THE LEACHING OF MANGANESE ORE WITH SULFUR DIOXIDE

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INTRODUCTION

The steel industry is one of the largest in the United States. Most of the world's manganese is used directly or indirectly in the production of steel. Most of the manganese ore found in the United States is of a low grade. (2)

This study was made in connection with a project of The Tennessee Valley Authority for the development of a more efficient method of producing manganese from the low grade ore found in the Tennessee Valley.

The work was done in order to find a better means of leaching the manganese ore with sulfur dioxide gas, for up to the present time, no very satisfactory means of extracting manganese from the ore has been found, due to the fact that manganese dithionate, a very corrosive compound, is usually formed in the reaction with sulfur dioxide. (3)

GENERAL SURVEY OF THE FIELD

History

"The metallurgy of manganese has developed along the lines of iron metallurgy." (4) Low-grade ore has come in for consideration only since 1914, when the foreign supply of high-grade ore to the United States was cut off. "Two types of processes received the most consideration. First, hydrometallurgical processes to produce a concentrate which could be smelted like the higher-grade ore; and, second, processes involving concentration of the manganese from manganiferous iron ores by preferential reduction of the iron." (4)

Early in 1918 the Bureau of Mines started an investigation of possible methods of recovering manganese from the low-grade ores of the Southwest. In May, 1918, leaching tests were made on an ore, and fairly good results were obtained. Plans were in progress for further investigation and for the erection of a 250 ton plant when the economic situation as regards manganese was entirely changed by the Armistice, and further investigation was abandoned. (3)

Present State of the Science

The information in the following section is taken from the U.S. Bureau of Mines, Information Circular 6770. See Bibliography. Many methods have been proposed and investigated, but few have had much commercial value. There are, however, some fairly good methods that have been used for the past decade. All of these make use of the affinity that manganese has for sulfur,

either directly or indirectly.

The usual solvent method that has been used is that in which sulfurous acid is used as the solvent. This method, due to its limited range, can only be used on certain types of ore. The differences in the physical and chemical properties of the ores cause the results to vary greatly.

The Bradley process is used almost exclusively on the ore found in the Lake Superior region, and is the most prominent method used in Minnesota. This method uses ammonia gas for leaching purposes and is primarily intended for leaching siliceous manganese iron ores, but it can be adapted for the higher oxides of manganese. Manganese sulfate and ammonia are formed from the reaction of ammonium sulfate and manganese dioxide. The manganese sulfate is then met by a countercurrent flow of the ammonia gas, and manganese hydroxide and ammonium sulfate are formed. The latter is cleansed and reused.

The Sweet process is the most important used in Michigan. The process calls for the roasting of carbonate or lime ores with ammonium sulfate. However, if the treatment of low-lime or relatively high manganese ores is required, sulfuric acid is used instead of ammonium sulfate. The most stressed point of the process is that the roasting temperature must be higher than the decomposition point of iron sulfate.

One of the most important processes advocated for use is the Leaver Drum-Leaching Process.

The carbonate of manganese is made soluble in sulfurous acid, and the silicate is made insoluble by roasting. " Hot sulfurous acid is formed by introducing hot furnace gas containing two to six

percent sulfur dioxide (by volume) countercurrent to a pulp flow having a consistency of two of water and one of ore crushed to about twenty mesh." (4)

A double-drum system is best. The pulp enters one end of the drum, and the hot waste furnace gas containing the sulfur dioxide enters the opposite end. Intimate mixing during the countercurrent flow results in the pulp becoming progressively warmer until it leaves at about forty-five degrees centigrade, at which temperature it retains practically no free sulfur dioxide gas. All of the dissolved manganese is in the form of the sulfate when the pulp flows from the drum.

"By the use of tandem drums the iron and phosphorous that dissolved in removing virtually all the manganese during treatment in the second drum will be precipitated on returning this solution to the new charge in the first drum. This is explained by the changed condition in the operation. The advanced solution is used to pulp fresh manganese ore and immediately loses its slight acidity in dissolving manganese. In this neutral solution, the remaining large excess of undissolved manganese, having a greater affinity for the sulfate iron, readily replaces the iron and phosphorous. The precipitated iron and phosphorous become part of the residual ore flowing through the circuit." (4)

The almost saturated manganese sulfate passes through a filter press to remove partly leached ore which is sent back to the drums. The filtrate is then evaporated and crystallized. The sulfate is roasted by direct flame in a rotary type clinker furnace. Waste heat from the furnace is used in the above evaporation and crystallization. The product averages from 60 to 64 percent manganese. (4)

The American Manganese Products Co. in Redwood City, California, uses the Westling nitrate process. The oxidized manganese ores, after fine grinding, are agitated in tanks while the pulp is digested with sulfur dioxide gas and some air to produce sulfates. The coarse particles settle out, and the iron and other impurities are precipitated out by the use of powdered calcium carbonate. The calcium sulfate, formed in the preceding reaction, precipitates out when calcium nitrate is added and the solution heated in open pans. The calcium sulfate is removed by an Oliver filter. The manganese nitrate solution is heated under pressure and changes to manganese dioxide and nitrous gases, the latter being reclaimed for future use. The product, manganese dioxide, is of chemical grade, but does not find a ready market.

There are several processes which have been proposed by the U.S. Bureau of Mines. The three main ones all use calcination in order to get the final product. They differ in the initial and intermediate steps, however. (4)

The first of the proposed processes uses waste smelter gas (SO_2) to get manganese sulfate. This solution is precipitated with ammonia plus air giving manganese hydroxide and ammonium sulfate. The hydroxide is filtered out, and the filtrate is boiled with calcium oxide to expel the ammonia which is reclaimed for reuse. The calcium sulfate is discarded. The manganese hydroxide is calcined to obtain Mn_xO_y.

The next suggested method calls for the dissolution of the ore with sulfur dioxide to obtain manganese sulfate. Calcium chloride is added forming manganese chloride and calcium sulfate, the latter being filtered out. Calcium hydroxide is added to the filtrate and

agitated with air to precipitate the oxides of manganese and to regenerate calcium chloride for reuse. The manganese precipitate is calcined to give the product.

The third method proposes that the manganese minerals be reduced to manganese oxide by roasting with producer gas. The product of this reaction is leached with sulfur dioxide out of the presence of air or oxygen to obtain manganese as the sulfite. The pregnant solution is heated to expel the sulfur dioxide and to precipitate the manganese as sulfite or hydroxide. The sulfur dioxide is reused and the product is calcined to give the final result.

Although many different methods have been studied and developed in the United States for the extraction of manganese from low grade ores, none of these methods have proven very economical. Due to low tariff rates on imported high grade ores there is very little demand for the more expensive product made from the low grade ores of this country.

The research that has been made in the past or that will be made in the future is not wasted, for in case the manganese imports should be cut off, the United States would not be dependent on any other nation for its supply. If tariff rates on manganese were suddenly increased, or war was declared, the best methods as suggested by research could be easily made to give the country its necessary manganese.

Uses

A pproximately ninety-five percent of the world's supply of manganese is used in the production of steel. "Usually it is added to the steel in the form of spiegeleisen or ferromanganese. Spiegel-

eisen is a white iron with four to five percent carbon, five to twenty percent manganese, and is low in sulfur and phosphorous. The twenty percent product is considered standard. Ferromanganese is a white granular iron containing twenty-five to eighty-five percent manganese with the carbon increasing with the manganese. The standard alloy is eighty percent manganese." (2)

Besides its use in the steel industry, manganese is used for the textile industry, the manufacture of electric batteries, glass, pottery, tile, brick, paint, ink, and fertilizers. (4)

GENERAL THEORY

The main point in the theoretical discussion of the leaching of manganese ores with sulfur dioxide is the affinity of manganese for sulfur. The sulfates, sulfites, and other sulfur compounds are some of the easiest to form from the manganese ore. Upon the affinity of manganese for sulfur the theory for the entire problem is built. Most of the near-successful methods of the past and those under investigation at the present time make use of the fact that manganese combines with sulfur very easily.

The two types of ore processing that have received the most consideration are: (1) processes involving concentration of the manganese from manganiferous iron ores by preferential reduction of the iron, and (2) hydrometallurgical methods. The latter type is by far the most important.

"The hydrometallurgical methods present a difficult problem in comparison with the usual leaching processes for the recovery of precious metals or even with the process of leaching one percent copper. The high cost of dissolving the mineral manganese and the ease with which its solutions can be purified favor the preparation of a high grade product." (4)

There are five general types of ores. First, ores in whihh the manganese mineral is soluble in at least one solvent; second, a type for which preliminary treatment must be given to make the manganese soluble; third, the manganese is in an entirely insoluble form; fourth, ores which destroy excessive amounts of solution due to certain soluble impurities; and fifth, ores having certain physical properties which increase cost of treatment. The tests in this study were made using an ore of the first type.

Object

The object of this thesis is to find a more successful method for the leaching of low-grade manganese ore with sulfur dioxide, trying to determine the essential factors governing the leaching and the formation of manganese dithionate.

Ore Used

Only one ore was used. This came from Valley Forge Mine in Upper East Tennessee.

The chemical analysis of this ore is

Mn	30.00%
CaO	trace
Fe	14.93%
P	0.43%
Insoluble	16.43%
Ignition loss	11.52%

The screen analysis was made on a Ro-Tap machine, using Tyler Standard screens. The analysis is as follows:

left on (mesh)	grams
65	7
80	10
100	33
150	66
200	61
Less 200	118
	295

PROCEDURE

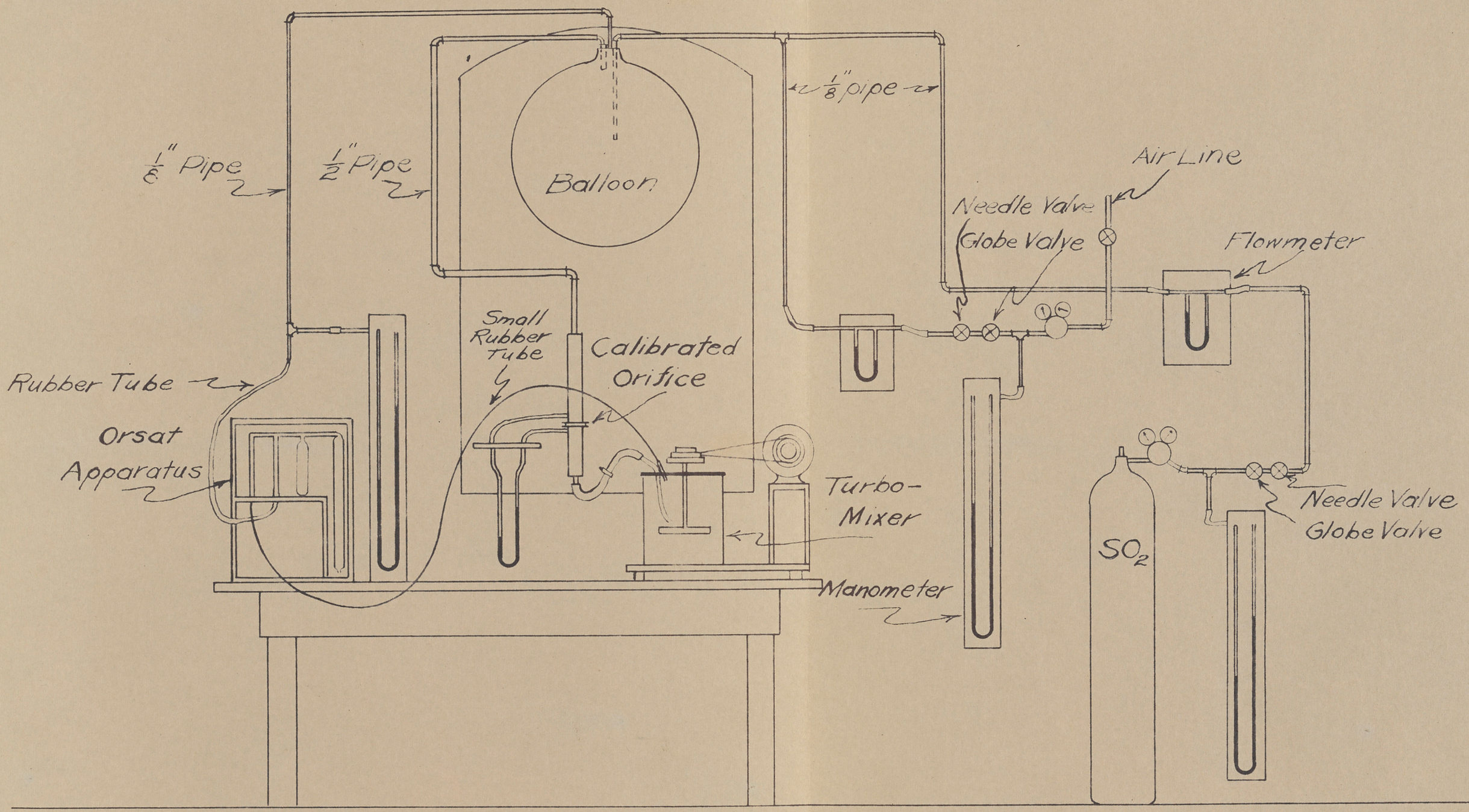
At the start of each run 680 grams of thirty percent manganese ore and five liters of water were placed in the glass container of a small laboratory turbo-mixer. The impeller was placed in the mixture, and the lid was clamped on securely. The motor was started and the thorough agitation of the mixture begun.

The sulfur dioxide and air were each allowed to flow into the balloon through their respective flowmeters and lines. After the balloon was filled and the needle valves on the air and sulfur dioxide lines were adjusted, the gas mixture was allowed to flow through a calibrated orifice into the mixer. From this point on, data were recorded. The temperatures of the gas mixture and of the suspension in the mixer were read at regular intervals. Barometric pressure and room temperature were recorded at the start of each run.

Approximately every five minutes a sample of gas from the balloon was analysed by means of the Orsat apparatus. Samples of gas leaving the mixer were also analysed at regular intervals by means of the Orsat. At intervals of from five to ten minutes samples of the suspension were withdrawn for future analysis. Each continued until the suspension became a light brown color, and the temperature of the suspension became fairly constant, both indicating complete leaching. The analysis of the exit gas from the mixer also was an indication of the completion of the reaction.

Run #15 was the only run at constant temperature. This was done because some information was wanted to show how leaching

Apparatus For Leaching Manganese Ore with SO_2



proceeded when there was no temperature rise. The suspension was first heated by an electric coil completely immersed in the suspension. The temperature was held as near constant as possible by controlling the heat input with a rheostat.

CRANES
VANESE LINEN
MADE IN U.S.A.

DISCUSSION OF METHOD

There were several reasons for selecting the method used. A method was wanted which would determine the optimum mixture of sulfur dioxide and air as a leaching agent, and to mix this gas completely with the suspended ore. The mixer chosen did this very well. The reason that this method was chosen over other methods which might accomplish the same results was that the apparatus was comparatively easy to set up.

Difficulties

The main object was to keep the ore in suspension, and at the same time, to feed to it a steady flow of well mixed gas. The first presented no difficulty because the mixer chosen was a good one. The difficulty which presented itself most was the problem of providing well mixed gas at a constant composition under a practically constant pressure.

On each of the inlet lines of air and sulfur dioxide there were two valves, one a needle valve to give good regulation, the other a globe valve so that the supply could be completely cut off without changing the setting of the needle valve. This allowed the flow of gas to be cut off and then turned on again, getting the same composition of gas.

Since the gas was allowed to enter at the rate at which it was absorbed, it was not possible to get the exact amount of gas needed. To overcome this, a large balloon, was inserted in the intake line between the mixing point and the flow meter. A supply of gas was

collected in the balloon before the start of the run, which would carry the run if more gas was used than had been allowed for in the setting of the valves. The balloon also put an almost constant pressure on the line. An accurately calibrated flowmeter with a differential manometer was used to determine the amount of gas entering the mixer.

Theoretical Considerations

A few theoretical considerations which were not covered in the general theory, and are peculiar to these tests will be taken up in the following.

A delicate, differential flowmeter was used to determine the volume of gas which was used in each run; about this most of the technicalities arose. When taking an average reading for each run, the general average was used if the variation was less than ten percent, but if the readings varied more than ten percent, the average of the square roots of each reading was taken, and the square of this average was used for calculating the velocity.

To calculate the velocity of the gas in from the flowmeter readings the following formula was used:

$$u = C_o \sqrt{2g\Delta H}$$

where u is the velocity in centimeters per second, g is acceleration due to gravity, ΔH is the flowmeter reading, and C_o is an orifice constant as seen below:

Orifice 1. C_o .72 diameter .24 cm

Orifice 2. C_o .68 diameter .40 cm

Orifice 3. C_o .65 diameter 1.48 cm

These orifice coefficients were previously determined and

the differential manometer on the flow meter was calibrated by R. H. Beck.

Sources of Error

The composition of both gases entering and leaving is not at all accurate. The flow meters on the entering sulfur dioxide and air gave only an approximation of amounts of sulfur dioxide and air coming in and were used mainly in that it was possible to know how much to change the flow of one of the constituents in altering the composition as read from the Orsat.

The readings from the Orsat are taken as correct, but where the composition of the gas changed during a run the averages are probably not exact because each reading on the Orsat apparatus took too much time to get a sufficient number of readings.

Exactly five liters of water and 680 grams of sample ore were introduced into each run. Since there was a continual flow of gas through the liquid and because the temperature rose to a fairly high point, there was some evaporation. The volume of the liquid remaining should have been ascertained, but this was not done. This caused some error, since the final analyses were made on a percentage basis and the total amount of manganese in the final solution could not be definitely determined.

Samples of between 25 and 50 cc were taken during each run, usually about five to the run. This would cause a large change in the volume, but since some of the manganese was taken out in each sample this error is not as large as it might seem.

METHOD OF CALCULATION

Grams of manganese in solution per liter

Given in chemical analysis.

Percent of manganese extracted

$$\frac{\text{gm. Mn/L} \times 5}{\text{gm. ore in} \times \text{Mn in ore}} \qquad \frac{31.5 \times 5}{680 \times .30} = 77.20\%$$

Percent Manganese extracted as manganese dithionate

Given in chemical analysis

Percent manganese extracted as manganese sulfate

100% - percent extracted as manganese dithionate

100 - 5.98 = 94.02

Temperature rise of solution per gram mol of reaction

$$\frac{\text{Temp. rise of sol.} \times \text{molecular weight of manganese}}{\text{gm of manganese in sol per liter} \times \text{no. of liters}}$$

$$\frac{100 \times 54.93}{31.5 \times 5}$$

Percent of sulfur dioxide in inlet gas

Found experimentally. In original data.

Percent of air in inlet gas

100% - percent of SO_2 in

Percent of oxygen in inlet gas

percent air in x .21

Percent of nitrogen in inlet gas

percent air in x .79

Rate of flow of sulfur dioxide in, in grams per minute

$$\frac{\text{vol. gas in} \times \text{to std. conditions} \times \%\ SO_2 \text{ in} \times \text{den.} SO_2}{\text{length of run in minutes}}$$

$$\frac{472 \times 29.22 \times 492 \times .217 \times 2.93}{29.92 \times 542}$$

Percent of sulfur dioxide in exit gas

Found experimentally. In original data.

Grams of sulfur dioxide as manganese sulfate

$$\frac{\%\ Mn\ extracted \times \%\ Mn\ as\ MnSO_4 \times gm\ Mn\ in\ sample \times MW\ SO_2}{mol\ weight\ of\ Mn}$$

$$\frac{0.772 \times 0.9402 \times 204 \times 64}{54.93} = 173.5$$

Grams of sulfur dioxide as manganese dithionate

$$\frac{\%\ Mn\ ext. \times \%\ Mn\ as\ MnS_2O_6 \times gm\ Mn\ in\ sample \times MW.\ SO_2}{mol\ weight\ of\ Mn}$$

$$\frac{0.772 \times 0.0598 \times 204 \times 64}{54.93} = 11.0$$

Grams of sulfur dioxide absorbed

$gm\ SO_2$ as $MnSO_4$ + $gm\ SO_2$ as MnS_2O_6

$173.5 + 11 = 184.5$

Percent of sulfur dioxide reacting

$$\frac{(gm\ SO_2\ as\ MnSO_4\ \ gm\ SO_2\ as\ MnS_2O_6) \times 100}{gm\ SO_2\ in}$$

$$\frac{184.5 \times 100}{260} = 71.0$$

Density, in grams of air in one liter of mixture

percent air per liter x std cond. x den.air

$$\frac{783 \times 29.22 \times 492 \times 1.294}{29.92 \times 535} = 0.912$$

Density of sulfur dioxide, grams per liter

percent SO_2 per liter x std. cond. x density SO_2

$$\frac{217 \times 29.22 \times 492 \times 2.9266}{29.92 \times 535} = 0.571$$

Density of mixture, grams per liter

Density of air+density of SO_2

$0.912 + 0.571 = 1.483$

ΔH (in orifice formula)

$$\frac{(\text{average sq. root flow meter reading})^2(\text{flow meter constant})}{\text{density of mixture} \quad \text{gm per cc}}$$

$$\frac{(3.02)^2(.2759)}{0.00148} = 1725$$

u (velocity in centimeters per second)

$u = C_o \sqrt{2g\Delta H}$ (see detailed theory)

$0.68 \sqrt{2 \times 980 \times 1725}$

Volume of gas in

$$\frac{\text{length of run} \times 60 \times \text{velocity} \times \text{area of orifice opening}}{1000}$$

$$\frac{50 \times 60 \times 1250 \times 0.1255}{1000} = 472$$

Rotor speed, revolutions per minute

Taken with tachometer for original data

COMBINED DATA AND RESULTS

The following tables show the averages of the original data and the calculated results.

TABLE I

Run #	Gm. Mn. in sol. per liter	% Mn. extracted	% Mn. extracted as dithio.	% Mn. extracted as $MnSO_4$	Temp. rise of solution /gm.mol. of reaction
1	31.50	77.20	5.98	94.02	34.70
2	12.32	30.20	4.13	95.87	77.60
3	34.30	84.00	11.24	88.76	32.30
4	38.20	96.00	86.10	13.90	24.70
5	37.55	92.00	49.10	50.90	26.30
6	37.95	93.00	70.90	29.10	25.60
7	37.64	92.30	99.90	00.10	25.30
8	37.40	91.60	---	100.00	24.65
9	27.10	66.40	11.22	88.78	35.00
10	26.80	65.70	9.85	90.15	31.20
11	37.60	92.10	17.20	82.80	26.40
12	32.10	78.60	29.00	71.00	27.40
13	31.85	78.00	12.68	87.32	30.00
14	24.60	60.30	7.28	92.72	43.50
15	22.22	54.50	6.79	93.21	---

TABLE II

Run #	Inlet gas comp. % Air			Rate of flow of SO_2 gm./min.	% SO_2 Exit gas
	% SO_2	% O_2	% N_2		
1	21.7	16.44	61.86	5.20	1.44
2	7.2	19.50	73.30	2.95	0.50
3	16.3	17.58	66.12	6.40	1.62
4	100.0	0.00	0.00	16.30	18.04
5	49.2	10.68	40.12	46.00	13.70
6	59.5	8.51	31.99	124.30	21.05
7	79.4	4.33	16.27	113.00	18.20
8	37.0	13.23	49.77	70.00	13.06
9	10.8	18.74	70.46	20.80	2.11
10	10.4	18.80	70.80	20.30	3.55
11	10.4	18.80	70.80	20.50	3.22
12	10.4	18.80	70.80	20.00	4.74
13	9.8	18.95	71.25	24.70	2.91
14	10.2	18.88	70.92	22.60	1.26
15	10.0	18.90	71.10	20.20	6.51

TABLE III

Run #	gm. SO_2 as $MnSO_4$	gm. SO_2 as MnS_2O_6	gm. SO_2 absorbed	gm. SO_2 in	% SO_2 reacting
1	173.5	11.0	184.5	260	71.0
2	68.9	2.9	71.8	278	25.9
3	177.5	22.5	200.0	332	60.2
4	31.8	197.0	228.8	570	43.1
5	111.5	107.5	219.0	1152	19.0
6	64.5	157.0	221.5	1370	16.1
7	0.2	220.0	220.2	2040	10.8
8	218.0	---	218.0	1400	15.6
9	140.0	17.8	157.8	1040	15.2
10	141.0	15.4	156.4	1228	12.7
11	181.0	37.7	218.7	1332	16.5
12	132.8	54.2	187.0	1260	14.9
13	162.5	23.5	186.0	1285	14.5
14	133.5	10.5	144.0	903	15.9
15	121.2	8.8	130.0	1090	11.9

TABLE IV

Run #	Density-gm. of air in 1 lit. of mix.	Density-gm. SO_2 in 1 lit. of mix.	Density-gm. of mix. per lit.
1	0.912	0.571	1.483
2	1.072	0.187	1.259
3	0.974	0.428	1.402
4	----	2.638	2.638
5	0.589	1.290	1.879
6	0.470	1.562	2.032
7	0.240	2.093	2.333
8	0.742	0.986	1.428
9	1.045	0.286	1.331
10	1.056	0.275	1.341
11	1.083	0.284	1.367
12	1.072	0.283	1.355
13	1.065	0.262	1.327
14	1.062	0.273	1.335
15	1.062	0.267	1.329

TABLE V

Run #	ΔH	u (cm./sec.)	Volume (liters)	Rotor speed (r.p.m.)
1	1725	1250	472	1220
2	4350	1980	1405	1220
3	4480	2010	790	1220
4	765	837	221	1220
5	151	354	912	1220
6	751	790	896	1220
7	352	540	1000	1220
8	588	698	1440	1220
9	609	710	3650	1220
10	620	719	4475	1060
11	612	712	4780	900
12	640	730	4510	675
13	1000	910	4880	1410
14	774	800	3300	1540
15	641	730	4070	1220

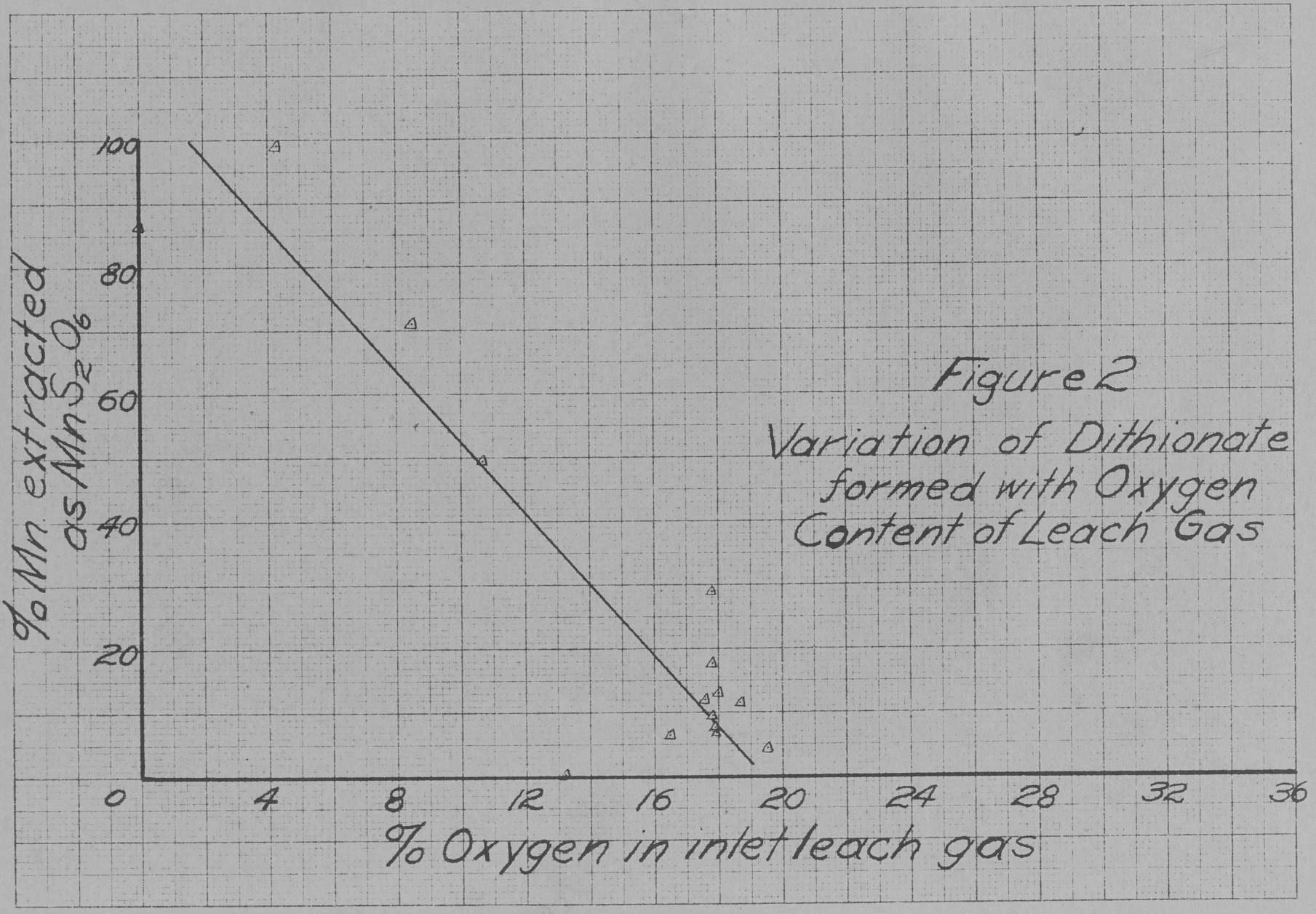


Figure 2
Variation of Dithionate formed with Oxygen Content of Leach Gas

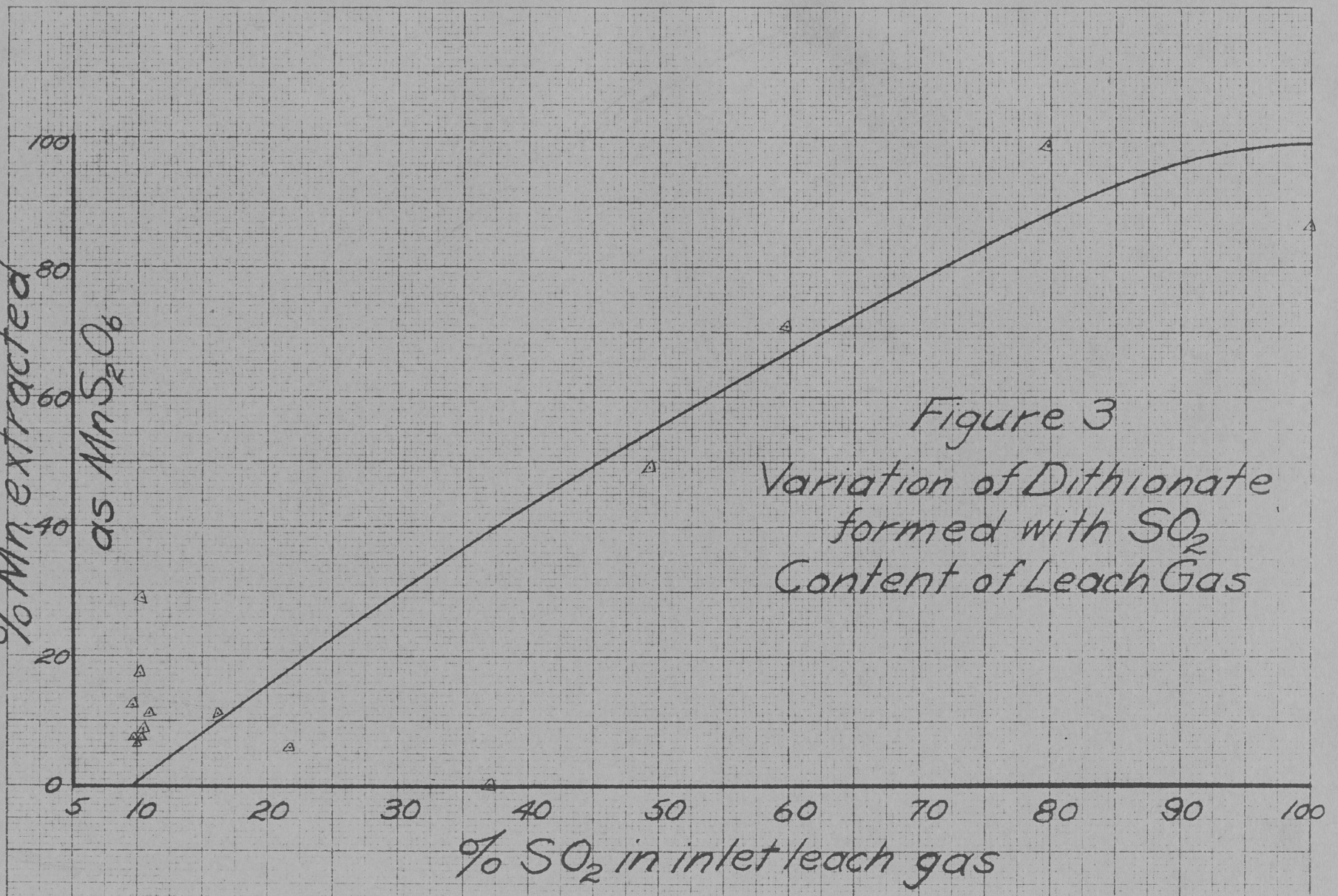


Figure 3
Variation of Dithionate formed with SO_2 Content of Leach Gas

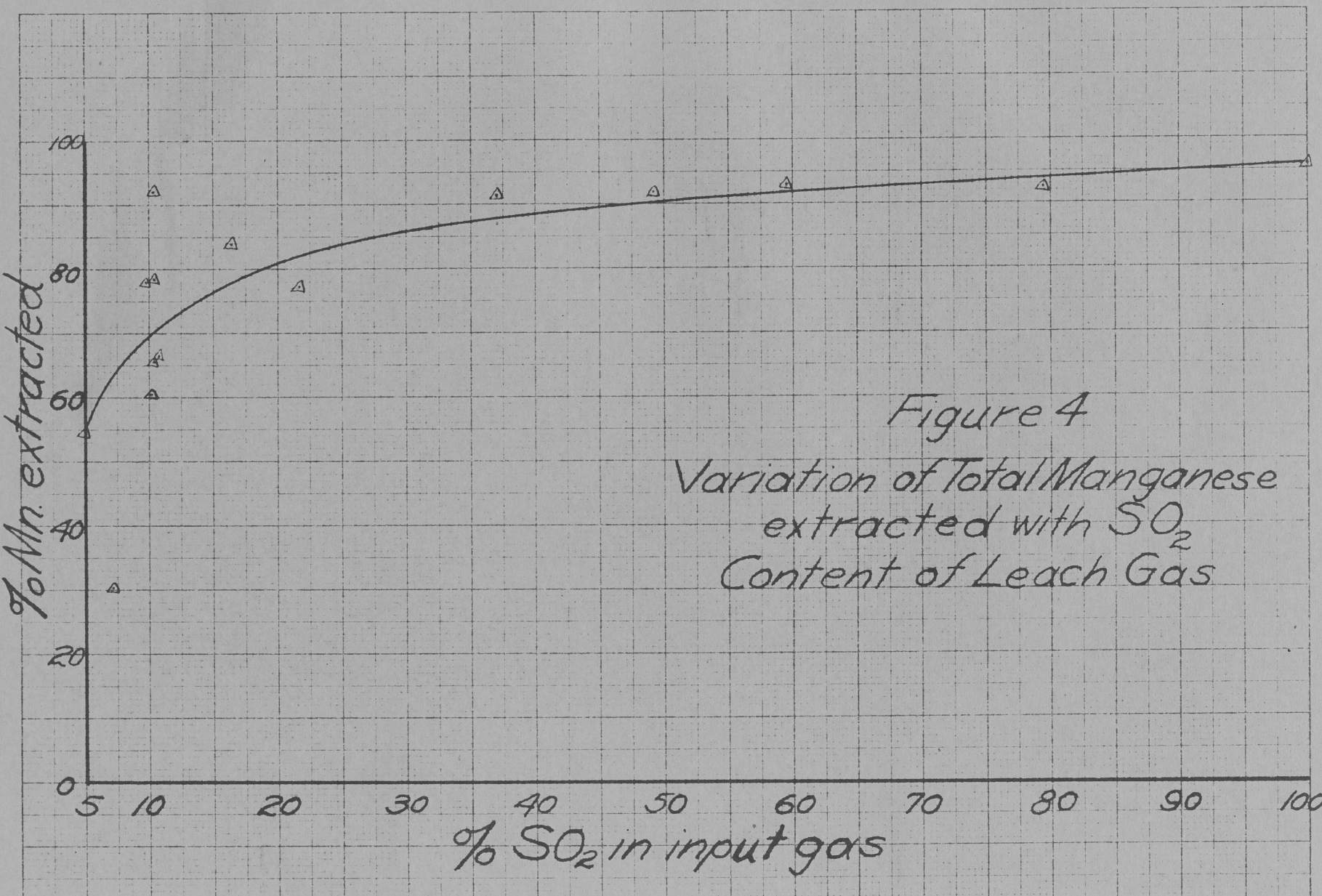


Figure 4
Variation of Total Manganese extracted with SO_2 Content of Leach Gas

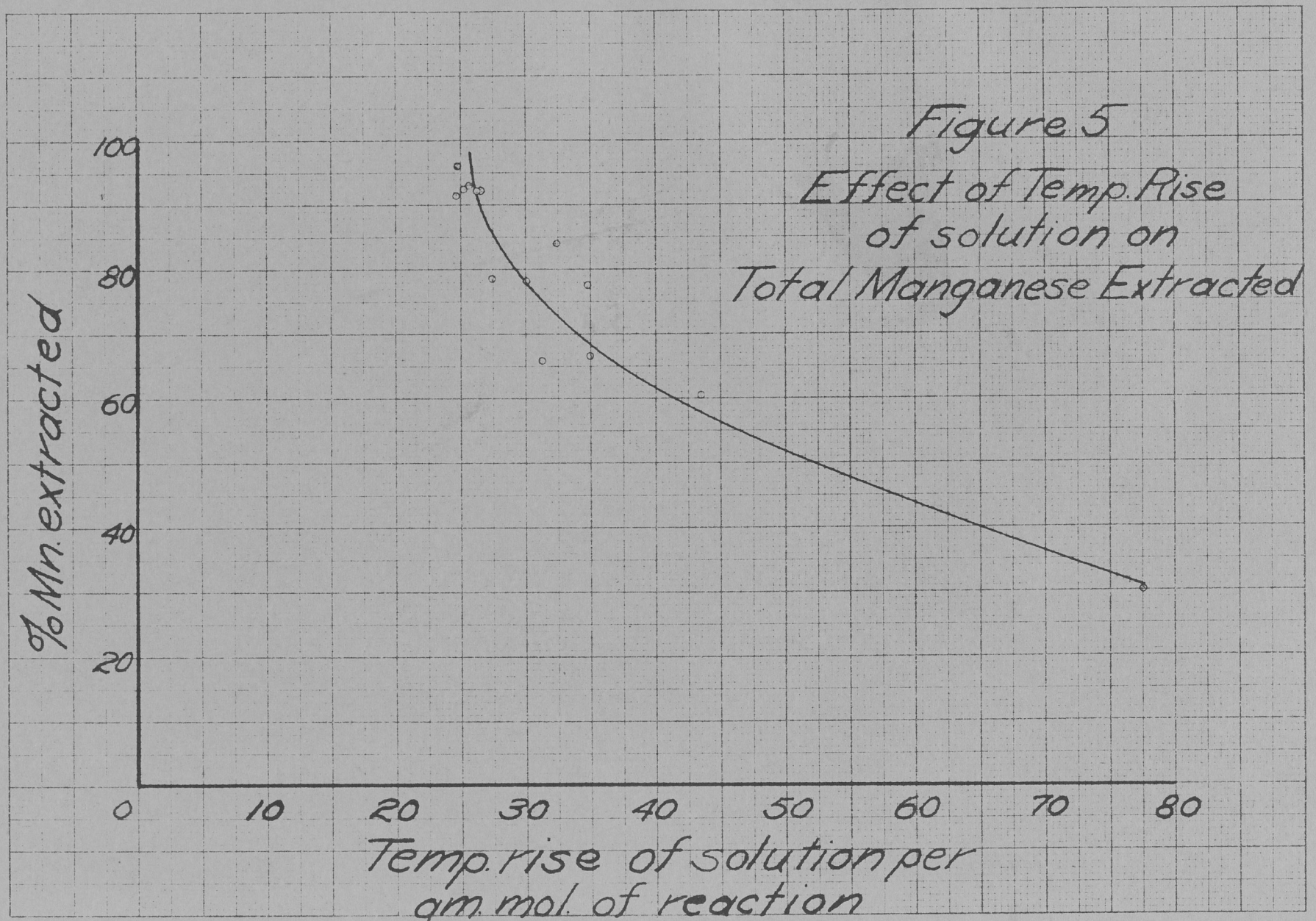


Figure 5
Effect of Temp. Rise
of solution on
Total Manganese Extracted
% Mn. extracted
100
80
60
40
20
0
10
20
30
40
50
60
70
80
Temp. rise of solution per
gm. mol. of reaction

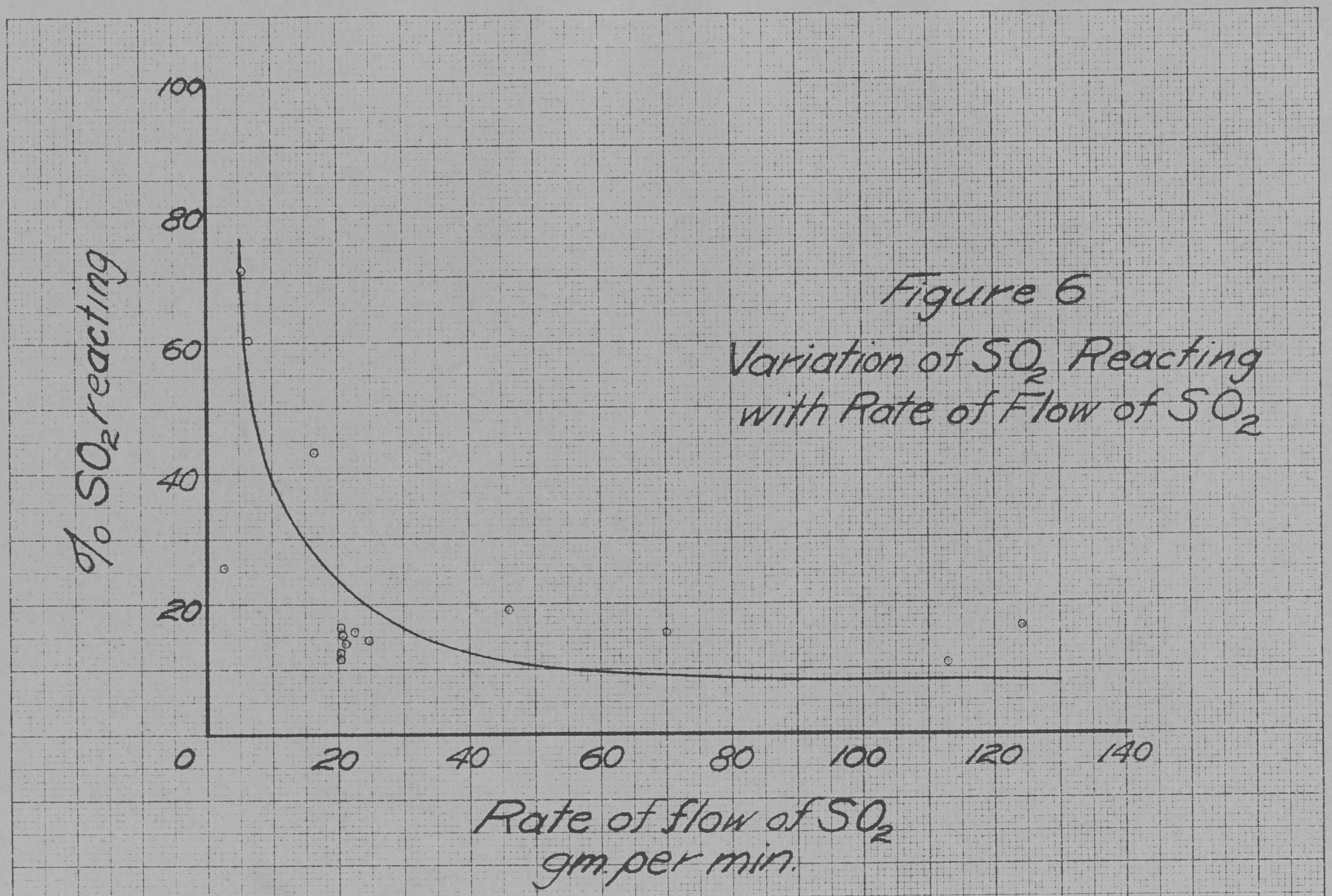


Figure 6
Variation of SO_2 Reacting with Rate of Flow of SO_2

DISCUSSION OF RESULTS

There is one important observation that justifies all of the work. This is that the percentage of manganese which is extracted as manganese dithionate (MnS_2O_6) decreases from 100 to 6% as the percentage of oxygen in the leaching gas increases from 0 to 18%. Since manganese dithionate is very corrosive, the percentage in the extracted solution becomes very important in designing the apparatus to convert the extracted manganese into a form which can be used commercially. Also the percent of manganese dithionate increases from 6 to 100% as the percent of sulfur dioxide in the leaching gas increases from 7 to 100%, which is a check on the assumption that the waste gas from smelters with a low percent of sulfur dioxide could be used commercially as a leaching agent, provided that the oxygen content is high. See Figures 2 and 3. Although the total percent of manganese extracted increases from 30 to 96% with the increase of sulfur dioxide content in the leaching gas from 7 to 100%, as shown by Figure 4, it is known that part of the total manganese extracted is made up of the detrimental dithionate.

Figure 5 shows that the percent of manganese extracted increases from 30 to 96% with the decrease of the temperature rise of the solution per gram mol of reaction from 77.5 to 25%, and it is suggested that a higher percent of manganese extraction could be obtained by keeping the temperature of the solution constant.

No conclusive results were obtained concerning the amount of manganese extracted with various rotor speeds. The only conclusion

drawn is that a rotor speed sufficient to keep the ore in suspension is necessary.

From Figure 6 it is seen that the percent of sulfur dioxide reacting decreased from 71 to 11% as the rate of flow of sulfur dioxide into the mixer increased from 3 to 124 grams per minute. It is concluded from this that if the sulfur dioxide comes in too fast, part of it is wasted, since it does not have time to react.

Conclusions

1. This study shows that manganese ore, containing approximately thirty percent manganese, can be leached successfully with a gas containing a low percent of sulfur dioxide and a high percent of oxygen.

2. The percent manganese as dithionate increases as percent oxygen in the leach gas decreases and the percent sulfur dioxide increases.

3. Total manganese extracted increases with the decrease in temperature rise of the solution.

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APPENDIX

The appendix contains the data as originally taken.

RUN #1

Bar. Press.
29.22 in. Hg.
at 82° F.

Orifice
#2

(min.) Time	%SO_2 in	%SO_2 leaving	CM. H_2O Man. Read. Bal. press.	CM. Hg. Man. Read. flow meter	Gas Temp.	Samp. Out	Temp. sol.
2:10	23.5	0.5			75		78
4:30							86
6:30						1	
8:55							97
9;05	21.5		8.1				
11:50							107
13:45							113
15:00				8 to 10			120
17:10							123
18:15						2	
19:15		0.0					130
22:20							137
24:20	21.1						140
27:10							144
28:00						3	
30:30		2.0					150
34:00				10 to 11			156
37:00		1.8		8			
37:15							162
38:00						4	
40:15							163
43:00	20.9						166
44:00							
45:00							171
48:40						5	172
50:00							176

RUN #2

Bar. press.
29,065 in. Hg. at 82° F

Orifice #2

Time (min.)	%SO_2 in	%SO_2 leaving	cm.water Man. Read. ball. press.	cm.Hg. Man. Read. flowmeter	Gas Temp.	Sample Out	Temp. of sol.
00:00	7.7		8.5	18.4	75		69
04:00				18.4			75
05:00				25.0			
06:00		1.3		24.8			
15:00		0.5		22.6		6	93
20:30	7.2			22.8			100
25:40		0.3		23.5			106
30:00				23.6	75	7	111
32:00	8.1		8.0				
38:15		0.2	7.7	22.8			120
41:25				23.0		8	123
42:50	7.6			23.6			126
48:00		0.4		24.3			130
50:30				24.6		9	133
51:50	7.7		8.0	24.6			134
56:15		0.2		24.8			138
60:00				24.8		10	141
61:00	7.7						142
65:00		0.5	7.7	25.2			144
68:00				21.0			
70:00	7.6			20.8		11	147
74:45		0.2		21.0			149
76:00			8.7	15.0			
80:00	8.0		8.7	16.0		12	151
83:00	10.0			16.0			152
83:30				11.8			
85:00				9.5	78		
87:00				7.9			
89:00				6.5			156
92:00				4.6			156
94:00							

RUN #3

Bar. press.
29.065 in. Hg. -82°F

Orifice #2

Time (min.)	%SO_2 in	%SO_2 leaving	cm. water Man. Read. ball. press.	cm. Hg. Man. Read. flowmeter	Gas Temp.	Sample Out	Temp. of sol.
0	15.5	0.5	8.3	26.0	72		66
2				25.5			70
7	16.6		8.3	25.0			80
13		0.2	8.3	25.0			96
15				25.0	72	13	100
18	16.9			24.8			108
23		0.4	7.6	22.8			120
25				22.4		14	125
30			7.9	24.0			137
35			8.0	24.0		15	146
37	15.5		8.0	24.4			150
42		2.0		24.0			159
45				24.0	71	16	163
47	16.8		7.8	20.0			165
50				14.5			166
52		5.0	7.8	14.0		17	167

RUN #4

Bar. press.
29.08 in. Hg.
at 84° F

Orifice #2

Time (min.)	$\%SO_2$ in	$\%SO_2$ leaving	cm. water Man. Read. ball. press.	cm. Hg. Man. Read. flowmeter	Gas Temp.	Sample out	Temp. of sol.
1:00	100	0.2	8.2	9.2	74		72
5:30				8.8		18	96
6:30		1.1	8.4				100
11:00				8.8		19	116
12:00		1.3	8.4	9.0	71		120
15:00			8.6	9.0		20	132
16:00		1.5	8.6	9.2			135
20:00		5.5	9.5	7.0	70	21	150
25:00		19.8	10.5	7.0	70	22	160
30:30			6.0	3.5		23	161
35:00		96.9		3.0	70	24	160

RUN #5

Bar. press.
29.08 in. Hg. 84° F

Orifice #3

Time (min.)	$\%SO_2$ in	$\%SO_2$ leaving	cm. water Man. Read. ball. press.	cm. Hg. Man. Read. flowmeter	Gas Temp.	Sample out	Temp. of Sol.
2:00		9.5	8.5	4.8	76		78
5:00			9.0	6.0		25	119
6:00	51.2			1.0			122
8:00			1.5	1.0		26	128
10:00		1.6		1.0			136
11:00			1.5	1.0	74	27	140
12:00	49.9			0.8			143
14:00				0.8		28	150
16:00		1.9	1.4	0.8			156
19:00			1.0	0.6		29	161
20:00	46.4		1.0	0.6			162
22:00		19.9		0.8		30	166
25:00		35.6	1.0	1.0		31	168

RUN #6

Bar. press.
29.08 in. Hg. 84° F

Orifice #3

Time (min.)	$\%SO_2$ in	$\%SO_2$ leaving	cm. water Man. Read. ball. press.	cm. Hg. Man. Read. flowmeter	Gas Temp.	Sample out	Temp. of sol.
0	58.0	8.4	8.9	6.0	74		72
1:30			8.9	6.0			94
2:30			9.0	6.0		32	106
5:00	61.1		9.2	6.1	74	33	132
7:30		33.7	10.6	7.0		34	158
9:00				4.0			160
11:00			8.1	4.0		35	161

RUN #7

Bar. press.
29.08 in. Hg. at 84° F

Orifice #3

Time (min.)	$\%SO_2$ in	$\%SO_2$ leaving	cm. water Man. Read. ball. press.	cm. Hg. Man. Read. flowmeter	Gas Temp.	Sample out	Temp. of sol.
0:00	80.1		8.5	4.0	72		72
1:00		11.7	8.5	4.0			82
3:00			8.6	4.0		36	100
5:20	79.1		8.7	4.0			126
6:00				3.0			138
7:00			9.0	3.0		37	148
10:00		24.7	5.0	1.5		38	156
12:00			4.2	1.4		39	160
14:30	79.0		4.0	1.4			159
18:00			4.0	1.4			

RUN #8

Bar. press.
29.42 in. Hg.
at 78° F

Orifice #3

Time (min.)	$\%SO_2$ in	$\%SO_2$ leaving	cm. water Man. Read. ball. press.	cm. Hg. Man. Read. flowmeter	Gas Temp.	Sample out	Temp. of sol.
0	36.6		8.2	2.8	72		78
2		0.2					92
6	37.3		8.0	2.8		40	108
10			8.0	3.0		41	132
11:30		5.2	8.0	3.0	72		145
14			8.0	3.0		42	154
15	37.2		8.0	3.0			160
17			8.0	3.0		43	162
20		33.8	8.6	3.8		44	162

RUN #9

Bar. press.
29.42 in. Hg. at 78° F

Orifice #3

Time (min.)	%SO_2 in	%SO_2 leaving	cm. water Man. Read. ball. press.	cm. Hg. Man. Read. flowmeter	Gas Temp.	Sample out	Temp. of sol.
0	10.1		6.0	3.0	75		72
2:30		0.8	8.0	3.0			80
5			8.0	3.0	75	45	82
7	4.9		8.0	3.0			86
11			8.0	3.0		46	98
14		0.8	8.0	3.0	75		106
18:30	9.9		8.0	3.0			117
20			8.0	3.0		47	120
24:30		1.0	8.0	3.0			130
29	11.8		8.2	3.0			139
30			8.0	3.0		48	142
33		0.1	8.0	3.0			145
38:30	11.4		6.0	2.8		49	152
40			6.0	2.8	74		154
43		4.3	6.0	2.8			155
46:15		5.7	6.0	2.8		50	158
50			5.8	2.6			158

RUN #10

Bar. press.
29.422 in Hg. at 78° F

Orifice #3

Time (min.)	%SO_2 in	%SO_2 leaving	cm. water Man. Read. Ball press.	cm. Hg. Man. Read. flowmeter	Gas Temp.	Sample out	Temp. of sol.
0	10.1		7.6	3.0	72		76
3		0.2	7.6	3.0			80
7	10.2		8.4	3.0			92
10:30		2.2	8.4	3.0		51	98
15:30	10.1		8.4	3.0			108
20		2.6	7.6	3.0		52	114
26			7.4	3.0		72	125
30			7.4	3.0		53	131
33		4.5	7.4	3.0			135
40	10.4		7.8	3.2			142
41			7.8	3.2		54	143
47		4.4	8.1	3.0			148
51		4.6	9.0	3.0		55	150
56	11.1		8.0	3.0			151
60:30		6.4	7.4	2.8			152

RUN #11

Bar. press.
29.62 in Hg. at 72° F

Orifice #3

Time (min.)	$\%SO_2$ in	$\%SO_2$ leaving	cm. water Man. Read. ball. press.	cm. Hg. Man. Read. flowmeter	Gas Temp.	Sample out	Temp. of sol.
0	10.6		7.9	4.0	60		60
4:30		0.3	7.8	4.0			70
10	9.8		7.2	3.2	62		85
14			7.0	3.0		57	93
16		0.5	7.0	3.2			98
22		0.4	6.8	3.2		58	106
28	11.3	2.8	7.0	3.0			119
33			7.2	3.0	64		129
35			8.0	3.5		59	131
36	919		7.0	3.0			135
45		3.5	6.8	3.0		60	144
50:30		4.2	6.2	3.0			148
55			6.5	3.0		61	150
58:30		6.8	6.2	3.0			150
65		7.3	5.8	2.8		62	150

RUN #12

Bar. press.
29.62 in Hg. at 72° F

Orifice #3

Time (min.)	%SO_2 in	%SO_2 leaving	cm. water Man. Read. ball. press.	cm. Hg. Man. Read. flowmeter	Gas Temp.	Sample out	Temp. of sol.
0	10.1	2.4	7.8	4.0	64		60
2			7.8	4.0			66
8	10.8		7.8	4.0			82
12:30	10.6		7.4	4.0			92
15		4.7	7.4	4.0	66	63	100
19			7.8	4.2			102
22		4.1	5.9	2.7			107
26		4.2	5.9	2.6			112
29			5.9	2.6			119
31		5.0	6.0	2.8		64	121
38			6.0	2.6			130
40		5.4	6.0	2.6		65	131
48			5.5	2.8	70		138
52:30	10.2		5.5	2.8			140
57		7.4	5.5	2.8		66	140
60			5.5	2.6			140

RUN #13

Bar. press.
29.62 in. Hg. at 72° F

Orifice #3

Time (min.)	$\%SO_2$ in	$\%SO_2$ leaving	cm. water Man. Read. ball. press.	cm. Hg. Man. Read. flowmeter	Gas Temp.	Sample out	Temp. of sol.
0:00	10.0		8.0	5.0	76		64
3:30		1.4	7.8	5.0			78
10:00		1.1	7.4	4.6			94
11:00			7.4	5.0		67	99
14:00	9.6		7.5	5.0	76		108
17:00		2.2	8.0	5.0	75		117
20:00			8.0	5.0		68	120
25:00		2.4	8.0	5.0			134
28:00		3.0	8.0	4.8		69	140
32:00	10.0		8.0	5.0			145
35:00		3.1	8.0	5.0			146
40:00		4.7	8.0	5.0		70	149
49:00		5.4	8.0	5.2	74		150
52:00			5.0	3.0		71	151

RUN #14

Bar. press.
29.62 in. Hg. at 72° F

Orifice #3

Time (Min.)	$\%SO_2$ in	$\%SO_2$ leaving	cm. water Man. Read. ball. press.	cm. Hg. Man. Read. flowmeter	Gas Temp.	Sample out	Temp. of sol.
0:00	10.1		8.0	5.0	74		62
3:00		2.1	7.0	5.0			70
7:00			6.8	4.0			80
10:00		0.4	6.8	4.0		72	89
14:30	10.2		6.6	4.0	74		103
20:00		0.8	6.6	4.0		73	120
27:00		1.1	5.0	3.0			140
30:00			5.0	3.0		74	148
35:00		1.9	5.0	3.0		75	156
40:00			5.0	3.0		76	160

RUN #15

Bar. press.
29.62 in Hg. at 72° F
Constant Temp. at 208 F

Orifice #3

Time (min.)	%SO_2 in	%SO_2 leaving	cm. water Man. Read. Ball. press.	cm. Hg. Man. Read. flowmeter	Gas Temp.	Sample out	Temp. of sol.
0	10.1	5.9	7.6	3.0	76		198
3			7.6	3.0			194
5			7.6	3.2			192
11			7.6	3.2		77	192
12	9.8		7.6	3.2			190
20		5.3	7.4	3.2		78	189
24		6.4	7.3	5.0			188
33		6.8	6.9	3.2			186
37			9.0	2.5		79	183
40		7.4	7.0	2.8			185
46			6.8	2.8		80	185
		Heating coil above surface of liquid: Turned off					
54		7.3	6.4	2.8		81	184

APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it is submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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