CEMENT DUST AS AN ABSORBENT FOR SO_2 REMOVAL FROM STACK GASES

A Thesis

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In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by

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The undersigned, appointed by the Dean of the Graduate Faculty, have examined a thesis entitled

Cement Dust as an Absorbent For SO_2 Removal From Stack Gas

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a candidate for the degree of Master of Science

and hereby certify that in their opinion it is worthy of acceptance.

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SUMMARY

The limestone-wet scrubbing process for SO_2 removal from stack gases has undergone much study which has resulted in construction of at least three full scale operating plants. The process used in these plants is based on calcining the limestone, by injection into the boiler, which is subsequently absorbed from the flue gases in a wet scrubber where reaction with the SO_2 takes place (injection-scrubbing process). A variation of this process, whereby limestone is added directly to the scrubber slurry has also been investigated (scrubber addition process). However, this process has not been utilized because it requires more limestone than the injection process to achieve the same SO_2 removal. It therefore has higher operating cost. Lime is known to be a more effective absorbent in this process, but it is much too costly.

It was postulated that waste cement dust, having a calcium content comparable to limestone, might be a lower cost absorbent; but, it was not known how cement dust compares with limestone or lime for removal of SO_2 in the scrubber addition process. Therefore, a bench scale scrubber system was built and this experimental investigation was conducted in an effort to obtain a preliminary comparison of cement dust with lime and limestone as a scrubber addition absorbent for removal of SO_2.

The results of these experiments indicate that the cement dust is a better absorbent than limestone and its effectiveness approaches that of lime. It has been recommended that further testing be conducted in a pilot scale system.

PREFACE

The use of a limestone or lime slurry for wet scrubbing of SO_2 from stack gases has been under development for many years. It has received more attention in recent years with the increased concern with pollution problems and the formulation of emission control regulations.

The limestone-wet scrubbing process has two major variations. The limestone may be used directly as a slurry that is pumped to the wet scrubber, or it may be injected into the boiler to calcine the limestone to lime (CaO) which is subsequently absorbed in the wet scrubber. The injection method has received favor in recent years because the calcined limestone is more reactive so that less is required to accomplish the SO_2 removal. Lime could be added directly to the scrubber slurry to avoid injection of limestone into the boiler, but, the cost of lime is much higher than limestone and precludes its use.

Because cement dust contains a high percentage of calcium, it was postulated that it might serve as a substitute absorbent.

Cement dust itself is a pollutant material that is collected in most cement plants where all or part of the collected dust may present a waste disposal problem. Since cement dust may already be partially calcined, it could very possibly be used in the SO_2 wet scrubbing process and may be available at low cost from the cement plants which in many cases consider it a waste material, having little or no value.

Therefore, the objective of this research project was to obtain a preliminary comparison of cement dust with limestone and lime for removal of SO_2 when these materials are added directly as a slurry, similar to the limestone-scrubber addition process.[1/]

CHAPTER I

INTRODUCTION

The use of limestone and lime, in water slurry form, for scrubbing of SO_2 from stack gases has been studied over a period of more than 30 years. These studies demonstrated that lime is a good absorbent, capable of removing 90% or more of the sulfur oxides. Raw limestone may also be used under similar scrubbing conditions, but at somewhat lower efficiency. A more recent development is direct addition of limestone into the boiler followed by absorption in a wet scrubber where reaction with most of the SO_2 takes place.

A very comprehensive description of the development and status of these limestone-wet scrubbing processes is contained in the conceptual design and cost study prepared in 1969 by the Tennessee Valley Authority for the National Air Pollution Control Administration (1). A thorough analysis of this process and its variations are contained in the TVA report so will not be repeated here, except the finding that the limestone injection was the more economical process. This seems to be substantiated by the fact that at least three full scale limestone injection-wet scrubbing units have been built. The first of these was installed at Union Electric Company's Meramec Station in St. Louis. Two other units have been installed on the 125 megawatt (mw) generator and the 420 megawatt (mw) generator at the Kansas Power and Light Company in Lawrence, Kansas.

Although the limestone injection process may be in favor, it has not been without its problems. The most serious problem has been scaling and plugging of the scrubbing equipment. The TVA report points out that the direct addition of limestone into the scrubber circuit may still be attractive. The report states that work is needed on increasing limestone utilization because if good absorbent efficiency could be obtained the process might well be superior to the injection-scrubbing method - in better boiler operation, lower operating cost and avoidance of scaling (2).

Considering that scrubber addition of limestone requires more material and that lime is an effective but expensive absorbent, it was theorized that cement dust could be used for direct scrubber addition. The cement dust might be more effective than limestone and would certainly be less expensive than lime and perhaps less expensive than limestone.

Thus, if the waste cement dust, which is collected to minimize particulate air pollution, could be used to minimize gaseous SO_2 pollution it would be serving a dual purpose.

The cement dust produced in many cement plants is a waste material collected by cyclones, electrostatic precipitators, or filters from the cement kiln exhaust gases to decrease the level of particulate emissions. Some or part of this "dust" may be recycled to the kiln, but it usually has too high an alkali content (Na and K) to be totally recycled.

The alkali content of cement dust produced in different cement plants can vary from approximately 1% up to 8% or more depending on the raw materials used, on the process used (wet or dry process), and other operating conditions. It is known that the alkali tends to concentrate in the dust emitted from the kilns and this limits the quantity of dust that can be recycled because alkali is an undesirable component in the product cement. The alkali in the cement dust would probably also prevent its use in the injection-wet scrubbing process because of increased slagging problems in the boiler. If used in the scrubber-addition process, this would be expected to aid in SO_2 absorbtion due to the high solubility and reactivity of alkali salts.

Even if the cement dust was as effective as limestone, only those coal-burning power plants located within reasonable distance from cement plants could make use of the material. The TVA report showed that a 200 mw power plant burning 3.5% sulfur coal would require 96,000 tons/year of limestone.

Most cement plants range in capacity from 1-5 x 10^6 barrels/year. A cement plant producing 2 x 10^6 barrels/year may collect as much as 33,000 tons/year of cement dust. Therefore, if the cement dust were only as effective as limestone for removal of SO_2 the above cement plant could supply only about one-third the requirement of the 200 mw power plant. However, if the cement dust were more effective than limestone it could probably provide a greater portion of the power plant requirement. In either case, the cost of the waste cement dust may be considerably lower than that of limestone and its use might represent a saving for the power plant while providing a use for the waste cement dust.

Cost of the limestone (FOB) for the TVA process evaluation was \$1.35/ton. This report also computed an additional grinding cost for the limestone of approximately \$0.30/ton. The small particle size of the cement dust would eliminate this grinding cost and the small particle size may also improve absorption (3). The sum of these two costs is \$1.65/ton for the limestone. This gives some indication of the potential value of the cement dust if it were equivalent to limestone in the limestone-scrubber addition process.

The cost of shipping the absorbent to the power plant is also a major cost factor. The shipping cost for the cement dust would probably be nearly the same as that for limestone which was reported to be about \$1.40/ton for 100-mile shipment by rail. This cost can vary considerably dependent on the shipping method, distance, and quantity.

The primary purpose of the experimental work described herein was to collect data that would give a preliminary comparison of cement dust with lime and limestone for removal of SO_2 by the scrubber addition process. The TVA report, mentioned earlier, contains some information regarding the use of limestone and the reaction that may be involved for removal of SO_2.

Previous work, reviewed in the TVA report, indicated that the effective reactant is calcium bicarbonate, formed by the reaction of calcium oxide or calcium carbonate with dissolved carbon dioxide. The following reactions were postulated:

$$CaO + H_2O \longrightarrow Ca(OH)_2$$

$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O$$

$$CaCO_3 + CO_2 + H_2O \longrightarrow Ca(HCO_3)_2$$

$$Ca(HCO_3)_2 + SO_2 + H_2O \longrightarrow CaSO_3 \cdot 2H_2O\downarrow + 2CO_2$$

$$CaSO_3 \cdot 2H_2O + 1/2O_2 \longrightarrow CaSO_4 \cdot 2H_2O\downarrow$$

In simpler terms, the reaction is more often presented as:

$$2CaO + H_2O + 2SO_2 \xrightarrow{O_2} CaSO_3 + CaSO_4 + H_2O$$

Other pilot plant work discussed in the TVA study has shown that the scrubber effluent did contain approximately equal amounts of sulfate and sulfite.

The TVA report concluded that the scrubber slurry contains mainly $CaCO_3$, $CaSO_3$ and $CaSO_4$ in suspension, plus a variety of compounds and ions in solution. It also concluded that the solubility relationships in the complex phase system have not been worked out, making it difficult to determine the mechanism of reaction and the products produced.

The TVA study found that little information is available on the kinetics of the reactions, the dissolution of the limestone, the absorbtion of SO_2 (and CO_2) into the liquid phase, and transfer of SO_2 to the reaction site and reaction with the absorbing species. It further stated that data on the above must be obtained before the controlling mechanism or mechanisms can be determined. In summary, the report found that the chemistry and kinetics of the limestone-wet scrubbing process are quite complex and largely unexplored.

It was also mentioned in the TVA report, that in the limestone-wet scrubbing process the particle size of the absorbent may have an effect on the SO_2 absorption. It was not possible in this study to investigate the effect of particle size, except to determine the particle size distribution of the three absorbents. These are presented and discussed as part of the experimental data in Chapter IV of this report.

It was not the purpose of this research to investigate the above areas, although this would be useful information. Rather, the purpose was to obtain a preliminary comparison of cement dust with lime and limestone for removal of SO_2. Earlier work, described in the TVA report, had indicated that the absorption was closely related to the liquid to gas ratio and to the gas velocity. Bearing this in mind, the experimental apparatus and procedures were intended to compare the SO_2 removal for the three absorbents as a function of the following parameters:

SO_2 Concentration
Slurry Flowrate
Gas Flowrate
Absorbent Feedrate

Equipment limitations would not allow investigation of other parameters, such as gas temperature and slurry concentration. However, the major objective of a comparison of cement dust with lime and limestone was accomplished.

CHAPTER II

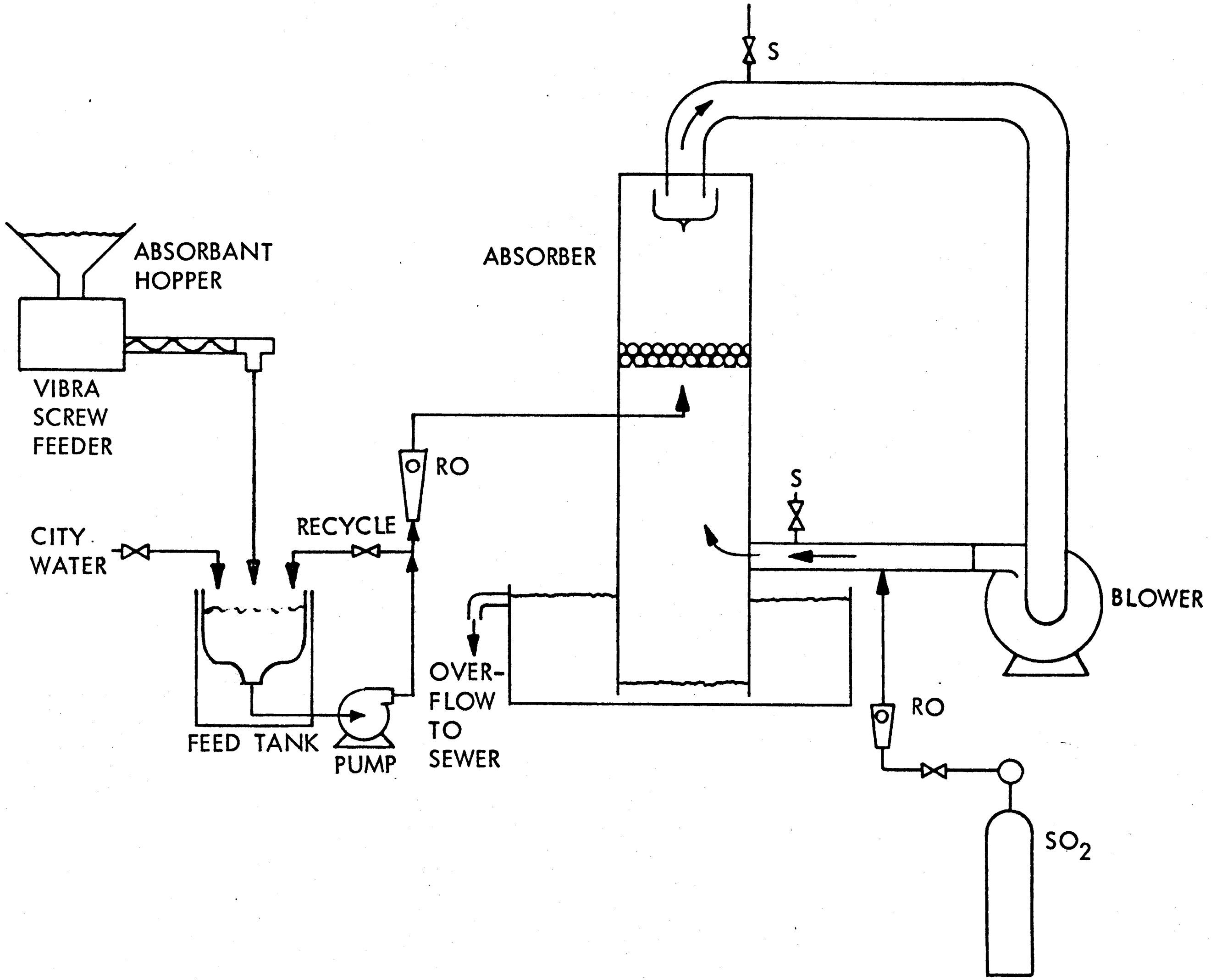
DESCRIPTION OF EXPERIMENTAL APPARATUS

The equipment used in this investigation was originally designed with the intent to construct a bench-scale scrubber system that would duplicate, as much as possible, the operating conditions in the pilot-scale scrubber used in the Combustion Engineering Studies described in Reference 4. Considerable modifications were necessary in constructing the apparatus, mainly due to limitations of available equipment. The final equipment arrangement is shown schematically in Figure 1 and pictured in Photos 1, 2, and 3. Specific information about the equipment is given in Appendix A.

The basic idea of the bench-scale system was to construct a marble-bed scrubber in which a simulated flue gas containing SO_2 could be introduced and scrubbed with an absorbent slurry of cement dust, lime, or limestone. The SO_2 content of the inlet and outlet gases would be measured to determine the efficiency of SO_2 removal.

Marbles (1/2 in. dia.) were used in the scrubber, rather than other packing materials such as Raschig rings to minimize the possibility of scaling and plugging. Packings similar to marbles are also used in actual SO_2 scrubbers for the same reasons. From the standpoint of mass transfer, the type of packing is probably relatively

Figure 1 - Sketch of Absorber System



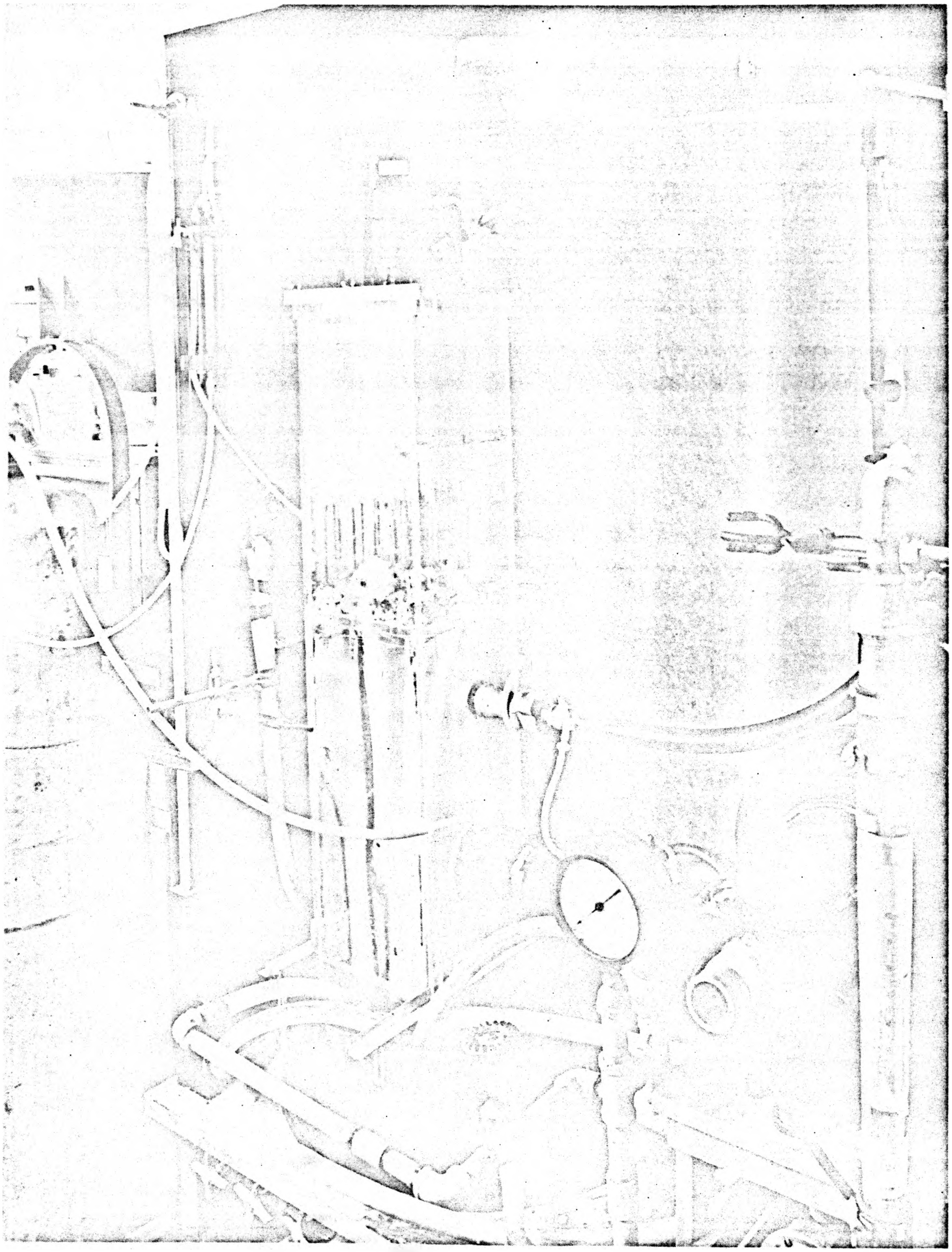


Photo No. 1

Right-Front View of Experimental Apparatus
(Including Absorber and Blower)

Photo No. 2
Left-Front View of Experimental Apparatus
(Including Absorber, Blower and Slurry Pump)

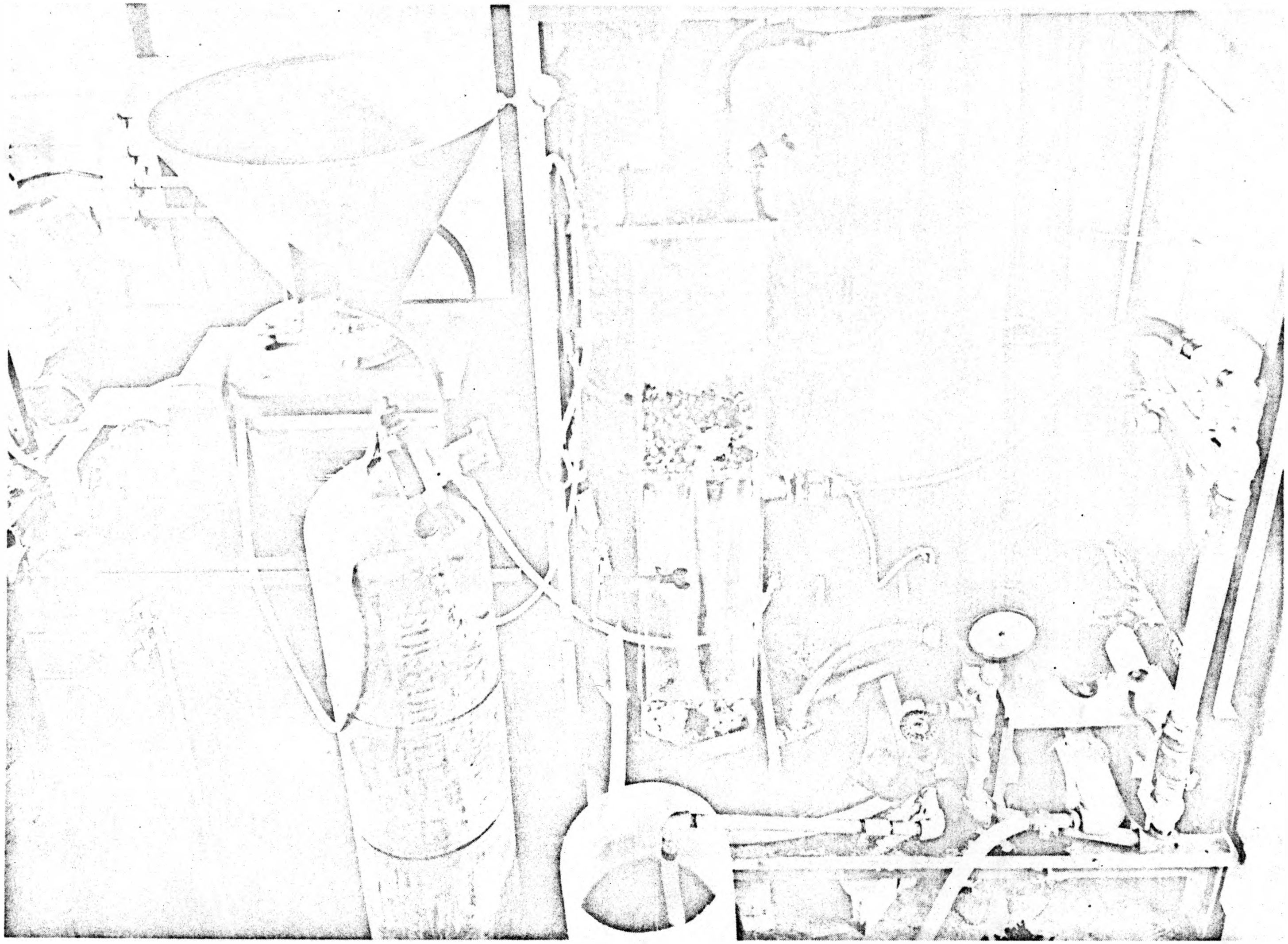


Photo No. 3
Front View of Experimental Apparatus
(Including Absorber, Blower and Slurry Feed System)

unimportant because much of the mass transfer probably takes place in the frothing turbulent liquid layer that is sustained above the packing by the upward flowing gases.

The cement dust used in these experiments was provided by Northwestern States Portland Cement Company in Mason City, Iowa. It was a combination of the dust collected from the exhaust gases from one large kiln equipped with a baghouse and from one smaller kiln equipped with a cyclone and a baghouse. The pulverized lime and limestone used in the experiments were commercial products intended for soil application purposes and were purchased locally in 50 lb bags. The ground limestone was produced at a limestone quarry in Kansas City. The lime used was a pulverized quicklime (CaO) and was not slaked lime ($Ca(OH)_2$). (See Appendix A-1 for additional information regarding the purchased lime and limestone.)

The best blower available at MRI for this project would have been unsuitable except that the 1,750 rpm - 1/4 hp motor was replaced with a 3,600 rpm - 1/2 hp motor. Even then, the capacity was only about 250 cfm. The CE pilot unit scrubber had operated at a superficial gas velocity of 500 ft/min so this bench-scale scrubber was designed with a cross-sectional area of 0.5 ft^2. The scrubber was constructed of plexiglass in order to permit observation of the scrubbing action.

Since no source of flue gas was available, and a burner system would have been too complex, it was decided to use a recycle gas system and inject a measured flow of SO_2 into the inlet gas stream. No provision was made for heating this gas stream and the experimental data was taken at the temperature of the water slurry which ranged from 40-80°F. This is considerably lower than the gas temperatures in the CE pilot-scale system in which the inlet gas temperature was about 250°F and the outlet was 120°F. It is assumed that higher operating temperature would improve the SO_2 removal as a result of higher dissolution of the slurry. If subsequent investigation of the use of cement dust were to be carried out, it should be done at the higher temperature that would exist in a full-scale plant. The lower temperature used in these experiments limits the applicability of the data but does still permit comparison of the cement dust, lime and limestone at these lower temperatures.

Use of the recycle gas stream resulted in two procedural disadvantages, but apparently without serious effect on the results. The first of these disadvantages was the inability to select inlet SO_2 concentrations. For any selected SO_2 feedrate, the concentration of SO_2 in the inlet gas was a function of the SO_2 concentration in the outlet gas. This in turn was a function of the absorption efficiency in the scrubber. The absorber always absorbed all the SO_2 introduced into the system by virtue of the fact that whatever SO_2 escaped with the outlet gas was recycled back to the inlet after combining with the fresh SO_2 feed. Therefore, the inlet concentration increased to the level at which the absorbent was removing the quantity of SO_2 equal to the makeup SO_2. The experimental results showed that this equilibrium condition was reached in less than 15 min, which was the time interval between gas samplings. This inability to select the inlet SO_2 concentration was inconvenient, but had no effect on the results.

A second disadvantage of the recycle gas system was the difficulty in maintaining a desired CO_2 content in the gas stream. A cylinder of synthetic flue gas containing 16.1% CO_2, 3.1% O_2, 0.30% SO_2, and 80.5% N_2 was used to purge the system before each experimental run. It was hoped that this gas composition could be maintained throughout each run. However, the water slurry sprayed into the scrubber rapidly absorbs the CO_2, although the rate of absorption decreases as the SO_2 feedrate increases and the pH of the slurry decreases. A cylinder of CO_2 was used to make up CO_2 into the system to maintain some CO_2 in the recirculating gas stream. Samples of the gas were taken during each run, and analyzed by Orsat apparatus, so that adjustments could be made in the CO_2 make-up rate. This procedure was not very effective in controlling the CO_2 content and large variations in the CO_2 content occurred in many of the experimental runs. However, there was no indication that this had any effect on absorption of SO_2.

Analysis of the CO_2 and O_2 content of the recycle gas stream was done using a conventional Orsat apparatus in which the CO_2 is absorbed from the gas sample so the decrease in sample volume gives the percent CO_2 in the sample. The O_2 in the remaining sample is absorbed next, and similarly, the decrease in sample volume gives the percent

O_2. The absorbing solution for the CO_2 also absorbs other acid gases including SO_2. Therefore, the results reported herein for percent CO_2 also includes the SO_2, but the quantity of SO_2 was only about 0.3% which is relatively small in comparison to the percent CO_2 of about 7%.

A once-through slurry system was used in these experiments. The slurry system in the CE study and in full-scale units is a recirculating system which improves utilization of the absorbent. The once-through system was selected for its simplicity. This does not efficiently utilize the absorbent, but should still give a good relative comparison of the absorbents. The water used to prepare the slurry was ordinary tap water, but it does have a relatively high pH of about 9, which could have some affect on the pH values obtained for the inlet slurrys.

The absorbent slurry used in the experiments was prepared in the slurry feed tank using a Vibrascrew feeder. Absorbent dropped from the Vibrascrew feeder into the slurry feed tank and mixed with the make-up water. Flow of make-up water into the tank was manually controlled to maintain a constant level.

This feed tank consisted of a 5 gal. bucket supporting an inverted plastic bottle from which the bottom had been removed as shown in Figure 1. Sloping sides of the plastic bottle and the bottom center outlet insured that no holdup of solid could occur.

The slurry was pumped from the bottom of the feed tank with a Moyno pump through the slurry rotameter and into the scrubber spray nozzle. This pump had a much higher capacity than required, so flow to the scrubber was controlled by means of a valve in a recirculation line from the pump discharge back to the feed tank. This provided good flow control, and the portion recirculated back to the feed tank provided agitation for mixing of the absorbent in the slurry which prevented any sedimentation.

The slurry used in these experiments normally contained about 1% solids, which is considerably lower than the 10% slurry in the TVA study. This lower concentration was desired in order to minimize the quantity of absorbent used in each experimental run and to attain the desired range of SO_2 concentration in the inlet gas (1,000-5,000 ppm) while also minimizing the quantity of SO_2 required for each run.

The slurry was fed into the scrubber through a single full cone spray nozzle centered below the marble bed. The inlet gas stream flowed up through the marble bed and sustained a 4-6 in. turbulent frothing level of slurry above the marble bed. The slurry flowed from above the marble bed to the bottom of the scrubber tank through four 1-in. diameter plastic tubes. The opening into these tubes was located just above the top of the marble bed. The outlet slurry was not analyzed except for pH.

The scrubber itself was open at the bottom and was located in a tank 7 in. high. The tank had been cut from a 55 gal. drum. The absorber was suspended in the tank with 1/4 in. clearance between the bottom of the absorber and the bottom of the tank. Liquid level in the tank was maintained about 1/4 in. below the top of the tank by means of a raised outlet pipe connected to a sewer drain. Thus, if the pressure in the absorber should, for any reason, exceed atmospheric pressure by more than about 6 in. of water, the gas pressure would be relieved by escaping at the bottom of the scrubber. The entire apparatus was installed in a hood as a safety precaution against escape of gas containing high SO_2 concentrations.

CHAPTER III

GAS SAMPLING METHOD

The concentration of SO_2 in the inlet and outlet gas stream was measured by an Infrared Spectrophotometer which was available for use at Midwest Research Institute. The gas samples for this analysis were taken using 1,000 ml evacuated flasks as shown in Appendix A. The small liquid separator preceding the sample flask was used to prevent carry-over of droplets of liquid into the sample flasks.

CHAPTER IV

OPERATING PROCEDURE AND EXPERIMENTAL DATA

A total of 16 experimental runs were made in the course of this work. A run consisted of operating the scrubber at selected SO_2 make-up rates for a period of 1-2 hr during which time inlet and outlet gas samples were taken after each 15-min interval. After each run, these gas samples were analyzed using a Perkin Elmer Infracord Spectrophotometer and a 1 meter IR cell.

The first series of runs (Runs Nos. 1-8) were made using cement dust at a fixed feedrate. The effect of increased SO_2 concentration was the first variable to be investigated so the SO_2 feedrate was increased in each succeeding run.

As the first series of runs progressed and analytical results were obtained, it became obvious that for any selected SO_2 feedrate the concentration of SO_2 in the inlet and outlet gas streams stabilized within the first 15-min of the run so that the samples taken at succeeding 15-min intervals were essentially the same as the first samples. It was, therefore, decided that in following runs the SO_2 feed could be increased after each 15-min sampling interval. This made it possible to investigate a range of SO_2 concentrations to obtain considerably more data from each run.

Following the first series of runs, two additional runs were made using cement dust. One was made at increased slurry flowrate and the other with higher cement dust feedrate. It was possible to cover a range of SO_2 concentrations in both of these runs as concluded in the above paragraph. The next runs also took advantage of this fact and two runs were made using limestone and four runs using lime. A capsule outline of each run is given in Table I with specific experimental data tabulated in Table II.

The actual procedure used in obtaining the experimental data for each run consisted of several steps. The first step for each run was to clean out the absorber tank to remove the absorbent which had settled out in this tank during the previous run. Then the supply of fresh absorbent was put into the hopper of the Vibrascrew feeder and the gas sample flasks were evacuated.

Prior to the run, the absorber system was purged for at least 1 hr with synthetic flue gas. During this time, absorbent feedrate from the Vibrascrew feeder was measured and adjusted by weighing the quantity of absorbent fed into a beaker in a 2-min period. This feedrate was rechecked by the same method at the conclusion of the run.

After the purge period, water was turned on into the slurry feed tank and the slurry pump was started. Flow into the scrubber was adjusted to the desired rate using the slurry rotameter and the bypass valve. Make-up water to the slurry feed tank was then adjusted to maintain constant level. Following this, the Vibrascrew feeder was started. CO_2 flow was then started and later adjusted on the basis of Orsat analysis and on the basis of increasing or decreasing

TABLE I

OUTLINE OF EXPERIMENTAL RUNS

	Cement Dust
Runs Nos. 1-8	Increased SO_2 feedrate in each succeeding run
Run No. 9	Higher slurry flowrate (and decreased gas flowrate)
Run No. 10	Higher absorbent feedrate
	Limestone
Run No. 11	Normal absorbent feedrate
Run No. 12	Higher absorbent feedrate
	Lime
Run No. 13	Higher absorbent feedrate
Run No. 14	Higher absorbent feedrate, decreasing gas flowrate
Run No. 15	Normal absorbent feedrate, lowest gas flowrate
Run No. 16	Normal absorbent feedrate

TABLE II

TABULATION OF EXPERIMENTAL DATA

Absorbent	Run No.	SO_2 Feedrate (lbmols/min)	Slurry Flowrate (gpm)	Absorbent Feedrate lb/min (lbmols Ca/min)a/	Calculated Gas Flow b/ ACFM	Gas Analyses ppm SO_2 Inlet	Gas Analyses ppm SO_2 Outlet	Pressure Drop Inches of H_2O Absorber	Pressure Drop Inches of H_2O Total	Gas Analysis Variations % CO_2	Gas Analysis Variations % O_2	Slurry Conc. Wt. % Solids	Slurry pH c/ Feed	Slurry pH c/ Abs. Outlet
Cement Dust	1	Thrown out - simultaneous inlet and outlet samples not taken												
	2	0.000169	2.1	0.21 (0.00189)	273	267	34	2.5	5.2	1-0	14-16	0.97	(12.0)	(11.3)
	3	0.000289	2.4	0.21 (0.00185)	264	623	211	1.5	4.2	19-11	12-15	0.71	(12.2)	(7.7)
	4	0.000362	2.9	0.21 (0.00187)	235	815	246	4.0	4.7	15-12	7-10.5	0.94	(12.2)	(8.1)
	5	0.000509	3.0	0.21 (0.00187)	323	1,179	565	2.8	4.9	14-3	4-9	0.91	11.8 (11.9)	6.3 (6.7)
	6	0.000681	3.0	0.22 (0.00199)	331	1,729	931	3.3	4.9	15-15	7-7	0.96	11.8 (12.1)	5.6 (6.5)
	7	0.000869	3.2	0.23 (0.00209)	387	2,498	1,626	2.3	4.3	19-2.0	6-9.5	0.99	12.0 (12.2)	5.5 (5.6)
	8	0.001245	2.9	0.24 (0.00215)	331	5,059	3,589	2.2	4.9	16-30	6-3	0.99	11.8 (11.8)	4.8 (4.6)
	9 (a)	0.001059	3.3	0.24 (0.00216)	317	4,037	2,725	2.4	5.2	20	3.5	0.92	11.6 (12.3)	5.0 (5.2)
	(b)	0.001059	4.5	0.24 (0.00216)	221 d/	3,570	1,689	2.2	3.7	12	3.0	0.48	11.2 (12.2)	5.1 (4.7)
	(c)	0.000678	4.5	0.24 (0.00216)	211 d/	1,925	661	2.1	3.8	3	3.5	0.49	11.3 (12.2)	5.5 (5.4)
	10 (a)	0.000506	3.0	0.48 (0.00429)	311	842	204	2.0	5.0	NS		1.87	12.0 (12.4)	9.3 (11.8)
	(b)	0.000856	3.0	0.48 (0.00429)	278	1,880	669	2.6	4.8	NS		1.78	12.0 (12.5)	7.1 (10.5)
	(c)	0.001251	3.0	0.48 (0.00429)	301	3,815	2,185	2.1	4.0	14	3.0	1.88	12.0 (12.5)	5.3 (5.7)
Limestone	11 (a)	0.000355	3.4	0.22 (0.00202)	352	1,127	737	2.3	4.9	NS		0.93	9.3 (10.4)	5.3 (5.7)
	(b)	0.000506	3.4	0.22 (0.00202)	340	1,767	1,189	2.8	5.1	NS		0.89	9.2 (10.8)	5.1 (5.6)
	(c)	0.000428	3.4	0.22 (0.00202)	367	1,500	1,048	2.2	4.6	17.5	9.0	0.88	9.4 (10.2)	5.1 (5.7)
	12 (a)	0.000358	3.0	0.50 (0.00453)	460	908	605	2.6	4.7	NS		2.17	10.6 (9.3)	5.8 (5.3)
	(b)	0.000509	3.0	0.50 (0.00453)	346	1,630	1,058	2.6	5.1	NS		NS	10.7	5.6
	(c)	0.000222	3.0	0.50 (0.00453)	736 e/	375	258	3.5	4.7	20.5	4.5	2.15	9.8 (8.6)	6.0 (5.7)
Lime	13 (a)	0.000508	3.0	0.22 (0.00402)	281	854	152	2.1	3.6	4.5	6.0	1.09	12.0 (12.7)	12.1 (12.9)
	(b)	0.000856	3.0	0.22 (0.00402)	197 f/	1,995	299	2.6	4.8	3.0	4.5	1.03	12.1 (12.6)	12.1 (12.9)
	(c)	0.001259	3.0	0.22 (0.00402)	181 f/	3,610	912	3.3	5.1	6.5	3.0	1.03	12.2 (12.7)	12.1 (13.0)
	14 (a)	0.000503	3.0	0.23 (0.00409)	138 f/	1,540	< 50	2.8	4.9	NS		1.06	12.4 (12.4)	12.3 (12.4)
	(b)	0.000847	3.0	0.23 (0.00409)	85 f/	4,225	157	3.2	4.9	4.0	5.0	0.67	12.3 (12.4)	12.3 (12.4)
	(c)	0.001234	3.0	0.23 (0.00409)	58 f/	9,276	627	3.2	4.7	8.5	3.0	0.80	12.3 (12.4)	12.2 (12.4)
	15 (a)	0.000505	3.0	0.12 (0.00207)	53 g/	3,970	118	4.0	4.8	7.5	3.5	0.54	12.7 (12.4)	12.1 (11.7)
	(b)	0.000669	3.0	0.12 (0.00207)	56 g/	5,000	201	-	-	-	-	-	-	-
	(c)	0.000844	3.0	0.12 (0.00207)	48 g/	7,805	600	4.0	4.4	12.0	2.0	0.48	12.6 (12.5)	11.7 (11.5)
	(d)	0.001031	3.0	0.12 (0.00207)	47 g/	10,180	1,330	-	-	-	-	-	-	-
	(e)	0.001220	3.0	0.12 (0.00207)	44 g/	14,950	3,805	4.1	4.8	9.5	2.0	0.45	12.6 (12.6)	5.7 (2.6)
	(f)	0.001414	3.0	0.12 (0.00207)	47 g/	17,800	5,650	-	-	-	-	-	-	-
	16 (a)	0.000505	3.0	0.13 (0.00232)	166	1,500	280	2.2	3.9	10.0	3.5	0.55	12.3 (12.4)	11.9 (11.9)
	(b)	0.000670	3.0	0.13 (0.00232)	164	2,090	455	-	-	NS		NS	-	-
	(c)	0.000847	3.0	0.13 (0.00232)	186	2,505	678	2.4	4.0	18.0	2.0	0.62	11.6 (12.4)	10.2 (8.5)
	(d)	0.001034	3.0	0.13 (0.00232)	185	4,150	1,910	-	-	NS		NS	-	-
	(e)	0.001223	3.0	0.13 (0.00232)	202	5,270	2,840	2.8	4.4	25.0	1.5	0.59	11.9 (12.5)	5.5 (5.5)
	(f)	0.001414	3.0	0.13 (0.00232)	224	7,700	5,170	-	-	NS		NS	-	-

---

a/ Lbmols Ca/min computed from absorbent feedrate based on following values of Ca content of absorbents: Cement dust - 36% Ca; lime - 71.4% Ca; limestone - 36% Ca.

b/ Gas flow calculated on the basis of the SO_2 feedrate and the increase in the SO_2 concentration in the gas stream.

c/ Values in parenthesis are pH of slurry samples analyzed after a period of 24 hr or more.

d/ Higher slurry flowrate caused decrease in gas flowrate.

e/ Calculated flow may be in error due to inaccuracies at low SO_2 flow and low SO_2 concentrations.

f/ Decreasing gas flow due to plugging in absorber bed.

g/ Low gas flow due to pluggage in absorber bed.

pressure in the absorber. After initiating the CO_2 flow, the blower was turned on. This completed the start-up procedure, except for initiating flow of SO_2 which was the last step in completing the startup to commence the run. The SO_2 was controlled with a needle valve following the gas cylinder pressure regulator. Downstream of the needle valve, the SO_2 flowed through a rotameter then past a thermometer and manometer connection and on into the inlet gas stream.

After the run had started, inlet and outlet gas samples were taken after each 15-min interval using the 1,000 ml evacuated flasks. In later runs, the SO_2 feedrate was increased after each 15-min sample interval as explained earlier.

During the runs, the following operating conditions were recorded:

SO_2 Flow (also temperature and pressure)

Slurry Flow

Gas Stream Temperature

System Pressures

Slurry Feed pH (grab samples were also taken for later pH measurement and to determine slurry concentration)

Outlet Slurry pH

O_2 and CO_2 content of gas (by Orsat)

Absorbent Feedrate (measured at the beginning and end of each run)

When the last gas samples had been taken, the SO_2 flow was stopped and the Vibrascrew feeder was shut off. The unit was then allowed to run 10-20 min longer to flush out the lines and the absorber. Actual run time was about 1 hr although later runs were extended to 2 hr to obtain data for up to eight different SO_2 feedrates.

Following the run (usually 2 or 3 days later) the pH of the slurry grab samples was determined and the feed slurry samples were filtered, dryed and weighed to determine solids concentration. The inlet and outlet gas samples were analyzed by infrared spectrometer to determine SO_2 concentration.

After the analytical data for each run had been obtained, the actual SO_2 flow was calculated using a calibration curve prepared during initial construction of the absorber system. The SO_2 feedrate was then used to calculate the moles of SO_2 removed per mole of Ca in the absorbent and to determine how this varied in relation to the concentration of SO_2 in the inlet gas. Example calculations, including all calibration curves, are shown in Appendix B.

Many of the initial calculations for each run were later recalculated after the first infrared calibration curve was found to be in error.

The chemical analysis of the three absorbents is pertinent to this investigation, so, samples of each were analyzed by atomic absorption equipment at MRI. An analysis of the cement dust by x-ray fluorescence was supplied by the cement company. This investigator also analyzed the cement dust by Neutron Activation Analysis at the University of Missouri in Columbia, Missouri, with direction and help given by the staff of the Reactor Research Center at MU. The results of these analyses are shown in Table III.

The calcium content of the absorbents is important since this gives some indication of the probable absorption capacity for SO_2. However, the analyses of the cement dust by AA show higher Ca content than that by NAA or X-ray fluorescence. In addition, the AA analyses show 75.0% Ca in the lime which could contain no more than 71.4% Ca if it were pure CaO. Also, the supplier of the limestone stated that it was 90% $CaCO_3$ which is equivalent to 36% Ca. These facts indicate that the analyses by AA may be in error. Therefore, all calculations presented herein have been based on Ca content of the absorbents as given below. The value of 36% Ca used for the cement dust is probably high, but this gives a conservative value for the absorption efficiency of the cement dust because results are presented on the basis of the moles of SO_2 removed per mole of Ca in the absorbent.

Cement Dust	36.0% Ca
Limestone	36.0% Ca
Lime	71.4% Ca

The Ca content of the limestone is presumed to be mainly in the form of $CaCO_3$ and in the lime it is CaO. However, it was not determined in what form the Ca may be in the cement dust. It may be CaO or $CaCO_3$ or both. It was observed during the experimental runs that whereas the limestone released considerable amounts of CO_2 to cause overpressuring of the absorber system, the cement dust did not

TABLE III

CHEMICAL ANALYSES OF ABSORBENTS

	Atomic Absorption			Neutron Activation Analysis	Fluorescent X-Ray[a]
Element	Limestone (%)	Lime (%)	Cement Dust (%)	Cement Dust (%)	Cement Dust (%)
Ca	38.9	75.0	36.0	27.4	28.6
K	1.6	1.6	1.0	2.3	2.3
Na	0.1	0.1	0.3	0.2	na
Al	0.2	0.1	0.9	2.9	1.4
Fe	0.4	0.1	1.4	na	0.8
Mg	na	na	na	0.85	na
Si	na	na	na	na	5.8

---

a/ X-ray analysis by supplier of cement dust stated that analysis may be inaccurate because standarization curve was for the raw kiln feed which is different than the cement dust.

na - not analyzed

have a similar effect. It is, therefore, thought that the Ca in the cement dust may be mainly in the form of CaO.

Analyses of the absorbents given in Table III indicate that the alkali content of the cement dust was relatively low (1-2%). As mentioned earlier, the alkali content of many cement dusts may be considerably higher; as high as 8% or more. It is expected that higher alkali content would probably aid in SO_2 absorbtion due to the high solubility and reactivity of alkali salts.

The particle size of the three absorbents used in these experiments may also be pertinent to the results so the size distribution of each was determined by a Bahco Particle Classifier. These particle size distributions are presented in Appendix C, and have been combined as shown in Figure C-4. These figures show that the mean particle size for the three absorbents was:

Absorbent	Mean Particle Size
Cement Dust	10 μ
Limestone	13 μ
Lime	20 μ

The particle size of the three absorbents, as above, shows that the cement dust had the smallest mean particle size of 10 μ. This is probably smaller than the mean size of the limestone used in commercial scrubbing units, which is usually ground to 70% less than 200 mesh. The small size of the cement dust probably enhances its ability to react with SO_2 and this reactivity is of primary importance to the purpose of this study.

The SO_2 analysis of the inlet and outlet gas samples by infrared spectrophotometry were critical to this experimental investigation. The description of this method and the problems encountered are presented in the following section.

CHAPTER V

SO_2 ANALYSIS METHOD

Inlet and outlet gas samples were collected in 1,000 ml evacuated flasks during each run as previously explained. These samples were set aside and later analyzed by infrared spectroscopy.

The analysis method consisted of first transferring part of the gas from the flask into a 1 meter path length IR cell. This was accomplished by means of a vacuum system as shown in Figure 2. The flask and IR cell were connected to the vacuum system and the IR cell was evacuated. Then stopcock No. 1 was closed and No. 2 was opened to expand the gas from the flask into the IR cell. After the pressure had equilibrated the pressure was read on the manometer, the valves were closed, and the IR cell was disconnected. The IR cell was then placed in the scanning spectrophotometer to obtain a scan of the infrared absorption.

To determine the SO_2 concentration in the IR cell, the percent transmittance was measured at the wavelength of 7.35 μ (Wave No. 1361 cm^{-1}). The corresponding partial pressure of SO_2 was read from the calibration curve previously prepared (as discussed below). This value of the partial pressure of SO_2 was divided by the total pressure of the IR cell, which had been read on the manometer, to calculate the percent SO_2 in the gas sample.

The initial calibration curve (Figure 3, Curve A) was prepared using a cylinder of calibration gas standard containing 3,000 ppm SO_2. A set of six calibration data points were obtained by first evacuating the IR cell and then admitting the standard gas into the IR cell to a desired pressure as indicated on the manometer using the same vacuum system shown in Figure 2. Thus, the partial pressure of SO_2 in the cell was known and the corresponding transmittance was measured on the infrared spectrophotometer. The pressure of the standard gas in the IR cell was increased in six steps from 28 mm Hg up to 431 mm Hg and the respective transmittance decreased from 88.1% to 11.7%.

The six calibration points were plotted on semilog paper as shown in Figure 3 (Curve A). These points formed a straight line on the semilog paper as would be predicted from the Lambert-Beer Law which states that (5):

$$\ln T = k\ c\ b$$

where T = Transmittance

k = proportionality constant

c = concentration of absorbing molecules

b = path length through the sample (a constant for the 1 meter IR cell)

It was reasoned from this relationship that the ln of the transmittance should be directly proportional to the number of SO_2 molecules in the IR cell, expressed as the partial pressure of SO_2 in the IR cell. The six calibration points obtained did fall on nearly a

Figure 2 - Diagram of Vacuum System

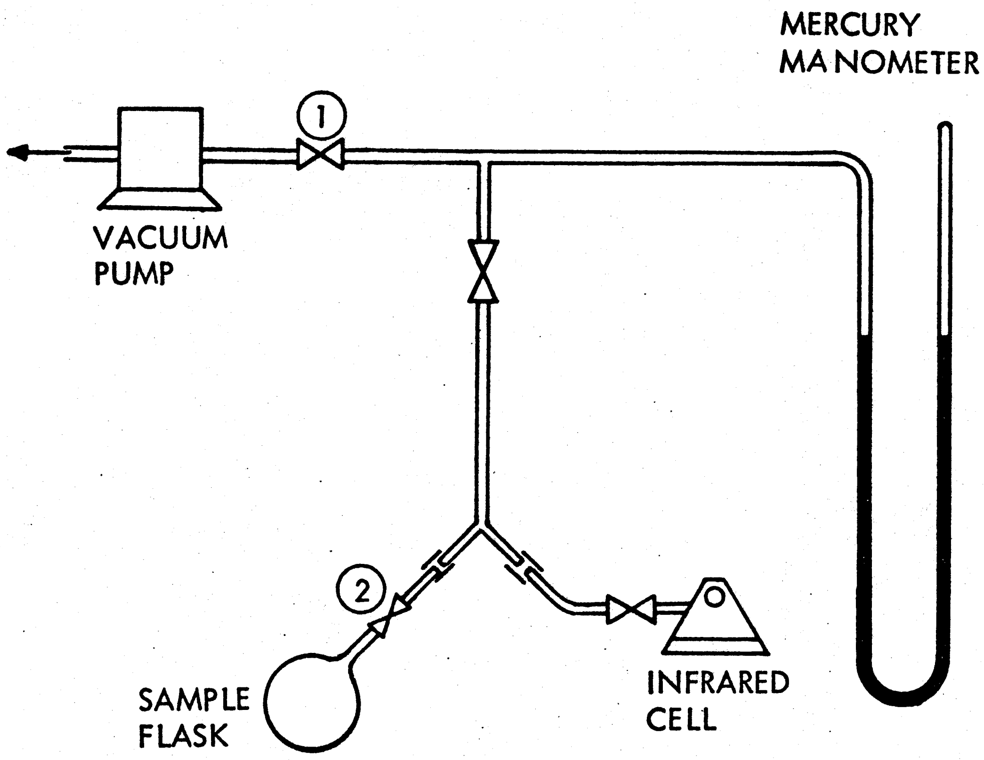
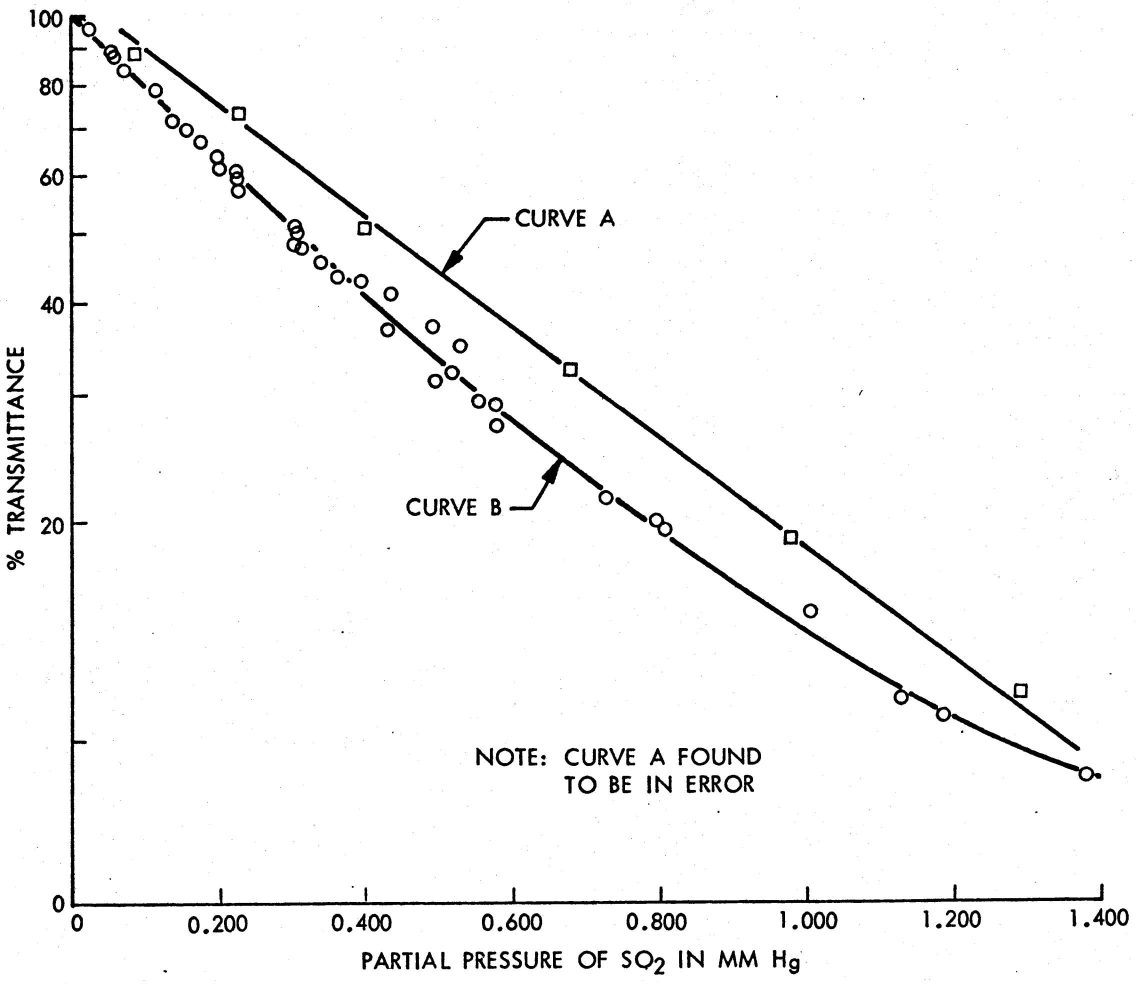


Figure 3 - Calibration Curves for Infracord Analyzer



straight line on the semilog paper (Curve A) as would be predicted. However, a discrepancy occurred in later experiments using this calibration curve which indicated that the curve was not correct.

While analyzing the gas samples from Run No. 3, one of the flasks was expanded into the IR cell and the analysis, using Curve A, showed the SO_2 concentration to be 935 ppm. (The total pressure of the sample in the IR cell was 321 mm Hg.) This same flask was again expanded into the IR cell a second time and the resultant total pressure in the IR cell was 147 mm Hg. The second infrared analysis, using Curve A, showed the SO_2 concentration to be 1,090 ppm. These two analyses should have yielded identical results, when in fact they differed by more than 10%.

The six samples taken in Run No. 4 were all analyzed twice by expanding each sample into the IR cell a second time. In each case the second analysis was higher than the first analysis by as much as 38%. Experimental runs were halted at this point to investigate the reason for this large an error in the infrared analysis method.

The first part of the investigation of this problem was to prepare two samples of known SO_2 concentration in the sample flasks. This was done by admitting the standard gas into the flasks up to 228 mm Hg and 374 mm Hg. Following this, atmospheric air was admitted into the flasks up to 720 mm Hg. The SO_2 concentrations in the two flasks were thereby calculated to be 950 ppm SO_2 and 1,560 ppm SO_2, respectively. The flask samples were twice expanded into the IR cell and analyzed by the same method described earlier.

The resultant analysis, using the calibration curve (Curve A), showed concentrations of 1,290 ppm and 1,550 ppm for the first flask (prepared as 950 ppm) and concentration of 2,190 ppm and 2,400 ppm for the second flask (prepared as 1,560 ppm). It was, therefore concluded, that the calibration curve was in error. It must be remembered at this point that the calibration curve was prepared using different pressures of standard gas admitted directly into the IR cell whereas the experimental samples were intially at atmospheric pressure and were expanded into the IR cell.

Data for preparation of a new calibration curve was obtained by admitting known pressures of standard gas into the sample flask, then admitting air up to atmospheric pressure. The resultant concentration of SO_2 was computed and was used to calculate the partial pressure of SO_2 in the IR cell after the sample had been expanded into the cell. The cell was then inserted in the Infracord analyzer to determine the percent transmittance corresponding to this partial pressure.

Several additional calibration samples were prepared using dry air and saturated air in bringing the samples up to atmospheric pressure. The purpose of this was to determine if the data from these samples might be significantly different from the other new calibration data. This was not the case, so these samples served to increase the quantity of calibration data.

All the calibration data that was determined by bringing the sample up to atmospheric pressure and then expanding it into the IR cell has been plotted on Figure 3 and was used to draw Curve B. Because these data were obtained by the method that closely duplicates that used for analyzing the absorber samples, calibration Curve B was used in all succeeding experimental runs and it was also used to recalculate the SO_2 analysis for the four preceeding runs.

The procedure for analyzing the gas samples taken during the succeeding four runs included repeating the analysis for each sample flask to determine the deviation using the new calibration curve. Results were considerably improved as the two analyses usually showed less than 10% error. This much error is certainly not insignificant but could probably be tolerated for the purpose of this investigation.

CHAPTER VI

RESULTS AND CONCLUSIONS

The purpose of this investigation was to obtain a comparison of cement dust with lime and limestone for removal of SO_2 from a gas stream. This also included investigation of the effect of SO_2 concentration, absorbent feedrate, gas flowrate, and slurry flowrate. Various methods of presenting the experimental results were considered in order to select the simplest and most meaningful method. It was felt that the most important considerations were the concentration of SO_2 in the inlet gas and the ratio of the moles of SO_2 removed to the moles of Ca contained in the absorbent. Therefore, all the results have been plotted in this manner.

Many other means of analyzing and presenting the results are possible including the percent SO_2 removal or calculated mass transfer coefficients. It was felt that the percentage of SO_2 removal might be somewhat misleading due to the differences between this experimental system and the operating conditions in pilot scale and full scale plants. Some preliminary values of mass transfer coefficients were calculated but it was found these decreased as a function of increasing SO_2 concentration which limited their usefulness. However, the data in Table II would enable analysis of the data by any of these methods by anyone who might desire to do so.

Comparison of Absorbents

A comparison of the absorbents is presented in Figures 4 and 5. These figures show the ppm SO_2 in the inlet gas versus the ratio of the rate of SO_2 removal and the Ca feedrate for each absorbent. This ratio of the moles of SO_2 removed per mol of Ca fed has been termed the "absorption ratio."

Figures 4 and 5 give a comparison of the absorption ratio for the three absorbents at two different absorbent feedrates. The respective calcium feedrates were about the same for each absorbent in both cases. Only two different Ca feedrates were used in these experiments and these are expressed in relative terms as the "normal" Ca feedrate and the "high" Ca feedrate.

Figure 4 shows a higher absorption ratio for cement dust than for lime or limestone and indicates that the absorption ratio is about the same for lime and limestone. Only a small amount of data was obtained for limestone due to the problems created by the excessive quantities of CO_2 released by this material which overpressured the absorber system. It would be expected that lime should show a higher absorption ratio than limestone and this was the case for the high Ca feedrate as shown in Figure 5. It can be seen that the absorption ratio for cement dust was comparable with that of lime at lower SO_2 concentrations but that the lime had a somewhat higher absorption ratio at the higher SO_2 concentrations.

Figure 4 - Absorption Ratio for Cement Dust, Lime, and Limestone (at "Normal" Ca Feedrate)

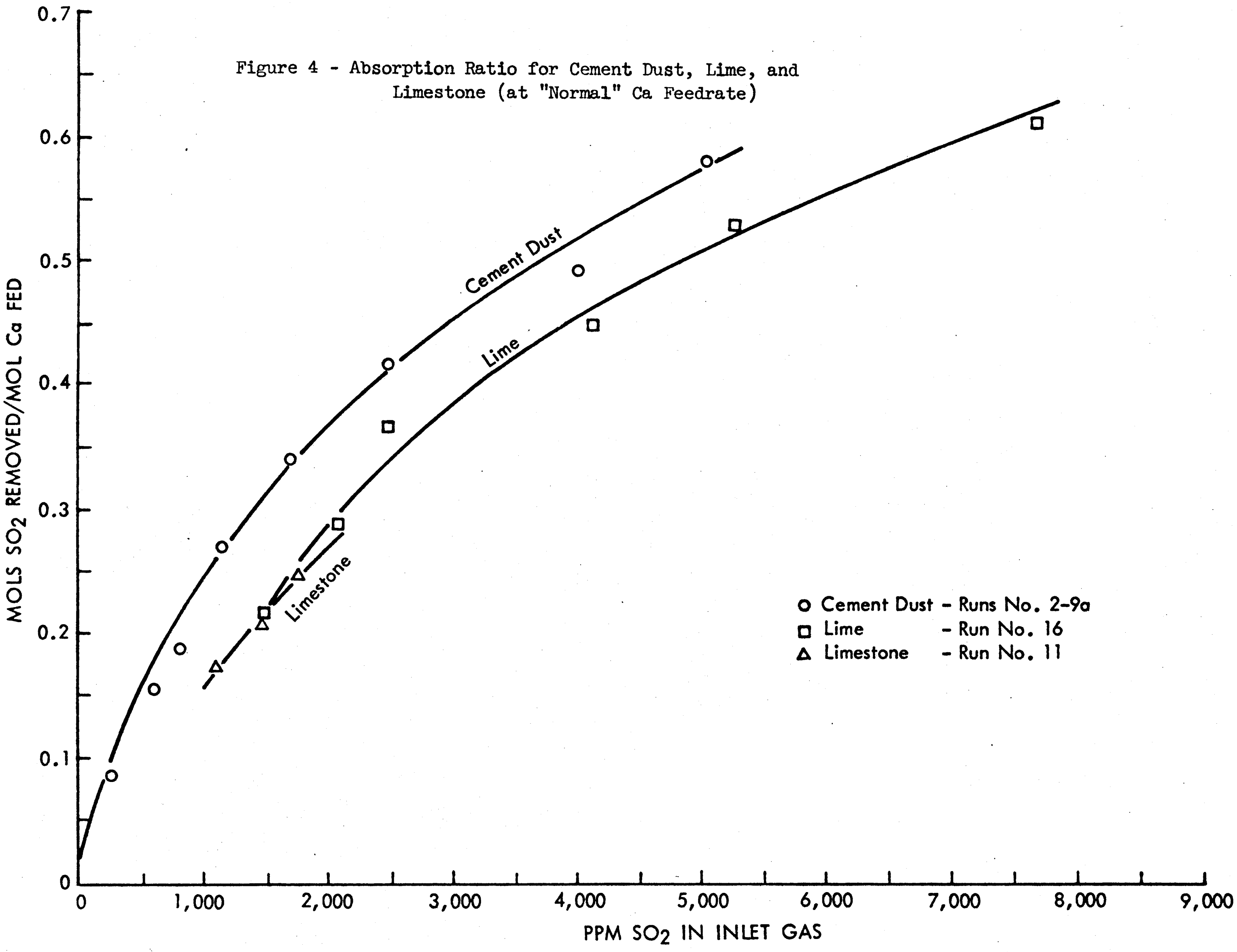
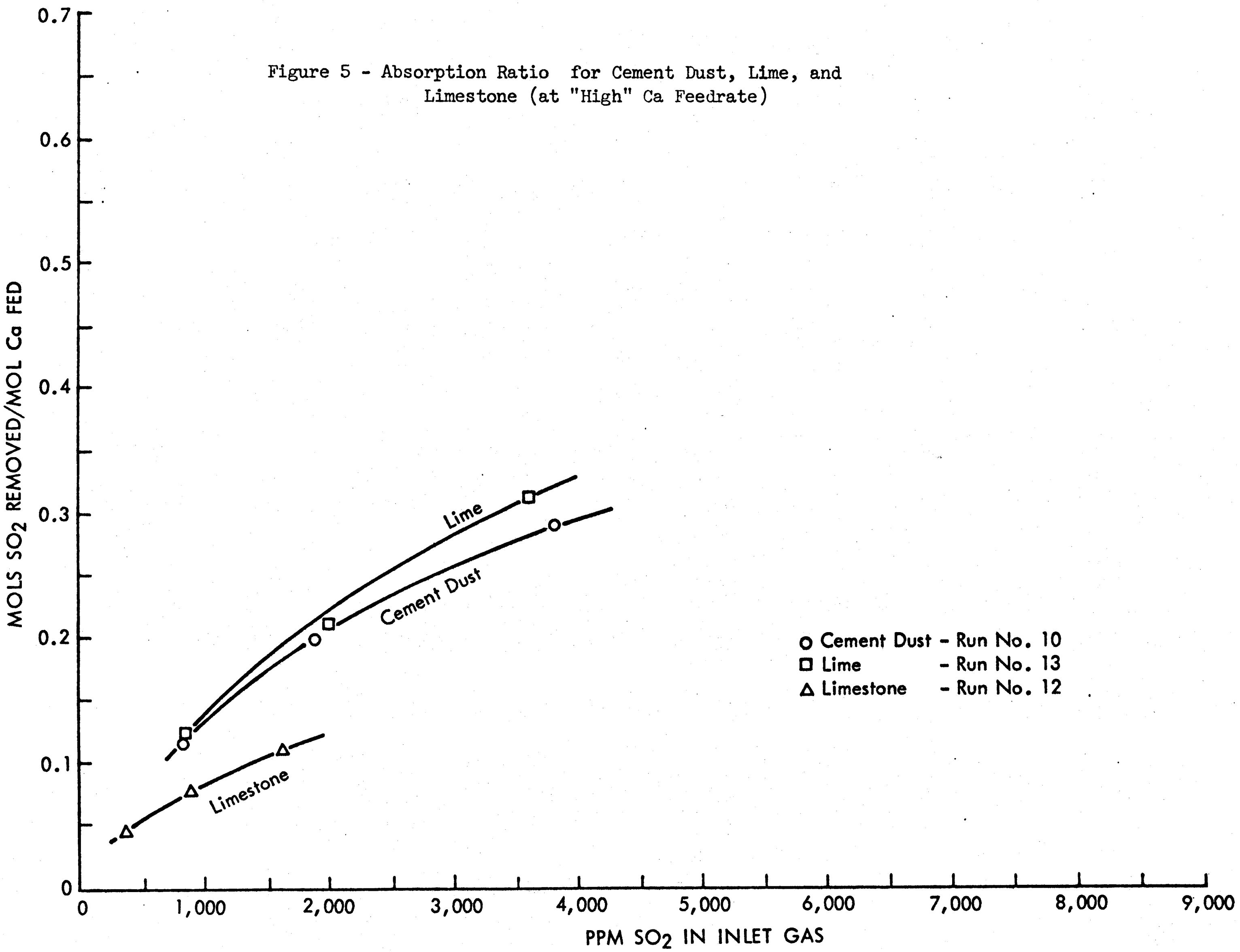


Figure 5 - Absorption Ratio for Cement Dust, Lime, and Limestone (at "High" Ca Feedrate)



It must be noted that the above data for lime in Figure 4 was obtained at calculated gas flowrates of 164-224 acfm while the data for cement dust was obtained at calculated gas flowrates that ranged from 235-387 acfm. The lower gas flowrates for lime would tend to show lower absorption ratios for this material. Subsequent investigation of the effect of gas flowrate on absorption ratios of lime (presented herein) indicates that much lower gas flowrates, i.e., Run No. 16 at an average gas flow of approximately 180 cfm compared to Run No. 15 at an average gas flow of approximately 50 cfm, could lower the absorption ratio by as much as 60-70%. However, the differences in gas flows for the data in Figures 4 and 5 are not nearly this great. The data obtained in these experiments were not sufficient to determine quantitatively the effect of such changes in gas flow on the absorption ratio. The partial data from Runs 13 and 14 for lime indicates that the effect of gas flowrate decreases in the region of higher gas flows for the experimental data depicted in Figures 4 and 5. The fact that lower gas flowrates do lower the absorption ratio probably explains why the absorption ratio curve for lime in Figure 4 is lower than that for cement dust. It could also be concluded that the curve for lime in Figure 5 might have been somewhat higher if the gas flow during Run No. 13 had been as high as that for cement dust (Run No. 10).

Based on the results shown in Figures 4 and 5, but considering the effect of gas flowrates discussed above, the following conclusions have been drawn:

1. The absorption ratio of cement dust is considerably better than that of limestone.
2. The absorption ratio of cement dust approaches that of lime.

Absorbent Feedrates

The effect of two different absorbent feedrates on the absorption ratio for each of the three absorbents is shown in Figures 6, 7, and 8. These figures show that absorption ratio was lower when the absorbent feedrate was higher. This does not mean that less SO_2 was removed at the higher absorbent feedrate. It does mean, however, that less SO_2 was removed per unit of absorbent fed.

Gas Flowrates

The effect of gas flowrate on the absorption ratio was investigated only for the lime absorbent. It was originally intended that this would be investigated for the other two absorbents. Problems encountered with the lime actually provided the data for this absorbent by necessitating more runs with the lime than had been planned which did not leave adequate time to conduct further experiments using the other two absorbents.

It is certainly significant that the problems encountered during the runs with lime provided some data on the effect of lower gas flow. This occurred because of increased scaling and plugging when using lime. Referring to the calculated gas flows for lime in

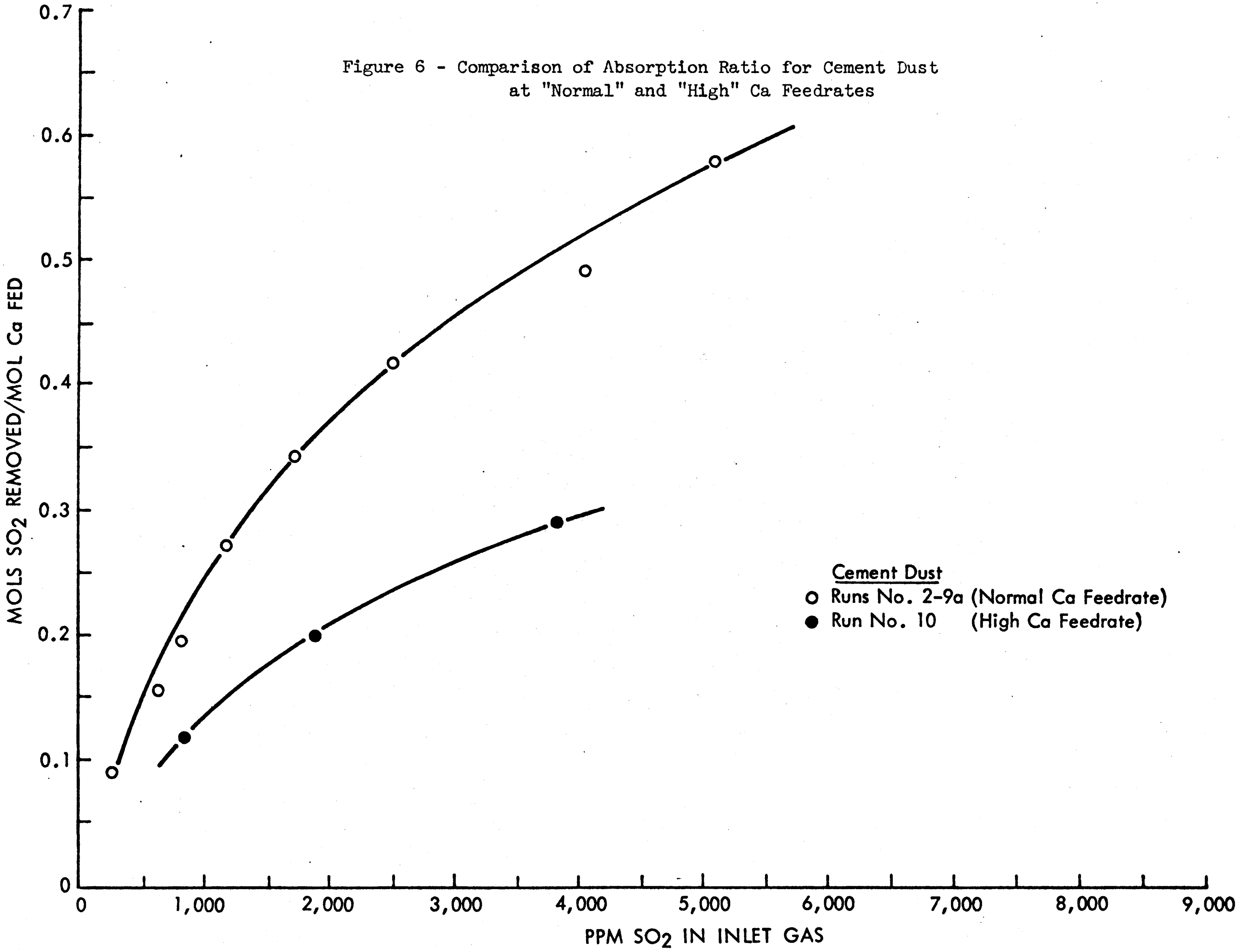
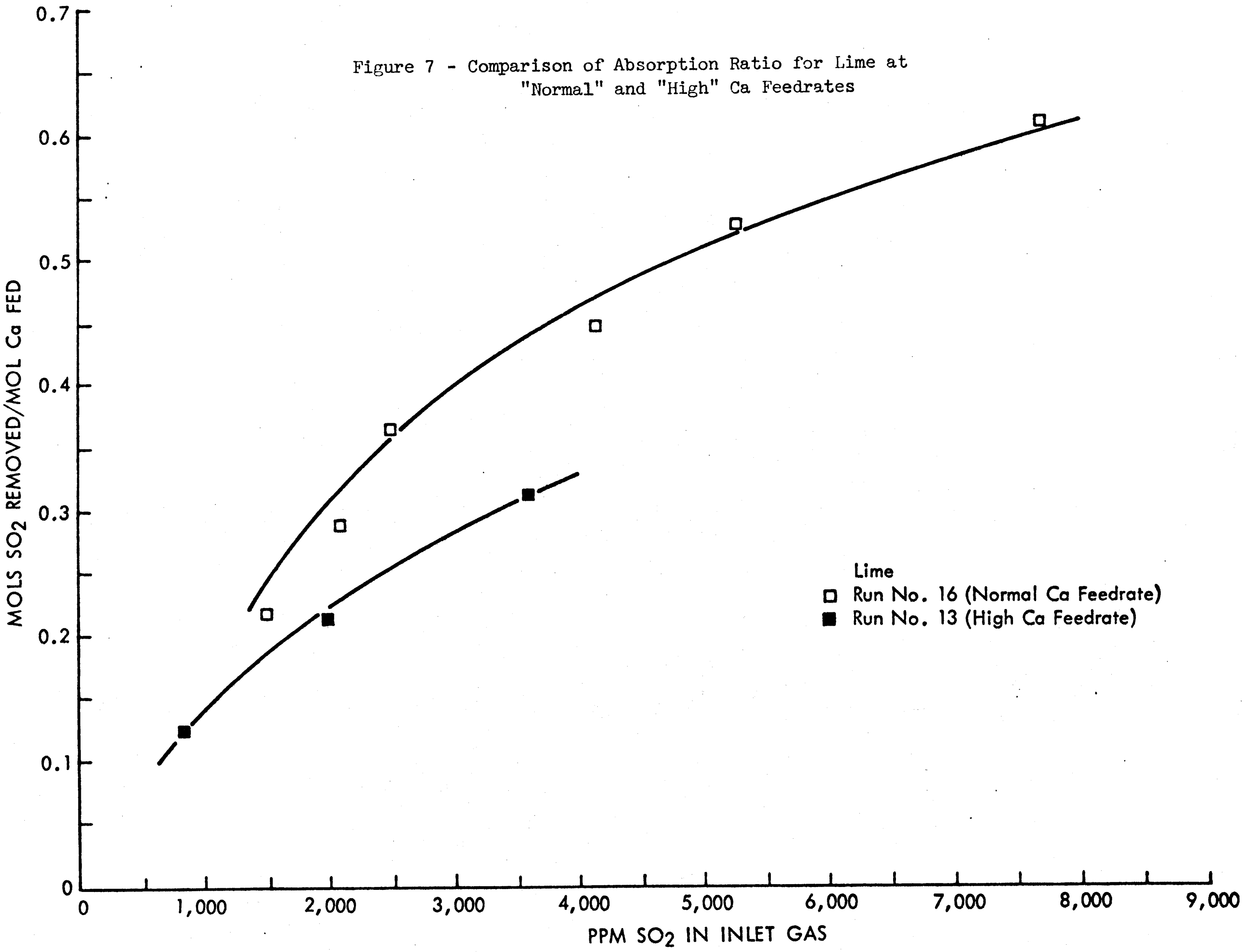


Figure 6 - Comparison of Absorption Ratio for Cement Dust at "Normal" and "High" Ca Feedrates

Figure 7 - Comparison of Absorption Ratio for Lime at "Normal" and "High" Ca Feedrates



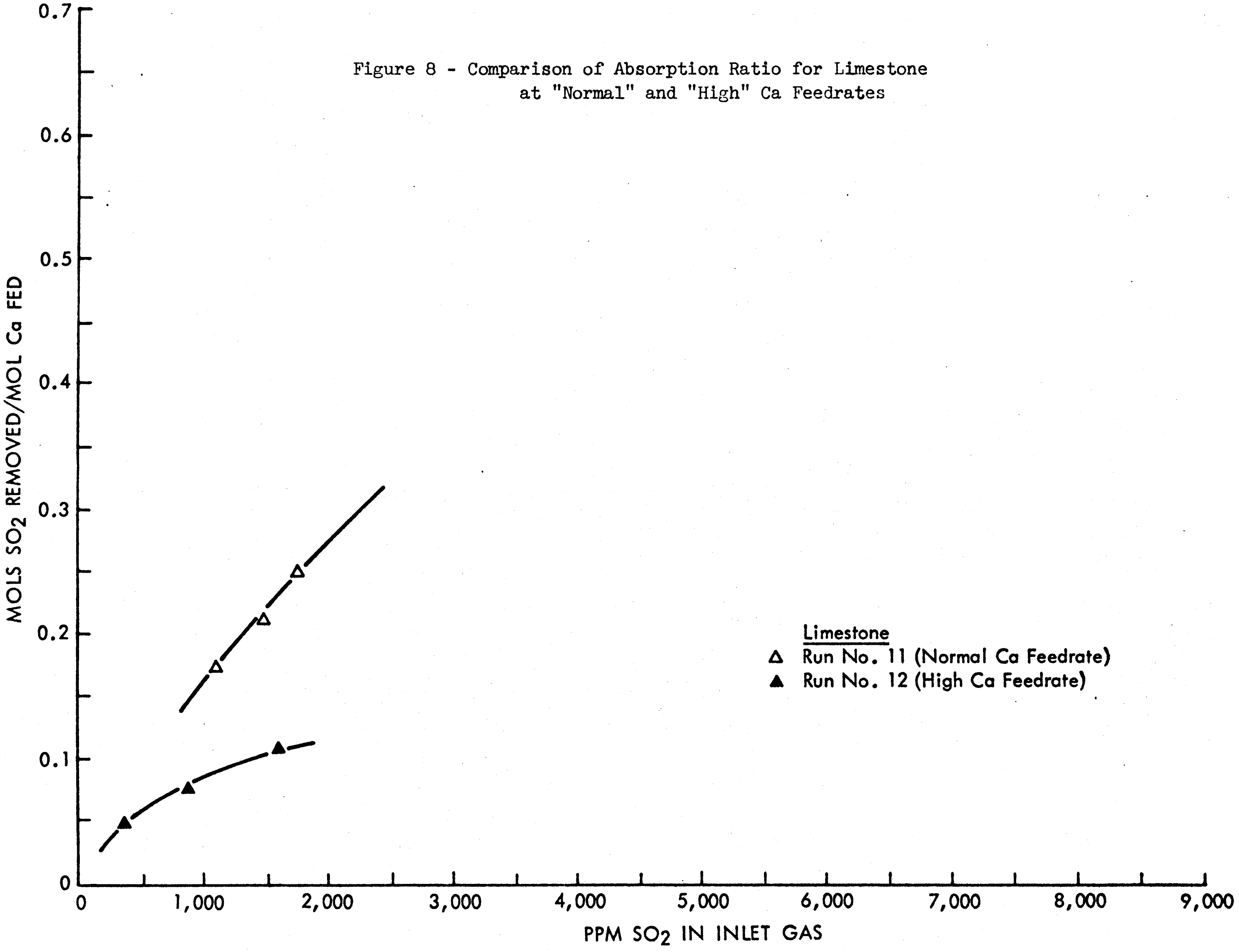


Figure 8 - Comparison of Absorption Ratio for Limestone at "Normal" and "High" Ca Feedrates

Table II (Runs Nos. 13-15) it can be seen that the gas flowrate was decreasing and was severely restricted in Run No. 15. Inspection of the absorber following this run showed that the scale on the marbles was as much as 1/8 in. thick. The absorber was cleaned up prior to Run No. 16 although some scaling was indicated even during this run when the sides of the absorber clouded over within the first 30 min of the run. This scaling and plugging is the same problem that has been experienced in the full scale units. This indicates another possible advantage of using cement dust since the scaling during the first 10 runs using cement dust was minimal.

The effect of decreased gas flowrate on the absorption ratio (for lime) is clearly shown in Figure 9 for two large differences in gas flowrate. However, these data do not permit determination of the effect on absorption ratio at other gas flowrates which would have been useful.

Partial data on the effect of gas flowrates is also shown in Figure 10, in which each data point was at a different gas flowrate (Runs Nos. 13 and 14). Due to lack of data, the information in Figure 10 is incomplete so dashed lines have been used to help separate and identify the data. It is difficult to draw conclusions from the data in Figure 10 except that, as in Figure 9, it too shows that absorption ratio is much lower at low gas flowrates. Considering the general

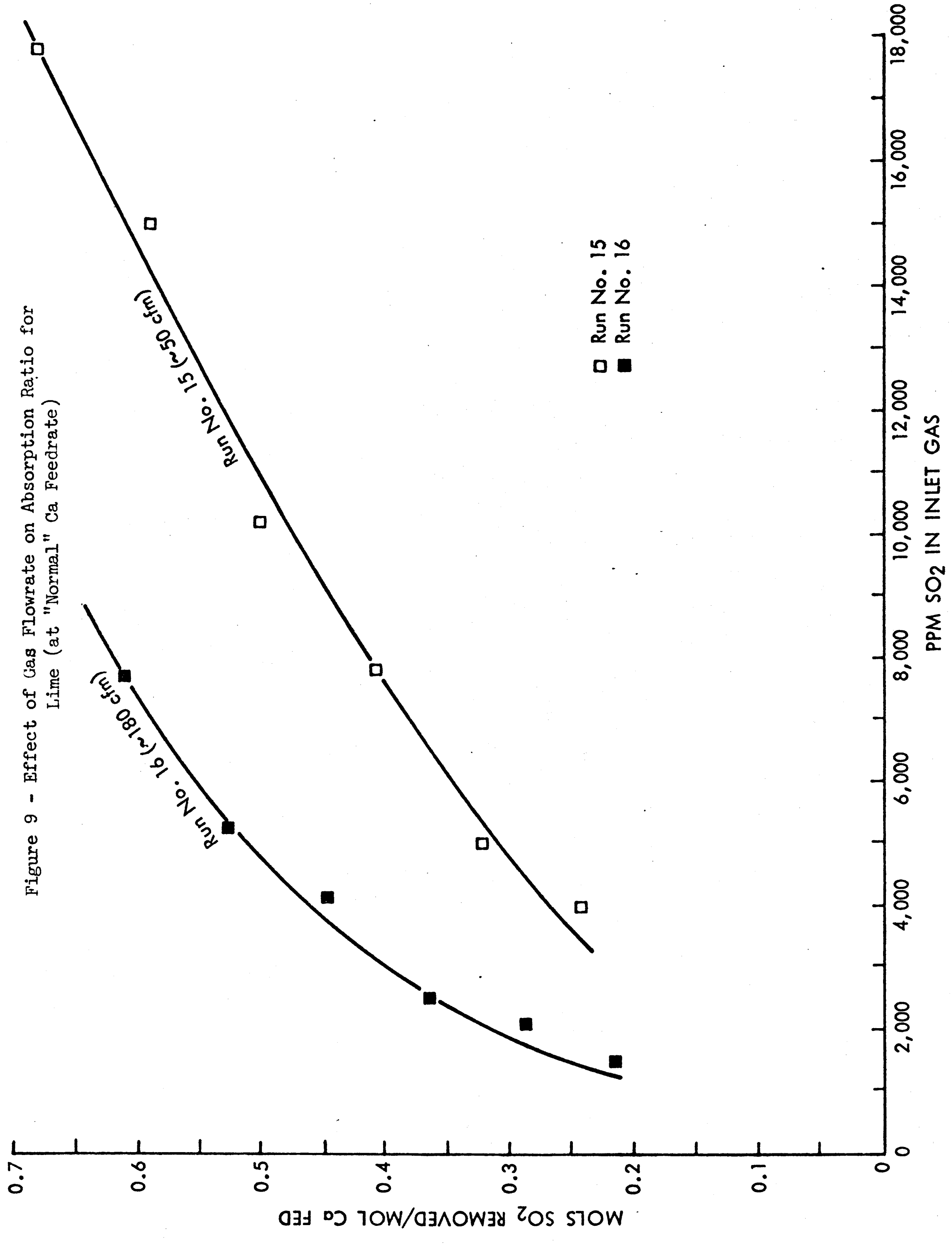


Figure 9 - Effect of Gas Flowrate on Absorption Ratio for Lime (at "Normal" Ca Feedrate)

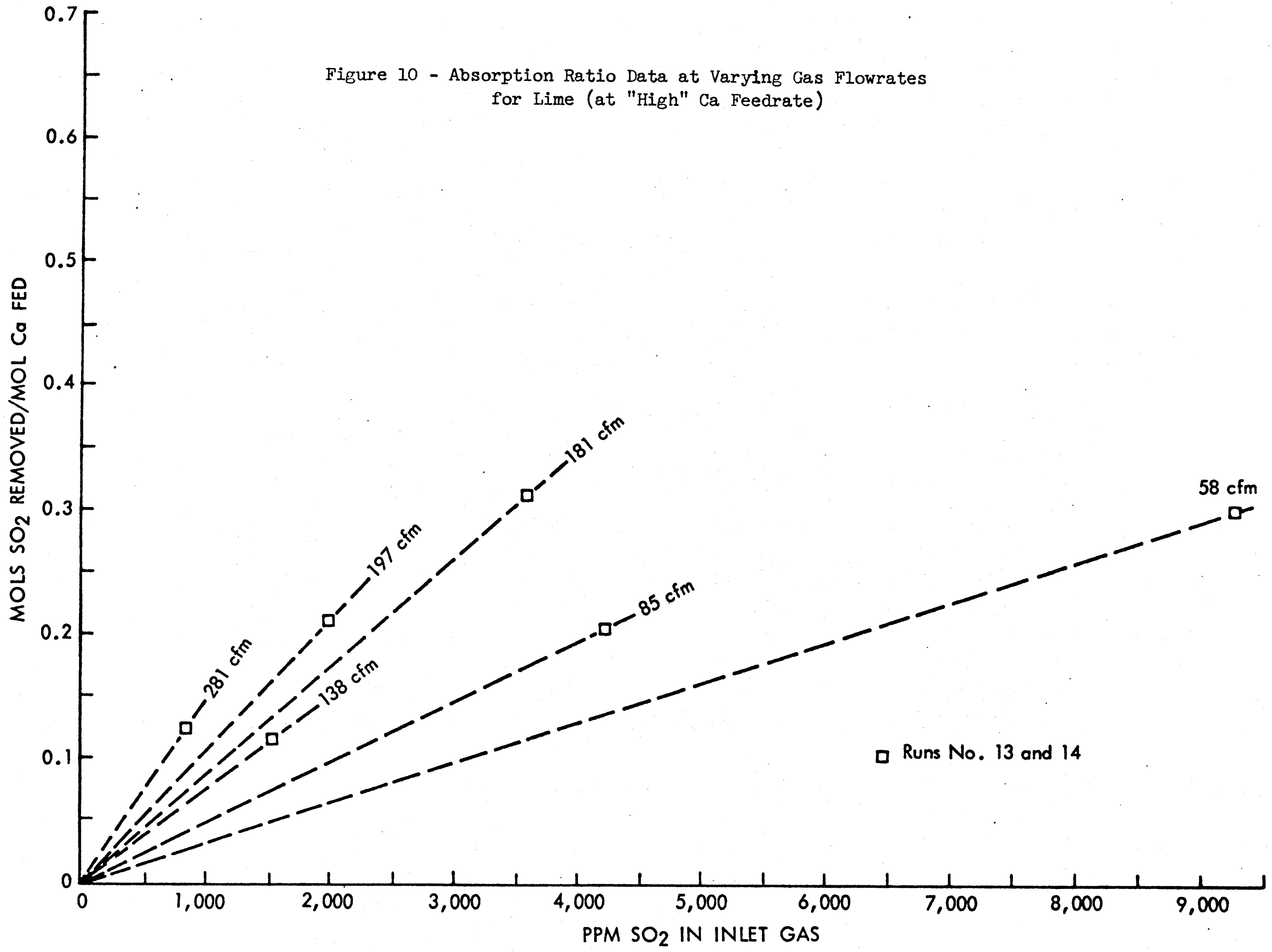


Figure 10 - Absorption Ratio Data at Varying Gas Flowrates for Lime (at "High" Ca Feedrate)

shape of the curves in Figure 9, and in previous figures, it was concluded that effect of gas flowrate probably decreases at the higher gas flowrates.

Slurry Flowrate

Only one run was conducted in an effort to investigate the effect of increased slurry flowrate (at constant absorbent feedrate). This was done in Run No. 9 using cement dust. The results was that the increased slurry flow raised the height of the frothing liquid above the marble bed and decreased the gas flowrate. Therefore, the results shown in Figure 11 reflect the effect of both increased slurry flow and decreased gas flow.

Figure 11 gives a comparison of the absorption ratio data at increased slurry flow (and decreased gas flow) with the data for the previous runs using cement dust (Runs Nos. 2-8). Data point 9a should fall on the same curve as Runs Nos. 2-8 because this represents the same operating conditions before the slurry flow was increased. At the higher slurry flowrate, data point 9b is actually closer to this curve while 9c is somewhat below this curve. It is concluded that the increased slurry flowrate and the decreased gas flow, in this region of gas flowrates, did not significantly affect the absorption ratio.

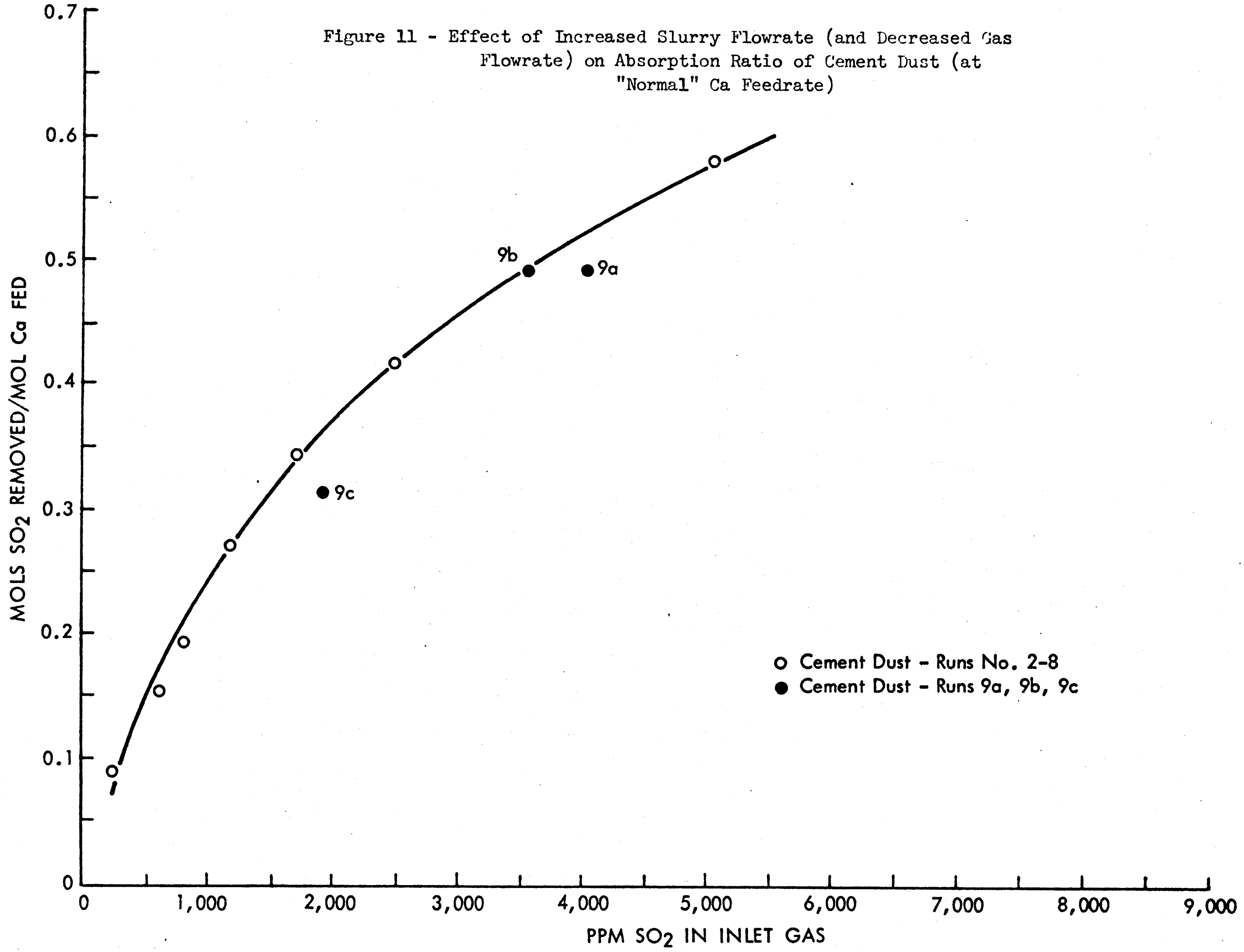


Figure 11 - Effect of Increased Slurry Flowrate (and Decreased Gas Flowrate) on Absorption Ratio of Cement Dust (at "Normal" Ca Feedrate)

CHAPTER VII

RECOMMENDATIONS

The main purpose of this investigation was to determine the effectiveness of a cement dust slurry as an absorbent for removal of SO_2 in comparison with similar slurries of lime and limestone. It has been concluded that the cement dust is a better absorbent than limestone and that its effectiveness approaches that of lime. It is, therefore, recommended that a pilot scale test program be conducted to further investigate the use of this absorbent in a system that would duplicate a full scale scrubber-addition process.

A pilot scale unit should preferably be installed at an actual coal-fired power plant, with a side stream of the dust-laden exhaust gases connected to a complete pilot scale system. This system would utilize once-through gas flow at actual operating temperatures and include a recirculating slurry process and instrumentation to continuously monitor the inlet and outlet SO_2 concentrations.

The primary purpose of the pilot scale unit would be to determine the minimum quantity of cement dust required to achieve the same reduction in SO_2 emissions as the full scale scrubbing systems. This would include investigation of the following parameters:

1. Absorbent feedrate
2. Slurry recirculation rate (liquid-to-gas ratio)

3. Slurry concentration
4. Inlet gas temperature

In addition to the above, cement dusts collected by different cement plants should be tested in the pilot scale system to determine if there are any significant differences in their ability to remove SO_2 and to determine any tendency to scale or corrode the scrubber system.

Data collected from the pilot scale system would be used to compare the other limestone scrubbing processes with the cement dust-scrubber addition process. This, of course, would include consideration of shipping costs of the absorbents and an estimate of the price to be paid for the cement dust.

APPENDIX A

EQUIPMENT RECORD

Figure A-1 - Drawing of Absorber

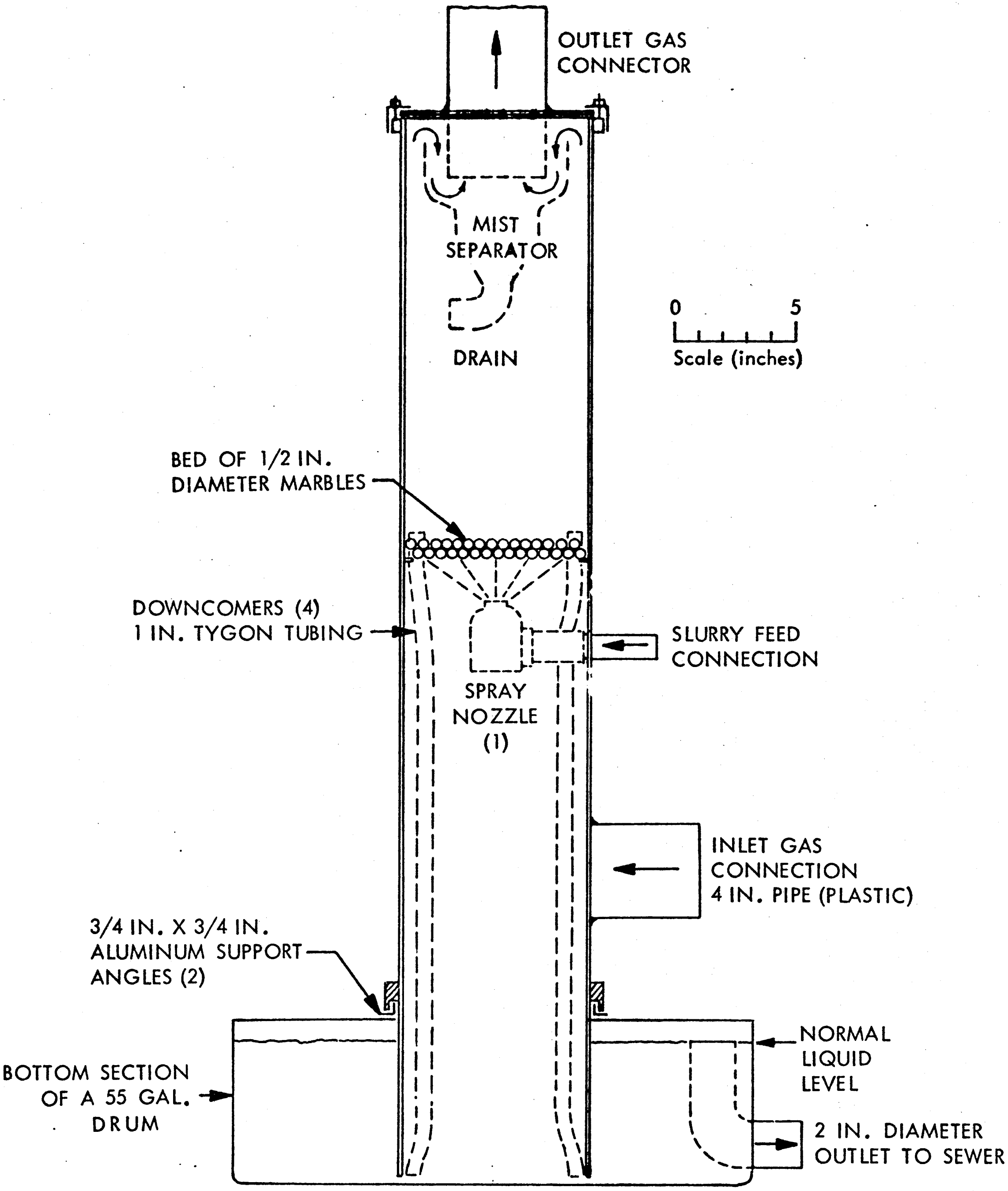


Figure A-2 - Gas Sampling Apparatus

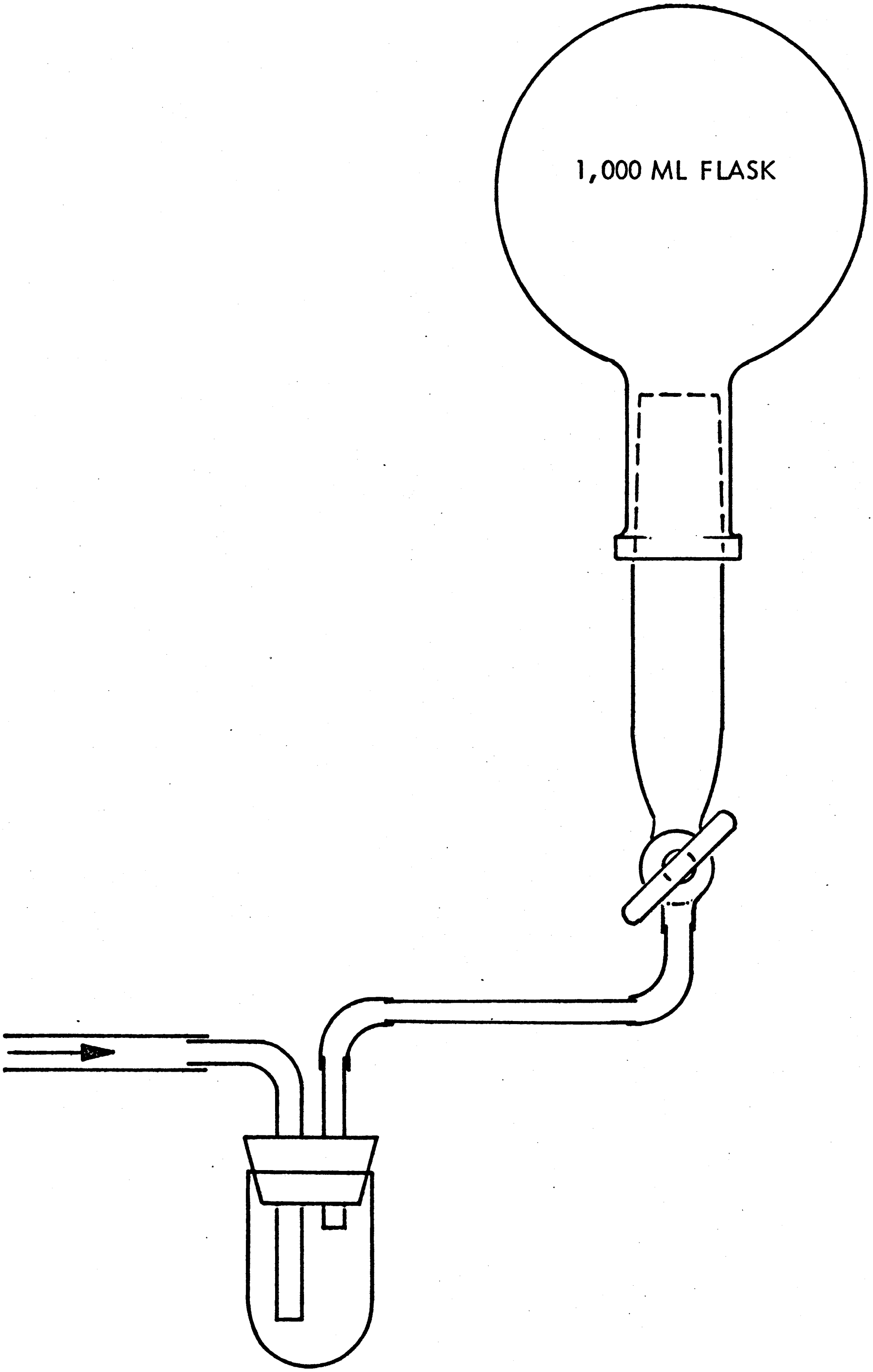


TABLE A-1

EQUIPMENT RECORD

Slurry Rotameter

Fischer and Porter Company
Model 10A1027 A
Serial No. 6801 A 4627 A1
MRI E-200
Marked: 100% = 12.4 GPM for lig Sp Gr 1.0

Fischer and Porter Company Precision Bore Flowrator
  Tube No. B6-35-10/27

SO_2 Rotameter

Fischer and Porter Company Precision Bore Flowrator
  Tube No. 2-L-150/13

Marked: 0-15

CO_2 Rotameter

Fischer and Porter Company Precision Bore Flowrator
  Tube No. 2-F 1/4-20-5/70
Marked: 0-20
Serial No. LK-73550
MRI 5945

Slurry Pump (Moyno)

MRI S-123
Motor 1/2 HP 1,725 RPM

Blower

Laboratory Construction Company, Kansas City, Missouri
  (12 in. O.D.) no other markings on blower

Motor: Capacitor Type
1/2 HP 3,450 RPM

APPENDIX B

EXAMPLE DATA AND CALCULATION METHODS

(INCLUDING ALL CALIBRATION CURVES)

TABLE A-1 (Concluded)

Vibra-Screw Feeder

Serial No. 508

w/Graham Variable Speed Transmission

Synthetic Flue Gas

Air Products Calibration Gas Standard

0.30% SO_2
3.13% O_2
16.1% CO_2

in nitrogen

Lime

Ash Grove

Cal-Max Pulverized Quicklime 50 lb CaO

High Calcium Lime

Exceeds quality standards of all ASTM Specifications covering high-calcium quicklime for chemical and industrial uses, etc.

Limestone

Ground Limestone

Produced by Centropolis Crusher, Inc., 2701 Manchester Trafficway, Kansas City, Missouri 50 lb

The experimental data recorded for Run No. 16 is shown in Table B-1. Similar data were taken in all other runs. Example calculation methods used in analyzing and converting these data are shown on the succeeding pages for the following items:

a. SO_2 Concentrations

b. SO_2 Feedrate

c. Absorbent Feedrate

d. Slurry Concentration

e. Gas Flowrate

f. Mols SO_2 removed/mol Ca

g. Slurry Flowrate

TABLE B-1

EXAMPLE DATA (RUN NO. 16)

Initial Purge with Synthetic Flue Gas

Barometric Pressure:
29.30 in. Hg

	Quicklime Feed			Gas Analysis	
Time	Vibrascrew Setting	Feed Rate (lb/min)	Setting on CO_2 Rotameter	CO_2 (%)	O_2 (%)
Prestart	2.2	0.121, 0.123			
4:35			9.0	10.0	3.5
5:17			9.0	18.0	2.0
5:47			8.0	25.0	1.5
Finish	2.2	0.139, 0.138			

		SO_2 Conc.		Slurry Samples		
				Inlet		Outlet
Gas Samples	Time	Inlet (ppm)	Outlet (ppm)	Conc. (%)	pH	pH
1	4:45	1,500	280	0.55	12.4	11.9
2	5:02	2,090	455			
3	5:18	2,505	678	0.62	12.4	8.5
4	5:35	4,150	1,910			
5	5:54	5,270	2,840	0.59	12.5	5.5
6	6:15	7,700	5,170			

		SO_2 Rotameter					System Pressures in in. H_2O				pH Readings	
	Time	Rdg.	Temp. (°F)	Pressure in. of H_2O	Slurry Rotameter Reading	Gas Stream Temp. (°C)	Inlet Pipe	Below Bed	Above Bed	Outlet Pipe	Feed Tank	Outlet Tank
Start-SO_2	4:30	4.0			22							
	4:40	4.0	73	2.0	23	26	2.8	3.8	1.6	- 1.1	12.3	11.9
	4:47	Increased SO_2 to 5.0										
	5:00	5.0	74	3.9								
	5:03	Increased SO_2 to 6.0										
	5:10	6.0	74	6.2	23	26	3.5	4.8	2.4	- 0.5	11.6	10.2
	5:20	Increased SO_2 to 7.0										
	5:30	7.0	74	9.2								
	5:36	Increased SO_2 to 8.0										
	5:45	8.0	74	12.1	23	27	3.8	4.9	2.1	- 0.6	11.9	5.5
	5:58	Increased SO_2 to 9.0										
	6:10	9.0	74	15.4								4.9
Stop-SO_2	6:18											

Note: Film on scrubber obscuring vision after first 30 min of run.

a. Determine SO_2 Concentration

The gas sample grabbed in the 1,000 ml evacuated flask was expanded into the IR cell by the method previously described. The pressure in the IR cell was recorded and the cell was inserted into the spectrometer.

Inlet Gas Sample No. 1 (4:45 p.m.)

Pressure in IR Cell - 286 mm Hg

Transmittance (from Figure B-1) = $\frac{37.8}{97.5}$ = 38.8%

Partial Pressure of SO_2 in IR Cell = 0.428 mm Hg (from Figure B-3)

SO_2 Concentration = $\frac{0.428 \text{ mm}}{286 \text{ mm}}$ = 0.001500 = 1,500 ppm

Outlet Gas Sample No. 1 (4:45 p.m.)

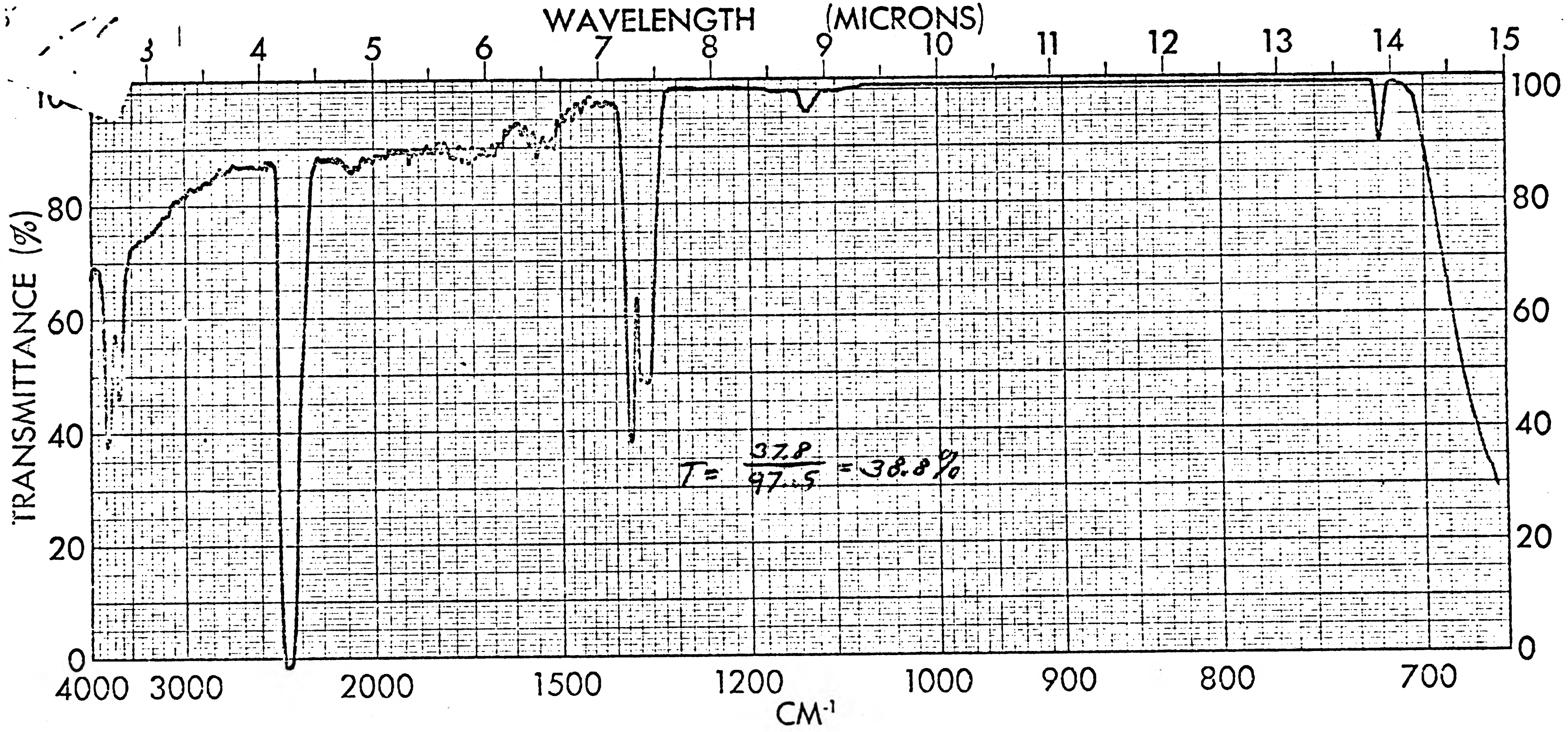
Pressure in IR Cell - 278 mm Hg

Transmittance (from Figure B-2) = $\frac{81.8}{98.0}$ = 83.4%

Partial Pressure of SO_2 in IR Cell = 0.078 mm Hg (from Figure B-3)

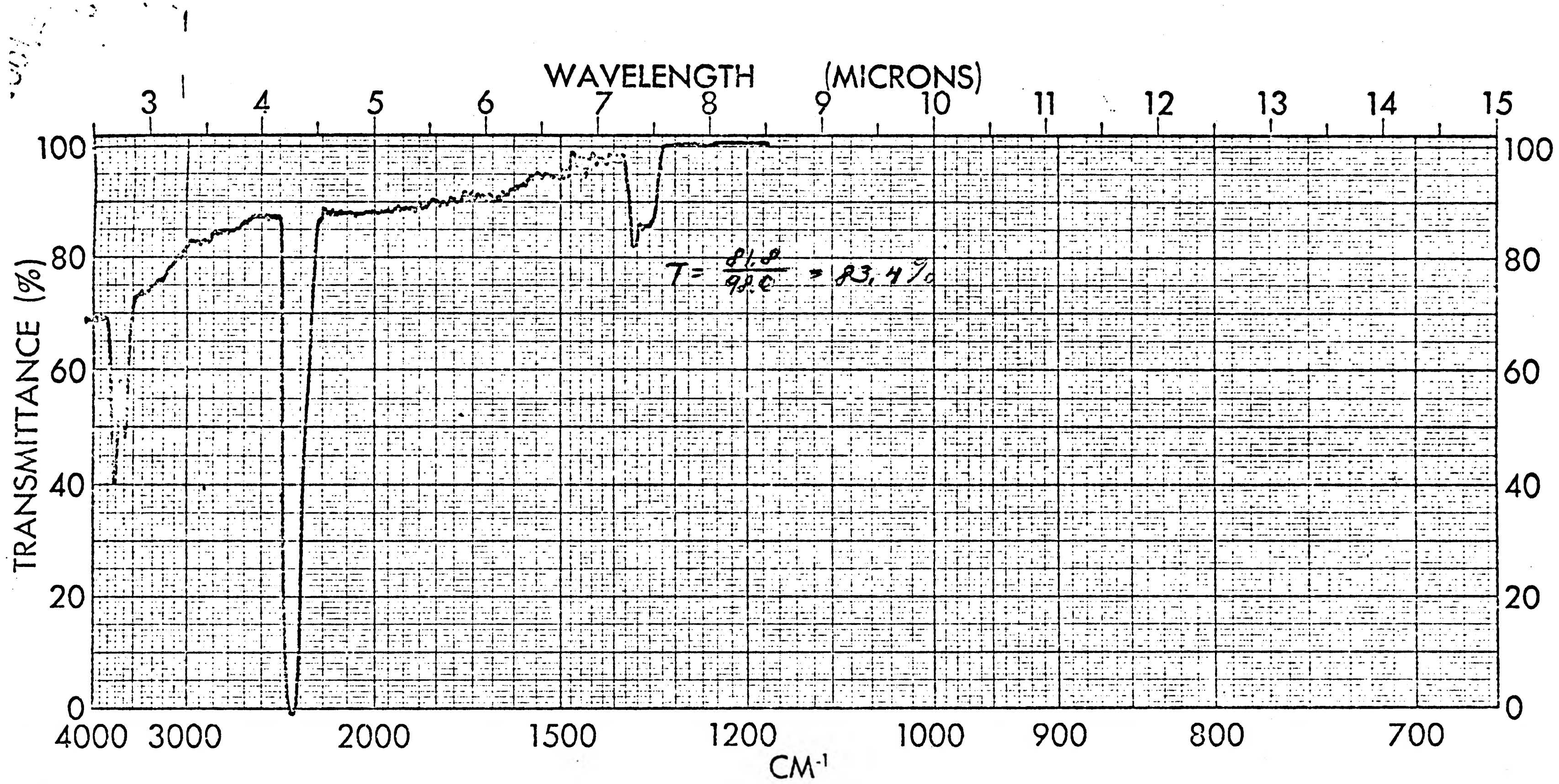
SO_2 Concentration = $\frac{0.078 \text{ mm}}{278 \text{ mm}}$ = 0.000280 = 280 ppm

Figure B-1 - No. 1 Inlet Sample Infrared Spectrum



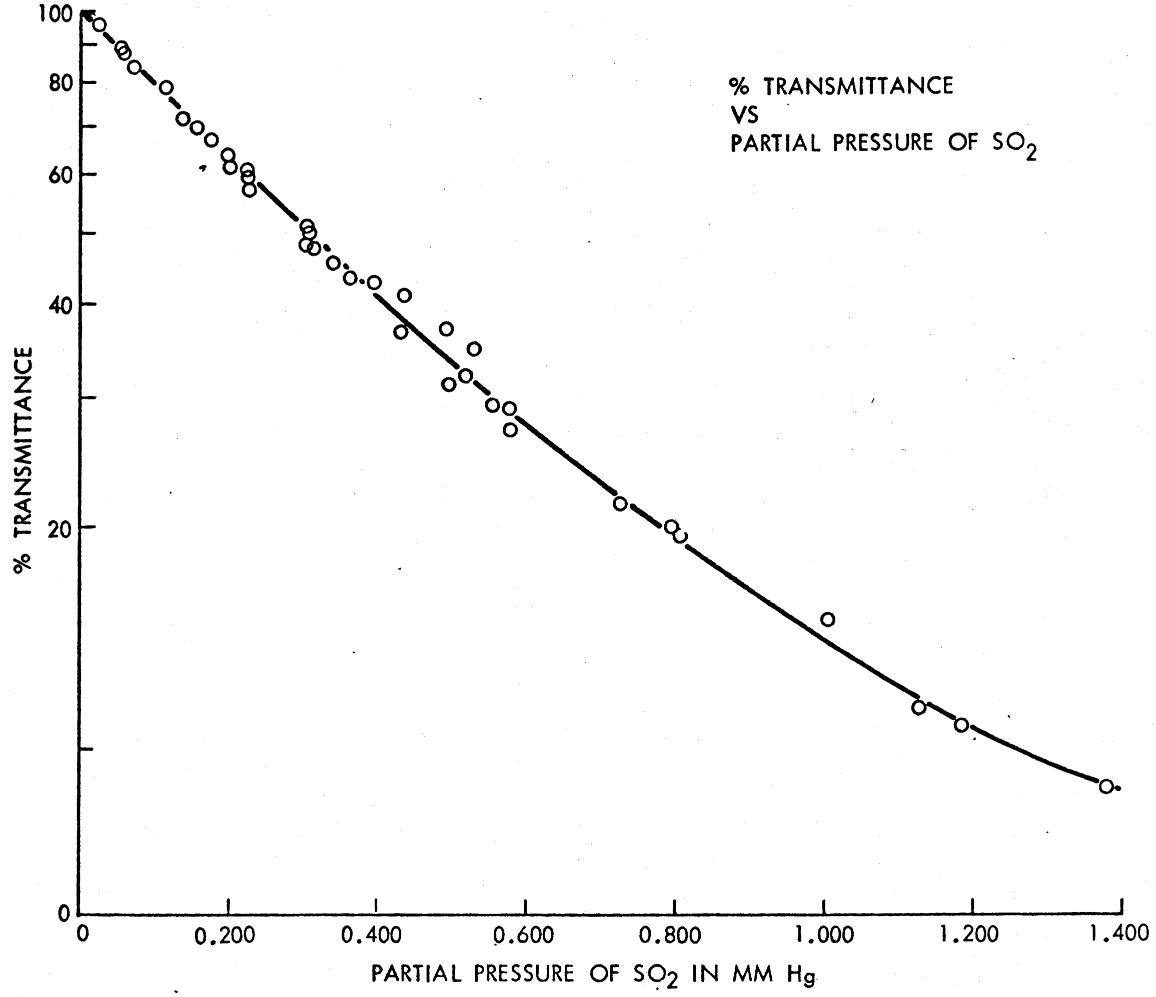
$T = \frac{37.8}{97.5} = 38.8\%$

Figure B-2 - No. 2 Outlet Sample Infrared Spectrum



$T = \frac{81.8}{98.0} = 83.4\%$

Figure B-3 - Infrared Calibration Curve



b. Calculate SO_2 Feedrate

Recorded Data:

SO_2 Rotameter Reading: 4.0

SO_2 Temperature at Rotameter: 73°F

SO_2 Pressure at Rotameter: 2.0 in. of H_2O

Barometric Pressure: 29.3 in. of Hg

SO_2 Pressure at Rotameter = 29.3 in. Hg +

$$\frac{2.0 \text{ in. } H_2O}{13.6 \text{ in. } H_2O/\text{in Hg}} = 29.45 \text{ in. Hg}$$

Density (ρ) of SO_2 at Std. Cond. (60°F, 29.92 in. Hg) = 0.169 lb/cf

$$\text{Density of } SO_2 \text{ at Rotameter} = 0.169 \left(\frac{520}{460 + 73}\right)\left(\frac{29.45}{29.92}\right) =$$

0.162 lb/cf

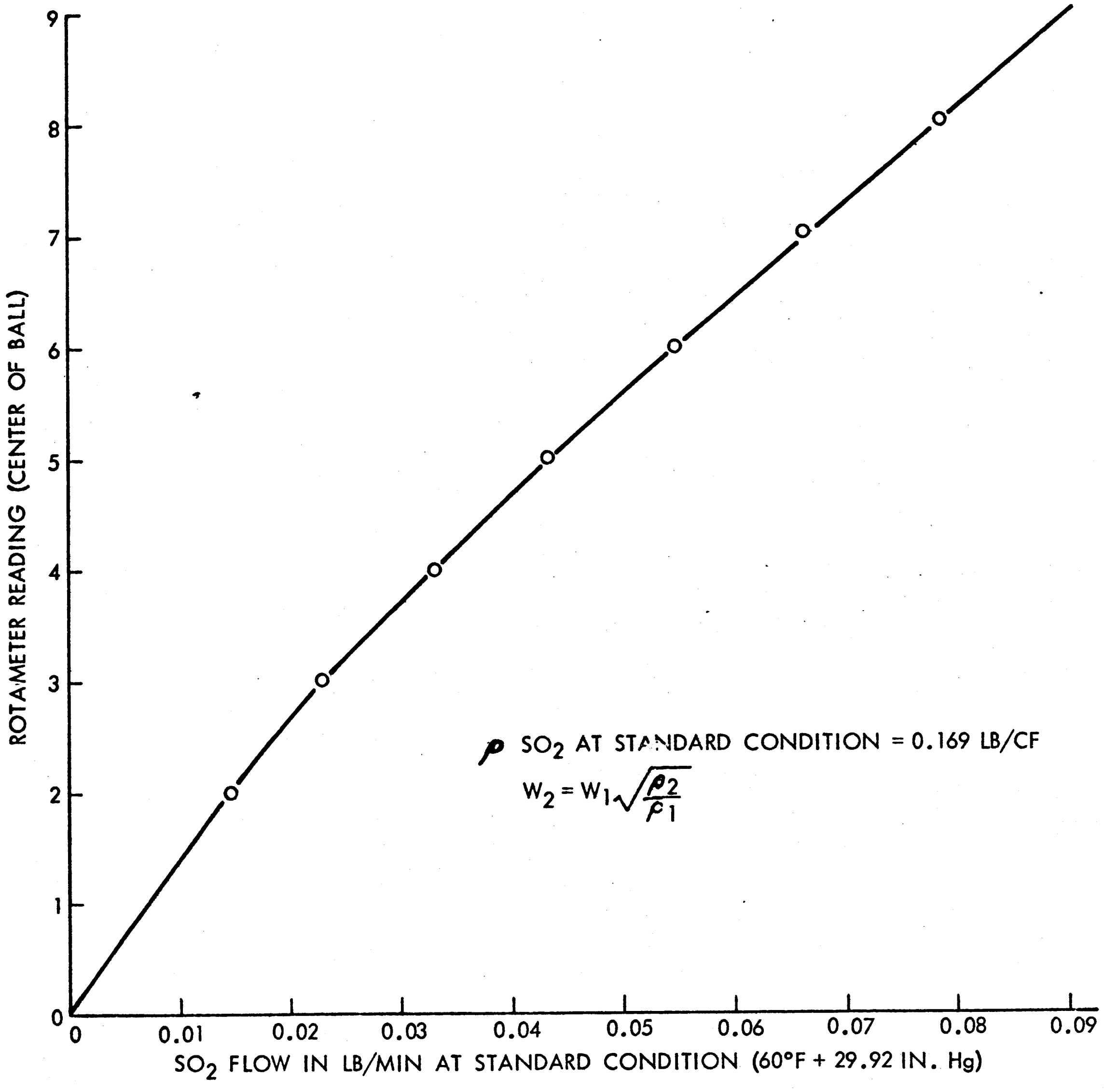
Rotameter Reading of 4.0 = 0.0330 $\frac{\text{lb } SO_2}{\text{min}}$ (from Figure B-4) (at Std. Cond.)

$$\text{Actual } SO_2 \text{ Flow} = 0.0330 \sqrt{\frac{0.162}{0.169}} = 0.0323 \ \frac{\text{lb } SO_2}{\text{min}}$$

$$\frac{0.0323 \ \frac{\text{lb } SO_2}{\text{min}}}{64 \ \frac{\text{lb } SO_2}{\text{lbmol } SO_2}} = 0.000505 \ \frac{\text{lbmol } SO_2}{\text{min}}$$

$$\left(0.000505 \ \frac{\text{lbmol } SO_2}{\text{min}}\right) \left(379 \ \frac{\text{SCF}}{\text{lbmol}}\right) = 0.191 \ \frac{\text{SCF } SO_2}{\text{min}}$$

Figure B-4 - Calibration Curve for SO_2 Rotameter



c. Calculate Average Feedrate of Absorbent

$$\text{Feedrate measured at beginning of run: } \begin{cases} 0.121 \text{ lb/min} \\ 0.123 \text{ lb/min} \end{cases}$$

$$\text{Feedrate measured at end of run: } \begin{cases} 0.139 \text{ lb/min} \\ 0.138 \text{ lb/min} \end{cases}$$

Average Absorbent Feedrate = 0.130 lb/min

Ca content of absorbent = 71.4%

$$\text{Ca feedrate} = \left(0.130\ \frac{\text{lb absorbent}}{\text{min}}\right)(0.714)\left(\frac{\text{mol Ca}}{40\ \text{lb Ca}}\right) =$$

$$0.00232\ \frac{\text{mol Ca}}{\text{min}}$$

d. Determine Concentration of Solids in Feed Slurry

The slurry grab sample was filtered and the volume of filtrate was measured. The filter paper and residue were dryed at room temperature for 24 hr and weighed.

Final weight of filter paper and residue	1.151 g
Initial weight of filter paper	0.770 g
Weight of Residue	0.381 g

Volume of Filtrate = 69 ml

$$\text{Solids in Slurry} = \frac{0.381}{69 + 0.38} = 0.0055 = \underline{\underline{0.55\%}}$$

e. Calculate Gas Flowrate

Calculation is based on the known SO_2 feedrate and the resultant increase in the SO_2 concentration in the gas stream.

Recorded Barometric Pressure = 29.3 in. Hg

Gas Stream Temperature = 26°C = 79°F

SO_2 Feedrate (Appendix B, pg.65) = $0.191 \frac{\text{SCF } SO_2}{\text{min}}$

SO_2 Feedrate at Absorber Temperature and Pressure:

$$(0.191 \frac{\text{SCF } SO_2}{\text{min}}) \ (\frac{29.92}{29.30} \times \frac{460 + 79}{520}) = 0.202 \frac{\text{ACF } SO_2}{\text{min}}$$

Inlet SO_2 Concentration = 1,500 ppm

Outlet SO_2 Concentration = 280 ppm

Change in SO_2 Concentration = 1,220 ppm

(from Appendix B pg.61) or

$$0.001220 \frac{\text{cf } SO_2}{\text{cf Gas}}$$

$$\text{Calculated Gas Flow} = \frac{0.202 \frac{\text{ACF } SO_2}{\text{min}}}{0.001220} = \underline{\underline{166 \text{ ACF/min}}}$$

f. Calculate $\frac{\text{mols } SO_2 \text{ removed}}{\text{mols Ca fed}}$

SO_2 Feed = SO_2 Removed = 0.000505 $\frac{\text{lbmol } SO_2}{\text{min}}$

(from Appendix B, pg. 65)

Ca Feed = 0.00232 $\frac{\text{lbmol Ca}}{\text{min}}$

(from Appendix B, pg. 67)

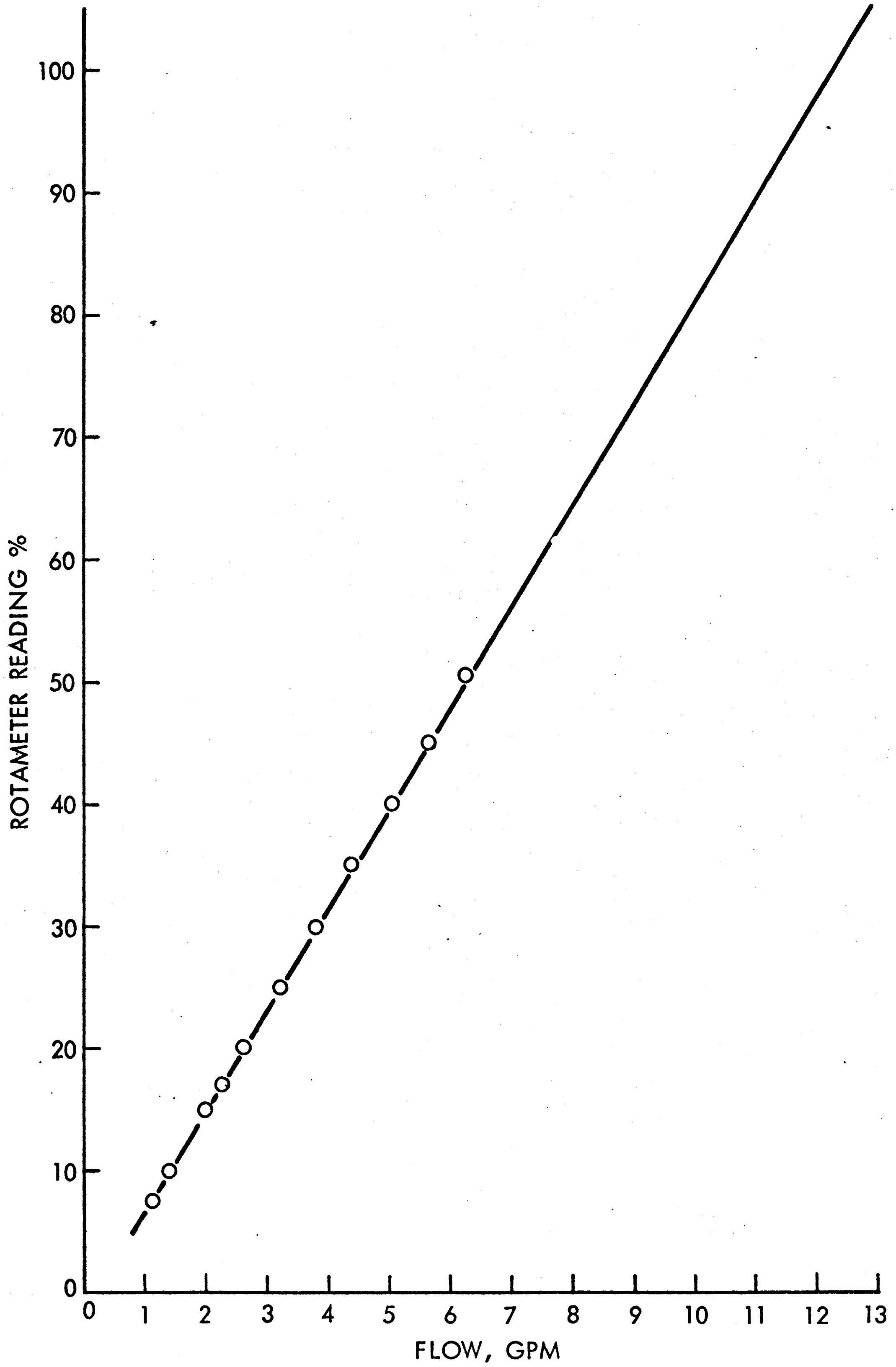
$$\frac{\text{mols } SO_2 \text{ removed}}{\text{mol Ca fed}} = \frac{0.000505}{0.00232} = \underline{\underline{0.218}}$$

g. Determine Slurry Flowrate

Average Slurry Rotameter Reading: 23 (from Table B-1)

Slurry Flow (from Figure B-5) = 3.0 gpm

Figure B-5 - Calibration Curve for Slurry Rotameter



APPENDIX C

PARTICLE SIZE DISTRIBUTION

For

Cement Dust, Limestone and Lime

by

Bahco Microparticle Classifier
(Courtesy of Pedco-Environmental, Cincinnati, Ohio)

Figure C-1 - Cement Dust Size Distribution

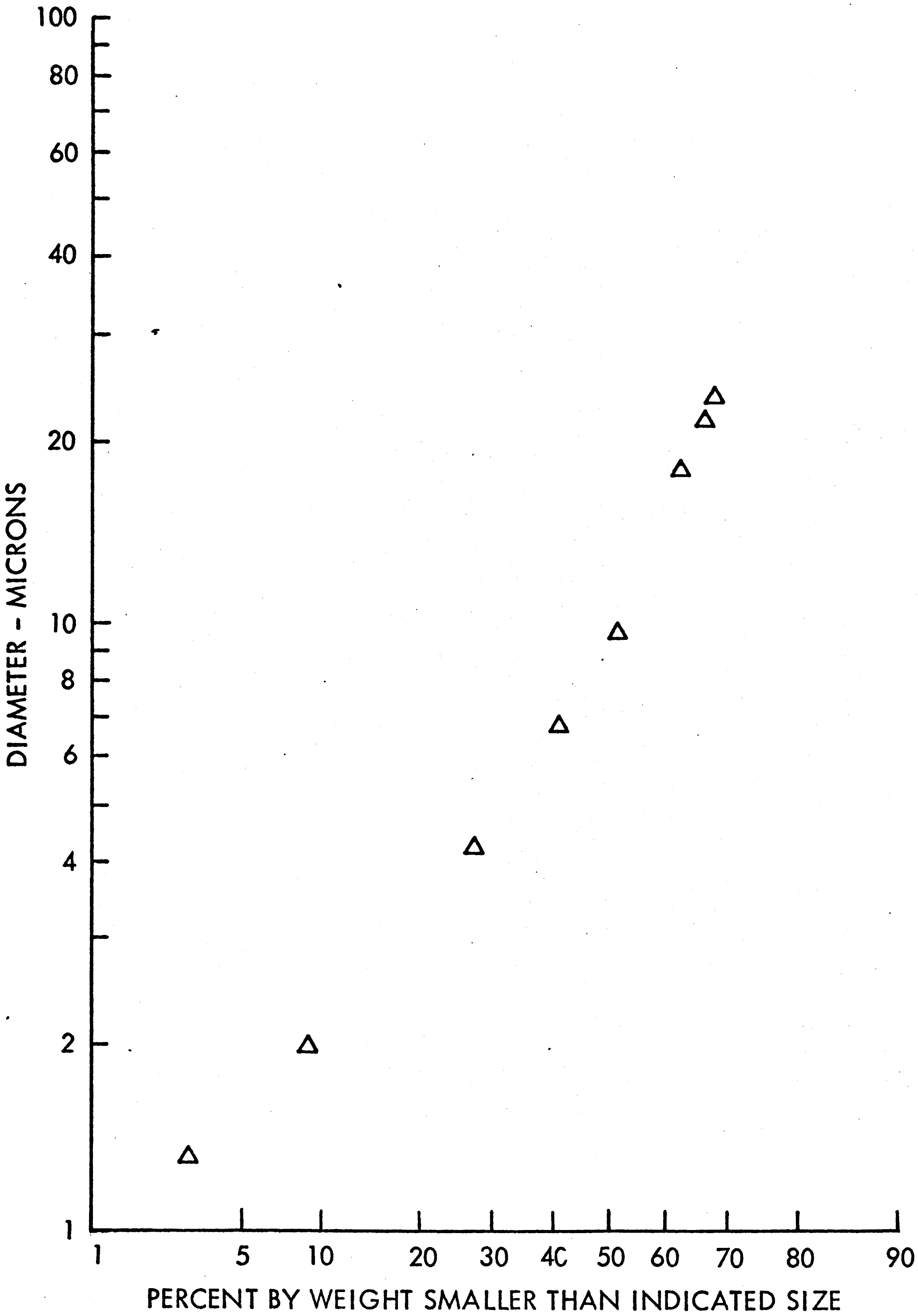
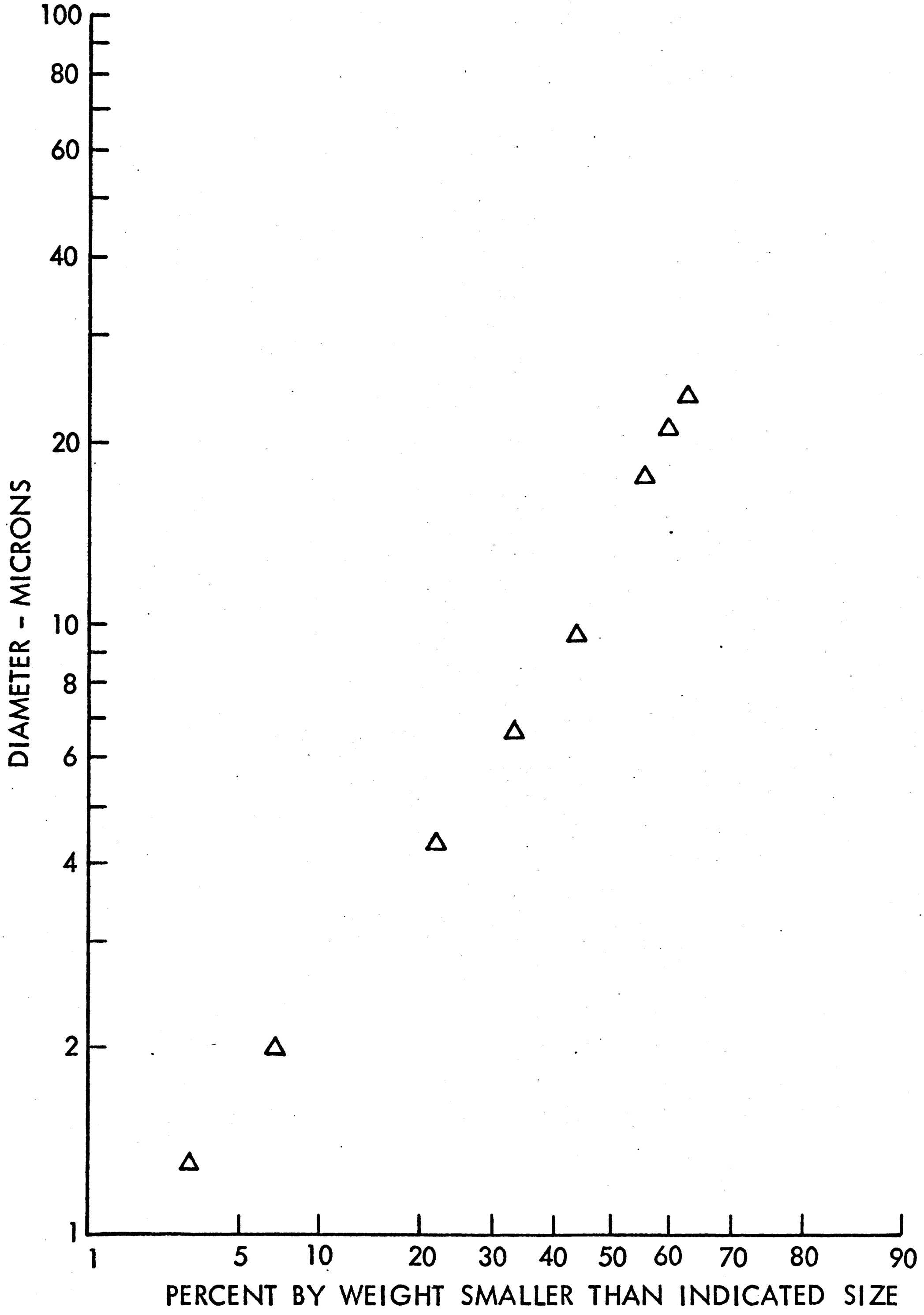


Figure C-2 - Limestone Size Distribution



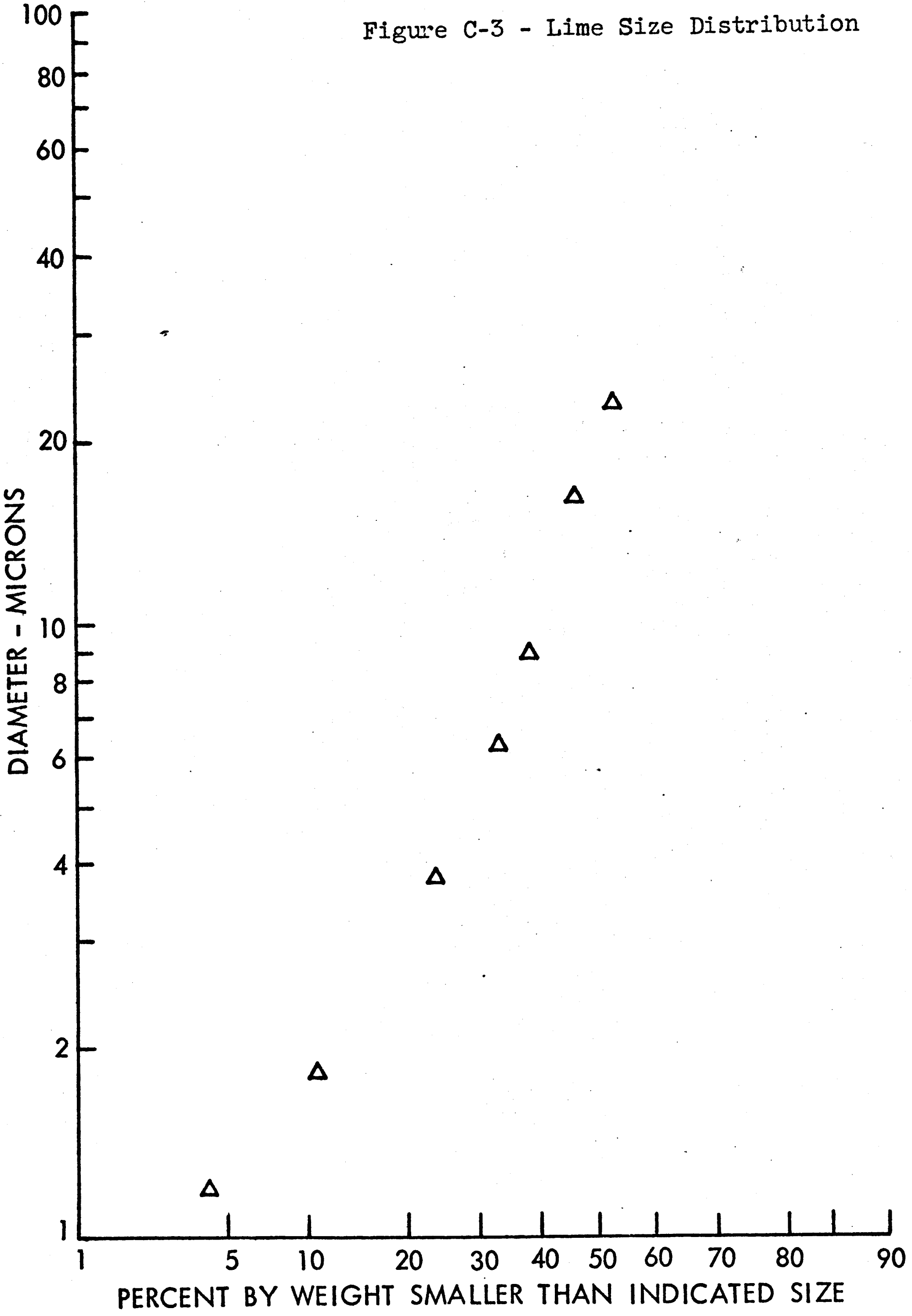
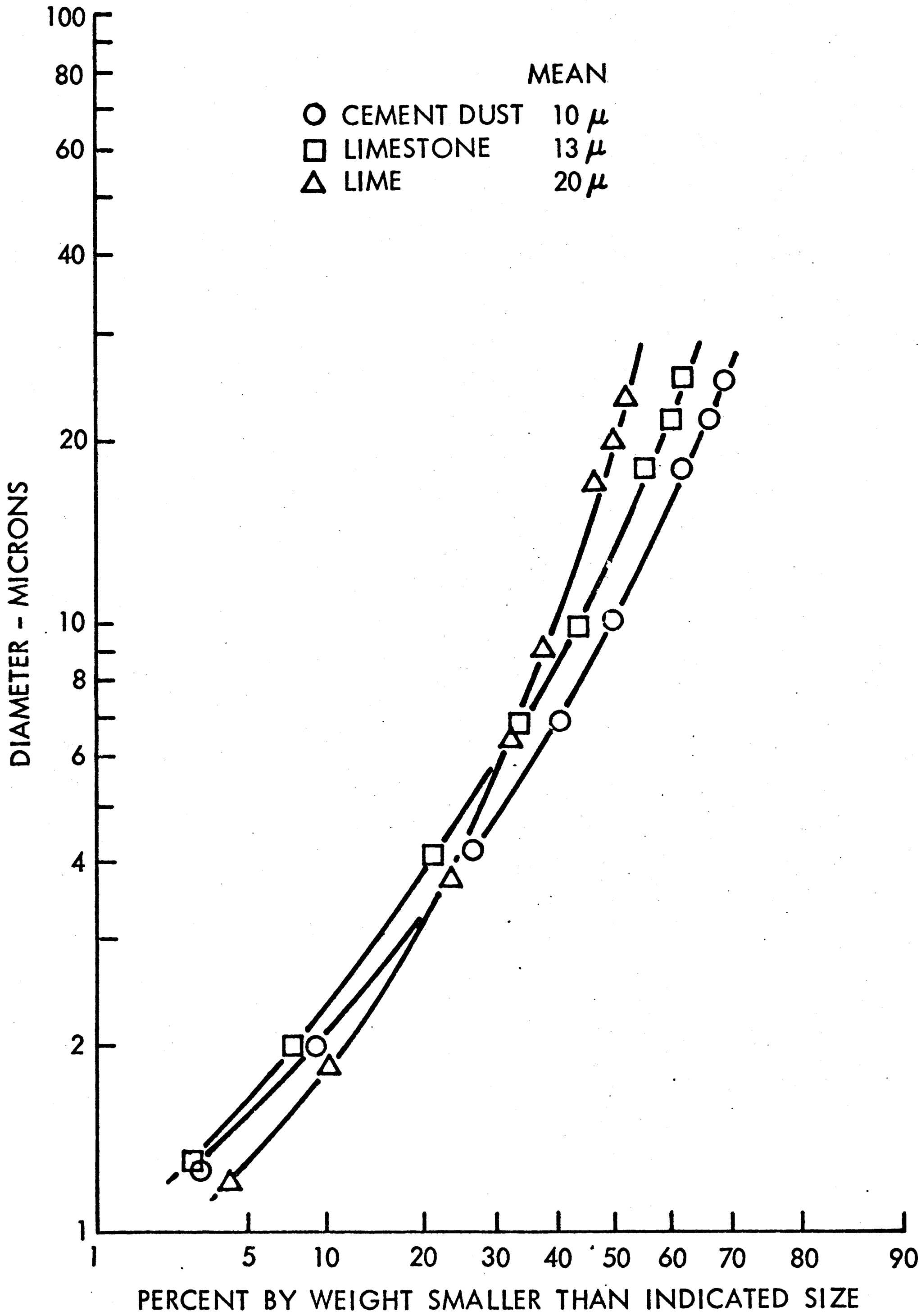


Figure C-3 - Lime Size Distribution

Figure C-4 - Comparison of Size Distributions of Adsorbents



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