

THE ABSORPTION OF SULFUR DIOXIDE
IN MILK OF LIME

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18 First Street
Bangor, Maine
February 7, 1944

Professor George W. Swett
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In accordance with the regulations of
the Faculty, we hereby submit a thesis entitled
"THE ABSORPTION OF SULFUR DIOXIDE IN MILK OF LIME"
in partial fulfillment of the requirements for the
degree of Bachelor of Science in Chemical Engineer-
ing Practice.

Very truly yours,

Signature redacted

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I SUMMARY

In the Barker Tower system sulfur dioxide in the low pressure relief gases from pulp digesters is absorbed by passing the gas counter-current to the effluent sulfite liquor from the Barker tower in a smaller relief tower. Previous investigations of the operation of the relief tower to determine the over-all absorption coefficient were made with the tower operating under a partial vacuum. At the present time, however, this tower operates under a positive pressure of from zero to ten pounds per square inch gauge. The packing, consisting of 15.9 feet of gridded 3-1/2 by 3-1/2" wood slats, is also new. It has become desirable, therefore, to determine the absorption coefficient under these new conditions; with attempts being made to improve the technique of the various analyses required.

In order to calculate the over-all coefficient for the absorption as defined by the equation

$$K_L a = \frac{L \, dc}{S (C_e - C) \, dh} \quad ,$$

where $K_L a = \text{pounds}/(\text{hr.})(\text{cu. ft.}) \left(\frac{\text{lb. mol SO}_2}{\text{lb. mol H}_2\text{O}} \right)$, it was necessary to construct an absorption diagram, from which the driving force, $(C_e - C)$, could be determined. The operating line for such a diagram required a complete knowledge of the terminal conditions, which was attained by analyzing the inlet and effluent liquors for total, combined and free sulfur dioxide, and the inlet and

exhaust gases for sulfur dioxide, carbon dioxide, and inerts. Also, the temperature, pressure, and density at both points were measured. The equilibrium curve was determined from the data of C. K. White (9).

L, the rate of flow of water through the tower, in pound mols per hour, was measured; and G, the rate of flow of total gas, also in pound mols per hour, was calculated from a material balance based on the amount of inerts in the inlet and exhaust gases. The cross-sectional area, S, of the tower and the height of packing, h, were obtained from plant records.

On a pressure-concentration plot of the absorption, both the equilibrium curve and the operating line were found to be approximately linear. It was thus possible to use a logarithmic-mean driving force in the calculation of the coefficient.

From the above measurements and calculations the value of $K_L a$ was found to vary from 1.7 to 3.9 (maximum error being 35 per cent) pound mols/(hour)(cubic foot) (mol SO₂/mol H₂O), with total gas rates varying from 0.4 to 0.9 (maximum error 71 per cent) pound mol per hour per square foot, and a liquor rate around 2300 pounds water/(hour)(square foot).

Previous investigations (4) found the absorption coefficient to vary from 2.0 to 5.0 lb. mol/(hr.)(cu.ft.)

($\frac{\text{lb. mol SO}_2}{\text{lb. mol H}_2\text{O}}$), with a total gas rate varying from 0.34 to 0.99 lb. mol/(hr.) (sq. ft.) and a constant liquor rate of 2890 lb./(hr.)(sq.ft.).

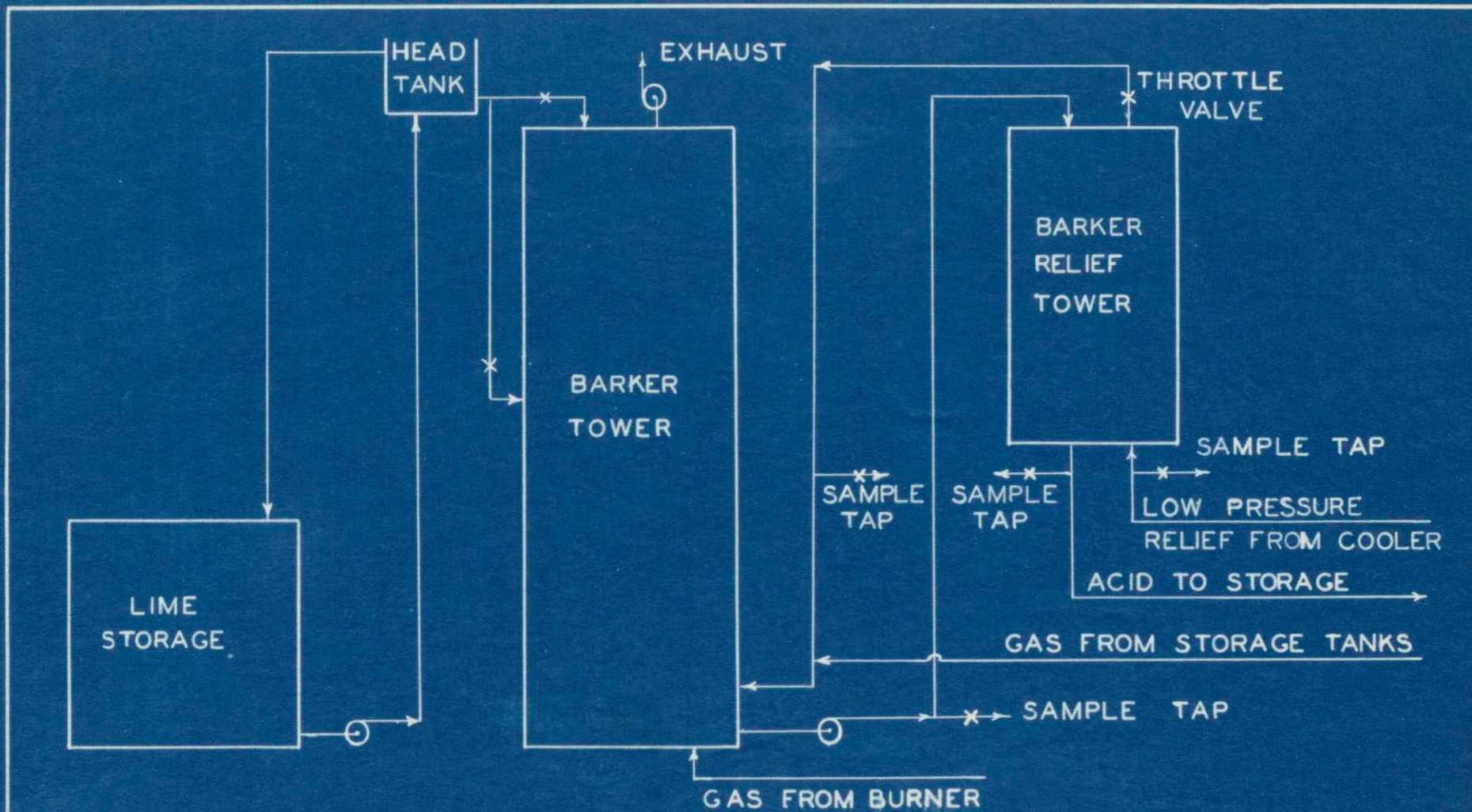
The correlation between the absorption coefficient and the gas rate is shown in Figure 2, indicating that $K_L a$ varies with the 1.1 power of the gas rate. Since the liquid rate and the temperatures in the tower remained substantially constant, no further correlations were possible. The greatest variation in the liquid rate in the tests made was from 1670 to 2350 \pm 9% pounds of water per hour per square foot.

It is recommended that the above over-all coefficients be applied to future design of wood-grid packed absorption towers for the absorption of SO_2 in bisulfite liquors over the range of gas and liquid rates investigated.

II INTRODUCTION

In the preparation of sulfite pulp, an estimated 16 per cent of the sulfur used in the pulp digestion is recovered from the low pressure relief gases (10). This recovery is effected by passing these gases counter-current to milk-of-lime in the Barker relief tower system shown in Figure 1. Since the concentration of sulfur dioxide in the relief gases is much greater than that in the sulphur dioxide gas produced by the burning of sulfur, this system not only permits a recovery of sulfur, but also makes it possible to produce a more highly concentrated sulfite liquor for use in the digestion of wood pulp.

In the Barker tower system, milk-of-lime is passed countercurrent to sulfur dioxide gas from the sulfur burners and from the accumulator. in the Barker tower. The effluent liquor from this tower is then pumped to the relief tower, where it is further concentrated by the absorption of sulfur dioxide from the low pressure relief gas. The exhaust gas from this second tower is mixed with vent gas from the sulfite storage tanks and is then fed to the Barker tower. The effluent liquor



SO₂ ABSORPTION SYSTEM

MIT STATION EASTERN CORPORATION	
REPORT NO. NI6-2B43	FIGURE NO. 1
2-5-44	F.B.M.

from the relief tower is pumped to storage tanks, from which it is charged to the digesters.

The Barker tower is a combination of a plate and packed system, containing four plates above a packed section. The relief tower consists of sections, totaling 15.9 feet, packed with 3 1/2 x 3 1/2 inch wood slats. The slats are placed in the tower about 3 inches apart horizontally and the layers thus formed are staggered vertically in such a manner that the packing offers a minimum pressure drop and at the same time prevents any liquid from flowing through the tower unimpeded.

Previous determinations of the absorption coefficients in the Barker relief tower were carried out with the tower operating under partial vacuum. The coefficient was found to vary from 2 to 5 lb. mol/(hr)(ft³)(lb. mol SO₂/lb. mol H₂O) with a total gas rate variation from 0.3 to 1 lb. mol/(hr)(ft²) and a water rate of 2090 pounds/(hr)(ft²). Since the tower is now operating under a positive pressure, varying from zero to ten pounds per square inch gauge and with a slightly different type of packing, it has become desirable to re-determine the value of this coefficient.

The purpose of this test is, therefore, to ascertain the new values for the over-all absorption coefficient

in the relief tower. The results of this test will indicate not only the relation between the coefficient and the rate of gas flow, but also the effect of the change in operating conditons (pressure and packing) on the coefficient.

III PROCEDURE

The equation for the rate of transfer of material from the gaseous phase, through the gas and liquid films, and into the liquid phase in terms of an overall coefficient when the liquid film is controlling is

$$(1) dN = K_L a S (C_e - C) dh$$

where dN is the rate at which the gas is transferred over a differential height of tower, dh , with a cross sectional area "S", with the concentration of solute in the liquid being "C". The absorption coefficient, $K_L a$, is expressed as pound mols per hour per cubic foot per unit driving force. The equation may also be written as

$$(2) Ldc = K_L a S (C_e - C) dh = G \frac{dp}{P_t}$$

It is seen that, on a pressure-concentration plot of the operating line and the equilibrium curve, the slope of the operating line is equal to $(L/G)P_t$.

In order to calculate the absorption coefficient $K_L a$ for the absorption of sulfur dioxide in milk of lime, it was necessary to establish the operating line from determined terminal conditions and slopes. For this

purpose the following data were taken.

1. Analyses of the liquid entering and leaving the tower, for total, free, and combined sulfur dioxide. From these concentrations the equilibrium for the system and the change in concentration of the liquor in the tower were determined.

2. The flow of lime slurry to the tower was measured by observing the fall in the level of the slurry in storage tanks over timed intervals to obtain L , the rate of flow of water through the tower. The density of this slurry was also measured.

3. The entrance and exhaust gases were analyzed for sulfur dioxide, carbon dioxide, and inerts. From an inert balance, the flow rate of liquor, and the change in total sulfur dioxide content of the liquor, the gas rate could be calculated.

4. The pressure in the tower, the temperature, and density of the inlet and effluent liquors were measured.

5. The height of packing and the cross-sectional area of the tower was obtained from plant records.

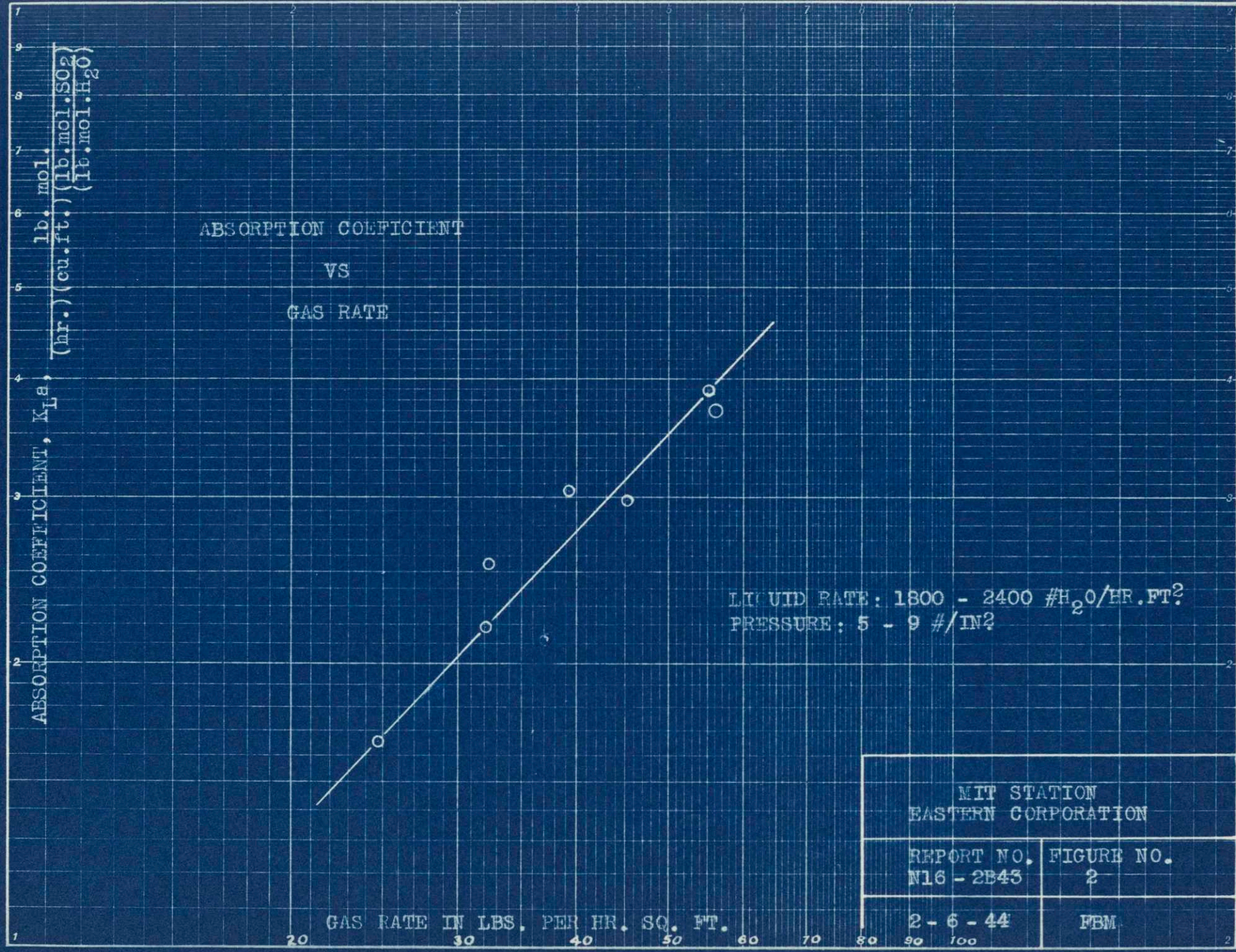
Because of the wide variation in gas rate and composition in the tower, the above measurements and samples were taken over as short a period as possible for each run.

With the aid of the equilibrium data of C. K. White (8), an absorption diagram was drawn on a pressure-concentration plot. The above data determined the operating line, from which all the quantities of equation (2) could be calculated and the equation solved for the unknown absorption coefficient $K_L a$.

After a series of preliminary runs to perfect the operating technique, seven final runs were made.

IV RESULTS

1. The over-all absorption coefficient, K_L of the Barker relief tower packed with $3\frac{1}{2} \times 3\frac{1}{2}$ inch wood slats, gridded (height, 15.9 feet), varies from 1.67 to 3.89 lb. mols/(hr.)(cu.ft.)(mol SO₂/mol H₂O) over the range of gas rates investigated, with a maximum possible error of 35 per cent.
2. The correlation of the over-all coefficient and the gas rate is shown in Figure 2, for a variation in gas rate from 0.4 to 0.9 lb. mols total gas/hr. ft.². The maximum error in the values of gas rate of flow is 71 per cent.



MIT STATION EASTERN CORPORATION	
REPORT NO. N16 - 2B43	FIGURE NO. 2
2 - 6 - 44	FEM

Table of Results

Run	$K_L a$	Total Gas Rate (lbs./hr.ft. ²)	Liquid Rate (lbs. H ₂ O/hr.ft. ²)
13	3.68	55.9	2300
14	2.92	45.3	2090
15	2.19	32.3	1690
16	3.04	39.2	1850
17	1.67	25.0	2260
18	3.89	55.3	2360
19	2.55	32.3	2300

V DISCUSSION OF RESULTS

In general, the absorption of sulfur dioxide in water is a case of a moderately soluble gas being transferred from the gaseous into the liquid phase, and the resistance of both gas and liquid films must be considered. However, both the equilibrium curve for sulfur dioxide in a bisulfite solution and the operating line were found to be essentially straight over the range of concentrations encountered; and, consequently, the operating data may be expressed in terms of $K_L a$ rather than as a combination of $K_L a$ and $K_G a$ (7). Under these conditions the over-all potential is $(C_e - C)$, where "C" is the liquid concentration of sulfur dioxide ("e" referring to equilibrium conditions).

The Barker relief tower investigated was packed with 16 feet of $3\frac{1}{2} \times 3\frac{1}{2}$ inch gridded wood slats with about 3 inches between slats. The "layers" of wood grid were staggered in the vertical direction to prevent any liquor from passing through the tower unimpeded, but at the same time allowing sufficient freedom for the gas to have a minimum pressure drop in the tower. In the tests conducted, the total pressure in the tower varied from five to nine pounds per square inch gauge.

The over-all absorption coefficient, $K_L a$, of the

relief tower was found to vary from 1.7 to 3.9 pound mols/(hour)(cubic foot)(lb. mol SO₂/lb.mol H₂O), with a maximum error of 35 per cent, based upon a precision of measurements analysis, in a series of seven instantaneous tests with varying gas rates from 0.4 to 0.9 (71 per cent maximum error) pound mols of gas per hour per square foot. The correlation between the coefficient and the gas rate is shown in Figure 2, indicating $K_L a$ to vary with the 1.1 power of the gas rate. The liquid rate in the tower ranged from 1670 to 2350 pounds of water per hour per square foot (9 per cent maximum error) throughout the tests, but most of the runs were conducted at a substantially constant liquid rate of about 2300 pounds of water per hour per square foot. Variation in the liquor rate can account for but one of the determined values of $K_L a$ which did not fall on the $K_L a$ vs. gas rate correlation line (See Fig. 2). Hence, no relation between the liquor rate and the coefficient could be obtained. Nor could any correlation between the $K_L a$ and the temperature in the tower be determined, since the latter did not vary appreciable in the course of the tests (never more than 2°F.).

Previous investigators (4) found values of the

absorption coefficient in the same tower to range from 2.0 to 5.0 lb. mol/(hr.)(cu.ft.) (lb. mol SO₂/lb. mol H₂O) with a gas rate variation from 0.3 to 0.9 lb. mols per (hr.) (ft.²). At the time the above coefficient was determined, the tower operated under a partial vacuum and was packed with 20 feet of wood slats, gridded somewhat differently from the present arrangement.

It is thus seen that no appreciable change in the absorption characteristics resulted from the changes in operating conditons of the tower (e.g., pressure and packing). The values determined in this investigation are slightly lower, but the precision on the determination does not justify a conclusion that the coefficient had been decreased.

In order to calculate $K_L a$ it was necessary to analyze the inlet and effluent liquor for total, combined, and free sulfur dioxide and the corresponding gas for sulfur dioxide, carbon dioxide, and inerts.

The partial pressure of sulfur dioxide, necessary for the construction of the absorption operating curve on the pressure-concentration plot, at the terminal conditons of the tower was obtained with sufficient accuracy by means of an Orsat mercury apparatus. The

liquor sampling operation was rendered somewhat difficult by the large amount of "bubbling" of free sulfur dioxide in the solution, hindering accurate measurement of sample volumes. Duplicate liquor samples were taken at both terminal points during each test. Since it was not always possible to obtain check analyses on these samples, it is believed that some sulfur dioxide may have been lost to the atmosphere while the sample was being pipetted into the excess iodine solution. The maximum error in the liquor analysis, based on a precision of measurement analysis, was calculated to be about 15 per cent in the combined sulfur dioxide content and about 3 per cent in the total sulfur dioxide content.

To calculate G, the total mols of gas per hour, it was necessary to analyze the gas for inerts and to calculate a sulfur dioxide-inert balance on the tower. The per cent inerts in the inlet gas was very low during all runs made and, consequently, it was difficult to obtain sufficient accuracy in the Orsat analysis to permit the accurate calculation of G. A second method for analyzing the gas for inerts was tested, the gas being bubbled through concentrated caustic contained in a liquid-sealed tube and the unabsorbed inerts collected

above the solution. While this method of inert analysis checked the Orsat method in many cases, it differed by as much as 50 per cent in a few runs. The calculated maximum error in the inert analysis by the second method was found to be 12 per cent.

Although the slope of the operating line, $(L/G)P_t$, on the pressure-concentration diagram was in error because of the above error in G (71 per cent maximum error), the terminal points were almost in a vertical line and the maximum possible deviation from a straight line was so limited that, in all cases, it was deemed within experimental accuracy to draw a straight line operating curve between the points. Hence, G actually influenced only the correlation of $K_L a$ and the gas rate, and not the coefficient itself.

The use of a logarithmic-mean driving force was consequently used in the determination of $K_L a$, the equation in this case being

$$K_L a = \frac{L (C_{in} - C_{out})}{Sh (C_e - C)_{l.m.}}$$

It is readily seen that when both C_{in} and C_{out} are small and when their difference is also small, as in the present case, a considerable error may be introduced by moderate errors in the values of C , in the

final determination of $K_L a$. From a precision of measurements analysis, the maximum error in $(C_{in} - C_{out})$ was found to be 6.5 per cent, and in $(C_e - C)_{l.m.}$, 17.4 per cent.

The maximum error in the water rate determination was 9.0 per cent and in the volume of packing, Sh , about 2.6 per cent.

It was determined that there was a loss in carbon dioxide from the gas while the latter passed through the tower, the amount varying from 0.4 to 4.0 pound mols per hour (maximum error 135 per cent). Since the liquor was not analyzed for carbon dioxide and since there is a possibility that air may have leaked into the exhaust gas line at the throttling valve (and before the exhaust gas sample tap), decreasing the carbon dioxide to inerts ratio, it cannot be stated whether or not the carbon dioxide was absorbed by the acid liquor.

It is recommended that the values of the overall absorption coefficient $K_L a$, determined in this test be applied to the future design of relief towers for the absorption of sulfur dioxide in sulfite liquor, when the operating conditions are within the ranges investigated.

VI CONCLUSIONS

It is concluded that:

1. The relation between the over-all absorption coefficient, $K_L a$, and the rate of flow of gas, G , is $K_L a \propto G^{1.1}$ over a range of gas rates of 0.4 to 0.9 mols total gas/(hr.)(sq.ft.), as indicated in Figure 2.
2. The over-all absorption coefficient of a Barker relief tower is not affected by a variation in total operating pressures from below atmospheric to ten pounds per square inch gauge.

VII RECOMMENDATIONS

It is recommended that the values of the over-all absorption coefficient determined in this investigation be applied to the future design of towers for the absorption of sulfur dioxide in sulfite liquor when the gas and liquid rates are to be within the ranges in which the coefficient was calculated and when the tower is to be packed as described herein.

VIII APPENDIX

A DETAILS OF PROCEDURE

Gas Analyses

The samples of gas to be analyzed were taken directly from the sample taps, through glass tubing, into the measuring burette of the mercury Orsat apparatus employed. Samples of approximately 200 ml. of the inlet gas and 100 ml. of the exhaust gas were taken. The gas was first bubbled through a bubbler pipette containing 200 ml. of standard 0.1N iodine solution until absorption of less than 0.5 ml. of gas was obtained per pass. The gas was then passed through a caustic pipette containing a 30 per cent potassium hydroxide solution until no further decrease in volume could be noted. The iodine was then titrated with standard 0.2N sodium thiosulfate to determine the quantity of sulfur dioxide absorbed.

Since the inlet gas to the tower contained only about 1 per cent inerts, it was necessary to obtain a more accurate determination of this value. This was accomplished by bubbling the gas through a concentrated caustic solution contained in a liquid-sealed sample tube and collecting the unabsorbed inerts above the solution, the displaced liquid being forced out the bottom of the

absorption tube. The volume of the inerts collected was then measured, together with the temperature and pressure. By acidifying the caustic solution, while maintaining a low temperature to avoid loss of sulfur dioxide, adding excess iodine, and titrating the excess with sodium thiosulfate, the quantity of sulfur dioxide absorbed could be calculated. Knowing both the inerts and the sulfur dioxide, a ratio between the two was found and applied, together with the corresponding ratio in the exhaust gas, to an inert balance in the calculation of the gas rate.

Liquor Analyses

Since the system investigated was operating under about eight pounds gauge pressure, it was necessary to take precautions against the flashing of dissolved sulfur dioxide from the liquor sample being taken. The liquor was allowed to run through a 10 ml. pipette for about a minute before a sample was pipetted directly into a measured excess of 0.1N iodine solution. The tip of this pipette was placed below the liquid level while the liquor was allowed to drain. Duplicate samples were taken from the entering and effluent liquor lines. A time of about five minutes elapsed after the entering

sample was taken until the effluent sample was taken.

Free sulfur dioxide in the form of sulfurous acid reacts with the iodine solution in the following manner:



The equation for the reaction of bisulfite with iodine is:



The excess iodine was titrated with 0.2N sodium thiosulfate. The same solution was then titrated to a phenolphthalein endpoint with 0.5N sodium hydroxide. From these data the total, free, and combined sulfur dioxide, may be calculated. The combined sulfur dioxide, z, is that sulfur dioxide which is tied up as calcium bisulfite and which will not boil off upon heating the solution to boiling, or one-half of the total amount of sulfur dioxide as bisulfite when only the bisulfite and free sulfur dioxide are present. In a solution in which both the bisulfite and monosulfite are present, the combined sulfur dioxide would be equal to one-half of the bisulfite plus the total amount of monosulfite. (Bisulfite, upon boiling, loses one-half its sulfur dioxide content—by mol— and forms the

monosulfite.) The free sulfur dioxide is defined as the sulfur dioxide present as sulfurous acid plus one-half the sulfur dioxide as bisulfite.

Flow of Liquor

The diameters of the two storage tanks in the lime room were measured. The rate of fall of the liquid level in the tanks was observed and the flow calculated.

Equilibrium Data

From the data of C. K. White (9) it was possible to plot the pressure of sulfur dioxide (p_{SO_2}) against the totally free sulfur dioxide (the total sulfur dioxide minus the total bisulfite, or minus $2z$) at a given temperature and at values of z , the combined sulfur dioxide, of 1.2 and 2.1 grams sulfur dioxide/100 grams water (See Fig. 3). Two straight lines were obtained which passed through the origin and lay in close proximity. By interpolation it was possible to obtain the p_{SO_2} and the totally free sulfur dioxide concentration for any value of z between 1.2 and 2.1. Thus at any given temperature and z , a pressure-concentration equilibrium curve could be drawn. On this diagram could be drawn the operating line (Fig. 4), and the driving force

for the equation

$$K_L a = \frac{L \, dc}{Sh (C_e - C)}$$

is then determined, $(C_e - C)$.

B SUMMARY OF DATA

Run No.		ml. Na ₂ S ₂ O ₃	ml. NaOH	Normality Iodine	Average Total SO ₂ Mols SO ₂ 100 Mol H ₂ O	Liquor Temp. F	Liquor Rate lb. Mol H ₂ O Hr.	Density
13	Inlet	21.98	47.50	0.09517	1.35	70	3200	1.043
		18.44	51.40					
	Exit	35.80	75.05					
		38.93	69.80		1.91	74		1.051
14	Inlet	21.53	49.32	0.0942	1.34	70	2910	1.043
		21.35	49.70					
	Exit	31.73	77.65					
		36.88	73.55		1.95	72		1.051
15	Inlet	22.50	46.10	0.0929	1.26	70	2340	1.043
	Exit	44.85	65.05					
		40.05	69.00		1.72	72		1.051
16	Inlet	40.50	39.08	0.0950	.96	70	2570	1.043
		39.08	31.25					
	Exit	62.16	52.00					
		56.72	57.85		1.48	72		1.051
17		44.05	45.15	0.1148	1.24	70	3140	1.043
		44.00	45.22					
		86.35	55.87					
		84.20	57.45		1.49	72		1.051

Run No.		Ml. $\text{Na}_2\text{S}_2\text{O}_3$	Ml. NaOH	Normality Iodine	Average Total SO_2 Mols SO_2 100 Mol H_2O	Liquor Temp. F	Liquor Rate lb. Mol H_2O hr.	Density	
18	Inlet	40.08	37.60	0.1008	1.10	72	3280	1.043	
		35.90	40.65						
	Exit	59.15	61.75		1.66	73			1.051
		55.58	64.80						
19	Inlet	36.92	48.00	0.1108	1.32	71	3190	1.043	
		36.55	48.40						
	Exit	72.30	62.75		1.69	74			1.051
		68.00	66.40						

Liquid sample 10 ML.

Volume of Iodine:

Run 14 - Sample 1 - Inlet 205 ML.
 Run 16 - Sample 2 - Exit 305 ML.
 All other inlet samples 200 ML.
 All other exit samples 300 ML.

Normality of $\text{Na}_2\text{S}_2\text{O}_3$ 0.21344

Normality of NaOH 0.487

SUMMARY OF DATA GAS ANALYSES

Run No.		Per Cent SO ₂	Per Cent CO ₂	Per Cent Inerts	SO ₂ Inerts	CO ₂ Inerts	Total Pressure cm. Hg.	Loss CO ₂ <u>lb. mol</u> Hr.
13		84.6*	13.2*	2.2*				
	Inlet	83.5	13.0	3.5	239	3.72	117.2	2.6

Exit	34.1	24.4	41.5	.822	.59			
14		97.5*	2.5*	0.15*				
	Inlet	97.3	2.5	0.24	412	10.4	117.2	3.7

Exit	33.6	41.2	25.2	1.33	1.63			
15		80.0*	18.8*	1.3*				
	Inlet	80.0	18.8	1.26	63.6	14.9	115.0	2.5

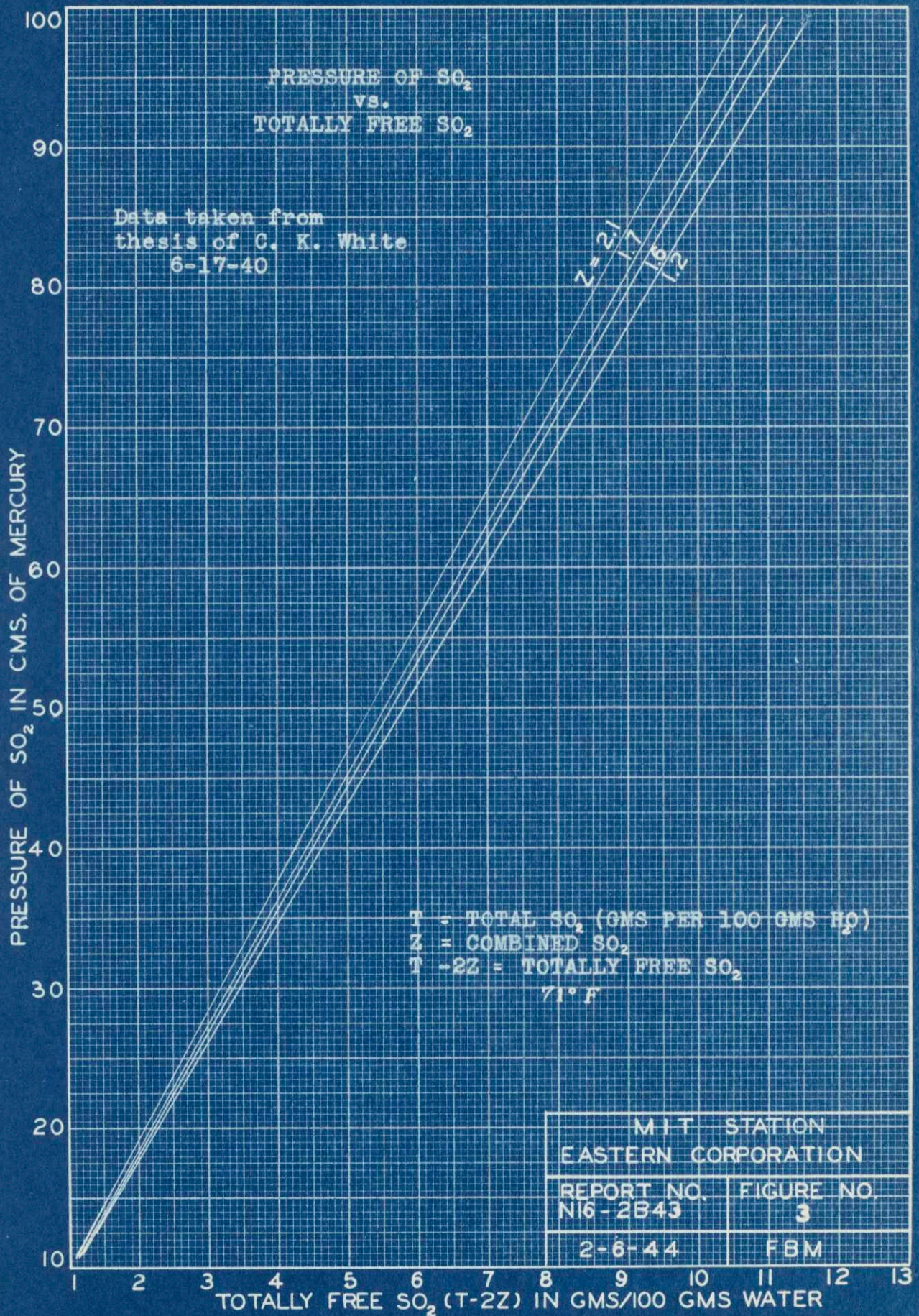
Exit	29.0	34.8	36.3	.80	.96			
16		82.0*	15.7*	2.3*				
	Inlet	82.1	15.7	2.16	38.0	7.26	104.4	2.4

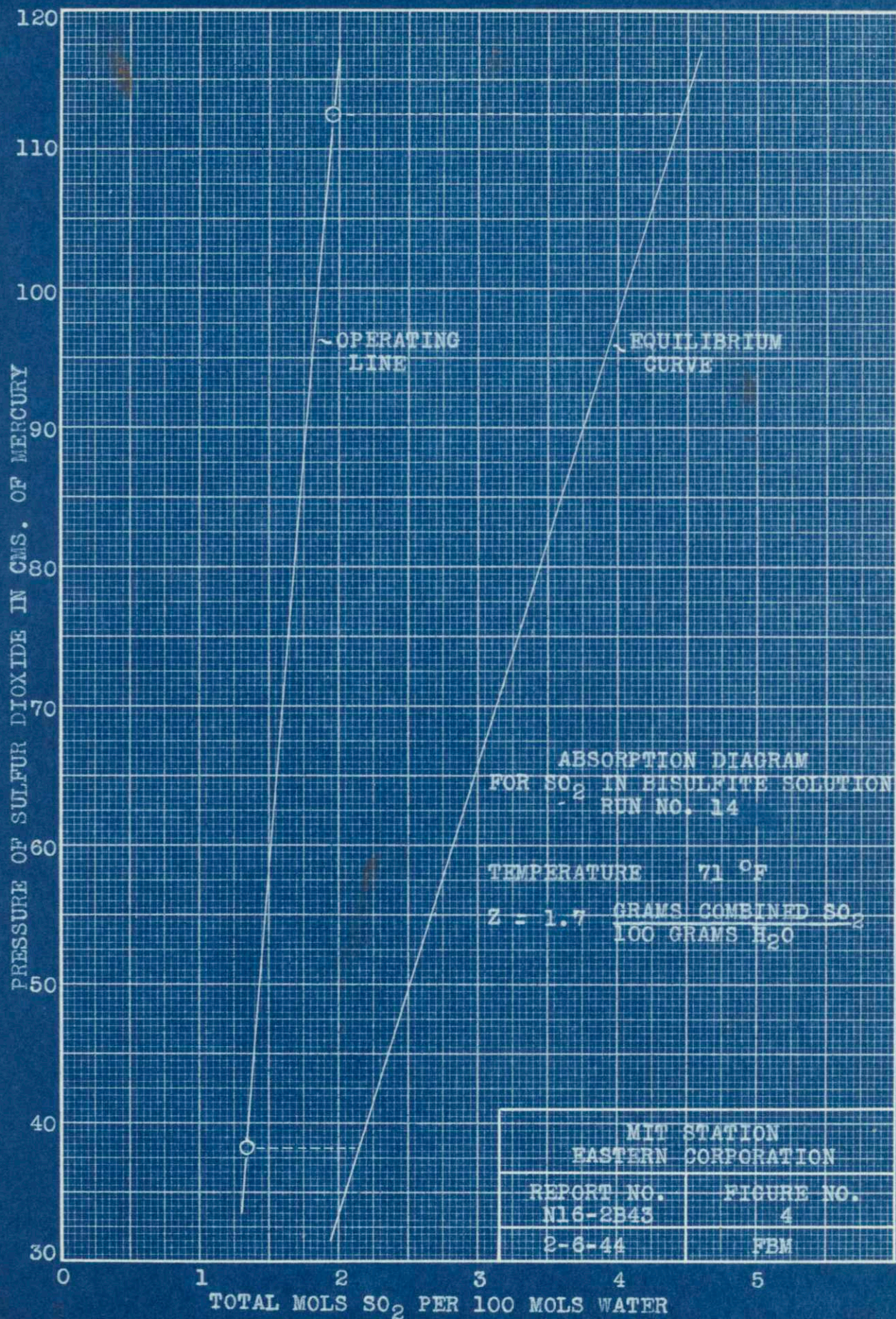
Exit	15.3	25.2	59.5	.26	.42			
17		77.5*	20.0*	2.6*				
	Inlet	77.2	19.9	2.93	26.3	6.8	120.0	1.1

Exit	23.1	59.0	17.9	1.29	3.3			

Run No.		Per Cent SO ₂	Per Cent CO ₂	Per Cent Inerts	SO ₂ Inerts	CO ₂ Inerts	Total Pressure cm. Hg.	Loss CO ₂ lb. Mol Hr.
18.		80.3*	17.9*	1.8*				
	Inlet	80.6	18.0	1.46	55.1	12.3	115.0	4.3
	Exit	21.0	25.4	53.6	0.392	.474		
19		86.9*	9.75*	3.4*				
	Inlet	88.8	9.98	1.20	74.1	8.32	117.2	1.2
	Exit	22.8	26.6	50.6	.450	.526		

* Analysis made with orsat apparatus.





C. SAMPLE CALCULATIONS

Run 14

Lime flow to tower

Radius of tank #1	3.90 ± 0.1 ft.
Radius of tank #2	3.95 ± 0.1 ft.
Initial depth	94 ± 0.5 in.
Final depth	48 ± 0.5 in.
Time	26.5 ± 0.25 min.
Area of tank #1	$= (3.14)(3.90 \pm 2.56\%)^2$ $= 47.8 \pm 5.12\% \text{ ft.}^2 = 47.8 \pm 2.5 \text{ ft.}^2$
Area of tank #2	$= (3.14)(3.95 \pm 2.53\%)^2$ $= 49.0 \pm 5.06\% \text{ ft.}^2 = \underline{49.0 \pm 2.5 \text{ ft.}^2}$
Total Area	96.8 ± 5 ft. ²
Decrease in depth	$= 94 \pm 0.5 - 48 \pm 0.5 = 46 \pm 1 \text{ in.}$
Lime flow	$= \frac{(46 \pm 2.2\%)(96.8 \pm 5.2\%)(28.32)(60)}{(26.5 \pm 0.9\%)(12)}$ $= 23,800 \pm 8.3\% = 24,000 \pm 2000 \text{ liters/hr.}$

Normality of standard solutions

K₂Cr₂O₇:

Weight of K ₂ Cr ₂ O ₇	2.4385 gm.
Volume of solution	500 ± 0.5 cc
Normality	$= \frac{(2.4385 \pm 0.0\%)(6000)}{(294.2)(500 \pm 0.1\%)} = 0.0995 \pm 0.1\%$

Na₂S₂O₃:

Volume of K ₂ Cr ₂ O ₇	100 ± 0.1 cc
Volume of Na ₂ S ₂ O ₃	46.62 ± 0.1 cc
Normality	$= \frac{(100 \pm 0.1\%)(0.0995 \pm 0.1\%)}{46.62 \pm 0.2\%}$ $= 0.2134 \pm 0.4\%$

Normality of standard solutions (cont.)

I₂:

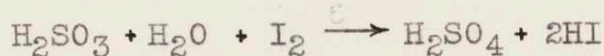
Volume of I ₂	100 ± 0.1 cc
Volume of Na ₂ S ₂ O ₃	44.15 ± 0.1 cc
Normality =	$\frac{(44.15 \pm 0.3\%)(0.2134 \pm 0.4\%)}{100 \pm 0.1\%}$
	= 0.0942 ± 0.8%

NaOH:

Volume of NaOH	48.0 ± 0.1cc
Volume of HCl	50.0 ± 0.05cc
Normality of HCl	0.467 ± 0.5%
	(Courtesy of vanRavenswaay and group)
Normality =	$\frac{(50 \pm 0.1\%)(0.467 \pm 0.5\%)}{48.0 \pm 0.2\%}$
	= 0.487 ± 0.8%

Liquor analyses

Reactions:



Let x = me. of SO₂ from HSO₃⁻

Let y = me. of total SO₂

Then: y - x = me. of SO₂ from H₂SO₃

3/2 x = me. of H⁺ from HSO₃⁻

2(y - x) = me. of H⁺ from H₂SO₃

Total H⁺ = 3/2 x + 2y - 2x = 2y - 1/2x

Liquor to the tower:

Normality of I ₂	0.0942 ± 0.8%
Normality of Na ₂ S ₂ O ₃	0.2134 ± 0.4%
Normality of NaOH	0.487 ± 0.8%

Liquor analyses (cont.)

Volume of I ₂	205 ± 0.2cc
Volume of Na ₂ S ₂ O ₃	21.53 ± 0.1cc
Volume of NaOH	49.32 ± 0.1cc
Volume of sample	10 ± 0.1cc
me. I ₂ = (205 ± 0.1%) (0.0942 ± 0.8%) =	19.32 ± 0.17
Na ₂ S ₂ O ₃ = (21.53 ± 0.5%) (0.2134 ± 0.4%) =	<u>4.60 ± 0.04</u>
me. I ₂ consumed = y =	14.72 ± 0.21
Total me. H ⁺ = (49.32 ± 0.2%) (0.487 ± 0.8%)	
= 24.0 ± 0.2	

$$2y - \frac{1}{2}x = 2(14.7 \pm 0.2) - \frac{1}{2}x = 24.0 \pm 0.2$$

$$x = 10.8 \pm 1.2$$

$$\text{HSO}_3^- = \frac{(10.8 \pm 11\%)(100)}{(2000)(10 \pm 1\%)} = 0.054 \pm 12\% \text{ mols/100cc}$$

$$\begin{aligned} \text{Total SO}_2 &= \frac{(14.72 \pm 1.5\%)(100)}{(2000)(10 \pm 1\%)} \\ &= 0.0736 \pm 2.5\% \text{ mols/100cc} \end{aligned}$$

$$\begin{aligned} \text{H}_2\text{SO}_3 &= (0.0736 \pm 0.0018) - (0.054 \pm 0.0065) \\ &= 0.0196 \pm 0.008 \text{ mols/100cc} \end{aligned}$$

Average of two samples:

$$\text{HSO}_3^- = 0.0491 \pm 12\% \text{ mols/100cc}$$

$$\text{H}_2\text{SO}_3 = 0.0237 \pm 34\% \text{ mols/100cc}$$

$$\text{Total} = 0.0728 \pm 2.5\% \text{ mols/100cc}$$

Liquor analyses (cont.)

Liquor from the tower:

Normality of I_2	$0.0942 \pm 0.8\%$
Normality of $Na_2S_2O_3$	$0.2134 \pm 0.4\%$
Normality of NaOH	$0.487 \pm 0.8\%$
Volume of I_2	$300 \pm 0.3cc$
Volume of $Na_2S_2O_3$	$31.73 \pm 0.1cc$
Volume of NaOH	$77.65 \pm 0.2cc$

$$\text{me. } I_2 = (300 \pm 0.1\%)(0.0942 \pm 0.8\%) = 28.26 \pm 0.26$$

$$Na_2S_2O_7 = (31.73 \pm 0.35\%)(0.2134 \pm 0.4\%) = \underline{6.77 \pm 0.05}$$

$$\text{me. } I_2 \text{ consumed} = y = 21.49 \pm 0.31$$

$$\text{Total me. } H^+ = (77.65 \pm 0.26\%)(0.487 \pm 0.8\%)$$

$$= 37.80 \pm 0.4$$

$$2y - \frac{1}{2}x = 2(21.49 \pm 0.31) - \frac{1}{2}x = 37.80 \pm 0.4$$

$$x = 10.36 \pm 2.0$$

$$HSO_3^- = \frac{(10.36 \pm 19.5\%)(100)}{(2000)(10 \pm 1\%)} = 0.0518 \pm 20.5\% \text{ mols/100cc}$$

$$\text{Total } SO_2 = \frac{(21.49 \pm 1.5\%)(100)}{(2000)(10 \pm 1\%)} = 0.1075 \pm 2.5\% \text{ mols/100cc}$$

$$H_2SO_3 = (0.1075 \pm 0.0027) - (0.0518 \pm 0.010)$$

$$= 0.0557 \pm 0.013 \text{ mols/100cc}$$

Average of two samples:

$$HSO_3^- = 0.0505 \pm 20.5\% \text{ mols/100cc}$$

$$H_2SO_3 = 0.0542 \pm 24\% \text{ mols/100cc}$$

$$\text{Total} = 0.1047 \pm 2.5\% \text{ mols/100cc}$$

Gas Analyses

Inlet relief gas:

Orsat analysis:

Volume of sample 198.5 ± 0.2 cc
" after I₂ absorption 2.3 ± 0.1 cc
" " caustic absorption 0.3 ± 0.1 cc

$$\begin{aligned} \text{Volume of SO}_2 \text{ and CO}_2 &= (198.5 \pm 0.2) - (0.3 \pm 0.1) \\ &= 198.2 \pm 0.3 \text{ cc} \end{aligned}$$

Iodine titration for SO₂:

Volume I₂ = 200 ± 0.2 cc 0.0942 ± 0.8% Normal

Volume Na₂S₂O₃ = 11.65 ± 0.1 cc 0.2134 ± 0.4% Normal

me. I₂ consumed by absorbed SO₂

$$\begin{aligned} &= (200 \pm 0.1\%)(0.0942 \pm 0.8\%) - (11.65 \pm 0.9\%)(0.2134 \pm 0.4\%) \\ &= 16.35 \pm 1.3\% \end{aligned}$$

Orsat temperature = 52 ± 0.5°F.

" pressure = 759 ± 0.1% mm

Partial pressure of water = $\frac{0.1918 \text{ \#/sq.in.}}{14.7}$

$$= 0.0130 \pm 8\% \text{ atm.}$$

$$\begin{aligned} \text{Volume of SO}_2 &= \frac{(16.35 \pm 1.3\%)(22,400)(512 \pm 0.1\%)(760)}{(2000)(1 - 0.013 \pm 0.1\%)(492)(759 \pm 0.1\%)} \\ &= 193.2 \pm 1.6\% \text{ cc} \end{aligned}$$

Volume of CO₂ = (198 ± 0.3) - (193.2 ± 3.1)

$$= 5.0 \pm 3.3 \text{ cc}$$

Volume of inerts = 0.3 ± 0.1 cc

Gas Composition

$$\text{SO}_2 = \frac{193.2 \pm 1.6\%}{198.5 \pm 0.1\%} = (97.5 \pm 1.7) \%$$

$$\text{CO}_2 = \frac{5.0 \pm 60\%}{198.5 \pm 0.1\%} = (2.5 \pm 1.5) \%$$

$$\text{Inerts} = \frac{0.3 \pm 33\%}{198.5 \pm 0.1\%} = (0.15 \pm 0.05) \%$$

Caustic absorption analysis

Volume of caustic sample 25.0 ± 0.05 cc

Total volume of caustic 157.4 ± 0.5 cc

Volume of iodine added 175.0 ± 0.2 cc

Normality of iodine $0.0929 \pm 0.8\%$

Volume of thiosulfate 11.2 ± 0.1 cc

Normality of thiosulfate $0.2134 \pm 0.4\%$

me. iodine consumed by SO_2

$$= (175.0 \pm 0.1\%)(0.0929 \pm 0.8\%) - (11.2 \pm 0.9\%)(0.2134 \pm 0.4\%)$$

$$= 13.86 \pm 0.17 \text{ me.}$$

$$\text{Total mols } \text{SO}_2 = \frac{(13.86 \pm 1.2\%)(157.4 \pm 0.3\%)}{(2000)(25.0 \pm 0.2\%)}$$

$$= 0.0435 \pm 1.7\%$$

Volume SO_2 at Orsat conditions

$$= \frac{(0.0435 \pm 1.7\%)(82.05)(284 \pm 0.1\%)}{\frac{(759 \pm 0.1\%)(1 - 0.013 \pm 0.1\%)}{760}}$$

$$= 1030 \pm 2.0\% \text{ cc}$$

Volume inerts = $2.7 \pm 7\%$ cc $t = 78 \pm 0.5$ °F
 $p = 758 \pm 1$ mm. Hg

The vapor pressure over a solution of 0.05# NaOH/# H₂O
is practically the same as over water - Int. Crit. Tables
Vapor pressure water at 78 °F 0.4747 #/in.²

$$\text{Partial pressure} = \frac{0.4747}{14.7} = 0.032 \pm 0.001 \text{ atm.}$$

Vacuum head of caustic under inerts 5.5 ± 4% in.

density 1.054 ± 0.1%

$$\text{head, in. Hg} = \frac{(5.5 \pm 4\%)(1.054 \pm 0.1\%)}{(13.6 \pm 0.1\%)}$$

$$= 0.42 \pm 4.2\% \text{ in.}$$

Volume of inerts at Orsat conditions

$$= \frac{(2.7 \pm 7\%)(512 \pm 0.1\%)(29.9 - 0.42 \pm 4.2\%)(1 - 0.032 \pm 0.1\%)}{(538 \pm 0.1\%)(29.9)(1 - 0.013 \pm 0.1\%)}$$

$$= 2.48 \pm 7.4\% \text{ cc}$$

$$\text{Ratio } \frac{\text{SO}_2}{\text{CO}_2} \text{ from Orsat analysis} = \frac{97.5 \pm 1.7\%}{2.5 \pm 60\%} = 39 \pm 62\%$$

$$\text{SO}_2 = 1030 \pm 2\% \text{ cc}$$

$$\text{CO}_2 = \frac{1030 \pm 2\%}{39 \pm 62\%} = 26.4 \pm 64\% \text{ cc}$$

$$\text{Inerts} = 2.5 \pm 7.4\% \text{ cc}$$

$$\text{Total} \quad \frac{1059 \pm 4\% \text{ cc}}{\quad}$$

Gas composition

$$\text{SO}_2 = \frac{1030 \pm 2\%}{1059 \pm 4\%} = (97.3 \pm 6) \%$$

$$\text{CO}_2 = \frac{26.4 \pm 64\%}{1059 \pm 4\%} = (2.5 \pm 1.7) \%$$

$$\text{In.} = \frac{2.5 \pm 7.4\%}{1059 \pm 4\%} = (0.24 \pm 0.03)\%$$

$$\text{Ratio } \frac{\text{SO}_2}{\text{Inerts}} = \frac{1030 \pm 2\%}{2.5 \pm 7.4\%} = 412 \pm 9.4\%$$

Outlet sample:

Volume of sample 98.9 ± 0.1 cc
" after I_2 absorption 31.6 ± 0.1 cc
" after caustic absorption 25.0 ± 0.1 cc
Volume of SO_2 and CO_2 = $(98.9 \pm 0.1) - (25.0 \pm 0.1)$
= 73.9 ± 0.2 cc

Iodine titration for SO_2

me. iodine absorber = 18.84 ± 0.16 (same as inlet)
volume of thiosulfate 75.10 ± 0.2 cc
Normality of thiosulfate $0.2134 \pm 0.4\%$
me. I_2 consumed
= $(18.84 \pm 0.16) - (75.10 \pm 0.2)(0.2134 \pm 0.4\%)$
= 2.81 ± 0.27

Volume at Orsat conditions

$$= \frac{(2.81 \pm 9.6\%)(22,400)(512 \pm 0.1\%)(760)}{(2000)(1 - 0.013 \pm 0.1\%)(492)(759 \pm 0.1\%)}$$

$$SO_2 = 33.2 \pm 9.9\% \text{ cc}$$

$$CO_2 = (73.9 \pm 0.2) - (33.2 \pm 3.3) = 40.7 \pm 3.5 \text{ cc}$$

$$\text{Inerts} = 25.0 \pm 0.1 \text{ cc}$$

Exhaust gas composition

$$SO_2 = \frac{33.2 \pm 9.9\%}{98.9 \pm 0.1\%} = (33.6 \pm 3.3) \%$$

$$CO_2 = \frac{40.7 \pm 8.6\%}{98.9 \pm 0.1\%} = (41.2 \pm 3.6) \%$$

$$\text{In.} = \frac{25.0 \pm 0.4\%}{98.9 \pm 0.1\%} = (25.2 \pm 0.1) \%$$

$$\text{Ratio } \frac{SO_2}{\text{Inerts}} = \frac{33.6 \pm 9.9\%}{25.2 \pm 0.5\%} = 1.33 \pm 10\%$$

$$\text{Total SO}_2 = \frac{(0.0698 \pm 1.7\%)(100)}{(93.95 \pm 1.2\%)}$$

$$= 0.0745 \pm 2.9\% \text{ mols SO}_2/100 \text{ gm water}$$

$$= (0.0745 \pm 2.9\%)(64) = 4.77 \pm 2.9\% \text{ gm SO}_2/100 \text{ gm water}$$

$$= (0.0745 \pm 2.9\%) \frac{(18)}{100} = 0.0134 \pm 2.9\% \text{ mols SO}_2/\text{mol H}_2\text{O}$$

$$\text{Combined SO}_2 = \frac{(0.0236 \pm 12.2\%)(100)}{(93.95 \pm 1.2\%)}$$

$$= 0.0252 \pm 13.4\% \text{ mols SO}_2/100 \text{ gm water}$$

$$= (0.0252 \pm 13.4\%)(64) = 1.61 \pm 13\% \text{ gm SO}_2/100 \text{ gm water}$$

Outlet liquor

$$\text{SO}_2 \text{ as HSO}_3^- \quad 0.0505 \pm 19.5\% \frac{\text{mols}}{100 \text{ cc}}$$

$$\text{Total SO}_2 \quad 0.1047 \pm 2.5\% \quad "$$

$$\text{Density of liquor} \quad 1.051 \pm 0.2\%$$

$$\text{Combined SO}_2 = \frac{(0.0505 \pm 19.5\%)}{2(1.051 \pm 0.2\%)} = 0.0240 \pm 19.7\% \text{ mols}/100 \text{ gm}$$

$$\text{Total SO}_2 = \frac{(0.1047 \pm 2.5\%)}{(1.051 \pm 0.2\%)} = 0.0995 \pm 2.7\% \text{ mols}/100 \text{ gm}$$

Grams H₂O/100 grams solution

$$= 100 - (0.0240 \pm 19.7\%)(195 \pm 1\%)$$

$$- [(0.0995 \pm 2.7\%) - 2(0.0240 \pm 19.7\%)] [64]$$

$$= 100 - (4.68 \pm 20.7\%) - (3.30 \pm 24\%)$$

$$= 92.02 \pm 1.9\%$$

$$\text{Total SO}_2 = \frac{(0.0995 \pm 1.7\%)(100)}{(92.02 \pm 1.9\%)}$$

$$= 0.1080 \pm 3.6\% \text{ mols SO}_2/100 \text{ gm water}$$

$$= (0.1080 \pm 3.6\%)(64) = 6.92 \pm 3.5\% \text{ gm}/100 \text{ gm water}$$

$$= \frac{(0.1080 \pm 3.6\%)(18)}{100} = 0.0195 \pm 3.5\% \text{ mols/mol water}$$

$$\begin{aligned}\text{Combined SO}_2 &= \frac{(0.0240 \pm 19.7\%)(100)}{(92.02 \pm 1.8\%)} \\ &= 0.0261 \pm 21.5\% \text{ mols/100 gm water} \\ &= (0.0261 \pm 21.5\%)(64) = 1.67 \pm 21.5\% \text{ gm/100 gm water}\end{aligned}$$

Mols of SO₂ absorbed in tower/100 gms. water

$$\begin{aligned}&= (0.1080 \pm 3.6\%) - (0.0745 \pm 2.9\%) \\ &= 0.0335 \pm 19\% \text{ mols SO}_2\text{/100 gm water}\end{aligned}$$

Lime rate

$$\begin{aligned}&= 23,800 \pm 1940 \text{ liters/hr.} \\ &= \frac{23,800 \pm 8.3\%}{28.32} = 842 \pm 8.3\% \text{ cubic feet/hour}\end{aligned}$$

Lbs. slurry/lb. water

$$\text{Slurry density} \quad 1.010 \pm 0.5\%$$

Average molecular weight of lime:

Assume lime is 50% CaO and 50% MgO by weight.

$$\text{CaO} = 56$$

$$\text{MgO} = \underline{40}$$

$$96 \text{ av.} = 96/2 = 48 \pm 1\%$$

$$\begin{aligned}\text{One equiv. CaO (or MgO) plus one equiv. SO}_2 \\ &= \text{one equiv. of combined SO}_2\end{aligned}$$

$$\text{Average mols combined SO}_2\text{/100 gms H}_2\text{O} = 0.0269 \pm 18\%$$

$$\text{Grams lime/100 gms H}_2\text{O} = \frac{\text{mols combined SO}_2 \text{ (M.W.)}}{100 \text{ gms H}_2\text{O}}$$

$$= (0.0269 \pm 18\%)(48 \pm 1\%)$$

$$= 1.29 \pm 19\%$$

$$\frac{\text{lbs. slurry}}{\text{lb. water}} = 1 + \frac{\text{lbs. lime}}{\text{lb. water}} = 1 + \frac{(1.29 \pm 19\%)}{100}$$

$$= \frac{101.29}{100} \pm 0.2\%$$

Lbs. water/ hour

$$\begin{aligned} &= \frac{\text{lbs. slurry}}{\text{hr.}} \times \frac{\text{lbs. water}}{\text{lbs. slurry}} \\ &= \frac{(842 \pm 8.3\%)(62.4)(1.01 \pm 0.5\%)(100)}{(101.29 \pm 0.2\%)} \\ &= 52300 \pm 9\% \end{aligned}$$

$$\text{Lb. mols H}_2\text{O/hr.} = \frac{52300 \pm 9\%}{18} = 2910 \pm 9\% = \text{L}$$

Mols of SO₂ absorbed in tower/hr.

$$\begin{aligned} &\text{gm. mols absorbed/100gms. H}_2\text{O} = 0.0335 \pm 19\% \\ &\frac{\text{gm. mols absorbed}}{\text{hr.}} = \frac{(0.0335 \pm 19\%)(454)(52300 \pm 9\%)}{100} \\ &= 7970 \pm 28\% \end{aligned}$$

Decrease in mols of SO₂/mols inerts ratio

$$\begin{aligned} &= (412 \pm 9.4\%) - (1.3 \pm 10.4\%) \\ &= 411 \pm 19.8\% = \frac{\text{gm. mols SO}_2 \text{ absorbed in tower}}{\text{gm. mol inerts}} \end{aligned}$$

Gm. mols inerts/hour

$$\begin{aligned} &= \frac{\text{mols SO}_2 \text{ absorbed}}{\text{hr.}} \times \frac{1}{\text{mols SO}_2 \text{ absorbed/mol inerts}} \\ &= \frac{7970 \pm 28\%}{411 \pm 19.8\%} = 19.4 \pm 48\% \end{aligned}$$

Lb. mols gas/hour

$$\begin{aligned} &= \frac{(\text{gm. mol inerts/hr.})(100/\text{per cent inerts})}{454} \\ &= \frac{(19.4 \pm 48\%)(100)}{(0.24 \pm 11\%)(454)} \quad (\text{inlet}) \\ &= 17.8 \pm 59\% \text{ lb. mols gas/hr. at inlet} \end{aligned}$$

$$= \frac{(19.4 \pm 48\%)(100)}{(25.2 \pm 0.5\%)(454)} \quad (\text{at outlet})$$

$$= 0.17 \pm 48\% \text{ lb. mols gas/hr at outlet.}$$

Calculation of slope at terminal points

$$L(dc) = \frac{G(dp)}{P_t} \quad \text{Gauge pressure} = 8.0 \pm 6\% \text{ \#/in.}^2$$

$$\frac{dp}{dc} = \frac{L P_t}{G}$$

At inlet: (gas)

$$\frac{L P_t}{G} = \frac{(2910 \pm 9\%)(14.7 + 8.0 \pm 6\%)(76.0)}{(17.8 \pm 59\%) 14.7}$$

$$= 0.19 \times 10^5 \pm 70\% \text{ cm. Hg(mol H}_2\text{O/mol gas)}$$

At outlet:

$$= \frac{(2910 \pm 9\%)(14.7 + 8.0 \pm 6\%)(76.0)}{(0.17 \pm 48\%) 14.7}$$

$$= 2.0 \times 10^6 \pm 59\%$$

Calculation of G', lbs. gas/hr.(ft.²)

$$\text{lb. mol gas/hr.} = 17.8 \pm 59\%$$

$$\text{wt. SO}_2 = (0.975 \pm 1.7\%)(17.8 \pm 59\%)(64) = 1112 \pm 61\%$$

$$\text{CO}_2 = (0.025 \pm 60\%)(17.8 \pm 59\%)(44) = 20 \pm 119\%$$

wt. inerts neg.

$$1132 \pm 70\%$$

$$G = \frac{1132 \pm 70\%}{25.2 \pm 1\%} = 45.4 \pm 71\% \text{ lbs. gas/hr.}$$

Calculation of CO₂ loss in tower

Decrease in mols CO₂/mol inert

$$= \frac{(26.4 \pm 64\%)}{(2.6 \pm 7.4\%)} - \frac{(41.2 \pm 3.6\%)}{(25.2 \pm 0.1\%)}$$

$$= 8.8 \pm 87\%$$

$$\text{Lb. mols inerts/hr.} = 19.4 \pm 48\%$$

$$\begin{aligned} \text{Lb. mols CO}_2 \text{ lost/hr.} &= \frac{(8.8 \pm 87\%)(19.4 \pm 48\%)}{454} \\ &= 0.4 \pm 135\% \end{aligned}$$

Calculation of $K_L a$

$$\text{Gauge Pressure} = 8.0 \text{ \#/in.}^2 \pm 0.5$$

$$\text{Total Pressure} = (14.7 \pm 8.0) = 22.7 \pm 0.5 \text{ \#/in.}^2$$

$$L = 2910 \pm 9\% \text{ lb. mols H}_2\text{O/hr.} \quad p_{\text{H}_2\text{O}} = 20 \pm 0.5 \text{ mm. Hg (5)}$$

$$(\text{Av.}) C_{\text{in}} = 0.0134 \pm 3\% \quad \text{mol SO}_2/\text{mol water}$$

$$(\text{Av.}) C_{\text{out}} = 0.0195 \pm 3.5\% \quad "$$

$$S = 25.2 \text{ sq. ft.} \pm 1\%$$

$$h = 15.9 \text{ ft.} \pm 1.6\%$$

$$Ldc = K_L a S (C_e - C) dh$$

Since the p-c diagram indicates an approximately linear operating line and since the equilibrium curve was straight, a logarithmic-mean driving force may be used, and the above equation becomes:

$$K_L a = \frac{L (C_{\text{out}} - C_{\text{in}})}{S (C_e - C)_{\text{l.m.}} (h)}$$

$$\begin{aligned} \text{Total pressure} - p_{\text{H}_2\text{O}} &= p_{\text{SO}_2} + p_{\text{CO}_2} + p_{\text{inerts}} \\ (1172 \pm 2.2\%) - (20 \pm 0.5\%) &= " \quad " \quad " \end{aligned}$$

$$1152 \pm 2.3\% \text{ mm. Hg} = p_{\text{SO}_2} + p_{\text{CO}_2} + p_{\text{inerts}}$$

$$\begin{aligned} p_{\text{SO}_2} (\text{in}) &= (1152 \pm 2.3\%) \times (\% \text{SO}_2) / 100 \\ &= (1152 \pm 2.3\%) (97.5 \pm 6.2\%) / 100 \\ &= 112.5 \pm 8.5\% \text{ cm. Hg.} \end{aligned}$$

$$\begin{aligned} p_{\text{SO}_2} (\text{out}) &= (1152 \pm 2.3\%) (33.1 \pm 10\%) / 100 \\ &= 38.2 \pm 12.3\% \text{ cm. Hg.} \end{aligned}$$

From the equilibrium curve (Fig. 4)

$$C_e (\text{out}) = 0.0445 \pm 6.8\% \text{ mol SO}_2 / \text{mol H}_2\text{O}$$

$$C_e (\text{in}) = 0.0215 \pm 6.5\% \quad "$$

$$\begin{aligned} (C_e - C)_{\text{in}} &= (0.0215 \pm 6.5\%) - (0.0134 \pm 3\%) \\ &= 0.0081 \pm 22.3\% \text{ mols SO}_2 / \text{mol H}_2\text{O} \end{aligned}$$

$$\begin{aligned} (C_e - C)_{\text{out}} &= (0.0445 \pm 6.8\%) - (0.0195 \pm 3.5\%) \\ &= 0.0250 \pm 14.8\% \text{ mols SO}_2 / \text{mol H}_2\text{O} \end{aligned}$$

$$\begin{aligned} (C_e - C)_{\text{l.m.}} &= \frac{(C_e - C)_{\text{out}} - (C_e - C)_{\text{in}}}{\ln (C_e - C)_{\text{out}} / (C_e - C)_{\text{in}}} \\ &= \frac{(0.0250 \pm 0.0037) - (0.0081 \pm 0.0018)}{\ln (0.0250 \pm 0.0037) / (0.0081 \pm 0.0018)} \\ &= \frac{0.0169}{\ln 3.09} \\ &= 0.0150 \pm 0.0026 \\ &= 0.0150 \pm 17.4\% \end{aligned}$$

Therefore:

$$\begin{aligned} K_L a &= \frac{(2910 \pm 9\%)(0.0060 \pm 6.5\%)}{(25.2 \pm 35\%)(15.9 \pm 1.6\%)(0.0150 \pm 17.4\%)} \\ &= 2.92 \pm 35\% \frac{\text{lb. mol}}{(\text{hr.})(\text{cu.ft.})(\text{lb.mol SO}_2/\text{lb. mol H}_2\text{O})} \end{aligned}$$

Slope of $K_L a$ vs. G' (lbs. gas/hr.,ft.²)

$$= 1.06$$

D. PRECISION OF MEASUREMENTS

Pipettes: 25 cc	± 0.05 cc
10 cc (Liquid sample)	± 0.1 cc
50 cc	± 0.05 cc
100 cc	± 0.1 cc
Volumetric flask: 500 cc	± 0.5 cc
Burette readings: Liquid	± 0.05 cc
Gas	± 0.1 cc
Gas analysis tube:	
Volume of caustic	± 0.5 cc
Volume of inerts	± 0.2 cc
Liquid pressure head	± 0.2 in.
Depth of lime tank	± 0.5 in.
Radius of lime tank	± 0.1 ft.
Area of tower	± 1.0 %
Height of packing	± 3.0 in.
Density of NaOH	± 0.1 %
Density of liquid sample	± 0.2 %
Density of lime slurry	± 0.5 %
Time	± 15 sec.
Temperature	± 0.5 °F
Pressure: Tower	± 0.5 #/in.
Barometric	± 1.0 mm. Hg
Weight	± 0.1 mg.

E TABLE OF NOMENCLATURE

- $K_L a$ = Over-all coefficient, lb. mol/(hr.)(ft.³) $\left(\frac{\text{mol SO}_2}{\text{mol H}_2\text{O}}\right)$
- L = Liquor rate, lb. mols water/hr.
- S = Area of tower cross section, square feet.
- h = Height of packing, feet
- C_e = Concentration of solute in liquid phase corresponding to equilibrium with gas, $\frac{\text{lb. mol SO}_2}{\text{lb. mol H}_2\text{O}}$
- C = Concentration of solute in the liquid phase, $\frac{\text{lb. mol SO}_2}{\text{lb. mol H}_2\text{O}}$
- G = Total gas rate, lb. mols/hr.
- G' = Total gas rate, lbs./hr. ft.²
- $(L/G)P_t$ = slope of operating line on p-c plot, $\frac{\text{cms. Hg.}/(\frac{\text{mol H}_2\text{O}}{\text{mol gas}})}$
- dN = mols gas transferred/(hr.)(ft.²)
- P_t = Total pressure, cms. Hg.
- p = Partial pressure
- ρ = Density, lb. solution/cu. ft.

F LOCATION OF ORIGINAL DATA

Data book #161	pages 138 to 160
Data book #165	" 151 to 155
Data book #169	" 145 to 156
Data book #184	" 75 to 112

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