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Pulsatile Fluidic Pump Demonstration and Predictive Model Application

J. G. Morgan
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Fuel Recycle Division

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ABSTRACT

Pulsatile fluidic pumps were developed as a remotely controlled method of transferring or mixing feed solutions. A test in the Integrated Equipment Test facility demonstrated the performance of a critically safe geometry pump suitable for use in a 0.1-ton/d heavy metal (HM) fuel reprocessing plant. A predictive model was developed to calculate output flows under a wide range of external system conditions. Predictive and experimental flow rates are compared for both submerged and unsubmerged fluidic pump cases.

1. INTRODUCTION

The purpose of this investigation is to demonstrate a prototypic fluidic pump application and to develop a model to predict performance under different system conditions. Fluidic pumps have been under development for some time and have found application in fuel reprocessing, especially in the United Kingdom.[1,2] Having no moving parts, these pumps are maintenance free and do not dilute or heat the pumped fluid as do steam jets. Air is not entrained in the fluid as in air lifts. Fluidic pumps have been suggested for use at several places in a small [0.1-ton/d heavy metal (HM)] fuel reprocessing plant. As shown in Table 1, a total of 12 pulsatile fluidic pumps are listed. They act as product tank mixers; transfer pumps in accountability tanks; and supply metering devices that, in turn, feed contactor banks. The lowest flow requirement for a pump is around 8 L/h and the highest is about 300 L/h.

Table 1. Fluidic pump in a typical small reprocessing plant flowsheet

Number of pumps	Head (ft)	System	Flow (L/h)
4	17	Plutonium nitrate storage	300
2	32	Plutonium concentration	150
1	32	H-cycle solvent extraction (HA)	12–20
1	16	Partitioning (1A)	34.3–50
1	10	Uranium purification (2D)	30–58
2	16	Plutonium purification	51.7–78
1	9	Back cycle	8–12

The largest pumping capacity is required for plutonium product storage. The product is pumped from the accountability tanks in the product concentration area to the first of four slab tanks. Each slab tank has its own fluidic pump in an adjacent stand pipe (Fig. 1). The contents of the first slab tank are pumped up to an overhead tank and returned. This mixing proceeds to the other two slab tanks by overflow as the first slab tank overfills.

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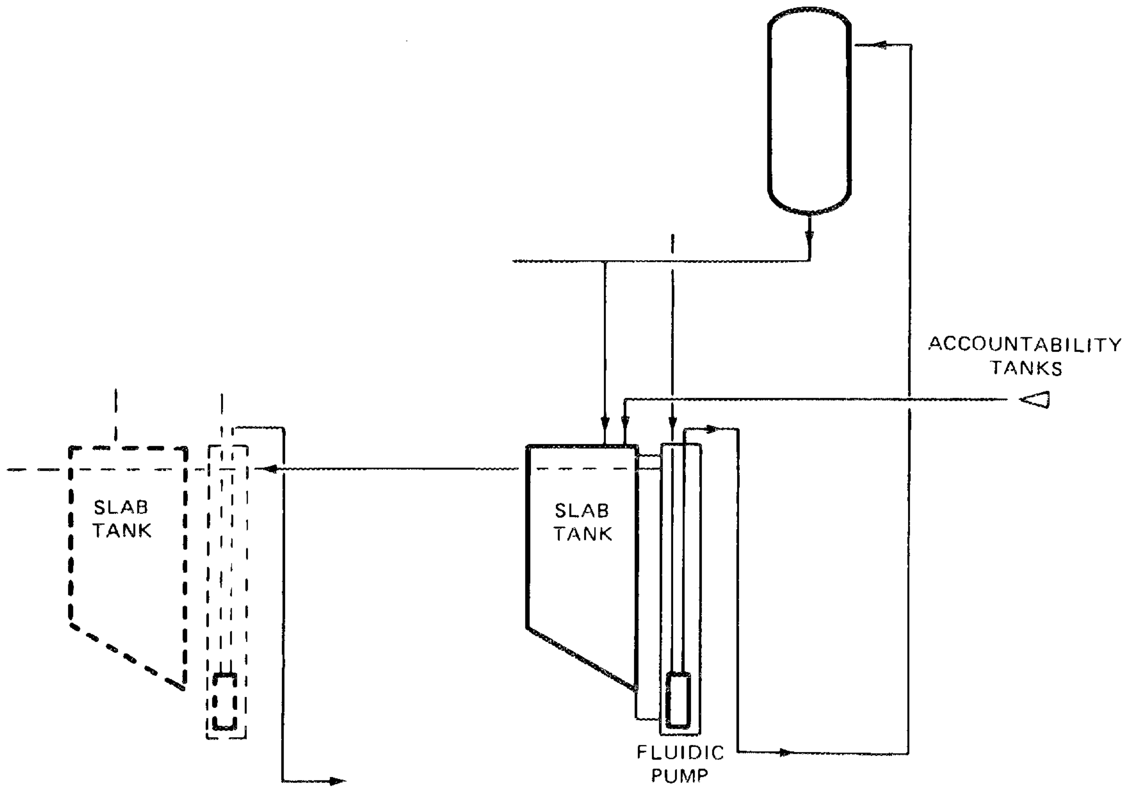

Fig. 1. Product tanks.

2. FLUIDIC PUMP DESCRIPTION

Two types of pulsatile fluidic pumps were tested. Both types, top loading and bottom loading, are to operate submerged in the liquid that is to be pumped with only a discharge line and air line leading to the outside. The top-loading pump is easier to fabricate; it is shown in Fig. 2. During the pump stroke, the pump chamber is full of liquid, and pressurized air is forced into the chamber through a three-way control valve. The liquid stream passes through a nozzle and is directed into a diffuser and up the discharge tube. The amount of liquid flowing into or out of the refill port depends on the resistance of the discharge system. At the end of the pump stroke, the level in the chamber falls to the bottom of the discharge line, and the air pressure is exhausted to atmospheric pressure. The refill cycle begins with liquid refilling the chamber through the refill port. A column of liquid in the discharge tube above the diffuser also falls back into the chamber; this is referred to as fall back. The pump tested had a diameter of 6 in. and was 15 in. tall. If the pump chamber were refilled from the bottom, the host tank could be nearly emptied. A bottom-loading pump is shown in Fig. 3. The pump and refill cycles are similar to the top-loading pump except that the pump chamber refills through the port, which is now at the bottom. A prototypic product tank pump was made of 4-in. schedule 40 pipe. This critically safe restriction increased the height of the pump chamber to 4 ft, a height that allows a longer, more easily controlled pump time. A reverse-flow diverter (RFD) is a generic name for a device that redirects flow in one of its inlets. The design of the nozzle-diffuser used in this investigation was based on earlier work by Smith and Counce, who characterized flat-walled, venturi-like RFDs[3] and later investigated axisymmetric RFDs.[4] They found that the characteristic curves for RFDs were similar over a range of nozzle-diffuser throat diam of 0.37–0.73 in. Nozzle-included angles ranged from 14 to 26°, and diffuser angles ranged from 4 to 8°. The gap between nozzle and diffuser was found to have little effect on the performance between 0.5 and 1.5 gap ratio. The gap ratio is the gap width divided by nozzle diameter. The nozzle-diffuser dimensions are given in Fig. 4 for the current investigation.

2.1 PUMP CALIBRATION

Calibration data were obtained by immersing the pump in a tank filled with water and measuring the delivered volume during a complete pumping cycle as a function of motivation pressure and system resistance. The system resistance was varied by incrementally closing a valve on the output line. The pump output pressure was measured with a pressure cell tapped into the discharge line above the pump. When delivered volume

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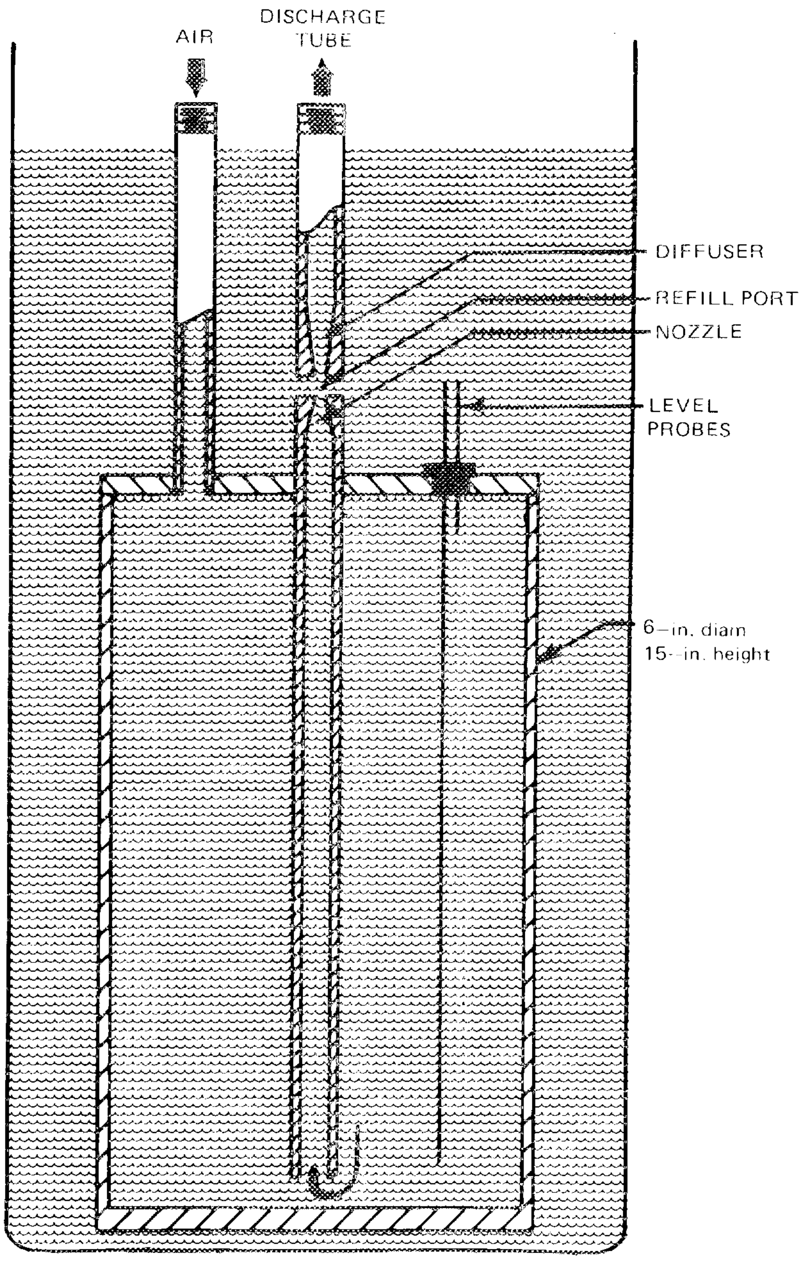

Fig. 2. Top-loading pump.

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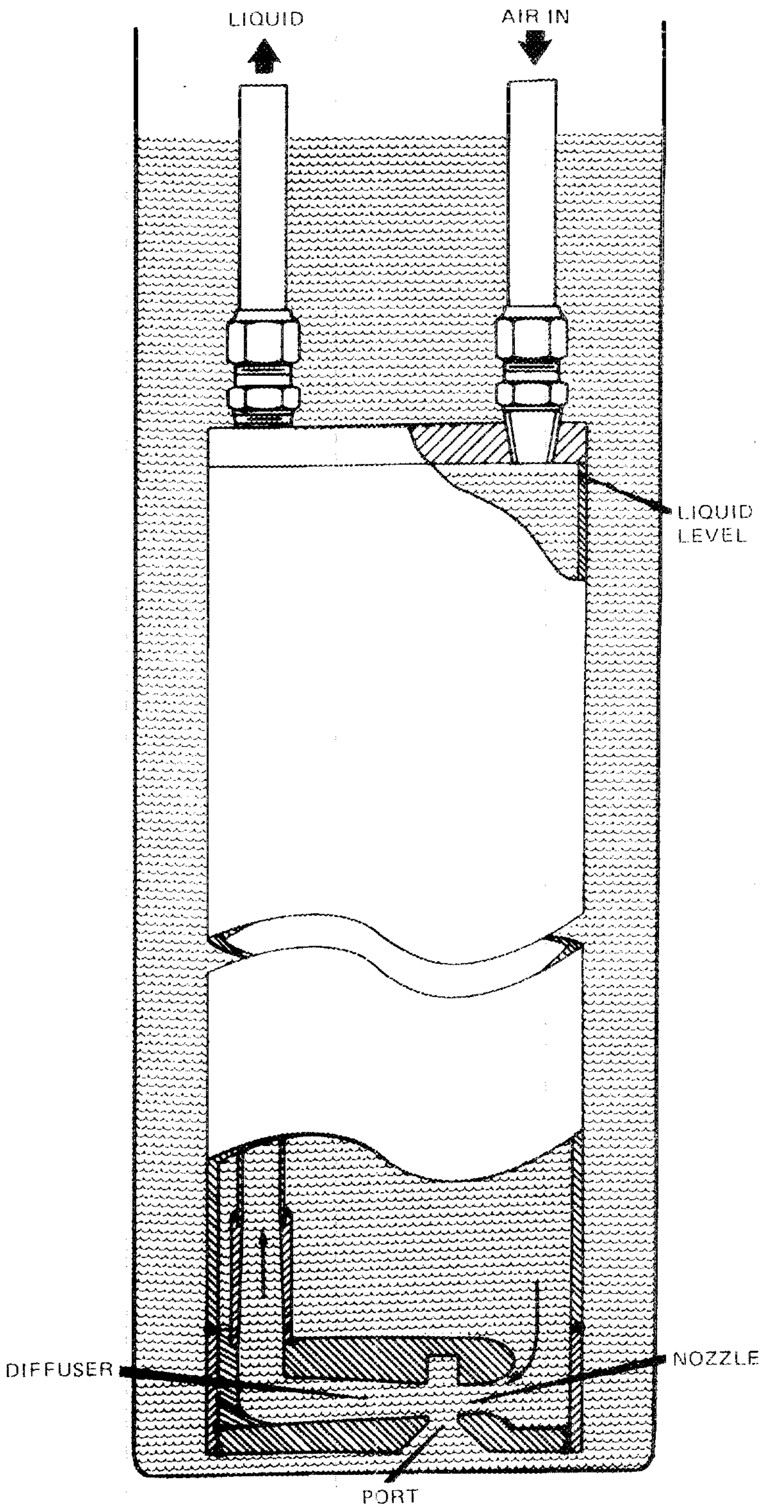

Fig. 3. Bottom-loading pump.

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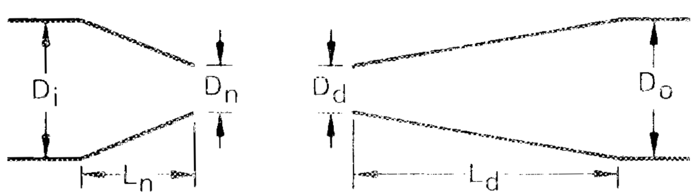

	Nozzle			Diffuser		
	D_n	D_i	D_n	D_d	D_o	L_d
Top loading	0.37	1.098	1.5	0.37	0.622	3.428
Bottom loading	0.35	*a*	*a*	0.35	0.562	1.60

Fig. 4. Nozzle-diffuser dimensions (in.) (gap ratio = 1). (a) Nozzle is trumpet shaped, decreasing from 0.71-in. diam to 0.35-in. diam over a 0.35-in. length.

(L/cycle) is plotted against pump output pressure, a series of curves result, each curve representing a different motivation pressure (Fig. 5). These data were obtained on a bottom-loading pump with an 8-ft refill head. Normalizing the data (see Fig. 6),[3] to arrive at a single calibration curve, the ordinate Q is changed to $\overline{Q} = Q_o/Q_i$. In this ratio Q_o is the volume of fluid delivered, and Q_i is the volume of fluid in the pumping chamber.

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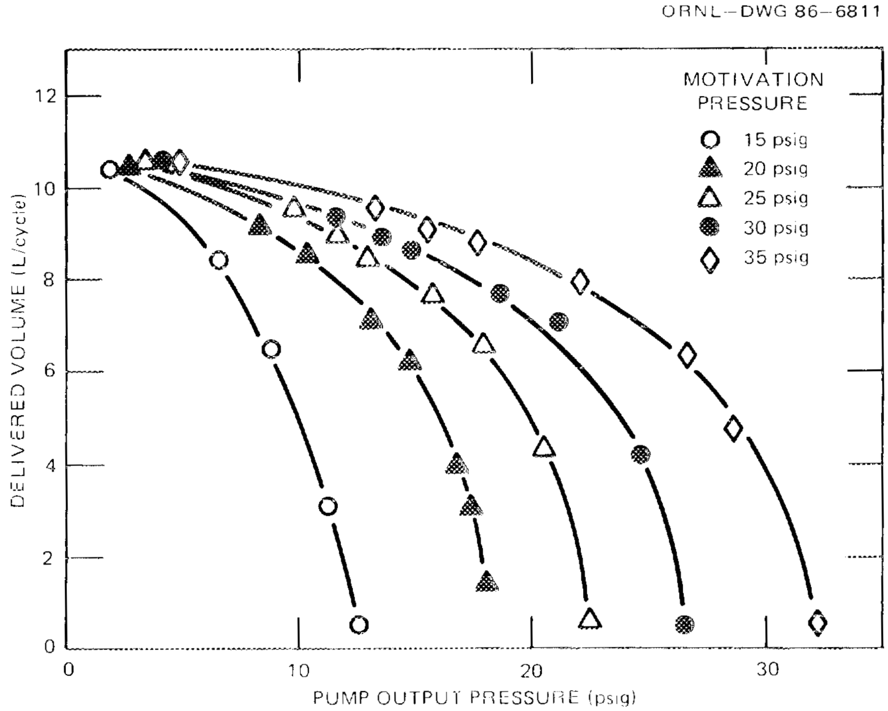

Fig. 5. Prototype pump output.

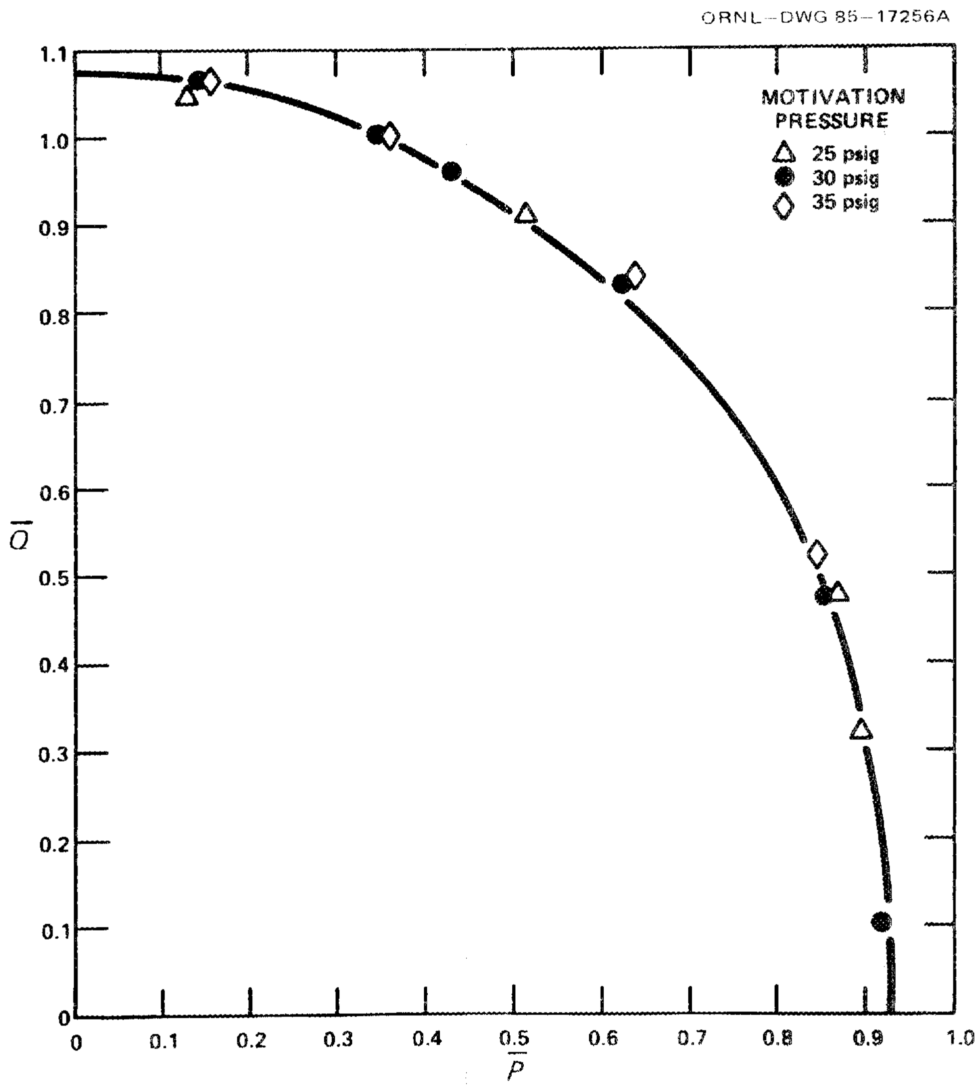

Fig. 6. Bottom-loading pump calibration curve.

The abscissa is changed to $\overline{P}$, which is

$$\frac{P_2 - P_3}{P_1 - P_3} ,$$

where

P_1 = motivation pressure,

P_2 = pump output pressure,

P_3 = pressure exerted by the refill head.

A similar calibration curve was obtained for the top loading pump as seen in Fig. 7. Calibration curves are used in the predictive model discussed in a later section.

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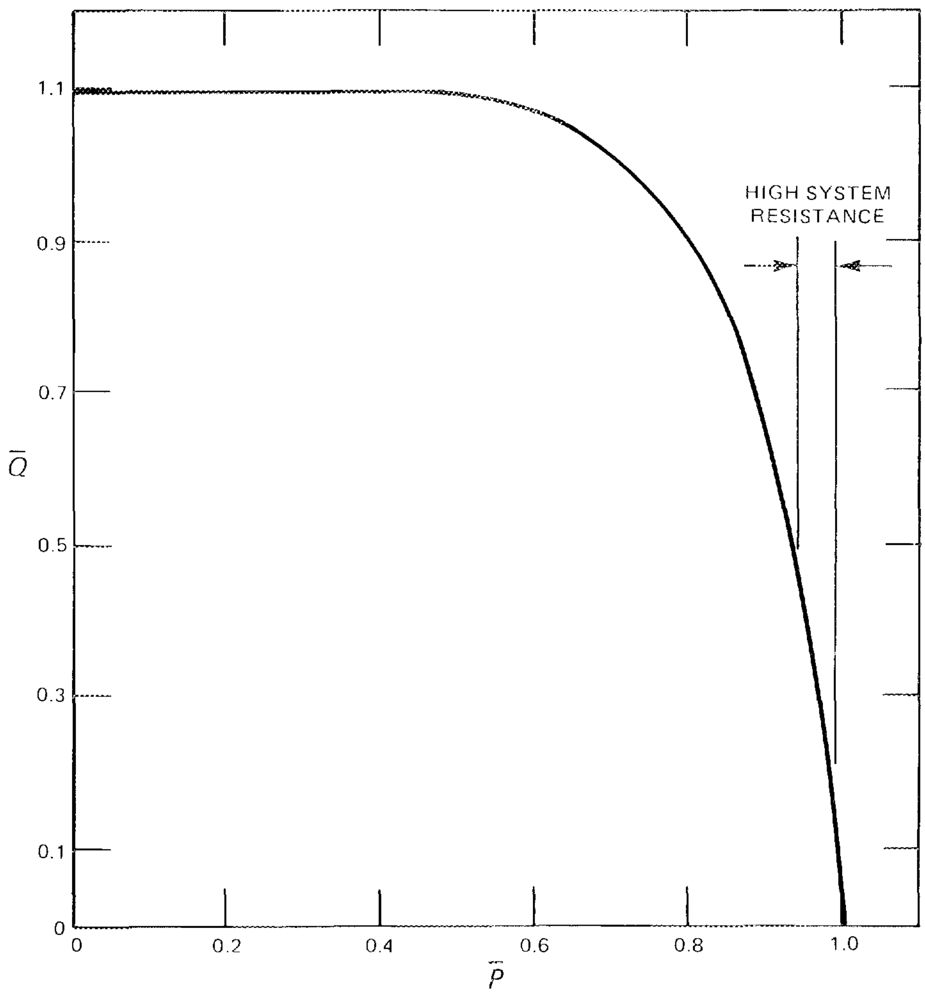

Fig. 7. Calibration curve, top-loading pump.

Smith and Counce have presented mathematical models to describe the output characteristics of an RFD. They conclude that the flattening of the calibration curve at low system resistance results from cavitation at the entrance of the diffuser.[4] Priestman and Tippets call this the cavitation limit which is analogous to the effect of cavitation in jet pumps.[5]

2.2 TOP-LOADING PUMP DEMONSTRATION

The first fluidic pump tested was a small top-loading pump with the RFD mounted in the discharge tube at the top of the pumping chamber. Conductivity probes near the top and bottom of the pump signaled when the refill and pump cycles had ended. The ending of the cycles could also be confirmed visually by observing, using plastic lines, the refill liquid advancing up the vented air line and, at the end of the pump stroke, air bubbles emerging from the nozzle-diffuser port. Because of the relatively small volume of the pump chamber (5.8 L), the pump stroke was shorter than the larger pump described later. The effect of motivation pressure on pump time is shown in Fig. 8. The instrument control setup allowed the pump to be operated automatically from the probes or by timers set for a certain pump and refill time.

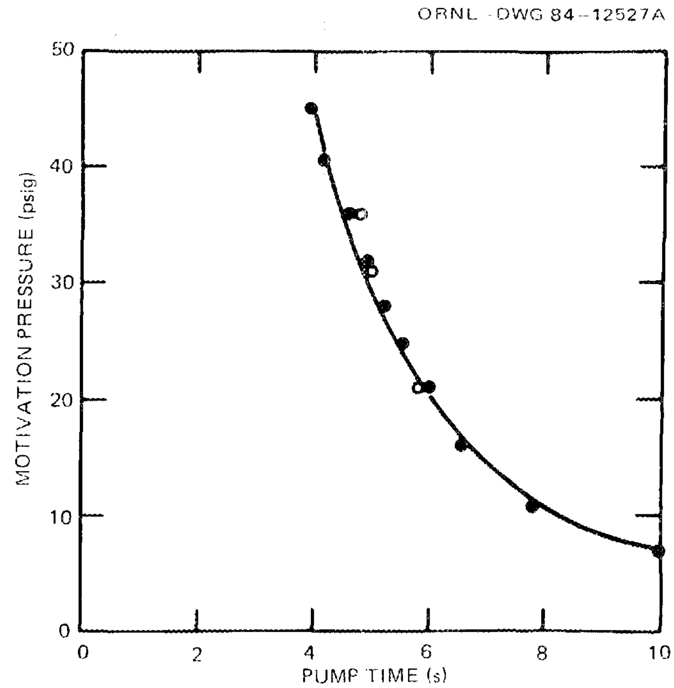

Fig. 8. Pump time for top-loading pump.

The placement of the RFD in the straight exit line eliminated sharp bends in the entry and exit of the nozzle-diffuser pair. It was tested while immersed in a 55-gal drum with about a 1-ft refill head. The pump was operated to deliver its output at different heights through 0.5-in.-O.D. tubing (see Fig. 9). The volume of liquid in the pump chamber was 5.8 L, and the fallback at the 30-ft height was 0.6 L. Results are shown in Fig. 10, where delivered volume, L/cycle, is plotted against motivation pressure. The curves represent the delivered volume of water at 10-, 20-, and 30-ft elevations. When a zinc bromide solution was used as the pumped fluid (sp gr = 2.12; viscosity = 8.2 centipoise), the pumping rate decreased, as shown in the plot for 10- and 30-ft elevations. Even at the 30-ft elevation, the main resistance to flow is the friction in the small 0.375-in.-I.D. tubing. Because most of the experiments were on the steep part of the calibration curve, predictions determined by using the model were uncertain.

A 5% uncertainty in the calculated resistance of the system can result in an output flow change of 40%. The 10-ft elevation run using water revealed a lower system resistance

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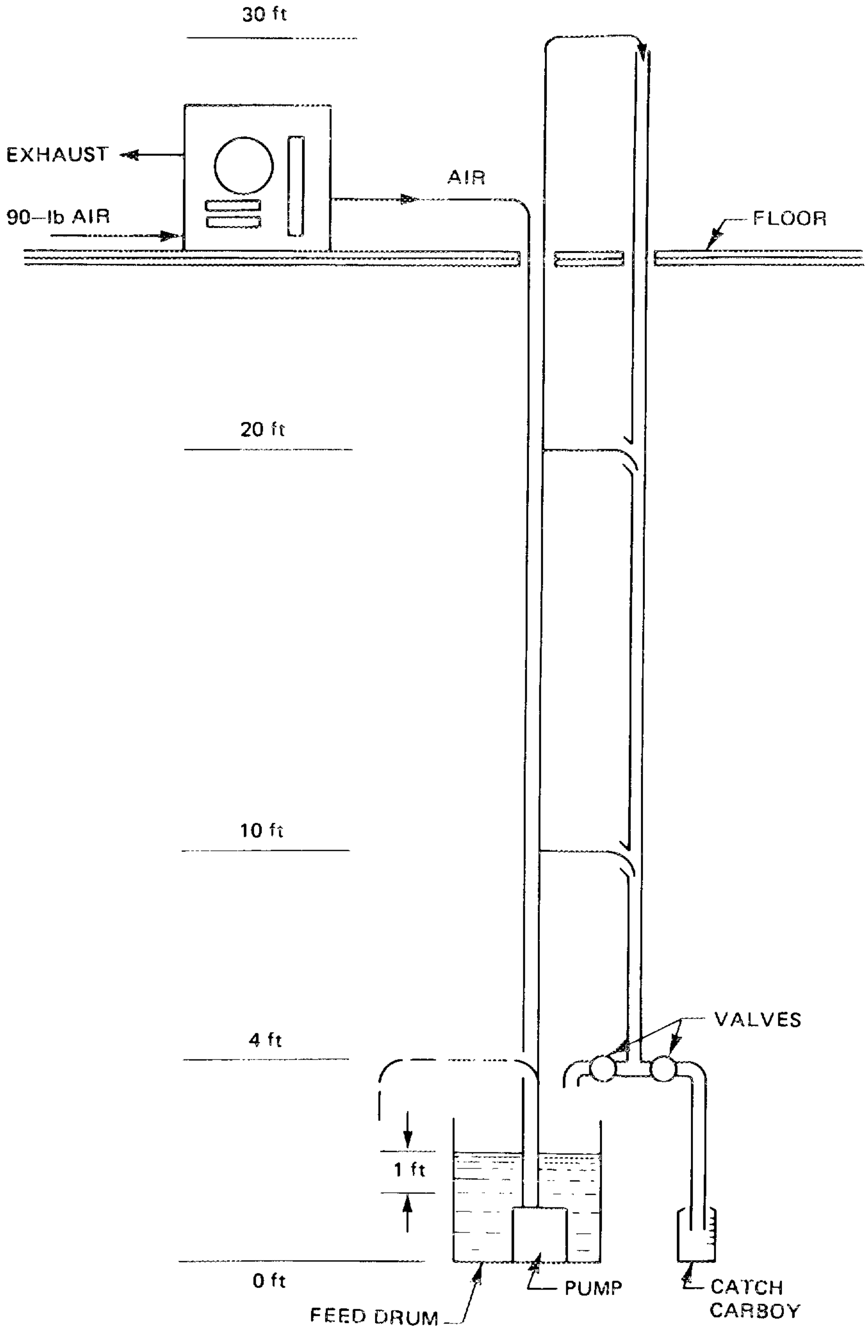

Fig. 9. Top-loading pump test.

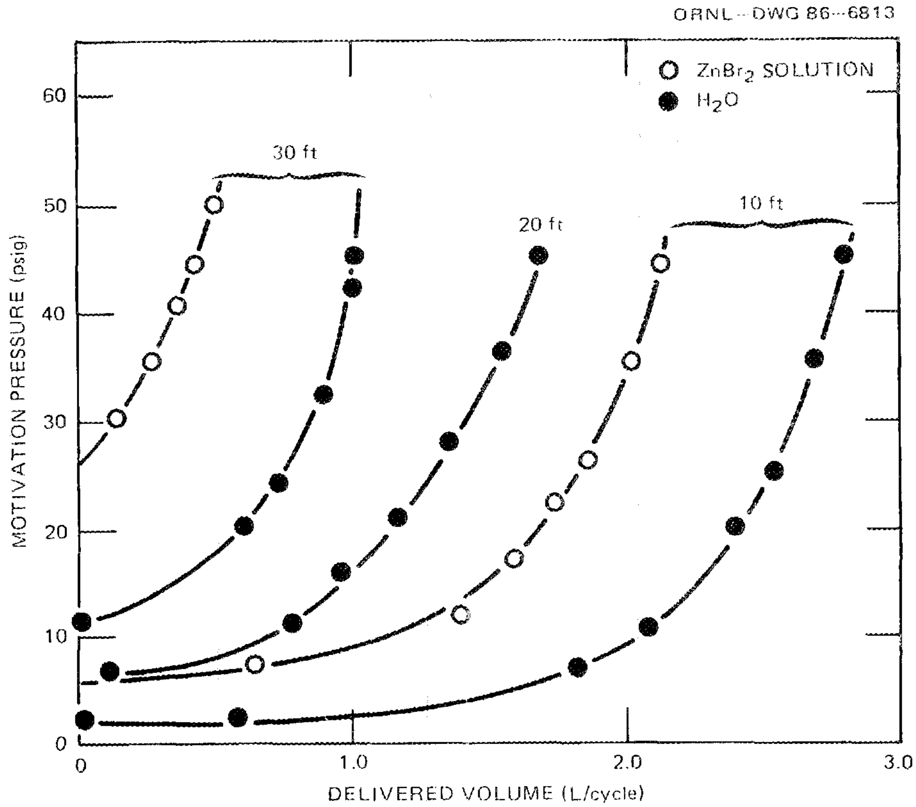

Fig. 10. Top-loading pump, using $ZnBr_2$ in solution.

and was more predictable. When one uses zinc bromide ($ZnBr_2$) in solution, the resistance from increased density has increased the $\bar{P}$ term value to 0.985, again on the steep part of the calibration curve.

2.3 BOTTOM-LOADING PUMP DEMONSTRATION

The prototypic bottom-loading pump was tested in the Integrated Equipment Test (IET) facility by simulating a product pumping situation. As shown in Fig. 11 (fluidic pump test), the 4-ft fluidic pump rested in the bottom of the 3000-L host tank 11F03. Uranyl nitrate solution was used as the pumped medium with 1.47 sp gr at the operating temperature of 40°C (0.3-*M* HNO_3). The discharge line reached an elevation of 16 ft and ran nearly horizontally another 9 ft before it turned down and emptied into a receiving tank stand pipe, 11F01.

The stand pipe was installed to prevent siphoning when the host tank was full. Except for manually setting the motivation pressure, the entire operation of the experiment was conducted from the IET control room. Starting with the host tank filled to the 7-ft level, the pumping cycles were started using previously determined refill times, which were changed with each 1-ft refill height decrease. The pump times for each motivation pressure

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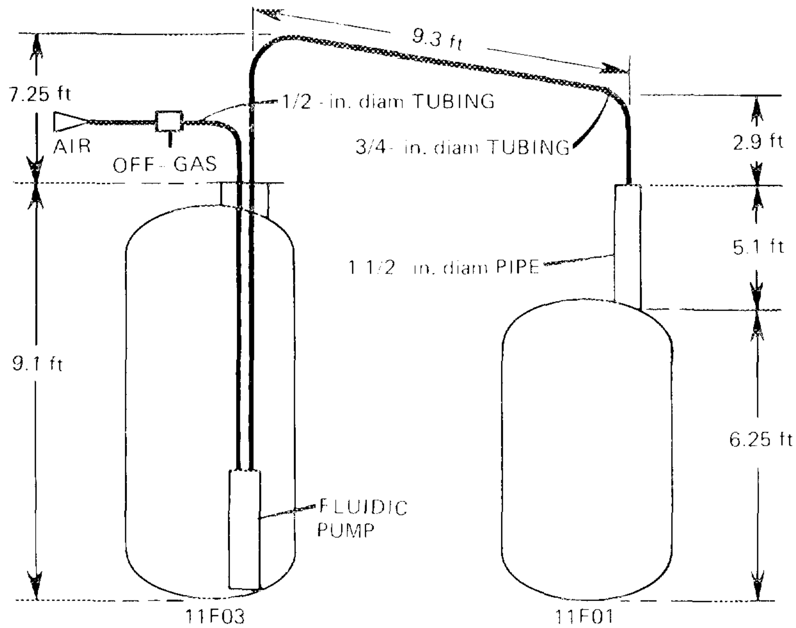

Fig. 11. Fluidic pump test.

had been previously determined, but as an added control, a microphone, attached to the host tank, signaled when air was exhausted through the port. The pump time was then decreased 1 s to operate without blowout. Data, displayed on the console screen and retrieved as a printout, were taken each minute. These data included cycle number, motivation pressure, pump status, level in host tank, level in receiving tank, temperature of host tank liquid, specific gravity of host-tank liquid, and pump and refill cycle times. The run continued until the level of the host tank reached the top of the pump. The fluid in the receiving tank was then transferred to another area, and the test continued until the pumping essentially stopped. These results are compared to Sect. 3.3 to calculated results using the predictive model.

2.4 FLUIDIC DIODE TEST

Fluidic diodes have been used in fluidic pumps.[6] These devices have a low resistance to flow in one direction and a high resistance to flow in the other direction. A very simple baffle arrangement[7] was installed at the refill port in the bottom-loading 4-ft pump. The baffles were slanted, as shown in Fig. 12, to allow easy refill, but they offered resistance to flow out of the bottom of the pump during the pumping cycle. The plot of delivered volume vs pump output pressure (Fig. 13) shows the increase in pump performance. At a motivation pressure of 35 psig, the baffled pump delivered twice the volume of water at the

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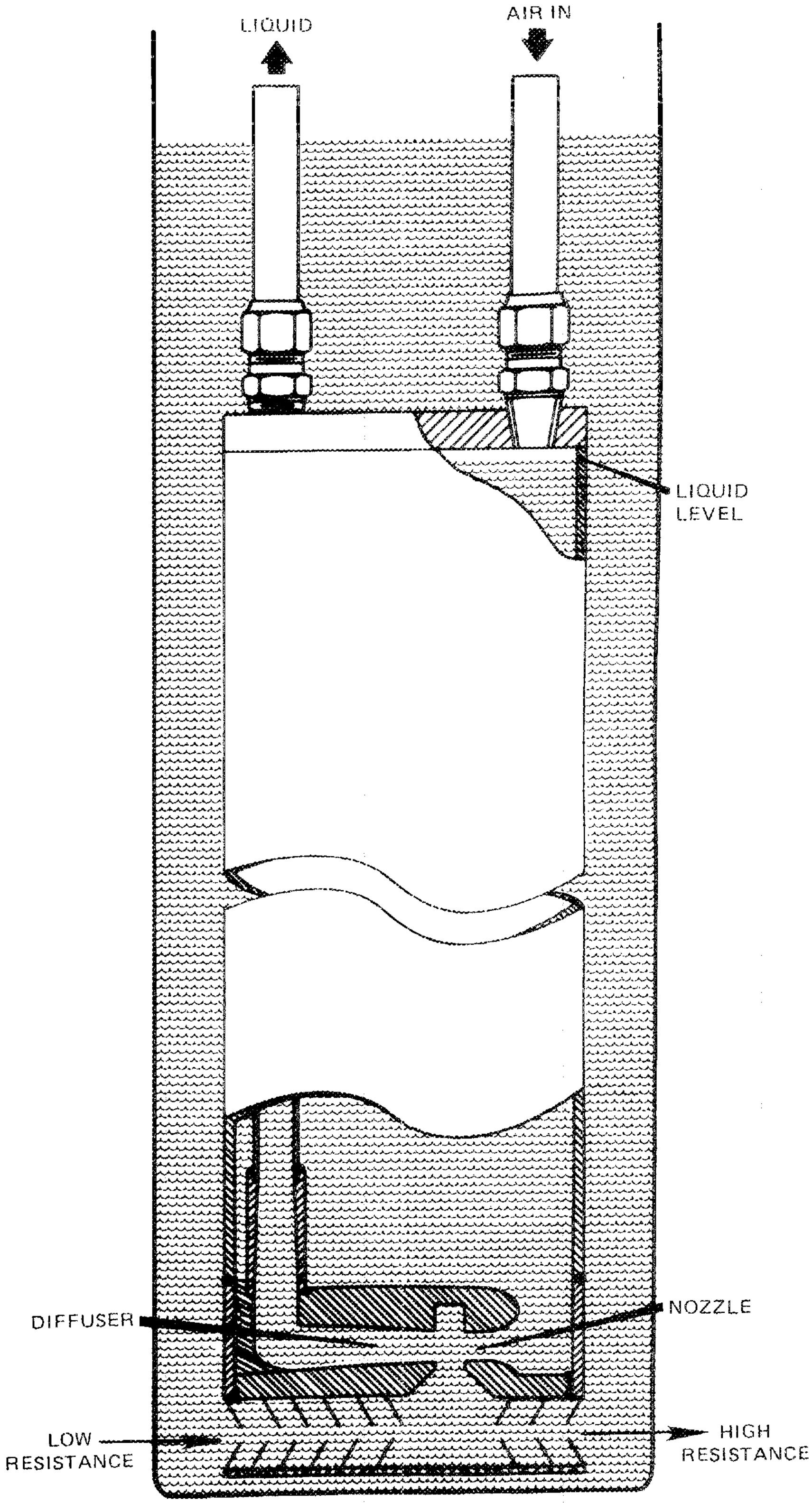

Fig. 12. Baffle geometry.

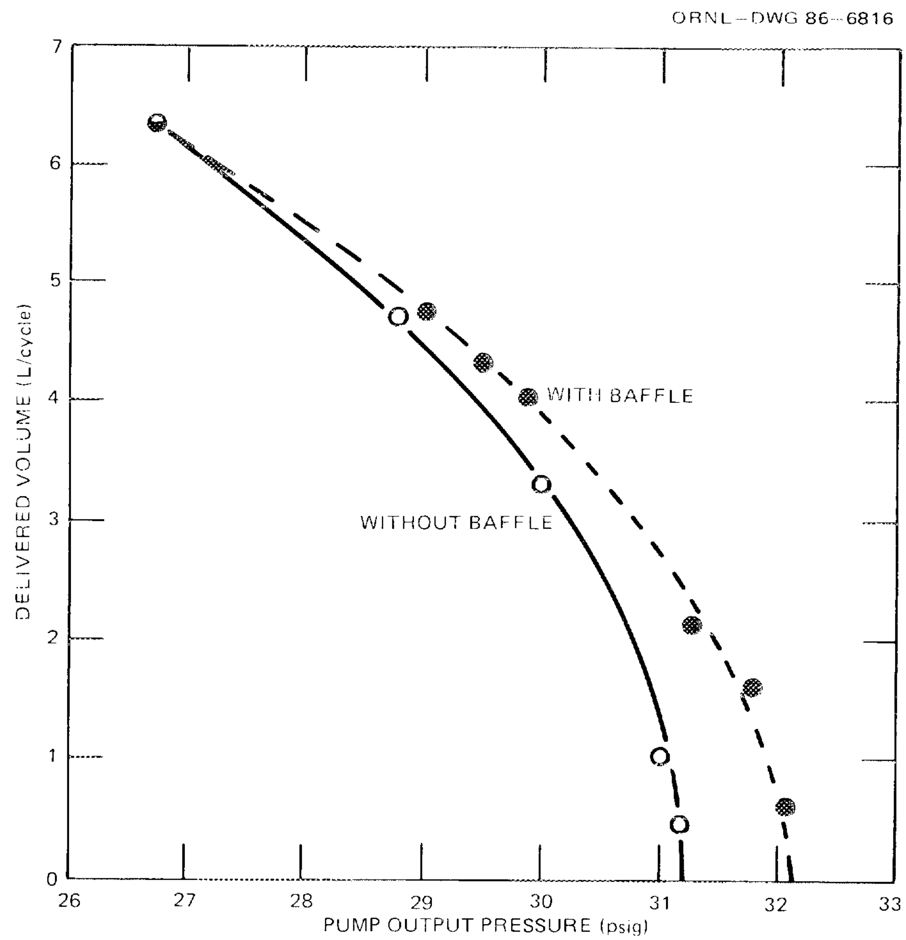

Fig. 13. Effect of inlet baffle on pump performance with water at a motivation pressure of 35 psig.

same pump output pressure of 31 psig. The advantage of the baffle lessened as the system resistance lessened. Also, the effect of the baffle was less at lower motivation pressures. The refill time through the baffle increased by about 10 s. A vortex diode[8] has been developed that will give better performance, but it would be more difficult to install because an existing pump would have to be retrofitted.

3. PREDICTIVE MODEL

3.1 GENERAL DESCRIPTION

The performance of a fluidic pump is highly dependent on the flow configuration of the output system. If one has available a normalized calibration curve and a description of the output piping arrangement (lengths and diameters of pipes, heads, fittings), it is possible to estimate the performance of a particular pump. It may be recalled that the normalized calibration curve consists of a plot of the fraction of the fluid in the chamber which is delivered to the output system, $\overline{Q} = Q_o/Q_i$, vs a dimensionless pressure ratio:

$$\overline{P} = \frac{P_2 - P_3}{P_1 - P_3} .$$

This curve is unique to a given pump geometry over a wide range of fluid properties.[5]

The quantities Q_i, P_1, and P_3 are fixed by the volume of the pump chamber, the driving pressure, and the head above the RFD, respectively. The remaining two variables, Q_o and P_2, are related both by the calibration curve and the pressure drop-flow rate relation in the piping system. This is because P_2 is the pressure drop through the piping system and Q_o divided by the fixed pumping time is the volumetric flow rate through the system. The volumetric flow rate is related to the pressure drop by the Bernoulli equation using tabulated values for friction factors and resistances caused by fittings, contractions, and bends.

The solution to the flow relations requires an iterative procedure in which a "split" of the fluid stream, $\overline{Q}$, is presumed.* From this value, a flow rate through the piping system is calculated. Next, Reynolds number and friction factors for the piping system and associated fittings are calculated, and finally the pressure driving force necessary to sustain this flow rate is computed. The pressure, P_2, is used to calculate $\overline{P}$, which is then checked using the calibration curve to compare with the assumed Q_o/Q_i. This procedure is repeated until satisfactory agreement between assumed and resultant "splits" is obtained.

A computer program was written to accomplish the calculations described above. The program, written in BASIC, is user interactive and allows the user to provide assumed "splits" and calculates "splits" based on the calibration curve for comparison. The calibration curves are fitted to polynominal approximations for calculation purposes. A listing of the program is given in Appendix A and an example of its execution is presented in Appendix B.

---

*$\overline{Q}$ is called the "split" because the pumped stream, Q_i, is split into two parts: Q_o, which reaches the delivery piping system, and $(Q_i - Q_o)$ which is lost through the refill port.

Once agreement between assumed and resulting splits is achieved, the program calculates the flow per cycle. In addition, because the refill time and pump time are known, the program calculates the expected flow rate in liters per hour. This value is corrected for "fallback" (the amount of fluid which is in the piping system but falls back into the pump chamber at the end of the pump cycle). The resulting value gives an estimate of expected pump performance in the particular flow configuration.

3.2 PUMP CYCLE TIMES

The total pump cycle time is the refill time plus pump time as illustrated in Fig. 14. The refill time for the prototypic pump is four to seven times longer than the pump time,

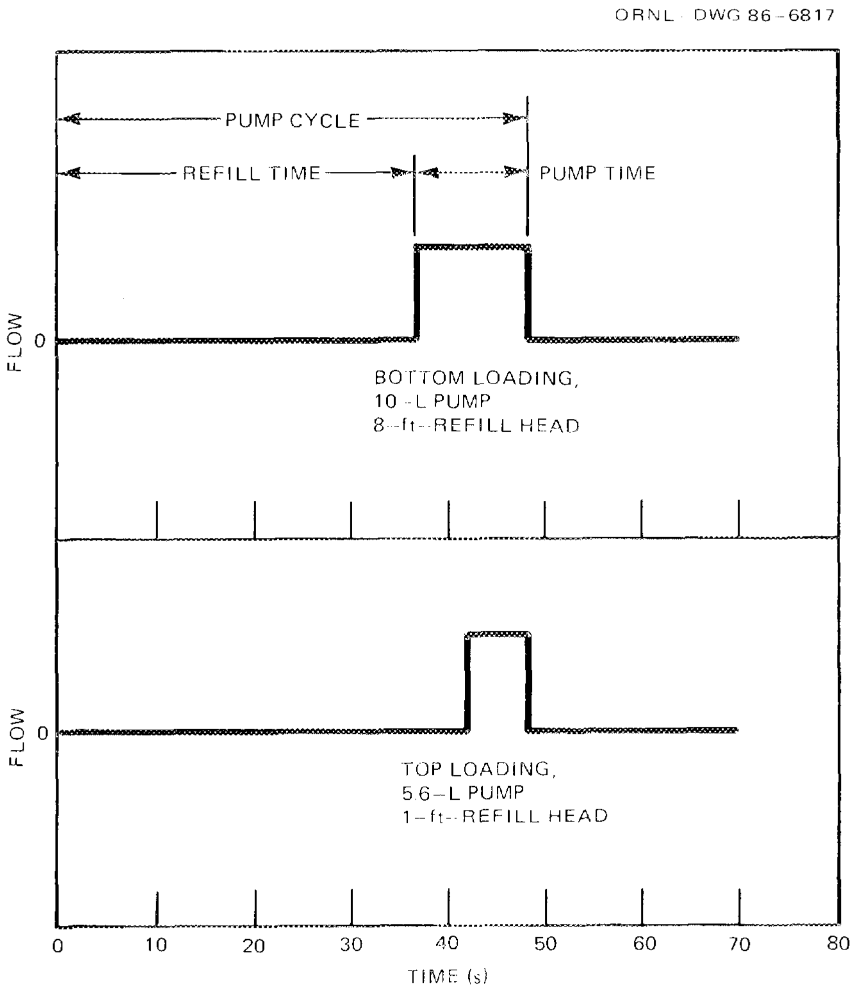

Fig. 14. Typical pumping cycles (35 psig motivation pressure).

depending on the refill head. A refill time can be calculated using an orifice coefficient of 0.73 and taking into account the refill head change as the chamber fills:

$$t_f = 2[(H_o)^{1/2} - (H_o - H_f)^{1/2}]/K,$$

where

t_f = refill time, s,

H_o = refill head, ft,

H_f = final height in pump chamber, ft,

$$K = \frac{4C_o S_o \sqrt{2g}}{\pi D^2},$$

where

S_o = orifice area, ft^2,

D = diameter of the pump chamber, ft,

C_o = orifice coefficient (0.73),

g = acceleration of gravity, 32.17 ft/s^2.

Values of refill time were also determined experimentally. They are shown in Fig. 15.

Pump time was determined experimentally as a function of motivation pressure and, in the prototypic pump case, the level in the pump chamber. A plot of pump level vs pump time results in a series of straight lines with different slopes for different motivation pressures as shown in Fig. 16 (prototypic pump times). These data can be reduced to an equation accounting for the change of slope for different motivation pressure. The pump time can be expressed as:

$$t_1 = (H_1)[0.001571(P_1)^2 - 0.1453(P_1) + 5.751],$$

where

t_1 = pump time, s ,

H_1 = pump chamber level, ft ,

P_1 = motivation pressure, psig.

The pump time may also be calculated if no data are available by dividing the liquid volume in the pump chamber by the volumetric flow rate through the nozzle. $t_1 = V_1/Q_1$,

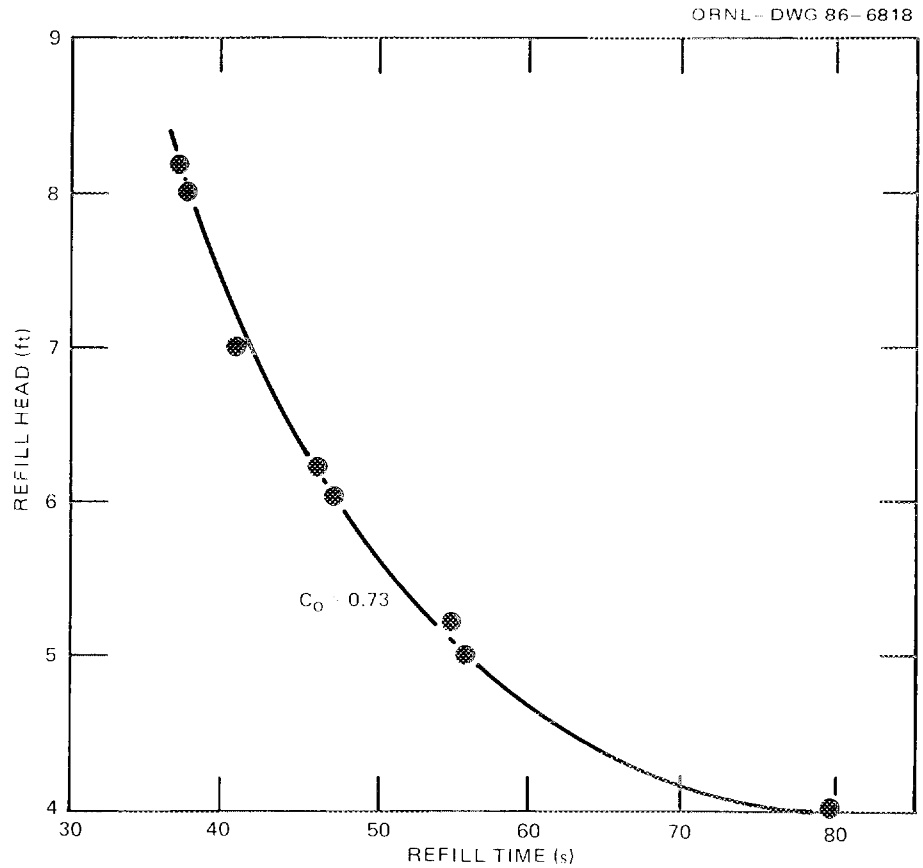

Fig. 15. Prototypic pump refill times.

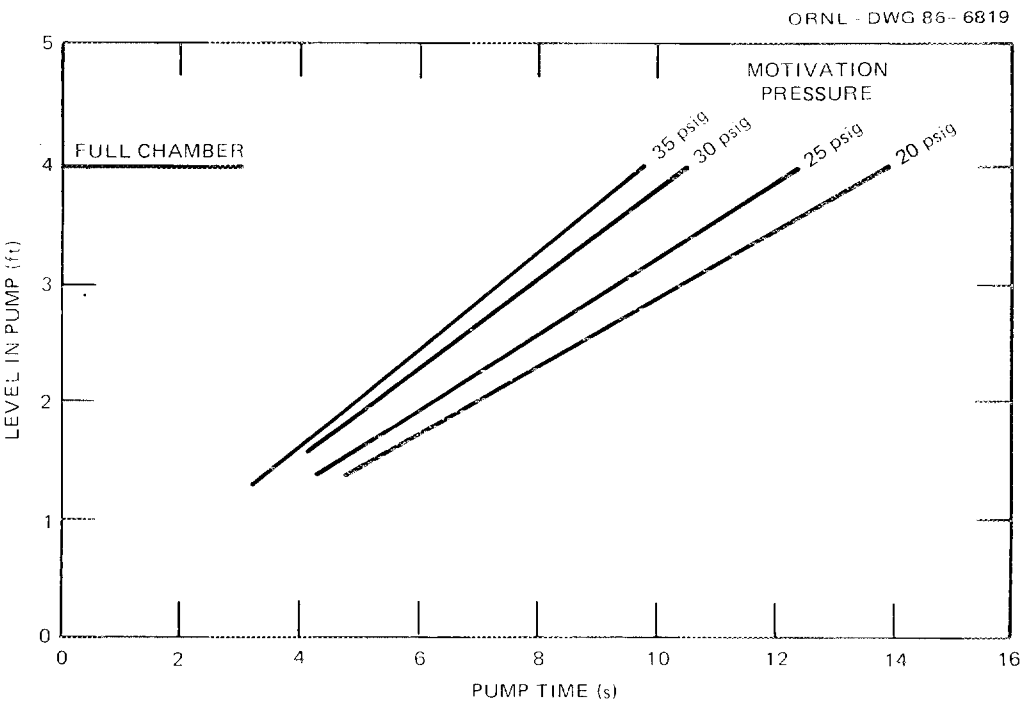

Fig. 16. Prototypic pump times.

where

$$V1 = \frac{(\pi)(D_1^2)(H_1)}{(4)(144)} ,$$

where

V_1 = liquid volume in pump chamber, ft^3 ,

D_1 = diameter of pump chamber, in.,

H_1 = liquid level in pump chamber, ft ,

$$Q_1 = 12(C_2)(A_1)\left[\frac{2(P_1 - P_3)g_c}{\rho}\right]^{0.5} ,$$

where

Q_1 = flow through nozzle, ft^3/s,

C_2 = nozzle discharge coefficient (assumed unity),

A_1 = area of nozzle, ft^2,

P_1 = motivation pressure, psi,

P_3 = refill head, psi,

g_c = 32.17, conversion factor, $ft\text{-}lb_m/lb_f\text{-}s^2$,

ρ = fluid density, lb/ft^3.

Some of the terms used in the text, as well as the predictive model, are illustrated in Fig. 17 (definition of terms). Fallback after each pump stroke is calculated in the model. It was experimentally determined that in the IET facility experiment, the entire volume of the delivery line (except for ~200 cm^3) fell back and thus must be subtracted from the predicted delivered volume/cycle. This volume, ~1.7 L, although small compared to a full pump chamber, becomes important and is the limiting value when pumping a nearly empty host tank.

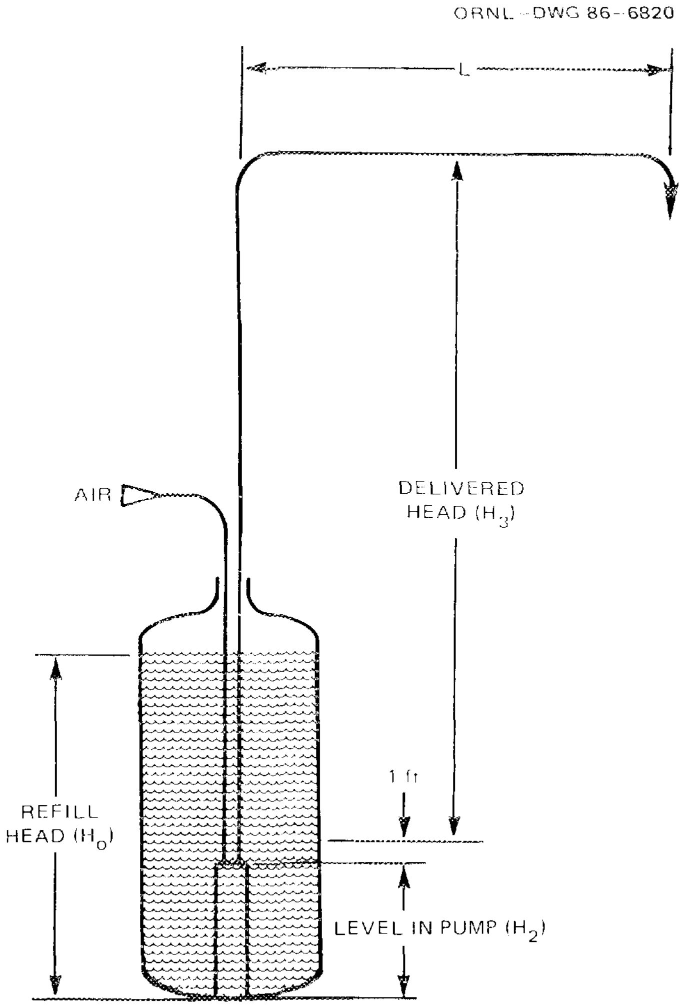

Fig. 17. Definition of terms.

3.3 PREDICTIVE MODEL APPLICATION

As stated previously, results of the top-loading pump test with water at 10-ft delivery elevation were compared with values generated using the predictive model. This comparison is shown in Table 2. Good agreement was obtained over the pressure range of 11 to 43 psig.

During the calibration test of the bottom loading prototype, a run was made with an 8-ft refill head and a 6-ft delivered head. This resulted in the largest flow obtained in any of the tests. The results are shown in Fig. 18 together with the predicted values using the model. A flow rate of over 750 L/h was reached under these conditions.

In comparing the results of the IET tests with the predictive model calculation, actual pump and refill times from the data printouts were used. The experimental and predicted flow values are shown in Table 3. The motivation pressures are nominal set pressures. The

Table 2. Comparison of experimental and predicted values obtained using a top-loading pump

Motivation pressure (psig)	Output flow of water: Experimental	Output flow of water: Predicted (L/cycle)
11	2.06	1.99
16	2.23	2.34
21	2.36	2.50
24.5	2.45	2.56
28	2.55	2.58
32	2.56	2.59
36	2.62	2.59
40.7	2.58	2.59
43	2.60	2.60

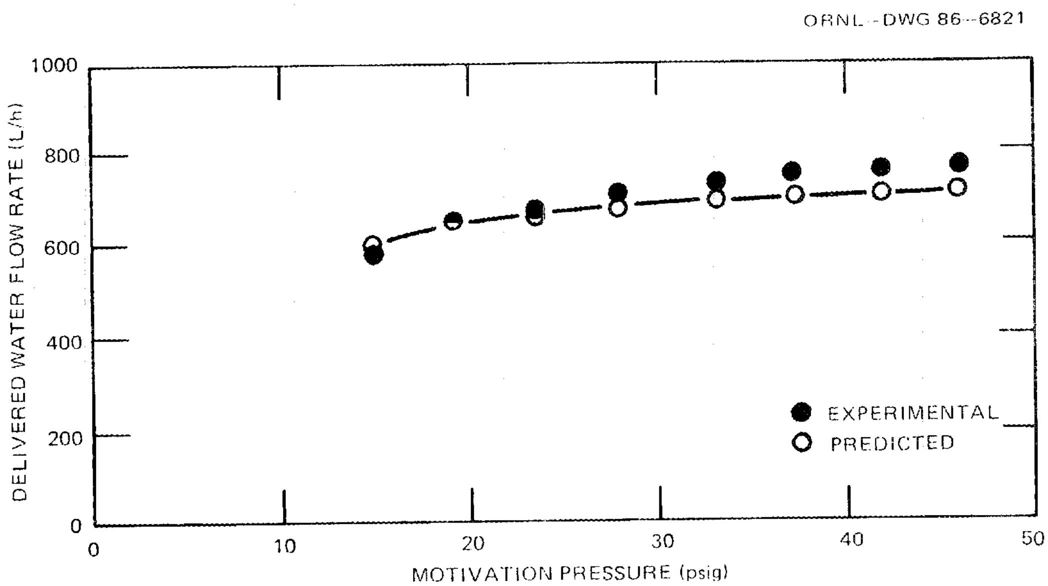

Fig. 18. Prototypic pump flow rates.

actual pressure during pumping, as measured by the pressure cell, was about 5 psi lower. The host tank level was pumped down in about 1-ft increments, at which time the refill time was increased. This resulted in a lower value of average flow (L/h) as the runs progressed, although the amount of liquid delivered each cycle remained nearly constant. The pump times for each of the three runs at a given motivation pressure had the same value except for the third run at 40 psig, which was 9 s instead of 10 s. This resulted in a low flow value.

Table 3. Summary of IET submerged tests

Motivation pressure (psig)	Average flow (L/h) Experimental	Average flow (L/h) Predicted	Average host-tank level (ft)
25	333	365	6.4
	287	311	5.6
	241	255	4.8
30	370	382	6.4
	304	324	5.1
	256	264	4.4
35	382	406	6.7
	326	344	5.8
	267	278	4.4
40	388	413	6.7
	343	349	5.6
	256	251	4.5

When the level in the host tank dropped below 4 ft, the pumping chamber became unsubmerged. With the level in the pump chamber also below 4 ft at the beginning of the pump cycle, the pump times as well as the refill times decreased. The results of these unsubmerged tests are shown in Table 4 together with the predicted values. As the host-tank level and the level in the pumping chamber approach 1 ft, the predicted values deviate from the experimental values. Around 1 ft and below, the model predicts no flow. At a motivation pressure of 30 psi and a pump chamber height of 0.9 ft, the output flow of 13 L/h corresponds to only 150 mL/cycle. Fallback of 1.7 L and a split loss of 20% during the pump cycle result in essentially no delivered volume.

Table 4. Summary of IET unsubmerged tests

Motivation pressure (psig)	Average flow (L/h)		Average host-tank level (ft)
	Experimental	Predicted	
25	198	190	3.6
	167	167	3.1
	144	131	2.5
	116	99	1.9
	55	33	1.5
	7		1.3
30	144	133	3.6
	154	147	2.7
	87	58	1.6
	51	16	1.2
	13		0.9
35	184	186	3.0
	146	141	2.3
	140	105	1.9
	66	34	1.4
	17		1.1
40	220	214	3.3
	184	165	2.6
	83	49	1.6
	31		0.9

4. CONCLUSIONS AND RECOMMENDATIONS

The prototypic slab tank pump has been demonstrated to deliver the required average output flow for product mixing. It is also suitable for use in the other portions of the flow sheet requiring feed delivered to stations metering flow to contactor banks. We were able to confirm the validity of the predictive model and predict flows within 10% of actual experimentally determined values. This type pump should be demonstrated using liquid in a tank that contains a large amount of sediment as in a waste tank. With a 60 to 80% split, the pump should keep the sediment agitated to facilitate refill. In addition, a more efficient diode should be developed to extend the pump capacity under high system resistance.

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APPENDIX A

The basic program, FPUMP.ONE, is used to predict pump performance under various external system conditions using the calibration curve for this specific bottom loading pump. Changing the internal geometry, such as discharge tube diameter, drastically changes pump performance. A new calibration curve should be determined if design changes are made. The program can then be used with the new data.

```
C:\morgan>TYPE FPUMP.ONE
10 PRINT "  THE PUMP IS A BOTTOM LOADER OF 4 INCH DIAM"
20 REM PUMP CALCULATIONS
30 D1=4
40 PRINT "I NEED LEVEL IN PUMP (H1) IN FEET"
50 INPUT H1
60 PRINT "I NEED REFILL HEAD (H2) IN FEET"
70 INPUT H2
80 PRINT " I NEED DELIVERED HEAD (H3) IN FEET"
90 INPUT H3
100 PRINT "I NEED DELIVERY LINE LENGTH(L1) IN FEET"
110 INPUT  L1
120 PRINT " I NEED DELIVERY LINE INSIDE DIAMETER  (D2) IN INCHES"
130 INPUT D2
140 PRINT "I NEED MOTIVATION PRESSURE (P1) IN PSIG"
150 INPUT P1
160 PRINT " I NEED NOZZLE DIAMETER (D3) IN INCHES"
170 INPUT D3
180 PRINT " I NEED FITTING LOSS COEFFICIENT (K1)"
190 INPUT K1
200 PRINT " I NEED  FLUID DENSITY (R1) IN LBS/FT3"
210 INPUT R1
220 PRINT " I NEED FLUID VISCOSITY (M1) IN CENTIPOISE"
230 INPUT M1
240 P = 3.1416
250 P2 = R1*H2/144
260 C2 = 1
270 A1 = P/4*D3^2/144
280 G1 = 32.17
290 A2 = P/4*D2^2/144
300 M1 = M1*6.72/10000
310 V1 = P*D1^2/4/144*H1
320 IF D3 = .35 THEN 370
330 Q1 = C2*A1*SQR((2*(P1-P2)/R1*G1))*12
340 T1 = V1/Q1
350 GOTO 390
360 REM T1 IS PUMP TIME, DETERMINED FROM CURVES
370 T1 = (.001571*P1^2-.1453*P1+5.751)*H1
380 Q1 = V1/T1
390 PRINT "INITIAL SPLIT GUESS PLEASE"
400 INPUT Q2
410 Q3 = Q2*Q1
420 V2 = Q3/A2
430 R2 = D2/12*V2*R1/M1
440 F1 = .0791/(R2^.25)
450 IF R2<2100 THEN F1=16/R2
460 Z1 = R1*4*F1*L1/D2*12*V2^2/(2*G1)/144
470 Z2 = R1*H3/144
480 Z3 = K1*V2^2/(2*G1)/144*R1
490 Z5 = Z1+Z2+Z3
500 P3 = Z5
510 P4 = (P3-P2)/(P1-P2)
520 REM Q4 IS THE Q-TERM IN THE TWO CURVES
530 IF P4<.725 THEN 560
540 Q4 = -14.38*P4^2+20.5*P4-6.61
550 GOTO 570
560 Q4 = -.7776*P4^2+9.794999E-02*P4+1.057
570 PRINT "HERE IS QS" ,Q2,Q4
580 PRINT "MORE?"
590 INPUT M2
```

```
600 IF M2 = 0 THEN 630
610 Q2 = M2
620 GOTO 410
630 PRINT "OUTPUT"
640 PRINT "RE =" ,R2
650 PRINT " DPTOT IS" ,Z5
660 PRINT " SPLIT IS"Q2
670 PRINT "PTERM IS" P4
680 PRINT "TPUMP = " T1
690 Z6 = V1*Q2*28.316
700 PRINT " LITERS/CYCLE = ",Z6
710 PRINT
720 PRINT
730 PRINT
740 PRINT "CALCULATED  RESULTS"
750 PRINT
760 PRINT "TEST CONDITIONS"
770 PRINT
780 PRINT
790 PRINT  "TYPE = BOTTOM-LOADED"
800 PRINT
810 PRINT " PUMP DIAM = ";D1; "  PUMP HT = ";H1; " RESV HT = ";H2
820 PRINT  "  DELIV LINE LENGTH = ";L1;" DELIV LINE DIAM = ";D2
830 PRINT " DRIVING PRESS = ";P1; "  NOZZLE DIAM = ";D3
840 PRINT " FITTING LOSS COEFF = ";K1
850 PRINT  "DENSITY = ";R1;
860 PRINT  "VISCOSITY = ";M1/.000672; "THE HEAD IS";H3;"FEET"
870 PRINT
880 PRINT
890 PRINT " NOW DO YOU WANT FILL TIMES AND TOTAL "
900 PRINT " CYCLE PERFORMANCE.....NO=0, YES=1"
910 PRINT
920 INPUT  B7
930 IF B7= 0  THEN 1360
940 IF D3><.35 OR D1><4 THEN 1020
950 REM REFILL TIME - CURVES, TIME VS. REFILL HEAD.....
960 IF H2<4.5 THEN 990
970 T7 = 47.4*(H2^.5 - (H2-4)^.5)
980 GOTO 1050
990 T7 = 36.7*H2^.5
1000 GOTO 1050
1010 REM CALCULATE REFILL TIME
1020 A7=P/4*D1^2/144
1030 K7=.61*A1/A7*SQR(2*G1)
1040 T7=2/K7*(SQR(H2)-SQR(H2-H1))
1050 PRINT "FILLING TO A HEIGHT OF ";H1; " FEET TAKES ";T7; " SECONDS"
1060 PRINT
1070 PRINT
1080 T9 = T7 + T1
1090 PRINT " THE TOTAL CYCLE TIME IS";T9;"SECONDS"
1100 R7 = V1/T9*Q2
1110 R8 = R7*28.316*3600
1120 PRINT
1130 PRINT
1140 PRINT  "AVG PUMPING RATE IS ";R7;" FT3/SEC OR "R8;"LITERS/HR"
1150 PRINT
1160 PRINT
1170 PRINT " WOULD YOU LIKE VALUES CORRECTED FOR "
```

```
1180 PRINT " DISCHARGE LINE VOLUME?"
1190 PRINT "  YES = 1  ,  NO = 0 "
1200 INPUT  M6
1210 IF M6 = 0 THEN 1360
1220 V6 = (L1+1)*A2
1230 V7 = V6*28.316
1240 V8 = Z6 - V7
1250 PRINT  "CORRECTED  LITERS/ CYCLE IS ";V8
1260 PRINT
1270 PRINT " AMOUNT OF FALLBACK IS " ;V7;" LITERS"
1280 R9 = V8/T9*3600
1290 PRINT
1300 PRINT " ACTUAL PUMPING RATE IS ";R9;"LITERS/HOUR"
1310 PRINT " INDIVIDUAL RESISTANCES, PSI "
1320 PRINT " DELIVERY LINE FRICTION HEAD, Z1= ";Z1
1330 PRINT " VERTICAL HEAD, Z2= ";Z2
1340 PRINT "DROP THRU FITTINGS,Z3=";Z3
1350 PRINT "TOTAL HEAD LOSS,Z5=";Z5
1360 END
```

APPENDIX B

This is the result of running the predictive program FPUMP.ONE for a case shown in Fig. 16 with a motivation pressure of 19.2 psig.

```
LOAD"FPUMP.ONE
Ok
RUN
  THE PUMP IS A BOTTOM LOADER OF 4 INCH DIAM
I NEED LEVEL IN PUMP (H1) IN FEET
? 4
I NEED REFILL HEAD (H2) IN FEET
? 8
 I NEED DELIVERED HEAD (H3) IN FEET
? 9
I NEED DELIVERY LINE LENGTH(L1) IN FEET
? 11
 I NEED DELIVERY LINE INSIDE DIAMETER  (D2) IN INCHES
? .625
I NEED MOTIVATION PRESSURE (P1) IN PSIG
? 19.2
 I NEED NOZZLE DIAMETER (D3) IN INCHES
? .35
 I NEED FITTING LOSS COEFFICIENT (K1)
? .2
 I NEED  FLUID DENSITY (R1) IN LBS/FT3
? 62.4
 I NEED FLUID VISCOSITY (M1) IN CENTIPOISE
? 1
INITIAL SPLIT GUESS PLEASE
? .9
HERE IS QS      .9              1.034645
MORE?
? 1.02
HERE IS QS      1.02            1.017429
MORE?
? 0
OUTPUT
RE =            57072.27
 DPTOT IS       8.14255
 SPLIT IS 1.02
PTERM IS .297196
TPUMP =  14.16149
 LITERS/CYCLE =                 10.08185


CALCULATED  RESULTS

TEST CONDITIONS


TYPE = BOTTOM-LOADED

 PUMP DIAM =  4   PUMP HT =  4  RESV HT =  8
  DELIV LINE LENGTH =  11  DELIV LINE DIAM =  .625
 DRIVING PRESS =  19.2   NOZZLE DIAM =  .35
 FITTING LOSS COEFF =  .2
DENSITY =  62.4 VISCOSITY =  1 THE HEAD IS 9 FEET
```

```
 NOW DO YOU WANT FILL TIMES AND TOTAL
 CYCLE PERFORMANCE.....NO=0, YES=1

? 1
FILLING TO A HEIGHT OF  4  FEET TAKES  39.26745  SECONDS


 THE TOTAL CYCLE TIME IS 53.42894 SECONDS


AVG PUMPING RATE IS  6.663954E-03  FT3/SEC OR  679.3075 LITERS/HR


 WOULD YOU LIKE VALUES CORRECTED FOR
 DISCHARGE LINE VOLUME?
  YES = 1   ,   NO = 0
? 1
CORRECTED  LITERS/ CYCLE IS  9.357916

 AMOUNT OF FALLBACK IS  .7239383  LITERS

 ACTUAL PUMPING RATE IS  630.5291 LITERS/HOUR
 INDIVIDUAL RESISTANCES, PSI
 DELIVERY LINE FRICTION HEAD, Z1=  4.054967
 VERTICAL HEAD, Z2=  3.9
DROP THRU FITTINGS,Z3= .1875829
TOTAL HEAD LOSS,Z5= 8.14255
Ok
```

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