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PULSE PUMPING: A MEANS FOR TRANSFER OF PULSE COLUMN FLUIDS

A. R. Irvine

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CHEMICAL TECHNOLOGY DIVISION

PULSE PUMPING:
A MEANS FOR TRANSFER OF PULSE COLUMN FLUIDS

A. R. Irvine

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1.0 ABSTRACT

A pulse pump, which uses the energy of the pulser to pump fluids to or from a pulsed solvent extraction column, was steady in operation, and results were reproducible. Performance was satisfactory with 2- and 12-in.-dia concatenated columns and with a 5-in.-dia straight column.

2.0 INTRODUCTION

The pulse pump is a method for using part of the energy of the pulse in pulsed solvent extraction columns to cause fluids to flow to or from the bottom of the column. Its use eliminates the need for auxiliary pumps or for gravity flow. Experiments were made with 2- and 12-in.-dia concatenated columns and with a 5-in.-dia straight column. The total operating time was 48 hr for both the 2- and 5-in.-dia columns and three months with the 12-in.-dia column.

In order for the pulse energy to be used for pumping, what amounts to an energy rectifier must be installed, since positive and negative energy are being put into the system alternately. For this purpose a check valve, which allows liquid to flow in only one direction, was used. Energy of opposite sign meets a closed valve, so that the work done previously is not nullified.

Owing to the peculiarities of the column system, there was some difficulty in early experiments in obtaining consistent column operation. These difficulties were eliminated before the test was completed.

3.0 OPERATION OF THE PULSE PUMP

Though probably no column set can be classed as either a pure friction or pure acceleration system, most pressure variations in pulsed columns are largely the result of one or the other phenomenon. For this reason it is convenient to discuss the two separately.

3.1 Friction System

Since pressure drop due to friction losses is a function of the second power of the velocity, in a system where the pulse form is that of a sine wave maximum friction will be attained at the midpoint of each pulse stroke. In a system in which feed is to be admitted to a column from a lower pressure area than the column at rest, it is the check valve in the feed line which prevents back-flow from the column to the feed leg during periods of high column pressure (Fig. 1). As the column fluid proceeds through the negative stroke, pressures less than column static pressure are produced, the minimum pressure occurring at the time of maximum fluid velocity. When the column pressure falls slightly below the feed leg pressure, the check valve opens, admitting fluid and thereby preventing any further drop in column pressure.

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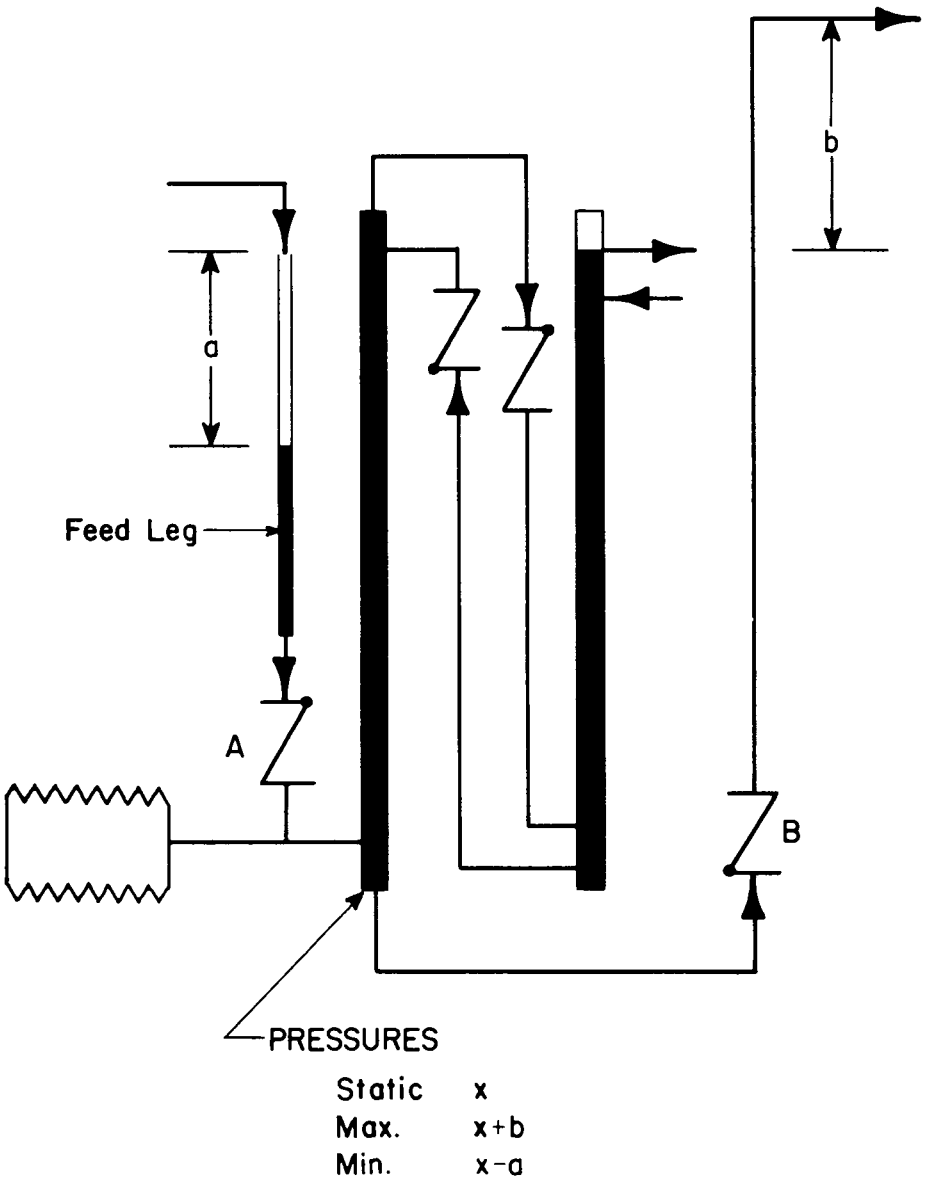

Fig. 1. Diagrammatic Sketch of Pulse Column with Pulse Pumps. Flow is through A when column pressure is minimum, through B when it is maximum.

Flow continues until the demand of the pulser subsides to the value at which flow was initiated, at which time the check valve closes and flow from the feed leg stops. In the ideal case, the pressure inside the column does not fall more than an incremental amount below the pressure in the feed leg since the differences in the demand of the pulse generator and the supply from the pulse column is made up by inflow from the feed pot.

3.2 Acceleration System

The operation of the pulse pump in a system dominated by acceleration pressures is identical to the operation in a friction system with the exception that the maximum surge in pressure occurs at the terminus of the stroke rather than at the midpoint. If the pulse wave is of the sine curve type, maximum acceleration occurs at the time of zero flow. Theoretically, once the rate of deceleration reaches the maximum value allowed by the pulse pump, the fluid in the column decelerates at a constant rate until the velocity reaches zero, which is after the negative stroke has started. Then it accelerates at a constant rate until the rate of flow in the column matches the rate of flow of the pulse generator, at which time the pressure in the column is the same as that in the feed leg and flow from the feed leg ceases. In order for the rate of flow in the column to catch up to the demand of the pulse generator, it is necessary for the rate of acceleration in the column to exceed the average rate of acceleration of the pulse generator. Therefore, once the two velocities are equal, the rate of acceleration immediately drops to that of the pulse generator and the pressure rises sharply. This theory has been confirmed by visual observation of a pressure gage on a pulse pump system. The rise in pressure was proportional to the amount of fluid being pumped.

4.0 PRESSURE CALCULATIONS AND PREDICTION OF PULSE PUMP PERFORMANCE

4.1 Calculation of Pressures due to Acceleration

Several publications[1-3] present methods of calculating the pressure in a pulsed column resulting from acceleration effects. It was observed during the tests at ORNL that the equations result in solutions which are low by as much as a factor of 2. Similar observations were made at Hanford.[4]

The use of a concatenated column presents an additional problem in calculating the magnitude of pressure variation. While the fluid in the column and pulse transfer line must follow the motion of the pulser exactly, the fluid in the transfer lines between concatenated sections is under no such restriction during periods of deceleration. The phenomenon may be explained thus: As fluid is moving forward in the organic transfer line at a time late in the positive stroke of the pulser, it must slow down rather rapidly if it is to follow the action of the pulser. However, since the fluid has a tendency to continue to flow in the same direction, a decreased pressure will be produced in the first section. And, as the pressure in the second (top) section of the column is not at all affected by the movement of the fluid in either of the transfer lines, its pressure remains constant. Therefore, the imbalance of pressures will cause fluid to return to the top of the first section, thereby allowing a lower rate of deceleration in the organic transfer line. Since fluid is already flowing in the aqueous transfer line at the end of the negative stroke, it follows that the peak has already been taken off the acceleration for this stroke.

In most instances, the organic transfer line will be of considerably smaller diameter than the aqueous transfer line. In this case, it appears that the deceleration at the end of the positive stroke cannot exceed the acceleration that would result if the organic transfer line was as large as the aqueous. Acceleration pressure in the small line will be unaffected by the presence of the large transfer line.

4.2 Calculation of Pressures due to Friction

Variations in pressure due to friction can be calculated by the usual means or by formulas previously published.[1-3] These pressures are ordinarily important only in small (2-in.-dia) pulsed column systems.

4.3 Performance of the Pulse Pump

Having calculated maximum pressure deviations due to acceleration and friction, it will usually be apparent that one or the other will be controlling. The maximum lift under no-flow conditions will always equal the maximum pressure deviation. However, when a finite quantity of fluid is pumped, the lift will be less than the maximum. If, in a friction system, the volume being pumped is as much as 20% of the pulsed volume, the lift can be expected to drop to 35-40% of the maximum (Fig. 2). The plot in Fig. 2 is applicable only for a pulse wave approximating that of a sine curve. If the pulse wave takes some other form, it will be necessary to make theoretical calculations similar to those in paragraph 6.1 in order to predict the performance.

In the event that acceleration is controlling (which will probably be the case in any column system 3 in. or greater in diameter), the reduction in lift from zero flow to 20% of the pulsed volume will be only about 30%. It could happen that the acceleration pressure and friction pressure will be of the same magnitude, in which case the maximum lift would be expected to be unaffected but the reduction in lift with flow to be less than that predicted by either curve in Fig. 2, because fluid will be pumped as a result of both friction and acceleration.

5.0 DESIGN OF PULSE PUMP SYSTEM

5.1 Check Valves

Most of the design criteria for a check valve to be used for pulse pumping are rather obvious. However, an item which is not so readily apparent is that the valve should be lightly spring loaded, as gravity is too slow in closing the valve in a system which operates at a rate of 40 or more cycles per minute. A spring of sufficient strength to cause a cracking pressure of 0.5-1.0 psi was found satisfactory.

In the test equipment three different types of check valves were employed: floating disk (non-spring-loaded), center-guided disk (spring-loaded), and swing check (spring-loaded). While the non-spring-loaded valve was passable, it is not considered good practice to use this type. The center-guided type is regarded highly but is rather bulky. The swing check has many parts and is more likely to fail than is the disk type. The "basic check unit", manufactured by Durabla Manufacturing Co., is the simplest and least expensive, as well as the most compact, that has been

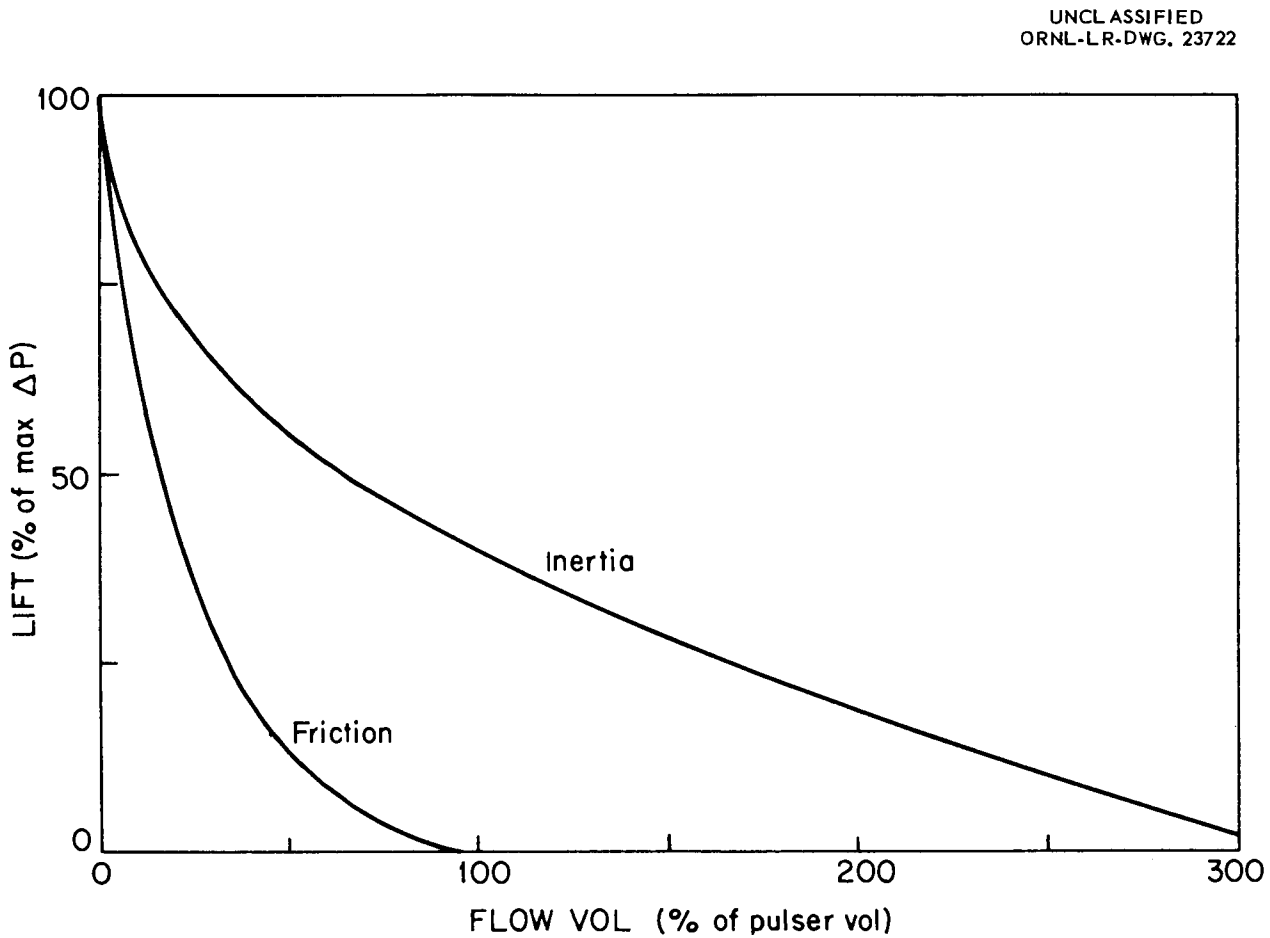

Fig. 2. Theoretical Pulse Pump Performance Curves for Friction System and for Air Inertia System.

found to date (Fig. 3). It has not been tested but there is no apparent reason why it will not be satisfactory.

5.2 Size of Connecting Lines

The lines which carry the fluids either into or out of the pulsed column via a pulse pump must be so sized that both acceleration and friction losses are minimal if the maximum lift is to be obtained when pumping usual quantities. Undersizing of connecting lines will not result in any decrease in lift when flow is near zero. Therefore, the significant result of friction and acceleration losses in the connecting line is that the difference in lift under no-flow and operating flow rates will be increased.

As flow is not continuous, connecting lines must be sized so that they can pass the given quantity of fluid in only a fraction of the total time. Under usual conditions a safe figure for that fraction is 20%. Although various connecting line sizes have not been tested, velocities in excess of 2 fps (during the flow interval) are not recommended.

7.0 REFERENCES

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3. A. C. Jealous, H. F. Johnson, "Power Requirements for Pulse Generation in Pulse Columns", Ind. Eng. Chem. 47, 1159 (1955).

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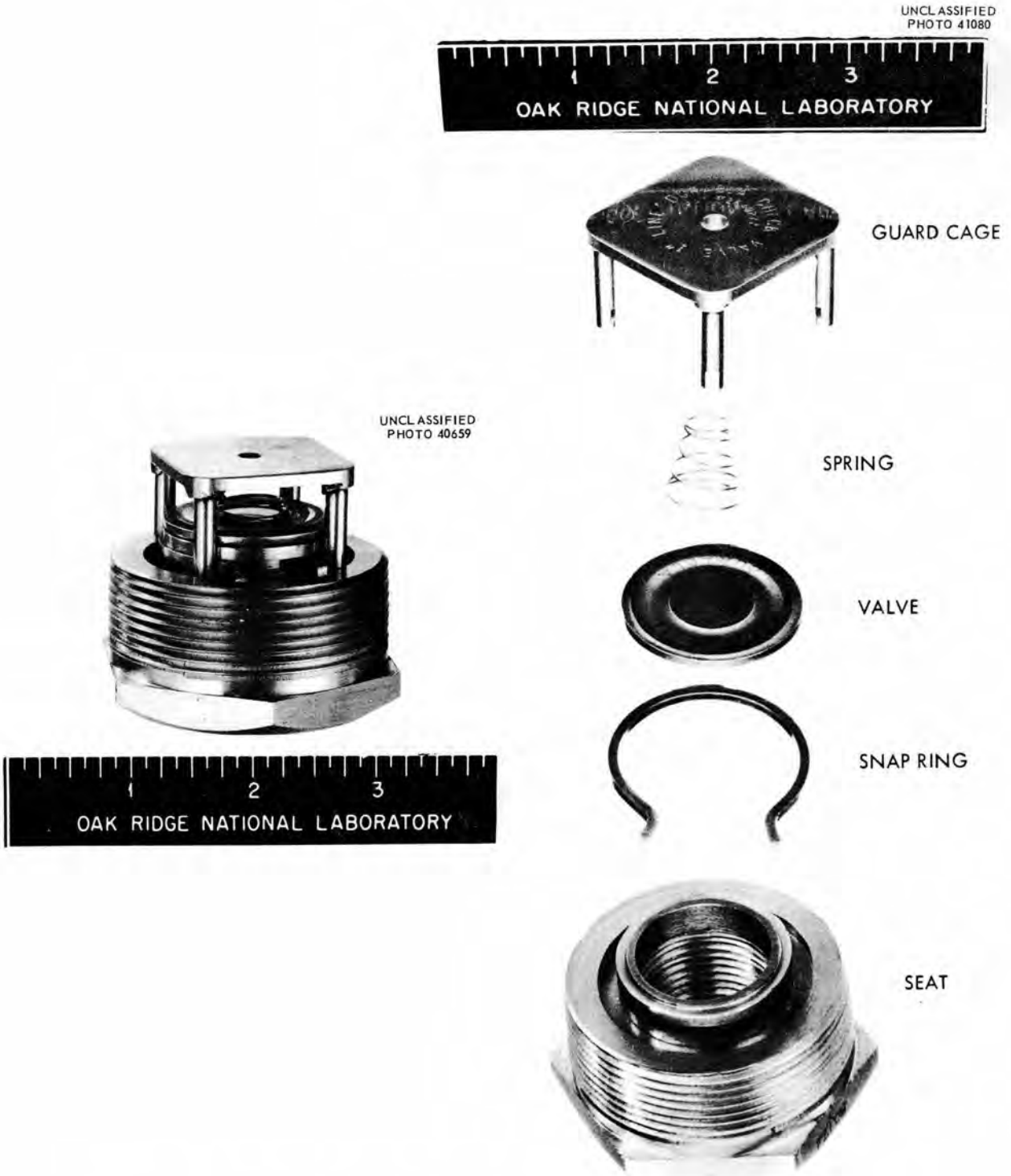


Fig. 3. A Simple Check Valve Suitable for Use in Pulse Pumping.

6.0 APPENDIX

6.1 Calculation of Theoretical Amounts Pumped in Pure Friction System when Pulse Is a Sine Curve

For a hypothetical system where the lift of fluid being pumped is equal to 50% of the maximum friction drop:

Since friction drop is proportional to the second power of the velocity, the velocity must equal $\sqrt{.50}$ or 0.707 of the maximum velocity before the pressure in the feed leg and in the column are equal (see Fig. 4). The angle at this point is 45°. It is also apparent that flow will stop at a point 45° after the maximum velocity has been reached (or 135°).

The velocity of fluid in the column during this interval of time (from 45° to 135°) must, by definition, remain at the same value as it possessed at 45°. As the pulser is traveling at a higher average velocity, there is a difference in demand of the pulser and the supply from the column, which must be supplied by the feed leg. In this case,

Vol pumped = vol of piston displacement - vol of fluid displaced in column

$= 2\,(0.5 \sin 45^{\circ}) - 0.25 \times \pi \times 0.707 = 0.153$ of stroke of piston or pulsed volume.

Volumes pumped under other conditions of lift are tabulated in Table 1 and plotted in Fig. 2.

Table 1. Theoretical Volumes which can be Pulse-Pumped in Inertia-Free Friction System — Sine Wave Pulse

Lift (% max. friction)	Volume Pumped (% of pulsed vol)
00	100.0
10	56.1
30	29.3
40	21.4
50	15.2
75	4.7
100	0.0

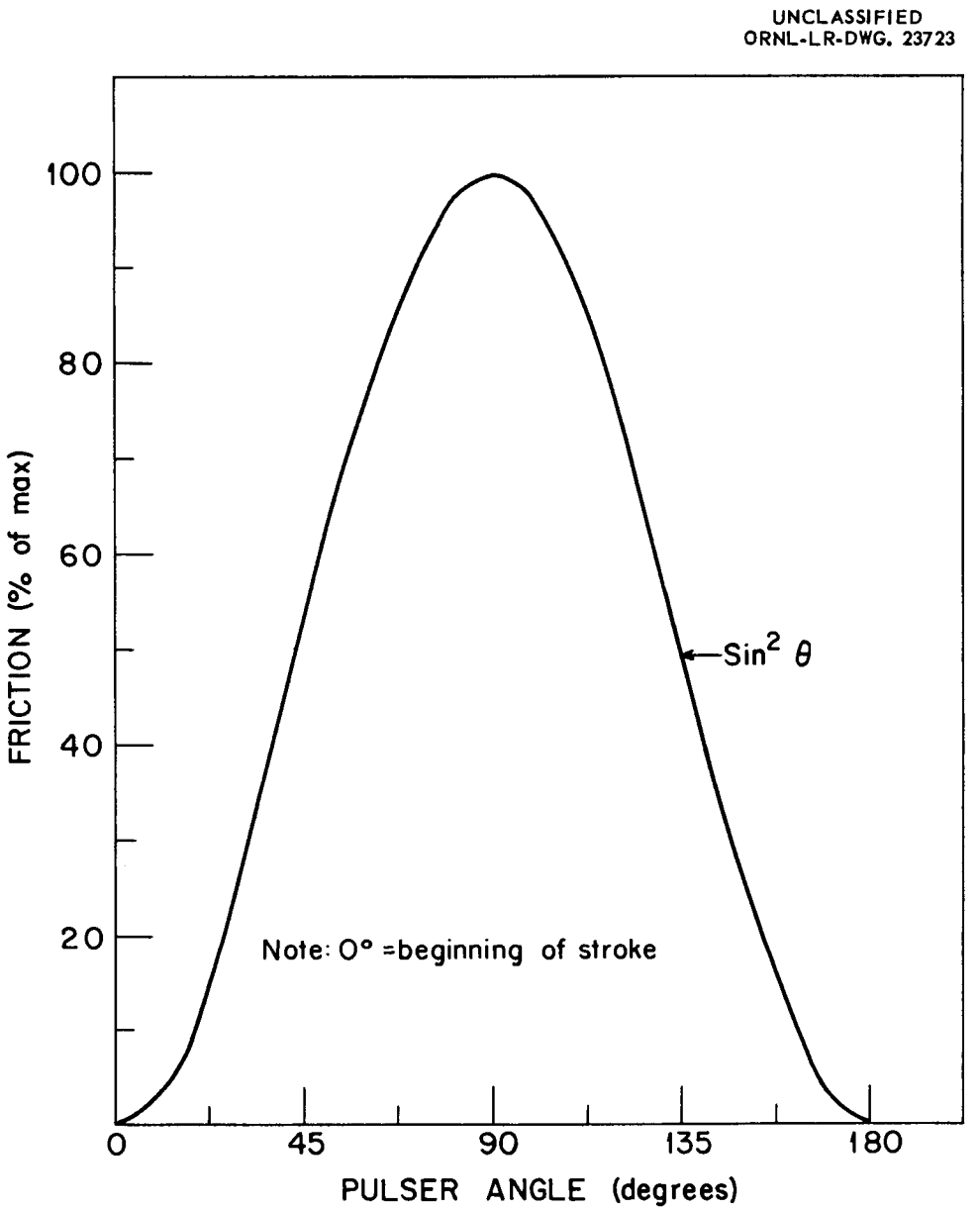
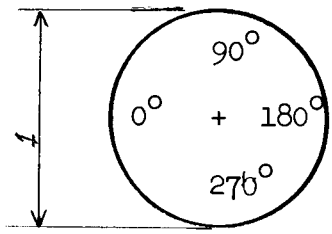


Fig. 4. Pressure Variation in Friction System as Function of Pulser Angle.

6.2 Calculation of Theoretical Amounts Pulse-Pumped in Frictionless Acceleration System when Pulse is a Sine Curve

Let the acceleration be limited to 50% of maximum value. Let 0° be defined as the point of maximum velocity. The angle at which acceleration = 50% of maximum where the sine is 0.5, or 30°:



Assume that amplitude and frequency each equals 1. Then

$$\text{Maximum velocity} = 3.14$$

$$\text{and Velocity at 50\% of maximum acceleration} = 3.14 \cos 30^\circ = 2.72$$

$$\text{Maximum acceleration} = \frac{(\text{max vel})^2}{\text{radius of circle}} = \frac{\pi^2}{0.5} = 19.74$$

$$\text{Rate of deceleration at } 30^\circ = 0.50 \times 19.74 = 9.87$$

$$\text{Time required to reach zero velocity} = \text{velocity/acceleration}$$

$$= 2.72/9.87 = 0.2756 \text{ of one cycle}$$

$$\text{Angle at which fluid in column comes to rest} = 30 + 99.2^\circ = 129.2^\circ$$

Refer to Fig. 5, which is a plot of acceleration and velocity of fluid in the column. One can see that the motion of the fluid in the column ceases to follow the action of the pulser piston at 30° and follows its own path of constant acceleration until the velocities of the column fluid and pulser piston are equal. In this case, the two velocities become equal at 219°.

Distance traveled upward by fluid in column = distance from 270° to 30° + distance traveled during constant deceleration period = $0.75 + 0.2756 \times 1.3 = 1.126$.

Distance traveled downward by fluid in column = distance traveled during period of constant acceleration (129.2° to 219°) + distance traveled from 219° to 270°

$$= \frac{9.87}{2} \times \left[\frac{89.8}{360}\right]^2 + 0.185 = 0.494$$

Volume pumped = upward travel in column - downward travel = $1.126 - 0.494$

= 63.2% of pulse volume.

Calculations were made in a similar manner for other lifts (Table 2 and Fig. 2).

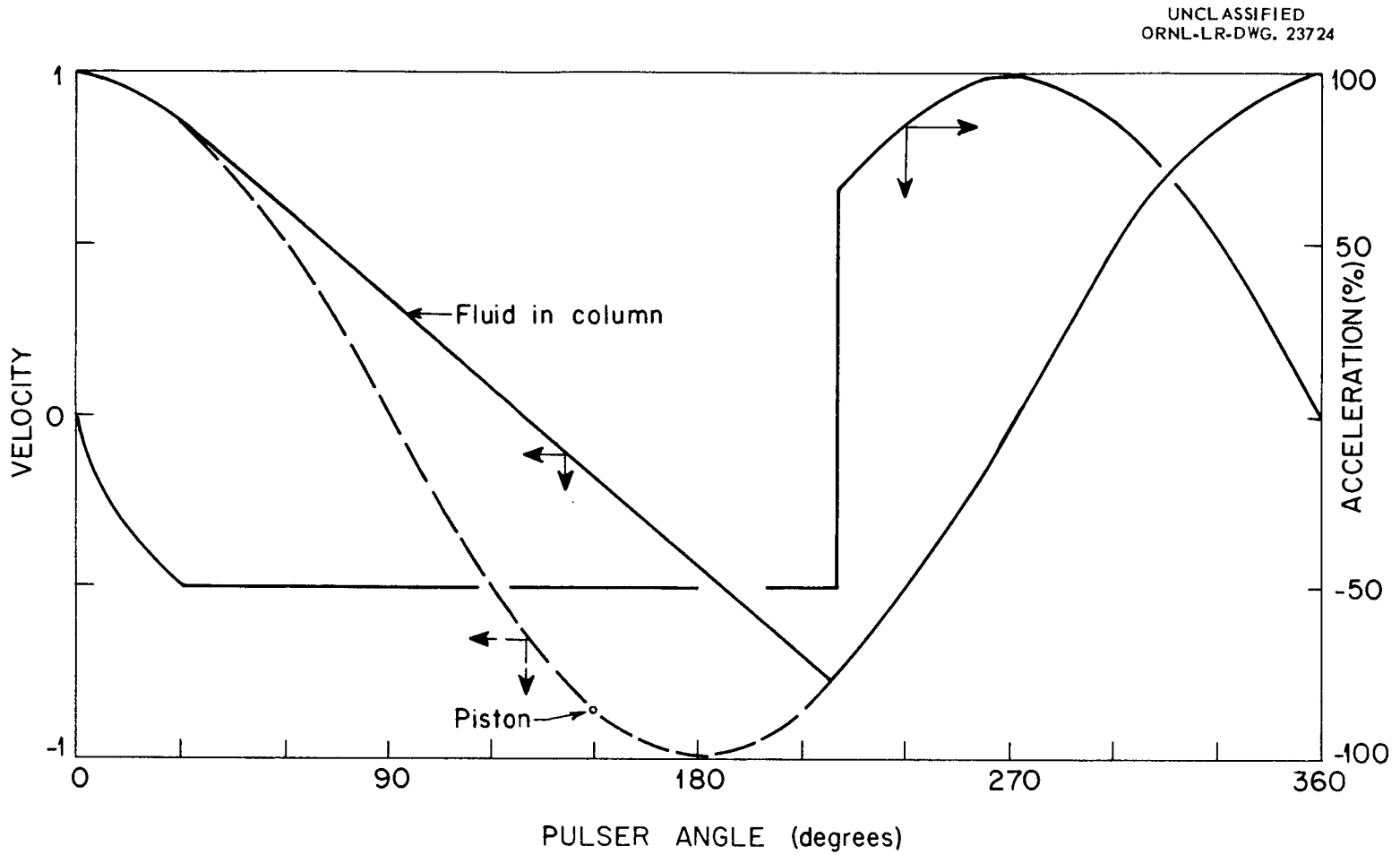


Fig. 5. Graph of Velocity and Acceleration in Column when Negative Pressure Deviation due to Acceleration is Limited to 50% Theoretical Maximum. Cylinder is at center of up stroke at 0°.

Table 2. Theoretical Volumes which can be Pulse-Pumped in a Frictionless Acceleration System — Sine Wave Pulse

Lift (% of max acceleration)	Volume pumped, (% of pulse volume)
0	314.2
50	63.2
75	14.8
90	02.1
100	00.0

6.3 Large Column Pulse-Pump Experience

The work on the large concatenated column set was quite difficult because of the design of major equipment pieces, which were not originally intended to be operated as a concatenated column. The large existing columns were used in the interest of economy and to obtain data on plant-scale equipment.

The features of the existing equipment which caused difficulty were various built-in air pockets, a leaky pulser piston, and, most important, improperly sized connecting transfer lines. While it is necessary to size the organic transfer line for average velocities of 1.5 fps, the aqueous transfer line must be so sized as to prevent cavitation and to allow the desired amount of pulse pumping. The test equipment had an aqueous transfer line which was undersized, thereby causing the pressure at the top of the first (or bottom) section to drop to 15 psi below static. Had the column system been operating under atmospheric pressure, cavitation would have resulted. As it was, the system was held under approximately 15 psig pressure; when minimum pressures occurred, dissolved air came out of solution and traveled up the column as bubbles. These bubbles, which appeared at the top of the first section, were carried out of the first section via the organic transfer line but did not appear in the next section, either at the bottom or top. Neither were any bubbles drawn back into the first section from the second section via the aqueous transfer line. The only conclusion which the writer could draw from these observations was that the bubbles which appeared at the top of the first section went back into solution before reaching the bottom of the second section.

First attempts at operation of the large column set pulse pump were made in July of 1955. Various air pockets were discovered and vented, and what appeared to be inleakage of air was noted. (It was the bubbles of air which were referred to in the above paragraph.) The pulser piston leaked about 1/3 gpm, so this plus an additional amount was returned to the bottom of the second section. Variations in the amount returned caused the lift of the pulse pump to change. It was not

until January of 1956 that a device for returning the pulser leakage directly to the column system was installed and successfully put into operation. This device uses the principle of the pulse pump to return the pulser leakage. After the leakage-return mechanism was put in operation and two built-in air pockets at the bottom of both sections were provided with continuous vents, reproducible results were achieved. Before this time, reasonably small but inconsistent variations crept in, rendering the data almost useless and completely inconsistent as to variation in lift with volume pumped. See Fig. 6, which is a photograph of the 12-in. column set, and Fig. 7, which is a flow diagram of the test equipment.

The performance curve is plotted in Fig. 8 and the data for the final week of operation are tabulated in Table 3. During this last week performance was quite steady and the individual points plotted out into a smooth curve, thus again affirming the consistency of the data.

Table 3. Operation Data for Final Week of Operation of Large Column Pulse Pump

Pulse Amplitude: 1 in.
Frequency: 48 cpm

Date	Flow*			Level (ft)	Lift	
	Reading	$\sqrt{\text{Reading}}$	% Pulse Vol.		(ft)	(% of max)
3/2/56	70	8.38	15.7	18.5	35.7	79
3/2/56	102	10.1	19.0	24.5	32.7	72.5
3/2/56	57	7.55	14.2	17.5	36.2	80.0
3/2/56	12	3.46	6.5	9.0	40.6	90.0
3/2/56	3	1.7	3.2	5.0	42.6	94.0
3/2/56	0	0	0.0	0.0	45.2	100.0
3/1/56	50	7.07	13.3	16.5	36.7	81.0
2/29/56	20	4.47	8.4	10.0	40.0	88.5
2/29/56	7	2.65	5.0	4.5	42.9	94.8
2/28/56	32	5.65	10.6	12.5		
2/27/56	32	5.65	10.6	12.5	38.7	85.5

*Flow, gpm = $0.44 \times \sqrt{\text{reading}}$

6.4 Two-Inch-Diameter Column Pulse Pump Experience

The equipment used in this series of tests is sketched in Fig. 9. Again the concatenated column system was an existing one to which a pulse pump was added. All the tests were carried out at a constant amplitude, with frequency varied from 30 to 72 cycles per minute. Both friction and acceleration pressure losses vary as the second power of frequency, so results at various frequencies could easily be related to each other by multiplying the observed lift by a factor to convert to lift at "standard" frequency. The volume pumped was always converted to a percent of pulse volume.

Calculated maximum values for friction and acceleration are 9 and 8.85 psi, respectively, which indicate that a significant amount of the pulse pumping would be due to both phenomena. However, owing to the slopes of the two theoretical

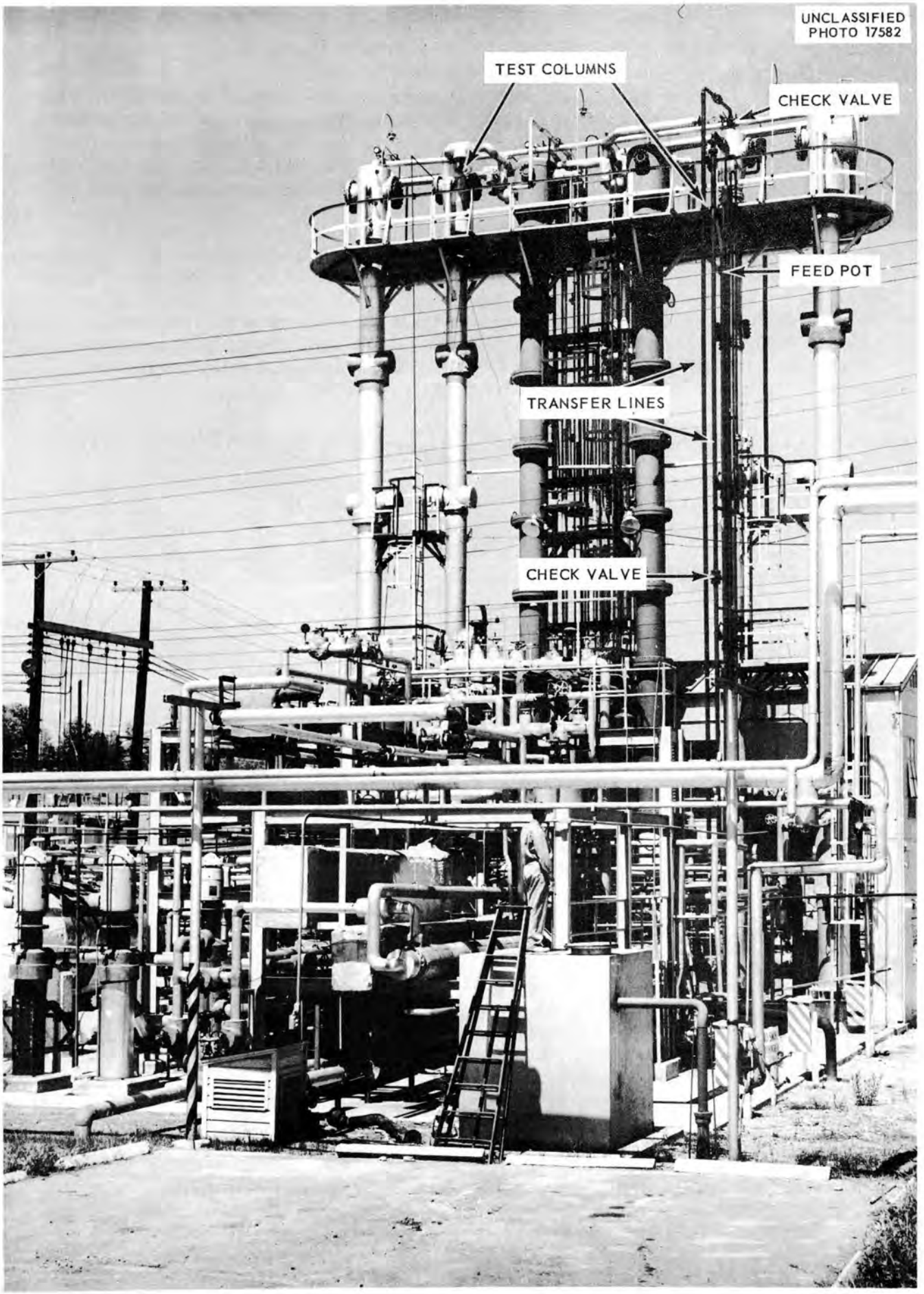


Fig. 6. 12-in.-dia Concatenated Pulse Columns.

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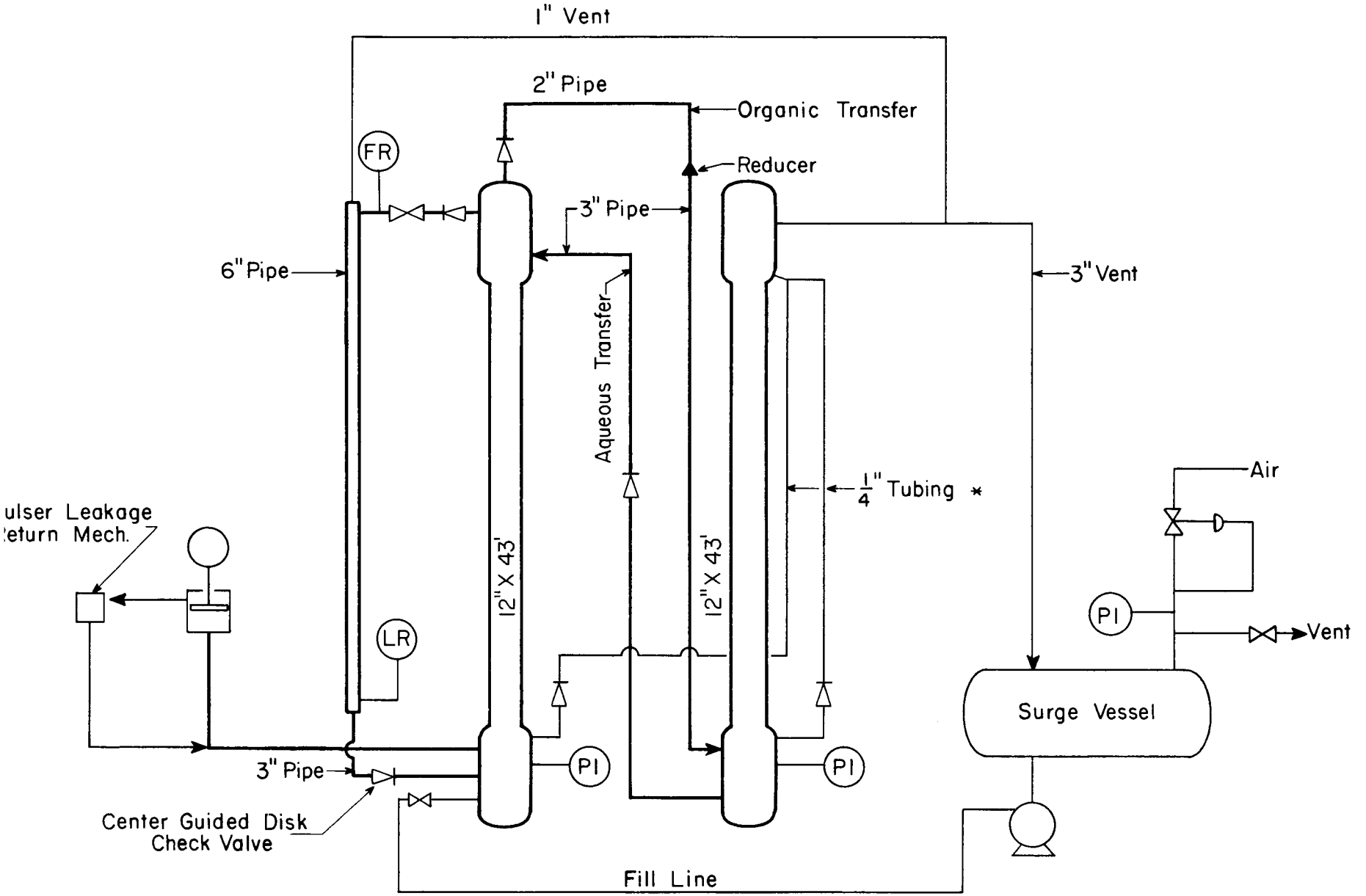

Fig. 7. 12-in-dia Column Pulse Pumping Test Flowsheet. * Erratic results were obtained until these two continuous bleeds were added.

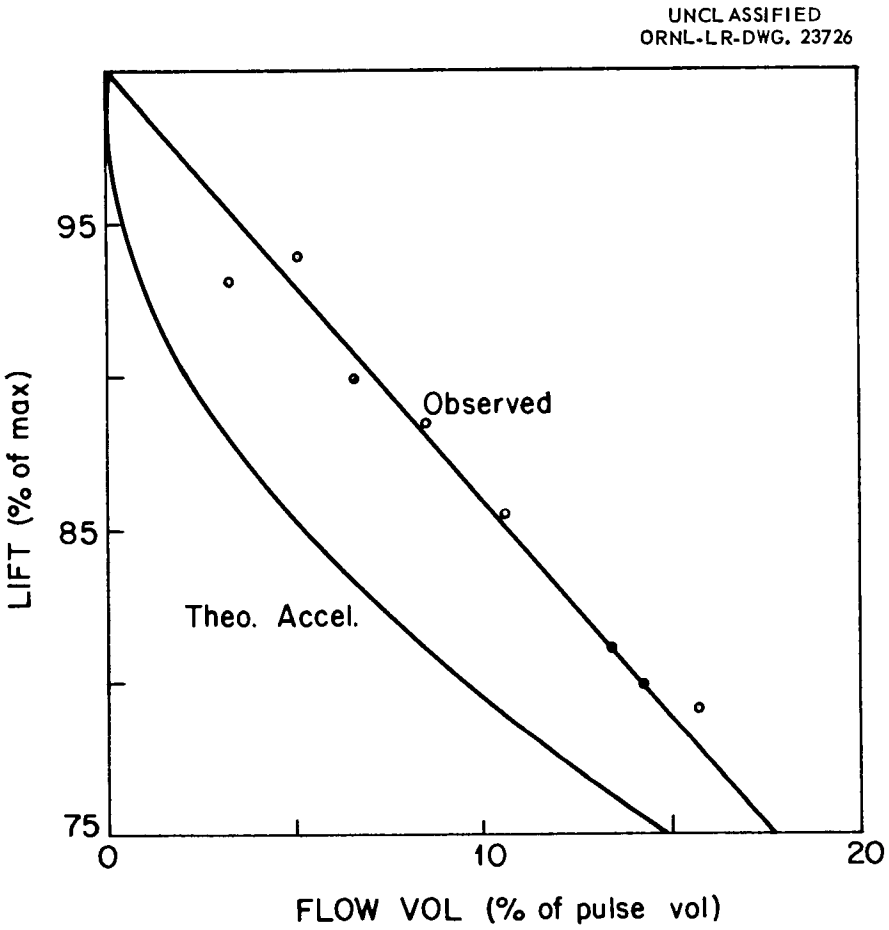

Fig. 8. 12-in-dia Concatenated Column Pulse Pump Performance Curve.

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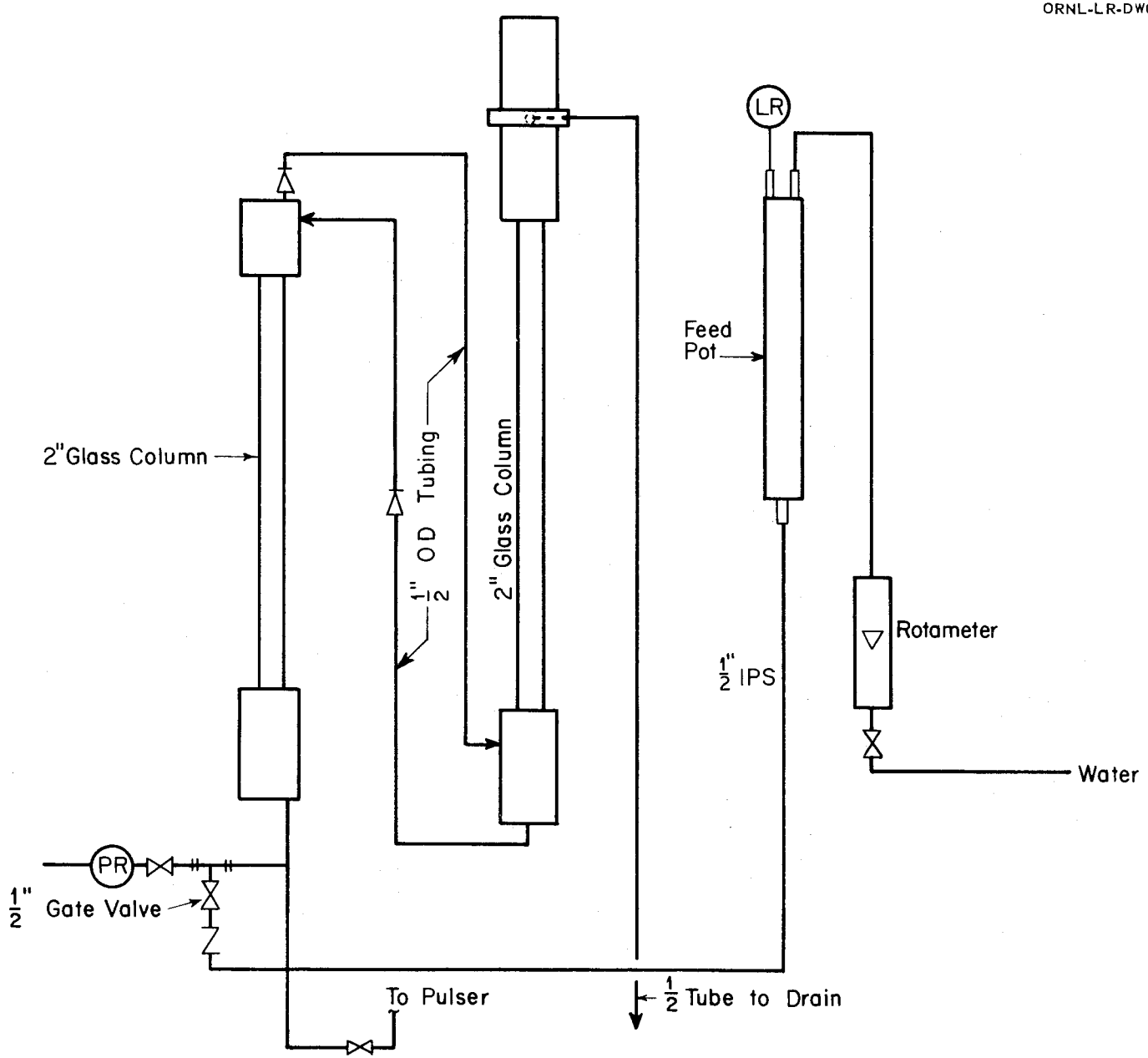

Fig. 9. 2-in-dia Column Pulse Pumping Flowsheet.

curves, one would expect the greater amount to be due to acceleration. (Acceleration and friction pressure were calculated by using a method presented by H. F. Johnson.[1] The pulse wave was assumed to be a sine curve although it actually deviated somewhat from a sine curve.)

During the course of the tests the theory concerning retrocirculation of fluids in the transfer tubes was evolved, so a series of runs was made with only one transfer tube which, of course, was not equipped with a check valve. Results of these and other runs are shown in Table 4 and Fig. 10. The runs with only one transfer tube were made March 18, 1955, and yielded pumping rates and lifts that were much higher than did the two-tube concatenated column. This is taken as substantial proof of the existence of retrocirculation.

One shortcoming of these runs was that no tests were made to determine lift at zero flow. Calculations of pressure variation indicate that the lift under no-flow conditions would be equal to 9.0 psi or almost 21 ft; however, extrapolation of the curve for the two-tube column (see Fig. 10) would lead one to believe the maximum is 14 to 15 ft. The system using only one transfer tube apparently would have produced a maximum lift even greater than 21 ft.

Referring to Fig. 10, one can see that the volume pumped was considerably less than theoretical for an acceleration system. As a portion of the pumping undoubtedly was due to friction losses, it is not possible to know how far the actual performance deviates from the theoretical. Inertia in the feed line also is a probable contributor to increased deviation from theoretical at higher flow rates.

6.5 Five-Inch-Diameter Straight Column Pulse Pump Calibration

The performance of a pulse pump installed on a 5-in. IPS straight pulse column was determined at three flow rates ranging from 0 to 21.5 percent of the pulse volume. The equipment tested is sketched in Fig. 11. Assuming the fluid in the column and the 3/8" IPS section of the pulse line has characteristics approximating those of water, the calculated maximum acceleration pressure is 19.9 feet while the calculated maximum friction pressure is 9.62 ft. Assuming the above values to be of the proper magnitude, it is apparent that the pumping will result primarily from pressure variations due to acceleration.

The three points are plotted in Fig. 12 along with the theoretical acceleration curve. The volume pumped at a given lift was some 85% of the theoretical volume.

6.6 Five-Inch-Diameter Straight Column Pulse Pump Operating Experience

The pulse pump described in paragraph 6.5 was modified to provide for varying conditions of pulse amplitude and frequency by substituting a 1/2-in. pipe and globe valve for the 2 ft length of 3/8-in. pipe. Since this modification, the pump has operated a total time of approximately six weeks. Though there has been some difficulty, this appears to have been eliminated and the performance is generally satisfactory.

It is not possible to be certain of the immediate cause of the troubles which were encountered as several factors could have been contributory. To wit: the initial installation was such that a very high pressure (40 psi) was developed on

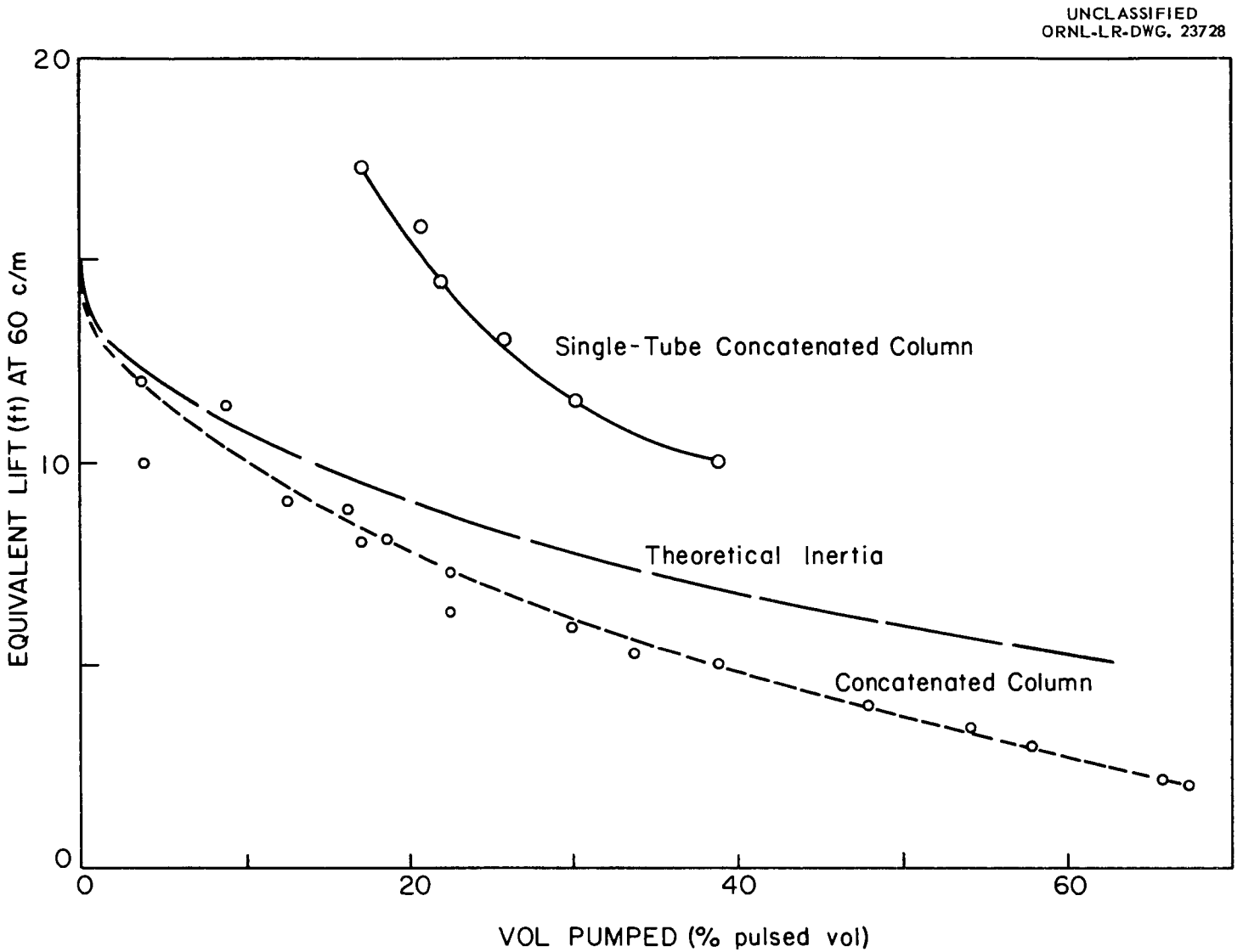

Fig. 10. Pulse Pump Performance Curve on 2-in-dia Concatenated Column.

Table 4. Results of Test of Pulse Pump on 2-in.-dia. Concatenated Column

Pulse Amplitude: 1 in.

Date	Time	Freq. (cpm)	Lift	Flow cc/min	Flow % P.V.*	L/(F/60)²**	Remarks
3/11/55	10:30	60	6'-1"	930	30.1	6'-1"	
	11:10	60	5'-0"	1195	38.7	5'	
	1:35	60	3'-0"	1785	57.8	3'	
	2:20	60	2'-0"	2082	67.4	2'	
	3:20	60	4'-0"	1480	47.9	4'	
3/14/55	2:10	60	6'-0"	990	32.0	6'	Pulse amplitude readjusted for this series of runs.
	2:30	60	5'-0"	1250	40.5	5'	
	2:50	60	4'-0"	1550	50.1	4'	
	4:00	60	3'-0"	1890	61.1	3'	
3/15/55	2:00	60	2'-0"	2045	66.3	2'	
3/16/55		45	3'-0"	800	34.5	5.34'	
		45	5'-0"	265	11.4	8.9'	
		60	5'-0"	1030	33.5	5.0'	
		72	5'-0"	2000	54.0	3.47'	
		72	3'-0"	2440	65.9	2.08'	
		45	3'-0"	780	33.6	5.34'	
		30	3'-0"	58	3.75	12.0'	
3/18/55		50	12'-0"	440	17.1	17.3'	Only one transfer tube open and had no check valve in it. Other tube plugged. Purpose of this run was to demonstrate existence of retrocirculation.
		50	11'-0"	530	20.6	15.8'	
		50	10'-0"	565	21.9	14.4'	
		50	9'-0"	665	25.8	13.0'	
		50	8'-0"	780	30.2	11.5'	
		50	7'-0"	1000	38.9	10.0'	
3/21/55	8:45	60	8'-0"	530	17.2	8.0'	
	9:00	60	9'-0"	385	12.5	9.0'	
	9:15	60	10'-0"	115	3.72	10.0'	
	9:30	70	10'-0"	810	22.5	7.35'	
	9:40	70	11'-0"	670	18.6	8.1'	
	9:45	70	12'-0"	590	16.4	8.8	

% of Pulse Volume

* L = Lift in ft

F = Frequency, cycles/min

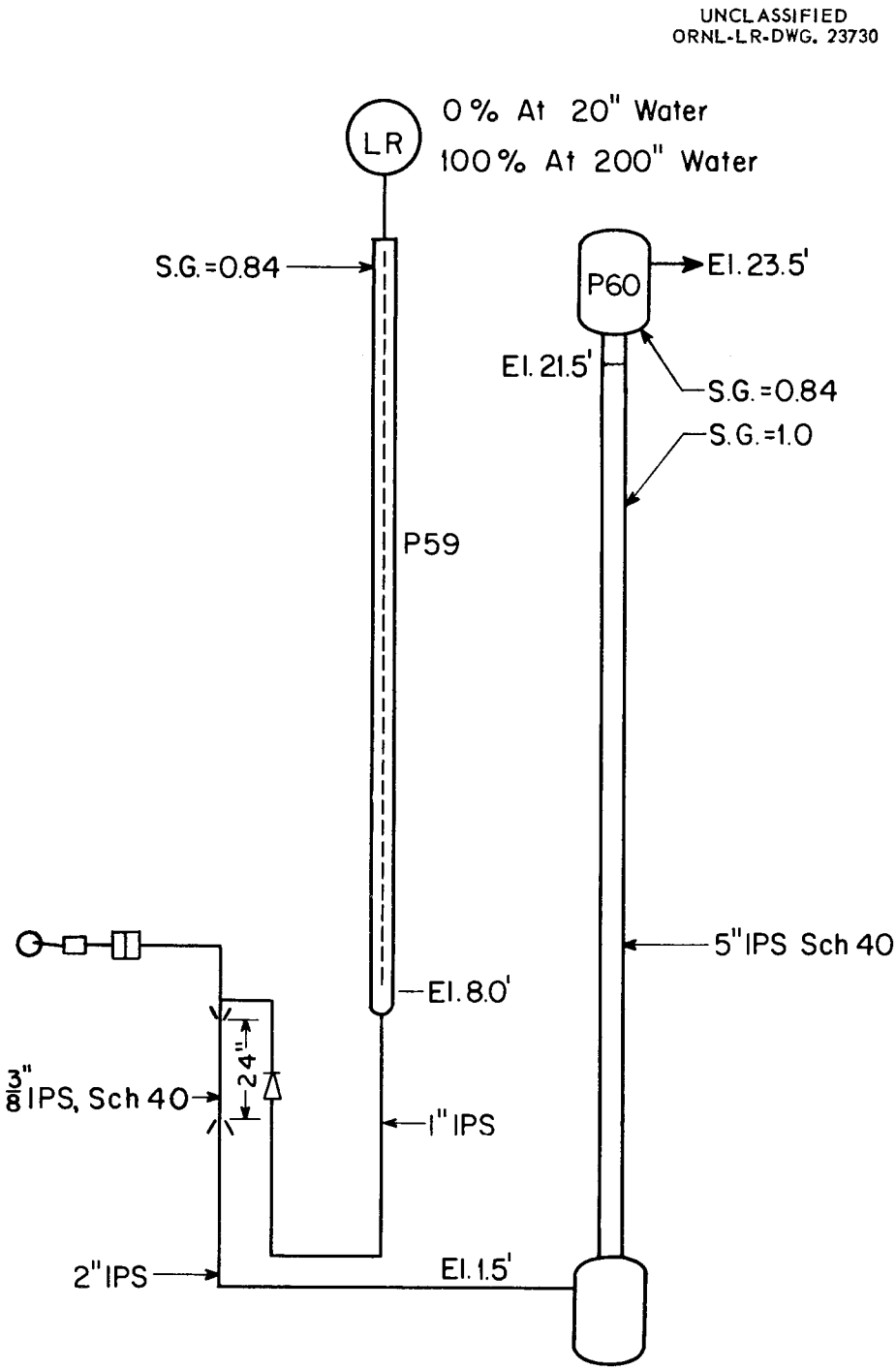

Fig. 11. 5-in-dia Straight Column and Pulse Pump.

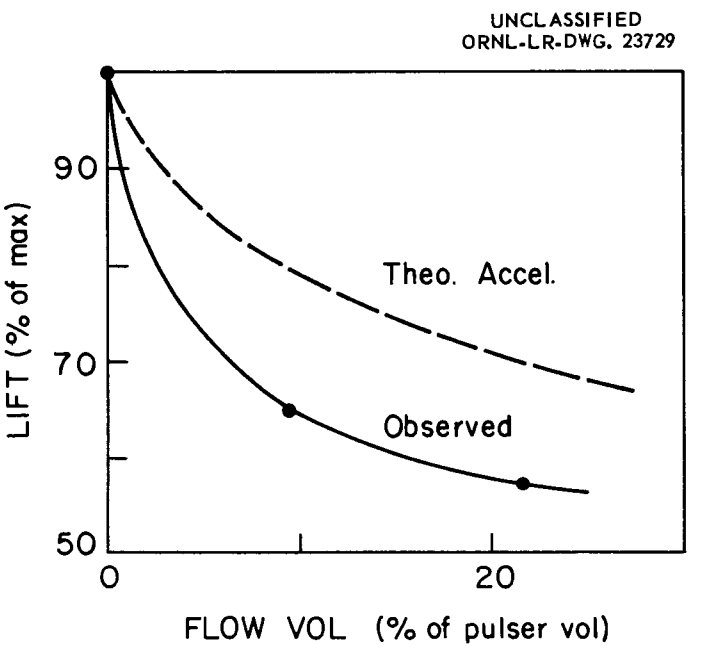

Fig.12. Performance Curve for 5-in-dia Straight Column Pulse Pump. Maximum lift = 14.8 ft; frequency = 40 c/min; amplitude = 0.8 in.

the positive stroke; it was found that the check valve could possibly become cocked; and it is also known that high discharge pressures can cause the loss of hydraulic fluid in a Lapp Pulsafeeder such as is used to pulse this column. Any of these three items could have been the source of trouble, but it was likely a combination of these. The check valve was replaced with one which was designed such that the disk could not become cocked, but the trouble persisted. The nature of the trouble can be described as follows:

In order to obtain adequate pumping of the organic into the column it was necessary to partially close the throttle valve shown in Fig. 13; when sufficient pumping was obtained by decreasing the valve opening, organic was observed to come from the column bottom outlet where only aqueous should appear. This appearance of organic could be due either to flooding of the column or to an extreme loss of pulse due either to check valve failure or to operation of pressure and vacuum relief valves on the Lapp Pulsafeeder pulser. Subsequently, the column was washed with detergent several times in an attempt to eliminate the possibility of flooding due to dirty pulse plates. Also, in order to prevent the buildup of high pressure on the positive stroke, a bypass with check valve was installed around the pulse line flow restriction as shown in Fig. 13. Since this was done the pulse pump has functioned satisfactorily for a total on-stream time of about one month.

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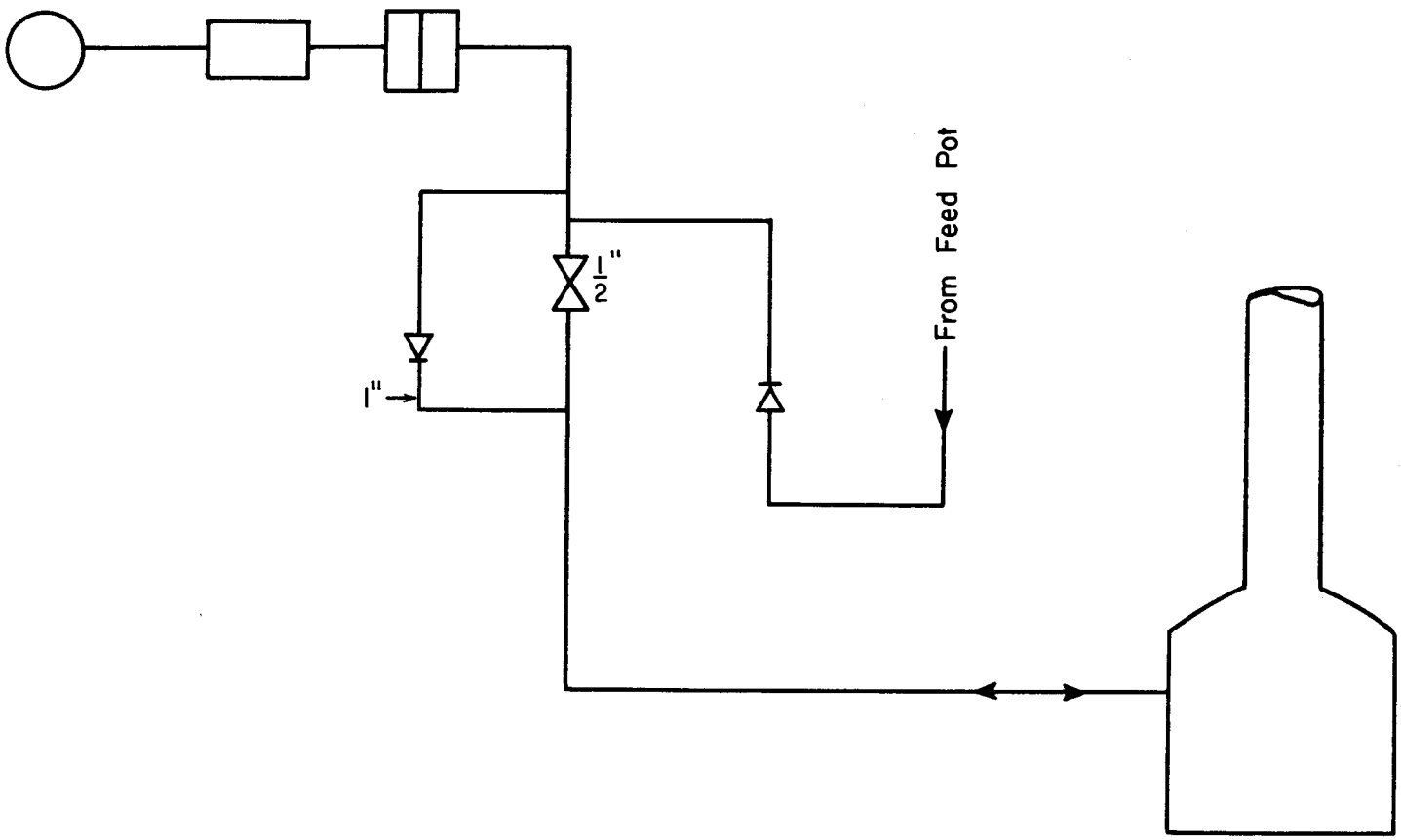

Fig. 13. 5-in-dia Straight Column Pulse Pump as Modified with By-pass.