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USE OF AN AIR LIFT AS A METERING PUMP FOR RADIOACTIVE SOLUTIONS

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CHEMICAL TECHNOLOGY DIVISION

USE OF AN AIR LIFT AS A METERING PUMP FOR RADIOACTIVE SOLUTIONS

G. W. T. Kearsley

Date Issued

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CONTENTS

		Page
0.0	Abstract	3
1.0	Summary	3
2.0	Introduction	4
3.0	Air-Lift Theory	6
4.0	Description of Test Apparatus	7
4.1	Air-lift Footpiece	8
4.2	Air-lift Diffuser	10
4.3	Auxiliary Equipment	11
4.4	Air Deentraining Equipment	12
5.0	Test Variables and Results	12
5.1	Column Characteristics	12
5.2	Characteristics of Pumped Fluids	15
5.3	Effect of Pressure on the System	19
5.4	Humidity of the Operating Air	20
5.5	Reproducibility and Constancy of Pumping Rates	20
5.6	Pumping Rates and Efficiencies	21
6.0	Conclusions and Applications	23
7.0	Graphical Presentation of Data	25
8.0	Bibliography	34

0.0 ABSTRACT

Performance tests have shown that small quantities of radioactive feed solutions may be pumped successfully with an air lift and that the pumping rate can easily be kept within 5% of any preset value. Air lifts were tested with columns ranging from 0.18 to 1 in. in inside diameter, with water, sodium chloride solution of specific gravity 1.12, and uranyl nitrate solution of specific gravity 1.45. Variables studied were diameter, height, and submergence of the columns; density, viscosity, and surface tension of the pumped liquid; back pressure on the system; presence of suspended solids in the system; and the humidity of the operating air. Derivations of simple equations are given, and the results are presented in tabular and graphic form.

1.0 SUMMARY

Results of tests indicate that small air lifts may be used for metered pumping of highly radioactive chemical solutions. Results of studies on the variables affecting the pumping rate, capacity, and efficiency indicate that the capacity does not increase in direct ratio to an increase in cross-sectional area. The length of the column does not materially affect the pumping rate when operation is below 80% of the maximum capacity. The pumping rate is roughly proportional to the submergence.

With an increase in density of the liquid, the air lift approximates constant volume, rather than constant weight, of liquid pumped per unit weight of air used. The effect of viscosity was not quantitatively determinable because of simultaneous changes in density and surface tension in the solutions tested. The effect of changes in surface tension on the free floating air bubbles was less than the experimental error. There is a minimum size column for each operating condition in which capillary resistance will stop the pumping. Operation is satisfactory under imposed pressure or vacuum if equal pressure is maintained in the feed tank and the receiving tank.

The presence of reasonable amounts of suspended solids in the liquid did not materially affect the pumping rate or abrade the equipment. Very dry air caused changes in the pumping rate and caused crystals to form at the diffuser when concentrated solutions were pumped. The small amount of air required to operate the air lifts was the most impressive observation made during the tests.

2.0 INTRODUCTION

Tests were made to determine the applicability of the air lift for transferring highly radioactive solutions and to investigate the limitations on its use for simultaneously pumping and metering radioactive process feed solutions.

Unpublished results of preliminary tests by A. R. Irvine, W. T. McDuffee, Jr., and D. O. Darby at ORNL led to the conclusion that airlift pumping of highly radioactive solutions was entirely feasible. These early experiments had also indicated that there was a portion of the air flow--liquid flow curve (see Fig. 1), extending roughly from minimum to maximum pumping capacity, with a relatively uniform slope and containing a zone in which an approximately straight-line relation existed between the quantity of motivating air supplied and the amount of liquid pumped, which offered possibilities for metered pumping.

Some of the known characteristics of the air lift--namely, low initial cost, absence of moving parts, ability to handle small particles of solid matter in the liquid, simplicity of operation and minimum maintenance--offer decided advantages over currently used pumping and metering schemes for radioactive solutions. The tests reported here were designed to determine experimentally the unknown characteristics of small air-lift pumps, ranging in capacity from 0.05 to 5.0 gpm, which would affect their operation in the desired applications.

Tests were made with air-lift columns of various diameters, all of which were 1 in. or less, and with lengths to 40 ft while pumping water, a 75% saturated sodium chloride solution, or a heavy solution of uranyl nitrate. The effect of changes in density, viscosity, surface tension, capillarity, suspended solids, pressure on the system, and the humidity of the operating air were studied and, where possible, separate determinations made for each.

An extensive bibliography is included because much of the older material is not readily available. The older papers contain the most useful practical information, many of the more recent experiments being simply repetitions for specific purposes with limited findings.

The air lift as a method of raising water was proposed as early as 1797 by Loescher, of Frieberg, and was mentioned by Collon in lectures in 1876. The first practical application probably was by Werner Siemens in Berlin in 1885. United States patents were issued to Pohle and Hill in 1886.[11] English patents were issued to Frizell[6] in 1880 and to Pohle[21] in 1892 covering operation with air diffused in a liquid stream and liquid diffused in an air stream, respectively.

Although the efficiency of an air lift is somewhat low, it was much used around the turn of the century, in sizes up to 10 in. dia or larger, for pumping oil and water wells. It has been gradually displaced for general pumping by more efficient equipment, but modern technology is finding special applications for it in the radiochemical field.[3, 24]

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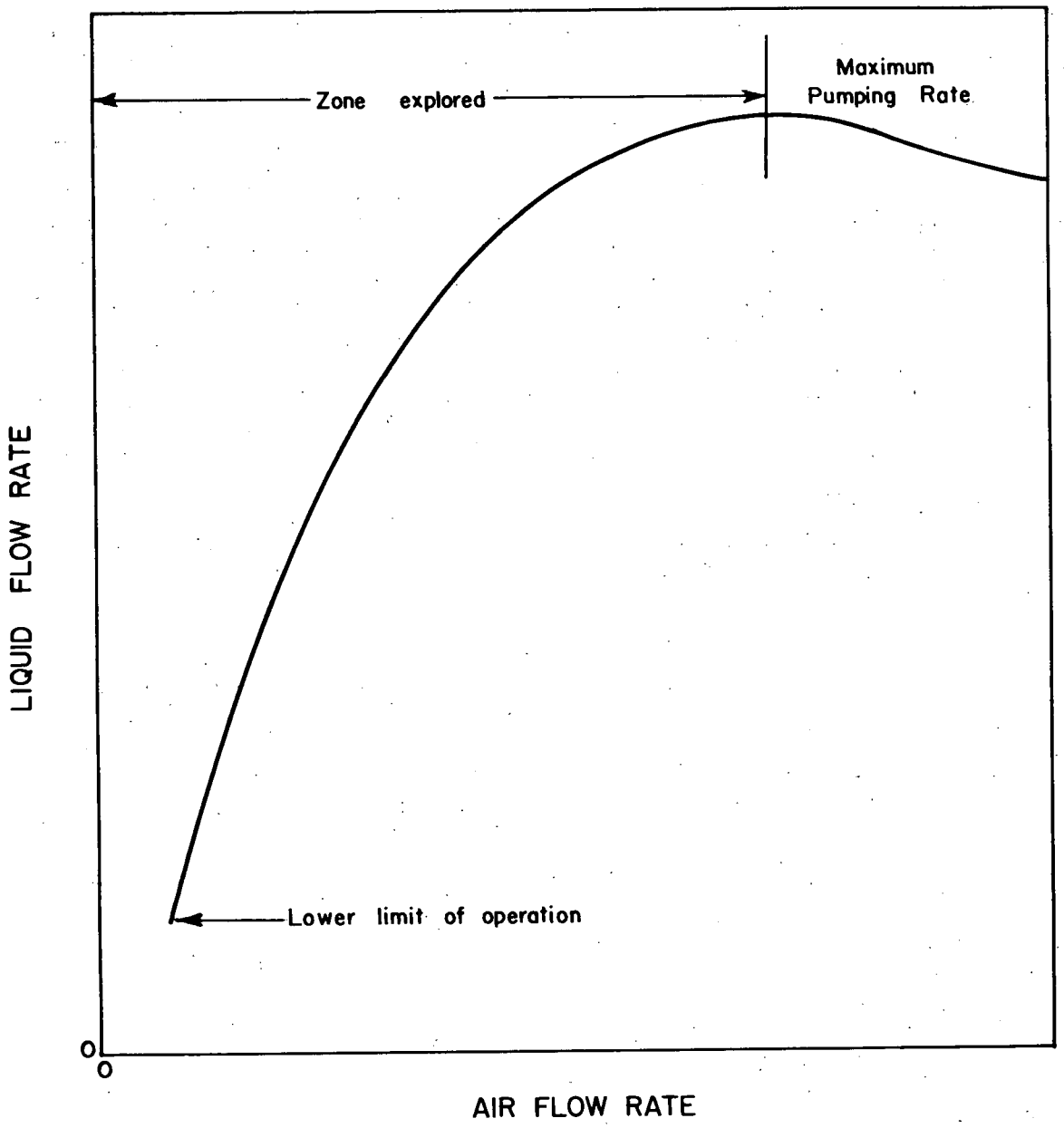

Fig. 1. Typical Curve Showing Relative Amount of Liquid Pumped by an Air Lift per Unit of Motivating Air Supplied. The zone of operation explored in the tests is indicated.

3.0 AIR-LIFT THEORY

The elementary air-lift pump consists of a vertical pipe with its lower end submerged in a well and a smaller pipe delivering air into it at the bottom. The rising column in the pipe consists of air mingled with water, the air being in bubbles of various sizes, and is therefore lighter than a column of water of the same height; consequently the water in the pipe is raised above the level of the surrounding water. If, under appropriate conditions, the water in the pipe is raised above the top of the water-pipe, a flow will ensue and will continue as long as these conditions exist.

An equation to express the air/liquid ratio for a completely efficient air-lift pump may be derived from a consideration of the work done on the liquid pumped and the work done by the entering air.[2] If W pounds of liquid is raised h_r feet, the net work done on the liquid is Wh_r ft-lb. The gross work done by w pounds of air entering the air lift at constant pressure P_e and then expanding isothermally to atmospheric pressure, P_a, is $P_eV_e + P_eV_e \ln (V_a/V_e)$ft-lb, where V_e and V_a are the volumes of the air at P_e and P_a, respectively. The net work done by the air when exhausting against atmospheric pressure is therefore $P_eV_e + P_eV_e \ln(V_a/V_e) - P_aV_a$.

Since the temperature of the air in contact with the liquid remains almost constant throughout the length of the column, the expressions

$$P_aV_a = P_eV_e \tag{1}$$

$$v_aw = V_a \tag{2}$$

are accepted, where v_a is the specific volume (ft^3/lb) of air at P_a (lb/ft^2) absolute pressure. Substitution of these terms in the expression for the net work done gives

$$\text{Net work done by the air} = P_av_aw \ln(P_e/P_a) \tag{3}$$

The pounds of air required to pump 1 lb of liquid is, therefore,

head

$$\frac{w}{W} = \frac{h_r}{P_av_a \ln(P_e/P_a)} \tag{4}$$

For this theoretical, frictionless pump the required entering air pressure, P_e, and the atmospheric pressure, P_a, can be expressed in terms of a column of the liquid thus:

$$P_e = \rho(h_a + h_s) \quad \text{and} \quad P_2 + \rho h_a \qquad \text{(5a and b)}$$

where ρ is the density of the liquid (lb/ft^3), h_a is the atmospheric pressure expressed in head of liquid (ft), and h_s is the submergence in feet.

The efficiency of an air lift is given by the expression

$$E = \frac{Wh_r}{wP_a v_a \ln\left[(h_s + h_a)/h_a\right]} \tag{6}$$

For the practical air lift Eq. 4 becomes

$$\frac{w}{W} = \frac{h_r}{EP_a v_a \ln(h_s/h_a + 1)} \tag{7}$$

and experimentally determined values for the efficiency of several air lifts given in Sec. 5.6 may be used in this equation.

A more convenient form of Eq. 7, for use where the pumped liquid has the physical properties of water, appears as

$$\text{Free air (ft}^3\text{) required to pump W pounds of water} = \frac{Wh_r}{EP_a \ln (h_s/h_a + 1)} \tag{8}$$

During the operation of a practical air lift, such as those used in these tests, the required pressure of the entering air, P_e, is reduced by any reduction in head, as a result of drawdown in the feed tank, and by all of the head losses in the short leg of the air lift. At the instant of startup, however, no such reductions in head will exist and, for design purposes, the entering air pressure is equal to $P_a + \rho h_s$.

Several empirical formulas of the general type

$$V_a = K \frac{h_r}{C \log(h_s + 34)/34} \tag{9}$$

have been developed for determining the volume of free air required to lift 1 gal of water with an air-lift pump.[21] Those investigated were based upon constant operation at an optimum rate and did not appear useful when applied to the performance of air lifts with columns of diameter as small as 1 in. and operated at various pumping rates.

4.0 DESCRIPTION OF TEST APPARATUS

In a practical application of an elementary air lift the immersion well is usually replaced with a feed tank which has a positive elevation with relation to the lower end of the pipe, or column, and is connected thereto by suitable piping. The upper end of the column is arranged to discharge into a receiving tank, where the air and liquid are separated. The metered and controlled motivating air is introduced into the column near its lower end through a specially designed footpiece containing a diffuser.

Figure 2 illustrates diagrammatically the modifications made in the original experimental air-lift system for these tests. The height of the feed tank was made adjustable, for tests involving variable submergence, and a separator, diversion box, and weigh tank were introduced in place of the receiving tank to permit accurate determination of the rates of liquid flow. A surge chamber was installed on top of the column and was interconnected with the separator and the feed tank by pressure-equalizing lines to prevent any accidental pressure differences, or siphon action, between these chambers.

Four sizes of air-lift columns, each 40 ft long, were constructed for the tests. The 0.18-in.-i.d. system was made from hard-drawn copper tubing. The 1/2-in.-dia column was of schedule 40 stainless steel pipe and the 3/8- and 1-in.-dia systems were of standard galvanized steel pipe. The length of the 1-in.-dia column was later reduced to 28 ft and the tests were repeated.

All the systems were tested with distilled water. The 1/2-in.-dia air lift was also tested with a 75% saturated solution of sodium chloride (sp. gr. 1.1235, viscosity 1.2881 centipoises at 77°F), and with uranyl nitrate solution (sp. gr. 1.4452, viscosity 2.3367 centipoises at 77°F).

4.1 Air-lift Footpiece

No elaborately designed footpiece is required for small air lifts intended for use in metered pumping of radioactive solutions in chemical processing plants because other considerations far outweigh the slight savings which might be effected in the cost of operation by an intricately designed footpiece. Power savings are of minor interest in such installations.

A very simple footpiece, consisting of a standard pipe tee installed near the lower end of the column, is shown in the detail of point A in Fig. 2. It was used during these experiments because it permitted changing the size of the orifice used as an air diffuser, or snubber. Air lifts are in use at ORNL in which the air line was butt-welded directly to the side of the column and a small hole, of predetermined size, drilled through the column wall to serve as a diffuser orifice.

The footpiece should be located at least 1 ft above the lower end of the column in order to prevent a backflow of air into the feed tank during startup. No attempt should be made to utilize the velocity head of the air stream entering the footpiece, and under no circumstances should an air jet be used for a footpiece. Introducing the air stream at right angles to the direction of liquid flow proved to be entirely satisfactory during the tests.

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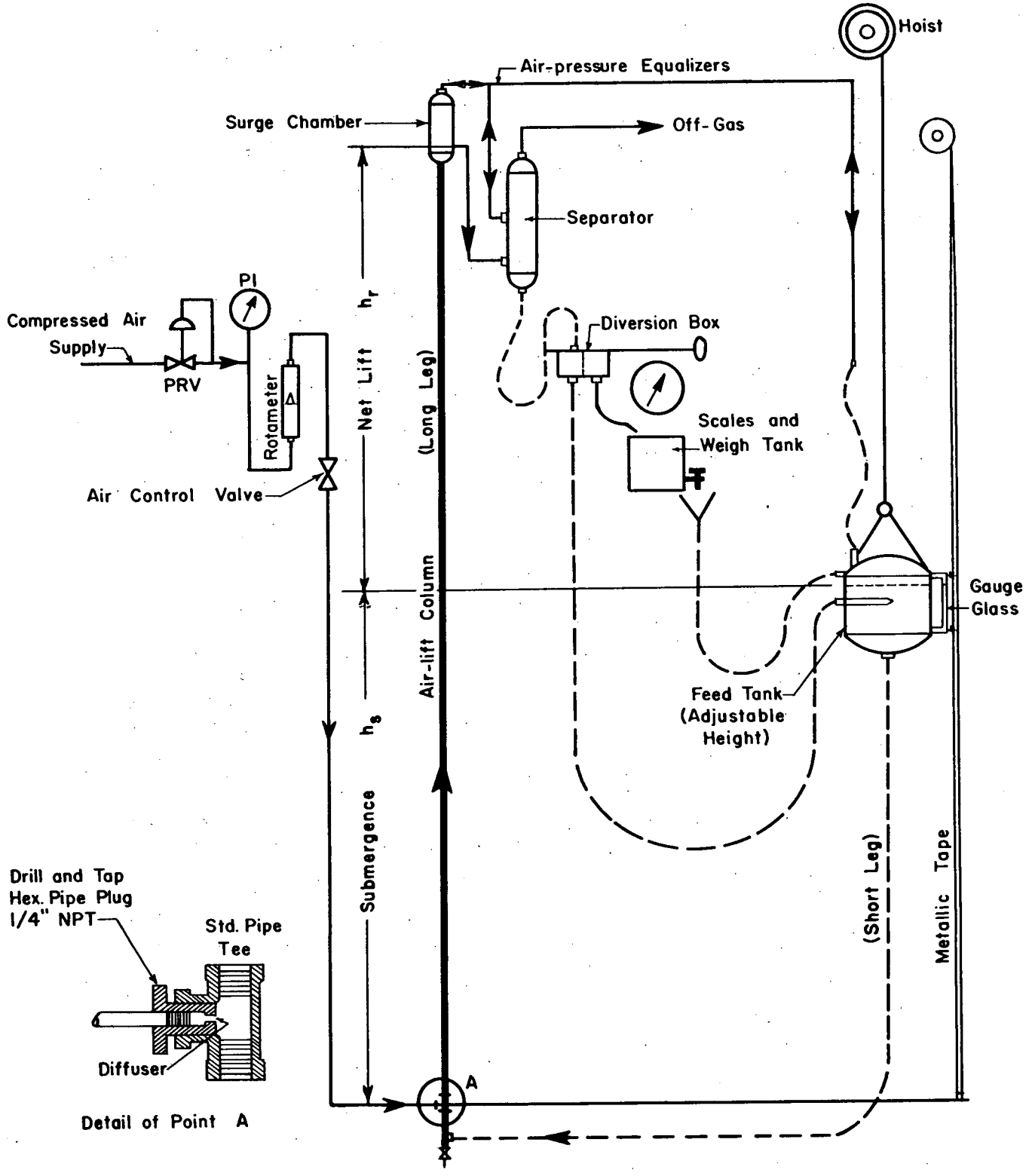

Fig. 2. Schematic Diagram of Experimental Air-lift System.

Dashed lines indicate flexible tubing.

4.2 Air-lift Diffuser

The purpose of a diffuser in an air lift is to break up the air stream into very small bubbles and distribute them uniformly throughout the liquid stream in the column, thereby increasing the economy of operation. If the air lift is to be used for pumping radioactive materials, extreme turbulence at the footpiece is undesirable because it increases the entrainment of the radioactive liquid in the off-gas.

It was found during the tests that the size and kind of diffuser used made little difference in the pumping rate because the air bubbles were recombining in the column soon after leaving the diffuser. Changing the diffuser in the 1/2-in.-dia air lift from two 1/16-in.-dia orifices to a single 1/4-in. pipe nipple reduced the pumping capacity only 1.5%. A similar effect was noted when the flow capacity of the diffuser orifice in the 3/8-in.-dia air lift was doubled. When the air lifts were operated with no diffusers, as such, the compressibility of the air in the pipe line between the air control valve and the footpiece caused the pumping to oscillate. Cycles as slow as two per minute occurred when the air lifts were operating in their lower pumping range, and rather violent surging occurred as the pumping rate approached the capacity of the air lift being tested.

Since the absence of moving parts is one of the chief advantages of the air lift, spring-loaded snubbers or adjustable orifices were not considered. In tests with small fixed-orifice type diffusers used as snubbers, surging and cycling were at a minimum when the orifices were of such a size as to pass only the amount of air required to operate the air lifts at the maximum required pumping rates, but operation was satisfactory when the orifices were sized for double these amounts.

Based on the results obtained in these tests, a single orifice in the diffuser is indicated (in preference to several smaller ones), and it should be of the size required to pass 1.25 times the air flow required for the maximum pumping rate when operated with a pressure drop of approximately 5 psi across the orifice.

The air flow through the orifice will be constantly changing at non-uniform rates, and it is difficult to develop an exact formula for the optimum size hole to be used. The following empirical formula, adapted from an approximate formula,[21] for the flow of air through a low-pressure nozzle may be used within the limits of this experiment:

$$D^2 = \frac{Q}{435\sqrt{(P_1-P_2)P2/T_1}} \qquad (10)$$

where D = diameter of hole, in.
Q = volume of air flowing, scfm (70°F, 14.7 psia)
P_1 = pressure on upstream side of orifice, psia
P_2 = pressure on downstream side of orifice, psia
T_1 = absolute temperature on upstream side, °R

The air supply line between the control valve and the footpiece must be designed to have the minimum volume, consistent with structural and flow requirements, in order to minimize the capacity effect, which is the principal cause of cycling in the pumping rate.

4.3 Auxiliary Equipment

The following auxiliary equipment was used during the testing of four sizes of air lifts:

PRV	A pressure regulating valve used to reduce plant air supply pressure from 100 psig to 20 psig
PI	Indicating pressure gage, calibrated 0-30 psig
Rotameter	Four flowmeters having ranges of 0.002-0.04, 0.02-0.2, 0.01-1.0, and 0.04-4.0 cfm at 70°F and 14.7 psia for metering air at 20 psig to the air lifts
Air-control valve	A small globe valve equipped with an extended lever handle for precision adjustments of the air flow
Gas meter	A precision wet-type gas meter used to calibrate the rotameters
Diversion box	A quick-operating two-way gate used to divert the circulating liquid stream into, or around, the weigh tank in taking timed weigh samples to determine rate of flow
Weigh tank and scales	A 10-gal stainless steel tank, resting on a 60-lb-capacity dial type springless scales graduated in ounces, used to receive the timed flow from the air lift, weigh it, and return it to the adjustable feed tank
Stop watch	Conventional stop watch, graduated in 0.2 sec, used to time liquid flow into the weigh tank
Graduated cylinder	A 1000-ml glass graduated cylinder used to measure liquid flow from a small air lift
Hoist	Conventional four-part, manila rope, block and fall used for hoisting and positioning the feed tank for tests of air lifts at various submergences
Metallic tape	Measuring tape used to indicate the height of the liquid surface in the feed tank above the diffuser orifice in the footpiece
Thermometers	Wet- and dry-bulb thermometers used in determining the temperatures and humidities of the supply air and the off-gas and the temperatures of the pumped liquids

4.4 Air Deentraining Equipment

In the experimental air lifts the entrained motivating air was liberated at the liquid surfaces in a surge chamber (2 in. dia IPS) and in a separator (3 in. dia IPS). The relative effectiveness of this arrangement, as compared with the use of a single larger separator tank, was not investigated, but the need for better separation was evident.

The liquid entrained in the off-gas became less as the viscosity of the liquid increased. When the 1/2-in.-dia air lift was used to pump water, the liquid entrainment ranged from 200 to 300 ppm (wt). For a NaCl solution with viscosity of about 1.3 centipoises, the entrainment varied from 25 to 50 ppm, depending largely on the pumping rate.

The liquid entrained in the off-gas can be reduced to less than 4 ppm by use of a low-resistance, impingement type deentrainer. Pyrex glass wool No. 800 was effective when the gas flow was approximately 2.5 ft/sec face velocity and York, style 421, stainless steel knitted fabric gave the same results when the velocity was 5.5 ft/sec and with less resistance. Neither of these deentrainers proved to be self-flushing when the entrained liquid carried dissolved solids and evaporation occurred.

5.0 TEST VARIABLES AND RESULTS

5.1 Column Characteristics

Diameter. In the perfect air lift, operated at constant terminal velocity of the air and water mixture, the pumping capacity is directly proportional to the cross-sectional area of the column. In the test air lifts this proportionality was not very good because all the losses resulting from nonrecovery of velocity head, surface friction, capillarity, turbulence, pulsating flow, and nonhomogeneity of the fluids in the various parts of the pump are affected, to a degree, by the diameter of the column. The diameter of an air-lift column required to pump a given amount of liquid may be computed with a probable error not exceeding 20% by using the following table of values taken from tests of air lifts with column diameters of 3/8, 1/2, and 1 in. IPS, length 40 ft, pumping water:

Submergence (%)	Max. Desirable Discharge Velocity (ft/sec)	Liq/Air Ratio (lb/scf)
35	5.0	10.9
50	5.0	22.0
65	5.0	38.5

Flow in the air-lift column is stabilized by frictional resistance, which varies approximately as the second power of the flow rate. In air-lift columns less than 50 ft high it is believed that no effort should be made to minimize the velocity near the top, by increasing the diameter, because the varying resistance in a high-velocity zone opposes inherent cycling tendencies in the air lift.

Air lifts with a column bore diameter of 0.269 in. have been used successfully for nonmetering pumping operations in connection with sampling equipment in a chemical plant. An unsuccessful attempt was made during these tests to operate a 40-ft air lift with a bore diameter of 0.18 in. with a designed pumping capacity of 50 to 300 ml/min. The cause of failure is discussed in Section 5.2, "Surface Tension".

Height. The results of a single test indicate that the length of the column does not greatly affect the pumping rate of an air lift except when it is operated near its maximum capacity (Fig. 3).

If the length of the column, L, is substituted for h_r in Eq. 7, the relative pumping rates of two otherwise identical air-lift pumps may be found from the equation

$$\frac{W_2}{W_1} = \frac{L_1 \ln \left[(NL_2/h_a - 1)\right] E_2}{L_2 \ln \left[(NL_1/h_a - 1)\right] E_1} \tag{11}$$

where the subscripts refer to the two pumps being compared and N is the fraction of the air-lift columns submerged.

In the experiment 12 ft of pipe was removed from the 40-ft column of the 1-in.-dia air lift, leaving a column 28 ft high, and its pumping rate W_{28} compared with corresponding values W_{40} for the 40-ft column when operated at the same air flow rate and percentage submergence. The theoretical and experimental values for the ratio W_{28}/W_{40} are shown in the following tabulation. Theoretical values were computed by Eq. 11.

Submergence (%)	W_{28}/W_{40} Theoretical	W_{28}/W_{40} Experimental
35	1.04	1.07
50	1.07	0.97
65	1.08	0.96

The experimental values indicate that, when the air lifts were operated at some submergence between 35 and 50%, the pumping rates became equal. It should be noted in this comparison that, while the submergence percentage is the same in the two cases, the net pumping lift, h_r, is not the same for the two air lifts with unequal column lengths.

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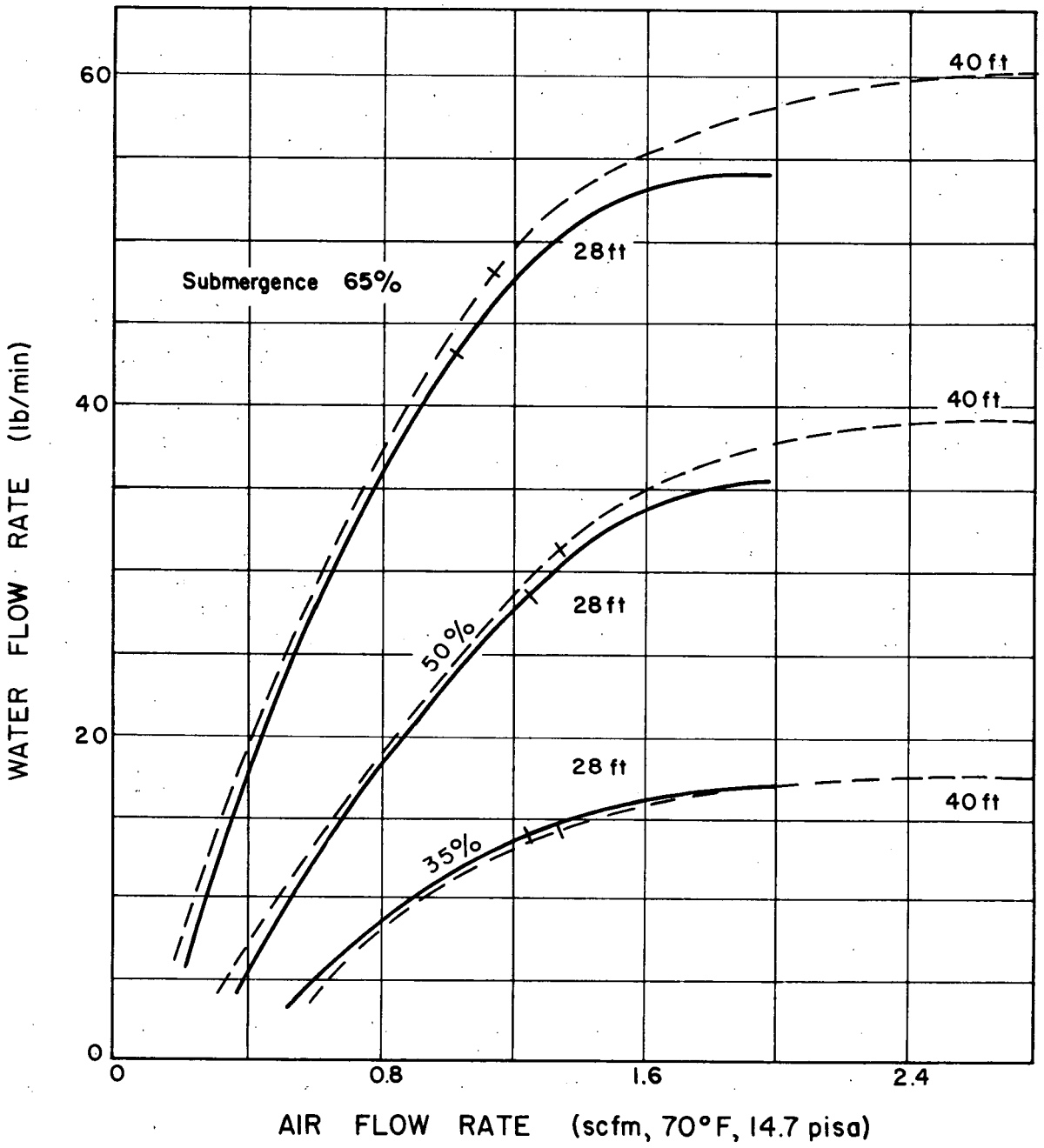

Fig. 3. Effect of Length of Column on Water Flow Rate in 1-in. Air-lift Column.

Submergence. The pumping rate increased as the fraction of the air-lift column submerged was increased from 0.35 to 0.65. With a constant motivating air flow rate, it can be shown that the driving force increases as the fraction of the column submerged increases. The pressure of the entering air increases and the net lift is reduced so that an increased flow is required to maintain an energy balance.

If W_1 and W_2 are the two pumping rates, E_1 and E_2 the efficiencies, N_1 and N_2 the fractions of the column submerged, and L the length of the column, the relative pumping rates at two submergences may be found by substituting values in the following formula derived from Eq. 7:

$$\frac{W_2}{W_1} = \frac{E_2(1-N_1)\ \ln\ (N_2L/h_a + 1)}{E_1(1-N_2)\ \ln\ (N_1L/h_a + 1)} \tag{12}$$

The performance of a 1/2-in.-dia air-lift pump with column 40 ft high pumping water while set at several submergences between 35 and 65% is shown graphically in Fig. 4. Operation of an air lift submerged less than 35% is possible but usually unsatisfactory because of excessive surging, cycling, and vibration. The experiments were not extended to cover more than 65% submergence because the amount of pipe required becomes excessive for the small net lift secured.

5.2 Characteristics of Pumped Fluids

The pumping characteristics of three liquids at 77°F, with physical properties more or less typical of those encountered in radiochemical processing, were determined experimentally in a 1/2-in.-dia air lift. The liquids were

	Specific Gravity	Viscosity (centipoises)
Water	1.0000	0.8937
Sodium chloride solution	1.1235	1.2881
Uranyl nitrate solution	1.4452	2.3367

The following tabulation of the volumetric pumping rates for these three liquids under identical conditions indicates the comparatively small effect on the pumping rate of the simultaneous increase in the density, viscosity, and surface tension of the liquid:

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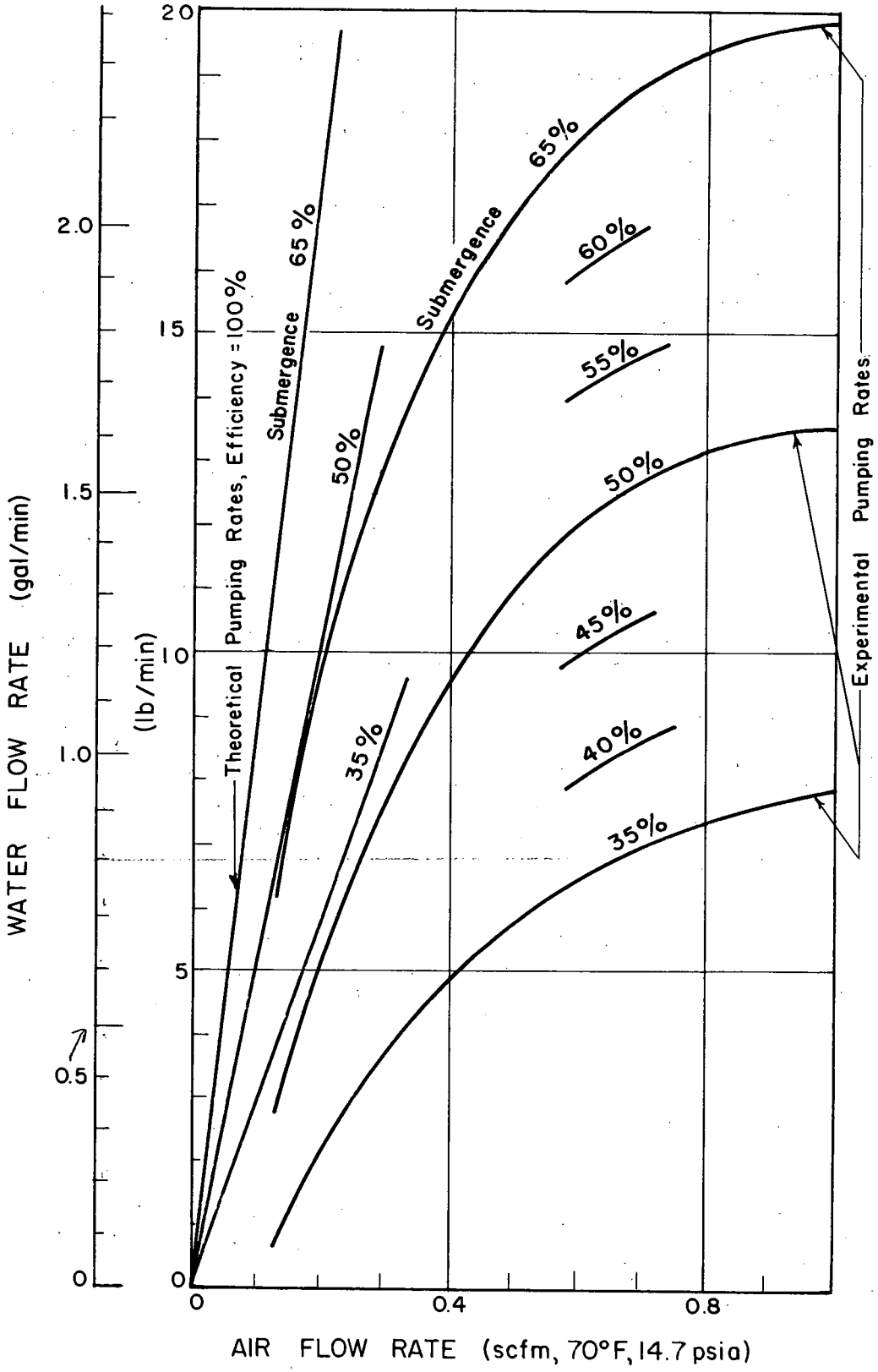

Fig. 4. Typical Curves Showing Effect of Changing Submergence On Water Flow Rate and Efficiency in a 1/2-in. Air Lift Column 40 ft High.

Submergence (%)	Air (scfm)	Pumping rate (gpm) Water	NaCl Solution	Uranyl Nitrate Solution
35	0.25	0.354	0.320	0.290
	0.50	0.682	0.654	0.598
	0.90	0.924	0.916	0.864
50	0.25	0.756	0.758	0.706
	0.50	1.308	1.298	1.222
	0.90	1.620	1.636	1.594
65	0.25	1.356	1.308	---
	0.50	2.016	1.933	1.888
	0.90	2.376	2.358	2.374

The apparent anomaly involving the tendency to maintain approximately constant volumetric pumping rates, with radical changes occurring in the density, viscosity, and surface tension of the liquid, may be somewhat rationalized by examining separately the known and the implied effects of changes in density, viscosity, and surface tension as shown in the following sections.

Density. The weight of the liquid pumped, per unit of motivating air, increased with the specific gravity of the liquid. Three liquids having increasing densities were pumped in an air lift which was operated at 80% of its maximum pumping capacity for each of the liquids. The increase in the liquid/air ratio (weight) and the decrease in the efficiency, when the heavier liquids were pumped, are shown in the following tabulation:

Liquid	Specific Gravity	Liquid/Air Ratio (wt) Experimental	Theoretical	Efficiency (%)
Water	1.0000	22.03	48.54	45.38
NaCl solution	1.1235	24.09	53.19	45.29
$UO_2(NO_3)_2$ solution	1.4452	28.41	64.52	44.03

An expression may be derived from Eqs. 4, 5, and 6 in Sec. 3.0 to show the relation between the density of the liquid and the weight of liquid pumped in an air lift:

$$\frac{W_2}{W_1} = \frac{E_2 \ln (\rho_2 h_s/P_a + 1)}{E_1 \ln (\rho_1 h_s/P_a + 1)} \tag{13}$$

Substitution of values in this equation will show that, as the density of the liquid increases, the weight of the liquid displaced by the air bubbles in the column increases at a faster rate than the volumes of the air bubbles decrease under the greater pressure.

When uranyl nitrate solution replaced water in the air lift, the weight of the liquid displaced by a unit weight of air increased about 34.5%, although the volume of the air had decreased about 7%. This increase of 34.5% in the driving force increased the useful work done by the air lift by 29%.

Viscosity. It was not possible to determine experimentally the effect of a change in the viscosity of the liquid upon the pumping rate of an air lift when there was a simultaneous change in the density and the surface tension of the liquid. By inference these tests appear to confirm the theory of other experimenters that there is an actual increase in the efficiency of the air lift as the viscosity of the pumped liquid increases. It appears that, within limits, the reduction in the rate of upward slippage of the air bubbles in the more viscous liquid more than offsets the increase in the resistance to flow due to the increase in the viscosity of the liquid. After initial startup the pressure of the entering air, P_e, is reduced by the head losses in the short leg of the air lift between the feed tank and the footpiece. This reduction in pressure of the entering air resolves itself into larger air bubbles, more bouyancy, and greater driving force exerted, for the same weight of operating air used, when there has been an increase in the viscosity of the pumped liquid.

Surface Tension. Under otherwise identical conditions an increase in the surface tension, σ, of the pumped liquid reduced the pumping rate of the air lift by (a) reducing the size of the air bubbles and (b) increasing the capillary resistance to flow when the bubble diameter, d, was greater than the column diameter. If the thin-wall concept is applied to a spherical air bubble with a diameter somewhat less than the column diameter, it can be shown that the average absolute pressure in the bubble is, approximately,

$$P_{av} = \frac{4\sigma}{d} + \frac{P_a + P_e}{2} \qquad (14)$$

Substitution of values thus found in the expression $PV = P'V'$ indicated that the change in the pumping rates of the liquids tested, due to the change in bubble size and bouyancy following a change in surface tension, was much less than the experimental error and, therefore, was not further investigated.

In very small diameter air-lift columns, in which the air and water rise in alternate piston-like slugs, the upper and lower menisci are unequally distorted by the flow, and the resulting imbalance causes capillary resistance to flow at each slug. These resistances are additive throughout the column length.

The effect of this capillary resistance to flow began to be apparent in the 3/8-in.-dia air lift and, under certain operating conditions, it entirely stopped the pumping in the 0.18-in.-dia air lift.

Suspended Solids in the Pumped Liquid. The air lift will continuously handle reasonable amounts of solid particles in the liquid stream without excessive changes in the pumping rate if the velocity and bouyancy are sufficient to keep the particles in motion and if they are small enough to pass each other in transit. The following described materials were added successively to a circulating NaCl solution (sp. gr. 1.1235) in the 1/2-in.-dia air lift, and weigh samples were taken to determine the pumping rates:

1. Two pounds of Permutit SK anion exchange resin, 10 to 20 mesh, sp. gr. about 1.15; circulated 1 hr

2. One pound of pulverized fuller's earth circulated 1 hr

3. River sand, brick mortar grade, occasional fragments of rock and gravel up to 1/4-in. mesh size, added until a good circulation of sand was continuous, total 6.625 lb; circulated 30 min

The pumping rates were:

Brine	13.062 lb/min
Brine plus Permutit resin	12.776 lb/min
Brine plus Permutit resin and fuller's earth	12.965 lb/min
Brine plus Permutit resin, fuller's earth, and sand	12.898 lb/min

The maximum change in the gravimetric pumping rate was 2.19 percent. No difficulty in operation was experienced, and startup was normal after overnight standing.

5.3 Effect of Pressure on the System

The air lift operates satisfactorily under imposed system pressures if the same pressure is applied simultaneously to the feed tank and the receiving tank. As the system pressure is increased, there is a corresponding decrease in the pumping rate.

The effect on the pumping rate and efficiency of a change in the system pressure was experimentally determined in a 1/2-in.-dia air lift 40 ft high, 50% submergence, air flow 0.5375 scfm, which pumped NaCl solution of sp. gr. 1.152 at two system pressures. It was necessary to maintain test pressures above atmospheric to avoid collapsing the plastic tubing used in the test apparatus. Results of the tests were

	Test 1	Test 2
System pressure (inches of water)	1.25	26.88
Pumping rate (lb/min)	13.12	12.49
Decrease in pumping rate (%)	--	4.8
Air/water ratio (scf/lb)	0.04097	0.04303
Efficiency of air lift (%)	44.68	44.52

At sufficiently low pressures it is only necessary to apply heat to the lower part of the column, and the vapor formed will cause the air-lift to function without any air being supplied.[17] If the air lift is started when the liquid is near the boiling temperature, steam will form in the column and cause a runaway in the pumping rate.[3]

If the pulsating back pressure at the top of the column, incident to the disengagement of the air from the water stream, is not cushioned by air space in a nearby receiving tank, then a surge chamber should be mounted on the top of the column. All submerged pipe in the short leg of the air lift must be designed to prevent the accumulation of air bubbles in it which might retard the flow.

5.4 Humidity of the Operating Air

The air leaving the top of the air lift is consistently very nearly saturated at the temperature of the liquid being pumped. When very dry motivating air is used, the volume of the vapor formed by evaporation of the liquid in the column may change the pumping rate as much as 1.25% above or below a median. When concentrated solutions were pumped with dry air, crystals were deposited on the diffuser orifice which restricted the air flow and, in some cases, closed it off completely. Humidifying the air prior to entry prevented the formation of crystals, or deposits, but contact with liquid was necessary to remove them after they had formed. If a mixture of organic solvents having different vapor pressures is pumped in an air lift, the proportions would be changed slightly by selective evaporation; this change could prove objectionable if the solvent is circulated for extended periods of time.

The actual loss of liquid by evaporation in the air lift is small even when the air is very dry. Water pumped 22 ft vertically at 74°F and at the rate of 3460 gal/day, using plant air containing only 0.0032 lb moisture/lb dry air, lost only 0.2135 gal/day or 0.006% of the water pumped. When the outside ambient temperature dropped to about 32°F, the plant compressed air supplied to the test site through exposed air lines contained about 8 grains of moisture per pound of dry air. A small drip feeder was installed and adjusted to feed the minimum amount of water required to prevent crystals from forming at the diffuser, and the tests were continued without further inconvenience. The exact quantities of water required were not determined, but a feed rate of 3 drops per minute usually proved adequate.

5.5 Reproducibility and Constancy of Pumping Rates

Reproducibility of the pumping rate was better than the ± 5% required by the problem statement at all pumping rates, and, in general, the requirement was exceeded by a factor of 2. The constancy of the pumping rate (ability to maintain a uniform set pumping rate over a period of time) was even better. Predetermined flow rates were established from six to twelve times at each of ten points along the pumping

range of the 1/2-in.-dia air lift while pumping water. The settings were made in the following order: at random from standstill, at random from previous setting, consecutively in ascending order; the water in the system was then changed and the series repeated. The maximum deviation in flow at any of the settings at a given point is shown in the following tabulation as a percentage of the average flow at that point:

Air Flow Rate (% of max)	Above Average	Below Average
10	4.8	4.4
20	2.7	2.8
30	4.2	3.3
40	3.8	2.4
50	2.0	1.6
60	1.8	0.9
70	2.2	2.6
80	2.4	2.7
90	2.4	2.7
99	1.8	3.2

It is important that the supply air be metered at low pressure, using the smallest needle valve and rotameter that cover the required range, in order to minimize errors incident to resetting the air flow rate.

The constancy of the pumping rate was determined by taking weigh samples at 5-min intervals during continuous operation of the air lift. Four weigh samples were taken at each of two flow rates, and the maximum deviation is shown in the following tabulation as a percentage of the average flow at that point:

Air Flow Rate (% of max)	Above Average	Below Average
40	0.7	1.3
50	0.6	0.4

5.6 Pumping Rates and Efficiencies

Four sizes, and two heights, of air lifts were tested at three submergences while pumping three liquids with different densities. From the observed data the experimental and theoretical air/liquid ratios were computed and the efficiencies of the several air-lift combinations determined (Table 1).

Table 1. Pumping Rates and Efficiencies of Experimental Air Lifts Compared at Pumping Rates Equal to 80% of Maximum Capacity

Column Dia (in.)	Column Height (ft)	Submergence (%)	Air Used (scfm)	Liquid Pumped (lb/min)	Air/liquid Ratio (ft^3/lb) Exptl.	Air/liquid Ratio (ft^3/lb) Theor.	Efficiency (%)
Distilled water, sp. gr. 1.0, viscosity 0.8937 centipoise at 77°F							
0.18	40	35	0.0215	0.352	0.0611	0.0359	58.76
		50	0.0185	0.517	0.0358	0.0206	57.54
		65	0.0159	0.733	0.0217	0.0118	54.38
3/8	40	35	0.313	3.71	0.0844	0.0359	42.54
		50	0.287	6.20	0.0463	0.0206	44.49
		65	0.242	8.70	0.0278	0.0118	42.45
1/2	40	35	0.590	6.30	0.0937	0.0359	38.31
		50	0.490	10.80	0.0454	0.0206	45.37
		65	0.442	15.90	0.0278	0.0118	42.45
3/4 (Interpolated)	40	35	0.920	9.60	0.0958	0.0359	37.50
		50	0.831	19.00	0.0437	0.0206	47.20
		65	0.750	29.10	0.0258	0.0118	45.70
1	40	35	1.350	14.40	0.0937	0.0359	38.31
		50	1.315	30.40	0.0433	0.0206	47.57
		65	1.200	49.10	0.0244	0.0118	48.36
1	28	35	1.242	13.60	0.0913	0.0341	37.35
		50	1.265	28.70	0.0441	0.0197	44.67
		65	1.050	43.00	0.0244	0.0109	44.67
NaCl solution, sp. gr. 1.1235, viscosity 1.2904 centipoises at 77°F							
1/2	40	35	0.592	6.92	0.0855	0.0352	41.17
		50	0.515	12.40	0.0415	0.0188	45.30
		65	0.490	17.80	0.0275	0.0116	42.18
Uranyl nitrate solution, sp. gr. 1.4452, viscosity 2.3409 centipoises at 77°F							
1/2	40	35	0.541	8.72	0.0620	0.0265	42.74
		50	0.550	15.60	0.0352	0.0155	44.03
		65	0.532	23.00	0.0231	0.0090	38.96

6.0 CONCLUSIONS AND APPLICATIONS

There is a generous overlapping in the pumping capacities of small air lifts constructed with standard pipe diameter sizes, which makes special bore diameters unnecessary for the columns. Also, the numerous variables that affect the pumping rate of an air lift make its precise design difficult, if not impossible. A simple approximate method of selecting the column diameter required for a given pumping rate is described in Sec. 5.1 and will be found accurate enough for ordinary use unless the air lift is to be operated too near the limits of its pumping range. Regardless of the method of design employed, the performance of an air lift should be verified before proceeding from nonradioactive to radioactive solutions.

The design of an air-lift system for a practical application is illustrated in the following example:

Required: From a feed tank 4 ft high, mounted 6 ft above an impenetrable cell floor, meter and pump at 77°F 1 gpm of solution with sp. gr. 1.12 to a top inlet, on a receiving tank, 29 ft above the cell floor. An off-gas pressure of 14.3 psia is imposed on the entire system in lieu of atmospheric pressure. Determine the number of stages required; column diameters; motivating air required by each stage; maximum pumping capacity; and diameters of the diffuser orifices needed.

Solution: In any case the centers of any footpieces will be located 1 ft above the cell floor (Sec. 4.1). If a single stage is used, the submergence can be only 5 ft and the column height must be 28 ft. The submergence of 17.9% is too small for satisfactory operation (Sec. 5.1, "Submergence") and two stages are indicated. Also the changes in the submergence head accompanying the filling and emptying of the 4-ft-high feed tank will require the use of a constant-head pot to feed the metering, or second-stage, air lift. The first-stage air lift will discharge into the constant-head pot and cause it to overflow continuously at elevation 15 ft, back into the feed tank. The maximum net lift of the first stage will then be 9 ft and its minimum submergence 5 ft, as measured from the lowest level in the feed tank.

First-stage Air-lift Selection:

The column diameter is determined by the approximate method described in Sec. 5.1, "Diameter":

Density (62.25)(1.12) = 69.72 lb/ft^3 (at 77°F)
Submergence = 5/14 or 35.7%
Liquid/air ratio (interpolated from tabulation, p.12) = 11.88 lb/scf (for water)
Liquid pumped = 1 gpm = 9.32 lb/min = 0.134 cfm
Density factor = sp. gr = 1.12
Air required = 9.32/(11.88 x 1.12) = 0.7 cfm
Total air and liquid flow at exit = 0.834 cfm
Maximum desired discharge velocity = 5 x 60 = 300 ft/min
Area of required column = 0.834/300 ft^2 = 0.00278 ft^2
Area of standard pipe column selected = 0.00371 ft^2
Nominal diameter = 3/4 in.

The corrected air flow rate is determined from Eq. 8, with temperature and pressure corrections:

$$\text{scfm} = \frac{(9.32)(9.0)(14.3)(530)}{(0.405)(2059.2)\ \ln(5.0/29.54 + 1)(14.7)(537)}$$

$$= 0.618$$

The possible operating range of this air lift may be approximately determined by converting the 9.32 lb/min of sp. gr. 1.12 solution pumped in the 14-ft-high column, at 35.7% submergence, by 0.618 scfm of air to an equivalent weight of water pumped in a 40-ft-high column at 35% submergence by the same volume of air and referring to the experimental curves in Fig. 10 for a 3/4-in.-dia air lift pumping water. The corrections for density, column height, and submergence will be made in steps to illustrate the method used:

The density is reduced to an equivalent weight of water pumped (Eq. 13):

$$W_2 = \frac{(9.32)(0.375)\ \ln(62.25 \times 5.0/2059.2 + 1)}{(0.405)\ \ln(69.72 \times 5.0/2059.2 + 1)} = 7.8 \text{ lb/min}$$

The column height is reduced to an equivalent weight of water pumped in a 40-ft-high column (Eq. 11):

$$W_3 = \frac{(7.8)(14.0)\ \ln\ (35.7 \times 40.0/29.54 + 1)(0.375)}{(40.0)\ \ln(35.7 \times 14.0/29.54 + 1)(0.356)} = 7.26 \text{ lb/min}$$

The submergence is reduced from 35.7 to 35.0% (Eq. 12):

$$W_4 = \frac{(7.26)(0.375)(1 - 0.375)\ \ln(0.35 \times 40.0/29.54 + 1)}{(0.380)(1 - 0.350)\ \ln(0.357 \times 40.0/29.54 + 1)} = 7.0 \text{ lb/min}$$

Inspection of the 35% submergence curve (Fig. 10) for a 3/4-in.-dia air lift shows that the maximum pumping rate probably extends to 11 lb/min of water and will require 1.2 scfm of air. The size of the diffuser orifice may now be computed.

The diameter of the diffuser orifice is calculated from Eq. 10 and a factor of 1.25:

$$D^2 = \frac{(1.2)(1.25)}{435\sqrt{(21.7 - 16.7)16.7/537}}$$

$$D = 0.0935 \text{ in.(or 3/32 in. drill)}$$

<u>Second-Stage Air Lift</u>: The diameter of the column required is determined by using data from a tabulation in Sec. 5.1 (p. 12):

Net lift = 14 ft
Submergence = 14 ft
Submergence = 14/28 = 50%
Liquid/air ratio, for water = 22.0 lb/scf

Density factor (sp. gr.) = 1.12
Liquid pumped = 9.32 lb/min = 0.134 cfm
Air required = 9.32/(22.0 x 1.12) = 0.378 cfm
Total air and liquid flow at exit = 0.512 cfm
Maximum desired velocity = 5 x 60 = 300 ft/min
Area of required column bore = 0.512/300 = 0.00171 ft^2
Area of standard pipe column selected = 0.00211 ft^2
Nominal diameter = 1/2 in.

By using the same methods employed in the case of the first-stage air lift, and referring to the 50% submergence curve on Fig. 8 for the 1/2-in.-dia air lift, the following values were determined for the second-stage air lift:

Corrected air flow for pumping 1 gpm = 0.382 scfm
Equivalent pumping rate in 40-ft-high column = 9.22 lb/min
Air required for maximum pumping = 0.75 x 1.25 = 0.9375 scfm
Diameter of diffuser orifice required = 0.069 in.(or 5/64-in. drill)

7.0 GRAPHICAL PRESENTATION OF DATA

The experimental data obtained in tests of air lifts with various combinations of column size, length, and submergence, and pumping liquids of several densities, are shown graphically in Figs. 5-12. The performance of each air-lift combination is shown by a separate curve on the chart when the column was submerged 35, 50, and 65% of its total length. From these curves may be determined the maximum and the minimum pumping rates, for any of the combinations, and the amount of motivating air required (scfm) to pump a given quantity of liquid, expressed in either lb/min or gal/min.

Figure No.	Column Diameter (in.)	Column Height (ft)	Liquid or Solution Pumped	Specific Gravity of Liquid
5	0.18	40	Water	1.0000
6	3/8	40	Water	1.0000
7	1/2	40	Water	1.0000
8	1/2	40	NaCl	1.1235
9	1/2	40	$UO_2(NO_3)_2$	1.4452
10	3/4	40	Water	1.0000
11	1	28	Water	1.0000
12	1	40	Water	1.0000

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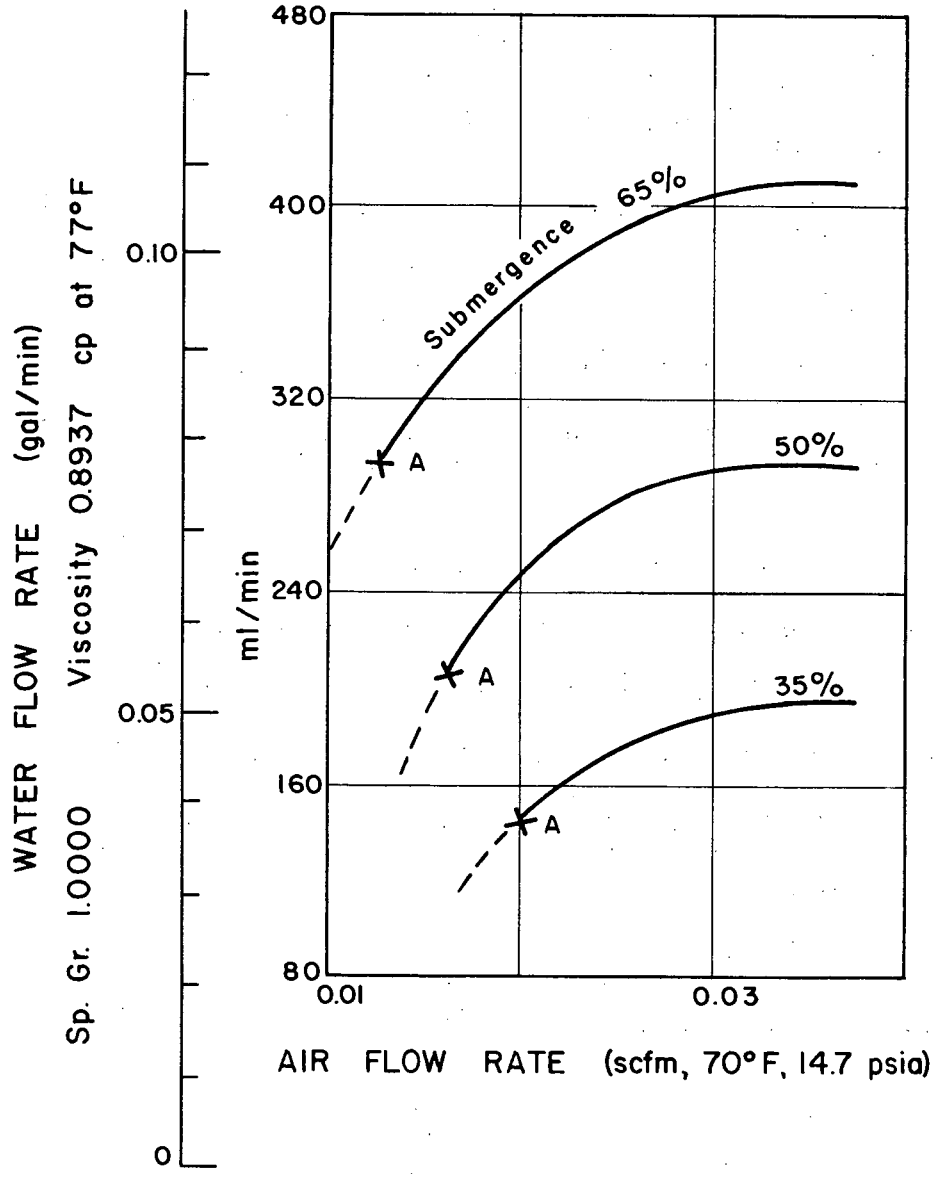

Fig. 5. Air Flow Rate vs. Liquid Flow Rate for Air Lift.

Column 0.18-in.-i.d hard-drawn copper tubing; total height 40 ft.

Note: At some point A (variable), as the pumping rate was progressively reduced the pumping suddenly changed from a flow to a medium drip and the operating air backed up into the feed tank.

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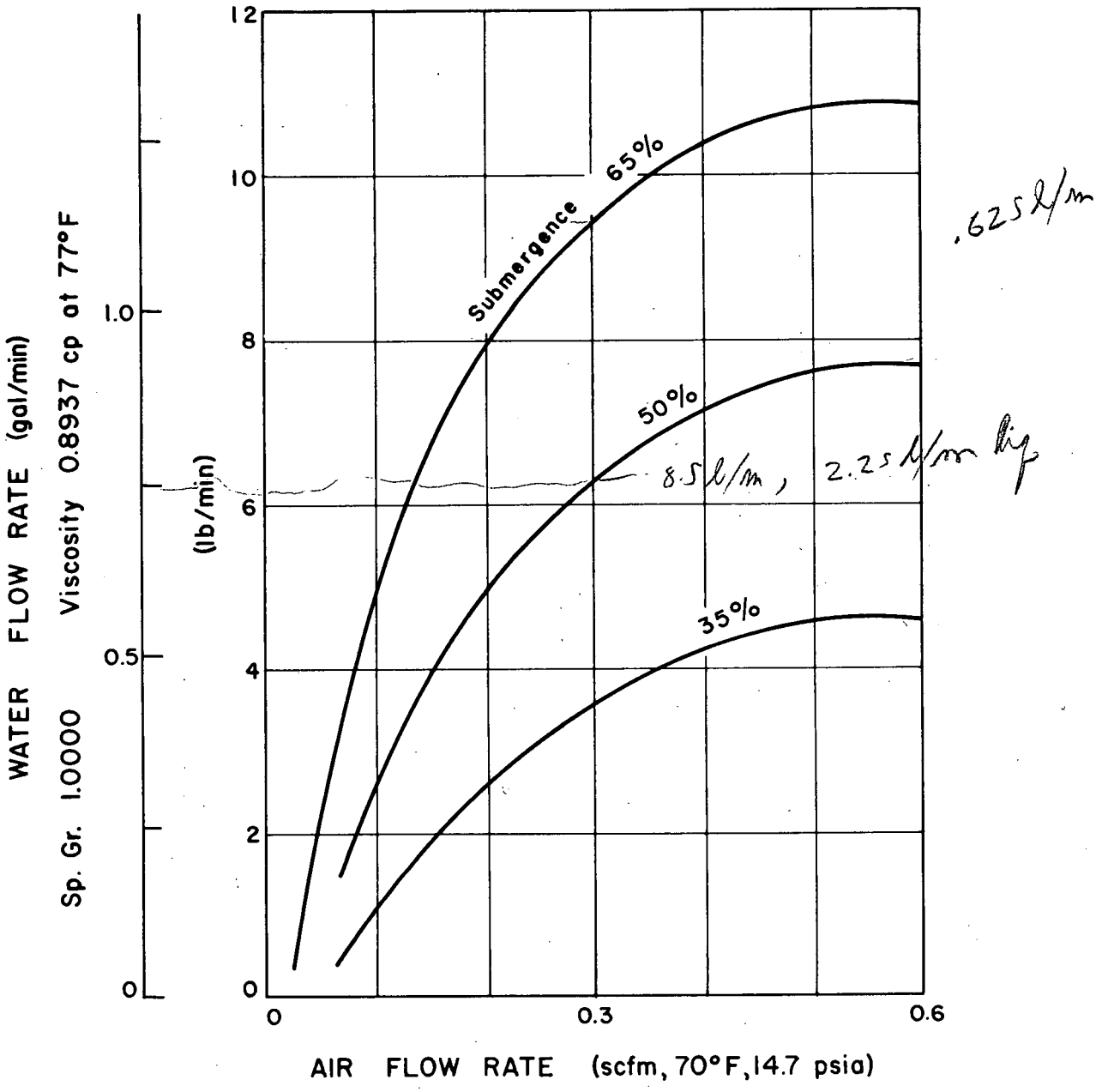

Fig. 6. Air Flow Rate vs. Liquid Flow Rate for Air Lift.

Column 3/8-in. standard galvanized steel pipe; total height 40 ft.

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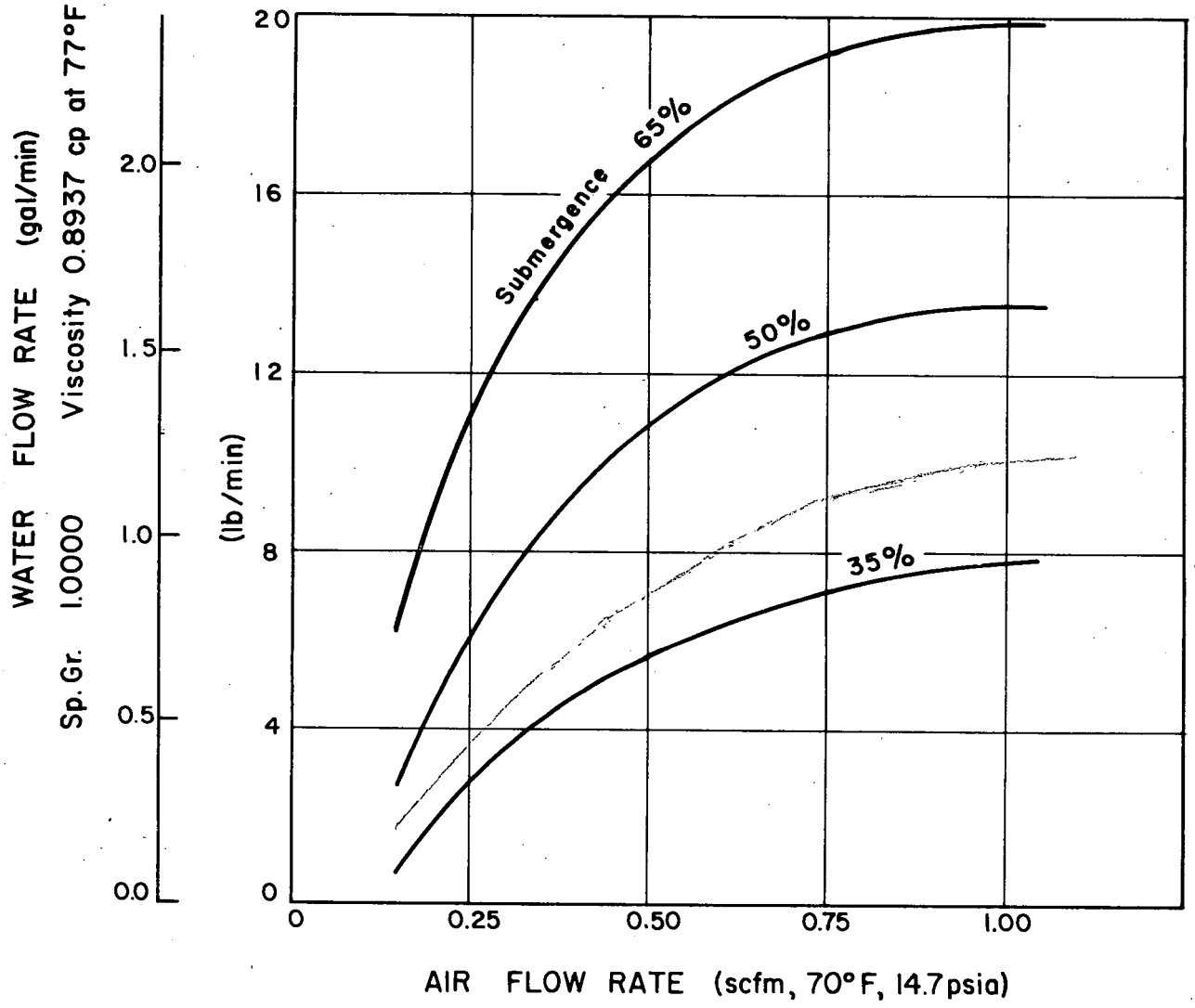

Fig. 7. Air Flow Rate vs. Liquid Flow Rate for Air Lift. Column 1/2-in. Sch. 40 stainless steel pipe; total height 40 ft.

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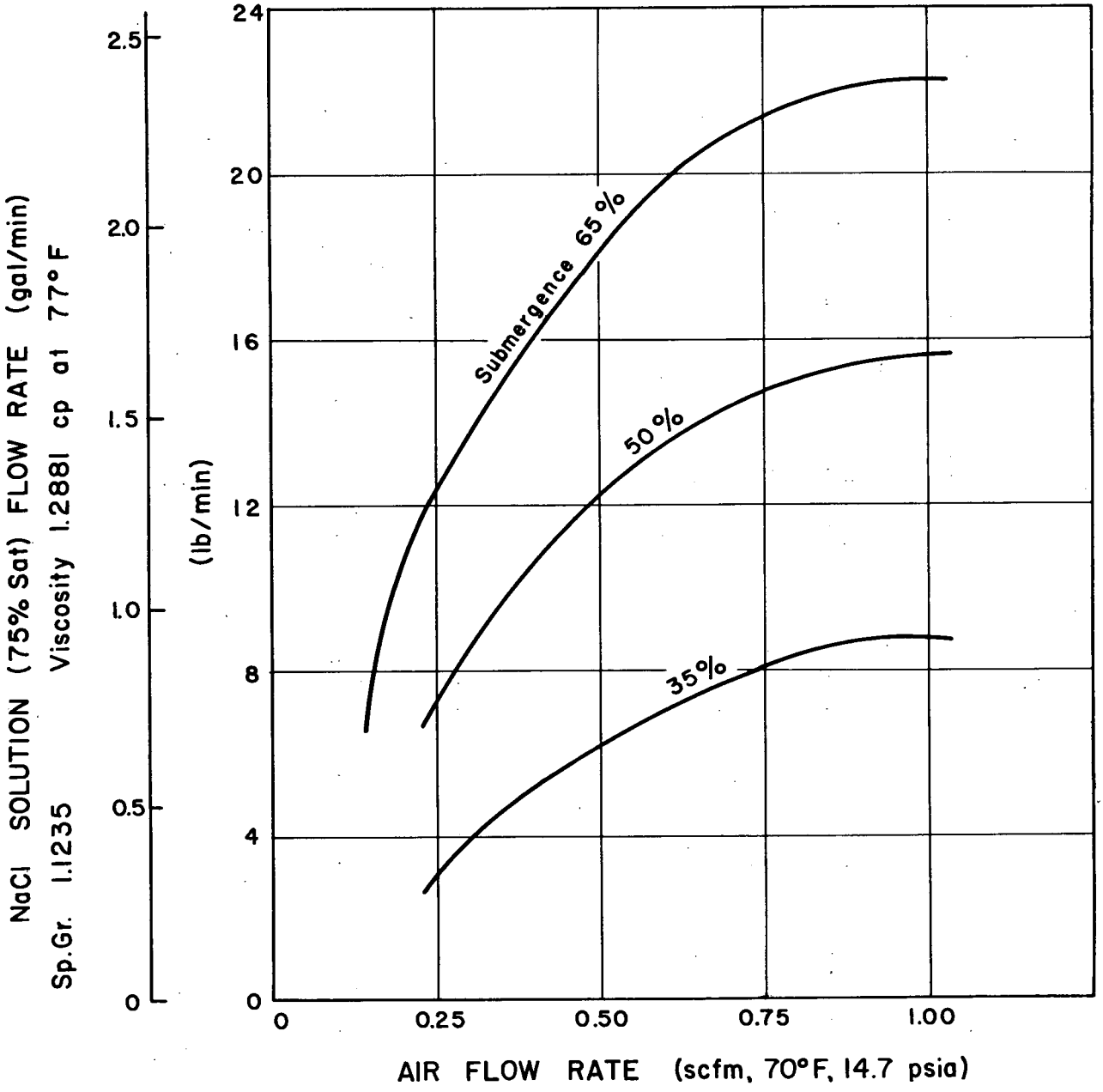

Fig. 8. Air Flow Rate vs. Liquid Flow Rate for Air Lift. Column 1/2-in. Sch. 40 stainless steel pipe; total height 40 ft.

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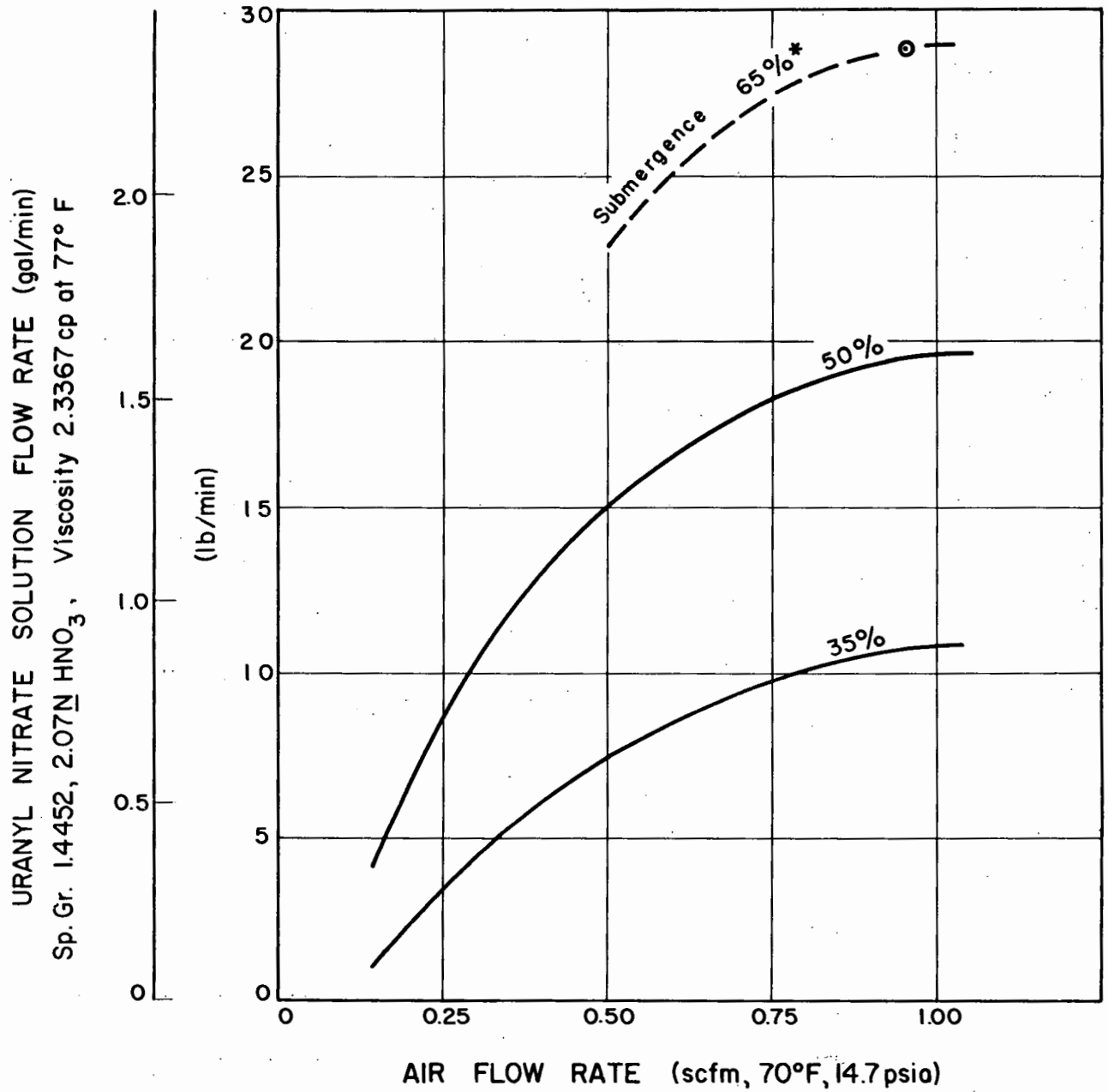

Fig. 9. Air Flow Rate vs. Liquid Flow Rate for Air Lift.

Column 1/2-in. Sch. 40 stainless steel pipe; total height 40 ft.

*Note: Run terminated after one observation to avoid threatened pressure failure of plastic tubing at footpiece.

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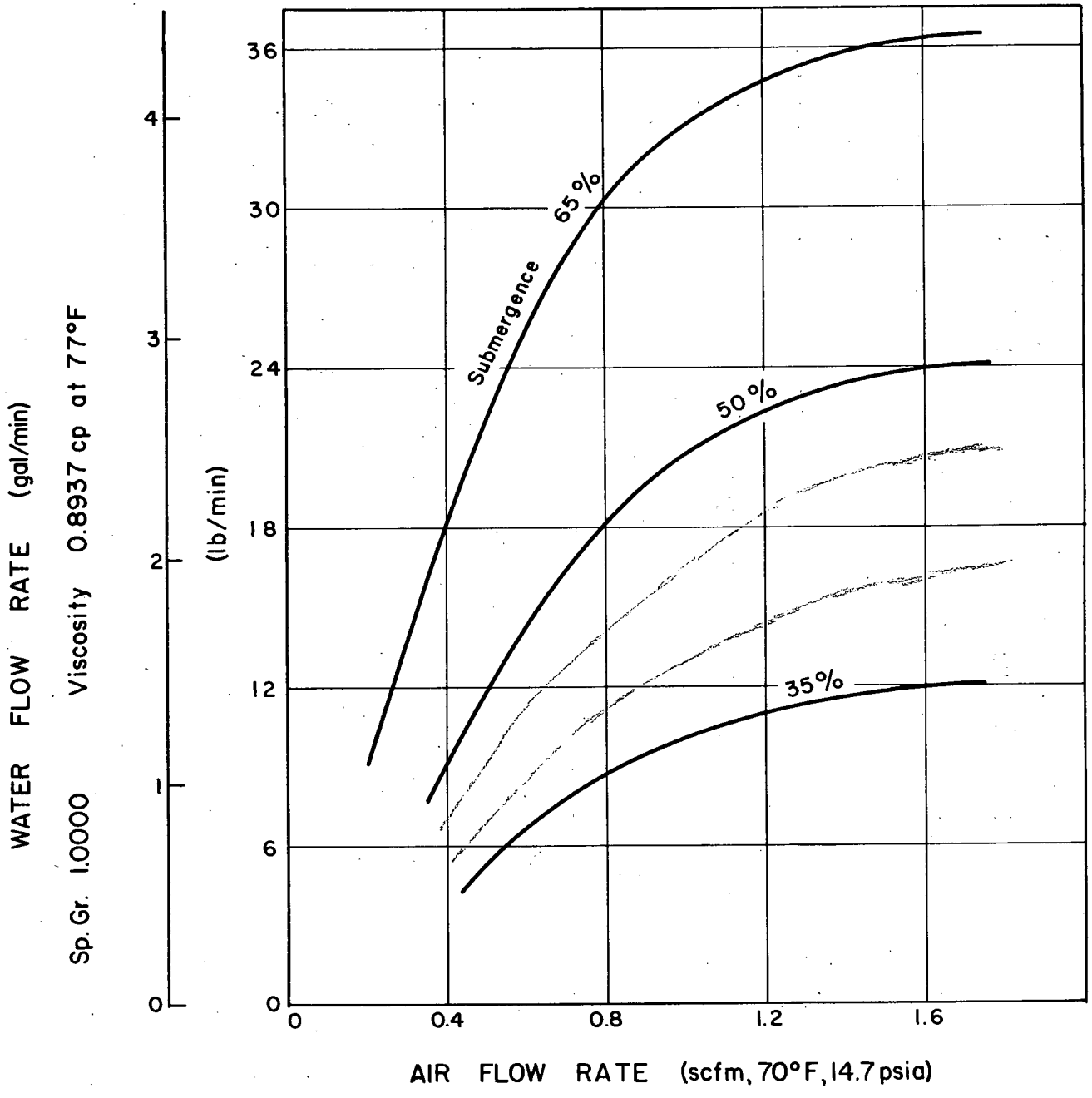

Fig. 10. Air Flow Rate vs. Liquid Flow Rate for Air Lift. Column 3/4-in. standard galvanized steel pipe; total height 40 ft.

Note: There was no test of a 3/4-in. air lift. Data shown here were obtained by interpolation, using test data for the 1/2 and 1-in. air lifts.

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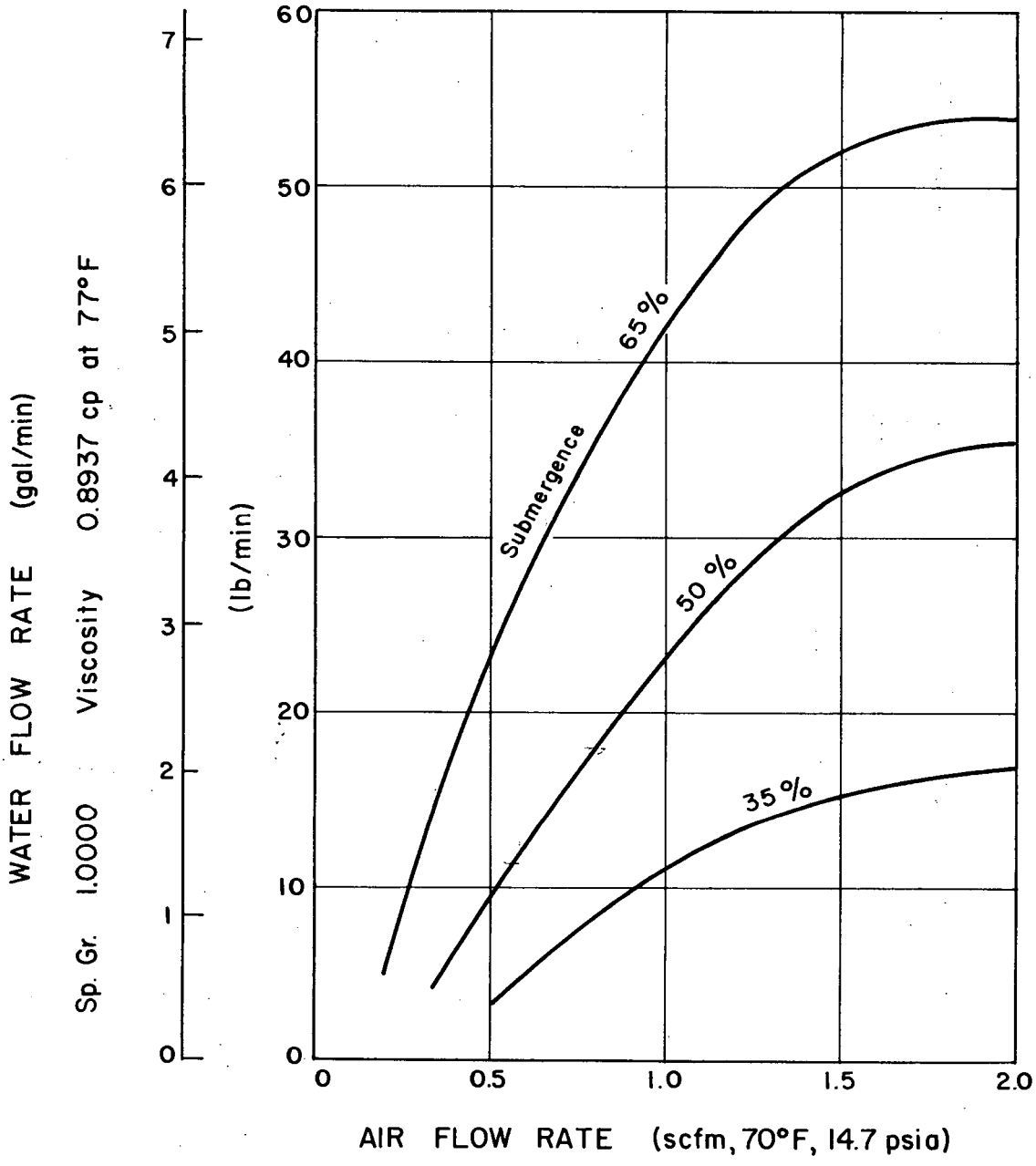

Fig. 11. Air Flow Rate vs. Liquid Flow Rate for Air Lift.

Column 1-in. standard galvanized steel pipe; total height 28 ft.

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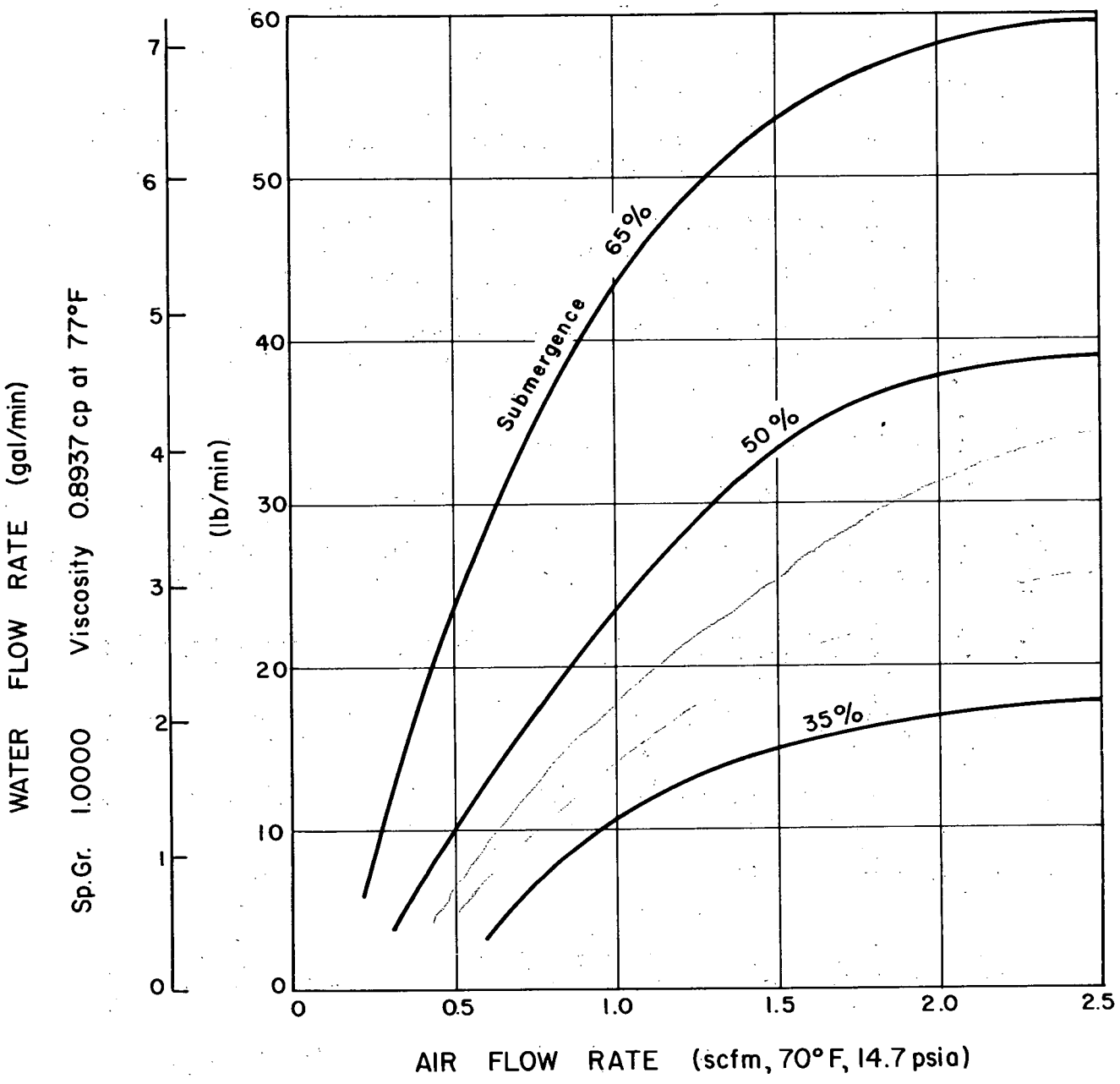

Fig. 12. Air Flow Rate vs. Liquid Flow Rate for Air Lift.

Column 1-in. standard galvanized steel pipe; total height 40 ft.

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