Theses and Dissertations

1973

Absorption in Jet-Venturi scrubbers

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ABSORPTION IN JET-VENTURI SCRUBBERS

BY

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A RESEARCH REPORT

PRESENTED TO THE GRADUATE FACULTY

OF LEHIGH UNIVERSITY

IN CANDIDACY FOR THE DEGREE OF

MASTER OF SCIENCE

IN

CHEMICAL ENGINEERING

LEHIGH UNIVERSITY

BETHLEHEM, PA.

OCTOBER 1973

CERTIFICATE OF APPROVAL

This research report is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering.

11/10/73
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ii

ACKNOWLEDGEMENT

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Increasing public demand for pollution control, coupled with the strict standards set by the government, has made the use of emission control devices such as the venturi scrubber and the jet-venturi scrubber commonplace in industry. Venturi scrubbers are being used for a wide variety of jobs. The steel industry uses venturi scrubbers to remove hydrogen chloride (HCl) gas from stack emissions. Electrical utility companies use venturi scrubbers to remove sulfur dioxide and particulate emissions from flue gases.

In industrial use, efficiencies of operation for these venturi and jet-venturi scrubbers are determined either from past experience with identical or nearly identical situations or with experimental data from pilot plant studies. This is due to the fact that there are, at present, no satisfactory correlations for mass transfer or particulate removal in venturi scrubbers. Pilot plant projects are expensive, so the development of correlations would certainly be a money saver, as well as a time saver.

This study involves an examination of mass transfer to see if a suitable theory can be found for venturi and jet-venturi scrubbers. Experimental data from an 8 inch jet-venturi scrubber system, in which HCl was scrubbed from air with water, is used to confirm or reject the theories examined.

Several mass transfer theories were examined, and the penetration theory was selected as the theory to be studied. The relationship between the liquid-gas contact time and the residence time in the scrubber throat was selected as the parameter to be examined. The results indicate that there is a

definite relationship between the contact time to residence
time ratio and both the liquid flow rate through the scrubber
and the gas cleaning efficiency. The results also indicate,
however, that the penetration theory, applied in this manner,
does not adequately describe mass transfer for the system
studied. Further examination of the problem is clearly indi-
cated.

THE JET-VENTURI SCRUBBER

The engineer, when dealing with objectional fumes discharged from industrial processes, has four major types of emission control equipment to choose from: filters, inertial systems such as cyclones, electrostatic precipitators, and wet scrubbers. Of these four types, wet scrubbers are the most versatile, and probably the closest to a universal answer to emission control problems.

Wet scrubbers, including venturi and jet-venturi scrubbers, as well as wet cyclones, spray towers and packed towers, all operate according to the same principles. Their scrubbing action is produced by passing the gas stream past the liquid stream, or vice versa, and spreading the liquid out so that it has sufficient surface area to contact all parts of the gas and insure rapid mass transfer.

Venturi scrubbers utilize a high velocity section (at the vena contracta or venturi) for bringing the gas and liquid into intimate contact with each other. They fall into two groups: (1) The standard venturi scrubber uses a mechanical blower to create a high velocity gas stream that passes by a slower moving liquid surface. The faster moving gas hits and disperses the slower moving liquid. (2) The ejector or jet-venturi scrubber studied in this work uses a mechanical pump to impart a high velocity to the liquid stream. The high velocity energy of the liquid stream acts to break up and distribute the liquid into a multitude of small drops, giving a large surface area for the liquid. The high velocity liquid stream also acts to pump the gas stream through the scrubbing system and the connecting duct work.

Venturi scrubbers have many advantages over the other types of wet scrubbers, as well as the other types of emission control devices. Versatility is a prime attribute of venturi scrubbers, in that they can handle solid particulates, liquid particulates

or aerosols, and soluble gases, all with high efficiencies. The venturi scrubber is also convenient in terms of size. It occupies the smallest area for comparable jobs of any of the wet scrubbers, and is smaller than most other emission control systems. Despite the small area it occupies, the venturi scrubber can handle great volumes of effluent gases with top efficiencies. A final advantage of the venturi scrubber is that it can be used to collect many highly corrosive materials that other systems cannot handle; it has no moving parts.

Along with these advantages, there are several disadvantages that must be considered before a venturi scrubber can be selected to handle a particular problem. Only one of these, however, is inherent to the venturi scrubber, while the other disadvantages are common to all wet scrubbers. The problems common to all wet scrubbers stem from the use of a liquid stream, usually water, to do the scrubbing. The first and most important problem with the use of water as a scrubbing medium is that the water must then be cleaned, and clarification costs can run very high. Climatic constraints must also be considered, and freezing water lines can be a problem. Vapor plumes, caused when small amounts of the scrubbing liquid exit the stack with the effluent gas stream, arouse public concern, and therefore are also a disadvantage of wet scrubber use. Power costs are a problem for the venturi scrubber, but not for the other wet scrubbers. Because of the pumping requirements for both the standard and jet-venturi scrubbers, power costs can run three or four times the costs for other wet scrubbers.

Should an engineer select the venturi scrubber, he must then decide which type of venturi scrubber to use, the standard or the jet. Each has its own particular advantages. In the standard venturi scrubber, a much smaller quantity of liquid (scrubbing medium) is required, because of the greater gas stream velocities produced by the gas pump or fan. The smaller quantity of liquid,

often from five to eight times less than with the jet-venturi unit, requires less expenditure for clarification and treatment. With the lower liquid stream flow rates, a smaller pump is needed to move the liquid through the unit. Also, due to the use of the gas fan, the standard venturi can handle greater gas flow rates than the jet-venturi scrubber can.

The jet-venturi scrubber, however, has many advantages as well. The high velocity liquid stream eliminates the need for a pump to move the gas stream. With no gas pump, there are no moving parts in contact with the gas. This makes the jet-venturi unit superior for dealing with highly corrosive materials. The high velocity energy of the liquid stream is also advantageous in that it is a much more efficient atomizer of the liquid stream than the lower velocity energy in the standard venturi scrubber. The better the atomization of the liquid stream, the greater the number of liquid droplets passing through the scrubber throat, and the greater the surface area with which to contact and scrub the gas stream. There are other advantages in using the jet-venturi scrubber that are related to the high velocity action of the liquid and the lack of a gas pump. First, there is a much lower overall pressure drop in the jet-venturi scrubber, making it more useful for systems requiring scrubbing between other process steps, and, hence, the smallest pressure drop possible. Also, the overall power expended in operation of the jet-venturi scrubber is usually less than in operation of the standard venturi scrubber.

Modifications can be made on venturi scrubbers to improve their efficiencies. A simple modification on the scrubber system is to change the scrubbing medium being used from water to some other medium. Caustic is a very popular alternative. Examples of the efficiencies attainable using caustic in jet-venturi scrubbers as reported by L. S. Harris[1] are: 98% for SO_2 removal, 99% for Cl_2, and 99.9% for I_2 removal (maximum efficiencies).

-- L. S. Harris - "Fume Scrubbing with the Ejector Venturi System" Chemical Engineering Progress, April 1966, page 55.

A second modification of the venturi scrubber system involves the use of scrubbers in series. The electrical operating costs at the higher scrubbing efficiencies can be reduced considerably at the expense of higher equipment costs. Harris reports that for a given HCl fume, similar to the gas stream studied in this report, at a rate of 1000 cubic feet per minute, and with a collection efficiency of 98%, the switch from a one stage jet-venturi unit to a two stage unit would result in the decrease of theoretical horsepower from 9 hp to 2 hp. This may be sufficient to justify the increased equipment costs required by the second stage.

Another modification of the venturi scrubber system is the flooded-disc wet scrubber[2]. The disc is positioned in a tapering duct section. The shearing action of the gas at the edge of this disc acts to atomize the liquid scrubbing medium very effectively. Optimum pressure drop at different gas flow rates can be maintained easily with the flooded-disc. This is done by raising or lowering the disc as required. This acts to increase or decrease the annular area through which the gas must pass, and increases the range of gas flow rates over which the scrubber can operate at peak efficiencies.

The jet-venturi scrubber is generally used in series with some type of separation device. The job of the separator is to remove the scrubbing medium from the exhaust gas stream. An efficient separator can remove the contacting liquid from the gas to within a value in the range of 5×10^{-7} to 5×10^{-8} gallons of liquid per cubic foot of gas. Various types of separators are used, including gravity separating chambers, inertia impact separators and cyclonic mist eliminators.

2 -- Bulletin R-C 1000, Research-Cottrell, Inc.

From the discussion of venturi scrubbers, and the jet-venturi scrubber in particular, it is clear that these scrubbers combine efficiency, versatility, capacity and cost factors in a unique combination that makes them very useful for many different emission control problems. At the present time, however, there is no way available to predict the performance of these scrubbers without actual experimentation with the effluent to be scrubbed. In the following sections of this report, we will examine several theories attempting to predict the performance of a jet-venturi scrubber, and compare these theories with experimentally collected data for the removal of HCl from air in an 8 inch jet-venturi scrubber.

MASS TRANSFER THEORY

Many of the basic equations describing mass transfer can be derived from similar equations involving heat transfer. One of the most important equations for which this is true is of the following form:

Flux = Coefficient X Driving Force

where the driving force is generally some concentration difference. For the heat transfer case, this equation takes this form:

$$g = h \times [T_2 - T_1]$$

where "h" is the heat transfer coefficient. For the case of mass transfer, the equation is as follows:

$$N_A = k \times [\Delta C_{driving\ force}]$$

where N_A = the rate of mass transfer, as a mass flux, in units of the mass of the transferred component "A" that is transferred per unit time per unit area over which the mass is being transferred

$\Delta C_{driving\ force}$ = the mass transfer driving force defined as the difference of concentrations of the transferred component between the phases which provide the mass transfer; this can be expressed as ΔC, Δp, Δx, etc.

The following diagrams show the system used and point out the driving forces for mass transfer.

LIQUID IN
$C_{L,in}$

GAS IN
$C_{G,in}$

GAS OUT
$C_{G,out}$

LIQUID OUT
$C_{L,out}$
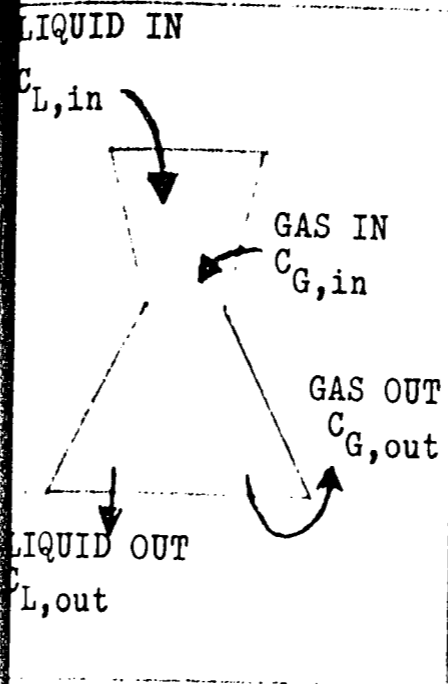
Driving force at the top of the ejector, as visualized by the two-film theory.

| LIQUID PHASE | GAS PHASE | $C_{G,in}$ |

$C_{L,in}$

$C_{Gi,in}$

$C_{Li,in}$

$C_{Gi,in} = f^{-1}(C_{Li,in})$ $C_{Li,in} = f(C_{Gi,in})$
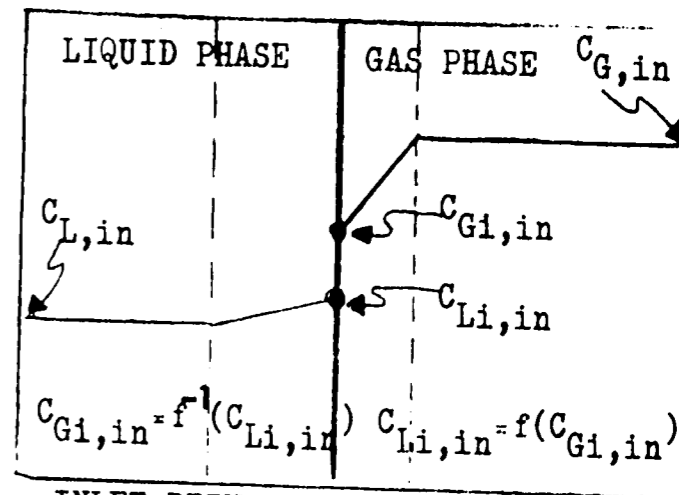
INLET DRIVING FORCE DIAGRAM

where 'f' is an equilibrium relationship.

Overall driving force at the inlet is:

In terms of the gas phase: $C_{G,in} - f^{-1}(C_{L,in})$

In terms of the liquid phase: $f(C_{G,in}) - C_{L,in})$

In a similar manner, the picture at the outlet position can also be shown with the two film theory:

| LIQUID PHASE | GAS PHASE | $C_{G,out}$ |

$C_{L,out}$

$C_{Gi,out}$
$C_{Li,out}$

$C_{Li,out} = f(C_{Gi,out})$

$C_{Gi,out} = f^{-1}(C_{Li,out})$
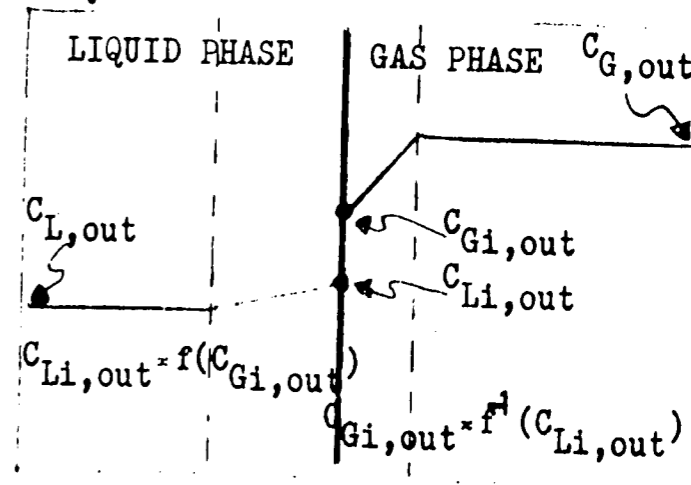
OUTLET DRIVING FORCE DIAGRAM

Overall driving force at the outlet is;

In terms of the gas phase: $C_{G,out} - f^{-1}(C_{L,out})$

In terms of the liquid phase: $f(C_{G,out}) - C_{L,out})$

FIGURE 1

The driving force for mass transfer calculation should be an average, (specifically the log-mean average), between the "inlet" and "outlet" driving forces. Therefore, the driving forces for mass transfer are:

GAS PHASE:
$$\frac{(C_G, \text{in} - f^{-1}(C_L, \text{in})) - (C_G, \text{out} - f^{-1}(C_L, \text{out}))}{\log_e \dfrac{C_G, \text{in} - f^{-1}(C_L, \text{in})}{C_G, \text{out} - f^{-1}(C_L, \text{out})}} = \Delta C_{\text{driving force, G}}$$

LIQUID PHASE:
$$\frac{(f(C_G, \text{in}) - C_L, \text{in}) - (f(C_G, \text{out}) - C_L, \text{out})}{\log_e \dfrac{f(C_G, \text{in}) - C_L, \text{in}}{f(C_G, \text{out}) - C_L, \text{out}}} = \Delta C_{\text{driving force, L}}$$

The equation for mass flux, "N_A", can also be written as:

$$N_A = (dm/dt)/A$$

where dm/dt = the rate of transfer of mass, as mass transferred per unit time; and A = the interfacial area over which the mass is transferred.

The two equations for N_A are combined to produce a single equation for the mass transfer coefficient:

$$k_e = (dm/dt)/A(\Delta C_{\text{driving force}})$$

The equation refers to the mass transfer coefficient as k_e since the equation provides a means for calculating the mass transfer coefficient from experimental measurements.

The uses of experimentally determined mass transfer coefficients are somewhat limited with respect to circumstances and situations, as well as to the range of fluid properties.

-10-

Therefore it is important that we be able to extend their applicability to the situations not covered experimentally.

To accomplish this, there are several theories which try to relate the behavior of mass transfor coefficients to fundamental system parameters. These include the film theory, the penetration theory, the surface-renewal theory and others. All of these are speculations, attempting to simulate and deal with situations that are not completely understood, and are continuously being revised. Each has its own merits, and each approximates certain cases of mass transfer better than others. Therefore, we should examine each of the mass transfer theories, and select the one that best fits the mass transfer mechanism that occurs inside the jet-venturi scrubber.

After choosing a mass transfer theory to apply to the jet-venturi scrubber, the theory will be used to calculate a k_t (theoretical mass transfer coefficient) to compare with the k_e (experimental mass transfer coefficient). A good correlation between the experimental and theoretical values would indicate that the theory is a good approximation for the mass transfer mechanism in the jet-venturi scrubber. A poor correlation would suggest that we either modify the theory used further, or try another theory altogether.

The three major theories to be considered are the film theory, the penetration theory, and the surface-renewal theory. The first theory we will consider is the film theory. This is the oldest and simplest picture of mass transfer coefficients. The theory states that when a fluid moving in turbulent flow passes a solid surface, the fluid velocity at the surface itself being zero, a viscous layer or "film" must be formed. The film theory assumes that the entire concentration difference, C_2-C_1, is described by molecular diffusion, and that an effective film thickness, 'z', can be defined such that the

-11-
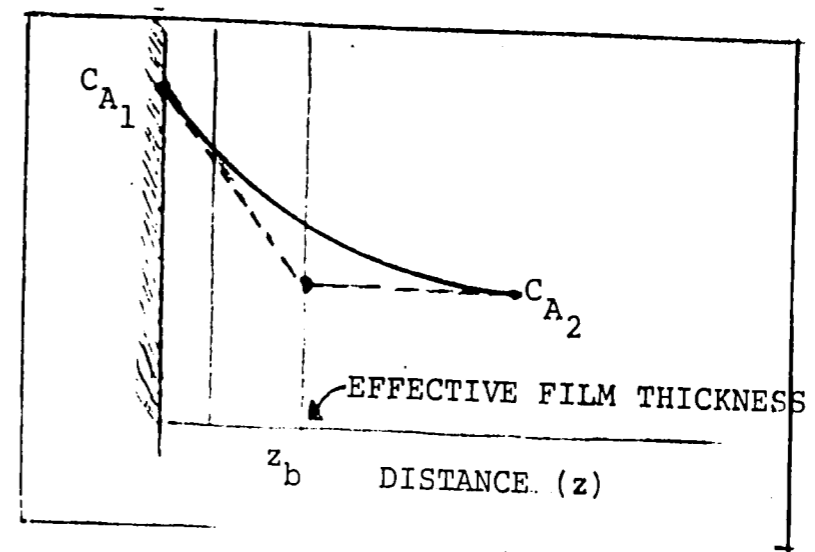
FIGURE 2   THE FILM THEORY MODEL

resistance to molecular diffusion in the film of thickness 'z' is equal to the actual resistance to mass transfer in the true system, comprised of the true viscous or laminar layer, the buffer region and the turbulent core. Using this theory the following equation for the mass transfer coefficient can be derived:

$$k = D_{ab}/z_f$$

where D_{ab} is the diffusivity of the transferred component in the medium in which the transfer takes place

and z_f is the effective film thickness as specified by the film theory.

The second theory to be considered is the penetration theory. This theory was proposed by Higbie as an alternative to the film theory because there are many situations in mass transfer where the time of exposure of a fluid to mass transfer is short, so that the concentration gradient of the film theory, which is characteristic of steady state operation, would not have sufficient time to develop. Higbie, therefore, developed a theory to describe short contact systems, and, in particular, the case where a gas bubble rises through a liquid which absorbs the gas.

-12-
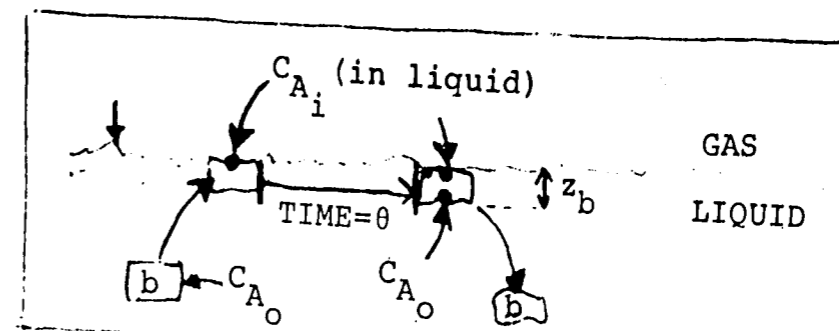
PENETRATION THEORY MODEL

FIGURE 3

A particle of the liquid, initially at the top of the bubble, is in contact with the bubble for a time, 'θ', which is equal to the time for the bubble to rise a distance equal to its diameter while the liquid particle slips along its surface. In this theory, the time of exposure or contact is taken to be constant for all such particles, or eddies for the case of turbulent flow.

Initially the concentration of the dissolved gas in the liquid is C_o. At the surface between the liquid and the gas, the concentration of the dissolved gas is C_i. During the unsteady state diffusion process, the following equation can be applied:

$$\frac{\partial C}{\partial \theta} = D_{ab} \frac{\partial^2 C}{\partial z^2}$$

The following boundary equations are then applied:

1) $C = C_o$ at $\theta = 0$ for all z
2) $C = C_o$ at $z = 0$ for all θ
3) $C = C_i$ at $z = 0$ for θ greater than 0

Using these boundary conditions, the following equation can be derived for the mass transfer coefficient:

$$k = 2 \sqrt{D_{ab}/\Pi\theta}$$

-13-

The final theory that we shall look at is the surface--renewal theory, which is a modification of the penetration theory. Dankwertz, who developed the theory, pointed out that the assumption that all of the eddies were exposed for the same length of time at the surface is, at best, a special case of what may be a much more realistic picture, where the eddies are exposed for varying lengths of time. His equation for the mass transfer coefficient was:

$$k = \sqrt{D_{ab}s}$$

where s is defined as the rate of production of fresh surface
    and is assumed to be constant
Dankwertz then attempted to solve for this term mathematically, and found:

$$\phi = se^{-s\theta}$$

where ϕ is defined in terms of ϕdt being the area of surface
    elements having residence times between t and t + dt
and θ is the average residence time of an eddy at the surface.

The penetration and surface renewal theories are probably the best approximations to the mechanism of mass transfer occurring in the jet-venturi unit. First, they are most applicable to cases in which there is turbulent flow, as in the scrubber. Also, they were designed for short contact time systems, and the jet-venturi scrubber can certainly be classified as a short contact time unit since the residence times in the scrubber of both the liquid and gas phases are always very small (less than one second for our experimental range). The penetration theory is the simplest of all of the theories based on the short contact time approach, and therefore, the easiest to apply to experimental systems.

Having selected the penetration theory, two major factors must be known for the determination of the theoretical mass transfer coefficients, the contact time 'θ', and the diffusivity 'D_{ab}'. The diffusivity can be found in many data sources as a function of temperature. The contact time cannot be found in any reference, nor can it be calculated directly to use in the prediction of mass transfer rates. We can, however, calculate the residence time inside the scrubber throat, and use this as an initial approximation for the contact time. Residence times for all runs and all phases are shown on Page 16. (Residence times are calculated by dividing the length of the scrubber throat by the velocity through the throat.) Studies on mass transfer in venturi scrubbers[3] reveal that virtually all of the mass transfer takes place in the first foot of throat length or less.

Because of this, the ability of the theory to predict mass transfer rates using residence times instead of contact times is suspect. Clearly, the relationship between these residence times and contact times is an important one. An equation relating them would be as follows:

$$\theta = t/_n$$

where θ is the contact time (seconds)

t is the residence time (seconds)

n is the contact time ratio, or number of contacts during a single pass

The value for 'n' can be calculated for each set of experimental conditions. The way that 'n' varies with liquid flow rate and gas flow rate through the scrubber, therefore, can be determined from experimental data. This term, therefore, will be the focus of our experiments and calculations. If 'n' can be shown to be a function of either gas flow rate, liquid flow rate, or scrubber throat size, it can then be used to predict mass transfer rates for other systems in the jet-venturi scrubber.

3 -- Atomization and Cloud Behavior in Venturi Scrubbing -
Howard E. Hesketh, Journal of APCA, July, 1973

RESIDENCE TIMES

UN IN TERMS OF LINE PRESSURE	LIQUID RESIDENCE TIME IN SCRUBBER	GAS RESIDENCE TIME IN SCRUBBER
P in psig	t_L in seconds	t_G in seconds
14	0.217	0.220
16	0.211	0.196
18	0.206	0.183
20	0.202	0.161
23	0.195	0.161
25	0.190	0.155
28	0.183	0.148
30	0.179	0.144

Calculation of flow conditions, interfacial areas, and contact time ratios (calculated from the first two parameters) for a given system in a given scrubber, should then be sufficient to predict mass transfer rates.

The particular system chosen to study is important because the system chosen may have its primary resistance to mass transfer in either the gas phase or the liquid phase. Studies of the HCl system being used in this report are unclear about mass transfer resistances. The location of the mass transfer resistance must be known to properly apply the penetration theory to venturi scrubber systems. Diffusivities, residence times, and concentrations used in the calculations are different for liquid phase and gas phase based systems. Because of the uncertainty about the HCl system, both cases (gas and liquid phase resistances to mass transfer) will be examined in the calculations and a determination will be made.

For the gas phase case: $k_{e_G} = \dfrac{dm/dt}{A(\Delta C_{\text{driving force}}, G)}$

and the theoretically determined mass transfer coefficient:

$$k_{t_G} = 2\sqrt{\frac{D_{\text{HCl-AIR}}}{\Pi \theta_G}}$$

When the diffusivity used is the diffusivity of the transferred component in the gas phase, and 'θ', the contact time, $= \theta_G$, the gas phase contact time, where $\theta_G = t_G/n_G$, and t_G is the residence time of the gas stream in the scrubber throat.

For the liquid phase case: $k_{e_L} = \dfrac{dm/dt}{A(\Delta C_{\text{driving force}}, L)}$

and the theoretically determined mass transfer coefficient:

$$k_{t_L} = 2\sqrt{\frac{D_{\text{HCl-H}_2\text{O}}}{\Pi \theta_L}}$$

Using $D_{HCl-Air} = 1.63 \times 10^{-4}$ ft^2/sec[*] and $D_{HCl-HOH} = 1.78 \times 10^{-8}$ ft^2/sec,[**] the values at 70°F, the following equations are found for liquid and gas phase based contact time ratios:

$$n_L = \left[\frac{dm/dt}{.544 x A x (\Delta C_{driving\ force,L})} \right]^2 t_L$$

$$n_G = \left[\frac{dm/dt}{51.9 x A x (\Delta C_{driving\ force,G})} \right]^2 t_G$$

where dm/dt is the mass transferred, measured experimentally,

--in units of lbs HCl/hour,

A is interfacial area in units of ft^2, also experimentally determined,

t_L and t_G are residence times in units of seconds,

Concentrations are in units of lbs HCl/ft^3, (where the driving forces have been defined earlier) and

n_L and n_G are dimensionless

The methods for obtaining the data to use in the above equations are outlined in the following sections. The results of the experiments, including contact time ratios, are presented following the experimental sections.

[*] 4 -- Progress in International Research in Thermodynamics and Transport Properties - ASME, Academic Press, 1962

[*] 5 -- Gas--Liquid Reactions - P. V. Dankwertz McGraw-Hill, 1970

THE OXYGEN-SULFITE PHASE OF THE EXPERIMENTS

Before we can try to predict the outlet concentration of an effluent in air for a given inlet concentration, using the jet-venturi scrubber as the emission controller, certain things must be known about the system being studied. These include: the effluent being studied; the scrubbing medium being used; the particular scrubber (dimensions and flow rate ranges) being used to clean the air stream; the operational flow rates of the liquid and gas streams; the interfacial areas for mass transfer as a function of flow conditions; and the mass transfer theory being used to calculate outlet effluent concentrations.

Hydrogen chloride (HCl) has been chosen as the effluent to be studied. Water will be the scrubbing medium. The scrubber being used for the experimentation is an 8" jet venturi fume scrubber provided by Croll-Reynolds Co., Inc of Westfield, New Jersey. A diagram of the experimental apparatus is shown on the next page. Liquid flow data has been collected up to 45 psig liquid line pressure, defining the range under which we may operate. The penetration theory has been selected as the mass transfer theory to be used, and the reasons for this choice have been discussed in the previous section.

The only parameter, therefore, that has not been specified is the interfacial area for mass transfer. Therefore, before we can apply the penetration theory to the HCl system, we must determine interfacial areas, which are a function of liquid flow rate through the scrubber. To do this, we must make a separate set of experimental runs, using a system other than HCl in air, and measure the interfacial areas, or calculate them, since they cannot be measured directly.

The system that has been chosen is one that uses sodium sulfite in water as the scrubbing medium to absorb oxygen out
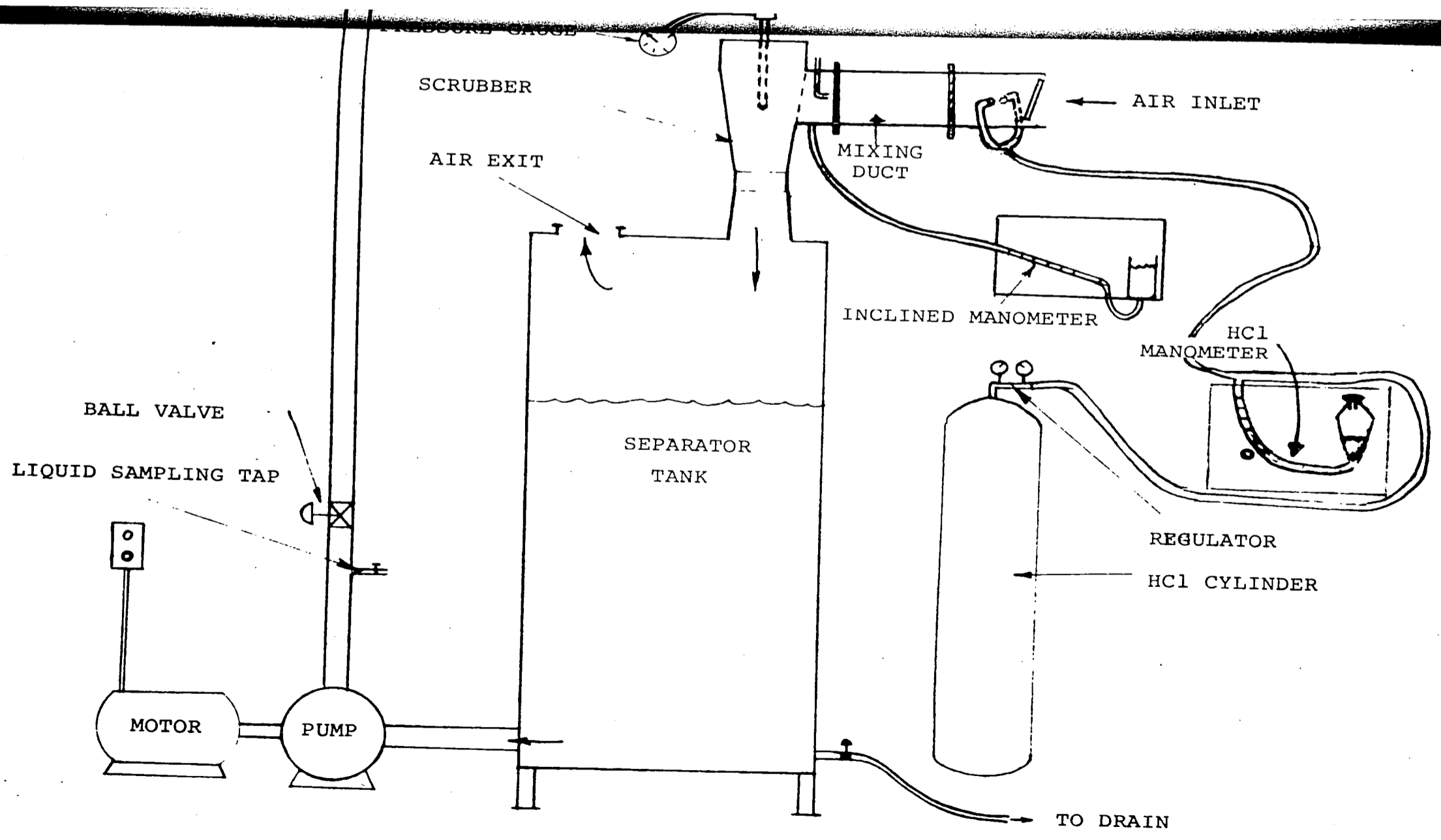
FIGURE 4   SCRUBBER APPARATUS

**ATTACH
TO
SCRUBBER**

PITOT SAMPLING
TUBE

MIXING SCREENS

HCl
Feed

BUTTERFLY VALVE

← 3"

AIR

Lucite
Duct

←2"

H_2O Draft
Manometer

6"

4"

12"

6"

6"

12"
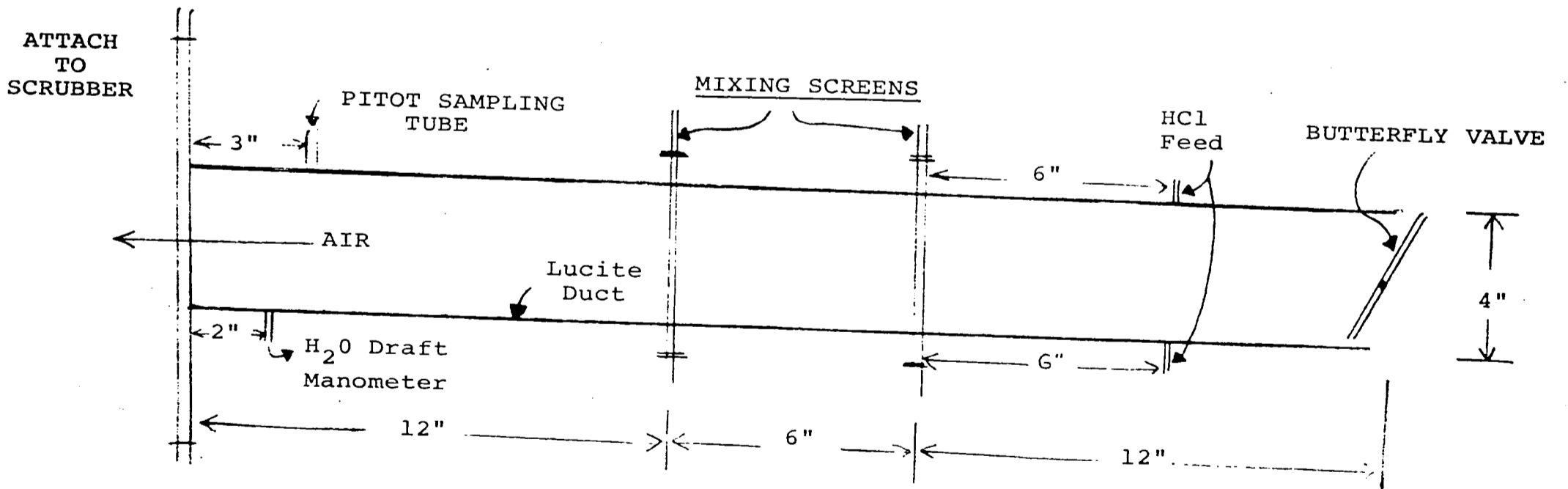
FIGURE 5   MIXING DUCT

of air. Oxygen reacts with solutions of sodium sulfite in the presence of catalysts such as cobalt ions, to produce sulfate:

$$SO_3^{-2} + \tfrac{1}{2}O_2 \xrightarrow{C_o^{+2}} SO_4^{-2}$$
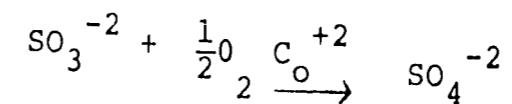
This system has been chosen to determine interfacial areas for two reasons. First, it is a system in which the resistance to mass transfer is well defined. Liquid phase resistance dominates with gas phase resistance being negligible. Second, much study has been done on the system, and a reliable method has been developed to calculate interfacial areas for mass transfer.

The reaction was studied by Reith,[7] who ran his experiments using a .8 molar solution of sodium sulfite. A cobalt chloride catalyst was used because the reaction is normally very slow. Cobalt chloride concentrations used ranged from 3×10^{-5} to 5×10^{-3} gm-moles/liter. Using the data collected, rate constants for the reaction were calculated as a function of solution pH, cobalt chloride concentration and temperature. The rate expression obtained from these calculations was as follows:

$$R = (A*)^{1.5}((2/3)k_2D_a)^{0.5}$$

where D_a is the diffusivity of oxygen in the reacting solution, and k_2 is a reaction rate constant. A* is the saturated concentration of oxygen in the solution, and is given by Dankwertz[6] as a function of temperature. Combining this equation and the data collected by Reith, the reaction rate 'R' can be calculated in units: gm-moles/ft^{2}sec. After calculating 'R', we experimentally determined (RA)avg., the product of 'R' and 'A', the interfacial area. We, then, divide (RA)avg by 'R' to get the value for the interfacial area at the particular operating conditions.

6 -- Gas-Liquid Reactions - P. V. Dankwertz, McGraw-Hill, 1970

7 -- T. Reith - Physical Aspects of Bubble Dispersions in Liquids, Thesis, Delft Technical University; Delstsche Uitgevers Maatschappij, N.V., 1968

(RA)avg is determined in the following manner. The scrubber is run with a recycling sulfite solution and liquid samples are taken at specific time intervals (a detailed description of the experimental procedure follows). The initial rate of decrease in the concentration of sulfite ions in the solution is determined graphically by plotting sulfite concentration versus time, and the resulting slope, having units of gm-moles/liter sec, or gm-moles/sec, is (RA)avg. In other words, although we cannot measure 'A' directly, we can measure it indirectly.

Eight runs were made, each one at a different liquid flow rate. The range of line pressures for liquid flow that were used varied from 14 psig to 30 psig. The lower limit was chosen because we cannot expect the scrubber to be effective to any degree much below this flow rate. The upper limit was chosen because great difficulty was experienced in attempting to run the sulfite solution through the scrubber at rates higher than at 30 psig. For each run, liquid samples were taken every 5 minutes over a 1 hour period. The sulfite concentration used for each run was .8 molar, and the cobalt chloride concentration used was 10^{-3} molar. The procedure for operation was as follows:

1) Prepare the necessary analytical solutions:
   (a) 0.21 M KIO_3
   (b) 0.60 M HCl
   (c) saturated starch indicator solution
2) Dissolve 45 lbs. of sodium sulfite (Na_2SO_3) into buckets of water and pour into the separator tank;
3) Add water to the separator tank until the level is at the mark. This will give 196 liters of solution, and a sulfite concentration of 0.8 M;
4) Fill the draft manometer to the zero level
5) Turn on the pump and open the ball valve until the line pressure gauge is at the desired setting
6) Adjust the butterfly valve to the desired draft

7) After several minutes to allow the solution to mix itself thoroughly, add 25 grams of cobalt chloride to the solution in the tank. This is the amount for a concentration of 10^{-3}M .

8) Take liquid samples every 5 minutes, starting at 1 minute after the addition of the catalyst

9) Titrate the samples with the KIO_3 solution, after adding 15 ml of the HCl solution and 7.5 ml of the starch solution to 15 ml samples

10) After 1 hour of samples have been taken, turn off the pump

11) Empty the separator tank immediately and flush the system to prevent the build-up of sodium sulfite crystals inside the unit

12) Wash the equipment thoroughly

The data obtained from the eight runs is presented in Appendix I. The graphs used in the determination of (RA)avg and interfacial areas are on the following pages, followed by a chart showing the determined values of (RA)avg and 'A' using the Dankwertz[8] data of

$$R = 5.42 \times 10^{-9} \text{ gm-moles/cm}^2\text{sec}$$

-- Gas-Liquid Reactions - P. V. Dankwertz, McGraw-Hill, 1970

FIGURE 6

GRAPHICAL DETERMINATION OF INTERFACIAL AREAS

RUN 1 & RUN 2

RUN 2

INITIAL SLOPE 2 =

$2.67 \times 10^{-5} \dfrac{\text{gram moles}}{\text{liter sec}}$

INITIAL SLOPE 1 =

$2.13 \times 10^{-5} \dfrac{\text{gram moles}}{\text{liter sec}}$

RUN 1

Concentration of SO_3^{-2} (gm-moles/lit)

.940
.930
.920
.910
.900
.890
.880
.870

0 5 10 15 20 25 30 35 40 45

Time (minutes)
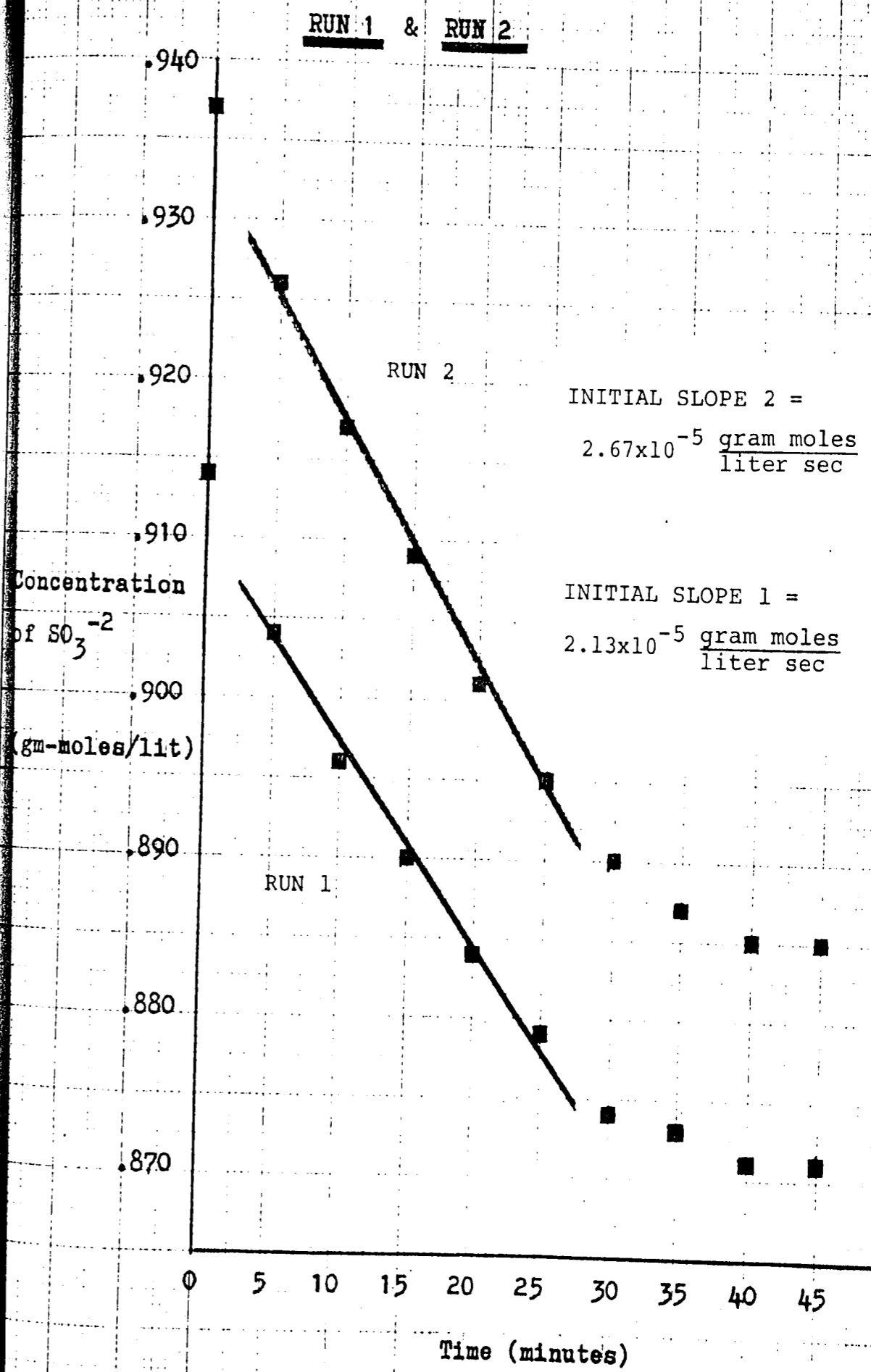
FIGURE 7

GRAPHICAL DETERMINATION OF INTERFACIAL AREAS

RUN 3 & RUN 4

RUN 3

INITIAL SLOPE 3 =

$3.27 \times 10^{-5} \dfrac{\text{gram moles}}{\text{liter sec}}$

RUN 4

INITIAL SLOPE 4 =

$3.42 \times 10^{-5} \dfrac{\text{gram moles}}{\text{liter sec}}$

Concentration of SO_3^{-2} (gm-moles/lit)

Time (minutes)

FIGURE 8

GRAPHICAL DETERMINATION OF INTERFACIAL AREAS

RUN 5 & RUN 6

INITIAL SLOPE 5 =

4.42×10^{-5} $\dfrac{\text{gram moles}}{\text{liter sec}}$

INITIAL SLOPE 6 =

4.61×10^{-5} $\dfrac{\text{gram moles}}{\text{liter sec}}$

RUN 5

RUN 6

Concentration
of SO_3^{-2}
(gm-mols/lit)

Time (minutes)

-27-
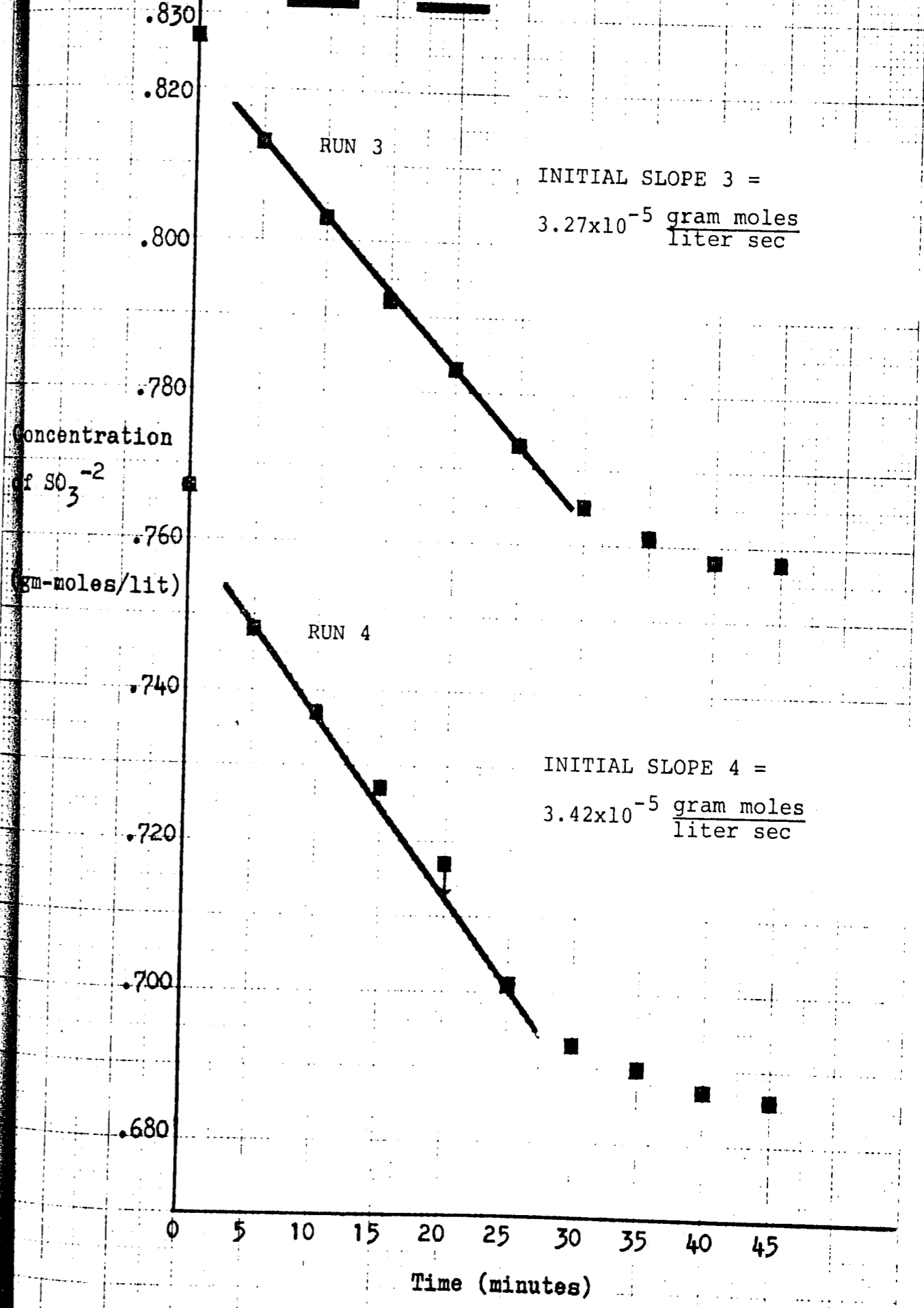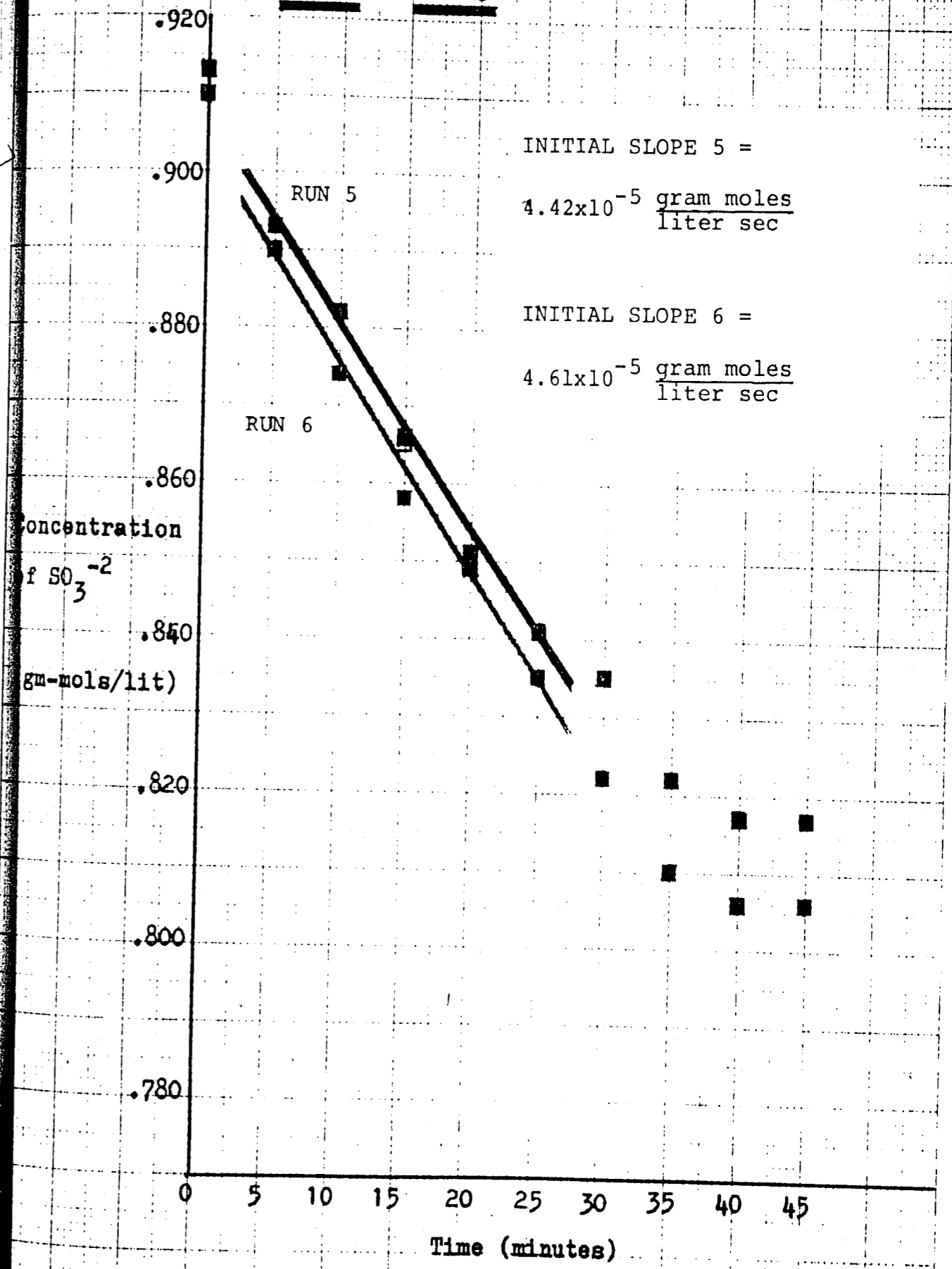
FIGURE 9

GRAPHICAL DETERMINATION OF INTERFACIAL AREAS

RUN 7 & RUN 8

INITIAL SLOPE 7 =

$5.50 \times 10^{-5} \dfrac{\text{gram moles}}{\text{liter sec}}$

INITIAL SLOPE 8 =

$5.92 \times 10^{-5} \dfrac{\text{gram moles}}{\text{liter sec}}$

Concentration

of SO_3^{-2}

(gm-mols/lit)

Time (minutes)
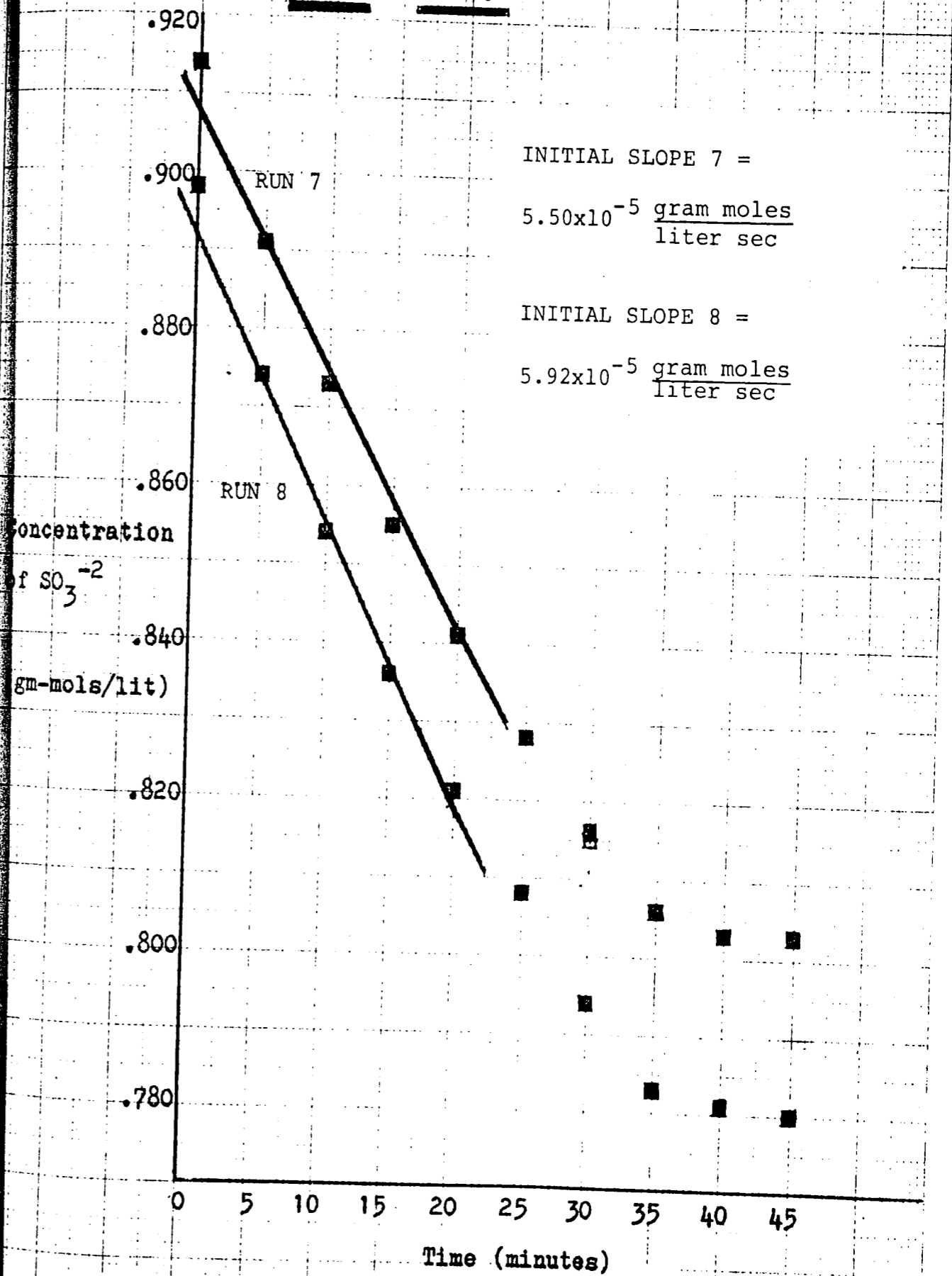
INTERFACIAL AREAS

RUN	LINE P	(RA)avg	INTERFACIAL AREA
	psig	$\frac{gm\text{-}moles}{second}$	feet squared
1	14	4.17×10^{-3}	828
2	16	5.23×10^{-3}	1040
3	18	6.41×10^{-3}	1270
4	20	6.70×10^{-3}	1340
5	23	8.65×10^{-3}	1720
6	25	9.04×10^{-3}	1800
7	28	1.08×10^{-2}	2140
8	30	1.16×10^{-2}	2300

WATER FLOW as line pressure VS. INTERFACIAL AREA
psig   ft²

Interfacial
Area
ft²

Line Pressure
psig
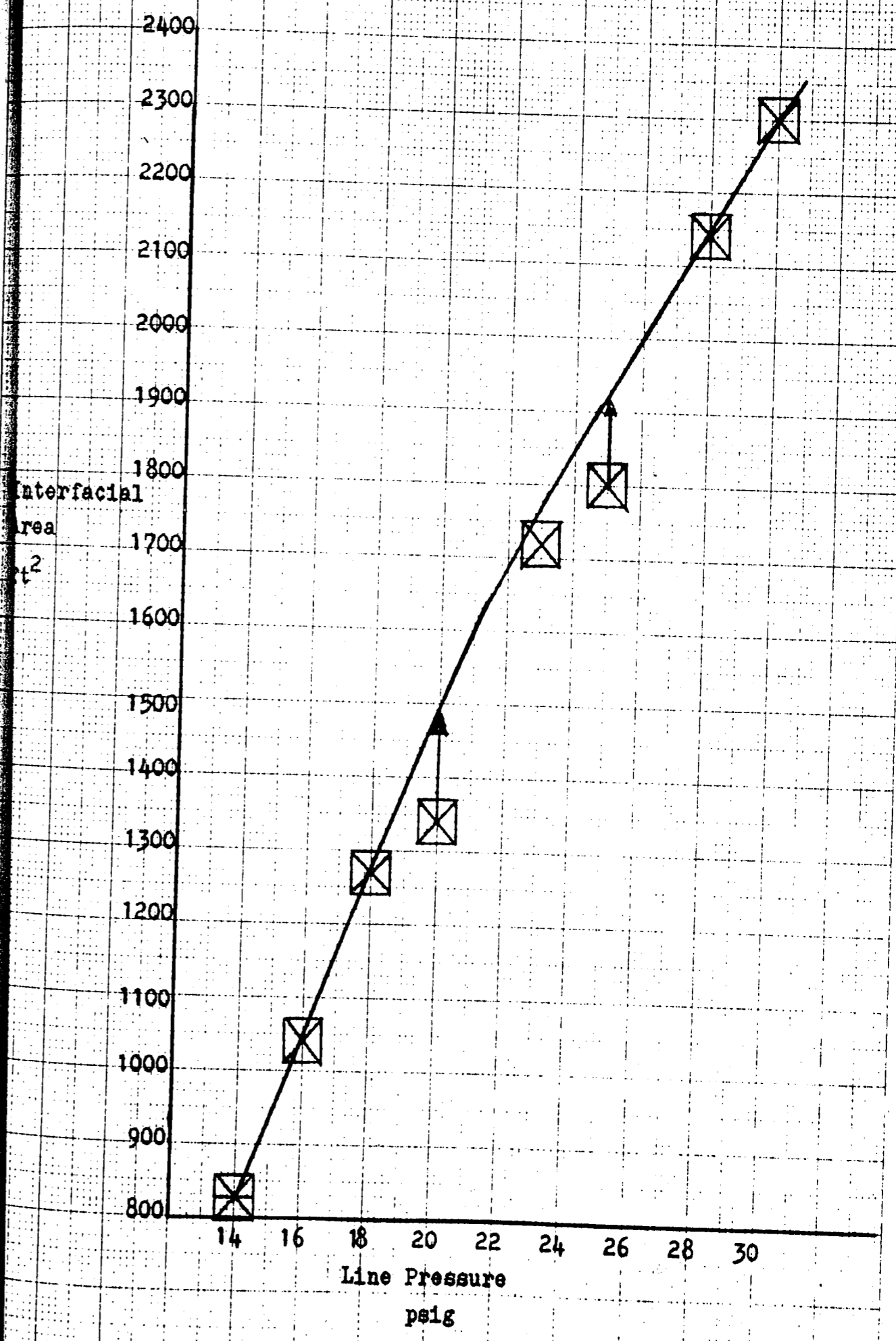
THE HCl PHASE OF THE EXPERIMENTS

After having calculated the interfacial areas for mass transfer over the appropriate range of flow rates, we should be able to calculate the theoretical mass transfer coefficient for the HCl system, and then run experiments with the jet-venturi scrubber and the HCl system to determine an experimental mass transfer coefficient with which to compare the theoretical value, and thus, examine the validity of the theory. However, because of the difficulties in measuring the contact time, 'θ', we will use the experimental data to calculate contact times, and relate them to the residence times inside the scrubber throat as described in the section on mass transfer theory.

Eight runs were made using water to scrub HCl gas out of air. The runs took 45 minutes each, and were limited to this time to minimize the use of HCl. Inlet and outlet gas samples were taken, and liquid samples were taken every 15 minutes. The gas samples were taken to determine inlet and outlet concentrations, and to determine the gas cleaning efficiency of the scrubber at each set of operating conditions. The liquid samples were taken to make a mass balance to compare HCl into the scrubber with the HCl leaving the scrubber. Because the liquid samples are easier to take, and more accurate than the gas samples, this should be a good check on the accuracy of the gas samples.

The following is the experimental procedure used in making the HCl runs:

1) Prepare the following solutions:
   .02 M NaOH, .05 M NaOH, .10 M NaOH, .01 M NaOH,
   .10 M HCl, .01 M HCl, and .05 M HCl
2) Fill the separator tank to the mark, at which point there will be 196 liters of water in the tank
3) Fill (2) 500 milliliter erlenmeyer flasks with 400 milliliters each of the .01 M NaOH; Fill (1) 500

milliliter erlenmeyer flask with 250 milliliters of the .01 M NaOH; these will be the vessels used to take the gas samples with, the first two for the inlet gas sample, and the third for the outlet sample (a diagram of the gas sampling apparatus is shown on the next page)

4) Fill the draft manometer to the zero level, and check the level on the carbon tetrachloride manometer used to measure the flow rate of the HCl gas

5) Turn on the pump and adjust the ball valve until the desired liquid line pressure is achieved

6) Adjust the butterfly valve until the desired draft is achieved

7) Open the HCl cylinder and adjust the regulator until the carbon tetrachloride manometer gives the desired reading

8) Check the time - this is the start of the run

9) Turn on the vacuum pump to evacuate the pressure vessel used to take the gas samples

10) Set up the outlet gas sample apparatus

11) Fifteen minutes after the start of the run, take the first liquid sample (three samples will be taken to protect against any errors in liquid sampling)

12) Collect the gas sample from the outlet:
This is done by drawing 1 ft^3 of gas through a 250 ml solution of .01 M NaOH

13) Evacuate the pressure vessel to prepare for the inlet gas sampling

14) Thirty minutes after the start of the run, take the second liquid sample

15) When the pressure vessel is evacuated, collect the inlet gas sample from the pitot tube:
This is done by drawing 1 ft^3 of gas through (2) 400 milliliter solutions of .01 M NaOH

16) Take the final liquid sample 45 minutes after the start of the run

GAS SAMPLING APPARATUS

pitot tube
air exit

NaOH solution

NaOH solution

fine control valve

vacuum vessel
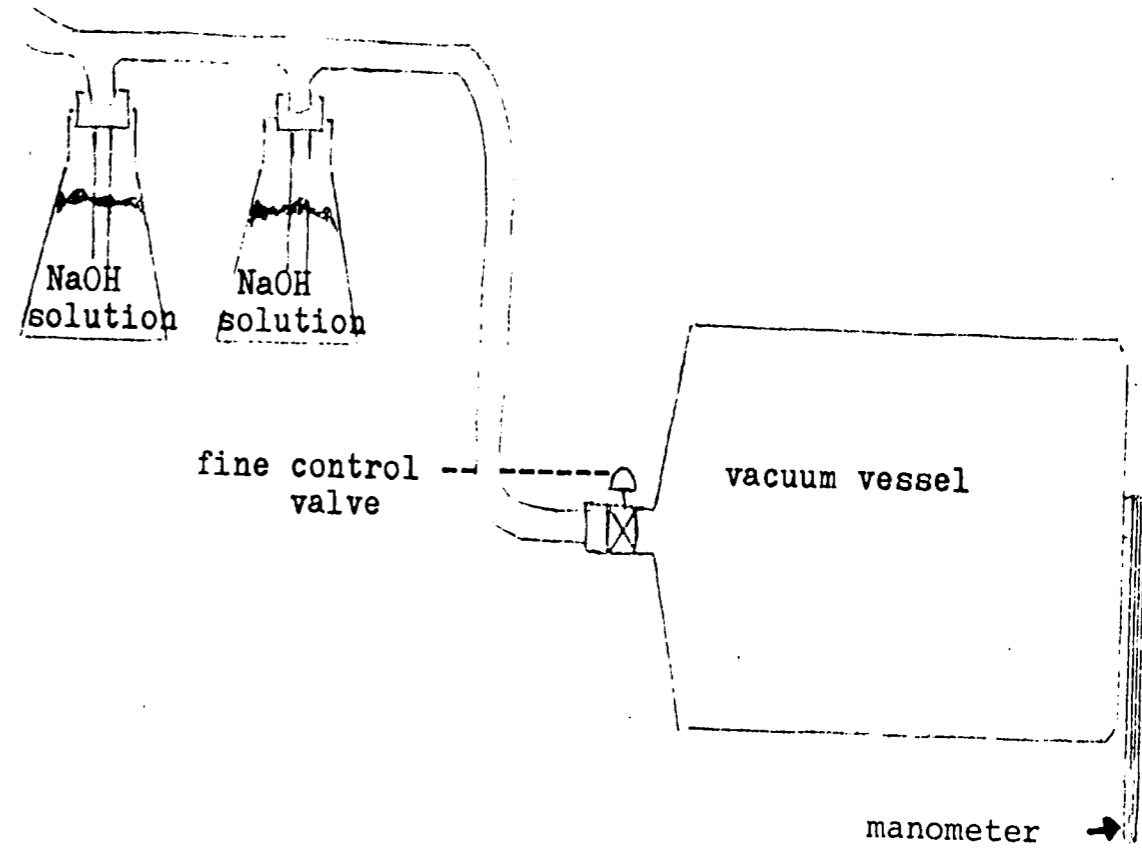
manometer

17) Turn off the HCl cylinder and close the Hoffman clamp that is between the regulator and the carbon tetra-chloride manometer to prevent damaging the regulator

18) After allowing the system to clear (wait about 5 minutes) turn off the pump and empty the separator tank

19) Carry out the titrations on the various samples

   (a) titrate the liquid samples with either .02 M NaOH, .05 M NaOH or .10 M NaOH depending on the expected outlet concentration of HCl; .02 M NaOH was used for runs 1 and 2, .05 M NaOH was used for runs 3 through 6, and .10 M NaOH was used for runs 7 and 8; phenolphthalein was used as an indicator, with a sharp endpoint shown as the pH of the titrated solution crossed 7.0

   (b) For the inlet gas sample bottles: titrate the first bottle from each sample (the erlenmeyer through which the gas being sampled passed first, where the majority of the HCl entering reacts) with .01 M HCl; titrate the second flask using .10 M HCl; phenolphthalein is again used as an indicator

   (c) titrate the outlet gas samples with either .01 M HCl or .05 M HCl; the first two runs (1 and 2) were titrated with .01 M HCl, and the remaining runs were titrated with the .05 M HCl

An explanation of the titrations should help explain the results obtained. The liquid samples contained HCl and water, and were titrated with NaOH. When the number of moles of NaOH in the titrated solution was equal to the number of moles of HCl in the sample, the endpoint was achieved. Hence, the milliliters of NaOH titrated defined the moles of NaOH titrated, which equaled the moles of HCl in the sample (all liquid samples were 15 milliliter samples), which defined the number of pounds of HCl in the 196 liter separator tank.

The HCl in the gas samples was absorbed in flasks containing NaOH. As the HCl passed through these flasks it reacted with the NaOH to neutralize it. The titrations were carried on using HCl to determine how much HCl was needed to complete the neutralization of the NaOH in these flasks. Hence, the following equation can be written to express the results of these titrations:

moles of HCl titrated + moles of HCl from gas =

moles of NaOH in sampling flask

Therefore, from these titrations, we can determine the number of moles, or the number of pounds of HCl in 1 ft^3 of inlet or outlet gas.

The data accumulated from these titrations and samples appears in Appendix II. The data, including graphical material, used in the selection and determination of operating parameters including inlet concentration for the HCl runs is presented in Appendix III.

The following pages are the results obtained from the data collected during the HCl runs. Such data will include: inlet and outlet concentrations of HCl in the air streams, concentrations of HCl accumulated in the scrubbing medium, the gas cleaning efficiencies of the jet-venturi scrubber under each set of operating conditions, and the mass balance of HCl for each run which strongly verify the accuracy of these experiments.

HCl RUN OPERATING CONDITIONS

LIQUID LINE PRESSURE	INLET AIR DRAFT	INLET AIR RATE	INLET HCl RATE
psig	inches H_2O	lb/hr	lb HCl/hr
14	0.363	1340	4.68
16	0.437	1510	5.14
18	0.500	1610	5.53
20	0.575	1700	5.93
23	0.667	1840	6.28
25	0.735	1900	6.61
28	0.825	1990	6.94
30	0.903	2050	6.94

HCl CONCENTRATIONS IN THE GAS AND THE LIQUID

P	INLET GAS CONCENTRATION	OUTLET GAS CONCENTRATION	FINAL LIQUID CONCENTRATION
sig	$\frac{\text{lb HCl}}{\text{ft}^3 \text{ gas}}$	$\frac{\text{lb HCl}}{\text{ft}^3 \text{ gas}}$	$\frac{\text{gm-moles HCl}}{\text{liter}}$
14	2.60×10^{-4}	1.53×10^{-4}	0.095
16	2.54×10^{-4}	1.07×10^{-4}	0.146
18	2.56×10^{-4}	7.62×10^{-5}	0.194
20	2.60×10^{-4}	5.10×10^{-5}	0.234
23	2.55×10^{-4}	3.14×10^{-5}	0.269
25	2.59×10^{-4}	1.85×10^{-5}	0.291
28	2.60×10^{-4}	9.00×10^{-6}	0.316
30	2.52×10^{-4}	7.20×10^{-6}	0.316

HCl MASS BALANCE

FLUID PRESSURE	HCl OUT in GAS	HCl OUT in LIQUID	HCl OUT TOTAL	HCL IN TOTAL	% DIFFERENCE HCl OUT RELATIVE TO HCl IN
psig	lb HCl	lb HCl	lb HCl	lb HCl	%
14	2.07	1.50	3.57	3.51	+1.68%
16	1.62	2.30	3.92	3.85	+1.79%
18	1.26	3.06	4.32	4.25	+1.62%
20	0.87	3.70	4.57	4.44	+2.95%
23	0.58	4.24	4.82	4.71	+2.28%
25	0.35	4.59	4.94	4.96	-0.45%
28	0.19	5.00	5.19	5.21	-0.39%
30	0.15	5.00	5.15	5.21	-1.17%

The accuracy of the mass balance, which combines liquid sample data with gas sample data, indicates that the titrations were not a significant source of error.

GAS CLEANING EFFICIENCIES

LIQUID LINE PRESSURE	GAS FLOW	GAS CLEANING EFFICIENCY
psig	SCFM	% EFFICIENCY
14	300	41.0%
16	337	58.0%
18	360	70.3%
20	380	80.4%
23	410	87.7%
25	425	92.9%
28	445	96.5%
30	480	97.1%

NOTE: Gas cleaning efficiency is defined as follows:

$$\text{Gas Cleaning Efficiency} = \frac{\text{lb HCl in Gas IN} - \text{lb HCl in Gas OUT}}{\text{lb HCl in Gas IN}} \times 100\%$$

GAS CLEANING EFFICIENCIES

-40-
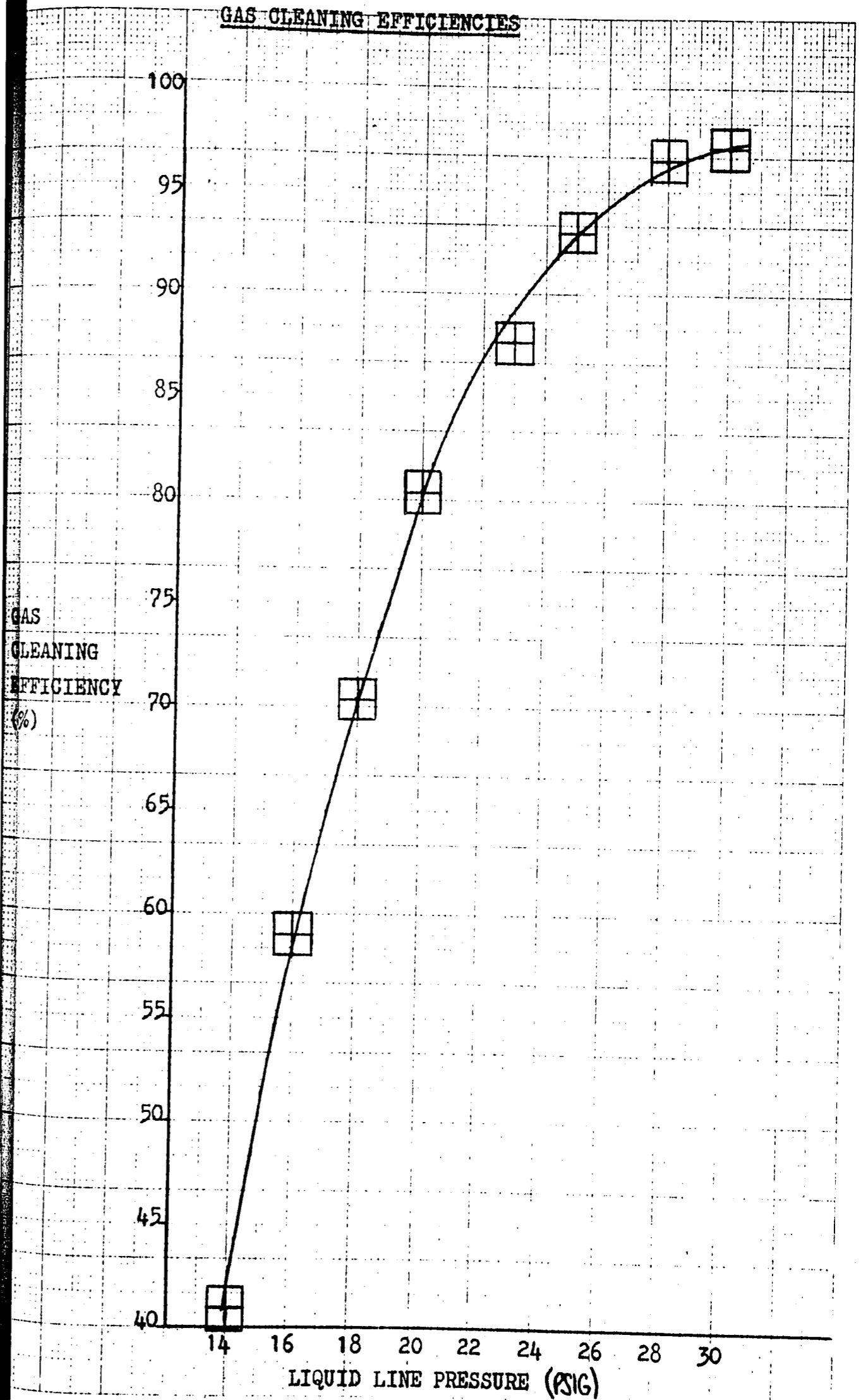
RESULTS AND CONCLUSIONS

From the inlet and outlet gas samples taken during the HCl phase of the experiments, liquid and gas phase driving forces can be determined using the equations previously presented. Over the experimental range used, certain simplifications in the equations can be made:

$$C_{G,\text{ in}} - f^{-1}(C_L,\text{in}) \approx C_{G,\text{ in}}$$

$$C_{G,\text{out}} - f^{-1}(C_L,\text{out}) \approx C_{G,\text{ out}}$$

$$f(C_{G},\text{in}) - C_{L,\text{in}} \approx f(C_{G},\text{in})$$

$$f(C_{G},\text{out}) - C_{L,\text{out}} \approx f(C_{G},\text{out})$$

Using the above simplifications, the following equations result for the driving forces:

$$\Delta C_{\text{driving force},G} = \frac{C_{G,\text{in}} - C_{G,\text{out}}}{\log_e \frac{C_{G,\text{in}}}{C_{G,\text{out}}}}$$

$$\Delta C_{\text{driving force},L} = \frac{f(C_{G},\text{in}) - f(C_{G},\text{out})}{\log_e \frac{f(C_{G},\text{in})}{f(C_{G},\text{out})}}$$

Driving force values are presented on the following pages.

Using these values for the driving forces, experimental liquid and gas phase mass transfers coefficients were calculated. These values have been presented on page 44. All of the experimental mass transfer coefficients appear to be valid with the exception of two determinations: the liquid phase calculations for the 20 psig and 30 psig runs. The driving force calculations were a major cause of this inaccuracy, since the equilibrium data used, although the best available, may be lacking in accuracy. In addition, the gas sampling procedures were a probable source of error.

GAS DRIVING FORCE

LINE P	C_G,in	C_G,out	$\Delta C_{driving\ force,G}$
psig	lb HCl/ft^3	lb HCl/ft^3	lb HCl/ft^3
14	2.60	1.53	2.02
16	2.54	1.07	1.66
18	2.56	.762	1.49
20	2.60	.510	1.28
23	2.55	.314	1.07
25	2.59	.185	0.910
28	2.60	.0900	0.746
30	2.52	.0720	0.690
	$\times 10^{-4}$	$\times 10^{-4}$	$\times 10^{-4}$

LIQUID DRIVING FORCE

LINE P	$f(C_G,in)$	$f(C_G,out)$	$\Delta C_{driving\ force,L}$
psig	$\dfrac{lb\ HCl}{ft^3}$	$\dfrac{lb\ HCl}{ft^3}$	$\dfrac{lb\ HCl}{ft^3}$
14	1.37	1.28	1.30
16	1.36	1.23	1.28
18	1.36	1.18	1.27
20	1.37	1.14	1.24
23	1.36	1.06	1.20
25	1.37	0.995	1.17
28	1.37	0.900	1.12
30	1.36	0.864	1.09
	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$

MASS TRANSFER COEFFICIENTS

LINE P	k_G	k_L
psig	ft/hr	ft/hr
14	8.96	.139
16	13.3	.173
18	16.2	.190
20	19.4	.200*
23	22.4	.200
25	26.2	.204
28	31.4	.209
30	31.6	.200*

Using the calculated driving forces, contact times and contact time ratios were also determined. The results, shown on page 46, again indicate that the calculations for the liquid phase for the 20 psig and 30 psig runs were inaccurate. The gas phase contact time ratios range from 0.00619 to 0.0534, and the liquid phase contact time ratios range from 0.0142 to 0.0274. In all cases, the contact time ratios are less than 1.0. Theoretically, mass transfer coefficients are meaningless where the contact time ratios are less than one. Therefore, either the experimental data is not accurate, or there is a flaw in the mass transfer theory being used. The graph of line pressure versus gas cleaning efficiency closely approximated predicted results, indicating that the flaw lies in the theory, rather than in the experimental data. Despite this, several important relationships develop when the theory is combined with the experimental data. The following pages show contact time ratios plotted versus liquid line pressure and gas cleaning efficiency. The results, particularly for the gas phase case, indicate definite relationships between the parameters in question. Gas phase contact time ratios, for example, vary linearly with liquid rate and parabolically with gas cleaning efficiency. If relationships such as these could be developed accurately, this would be an important step towards the prediction of mass transfer rates. One would merely have to select the gas cleaning efficiency desired, this would specify the contact time ratio to be used, which would in turn specify to liquid line pressure at which the scrubber would be operated to give the desired efficiency.

EXPERIMENTAL CONTACT TIMES AND CONTACT TIME RATIOS

P	θ_G	θ_L	n_G	n_L
psig	sec.	sec.	--	--
14	33.4	15.3	.00619	.0142
16	15.1	9.90	.0130	.0213
18	10.3	8.26	.0177	.0250
20	7.20	7.40*	.0242	.0274*
23	5.35	7.40	.0301	.0266
25	3.91	7.10	.0397	.0267
28	2.73	6.80	.0542	.0270
30	2.70	7.40*	.0534	.0243*

n_G vs. Liquid Rate (as line pressure)

Liquid Rate as Line Pressure (psig)

GAS BASED CONTACT TIME RATIO (n_G) x 10^{-2}

n_G vs. GAS CLEANING EFFICIENCY

GAS CLEANING
EFFICIENCY
(%)

GAS PHASE BASED CONTACT TIME RATIO (n_G) x 10^{-2}

n_L vs. Liquid Rate as Line Pressure

Liquid Rate
as
Line Pressure
(psig)

LIQUID PHASE BASED CONTACT TIME RATIO (n_L) x 10^{-2}

n_L vs. GAS CLEANING EFFICIENCY

GAS CLEANING
EFFICIENCY
(%)

LIQUID PHASE BASED CONTACT TIME RATIO (n_L) x 10^{-2}
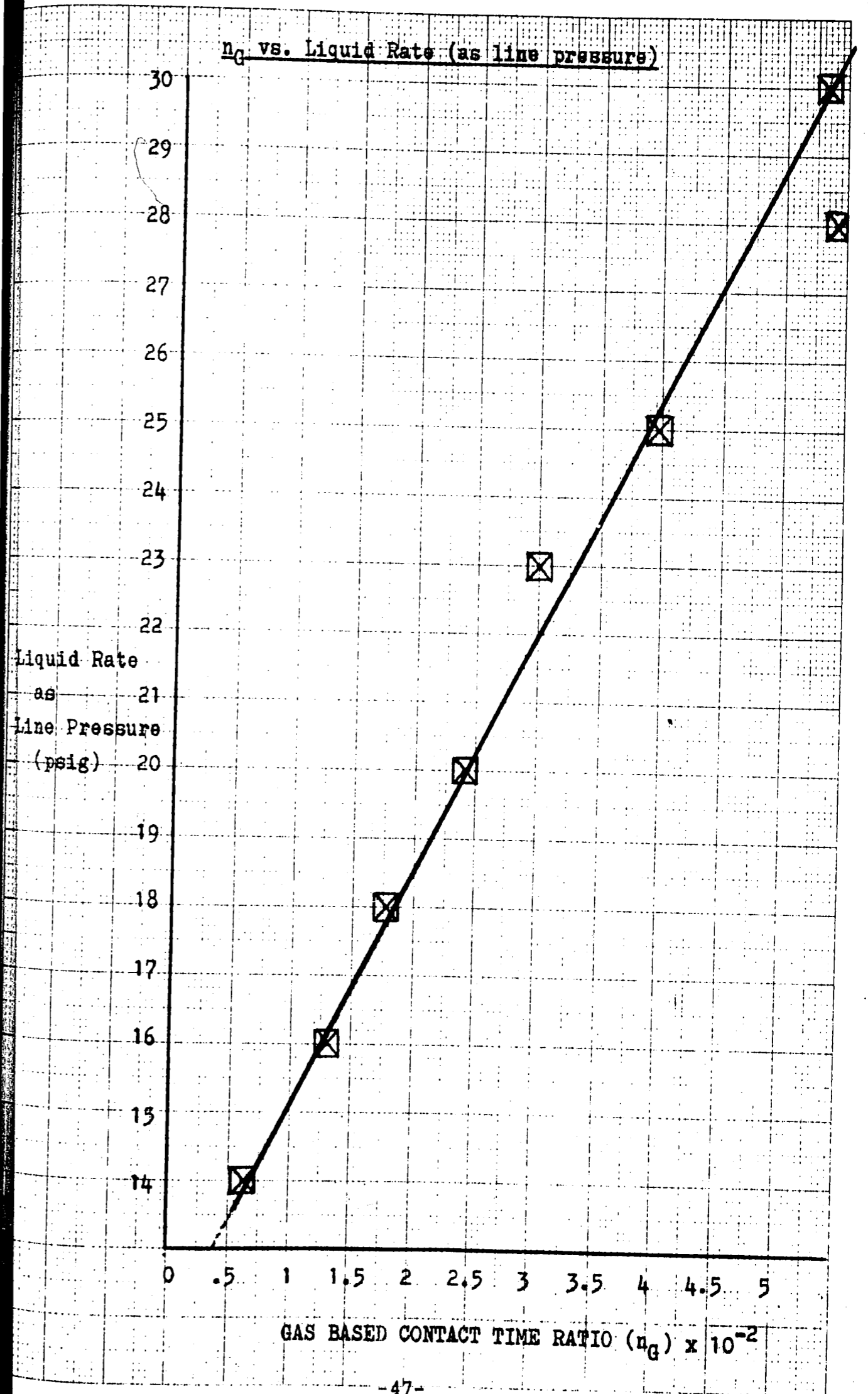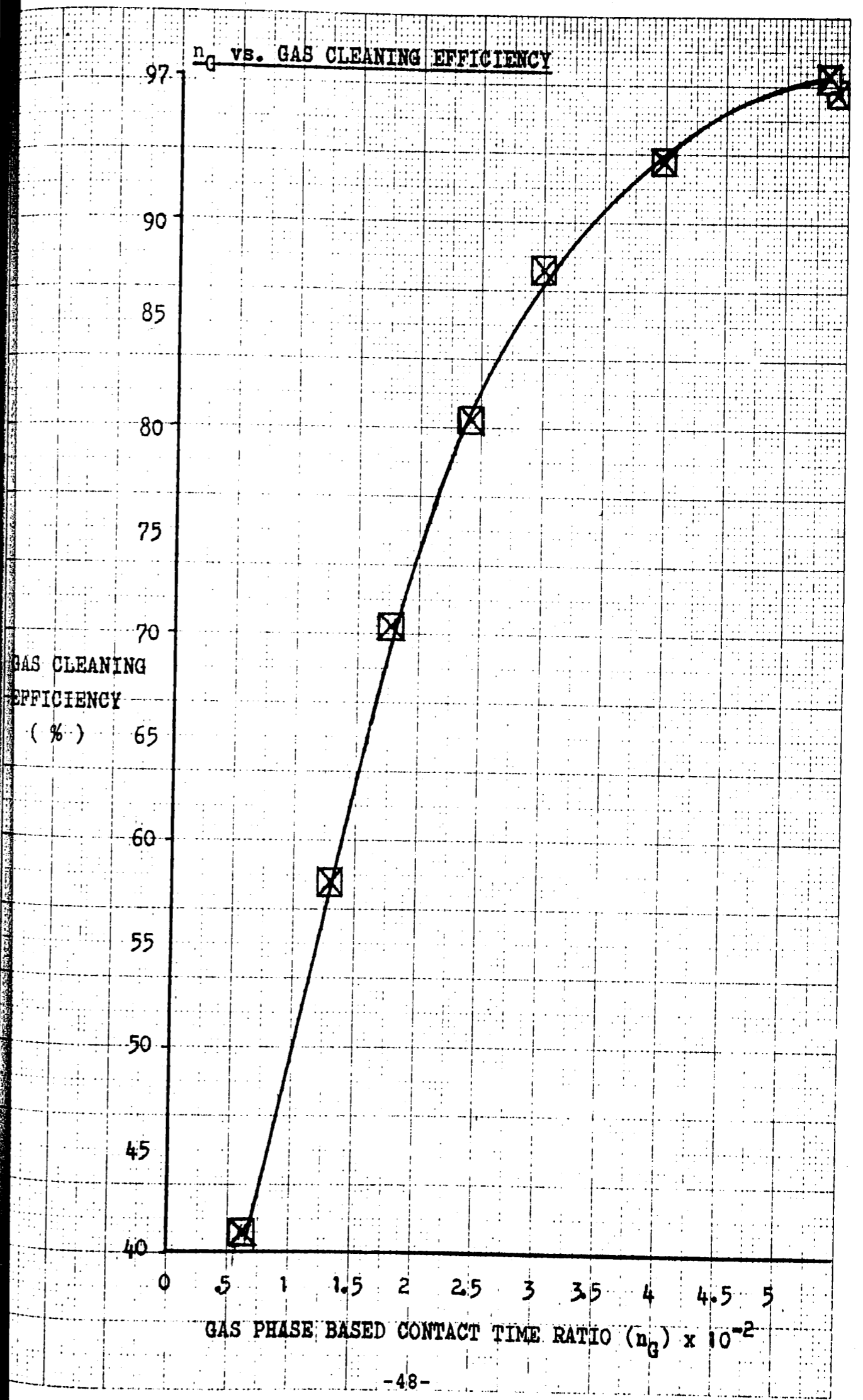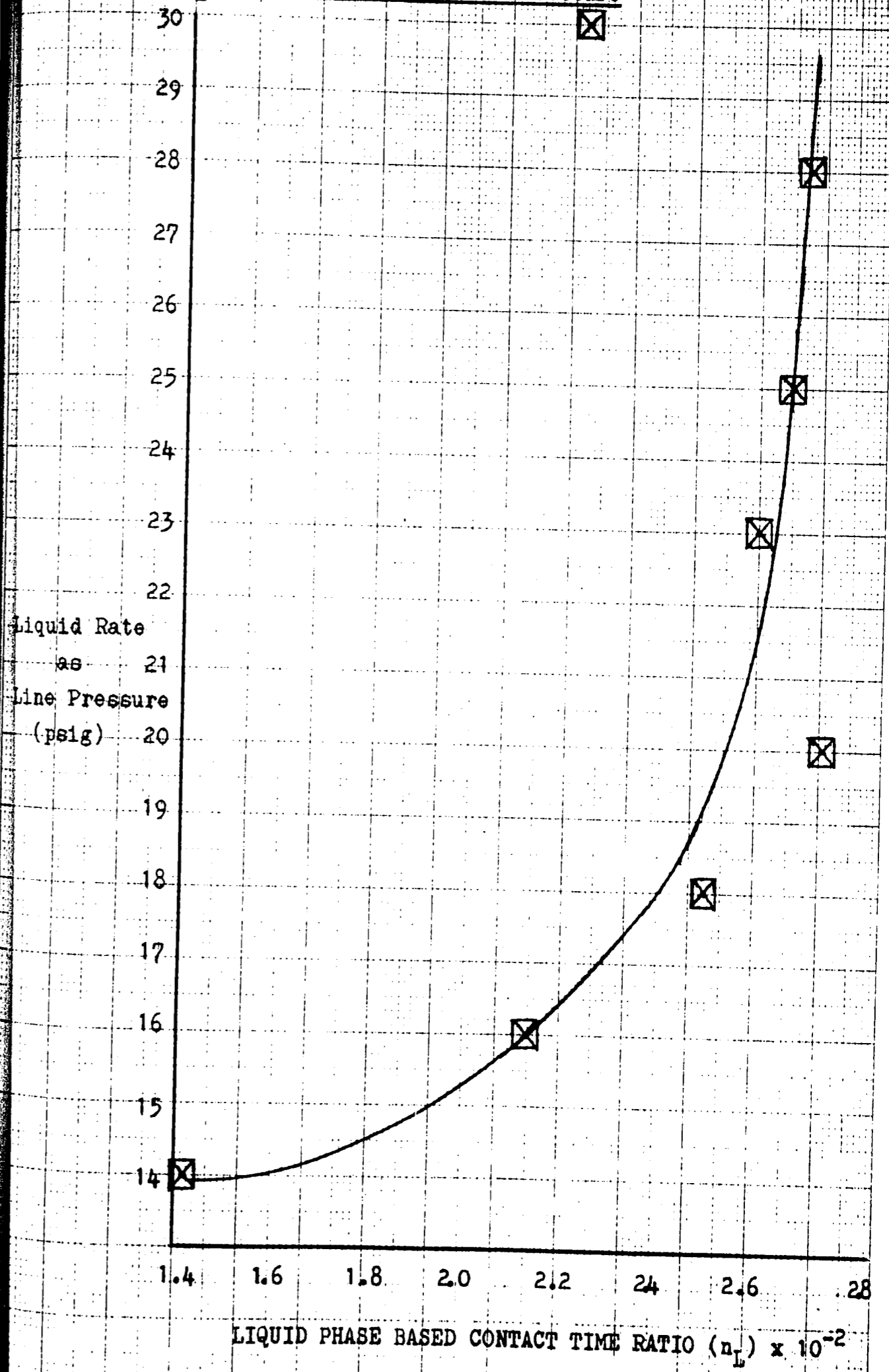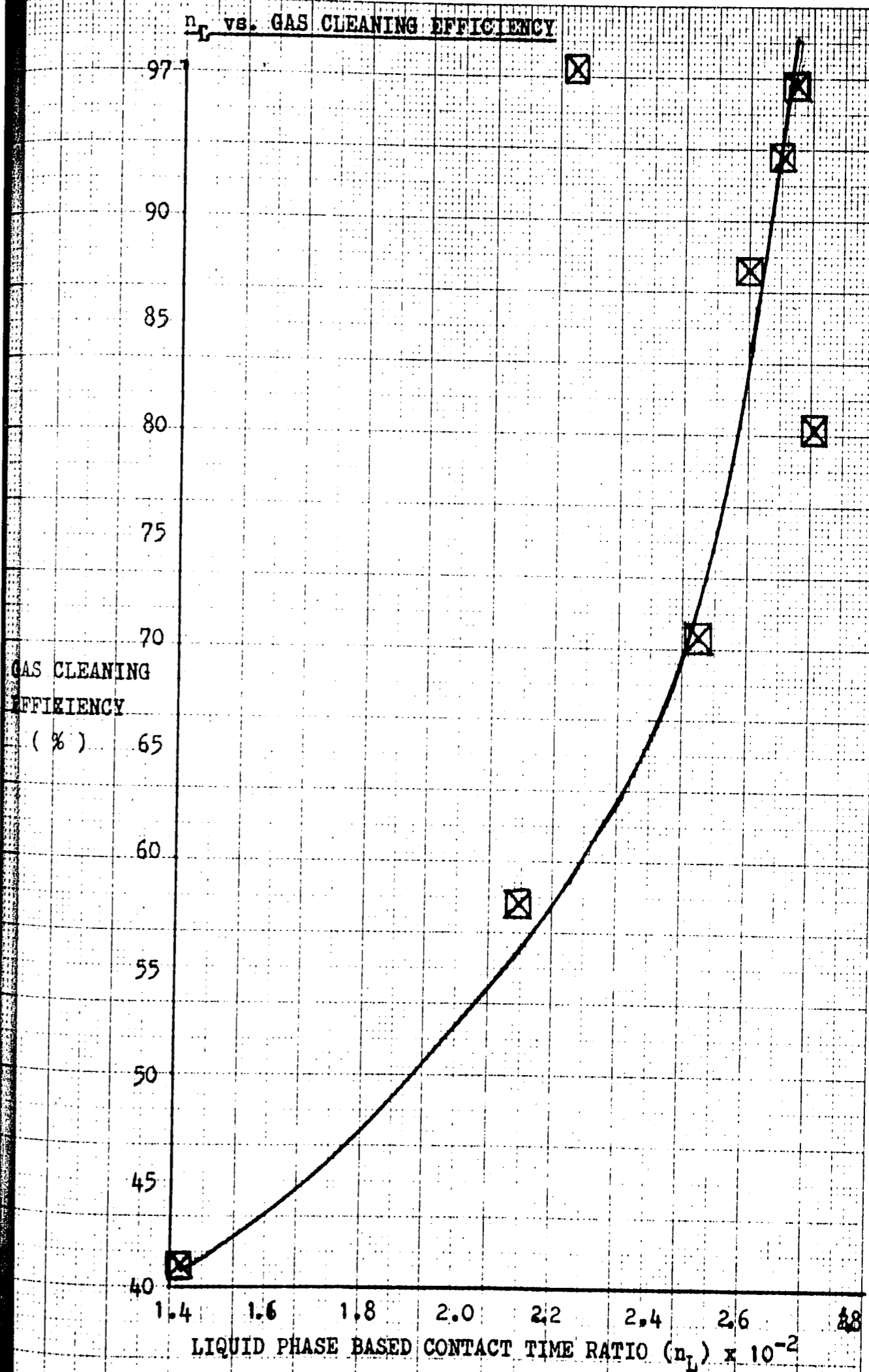
RECOMMENDATIONS

The following are recommendations for future study, as well as for optimization of the experimental procedures used in this study.

1) More data should be taken using the HCl system to study the relationships between n_L or n_G and liquid rate, gas rate and gas cleaning efficiency.

   a) Additional runs should be made on the same system at the liquid rates previously used with different gas rates, and at the gas rates used with different liquid rates.

   b) Less dilute inlet HCl concentrations should be tested.

2) The experimental procedures should be optimized.

   a) The gas sampling procedure is difficult to accomplish and is a certain cause of some experimental error.

   b) Considerable liquid escapes out of the gas outlet causing the liquid sample calculations to be of uncertain reliability.

   c) An HCl rotometer should be used to measure flow rates as the manometer employed was inconsistent.

3) Other systems should be studied, some with known mass transfer resistances primarily in the gas phase, and some with known liquid phase resistances, to fully evaluate the application of the penetration theory to mass transfer in jet-venturi scrubbers.

4) Pressure drop across the scrubber throat should be checked in future experiments, and should be considered as a major mass transfer parameter.

5) The effective length of scrubber throat for mass transfer should be examined as a mass transfer parameter.

6) Theories based on the high degree of atomization attained in jet-venturi scrubbers should be tested. One way of doing this would be to study the transfer of mass from a gas between two liquid drops to the drops, and to calculate the distance between the drops that gives a mass transfer rate equal to the rate found in experimental study. This distance could then be examined as a mass transfer parameter. The equations used would be the following:

$$\frac{dp_A}{dt} = D_{G,AB} \frac{d^2 p_A}{dz^2}$$

with boundary conditions: 1) $p_A = p_{A,o}$ @ t=0 for all Z

2) $\frac{dp_A}{dz} = 0$ @ Z=0 for all t

3) $\frac{dp_A}{dz} = \frac{D_L}{D_G} \frac{dC_A}{dz}$ @ Z = δ for all t

where A is the transferred component, B is the gas from which A is transferred (usually air), and δ is 1/2 the distance between drops.

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APPENDIX I

OXYGEN-SULFITE SYSTEM DATA

Liquid samples were taken for each of the eight experimental runs. With each succeeding sample, the concentration of sulfite ions in the solution decreases, as more and more of the sulfite reacts with the oxygen absorbed from the air passing through the scrubber to form sulfate. The concentration of sulfite ions in the solution for a given sample is directly proportional to the milliliters of KIO_3 used in the titration described in the experimental section, where

$$ml\ KIO_3 \times .0158 = \text{Concentration of } SO_3^{-2} \text{ in } \frac{gm\text{-moles}}{liter}$$

Graphing the concentration change versus time determines the interfacial areas for mass transfer, as shown in the experimental section.

APPENDIX I -- OXYGEN-SULFITE SYSTEM DATA

RUN 1

	Time (min)	ml KIO$_3$	Conc. SO$_3$
P = 14 psig	0	58.0	0.914
Draft = .363 in. H$_2$0	5	57.4	0.904
Air Rate = 5.000 cfs	10	56.9	0.896
	15	56.5	0.890
	20	56.1	0.884
	25	55.8	0.879
	30	55.5	0.874
	35	55.4	0.873
	40	55.4	0.871
	45	55.3	0.871

RUN 2

	Time (min)	ml KIO$_3$	Conc. SO$_3$
P = 16 psig	0	59.5	0.937
Draft = .437 in. H$_2$0	5	58.8	0.926
Air Rate = 5.610 cfs	10	58.2	0.917
	15	57.7	0.909
	20	57.2	0.901
	25	56.8	0.895
	30	56.5	0.890
	35	56.3	0.887
	40	56.2	0.885
	45	56.2	0.885

APPENDIX I -- OXYGEN-SULFITE SYSTEM DATA

RUN 3

P = 18 psig
Draft = .475 in. H_2O
Air Rate = 6.00 cfs

Time (min)	ml KIO_3	Conc. SO_3
0	52.5	0.827
5	51.6	0.813
10	51.0	0.803
15	50.3	0.792
20	49.7	0.783
25	49.1	0.773
30	48.6	0.765
35	48.3	0.761
40	48.1	0.758
45	48.1	0.758

RUN 4

P = 20 psig
Draft = .575 in. H_2O
Air Rate = 6.33 cfs

Time (min)	ml KIO_3	Conc. SO_3
0	48.7	0.767
5	47.5	0.748
10	46.8	0.737
15	46.2	0.727
20	45.5	0.717
25	44.5	0.701
30	44.0	0.693
35	43.8	0.690
40	43.6	0.687
45	43.5	0.686

APPENDIX I -- OXYGEN-SULFITE SYSTEM DATA

RUN 5

P = 23 psig

Draft = .670 in. H_2O

Air Rate = 6.83 cfs

Time (min)	ml KIO_3	Conc. SO_3
0	57.8	0.913
5	56.7	0.893
10	56.0	0.882
15	55.0	0.886
20	54.0	0.851
25	53.4	0.841
30	53.0	0.835
35	52.2	0.822
40	51.8	0.817
45	51.8	0.817

RUN 6

P = 25 psig

Draft = .725 in. H_2O

Air Rate = 7.08 cfs

Time (min)	ml KIO_3	Conc. SO_3
0	57.8	0.910
5	56.5	0.890
10	55.5	0.874
15	54.5	0.858
20	53.9	0.849
25	53.0	0.835
30	52.2	0.822
35	51.4	0.810
40	51.2	0.806
45	51.2	0.806

APPENDIX I -- OXYGEN-SULFITE SYSTEM DATA

7

28 psig

ft = .825 in. H_2O

Rate = 7.41 cfs

Time (min)	ml KIO_3	Conc. SO_3
0	58.0	0.914
5	56.6	0.891
10	55.4	0.873
15	54.3	0.855
20	53.4	0.841
25	52.6	0.828
30	51.8	0.816
35	51.2	0.806
40	51.0	0.803
45	51.0	0.803

8

30 psig

ft = .878 in. H_2O

Rate = 7.64 cfs

Time (min)	ml KIO_3	Conc. SO_3
0	57.0	0.898
5	55.5	0.874
10	54.2	0.854
15	53.1	0.836
20	52.1	0.821
25	51.3	0.808
30	50.4	0.794
35	49.7	0.783
40	49.6	0.781
45	49.5	0.780

APPENDIX II -- HCl PHASE OF THE EXPERIMENTS

RUN 1H

Line Pressure - 14 psig

Draft = 0.363 in. H_2O

LIQUID SAMPLES (all 15 ml)

--- titrant used was 0.02 M NaOH

Time (min)	ML Titrant
15	22.4
30	47.7
45	71.3

GAS SAMPLES

--- INLET:

First Flask - 400 ml of .01 M NaOH

titrant used - 96.5 ml of .01 M HCl

Second Flask - 400 ml of .01 M NaOH

titrant used - 38.0 ml of .10 M HCl

NaOH neutralized by HCl in titrant - 476 ml

NaOH neutralized by HCl in sample - 324 ml

Concentration of HCl in sample - 3.24×10^{-3} gm-moles/ft^3

--- OUTLET:

Collection Flask - 250 ml of .01 M NaOH

titrant used - 59.0 ml of .01 M HCl

NaOH neutralized by titrant - 59.0 ml

NaOH neutralized by HCl in sample - 191.0 ml

Concentration of HCl in sample - 1.91×10^{-3} gm-moles/ft^3

RUN 2H

Line Pressure - 16 psig

Draft - 0.437 in. H_2O

LIQUID SAMPLES (all 15 ml)

--- titrant used was 0.02 M NaOH

Time (min)	ML Titrant
15	34.5
30	71.5
45	109.5

GAS SAMPLES

--- INLET:

First Flask - 400 ml of .01 M NaOH

titrant used - 91.0 ml of .01 M HCl

Second Flask - 400 ml of .01 M NaOH

titrant used - 39.3 ml of .10 M HCl

NaOH neutralized by HCl in titrant - 484 ml

NaOH neutralized by HCl in sample - 316 ml

Concentration of HCl in sample - 3.16×10^{-3} gm-moles/ft^3

--- OUTLET:

Collection Flask - 250 ml of .01 M NaOH

titrant used - 117.0 ml of .01 M HCl

NaOH neutralized by HCl in titrant - 117.0 ml

NaOH neutralized by HCl in sample - 133.0 ml

Concentration of HCl in sample - 1.33×10^{-3} gm-moles/ft^3

APPENDIX II -- HCl PHASE OF THE EXPERIMENTS

RUN 3H

Line Pressure - 18 psig

Draft - 0.500 in. H_2O

LIQUID SAMPLES (all 15 ml)

--- titrant used was 0.05 M NaOH

Time (min)	ML Titrant
15	19.0
30	39.5
45	58.0

GAS SAMPLES

--- INLET:

First Flask - 400 ml of .01 M NaOH

titrant used - 91.0 ml of .01 M HCl

Second Flask - 400 ml of .01 M NaOH

titrant used - 39.0 ml of .10 M HCl

NaOH neutralized by HCl in titrant - 481 ml

NaOH neutralized by HCl in sample - 319 ml

Concentration of HCl in sample - 3.19×10^{-3} gm-moles/ft^3

--- OUTLET:

Collection Flask - 250 ml of .01 M NaOH

titrant used - 31.0 ml of .05 M HCl

NaOH neutralized by HCl in titrant - 155.0 ml

NaOH neutralized by HCl in sample - 95.0 ml

Concentration of HCl in sample - 9.50×10^{-4} gm-moles/ft^3

APPENDIX II -- HCl PHASE OF THE EXPERIMENTS

RUN 4H

Line Pressure - 20 psig

Draft - 0.575 in. H_2O

LIQUID SAMPLES (all 15 ml)

--- titrant used was 0.05 M NaOH

Time (min)	ML Titrant
15	22.5
30	46.8
45	70.3

GAS SAMPLES

--- INLET:

First Flask - 400 ml of .01 M NaOH

titrant used - 91.0 ml of .01 M HCl

Second Flask - 400 ml of .01 M NaOH

titrant used - 38.5 ml of .10 M HCl

NaOH neutralized by HCl in titrant - 476 ml

NaOH neutralized by HCl in sample - 324 ml

Concentration of HCl in sample - 3.24×10^{-3} gm-moles/ft^3

--- OUTLET:

Collection Flask - 250 ml of .01 M NaOH

titrant used - 37.3 ml of .05 M HCl

NaOH neutralized by HCl in titrant - 186.5 ml

NaOH neutralized by HCl in sample - 63.5 ml

Concentration of HCl in sample - 6.35×10^{-4} gm-moles/ft^3

APPENDIX II -- HCl PHASE OF THE EXPERIMENTS

RUN 5H

Line Pressure - 23 psig

Draft - 0.667 in. H_2O

LIQUID SAMPLES (all 15 ml)

--- titrant used was 0.05 M NaOH

Time (min)	ML Titrant
15	26.5
30	53.5
45	80.5

GAS SAMPLES

--- INLET:

First Flask - 400 ml of .01 M NaOH

titrant used - 93.0 ml of .01 M HCl

Second Flask - 400 ml of .01 M NaOH

titrant used - 39.0 ml of .10 M HCl

NaOH neutralized by HCl in titrant - 483 ml

NaOH neutralized by HCl in sample - 317 ml

Concentration of HCl in sample - 3.17×10^{-3} gm-moles/ft^3

--- OUTLET:

Collection Flask - 250 ml of .01 M NaOH

titrant used - 42.3 ml of .05 M HCl

NaOH neutralized by titrant - 211 ml

NaOH neutralized by HCl in sample 39.0 ml

Concentration of HCl in sample - 3.9×10^{-4} gm-moles/ft^3

APPENDIX II -- HCl PHASE OF THE EXPERIMENTS

RUN 6H

Line Pressure - 25 psig

Draft - 0.735 in. H_2O

LIQUID SAMPLES (all 15 ml)

--- titrant used was 0.05 M NaOH

Time (min)	ML Titrant
15	28.5
30	59.8
45	87.3

GAS SAMPLES

--- INLET:

First Flask - 400 ml of .01 M NaOH

titrant used - 95.0 ml of .01 M HCl

Second Flask - 400 ml of .01 M NaOH

titrant used - 38.3 ml of .10 M HCl

NaOH neutralized by HCl in titrant - 478 ml

NaOH neutralized by HCl in sample - 322 ml

Concentration of HCl in sample - 3.22×10^{-3} gm-moles/ft^3

--- OUTLET:

Collection Flask - 250 ml of .01 M NaOH

titrant used - 45.5 ml of .05 M HCl

NaOH neutralized by HCl in titrant - 227.0 ml

NaOH neutralized by HCl in sample - 23.0 ml

Concentration of HCl in sample - 2.30×10^{-4} gm-moles/ft^3

RUN 7H

Line Pressure - 28 psig

Draft - 0.825 in. H_2O

LIQUID SAMPLES (all 15 ml)

--- titrant used was 0.10 M NaOH

Time (min)	ML Titrant
15	15.5
30	31.5
45	47.5

GAS SAMPLES

--- INLET:

First Flask - 400 ml of .01 M NaOH

titrant used - 91.0 ml of .01 M HCl

Second Flask - 400 ml of .01 M NaOH

titrant used - 38.5 ml of .10 M HCl

NaOH neutralized by HCl in titrant - 476 ml

NaOH neutralized by HCl in sample - 324 ml

Concentration of HCl in sample - 3.24×10^{-3} gm-moles/ft^3

--- OUTLET:

Collection Flask - 250 ml of .01 M NaOH

titrant used - 47.8 ml of .05 M HCl

NaOH neutralized by HCl in titrant - 238.8 ml

NaOH neutralized by HCl in sample - 11.2 ml

Concentration of HCl in sample - 1.12×10^{-4} gm-moles/ft^3

RUN 8H

Line Pressure - 30 psig

Draft - 0.903 in. H_2O

LIQUID SAMPLES (all 15 ml)

--- titrant used was 0.10 M NaOH

Time (min)	ML Titrant
15	16.0
30	31.8
45	47.5

GAS SAMPLES

--- INLET:

First Flask - 400 ml of .01 M NaOH

titrant used - 97.0 ml of .01 M HCl

Second Flask - 400 ml of .01 M NaOH

titrant used - 39.0 ml of .10 M HCl

NaOH neutralized by HCl in titrant - 487 ml

NaOH neutralized by HCl in sample - 313 ml

Concentration of HCl in sample - 3.13×10^{-3} gm-moles/ft^3

--- OUTLET:

Collection Flask - 250 ml of .01 M NaOH

titrant used - 48.3 ml of .05 M HCl

NaOH neutralized by HCl in titrant - 241.0 ml

NaOH neutralized by HCl in sample - 9.0 ml

Concentration of HCl in sample - 9.00×10^{-5} gm/moles/ft^3

APPENDIX III

DETERMINATION AND SELECTION OF OPERATING PARAMETERS

AIR FLOW RATES

Line Pressure	Volumetric Flow Rate	Mass Flow Rate
psig	SCF/hr Air	lb/hr Air
14	18,000	1340
16	20,200	1510
18	21,600	1610
20	22,800	1700
23	24,600	1840
25	25,500	1900
28	26,700	1990
30	27,500	2050

NOZZLE
PRESSURE
VS
SCFH AIR

NOZZLE PRESSURE
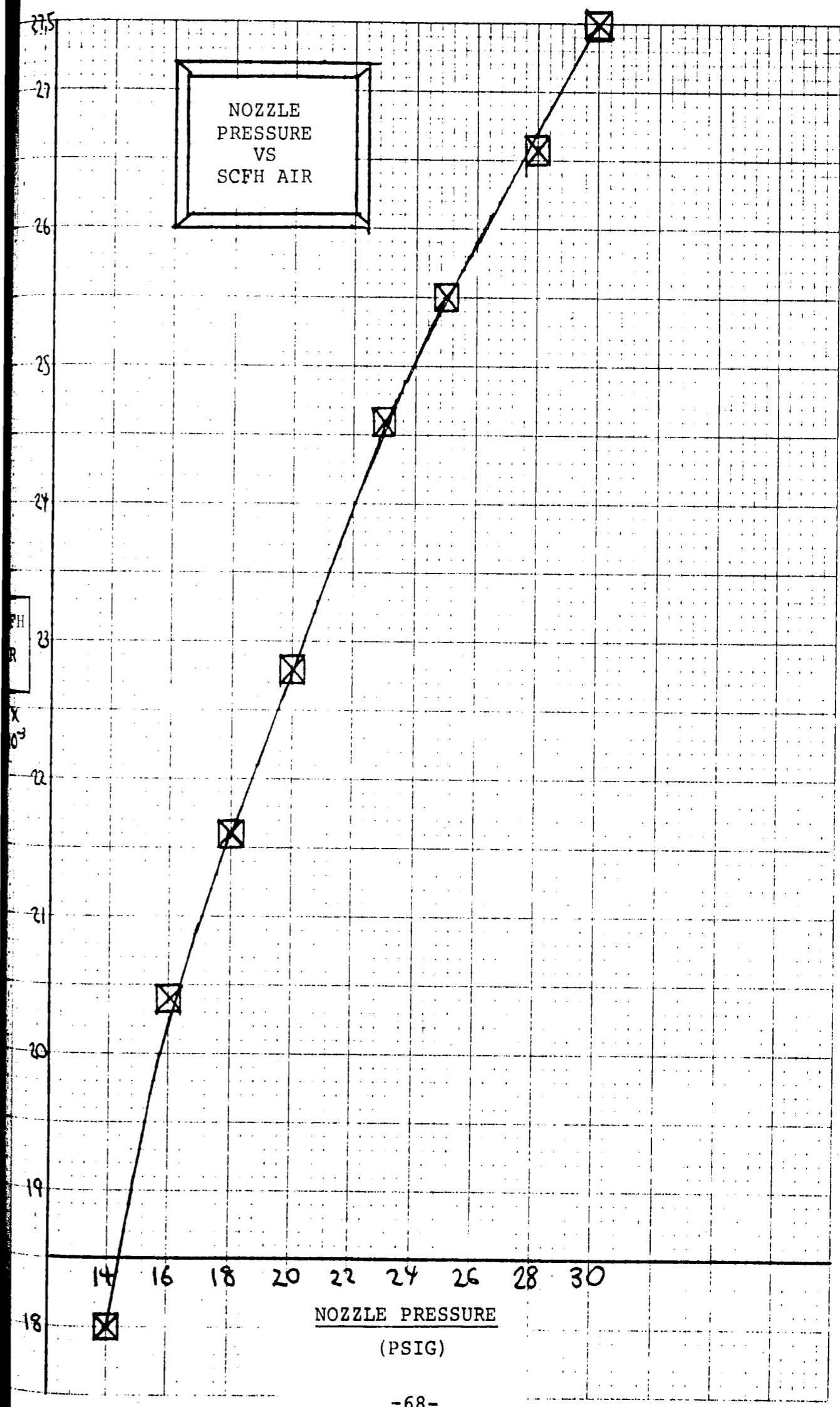
(PSIG)

APPENDIX III

NOZZLE (LINE) PRESSURE VS. DRAFT

LINE PRESSURE	OPERATING DRAFT
psig	inches of water
14	.363
16	.437
18	.500
20	.575
23	.667
25	.735
28	.825
30	.903

NOZZLE
PRESSURE
VS
DRAFT ("H₂O)

NOZZLE PRESSURE (PSIG)
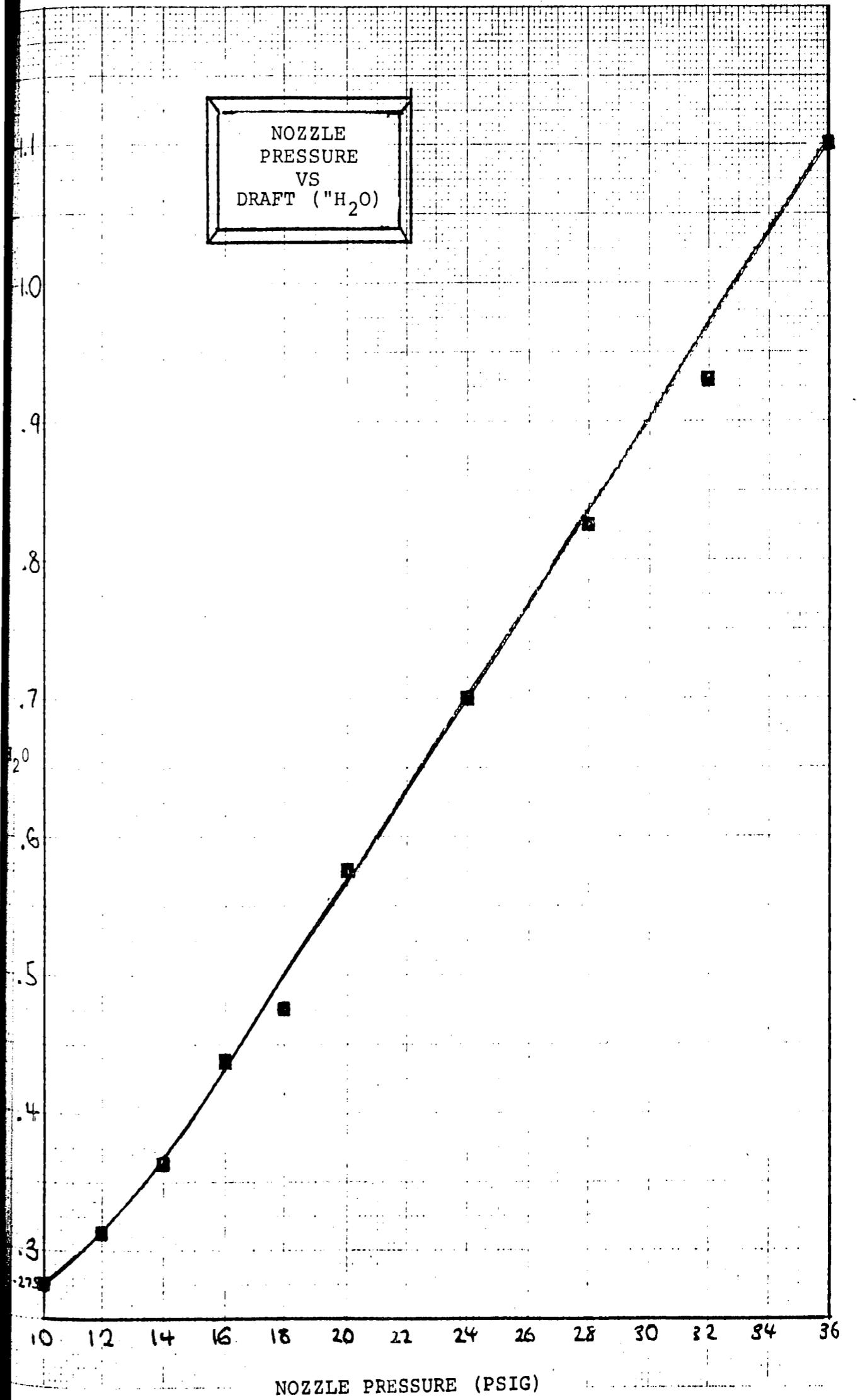
CALIBRATION OF CARBON TETRACHLORIDE MANOMETER

Manometer Reading inches CCl_4	HCl Gas Flow Rate $ft^3 HCl/hr$
0.04	10
0.16	20
0.35	30
0.63	40
0.99	50
1.19	55
1.33	58
1.42	60
1.51	62
1.67	65
1.83	68
1.93	70
2.22	75

NOTE: Calibration calculated from following equation:

$$\text{inches } CCl_4 = \frac{12\ (q)^2 (1 - B^4)(\text{density of HCl})}{2\ (C)^2 (Y)^2 (A_{throat})^2 (g)(\text{density of } CCl_4)}$$
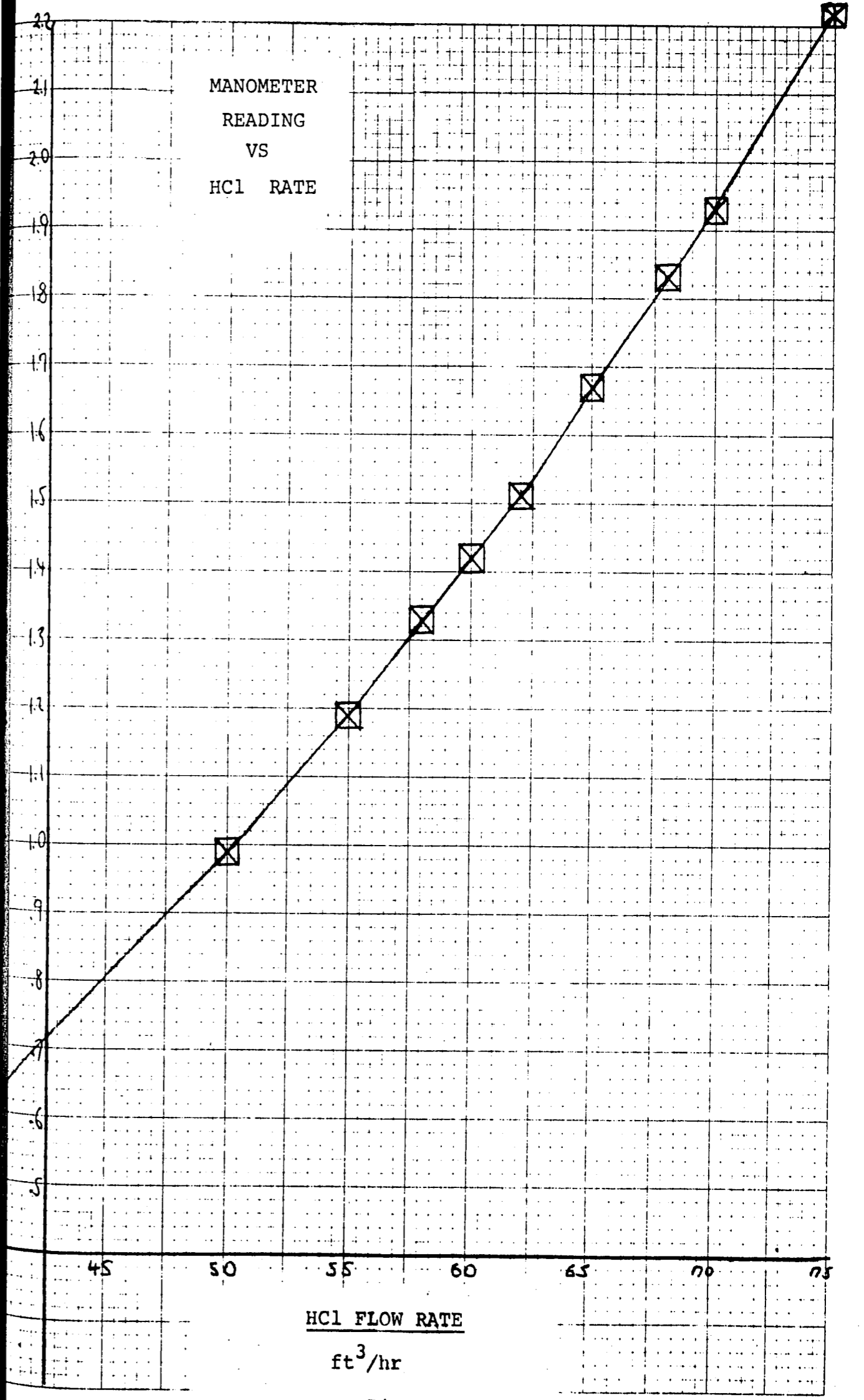
q = HCl rate in ft^3/sec

B = orifice to line diameter ratio

C = coefficient of discharge (dimensionless) = 0.61

Y = expansion factor (dimensionless) = 1.00

A_{throat} = orifice throat area in ft^2

g = gravity constant

MANOMETER
READING
VS
HCl RATE

HCl FLOW RATE

ft^3/hr

-72-

APPENDIX III

SELECTED OPERATING VALUES FOR HCl FLOW

ine Pressure	Manometer Reading	Volumetric HCl Rate	Mass HCl Rate
psig	inches CCl_4	SCF/hr HCl	lb/hr HCl
14	1.0	50.3	4.68
16	1.2	55.3	5.14
18	1.4	59.5	5.53
20	1.6	63.8	5.93
23	1.8	67.5	6.28
25	2.0	71.1	6.61
28	2.2	74.6	6.94
30	2.2	74.6	6.94

APPENDIX III

OPERATING INLET CONCENTRATIONS OF HCl

Line Pressure	% HCl in INLET GAS
psig	% by volume
14	0.280
16	0.274
18	0.276
20	0.280
23	0.274
25	0.279
28	0.280
30	0.271

APPENDIX III

WATER FLOW RATES THROUGH SCRUBBER

Line Pressure psig	Water Rate gallons/minute	Water Rate ft^3/second
14	35.7	0.0800
16	36.7	0.0820
18	37.7	0.0840
20	38.7	0.0861
22	39.7	0.0883
24	40.7	0.0905
26	41.6	0.0925
28	42.6	0.0947
30	43.6	0.0969
32	44.6	0.0991
34	45.5	0.1013

LINE PRESSURE vs. WATER FLOW RATE

WATER FLOW RATE (GPM)

LINE PRESSURE (PSIG)

-76-
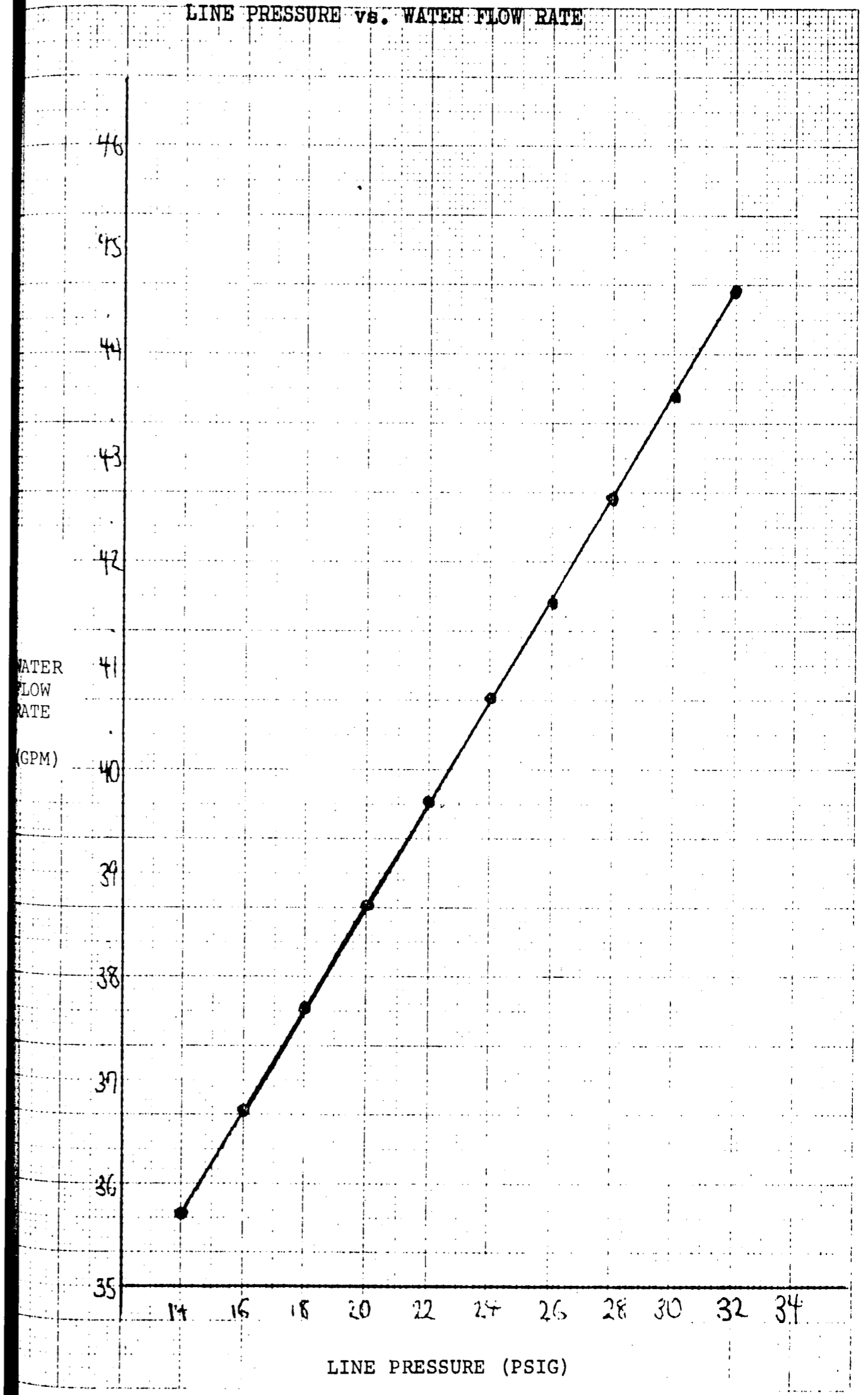
APPENDIX III

SELECTION OF LIQUID SAMPLE TITRANT CONCENTRATIONS

Separator Tank has 196 liters liquid = 433 lb H_2O

HCl has a molecular weight of 36.45 gm/gm-mole

Possible HCl concentrations in separator tank:

| LB HCl in Tank	Gm-Moles HCl in Tank	Conc. of HCl in Tank
1.0	12.4	0.0633
2.0	24.8	0.127
3.0	37.2	0.190
4.0	49.6	0.253
5.0	62.0	0.317
6.0	74.4	0.380
7.0	86.8	0.443
8.0	99.2	0.507

Sample size will be 15 ml

Want titrant used to be in range of 30 to 120 ml, preferrably in range of 50 to 90 ml

Therefore use:

      a) .10 M NaOH for 5 to 8 lbs HCl expected

      b) .05 M NaOH for 3 to 5 lbs HCl expected

      c) .02 M NaOH for 0 to 3 lbs HCl expected

EQUILIBRIUM CURVE
FOR HCl

Range of
inlet gas
concentrations

log x

log y = log p̄
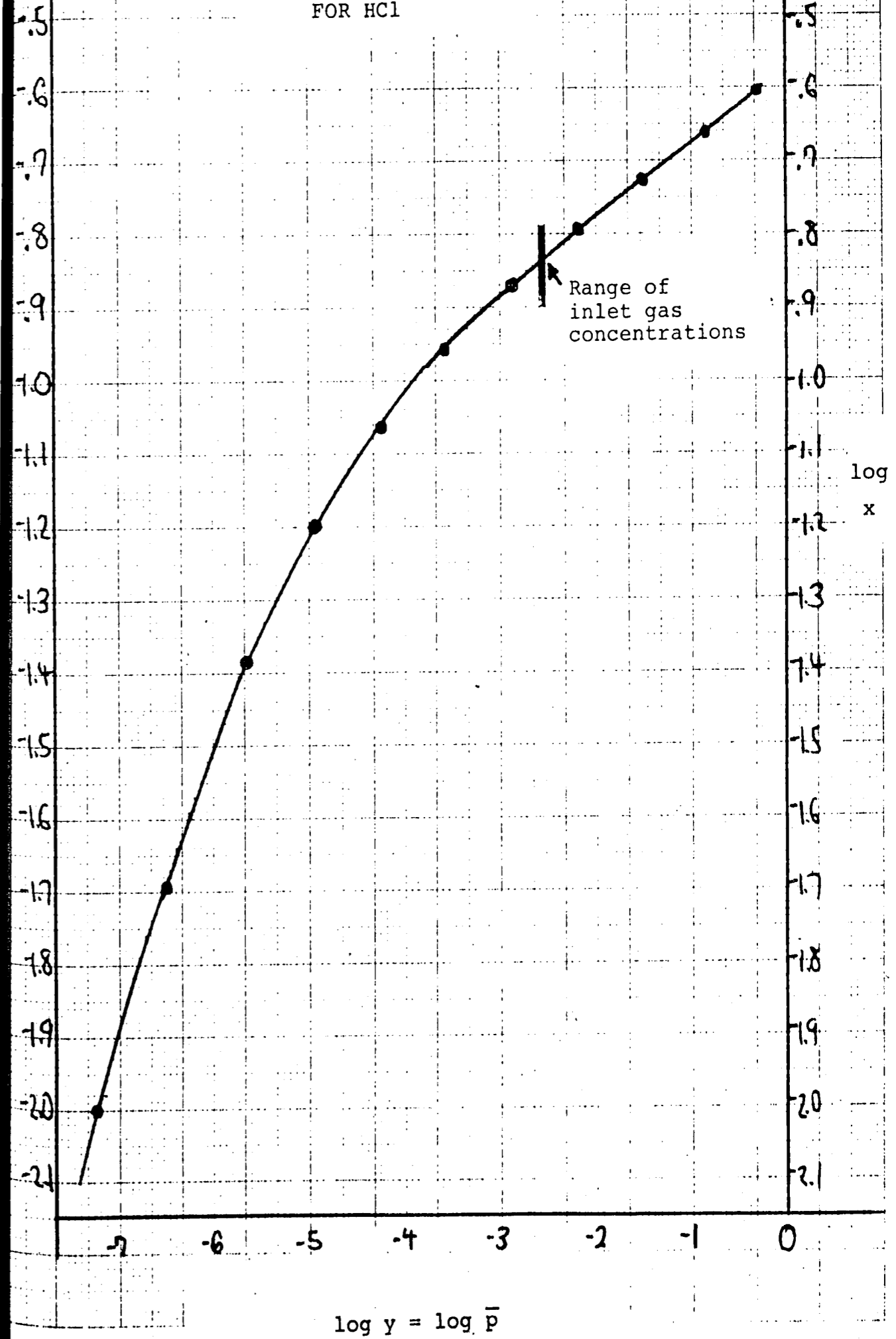
VITA

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