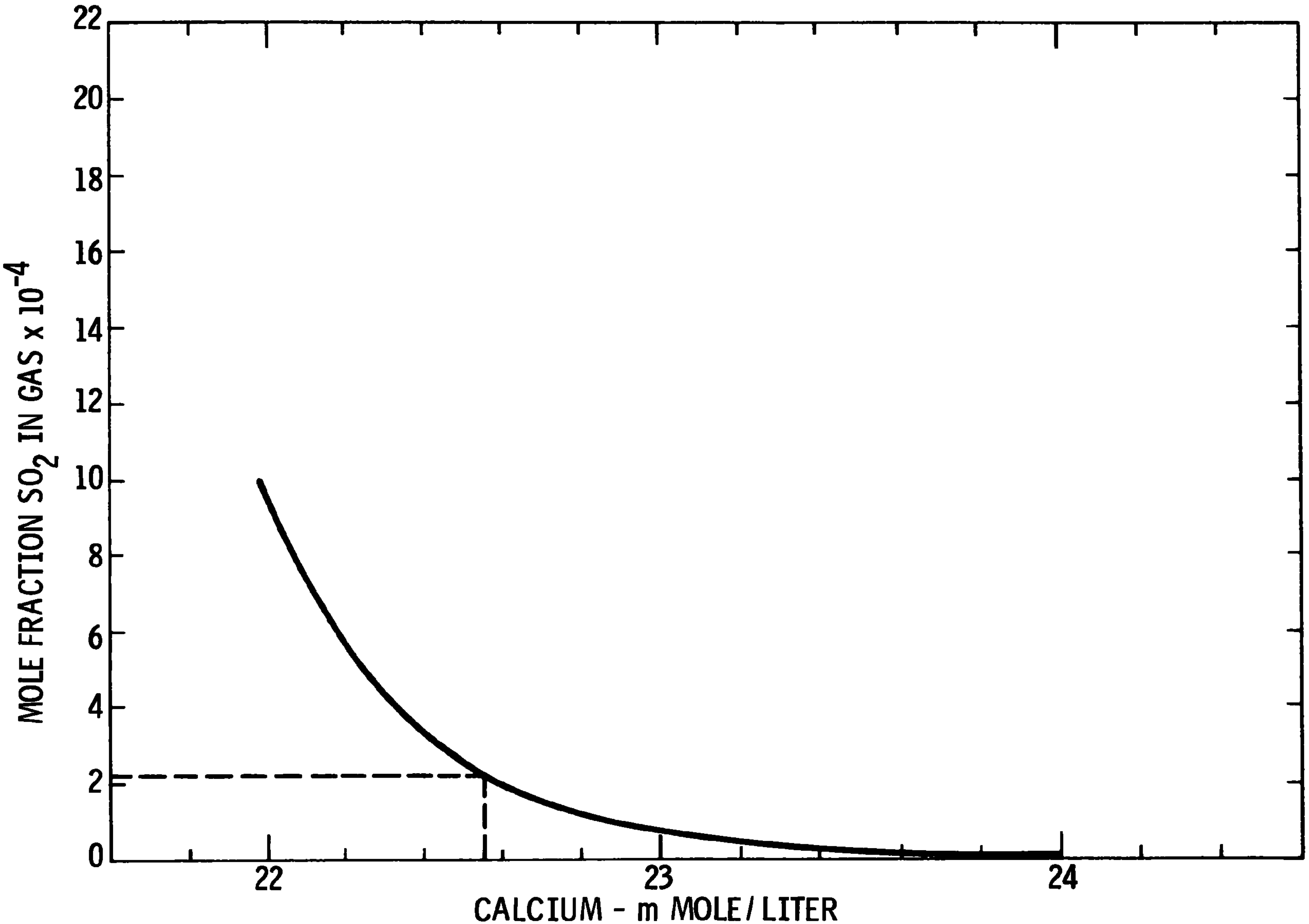


Figure L-6

PLOT OF CALCIUM vs PARTIAL PRESSURE OF SO_2 FOR SCRUBBER EFFLUENT - EXPERIMENT 29R

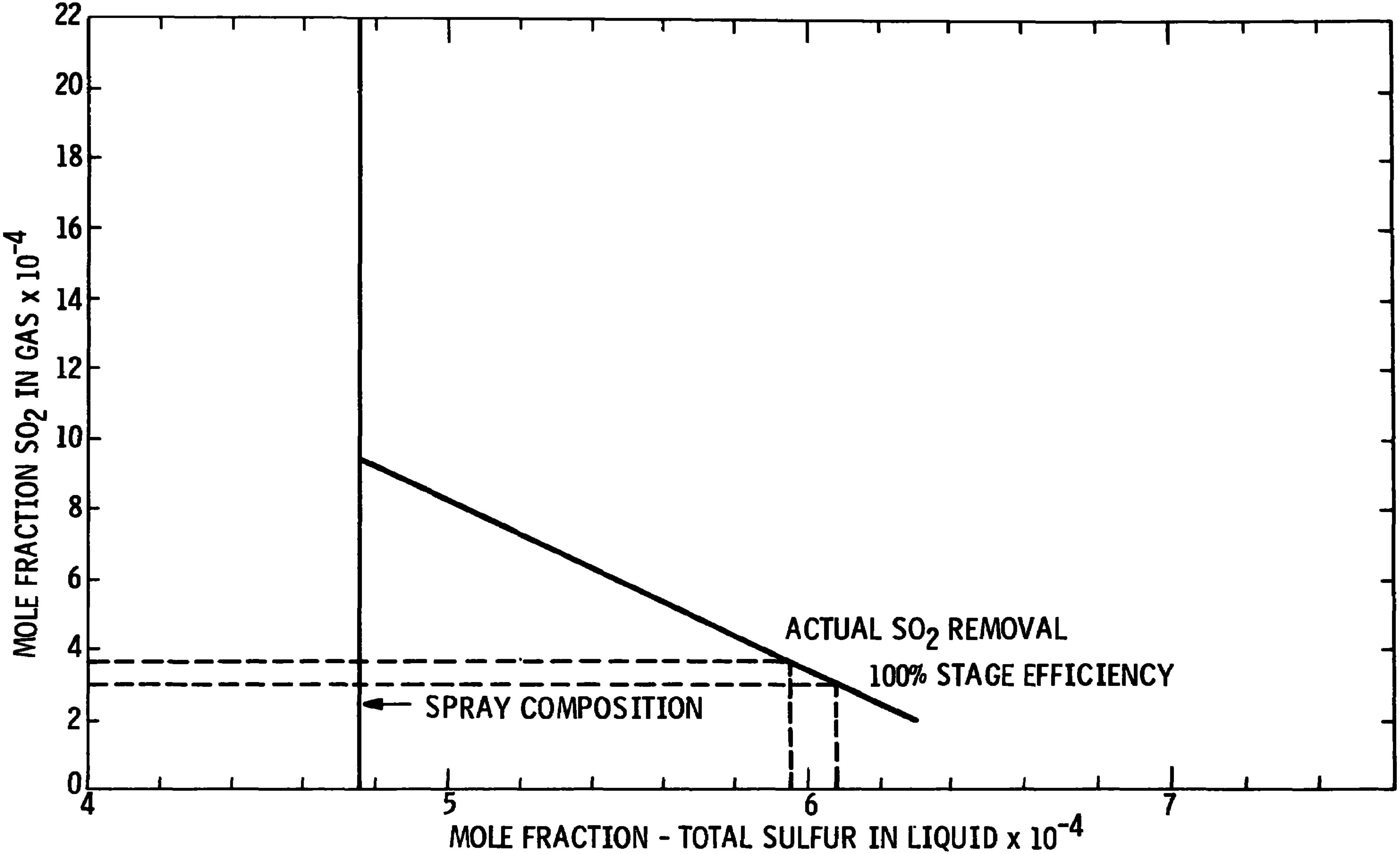
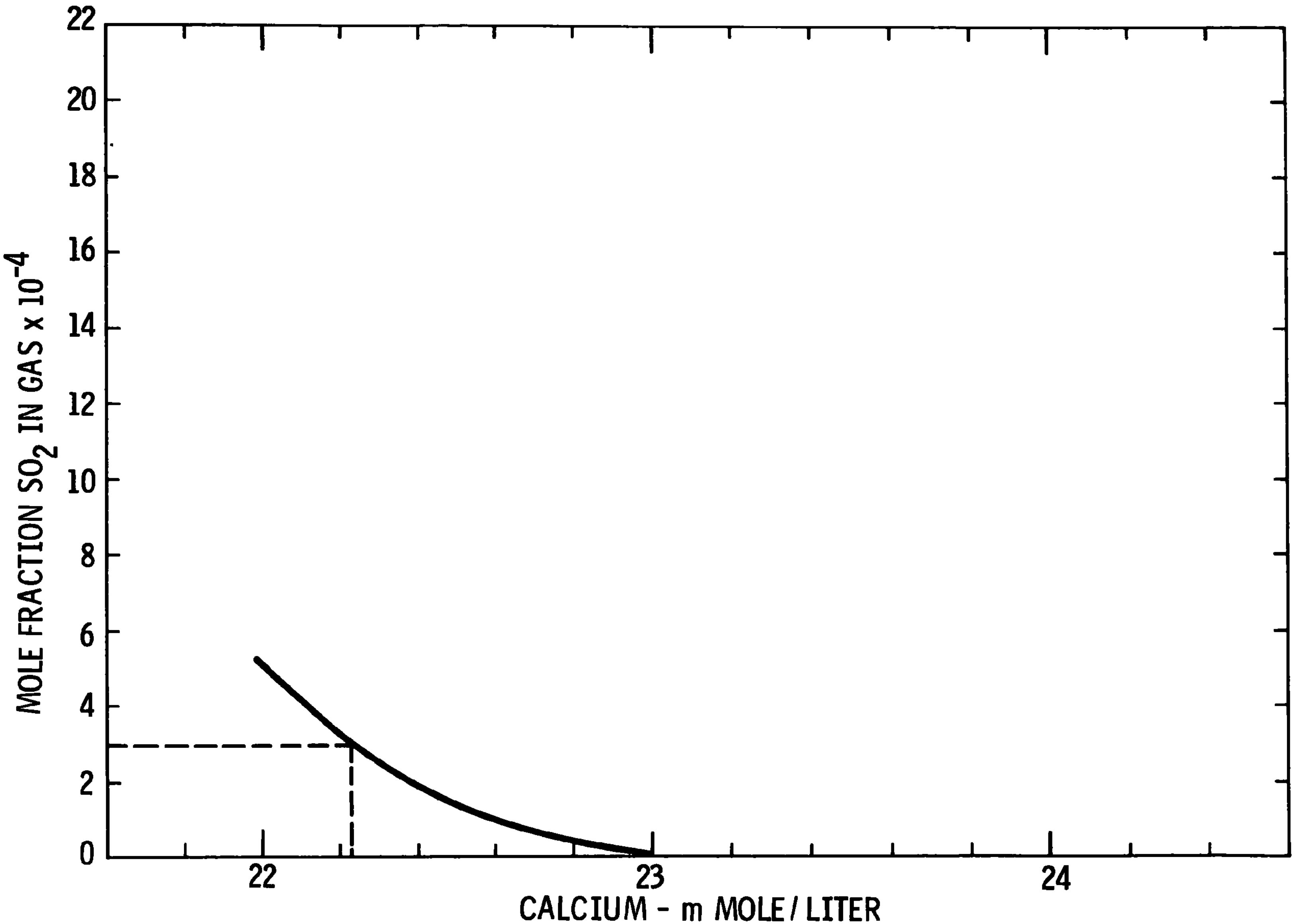


Figure L-7

PLOT OF OPERATING LINE FOR EXPERIMENT 30R

Figure L-8



PLOT OF CALCIUM vs PARTIAL PRESSURE OF SO_2 FOR SCRUBBER EFFLUENT - EXPERIMENT 30R

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15. SUPPLEMENTARY NOTES

16. ABSTRACT The report gives results of extensive testing of a prototype marble bed scrubber system. Results of 16 once-through soluble system tests, using sodium carbonate scrubbing solution, showed that the scrubber is a very good liquid/gas contacting device for SO2 removal from flue gases with an overall efficiency of 90 to 95 percent. Liquid/gas ratio and scrubber liquid composition significantly affected SO2 removal; other variables had little or no effect. Results of six limestone furnace injection system tests, using boiler calcined limestone and fly ash mixture, showed that solids concentration in the spray slurry and liquid/gas ratio signficantly affected SO2 removal. Results of six limestone tail-end system tests, using commercial limestone in a dual marble bed scrubber, showed that the SO2 removal efficiencies of the lower and upper beds are the same, based on the SO2 concentrations entering the respective beds. It was demonstrated that scale-free operation of both the furnace injection and the tail-end systems can be achieved in a closed loop system, without employing liquid blowdown, by maintaining 8 to 10 percent solids in the spray slurry.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution, Sulfur Dioxide	Air Pollution Control	13B
Scrubbers	Stationary Sources	07A
Calcium Oxides	Particulates	07B
Limestone	Marble-Bed Scrubber	
Flue Gases		21B
Fly Ash		

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