PN-AAT-111 40667

WATER AND SANITATION
FOR HEALTH PROJECT

Operated by
CDM and Associates

Sponsored by the U.S. Agency
for International Development

1611 N. Kent Street, Room 1002
Arlington, Virginia 22209 USA

Telephone: (703) 243-8200
Telex No. WUI 64552
Cable Address WASHAID

HYDROPNEUMATIC PUMP SYSTEM DEVELOPMENT

WASH TECHNICAL REPORT NO. 23

APRIL 1984

Prepared For:
Office of Health
Bureau for Science and Technology
U.S. Agency for International Development
Order of Technical Direction No. 68

WASH TECHNICAL REPORT NO. 23

HYDROPNEUMATIC PUMP SYSTEM DEVELOPMENT

Prepared for the Office of Health
Bureau for Science and Technology
Agency for International Development
Under Order of Technical Direction No. 68

Prepared by:

Yaron Sternberg

and

Jonathon French

April 1984

Water and Sanitation for Health Project
Contract No. AID/DSPE-C-0080, Project No. 931-1176
is sponsored by the Office of Health, Bureau for Science and Technology
U.S. Agency for International Development
Washington, DC 20523

TABLE OF CONTENTS

Chapter		Page
EXECUTIVE SUMMARY		iii
1.	INTRODUCTION	1
2.	DESCRIPTION AND THEORY OF OPERATION	4
3.	DESIGN AND CONSTRUCTION OF THE PHYSICAL MODEL	6
	3.1 Physical Model History	6
	3.2 Design Objectives	7
	3.3 Construction Preparation	7
	3.4 Construction of the Model	9
	3.5 Pump Operation	10
4.	THE COMPUTER MODEL	13
	4.1 Parameters	13
	4.2 Initial Conditions Assigned	14
	4.3 M = 1: Pump Mode	15
	4.4 M = 2: Drain Mode	15
	4.5 M = 3: Fill Mode	16
	4.6 Assumptions	16
	4.7 Calculation of Pipe Conveyance Values	16
5.	RESULTS OF COMPUTER RUNS	20
	5.1 Presentation	20
	5.2 Discussion	23
6.	SUGGESTIONS FOR FUTURE STUDY	26
	6.1 Steady-State Operation; Measurements	26
	6.2 Calibration and Verification of the Computer Model	26
	6.3 Development of Simple Formulas for Performance	27

Chapter Page

6.4 Study of Important Secondary Factors of Performance.. 27

6.5 Assessment of Range of Applicability and Degree of Utility..... 27

7. SUMMARY AND CONCLUSIONS..... 28

APPENDICES

A. Diagrams and Photographs..... 30

B. Memorandum by F. Reiff, PAHO..... 37

C. Computer Model Run Printouts..... 45

EXECUTIVE SUMMARY

The investigation of the concept of a hydropneumatic pump was initiated in November, 1981 with the issuance of Order of Technical Direction (OTD) No. 68. Under this OTD the development of a system was to be investigated which could serve a community of 5,000 persons and provide each person with 20 gallons of water during a 10 hour period.

This included the development of a mathamatical model as an aid to the design and construction of a functional prototype. It also included the construction of a full scale prototype model. Operation of this model was limited inasmuch as it was not equipped for continuous operation and trial runs were restricted to fill and discharge batch runs without exploring the varous parameters necessary for establishment of optimum scale and sizing of various components.

Should the task be resumed, it is recommended that future studies with the physical model and the computer model include:

A. Completion and full commissioning of the physical model with modified siphon size or multiple alternate siphon piping;

B. Calibration and verification of the computer model;

C. A determination of the relationship between the amount of lift and discharge of low rate of the unit with a means for expressing this relationship;

D. Better definition of pump capacity as a function of component pipe diameters and lengths and other geometric parameters;

E. Through use of the prototype, study the secondary hydraulic questions not fully addressed in the computer model such as unstable flow, air counterflow, and assured siphon priming;

F. An assessment of the range of applicability and the degree of utility of this type of pump.

HYDROPNEUMATIC PUMP:
DESCRIPTION AND COMPUTER MODEL
PRELIMINARY STUDIES

Chapter 1

INTRODUCTION

The hydropneumatic pump is a simple means for lifting water from a stream for long unattended periods. Like a hydraulic ram, it uses the potential energy of a flow drawn from a stream at a given elevation and discharged at a lower elevation, to pump a smaller flow to an elevation greater than the intake elevation. The hydropneumatic pump, like the hydraulic ram, operates cyclically. However, while the hydraulic ram harnesses the transient compressive pressures of water hammer shocks, the hydropneumatic pump's operating principles are based on hydrostatics.

The hydropneumatic pump was brought to the attention of WASH by Mr. Fred Reiff of the Pan American Health Organization. Mr. Reiff has built and used such pumps in Alaska, and built a small working demonstration model as well, described in Appendix B. The pump is of interest to WASH because:

1. It can be fabricated almost entirely out of such usually commonly available materials as standard 2-inch or 3-inch piping, and 55-U.S. gallon oil drums.

2. The pump is self-priming.

3. Up to its hydraulic capacity, determined chiefly by the size of the piping, the pump will accept whatever flow is delivered to it.

4. Aside from the armatures of two check valves, there are no moving parts.

5. Because pumping energy is derived from the water source, there is no need for electricity or fuel.

There are some drawbacks:

1. The water source must be a stream with an appreciable slope, or an impoundment with a dam; this pump cannot simply operate from any point on the shore of any lake.

2. For every liter of water lifted as payload through an elevation of H meters, there must be more than a liter of water lowered through a distance greater than H and eventually discharged, to provide the pumping energy.

3. The pump is not compact, but involves assemblages of tanks (oil drums) at two disparate elevations, with four separate pipelines running between the two assemblages, in addition to the intake pipe from the water sources and the lift pipe conveying the payload flow to its higher destination.

4. There are two pipe-to-drum connections which must be airtight, and numerous pipe-to-drum connections which should be watertight.

In balance, initial appearances are that the device deserves further exploration of its capabilities and identification of its liabilities, and assessment of its value as an appropriate pump under certain conditions.

To date under this Order of Technical Direction:

1. A prototype-scale physical model of the pump has been constructed by the Civil Engineering Department of the University of Maryland.

2. A computer model of the pump has been written. Runs have been made for a limited variety of conditions.

This report describes the construction of the physical model, and describes the computer model and presents the computer model results.

CHAPTER 2

DESCRIPTION AND THEORY OF OPERATION

The hydropneumatic pump is shown in Figure 1.* Near the intake there are two tanks (oil drums). At a lower elevation is another tank.

Water is drawn in from the source, S, through pipe 1 to tank 2. Water to be lifted as payload goes via pipe 3 to tank 4, and is pumped up through pipe 5 to its destination. Water to power the pump falls from tank 2 via pipe 7 to tank 8. Pumping pressure is transmitted pneumatically from tank 8 to tank 4 by air pipe 9. Water is drained from tank 8 by siphon pipe 6.

Operation is cyclical, progressing through three modes, somewhat analagous to the "intake-compression-combustion-exhaust" modes of the internal combustion engine cycle. The hydropneumatic pump modes may be called "pump-drain-fill".

Mode 1: pump. Tanks 2 and 4 are initially full to the level of the overflow weir into pipe 7, due to inflow from the source, S, through pipes 1 and 2. Tank 8 is initially empty. Water continues to be drawn from the source into tank 2, thence over the pipe 7 weir, down pipe 7, to tank 8. Filling tank 8 with water compresses the air in tank 8, and drives the air through pipe 9 to tank 4. Water in tank 4 is expelled, not via pipe 3 (which is closed by a check valve), but via pipe 5, to its payload destination. The pump mode ends when the water level in the rising limb of siphon pipe 6, in hydrostatic equilibrium with the rising water level of tank 8 plus the air pressure in pipe 9, reaches a level sufficient to prime siphon action in pipe 6. By the end of the pump mode, tank 4 is partially or completely empty.

Mode 2: drain. After siphon action is primed in pipe 6, water drains from tank 8 via the rising and falling limbs of pipe 6, to exhaust. For the moment, free air connection is established via pipe 7, tank 8, and pipe 9 to tank 4, and air pressure returns to atmospheric in tank 4.

*For diagrams and photographs, see Appendix A.

Mode 3: fill. With the return of atmospheric pressure to the (at least partially) dewatered tank 4, the flow of water from tank 2 via pipe 3 to tank 4 resumes. This temporarily draws the water level in tank 2 down to below the pipe 7 weir level; but water from the source, S, continues to replenish tank 2, and presently the tank 2 level rises again to the level of the pipe 7 weir, completing the 3-mode cycle. Further filling of tank 2 causes overflow ino pipe 7, and mode 1 begins again.

Thanks to a check valve in pipe 5, one may consider pipe 5 to always remain full of water. The water rests against the closed check valve during the drain and fill modes, and is driven upward during the pump mode.

CHAPTER 3

DESIGN AND CONSTRUCTION OF THE PHYSICAL MODEL

3.1 Physical Model History

In accordance with OTD 68 a full scale model of a hydropneumatic pump was designed and constructed by Dr. Y.M. Sternberg and Mr. R. Knight, Civil Engineering Department, University of Maryland, College Park, Maryland.

Prior to the Construction of the model, a preliminary design was prepared and submitted to WASH for review. Comments and suggestions were also solicited from Mr. F. Reiff, Pan American Health Organization (PAHO), Washington, D.C. (Mr. Reiff had bult a full-scale operational field unit in Alaska.) The initial proposed design configuration was similar to the one shown in Figure 1a except for the pipe diameters. The proposed water pipes were two inches and the air pipe one inch in diameter. At Mr. Reiff's suggestion the above dimensions where changed to three inches and two inches to maintain efficiency at higher operating rates.

After approval of the design, six 55-gallons drums were purchased. The drums were new and had never been used for storage of any liquids. Since new drums may not be available in some developing countries, an old drum used for storage of an organic solvent was obtained to ascertain whether such drums could be used for the purposed pump. The drum ws subjected to repeated cleaning with a mixture of water and mild detergent. The drum containing the liquid was agitated, drained, and flushed with clean water a number of times. Still, tap water left in the drums for a period of 24 hours had a slight objectionable smell to it. No chemical analysis of the water was performed to determine the residual concentration of the solvent in the water. It was concluded that used drums can probably be used for the construction of a hydropneumatic pump provided that: (1) the drum has not been used

for storage of any hazardous materials (pesticides, etc.), (2) the drum is thoroughly cleaned with a mild detergent solution, and (3) the drum is repeatedly flushed with clean water.

3.2 Design Objectives

- To assemble a working model at near-prototype scale out of materials likely to be recommended for field use (standard oil drums, standard piping).

- To achieve steady-state operation with a variety of flow rates, pumping heads, pipe sizes, and other dynamic and geometric parameters.

- To confirm the validity and veracity of predictive models of operations:

  - Computer model simulating operations
  - Approximate formula for estimating pumping rate

- To determine pump capacity as a function of system geometry

- To identify particular problems to be overcome or avoided, and conditions to be met, e.g., avoidance of air surging or burping, necessary and sufficient conditions for siphon priming, necessity for air-tight joints in some places.

3.3 Construction Preparation

Prior to construction, the four tanks (55-gallon drums, see Figure 1a) used in the model were prepared in the following manner:

1. Tank S (Supply Source): the bottom of this tank was removed using a welding torch and the tank was turned upside down. This

provided a two-inch pipe thread (normally the filler plug) where a PVC schedule 40 female adapter was inserted. (Care should be exercised when the base or top is removed to insure that the remaining edges are not sharp or rough.)

2. Tank 2: The top of this tank was removed using a welding torch and two three-inch couplings were welded to the base. The location of the couplings is not critical. It is best to locate them along the diameter about half way between the center and the circumference of the drum. The two couplings provided two three-inch female threads both inside and outside the tank.

3. Tank 4: Two two-inch couplings were welded into the base of this tank. This provided two two-inch female threads both inside and outside the tank. The top of this tank was left intact.

4. Tank 8: Two three-inch nipples were welded, one each on the top and the bottom. No particular problems were encountered in welding the steel couplings or nipples. The painted surfaces of the drums was well cleaned to insure good bonding. It is recommended that all of the welds be tested before the pipes are connected.

   Tank 2 and 8 were equipped with sight-glasses consisting of brass fittings brazed to the side of the tank, one near the top and one near the bottom. The two fittings were connected with plastic tube (tygon tubing). The purpose of the sight-glass was to allow the operator to observe the level of the water in the tanks. A sight-glass is not deemed necessary for the operation of the model.

The model was equipped with two check valves; one in pipe 3 and one in pipe 5.

Pipes 3 and 5 are standard two-inch diameter PVC pipes and various commercially available check valves (one-way valves) could be employed. For this model, two check valves (poppet type) were constructed from PVC with an "O" ring seal. The performance of the valves was checked prior to installation in the appropriate line.

3.4 Construction of the Model (see Figure 1a)

Tanks 2 and 4 were positioned on a grating at floor level of the Engineering Laboratory building. Tank S was elevated to a position where it could supply water by gravity to Tank 2. Tank 8 was positioned beneath the above tanks on the lower level of the Engineering Laboratory building. The integrity of all of the welds had been verified prior to placement of the tanks.

Plumbing of the system was done by two people. The tools required included a hand-saw, measuring tape, and a pipe wrench. Supplies used were various size PVC pipes, fittings, teflon tape, and solvent cement. To insure good bonding, fresh solvent cement should be used and the instructions on how to join PVC pipes should be followed. In all cases the transition from the metal fittings in the tanks to the PVC pipe was first accomplished and teflon tape was used on all threaded connections. All connections between PVC pipes was done with solvent cement. Specific construction details are given below:

1. The short two-inch PVC pipe line from tank S to tank 2 was equipped with a gate valve to regulate the flow from the storage tank. Such a valve will not be required in a field model.

2. Tank 2 was equipped with two three-inch couplings. A three-inch PVC pipe was fitted into the coupling on the inside of the tank. A three-inch female adapter was attached to the same coupling at the bottom of the

tank. Pipe 7 was connected to this female adapter. The other coupling was equipped with a three-inch-to-two-inch reducer. Pipe 3 was connected to this reducer.

3. Two two-inch PVC female adapters wer connected to the steel couplings in tank 4. The line from tank 2 to tank 4 included one of the PVC check valves which was installed just below the two-inch adapter. The delivery line (pipe 5) housed the other check valve.

4. Tank 8 had a three-inch socket adapter fitted to the two welded nipples. A two-inch female adapter was inserted into the filler plug thread.

5. The upper portion of the siphon was equipped with a short length of three-inch Plexiglass tubing and short lengths of three-inch rubber hose held in position with hose clamps. The Plexiglass provided means of visual observation on the level of the water in the siphon. The rubber hose and clamps provided elevation adjustments, i.e., raising or lowering the top of the siphon. In field installations, the siphon could be constructed from standard PVC pipe since there will be no need to observe the water level prior to the activation of the siphon.

It is essential to provide firm support to all the PVC piping and fittings. Schedule 40 PVC was used for plumbing but piping materials with a thinner wall such as drainage pipe which is available in many LDC's, can also be used.

3.5 Pump Operation

The pump did not function on the first trial. It was suspected that air leakage was a cause of the problem, but none was found. Following further examination, revealing that air was entrapped in the siphon,

two modifications were made. One modification was to extend the three-inch line in tank 8 to within three inches from the bottom of the base of the tank. The other modification was to change the siphon configuration from a horizontal to a 45 degree slope to reduce the potential for air locks. The new siphon configuration is shown in Figure 1a.

The model was operated a number of times to ascertain that the system did not leak. The tests were preliminary in nature and no data were collected. A garden hose was used as the inflow source but full flow from tank S was necessary to activate the siphon (without additional inflow discharge the siphon behaved as a weir). Although no outflow discharge was measured, it was estimated that about 25 gallons were pumped during each cycle.

Conclusion and Recommendations: No special difficulties were encountered in the construction of a prototype model from 55-gallon drums and PVC plumbing. Persons with some experience in welding and plumbing can construct such a prototype model. The model was subjected to only limited testing because time ran out. It is recommended that future experimental work include the following:

(1) The long term effects on water quality and expected life of the drums should be evaluated. Preliminary experience indicates that the use of steel drums will create a rust problem.

(2) Evaluation of the model with smaller diameter plumbing. A two-inch siphon may be more suitable than a three-inch one to achieve reliable siphon priming.

(3) Evaluation of practical operating capacity and optimum efficiency of the model as constructed.

Inasmuch as standard 55-gallon drums are generally available worldwide they were incorporated as a design feature. Use of the standard drums do pose a practical limitation on the capacity that can be built into the pump. Basically, two problems exist: (1) How fast the drums can fill and (2) proper operation of the siphon (without bubble propagation). An increase in tank capacity, by welding drums together, would provide some added capacity but only if provision was made to shorten the drum filling and evacuation times. These same provisions with a single drum might give almost an equal increase in capacity. Any further work should include considerations of the rate that drums are filled and evacuated in addition to overcoming problems related to siphon priming.

CHAPTER 4

THE COMPUTER MODEL

4.1 Parameters

The parameters by which the pump and its operation are described are listed below. SI units are used. Elevations are measured with respect to the water surface of the water source, S.

The constants are:

D = time step
K1 = conveyance (ratio of flow rate to square root of driving head) in pipe 1
A2 = area of tank 2
W2 = elevation of the weir at the inlet of pipe 7, located in tank 2.
K3 = conveyance in pipe 3, between tanks 2 and 4
A4 = area of tank 4
C4 = ceiling elevation of tank 4
K5 = conveyance in pipe 5
W5 = elevation of the payload destination end of pipe 5, and the static head through which payload water is pumped
K6 = conveyance of siphon pipe 6, when flowing full
W6 = siphon weir elevation of siphon pipe 6
B6 = inlet elevation of pipe 6; also the minimum water surface elevation in tank 8
E6 = outlet elevation of pipe 6, which is the exhaust elevation
C8 = ceiling elevation of tank 8
A8 = area of tank 8
L9 = length of air pipe 9
A9 = cross-sectional area of air pipe 9
PØ = atmospheric pressure, expressed in meters of water head
T1 = duration of simulated operation
VØ = the volume of air to be compressed, in tank 8, air pipe 9,

and tank 4 at the beginning of the pump mode

The time dependent variables are:

T = time
Z2 = the water level in tank 2
Z4 = the water level in tank 4
Z6 = the water level in the rising limb of the siphon pipe 6
V5 = the accumulated payload volume of water that has been pumped since time zero
V6 = the accumulated volume of water that has been exhausted through the siphon since time zero
M = the mode number: 1 for pump, 2 for drain, 3 for fill
V9 = the volume of air under compression at any instant during the pumping mode
T2 = the duration of a given 3-mode pump cycle
R5 = the average payload pumping rate during a cycle, i.e. the change in V5 over a cycle, divided by T2 for that cycle
R6 = the average water exhaust rate during a cycle, i.e. the change in V6 over a cycle, divided by T2 for that cycle

The computer model simulates flows within the pump for each mode, at each time step testing to see whether or not to advance to the next mode. The simulation begins at the beginning of a pump mode. The initial conditions, governing equations, and logic are summarized below.

4.2 Initial Conditions Assigned

T = Ø (Time zero)
Z2 = W2; Z4 = W2 (Water levels in tanks 2 and 4 are initially at the elevation of the weir inlet to pipe 7, the fall pipe)
Z6 = B6 (The water level in pipe 6 is at the elevation of the inlet to pipe 6; i.e. pipe 6 and tank 8 are empty)
V5 = Ø, V6 = Ø (Zero volumes of water have been lifted or exhausted at time zero)

M = 1 (start with pump mode)

4.3 M = 1: Pump Mode

Q1 equals K1, the conveyance of pipe 1, times the square root of -Z2, the head across pipe 1.

Q7 is assumed to be limited by and equal to Q1

V9, the volume of air under compression in tank 8, pipe 9, and tank 4, depends on the water levels in tanks 4 and 8 and in pipe 9

P4, the pressure head transmitted by air from tank 8 to tank 4, is related to atmospheric pressure head PØ, the initial air volume VØ, and variable air volume V9, by the formula: $P4(V9)^{G1} = P\emptyset(V\emptyset)^{G1}$ = constant, in which the exponent G1 equals 1.0 for perfectly isothermal conditions, or 1.4 for completely adiabatic conditions, or may be assigned an intermediate value for intermediate conditions.

Q5 equals K5, the conveyance of pipe 5, times the square root of the pressure head across pipe 5, but only when pressure in tank 4 is adequate to drive flow out of tank 4 through pipe 5. No backflow is allowed.

V5 is the time integral of Q5

Z6, the water level in the rising limb of pipe 6, exceeds Z8 by the pressure head difference P4 - PØ.

When Z6 exceeds the siphon crest elevation W6, advance to mode 2.

4.4 M = 2: Drain Mode

Q6, the siphon low rate, equals K6, the conveyance of pipe 6, times the square root of the head across pipe 6, which is Z8 - E6.

V6 is the time integral of Q6.

Q3, the inflow through pipe 3 to tank 4, is equal to K3, the conveyance of pipe 3, times the square root of the difference in water surface elevation between tank 2 and tank 4.

Z4 rises as Q3 fills tank 4.

Q1, the inflow through pipe 1 to tank 2, is equal to K1, the conveyance of pipe 1, times the square root of the difference

in water surface elevation between the water source, S, and tank 2.

Z2 is drawn down as Q3 drains tank 2, but rises when Q1 exceeds Q3.

When Z8, the water level in tank 8, falls to B6, the elevation of the siphon pipe inlet, siphon flow is broken. Advance to mode 3.

4.5 M = 3: Fill Mode

Q1 and Q3 continue to flow until Z4 approaches Z2, and Z2 reaches W2, the elevation of the weir inlet to pipe 7.

When Z2 exceeds W2, return to mode 1.

4.6 Assumptions

In the present version of the computer program it is assumed that:

1. The head on the pipe 7 weir, i.e. the amount by which Z2 must exceed W2 in order for the flow Q7 to equal the flow Q1, is small.
2. There is no counterflow of air from tank 8 up pipe 7.
3. There is no "burping" in pipe 7.
4. The advance from one mode to the next is accomplished within one time step.
5. Loss of air by joint leaks or by solution in water is negligible over one cycle.
6. Pressure loss in the air flow from tank 8 to tank 4 is negligible.
7. The two check valves work perfectly.

The program listing is given in Table 1. Written in BASIC, it has been used on a Tektronix 4054 computer.

4.7 Calculation of Pipe Conveyance Values

For each pipeline, there is a conveyance value (K1 for pipe 1, K6 for pipe 6, etc.), which is defined as the ratio of the discharge rate through the pipe to the square root of the pressure head, H, across the pipe, e.g.

$$Q5 = K5*SQR(H) \qquad \text{(Eq.1)}$$

The conveyance is a function of pipe cross-sectional area, and of the form losses and friction losses suffered by the energy head for a given flow through the pipe. If H is the sum of friction loss and form losses:

$$H = \frac{Q^2 n^2 L}{A^2 R^{4/3}} + \Sigma K \frac{Q^2}{2gA^2} \qquad \text{(Eq.2)}$$

ΣK = sum of the coefficients for entrance loss (0.5), plus bend and/or tee losses, plus sudden contraction or expansion losses, plus exit loss (1.5).

n = Manning friction factor (use 0.011 for smooth pipe)

A = $\pi/4*D^2$, the pipe area

D = pipe diameter

R = D/4, the hydraulic radius of a completely filled pipe

L = pipe length

Rearranging Equation 2:

$$\text{Conveyance} = \frac{A}{\sqrt{\frac{n^2 L}{R^{4/3}} = \frac{\Sigma K}{2g}}} \qquad \text{(Eq.3)}$$

For the preliminary computer mode runs presented herein, conveyances were computed assuming 3-inch (76 mm) pipe diameter, no wall friction loss, and only entrance and exit form loss. Hence, A = .00454 sq.m, ΣK = 1.5, and the conveyance equals 0.0165. During calibration and verification of the physical model, account must be properly taken of n, L, bends, and other form losses.

TABLE 1

PROGRAM LISTING

```
5 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 19, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.246
121 W2=-0.05
130 K3=0.0155
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 W5=5
160 K6=0.0165
161 W6=-0.01
162 B6=-5
163 E6=B6-1
180 C8=B6+0.5
181 A8=0.247
190 L8=B6
191 A9=4.9E-4
193 P8=10.4
195 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
196 G1=1
197 R1=0
198 R2=0
199 R3=0
200 T1=700
250 REM
255 REM INITIAL VALUES
260 T=0
262 Z2=W2
264 Z4=W2
266 Z6=B6
268 V6=0
270 V5=0
271 Z8=B8
300 PRINT "T=ELAPSED TIME IN SEC.  AT END OF CYCLE, T2=CYCLE DURATION,"
301 PRINT "R5=PAYLOAD PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT"
302 PRINT "CYCLE."
310 PRINT
312 PRINT " T"," T2 "," R5 "," R6"
400 REM
401 REM MODE 1, PUMP
402 M=1
410 D!=K1*SQR(-Z2)
415 D7=D1
416 IF C8>Z8 THEN 420
417 V8=L8*A8+(C4-Z4)*A4
418 GO TO 421
420 V8=(C8-Z8)*A8+L8*A8+(C4-Z4)*A4
421 V8=(C8-B8)*A8+L8*A8+(C4-W2)*A4
422 P4=P8*(V8/V8)↑G1
430 H=P4+Z4-W5-P8
431 IF H<0 THEN 434
432 D8=A8*SQR(H)
433 GO TO 436
```

TABLE 1 (continued)

```
434 [illegible]
435 V6=V6+Q3*D
436 IF Z8=Z6 THEN 449
437 Z8=Z8+Q7/(2*A9)*D
438 GO TO 441
440 Z8=Z8+Q7/A9*D
441 Z4=Z4-Q6/A4*D
442 Z8=Z8+P4-P8
470 T=T+D
480 IF Z8>V6 THEN 482
484 GO TO 650
482 M=2
483 GO TO 630
500 REM
501 REM MODE 2: DRAIN
510 Q5=K5*SQR(Z8-E6)
515 V6=V6+Q5*D
516 IF Z8<C8 THEN 520
517 Z8=C8-1.0E-4
518 GO TO 530
520 Z8=Z8-Q5/A8*D
530 Q1=K1*SQR(-Z2)
540 Q3=K3*SQR(Z2-Z4)
550 Z2=Z2+(Q1-Q3)/A2*D
560 Z4=Z4+Q3/A4*D
570 T=T+D
580 IF Z8<B8 THEN 592
591 GO TO 600
592 M=3
593 GO TO 650
600 REM
601 REM MODE 3: FILL
610 Q1=K1*SQR(-Z2)
620 Q3=K3*SQR(Z2-Z4)
630 Z2=Z2+(Q1-Q3)/A2*D
640 Z4=Z4+Q3/A4*D
650 T=T+D
653 IF Z2>V2 THEN 700
662 GO TO 666
666 GO TO 650
700 T2=T-R1
705 R6=(V6-R2)/T2
710 R3=(V3-R3)/T2
720 PRINT T,T2,R3,R6
725 R1=T
729 R2=V6
728 R3=V3
740 GO TO 450
650 REM
651 REM MODE ASSESSMENT
660 IF T>T1 THEN 680
661 IF M=1 THEN 483
662 IF M=2 THEN 580
663 IF M=3 THEN 650
680 PRINT
681 LIST 1,200
682 END
```

CHAPTER 5

RESULTS OF COMPUTER RUNS

5.1 Presentation

There is a great number of physical and hydraulic parameters to be systematically varied in an exhaustive investigation using either the physical model or the computer model. Since changes are much quicker and cheaper on the computer model, one should operate the physical model under a sufficient range of conditions to calibrate and verify the computer model, then with confidence use the computer model for extended investigations. If in the course of the computer studies there is a set of a conditions whose results are met with skepticism, those conditions can be checked with the physical model.

Until the physical model is operational and calibration/verification of the computer model is made, computer model runs must be considered preliminary. However, the limited series of runs to date provide some interesting qualitative insights which are reported below.

The run printouts are included in Appendix C, one run to a page. For each run, the printout shows:

1. The elapsed time, T, from run start (sec); the cycle duration, T2 (Sec); the average payload pumping rate, R5, over the cycle (cu m/sec); the average exhaust flow rate, R6, over the cycle (cu m/sec), printed at the end of each cycle. Each run is at least ten cycles long, to let the system approach a steady-state operation. Readings of T2, R5, and R6 were taken from the last cycle printed, for plotting in Figure 2.

2. A program listing sufficient to indicate the numerical values assigned to each of the parameters. (A complete program

listing was given at the end of the section describing the computer model. The program is simply re-edited every time a parameter is altered.)

For the runs presented below:

1. The tanks are assumed to be oil drums standing upright, with a base cross-sectional area of 0.245 sq m. The effective height of tank 8, C8-B6, is assumed to be 0.5 m.

2. All water piping (pipes 1, 3, 5, and 6) are assigned conveyance values of 0.0165, which would apply to 3-inch diameter pipes with sharp-edged inlets and outlets, but without wall friction losses or bend losses, or check valve losses. (Such losses must be taken into account when it comes to calibrating the computer model to the physical model; meanwhile the conveyance valves adopted provide an upper-limit estimate of pumping and exhaust flow rates.)

3. The air pipe is assumed to be one inch (.0254 m) in diameter, and to have a length numerically equal to B6, the difference in elevation between the water sources and the siphon inlet. (This equality will be approximately true only if tank 8 is located directly below tank 4. In practice, there will almost always be a significant horizontal distance, as well as a difference in elevation between tanks 4 and 8. Air pipe length becomes more important as its volume grows to rival or exceed the volume of tank 8.)

4. For all runs but one, the atmospheric pressure is assumed to be standard sea level pressure (10.4 m water). For one run, atmospheric pressure, PØ, was halved, to 5.2 m water.

5. Isothermal conditions were assumed: G1 = 1, for all runs.

6. The pipe 7 weir inlet level, W2, was set at 0.05 m below the

water surface elevation of the source.

7. The tank 4 ceiling level, C4, was assigned to be 0.005 m below the water surface elevation of the source.

8. The siphon pipe outlet level, E6, was assigned to be one meter less than B6.

9. The time step used was 0.2 sec.

For one set of runs, B6 = -3 m, i.e. the siphon pipe inlet is assigned to be 3 m below the source water level. For a second set of runs, B6 = -6 m. For each set, W5, the payload lift elevation, is varied between zero and the absolute value of B6.

The results are plotted in Figure 2. For each set of runs, there are 3 curves, showing cycle duration T2, average payload discharge R5, and total rate of water intake R5 + R6, as functions of payload lift W5. The curves for R5 are in conventional pump curve (H versus Q) format. One notes that:

1. For W5 equal to or exceeding -B6, there is no payload discharge, R5. That is, -B6 is a stagnation pressure head.

2. For W5 ranging from Ø to within a meter or so of -B6, the payload discharge r5 decreases with increasing lift elevation W5, but only slowly.

3. The exhaust discharge R6 increases slightly with increasing W5.

4. The total rate of water intake, R5 + R6, decrease very slightly with increasing W5.

5. The cycle duration, T2, decreases only very, very slightly with W5.

6. The functions T2, R5, and R5 + R6 actually are seen to be independent of B6, except when W5 increases to within about one meter of -B6.

7. The one test for reduced atmospheric pressure (PØ = 5.2 m instead of 10.4 m), conducted for B6 = -6 m and W5 = 5 m, shows a 25 percent decrease in R5, and a 5 percent decrease in R5 + R6, compared with results for PØ = 10.4 m.

5.2 Discussion

1. By continuity considerations, R5 + R6 must equal the inflow to the system, Q1, averaged over the cycle duration. In Figure 2, R5 + R6 is nearly constant with respect to W5, the lift elevation, showing only a very slight decrease due to back pressure as W5 increases.

2. The results on Figure 2 suggest that with fair accuracy one may approximate the average payload flow rate by the equation:

$$R5 = \frac{Q1}{2}\left[\frac{P\emptyset}{P\emptyset + W5}\right] \qquad \text{(Eq. 4)}$$

This equation is plotted in Figure 3 (crosses) for comparison with the computer results brought over from Figure 2 (circles). The ranges of approximate validity are:

0 < W5 < (-B6) minus about 1 m
0 < Q1 < "pump capacity"

That is to say:

A. The inflow Q1 is partitioned roughly equally between payload flow and exhaust flow, with the payload flow being reduced as increasing lift elevation introduces air compression;

B. The lift W5 cannot exceed the exhaust flow fall distance, and as a practical matter must be somewhat less than it;

C. The inflow rate, Q1, has an upper limit, the "pump capacity," that will be accepted by the pump in normal operation.

3. The present governing equations for the model have Q1 being dependent on Z2, the water level in tank 2. It would be simpler and little if any less general to make Q1 independent of Z2.

4. Now suppose that we have a Q1 that is clearly within the capacity of the pump; that is, the payload discharge is slightly less than half of Q1, and the exhaust flow is slightly greater than half of Q1.

   A. If Q1 is reduced, we may expect that the partition ratio of payload discharge to exhaust flow will remain fairly constant, both flows simply being reduced in proportion to the reduced Q1.

   B. But if Q1 is steadily increased, intuition suggests that for a given set of pipe sizes and lengths, there will be an upper limit to Q1 that will be handled by the pump beyond which the pump fails to operate as effectively, or at all. This would be the "pump capacity". It would be principally a function of the tank volumes and of the conveyances of pipes 3, 6, 7, and 9. (The conveyance of pipe 5 is best considered in terms of the discharge piping system conveyance; see Item 5 below). Further study is necessary to better define pump capacity in terms of system geometry.

5. Equation (4) can be improved by replacing W5 with "TDH", the total developed head, which is static head plus dynamic head:

$$TDH = W5 \text{ (static head)} + \left[\frac{Q5}{K5}\right]2 \text{ (dynamic head)} \qquad \text{(Eq. 5)}$$

CHAPTER 6

SUGGESTIONS FOR FUTURE STUDY

6.1 Steady-State Operation; Measurements

At this writing, the physical model is essentially complete but not yet fully operational. It has operated in "batch mode," but the experimental setup needs to be augmented by the appropriate addition of a sump reservoir and a recirculating pump so that steady-state operation of the hydropneumatic pump can be achieved.

Once the physical model is operational at steady state, a means of measuring pumping rate and exhaust flow rate must be devised. For this, very simple means may be adequate, such as measuring cycle duration and measuring the volume of water pumped per cycle, and exhausted per cycle. Atmospheric pressure at the laboratory is easily measured with a barometer. Pipeline conveyance values must be calculated as indicated in Section 4.7, or in some cases derived in the laboratory from stage-discharge measurements on individual pipe components. (This is particularly true for pipe 3, joining tanks 2 and 4, since it includes a check valve, whose conveyance is difficult to estimate accurately.)

6.2 Calibration and Verification of the Computer Model

As noted in Section 5.1, the physical model should be run under a range of conditions to be simulated as closely as possible by the computer model. The results of the two models should then be compared and the computer model modified and fine-tuned as necessary until it faithfully simulates physical model performance. Then the computer model may be used for extensive exploration of pump performance under a wide variety of geometric conditions.

Later, for any set of conditions giving rise to unexpected or not-easily-believed computer results, the physical model can be

used for verification.

6.3 Development of Simple Formulas for Performance

Equation 6, based on the preliminary computer results reported herein, appears to be a useful approximation of pump performance, but its accuracy should be checked with physical model test results. More important, simple but useful formulas relating pump capacity to pump geometry, are highly desirable. These can be developed by use of the computer model once it has been checked against the physical model.

6.4 Study of Important Secondary Factors of Performance

Design and construction techniques to avoid "burping" in pipe 7, the fall pipe; to ensure full siphon priming; and otherwise to ensure reliable operation should be developed and recorded. These factors involve flow phenomena not readily simulated in the computer model, and must be addressed with the physical model.

6.5 Assessment of Range of Applicability and Degree of Utility

Future studies should determine where and under what circumstances this device would be a viable alternative to other pumping means, and whether development of a construction manual is warranted.

CHAPTER 7

SUMMARY AND CONCLUSIONS

1. The hydropneumatic pump is a device, possibly suited for application in some remote areas, for pumping water using the potential energy of some of the water in the source stream. It can be built almost entirely out of oil drums and standard small-bore piping; it is self-priming; it will handle whatever flow is delivered to it, up to a limited capacity; and except for two check valves there are no moving parts. On the other hand, the water source must have an appreciable slope or fall in order to provide the pumping power; the flow rate of water required to power the pump must exceed the payload discharge rate, and the vertical drop of the powering flow (exhaust flow) must exceed the payload lift; the pump assembly is not particularly compact; there are several pipe-to-drum connections that must be airtight or watertight.

2. A physical prototype-scale model of the pump has been built, but not yet rendered fully operational.

3. A computer model of the pump has been written and several production runs have been made, whose results are reported herein. However, before one can use the model with full confidence, it must be calibrated and verified against the physical model, once the latter is operational.

4. The preliminary computer results indicate that, to a fair approximation:

$$R5 = \frac{Q1}{2}\left[\frac{P\emptyset}{P\emptyset + TDH}\right] \qquad \text{(Eq. 6)}$$

for: Q1 < pump capacity

and: TDH < vertical distance between the flow intake and the

flow exhaust evaluation

in which: R5 = the average payload discharge flow rate
PØ = atmospheric pressure head
TDH = static pumping head plus friction head in the discharge line

5. Future study with the physical model and the computer model should include:

A. Completion and full commissioning of the physical model with modified siphon size or multiple alternate siphon piping;

B. Calibration and verification of the computer model;

C. A determination of the relationship between the amount of lift and discharge of flow rate of the unit with a means for expressing this relationship. Confirmation of Eq. 6 as a useful approximation of pump performance with guidelines established for its application and use;

D. Better definition of pump capacity as a function of component pipe diameters and lengths and other geometric parameters;

E. Study of secondary hydraulic questions not fully addressed in the computer model, such as an unstable or "burping" flow in pipe 7, air counterflow in pipe 7, and assured siphon priming in pipe 6.

F. An assessment of the range of applicability and the degree of utility of this type of pump.

APPENDIX A

Diagrams and Photographs

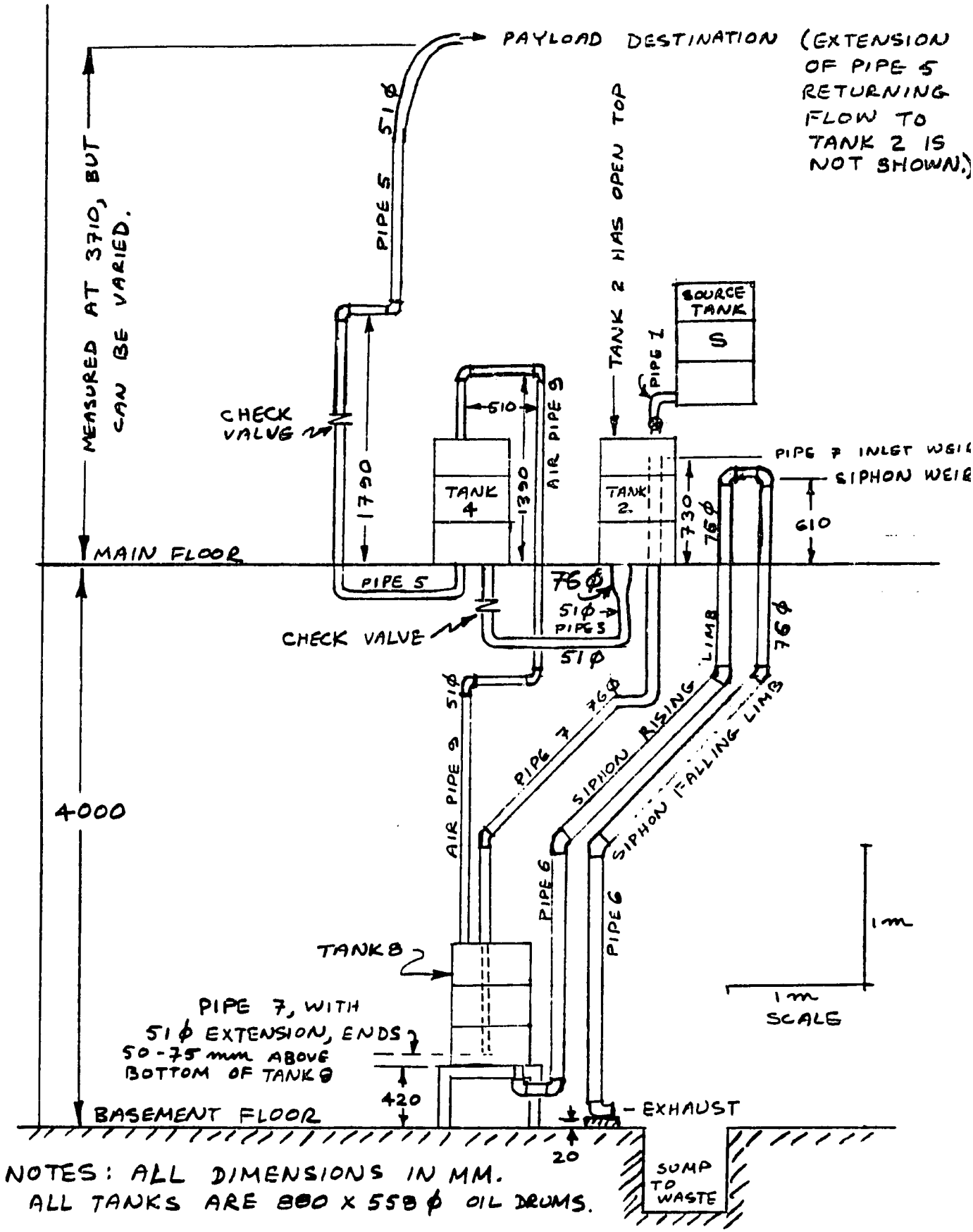


Figure 1a. Dimensioned Diagram of Physical Model Constructed at University of Maryland. (View From West)

Figure 1b. View from west on main floor.

Figure 1c. View from west in basement.

These two photos, viewed together, give nearly the same view as figure 1a.

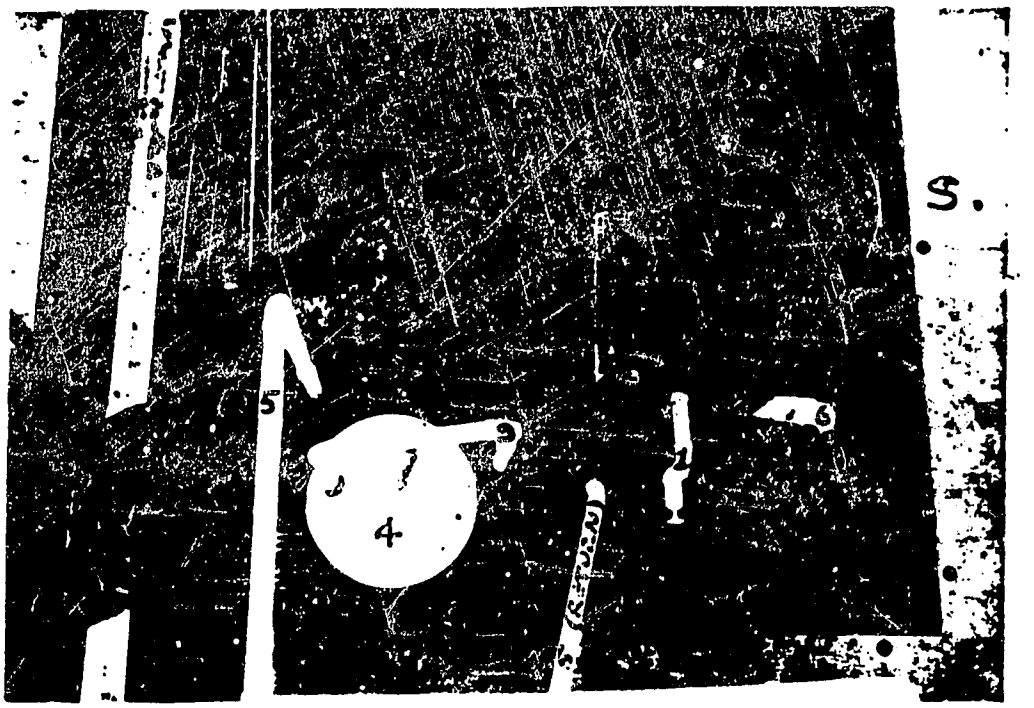


Figure 1d. Top view of tanks 2 and 4, and source 5.

Figure 1e. View from east on main floor. (Large rectangular tank is not part of this apparatus.)

Figure 1f. View from southwest on main floor, showing tanks 4, 2 and 5.

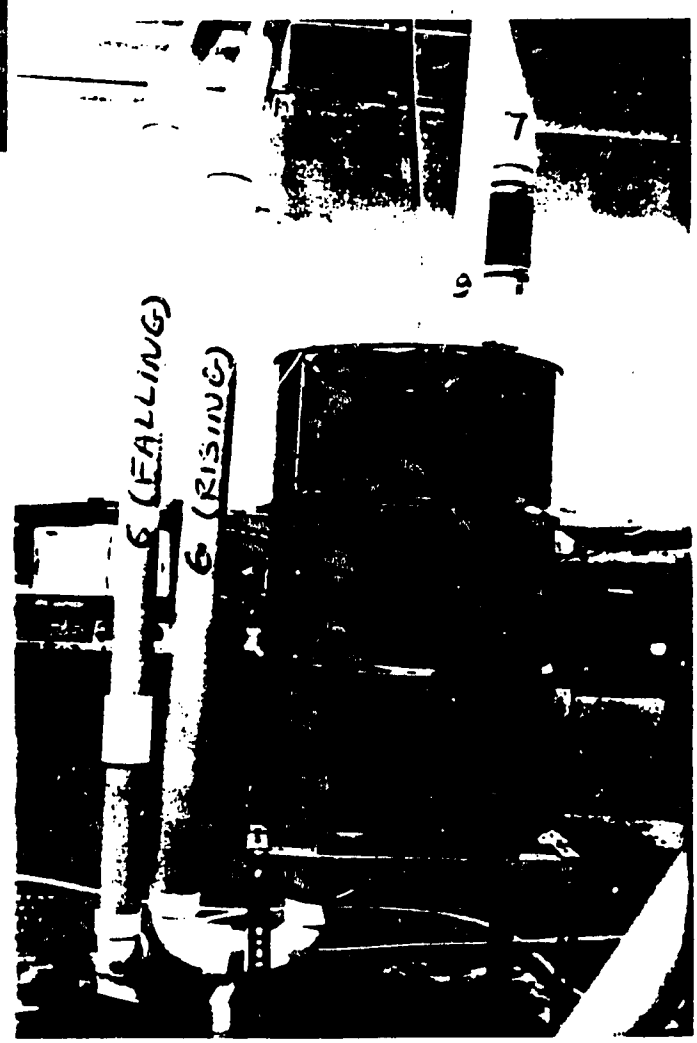


Figure 1g. View from north in basement of tank 8.

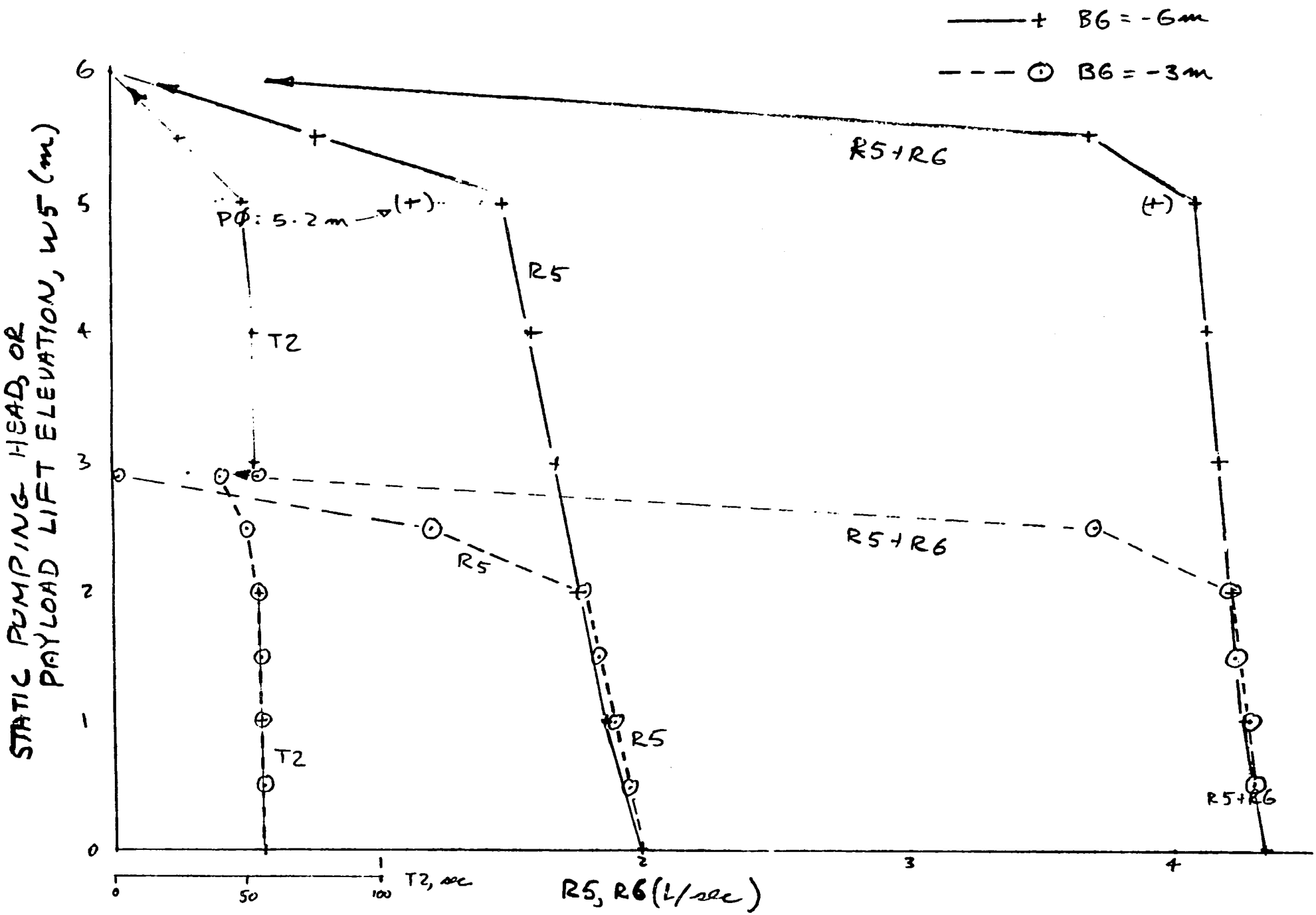


Figure 2. Cycle Duration T2, Payload Discharge Rate R5, and Exhaust Flow Rate RG, Versus Payload Lift Elevation W5.

DRESSER & McKEE
CLIENT
PROJECT
DETAIL
JOB NO.
DATE CHECKED
CHECKED BY
COMPUTED BY
DATE
PAGE NO.

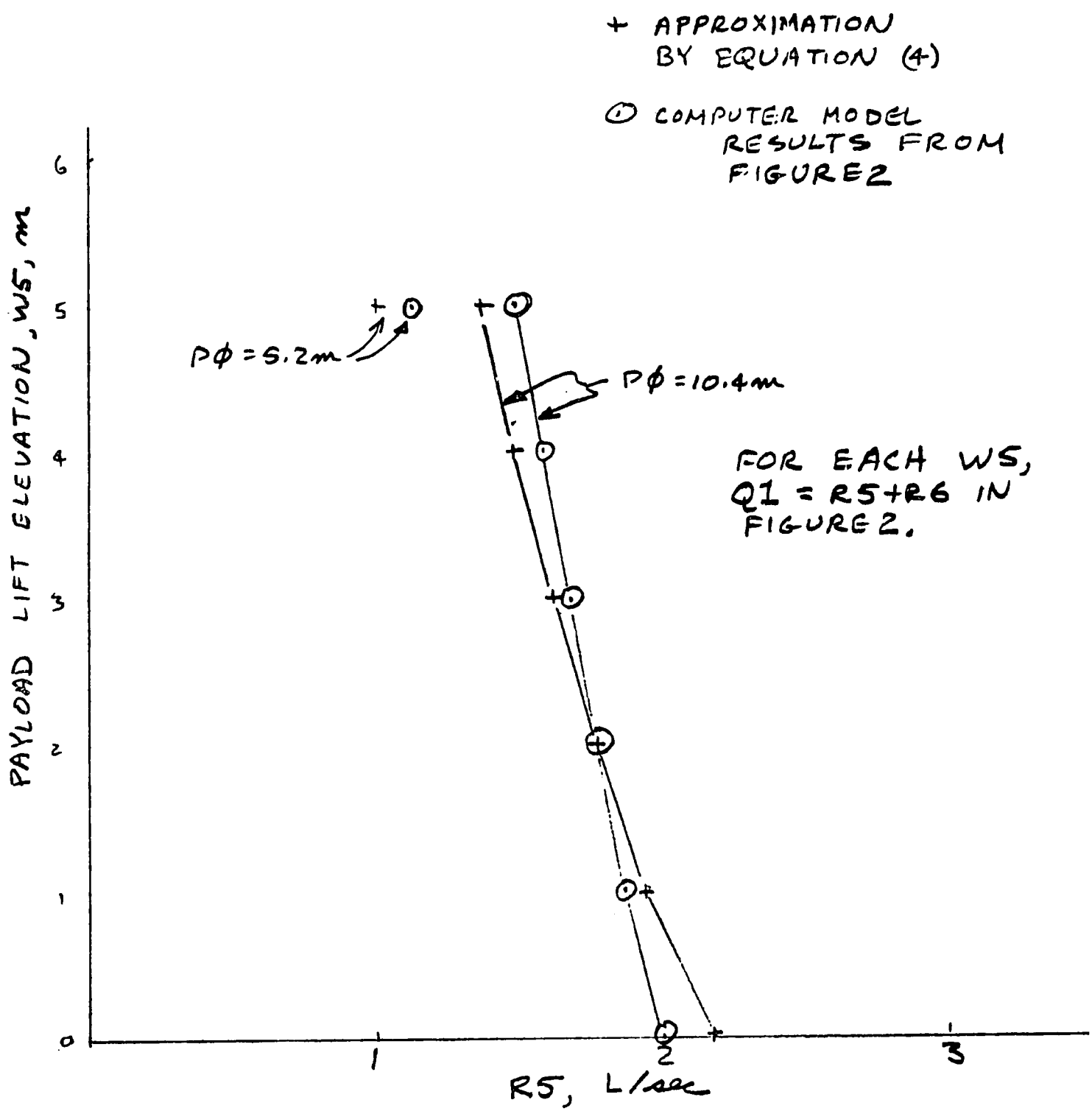


Figure 3. Comparison of Approximate Relationship Between Intake Rate, Pumping Rate and Static Pumping Head, with Computer Model Results.

APPENDIX B

MEMORANDUM BY MR. FRED REIFF, PAN AMERICAN HEALTH ORGANIZATION, DESCRIBING THE HYDROPNEUMATIC PUMP.

THE HYDRO-PNEUMATIC PUMP
A Modification of the Cherepnov Lifter

The hydropneumatic pump is a device designed to pump water without the use of a mechanical pump, without electricity, and without a motor. It utilizes the energy of falling water as the driving force. The pumping apparatus consists of nothing more than three tanks, two check valves, a dosing siphon for lifts of up to 5 meters and a level activated or pressure activated dump valve for greater lifts, and interconnecting piping. The only moving parts are two check valves which merely prevent backflow. On this working model, a water source (the square tank on the left) and a storage tank (the horizontal cylindrical tank at the top) have been added. They are not a part of the pumping device but respectively serve to model the water supply and the point of discharge.

Tank No. 1 is a bifurcating tank which alternately discharges water into Tank No. 2 and Tank No. 3. Tank No. 2 is the ejection tank which is first filled with water and then evacuated of water by compressed air. Tank No. 3 is the compression tank which utilizes the energy of falling water to compress entrapped air and then divert the compressed air to Tank No. 2. The dosing siphon discharges water from Tank No. 3 after the air is compressed to the desired pressure.

The tanks are interconnected in the following manner. Tank No. 1 is connected by a pipe to the water source. It is also connected by a pipe and a check valve to Tank No. 2 and it is connected by a vertical pipe to Tank No. 3 which is situated below Tank No. 1.

In addition to being connected to Tanks No. 1 and 2, Tank No. 3 is connected to a dosing siphon.

The device pumps water in the following manner. Water flows from the source through the interconnecting piping into Tank No. 1. As Tank No. 1 begins to fill, water also begins to flow from Tank No. 1 through check valve No. 1 into Tank No. 2. (The check valve allows water to flow only in that one direction.) When Tank No. 2 is filled, the water rises in Tank No. 1 until it overflows into, and "water-seals", the pipe which leads to Tank No. 3. Then Tank No. 3 begins to fill.

Tank No. 3 is connected with piping in such a way that the air in Tank No. 3 is trapped between Tank No. 3 and Tank No. 2. The air cannot flow upward into Tank No. 1 because of the water seal. Therefore, it is compressed and its only escape is up through the piping connecting Tank No. 3 to the top of Tank No. 2. Thus the compressed air is applied to the water surface in Tank No. 2. Since the water cannot flow backwards through Check Valve No. 1, it flows through Check Valve No. 2 up into the storage tank.

As the air is compressed, water rises in the dosing siphon. The dosing siphon is adjusted to a height so that just before Tank No. 2 is completely

evacuated of water the siphon begins to discharge the water from Tank No. 3. It discharges until the water level in Tank No. 3 drops to a level at which air is sucked into the siphon thus breaking the siphon action.

As Tank No. 3 is discharged by the siphon the pressure of entrapped compressed air is reduced. Then water again begins to flow from Tank No. 1 into Tank No. 2, the water level in Tank No. 1 drops below its overflow, and the cycle is repeated.

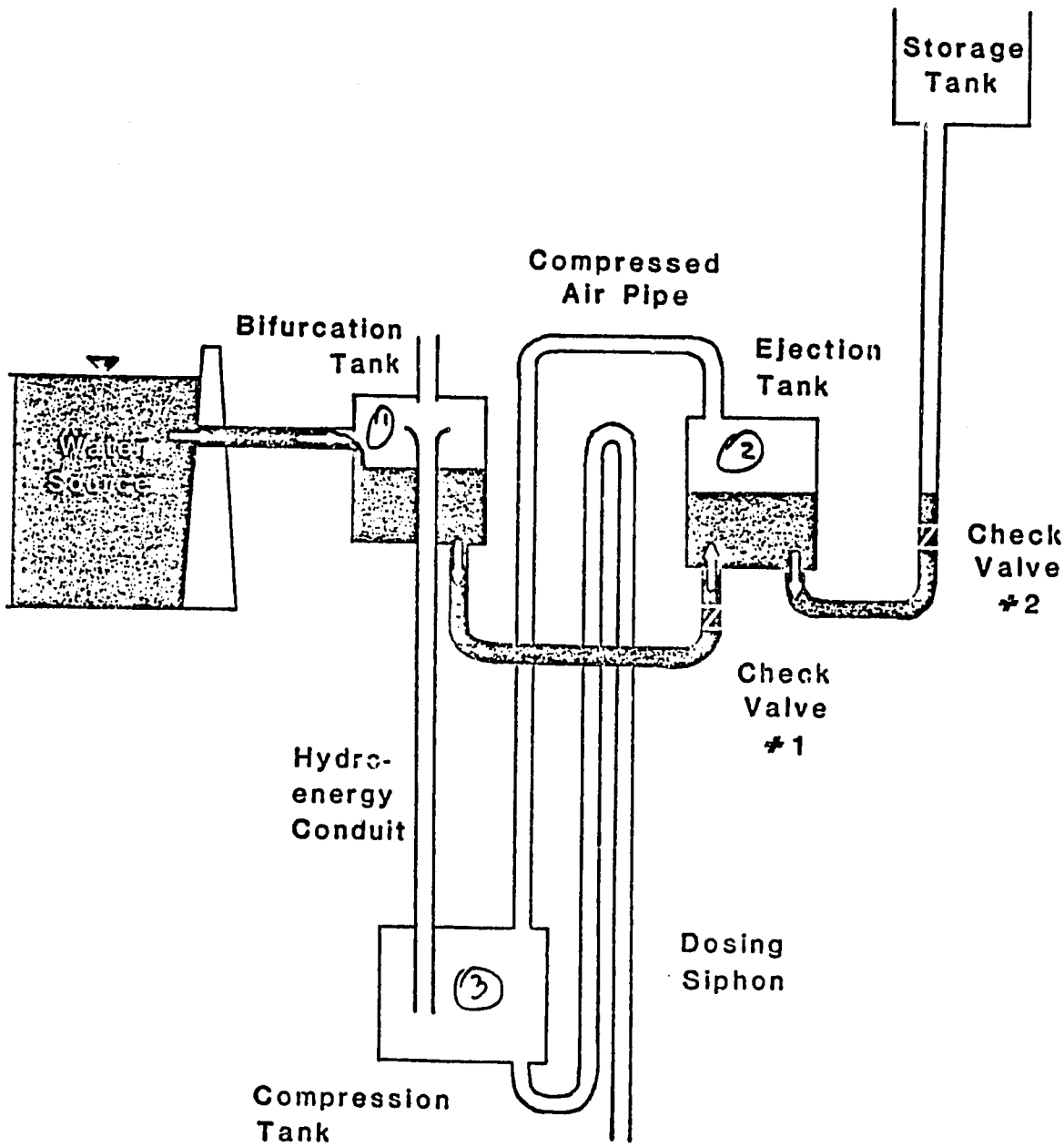
The ratio of water discharged to the water pumped is controlled by Boyle's Law, mathematically stated as $P_1V_1 = P_2V_2$ where P_1 and P_2 are absolute pressures and V_1 and V_2 are the respective volumes. Without going into the calculations this means that for a lift of 10 meters it will be necessary to discharge approximately twice as much water, as water pumped to the higher elevation. For a 20 meter lift the ratio will be about 3 to 1 and for 30 meter lift the ratio will be about 4 to 1. Of course, there will be losses due to the friction of the pipe, fittings, and check valves but this can be minimized by proper engineering and pipe size selection.

This device can be used advantageously in situations where there is a need to pump water to an elevation above the water source and where there is an equal or greater drop in elevation below the water source and where there is an ample supply of water.

Such a situation is often found in dam impoundments, in water distribution systems, and in hilly or mountainous terrain. It is especially appropriate where the water discharged from the siphon can be used beneficially at the lower elevation.

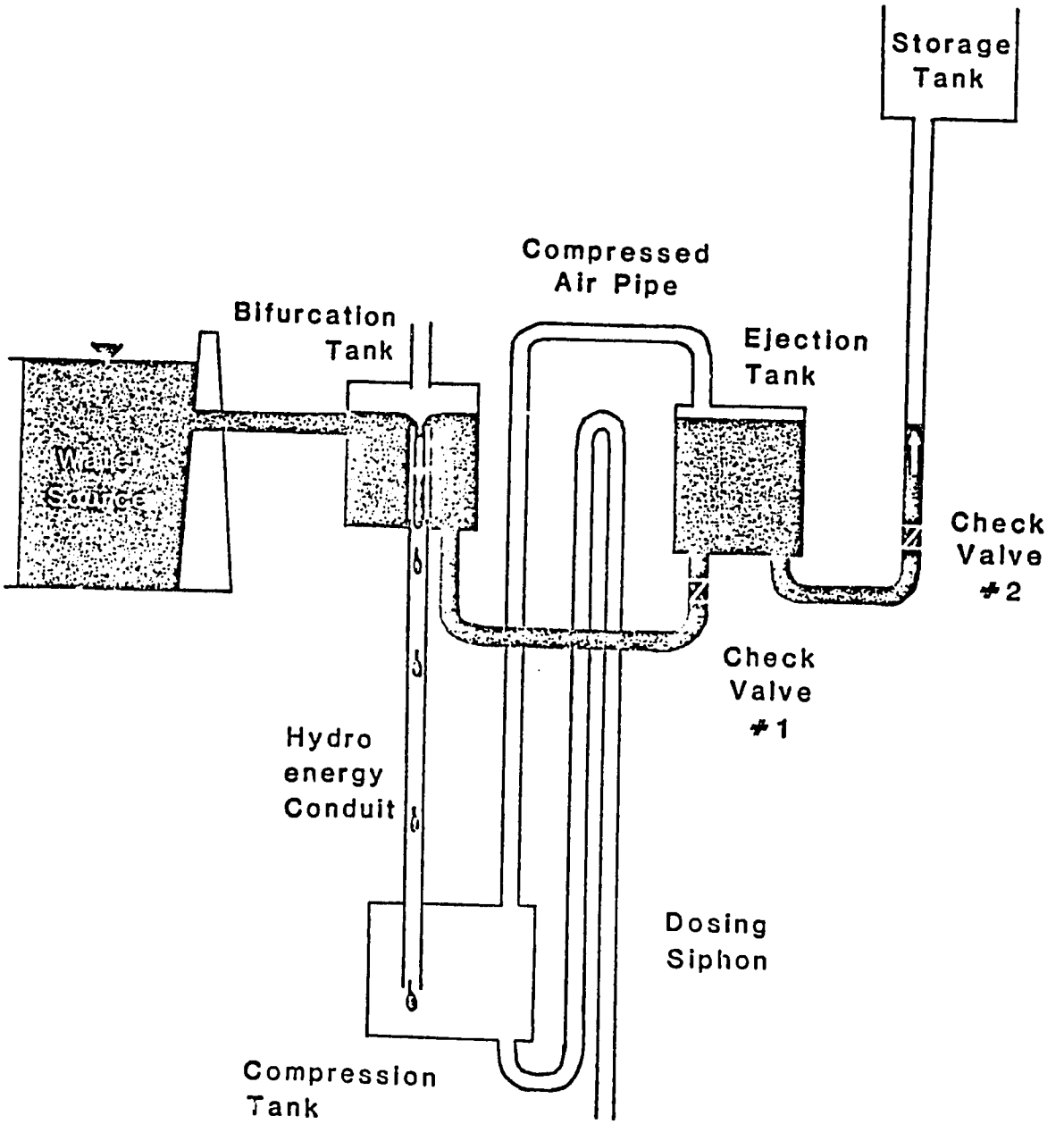
SIPHON ACTIVATED HYDROPNEUMATIC PUMP

(1)
FILL

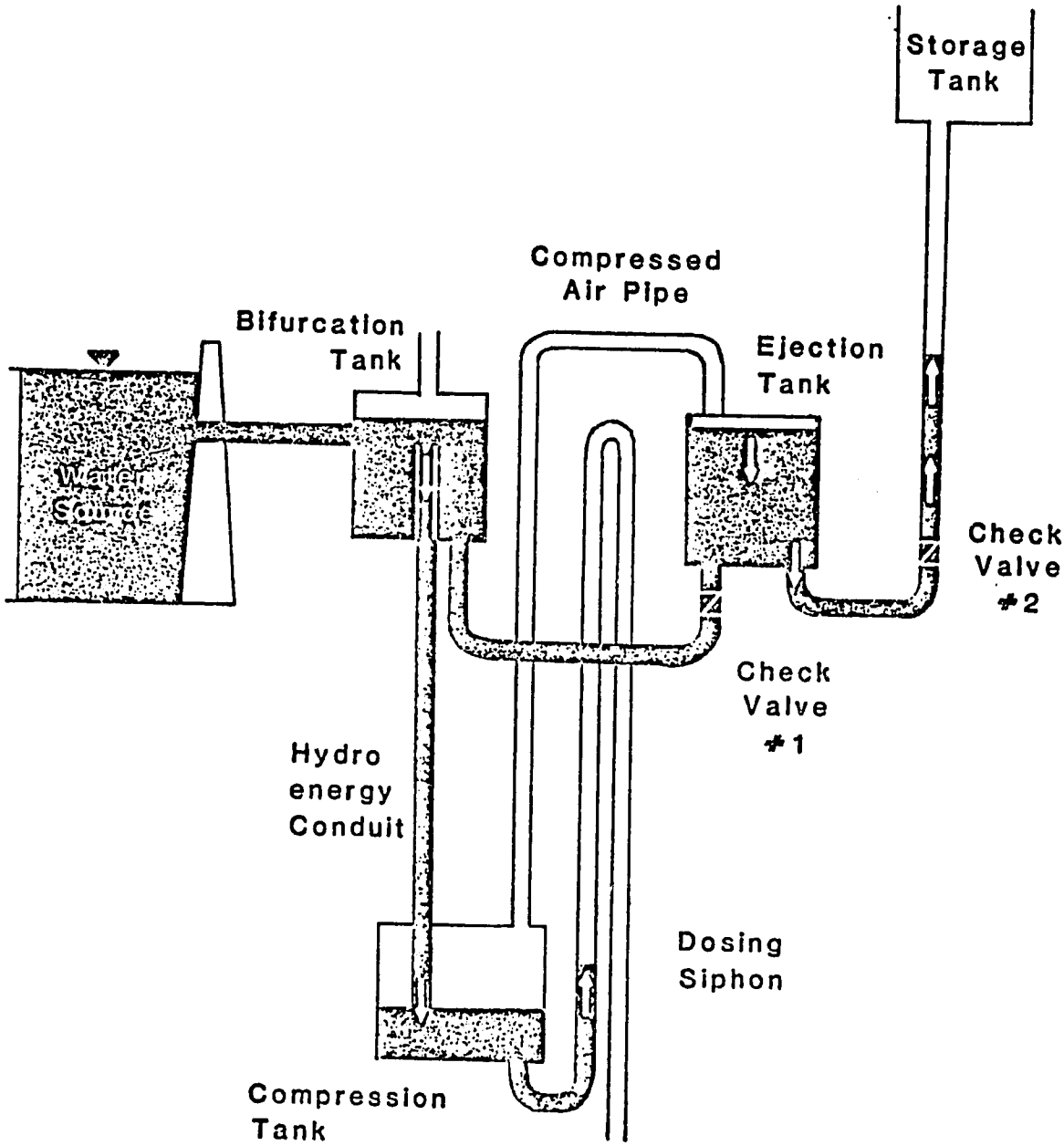


(2)

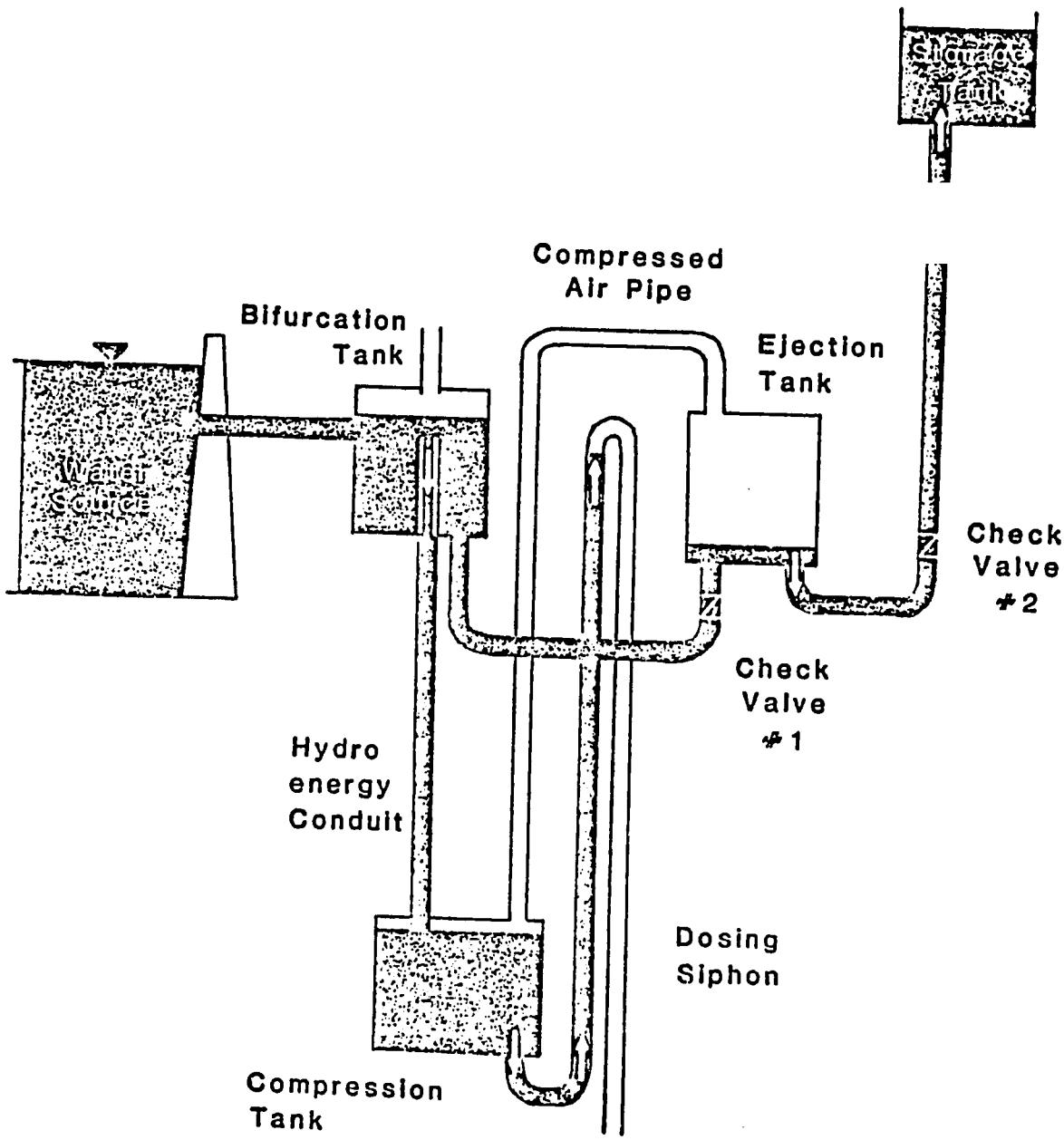
BIFURCATION AND EJECTION TANKS FULL WATER DIVERTED TO COMPRESSION TANK



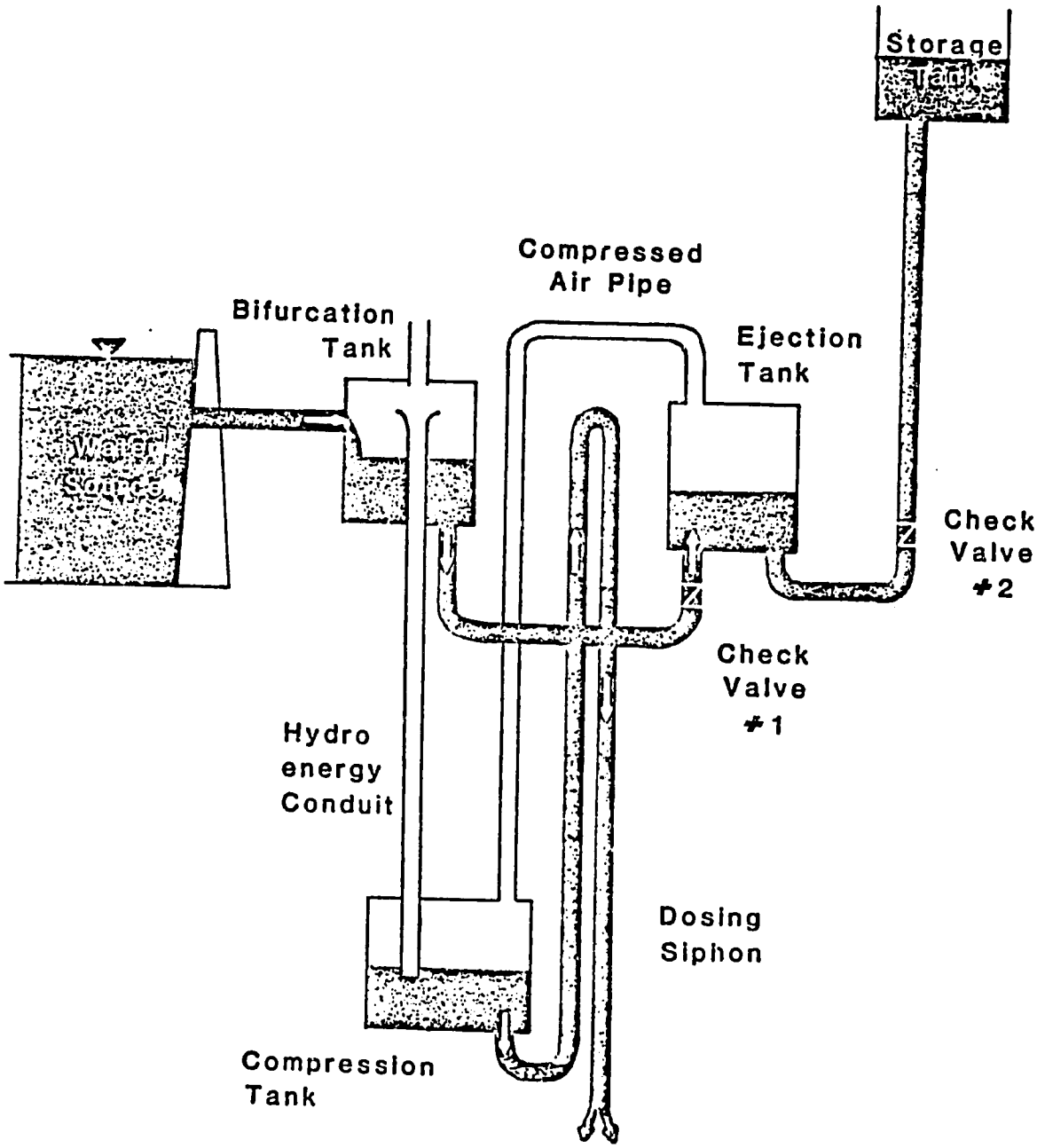
(3)
COMPRESSION AND EXPULSION



(4)
END EXPULSION



(5)
DUMP COMPRESSION TANK, REFILL GO BACK TO (1)



APPENDIX C

COMPUTER MODEL RUN PRINTOUTS

1-24-84 (3)

T=ELAPSED TIME IN SEC. AT END OF CYCLE, T2=CYCLE DURATION, R5=PAYLOAD PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT CYCLE.

T	T2	R5	R6
45.6	45.6	0.0012382768360 1	0.0020500000 03545
91.0000000000	46	0.0011201673 0117	0.0020252450000817
137.6	46	0.0011215300 0700	0.0020252042044 0
183.8	46.2	0.0011205340 7000	0.0020120077000
230.2	46.4	0.0011214422 0051	0.0020007354 1006
276.4	46.1000000000	0.0011243350 3552	0.0020130104 3355
322.300000000	45.0000000007	0.0011231066 4400	0.0020202702 0052
368.500000000	46.1000000007	0.0011246218 3465	0.0020130007 2136
414.000000000	46.3000000007	0.0011218804 3644	0.0020007205 2050
461.100000000	46.1000000007	0.0011236570 3042	0.0020120007 150
507.100000000	45.0000000007	0.0011278077 2481	0.0020252536231
553.100000000	45.0000000004	0.0011200232 0202	0.0020202201544
600.500000007	46.3000000003	0.0011215332 0182	0.0020000150 4735
645.000000006	46.3000000003	0.0011216660 6804	0.0020007308 6300
692.100000006	46.1000000003	0.0011246034 1623	0.0020130101 3060

```
5 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 10, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 V2=-0.05
130 K3=0.0165
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 V5=5
160 K6=0.0165
161 V6=-0.01
162 B6=-6
163 E6=B6-1
180 C0=B6+0.5
181 A0=0.247
190 L0=B6
191 A0=4.0E-4
193 P0=5.2
195 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
196 G1=1
197 R1=0
198 R2=0
199 R3=0
200 T1=700
```

1.24-84-(9)

T=ELAPSED TIME IN SEC. AT END OF CYCLE, T2=CYCLE DURATION, R5=PAYLOAD PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT CYCLE.

T	T2	R5	R6
24.0	24.0	0.00103035428285	0.00200361240654
49.0	25	7.531601863E-4	0.00206743143010
75.4	26.0	7.718721556E-4	0.00200115007010
100.6	25.2	7.701326505E-4	0.00204572200074
126.0	25.2	7.677002157E-4	0.00204601473025
151.2	25.4	7.67065064E-4	0.00202370774036
176.4	25.2	7.706338512E-4	0.00204500151070
201.6	25.2	7.600473530E-4	0.00204622062040
226.6	25	7.527060300E-4	0.00206735364003
252.2	25.6	7.76730100E-4	0.00200000002500
277.4	25.1000000000	7.773006271E-4	0.00204533007014
302.6	25.1000000000	7.643248440E-4	0.00204536067170
327.700000000	25.1000000000	7.665414014E-4	0.00204577426637
353.100000000	25.3000000000	7.647060177E-4	0.00202336[illegible]4165
378.300000000	25.1000000000	7.751638595E-4	0.00204407036207
403.500000000	25.1000000000	7.605433735E-4	0.00204464337005
428.700000000	25.1000000000	7.593274484E-4	0.00204430204735
453.900000000	25.1000000000	7.570740012E-4	0.00204306526050
479.300000000	25.3000000000	7.750038130E-4	0.00202353731540
504.300000000	24.0000000000	7.549306700E-4	0.00206751766260
529.500000000	25.1000000007	7.506467701E-4	0.00204423327504
555.100000000	25.5000000006	7.721265645E-4	0.00200012740260
580.300000007	25.1000000008	7.700341075E-4	0.00204567524457
605.500000007	25.1000000006	7.602711533E-4	0.00204620510303
630.500000007	24.0000000006	7.533006711E-4	0.00205747000070
656.100000006	25.5000000006	7.710020061E-4	0.00200120007401
681.300000006	25.1000000006	7.705367000E-4	0.00204570073570

```
5 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 10, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 W2=-0.05
130 K3=0.0165
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 W5=5.5
160 K6=0.0165
161 W6=-0.01
162 B6=-6
163 E6=B6-1
170 C0=B6+0.5
171 A0=0.247
180 L0=B0
181 A0=4.0E-4
185 P0=10.4
195 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
196 G1=1
197 R1=0
```

Best Available Document

1·2·1·84 (5)

T=ELAPSED TIME IN SEC. AT END OF CYCLE. T2=CYCLE DURATION,
R5=PAYLOAD PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT
CYCLE.

T	T2	R5	R6
49.4	49.4	0.00157983861023	0.00263005104011
99.1000000000	49.0	0.00148470680015	0.00268067277920
149	49.0	0.00147948771042	0.00268068200404
199.2	50.2	0.00147756340495	0.00250000443170
249.4	50.2	0.00147632057066	0.00250070647060
299.4	49.9999999999	0.00149157906047	0.00250021040051
349.100000000	49.7000000007	0.00148200060517	0.00268067021584
399.000000000	49.7000000007	0.00148720004269	0.00268065092762
448.700000000	49.7000000007	0.00148122206545	0.00268071025116
498.700000000	49.9999999997	0.00149210430066	0.00250021217780
548.000000000	50.1000000004	0.00147822307517	0.00250070470375
599.000000007	49.0000000003	0.00149142721	0.00250020013142
648.700000006	49.7000000003	0.00148356756060	0.00268067592060
698.500000006	49.7000000003	0.00148473430670	0.00268067200613

```
5 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 19, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 W2=-0.05
130 K3=0.0165
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 W5=5
160 K6=0.0165
161 W6=-0.01
162 B6=-6
163 E6=B6-1
180 C0=B6+0.5
181 A0=0.247
190 L0=B6
191 A0=4.9E-4
193 P0=10.4
195 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
196 G1=1
197 R1=0
198 R2=0
199 R3=0
200 T1=700
```

Best Available Document

1-24-84 (6)

T=ELAPSED TIME IN SEC. AT END OF CYCLE. T2=CYCLE DURATION,
R5=PAYLOAD PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT
CYCLE.

T	T2	R5	R6
50.6	50.6	0.0016571440 6917	0.0025036346517
101.8	51.2	0.0015584308 3031	0.0025531703 6635
153	51.2	0.0015592694716	0.0025531143477 0
204.2	51.2	0.0015599 3085956	0.0025532105097
255.4	51.2	0.0015576022 0860	0.0025531 0941546
306.6	51.1000000007	0.0015664082116	0.0025530720710
357.700000000	51.1000000007	0.0015606 3563334	0.0025532262 2084
408.000000000	51.1000000007	0.0015594507531 6	0.0025531 7097170
459.100000000	51.1000000007	0.0015640643920 2	0.0025531152621 8
511.300000000	51.1000000007	0.0015599431656	0.0025532101 0699
562.500000000	51.1000000003	0.0015574538 0565	0.0025531573 6972
613.700000007	51.1000000003	0.0015665481 1984	0.0025530 058760
664.000000006	51.1000000003	0.0015686582640	0.0025532267 2036

```
5 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 10, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 W2=-0.05
130 K3=0.0165
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 W5=4
160 K6=0.0165
161 W6=-0.01
162 B6=-6
163 E6=B6-1
180 C8=B6+0.5
181 A8=0.247
190 L9=B6
191 A9=4.0E-4
193 P0=10.4
195 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
196 G1=1
197 R1=0
198 R2=0
199 R3=0
200 T1=700
```

1-29-84 (9)

T=ELAPSED TIME IN SEC. AT END OF CYCLE, T2=CYCLE DURATION,
R5=PAYLOAD PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT
CYCLE.

T	T2	R5	R6
54.8	54.8	0.00184059273075	0.00242902681010
110.2	55.4	0.00185684390094	0.00240233663002
165.6	55.4	0.00185639051546	0.00240231003202
221	55.4	0.00185009720020	0.00240220500002
276.4	55.3000000000	0.00185025385001	0.00240210344124
331.700000000	55.3000000007	0.00185002103742	0.00240230440620
387.100000000	55.3000000007	0.00185773955336	0.00240237346756
442.800000000	55.3000000007	0.00185739763773	0.00240236022271
497.000000000	55.3000000007	0.00185698350400	0.00240234410370
553.300000000	55.3000000003	0.00185648214310	0.00240232475070
608.700000007	55.3000000002	0.00185033058710	0.00240230122003
664.100000006	55.3000000002	0.00185769005070	0.00240237036000

```
5 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 19, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 R1=0.0165
120 A2=0.245
121 W2=-0.05
130 R3=0.0165
140 A4=0.247
141 C4=0.005
150 R5=0.0165
151 W5=1
160 R6=0.0165
161 W6=-0.01
162 B6=-6
163 E6=B6-1
169 C6=B6+0.5
181 A8=0.247
190 L9=B6
191 A9=4.9E-4
193 P0=10.4
195 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
196 G1=1
197 R1=0
198 R2=0
199 R3=0
200 T1=700
```

1-24-84 (7)

T=ELAPSED TIME IN SEC. AT END OF CYCLE, T2=CYCLE DURATION,
R5=PAYLOAD PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT
CYCLE.

T	T2	R5	R6
51.0	51.0	0.0017482387557 5	0.0025368309431 8
104.2	52.4	0.0016814604741 2	0.0025678103838 4
156.6	52.4	0.0016515048338	0.0025678220712 1
209	52.4	0.0016517669824	0.0025678274722
261.4	52.3999999999	0.0016510028658 9	0.0025678334803
313.799999999	52.3999999997	0.0016522095862 0	0.0025678417554
366.199999999	52.3999999997	0.0016526747845 3	0.0025678516427 5
418.599999999	52.3999999997	0.0016531703523 6	0.0025678658000 6
470.999999999	52.3999999997	0.0016539428362	0.0025678628657 5
523.199999998	52.1999999998	0.0016601210851 5	0.0025172661849 0
575.399999997	52.1999999992	0.0016590033972 5	0.0025172742198 7
627.599999997	52.1999999992	0.0016590278118 9	0.0025172734 34
679.799999996	52.1999999992	0.0016590265628 9	0.0025172735239 9

```
5 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 19, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 W2=-0.05
130 K3=0.0165
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 W5=3
160 K6=0.0165
161 W6=-0.01
162 B6=-6
163 E6=B6-1
180 C8=B6+0.5
181 A9=0.247
190 L9=B6
191 A9=4.0E-4
193 P8=10.4
195 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
196 G1=1
197 R1=0
198 R2=0
199 R3=0
200 T1=700
```

1-24-84 (3)

T=ELAPSED TIME IN SEC. AT END OF CYCLE. T2=CYCLE DURATION, R5=PAYLOAD PUMPING RATE, AND R8=EXHAUST FLOW RATE OF CURRENT CYCLE.

T	T2	R5	R8
53.4	53.4	0.00103565518353	0.00249288045984
107.6	54.2	0.00174262812482	0.00244571478369
161.6	54	0.00174844286449	0.00245420257782
215.6	54	0.00174902176137	0.00245481430351
269.6	53.9999999999	0.00174924684607	0.00245481296278
323.599999999	53.9999999997	0.00174924238361	0.00245481317746
377.599999999	53.9999999997	0.00174924388248	0.00245481314112
431.599999999	53.9999999997	0.00174924262681	0.00245481314162
485.599999999	53.9999999997	0.00174924204519	0.00245481314543
539.599999999	53.9999999995	0.00174924264284	0.00245481314555
593.599999997	53.9999999992	0.00174924204432	0.00245481314555
647.599999996	53.9999999992	0.00174924204314	0.00245481314555

```
5 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 19, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 V2=-0.05
130 K3=0.0165
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 V5=2
160 K6=0.0165
161 V6=-0.01
162 B6=-6
163 E6=B6-1
170 C0=B6+0.5
181 A0=0.247
190 L0=B6
191 A9=4.0E-4
193 P0=10.4
195 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
196 G1=1
197 R1=0
198 R2=0
199 R3=0
200 T1=700
```

1-24-84 (10)

T=ELAPSED TIME IN SEC. AT END OF CYCLE, T2=CYCLE DURATION,
R5=PAYLOAD PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT
CYCLE.

T	T2	R5	R6
56.4	56.4	0.00287007409282	0.00236073603765
113.2	56.7000000000	0.00109415023349	0.00235193061700
170	56.7000000000	0.00109405068324	0.00235196768716
226.8	56.7000000000	0.00109402275307	0.00235196818764
283.6	56.7000000000	0.00109401734758	0.00235196260533
340.300000000	56.7000000007	0.00109401636007	0.00235196200700
397.100000000	56.7000000007	0.00109401619557	0.00235196203234
453.800000000	56.7000000007	0.00109401616453	0.00235196203603
510.700000000	56.7000000007	0.00109401615081	0.00235196203763
567.500000000	56.7000000002	0.00109401615084	0.00235196203770
624.300000007	56.7000000002	0.00109401615787	0.00235196203702
681.100000006	56.7000000002	0.00109401615784	0.00235196203702

```
5 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 19, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 W2=-0.05
130 K3=0.0165
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 W5=0
160 K6=0.0165
161 W6=-0.01
162 B6=-6
163 E6=B6-1
100 C0=D0+0.5
101 A0=0.247
109 L0=96
101 A0=4.9E-4
103 P0=10.4
105 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
106 G1=1
107 R1=0
100 R2=0
109 R3=0
200 T1=700
```

1-24-84 (11)

T=ELAPSED TIME IN SEC. AT END OF CYCLE, T2=CYCLE DURATION,
R5=PAYLOAD PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT
CYCLE.

T	T2	R5	R6
55.6	55.6	0.00210764862953	0.00236345078292
111.6	56	0.00282140621417	0.00234647585170
167.6	56	0.00282140568036	0.00234647063320
223.6	56	0.00282140237682	0.00234647055302
279.6	55.9999999998	0.00282140127415	0.00234647[illegible]854
335.599999999	55.9999999997	0.00282140001415	0.00234647006122
391.599999999	55.9999999997	0.00282140070744	0.00234647000265
447.599999999	55.9999999997	0.00282140007507	0.00234647000281
503.599999998	55.9999999997	0.00282140074740	0.00234647000680
559.599999998	55.9999999993	0.00282140074357	0.00234647000717
615.599999997	55.9999999992	0.00282140074220	0.00234647000751
671.[illegible]999996	55.9999999992	0.00282140074100	0.00234647000763

5 PAGE
```
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 10, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 W2=-0.05
130 K3=0.0165
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 W5=0
160 K6=0.0165
161 W6=-0.01
162 B6=-3
163 E6=B6-1
180 C8=B6+0.5
181 A9=0.247
190 L9=B6
191 A9=4.0E-4
193 P0=10.4
195 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
196 G1=1
197 R1=0
198 R2=0
199 R3=0
200 T1=700
```

1-24-84 (12)

T=ELAPSED TIME IN SEC. AT END OF CYCLE. T2=CYCLE DURATION,
R5=PAYLOAD PUMPING RATE. AND R6=EXHAUST FLOW RATE OF CURRENT
CYCLE.

T	T2	R5	R6
84.6	54.8	0.00203808664083	0.00238581605723
118.8	56.0	0.00103746430638	0.00235486700237
168.4	56.0	0.00103020223102	0.00235454412611
222.2	55.0	0.00103884433036	0.00235456023006
278	55.7000000009	0.00103886763015	0.00235454038426
333.700000000	55.7000000007	0.00103886373034	0.00235454052076
388.500000000	55.7000000007	0.00103886437562	0.00235454050402
445.300000000	55.7000000007	0.00103886426870	0.00235454050007
501.100000000	55.7000000007	0.00103886428546	0.00235454050021
556.900000000	55.7000000003	0.00103886428355	0.00235454050034
612.700000007	55.7000000002	0.00103886428403	0.00235454050033
668.500000006	55.7000000002	0.00103886428306	0.00235454050033

```
5 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 10, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 W2=-0.05
130 K3=0.0165
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 W5=0.5
160 K6=0.0165
161 W6=-0.01
162 B6=-3
162 E6=B6-1
180 C8=B6+0.5
181 A8=0.247
190 L0=B6
191 A0=4.0E-4
193 P0=18.4
195 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
196 G1=1
197 R1=0
198 R2=0
199 R3=0
200 T1=700
```

1·24 84 (13)

T=ELAPSED TIME IN SEC. AT END OF CYCLE, T2=CYCLE DURATION,
R5=PAYLOAD PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT
CYCLE.

T	T2	R5	R6
10.2	10.2	0	0.00380608507075
21.8	11.6	0	0.00263343126004
34.8	13	0	0.00200320840312
48.8	14	2.78634918E-5	0.00160102484165
63.6	14.8	0	0.00150435165006
82.3000000000	18.8	2.51428053E-5	0.00107671034220
102.6	20.2	1.63074622 3E-5	0.00100059277454
129.2	26.6	1.52653029 1E-5	7.50006396SE-4
166.8	37.6	2.035544702E-5	5.372879204E-4
201.4	34.6	3.213518051E-5	5.050066873E-4
232.0	31.4	1.321518245E-5	6.426021896E-4
279.6	46.7000000000	3.432668703E-5	4.319546601E-4
300.4	28.7000000000	1.455033024E-5	7.007070056E-4
358.300000000	41.0000000000	3.071307936E-5	4.013700497E-4
378.100000000	27.7000000000	1.507405243E-5	7.268709108E-4
417.000000000	39.7000000000	3.636852535E-5	5.070376474E-4
448.100000000	30.1000000000	3.605633117E-5	6.602536063E-4
477.000000000	29.7000000000	3.096057632E-5	6.702626133E-4
506.300000000	28.3000000000	2.663001440E-5	7.100700068E-4
542.000000000	36.6000000005	3.602060173E-5	5.621036313E-4
572.700000000	29.7000000006	1.016650053E-5	6.774436591E-4
610.700000007	37.0000000004	2.109350063E-5	5.312662430E-4
650.300000006	39.5000000004	2.492702630E-5	5.000106710E-4
687.500000006	37.1000000005	2.042607551E-5	5.420653776E-4

```
5 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 19, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 W2=-0.05
130 K3=0.0168
140 A4=0.247
141 C4=0.005
150 K5=0.0155
151 W5=2.9
160 K6=0.0105
161 W6=-0.01
162 B6=-3
165 E8=B5-1
180 C0=B6+0.5
181 A0=0.247
190 L0=B6
191 A0=4.0E-4
195 P0=10.4
196 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
198 G1=1
197 R1=0
199 R2=0
199 R3=0
200 T1=700
```

Best Available Document

1-24-84 (14)

T=ELAPSED TIME IN SEC. AT END OF CYCLE, T2=CYCLE DURATION,
R6=PAYLOAD PUMPING RATE, AND R8=EXHAUST FLOW RATE OF CURRENT
CYCLE.

T	T2	R5	R6
10.2	10.2	0	0.00308608587075
21.8	11.6	0	0.00263343126004
34.0	13	0	0.00200320040312
48.0	14	0	0.00160102484165
64	15.2	0	0.00155258058141
83.3000000000	19.4	0	0.00104327400202
106.4	23	0	0.782608181E-4
143.4	37	0	5.45150540OE-4

```
SIZE ERROR IN LINE 530 - MESSAGE NUMBER 6
LIST 1,200
5 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 10, 1984
150 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 W2=-0.06
130 K3=0.0165
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 W5=3
160 K6=0.0165
161 W6=-0.01
162 B6=-3
163 E6=B6-1
180 C8=B6+0.5
181 A8=0.247
190 L9=B6
191 A9=4.0E-4
193 P8=10.4
195 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
196 G1=1
197 R1=0
198 R2=0
199 R3=0
200 T1=700
```

1-24-84 (15)

T=ELAPSED TIME IN SEC. AT END OF CYCLE, T2=CYCLE DURATION, R5=PAYLOAD PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT CYCLE.

T	T2	R5	R6
24.8	24.8	0.0014188052888	0.0026810848125
50.6	25.8	0.0011784642833	0.0025784325624
76.4	25.8	0.0011816368122	0.0025785068848
102.2	25.8	0.0011826210136	0.0025780207844
128	25.8	0.0011840074573	0.0025782412706
153.4	25.4	0.0011801847332	0.0024874237229
178	24.6	0.0012144447208	0.0027838414013
203.4	25.4	0.0011605533643	0.0026175202882
228.8	25.4	0.0011685353382	0.0024871403869
253.4	24.6	0.0012133132231	0.0027828641213
278.8	25.3000000000	0.0011688407339	0.0024874693420
303.6	24.7000000000	0.0012868038872	0.0026317243753
329.300000000	25.7000000000	0.0011766182334	0.0025770632786
354.000000000	25.5000000000	0.0011651840604	0.0025078788122
380.300000000	25.3000000000	0.0011713854451	0.0026177248302
405.700000000	25.3000000000	0.0011693811718	0.0024874233672
430.500000000	24.7000000000	0.0012865242468	0.0026816478204
456.100000000	25.6000000000	0.0011582482888	0.0025072507783
481.700000000	25.5000000000	0.0011633691851	0.0025074003866
507.300000000	25.5000000000	0.0011816782173	0.0025074153822
532.700000000	25.3000000007	0.0011868156585	0.0024878782523
557.300000000	24.6000000006	0.0012121516427	0.0027827283534
582.700000007	25.3000000006	0.0011864656029	0.0024871113728
607.300000007	24.6000000006	0.0012128387118	0.0027828435152
632.700000007	25.3000000006	0.0011877523535	0.0024873101102
657.500000006	24.7000000006	0.0012863258894	0.0026814487186
683.100000006	25.6000000006	0.0011828648517	0.0025975077884

5 PAGE

```
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 10, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 V2=-0.05
130 K3=0.0165
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 V5=2.5
160 K6=0.0165
161 V6=-0.01
162 B6=-3
163 E6=30-1
170 C8=55+0.5
171 A8=0.247
180 L8=60
181 A9=4.0E-4
190 P0=10.4
195 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
196 G1=1
197 R1=0
```

1-24-84 (16)

T=ELAPSED TIME IN SEC. AT END OF CYCLE. T2=CYCLE DURATION, R5=PAYLOAD PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT CYCLE.

T	T2	R5	R6
94	54	0.0019748226342	0.0024280613583 2
108.6	54.5	0.0010059353710	0.0023041653 1004
153.2	54.6	0.0010006971467	0.0023042200741
217.8	54.6	0.0010042760612	0.0023041408 7 00
272.4	54.5000000000	0.0010006080052	0.0023042223745
326.000000000	54.5000000087	0.0010063555017	0.0023041524 0642
381.500000000	54.5000000007	0.0010060081507	0.0023042221 2954
436.100000000	54.5000000007	0.0010063507 4427	0.0023041522 6951
490.700000000	54.5000000007	0.0010060150546	0.0023042221 4502
545.300000000	54.5000000004	0.0010063501 5124	0.0023041522 0047
599.900000007	54.5000000002	0.0010060152100	0.0023042221 4410
654.500000006	54.5000000002	0.0010063502 0778	0.0023041522 0048

```
0 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 19, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 W2=-0.05
130 K3=0.0165
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 W5=1
160 K6=0.0165
161 W6=-0.01
162 B5=-3
163 E6=B6-1
180 C0=B6+0.5
181 A5=0.247
190 L0=B6
191 A0=4.0E-4
193 P0=10.4
195 REM GI IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
196 GI=1
197 R1=0
198 R2=0
199 R3=0
200 T1=700
```

1-24-84 (17)

T=ELAPSED TIME IN SEC. AT END OF CYCLE. T2=CYCLE DURATION,
RB=PAYLOAD PUMPING RATE, AND RG=EXHAUST FLOW RATE OF CURRENT
CYCLE.

T	T2	RB	RG
33.2	53.2	0.0010174322468	0.0024429331181
107.2	54	0.0010236394498	0.0024659684784
161.2	54	0.0010288260831	0.0024857000162
215.2	54	0.0010105774020	0.0024608721690
269.2	53.0000000000	0.0010224725[illegible]	0.0024655[illegible]
323.100000000	53.0000000007	0.0010288263460	0.0024658372052
377.100000000	53.0000000007	0.0010105145042	0.0024857389781
431.100000000	53.0000000007	0.0010105462178[illegible]	0.0024655387292
485.100000000	53.0000000007	0.0010235[illegible]	0.0024[illegible]4[illegible]3585
539.100000000	53.0000000006	0.0010210216[illegible]54	0.0024[illegible]4865
593.100000007	53.0000000002	0.0010284441365	0.0024[illegible]3243
647.100000006	53.0000000002	0.0010197222[illegible]	0.0024[illegible]4944

```
B PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 19, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 W2=-0.05
130 K3=0.0165
140 A4=0.247
141 C4=0.005
150 K5=0.0165
151 W5=1.5
160 K6=0.0165
161 W6=-0.01
162 B6=-3
163 E6=B6-1
170 C9=B6+0.5
171 A8=0.247
180 L0=B6
181 A0=4.0E-4
183 P0=10.4
185 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
186 G1=1
187 R1=0
188 R2=0
189 R3=0
200 T1=700
```

1-24-84 (18)

T=ELAPSED TIME IN SEC. AT END OF CYCLE. T2=CYCLE DURATION,
R5=PAYLOAD PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT
CYCLE.

T	T2	R5	R6
52.4	52.4	0.0018854660035	0.0024628410342
106.6	53.2	0.0017659915065	0.0024427438016
160.8	53	0.0017707900181	0.0024521100911
211.8	53.2	0.0017696291142	0.0024250224776
264.9	52.0000000000	0.0017720034243	0.0024340668120
317.300000000	52.6000000007	0.0017775146656	0.0024634810506
369.900000000	52.5000000007	0.0017770082402	0.0024534654016
422.700000000	52.7000000007	0.0017710346465	0.0024441786627
476.100000000	53.3000000007	0.0017842430644	0.0024335770354
529.300000000	53.1000000006	0.0017861235091	0.0024427460423
581.000000007	52.5000000002	0.0017772971018	0.0024534509103 2
634.500000007	52.5000000002	0.0017776702372	0.0024534630262
687.300000006	52.7000000002	0.0017714457160	0.0024441735541

```
5 PAGE
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 18, 1984
100 REM
101 REM ASSIGN VALUES
110 D=0.2
111 K1=0.0165
120 A2=0.245
121 W2=-0.05
130 K3=0.0165
140 A4=5.247
141 C4=0.005
150 K5=0.0165
151 W5=2
160 K6=0.0165
161 W6=-0.01
162 B6=-3
163 E6=B6-1
170 C8=B6+0.5
171 A8=0.247
180 L0=96
181 A0=4.0E-4
183 P0=10.4
185 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
186 G1=1
187 R1=0
188 R2=0
189 R3=0
200 T1=700
```

1-24-84 (19)

T=ELAPSED TIME IN SEC. AT END OF CYCLE, T2=CYCLE DURATION,
R5=AVERAGE PUMPING RATE, AND R6=EXHAUST FLOW RATE OF CURRENT
CYCLE

T	T2	R5	R6
47	47	0.0018501887878	0.0023562727685
85	38	0.0016400137753	0.0024000210043
128	37	0.0015481530536	0.0024213600067
172	52	0.0017003945740	0.0024506614751
214	42	0.0014656751650	0.0021447006547
264	50	0.0016072737113	0.0022007357273
303	39	0.0016478705200	0.0023220004285
347	44	0.0016035175000	0.0024717450357
397	50	0.0016102070410	0.0021070007007
437	40	0.0015744252716	0.0022551010207
480	43	0.0016254054445	0.0025073510137
531	51	0.0015721067246	0.0021530461487
571	40	0.0015615126400	0.0022522201466
623	52	0.0016015017010	0.0024540165614
678	55	0.0016103000000	0.0023231032407
730	52	0.0016036017000	0.0021210023014
767	37	0.0016153322606	0.0024202100734
810	51	0.0017051700157	0.0020002002334
850	41	0.0014002004732	0.0021040374763
890	39	0.0016005732004	0.0023120235450
930	40	0.0015001101420	0.0022500075144
987	49	0.0017212070272	0.0022520700127
1030	51	0.0017005315471	0.0020100404004
1081	43	0.0015351530056	0.0021132702400
1123	42	0.0016100034155	0.0020504320707
1166	43	0.0014747000015	0.0021000000505
1204	38	0.0016041404300	0.0023073240707
1243	39	0.0015670720306	0.0023121521004
1283	40	0.0015015100042	0.0022571004707
1326	43	0.0016400000030	0.0020110040031
1360	43	0.0015200000202	0.0021115105124
1407	38	0.0016300024134	0.0023700004570
1445	38	0.0016150274517	0.0023000500702
1489	44	0.0015470021016	0.0024000002225
1534	45	0.0015700000075	0.0023000400404
1576	42	0.0014740072367	0.0021400542105
1616	40	0.0015700215723	0.0022550147075
1660	44	0.0015010003361	0.0024032700001
1699	39	0.0015030700300	0.0023023171043
1739	40	0.0015772510304	0.0022014070720
1779	40	0.0015052200047	0.0022004221402
1815	36	0.0016312010004	0.0024040757116
1864	40	0.0017110411053	0.0022572657013
1905	41	0.0016027507102	0.0020320000100
1947	42	0.0014702000424	0.0021470047040
1991	44	0.0016724140004	0.0024040400104

5 PAGE

```
10 REM HYDROPNEUMATIC PUMP FOR WASH PROJECT JAN 19, 1984
100 REM
101 REM ASSIGN VALUES
110 D=1
111 A1=0.0165
```

1-24-84 (19-[illegible])

```
[illegible] A0=0.246
[illegible] [illegible]
[illegible] A0=0.0106
[illegible] A0=0.247
141 C4=0.[illegible]
[illegible] X0=0.0106
[illegible] W0=2
[illegible] X0=0.0106
181 W0=-0.01
182 B0=-3
183 E0=B0-1
[illegible] C0=B0+0.5
181 A0=0.247
[illegible] L0=B0
181 A0=4.0E-4
183 P0=10.4
106 REM G1 IS 1.0 FOR ISOTHERMAL, 1.4 FOR ADIABATIC CONDITIONS
106 G1=1
107 R1=0
108 R2=0
109 R3=0
203 T1=2000
```