GAS-DRIVEN PUMP FOR GROUND-WATER SAMPLES

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Principles of operation, actual operation techniques, gas-use analyses and operat ing experience are described in this report. Complete working drawings and a component list are included. Recent modifications for high-pressure applications are described.

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GAS-DRIVEN PUMP FOR GROUND-WATER SAMPLES

By

Donald C. Signor

ABSTRACT

Observation wells installed as a part of field work in artificial recharge research and wells used in other ground-water programs are frequently cased with small-diameter steel pipe. To obtain samples from these small diameter wells in order to monitor water quality and to calibrate solute-transport models, a small-diameter pump with unique operating characteristics is required that causes a minimum alteration of samples during field sampling.

A small-diameter gas-driven pump was designed and built to obtain water samples from wells of two-inch diameter or larger. The pump is a double-piston type with the following characteristics:

1. The water sample is isolated from the operating gas,
2. No source of electricity is necessary,
3. Operation is continuous,
4. Use of compressed gas is efficient, and
5. Operation is reliable over extended periods of time.

Principles of operation, actual operation techniques, gas-use analyses and operating experience are described in this report. Complete working drawings and a component list are included. Recent modifications and pump construction for high-pressure applications are also described.

INTRODUCTION

Observation wells installed as a part of the artificial-recharge research program of the U.S. Geological Survey have generally been cased with two-inch steel pipe. Small diameter wells are adequate for water-level measurements, easy to install, and reasonable in cost. However, as recharge proceeds it is often necessary to obtain samples from observation wells in order to monitor water-quality changes with time in the aquifer. Monitoring ground-water quality over extended periods of time requires periodic extraction of sufficient quantities of water from an observation well to ensure that a representative sample is obtained from the aquifer. Additionally, tracer tests require almost continuous samples over periods of several days. Such samples are difficult to collect in small-diameter wells. Consequently, a small-diameter pump with specifications and operating characteristics consistent with the field-sampling criteria is required.

The small-diameter pump described below meets the requirements for periodic or continuous sampling. It is gas driven and can be used in wells 2 inches (5 cm) or larger in diameter. The design principles are not new (Hedges, 1965) however, construction of the pump and control components on a small scale provide flexibility not previously available.

Conversion of U.S. Customary to Metric Units of Measurement

Measurements given in the text are in U.S. customary units with metric units following in parentheses. Components and drawings have only U.S. customary units specified. The following conversion table may be used to convert U.S. customary units to metric units or vice-versa.

U.S. customary units		Conversion factor	Metric units
Length			
inch (in)	x	2.54	= centimeter (cm)
foot (ft)	x	0.3048	= meter (m)
Pressure			
Pound per square inch (psi)	x	.07031	= Kilogram per cm^2 (kg/cm^2)
Pound per square inch absolute (psia)			
Volume			
Gallon	x	3.785	= Liter (L)
Cubic foot (ft^3)	x	28.32	= Liter (L)
Volume rate			
Cubic foot per hour (ft^3/hr)	x	0.4720	= Liter per minute (L/min)

EXISTING PUMPS

An examination of manufacturer's literature and other sources indicates that no electrically operated pump is commercially available for very-small-diameter well installations. Such a pump would require a continuous electrical power supply, which in many field situations is a disadvantage.

A pump for sampling from small-bore wells was developed by Bianchi and others (1962). The pump consists of a 1.25-inch (3.2 cm) brass-tube body, foot valve, discharge line, and air line. Submerging the pump fills the body, and the water sample is discharged to the surface through plastic tubing by using a hand-operated tire pump. After the water is expelled from the pump, the pressure is released and the pump refills. This pump worked satisfactorily for water lift from 100 feet (30.5 m) if it was submerged to a depth of no more than 5 feet (1.5 m).

A commercially manufactured pump 1/ utilizes the same principle as that of the pump described above, but incorporates several significant refinements. The pump system is composed of three basic parts: the sampler with depth indicator, a portable control unit and flexible connective tubing. The control unit consists of gages, valves and connectors for the pump tubing and gas supply. The pump is operated by compressed gas and the standard-size sampler with an outside diameter of 1.75-inch (4.4 cm) is specified to operate in the range 0-2000 feet (0-610 m) of water. Information provided by the company indicated that the pump could easily be modified by reducing the diameter for use in observation wells with a riser (or casing) of 1.5-inches (3.8 cm) ID (inside diameter).

A portable sampler operating on the principle of gas-lift pumping was developed using a single 14-ounce propane cylinder for energy (Smith, 1976). The sampler consists of a 0.25-inch (.6 cm) plastic tube telescoped within another 0.5-inch (1.3 cm) plastic tube. Small holes in the lower end of the internal plastic tube permit gas to be dispersed inside the annulus, resulting in gas-lift pumping. The 120-140 psi (pound per square inch) (8.4-9.8 kg/cm^2) pressure of the propane cylinder allows a submergence of the sampler tube to 250 feet (76 m). A test in an observation well with a static water level at 76 feet (23 m) and the sampler intake at 109 feet (33 m) produced 8.6 gallons (32.6 L) of water by exhausting a single 14-ounce propane cylinder. Thus the sampler worked well with 30-percent submergence. As the largest tubing is 0.5-inch (1.3 cm) in diameter, the sampler will operate in an observation well of very small diameter.

1/ Terra Tec Incorporated*, 3018 Western Ave., Seattle, Wash. 98121.

* The use of brand names or company names in this report is for reference and identification purposes only and does not imply endorsement by the U.S. Geological Survey.

Smith (1976) also reported that presence of propane gas in water did not affect a mineral analysis. Although no specific data are presented, it was indicated that results of a mineral analysis conducted on a sample obtained with the propane sampler were the same as an analysis made of water obtained with a turbine pump.

Air used for pumping, such as in the air-lift or gas-lift technique, alters the water sample. The turbulence with which the water is brought to the surface may have significant effects on pH, carbonate, bicarbonate and temperature, (Wood, 1976). Therefore, to obtain samples with assurance that their geochemical properties are representative of their original condition, it is required that the sample be isolated from any expulsive gas. Consequently, Middelburg (written communication, 1976) developed a pump based on a squeeze principle similar to that of the heart called the air squeeze pump (ASP). Water enters a rubber tube through a foot valve and the rubber tube is then compressed by air pressure between its exterior and a steel tube, expelling the water to the surface. The pump is operated by a timer-actuated solenoid valve operated by a battery.

Pumping rate depends on the interval setting of the timer operating the solenoid valve, gas pressure, pump submergence and pumping head. The pump construction allows a maximum operating pressure of approximately 160 psi (11.2 kg/cm^2) and thus can obtain water from 370 feet (113 m) below land surface. A volume of approximately .8 L (.2 gal) will be produced with one pump cycle from a full pump. As an example, if the pump is sufficiently submerged to completely fill and is operated at one cycle per minute, it will pump at a rate of .8 L/min (.2 gal/min).

A double-acting piston pump operating on alternating pulses of air or nitrogen was developed for sampling from observation wells in Kentucky (Hillerich, written communication, 1976). Wells as small as 1.5 inch (3.8 cm) in diameter can be sampled. The pump cycling is controlled at the surface by a solenoid valve that alternates pressure into and out of the pump air line. Operating pressure can vary from 90 to 250 psi (6.3-17.6 kg/cm^2). The pump can deliver approximately 4.2 ft^3/hr (2 L/min) from a well 80 feet (24 m) deep. Wells as deep as 320 feet (98 m) have been sampled.

Operation of the pumps described above requires that the pumping unit or lines be depressurized and then repressured for each pumping cycle. This is acceptable for limited sampling, but for continuous sampling, as during a tracer test lasting several days, the quantity of compressed gas required would be large.

This report describes the design and operation of a pump that obtains samples from wells two inches or more in diameter and which (1) isolates the sample from the operating gas, (2) requires no electrical power source, (3) operates continuously, (4) uses compressed gas[2/] economically, and (5) operates reliably over extended periods of time.

2/ Nitrogen has been used but any dry compressed gas or mixture of gases such as air would be suitable.

GAS-DRIVEN SAMPLE PUMP

Design Principles

The pump is a double-acting piston type operated by compressed gas. Two cylinders joined by an intermediate connector contain pistons joined by a common piston rod passing through the connector. The driving gas enters and exhausts from the gas chambers between the connector and the pistons. The connector holds a switching spindle unit actuated by piston travel that alternately pressurizes and exhausts the gas chambers. Built-in check valves at each end of the pump allow water to enter the cylinders on the suction stroke and to be expelled to the surface on the pressure stroke. The upper pump end has a built-in pilot valve actuated by a low-pressure pilot operator that is used, as necessary, to unidirectionally operate the switching spindle unit independently of piston travel. Figure 1 shows the schematic design and flow diagram of the pump and its operation.

Pump Components

A partially disassembled pump is shown in figure 2 and an exploded-assembly drawing is shown on plate 4. Dimensional details are contained in the shop drawings, plates 1 to 3. Components for a complete pumping system, number required, construction material used and supplier source are listed in table 1. The numbers shown in figure 2 and the plates correspond to numbers of those particular components listed in table 1.

The exploded-assembly drawing does not show the components and the arrangement used to connect the tube bundle to the pump inlets and outlets. These are connected on the assembled pump as shown in figure 3. The assembled pump is connected to a tube bundle consisting of three polyethylene tubes sheathed in polyethylene. The connective arrangement may be altered, for example, by using four tubes in the bundle to separate the pilot operator pressure from the exhaust line. This change has been made in recently constructed pumps. The pump manufacturer has also fabricated a connective "harness", eliminating asterisked components listed in table 1.

The pump, prior to use in a well, is sheathed in a PVC (polyvinyl chloride) pipe. A motorized, battery-operated storage reel, trailer, compressed-gas bottles fitted with pressure regulators, a support pulley attached to the well, appropriate tubing, valves and quick-disconnect couplings complete the system (figures 4 and 5).

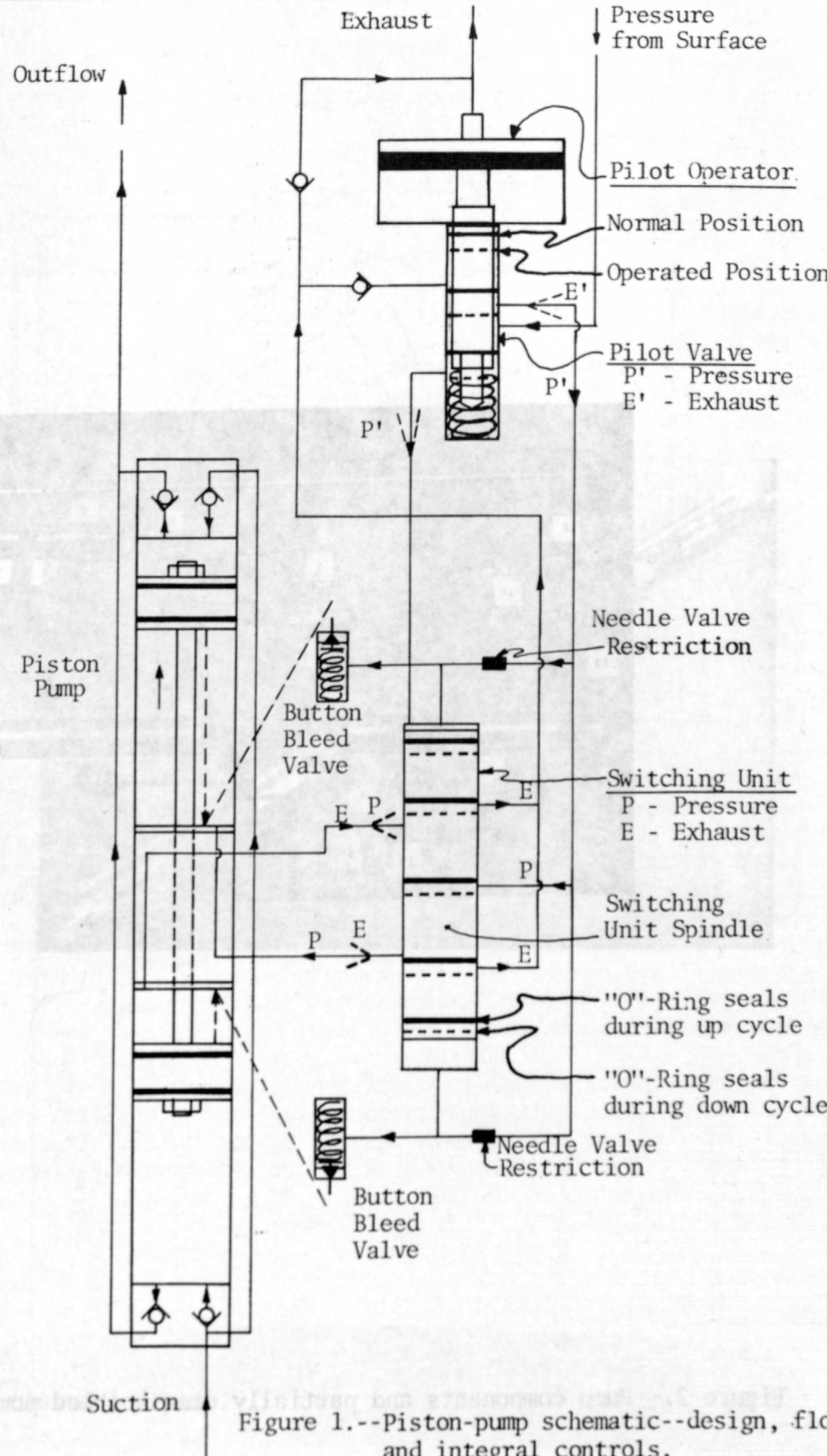

Figure 1.--Piston-pump schematic--design, flow, and integral controls.

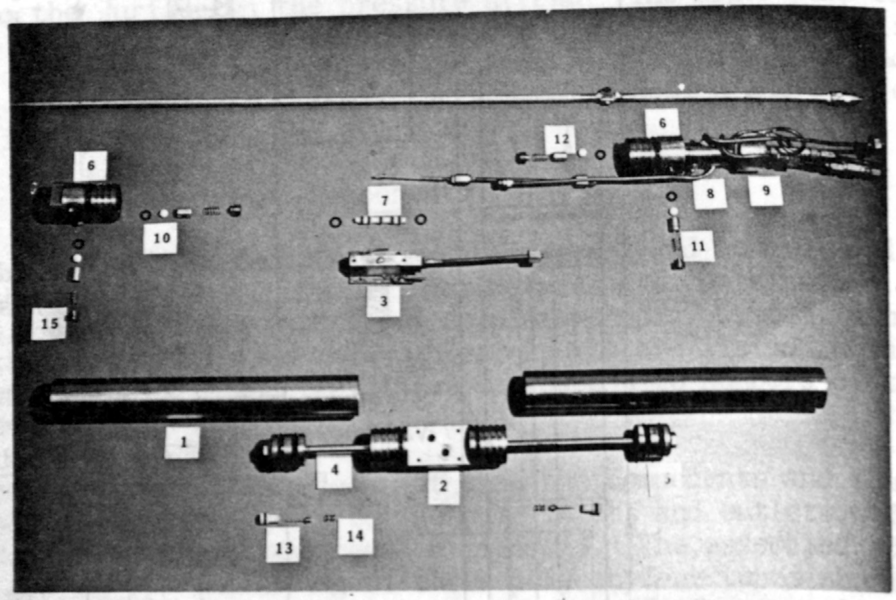

Figure 2.--Pump components and partially disassembled pump.

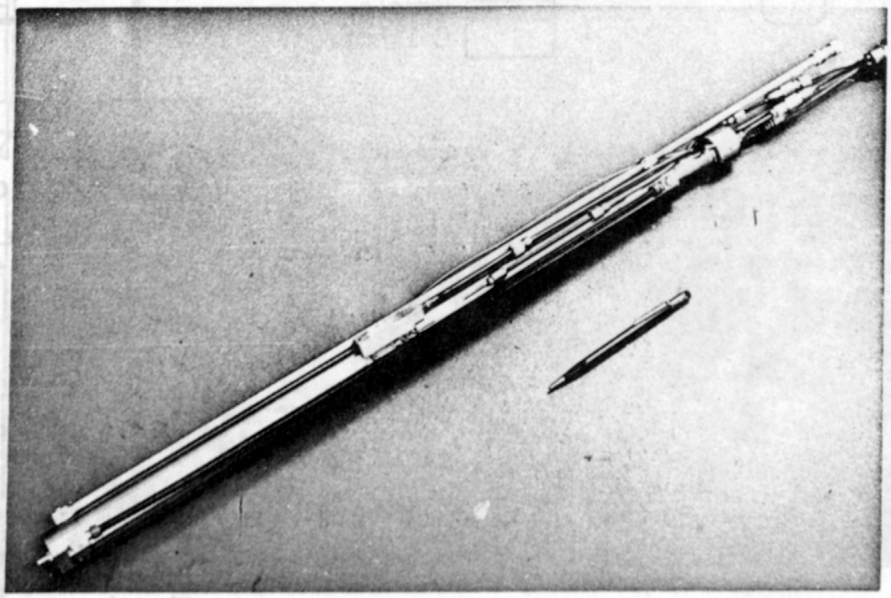

Figure 3.--Assembled pump.

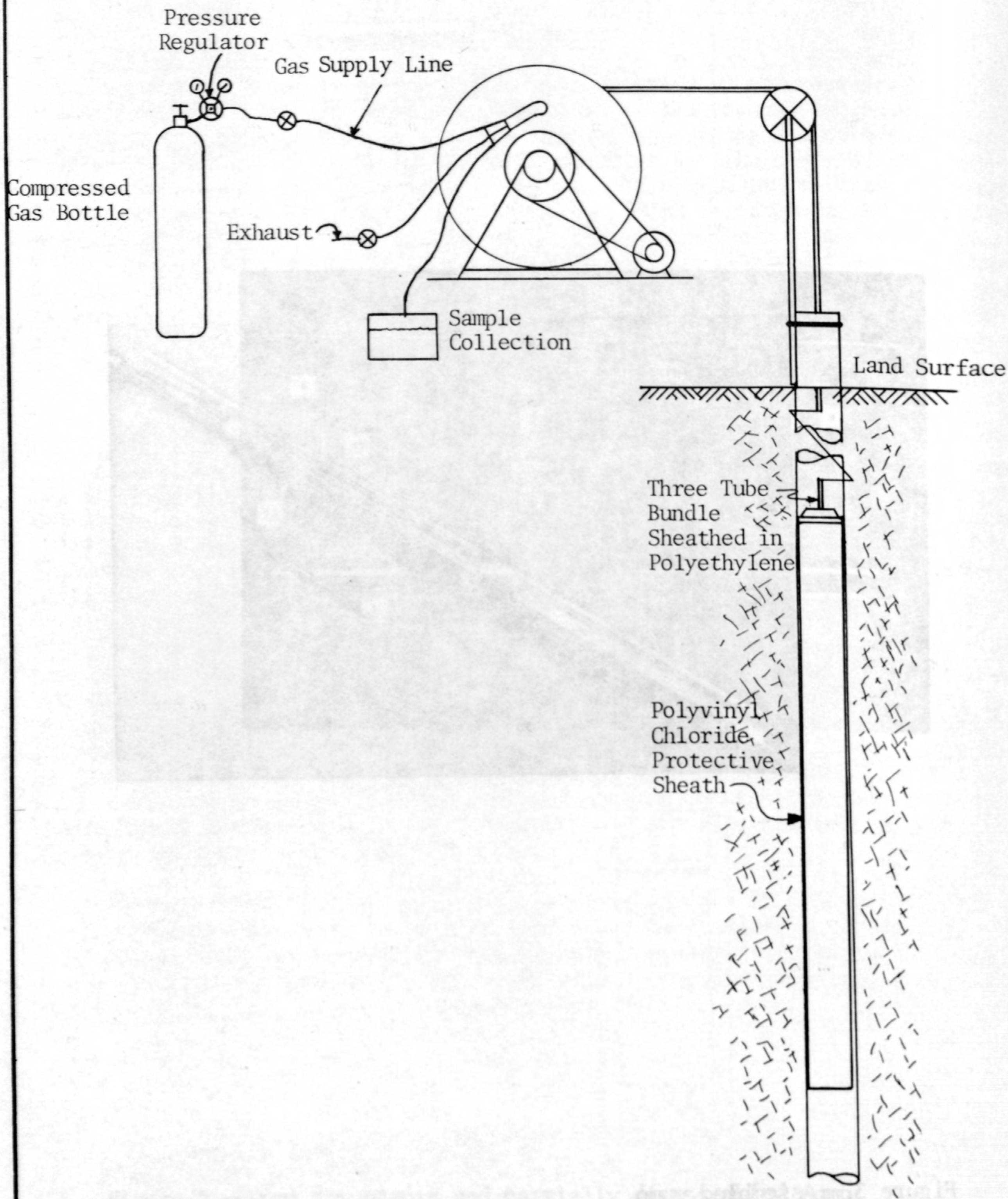

Figure 4.--Schematic of pump connections.

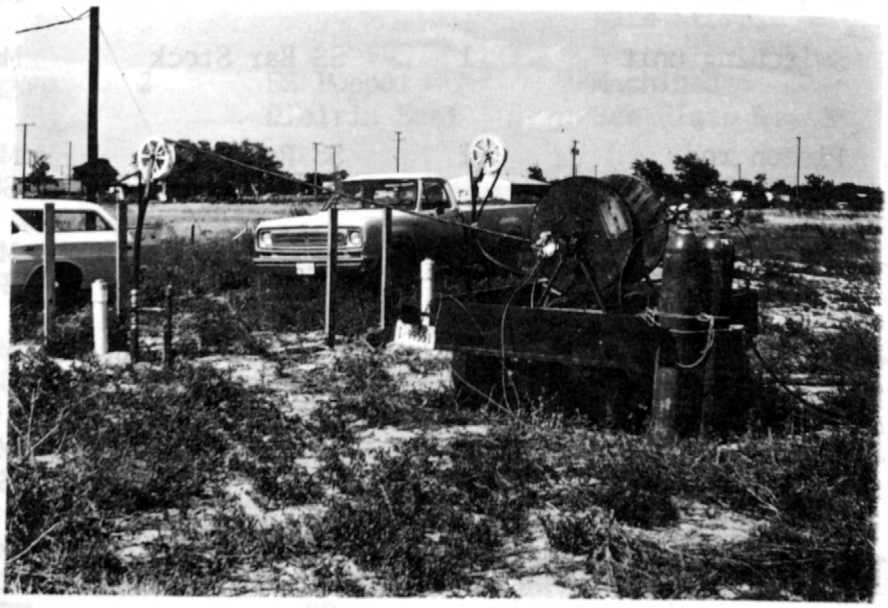

Figure 5.--Field operation of the pump showing a complete system (Stanton, Texas).

Table 1.--Components of small-diameter water pump

ITEM	NUMBER	MATERIAL	COMMENTS
1. Cylinders	2	SS Tubing	Machined See Plate No. 1
2. Cylinder connector	1	SS Bar Stock	Machined See Plate No. 3
3. Switching unit	1	SS Bar Stock	Machined See Plate No. 2
4. Piston rod	1	SS Rod	Machined See Plate No. 1
5. Pistons	2	Brass Bar Stock	Machined See Plate No. 1
6. Pump ends	2	Brass Bar Stock	Machined See Plate No. 1
7. Switching spindle	1	Dielrin	Machined See Plate No. 2
8. Pilot valve spindle and return spring	1 1	Brass SS	Machined, contained in top pump end. See Plate No. 1 (See note specifying spring)
9. Pilot valve operator1/	1	Brass	Catalog No. 341A Humphrey Products Kilgore at Sprinkle Rd., P.O. Box 2008, Kalamazoo, Mich. 49003 Ph. 616-381-5500
10. Inlet and Outlet Check valve balls	4	Teflon	Industrial Tectonic Inc., Ann Arbor, Mich. 48106 ¼ in. Type 1000 P
11. Check valve springs	4	SS	Spring No. 302-4C-P2-1 Nuclear Products Co., 15635 Saranac Rd., Cleveland, Ohio 44110

Table 1.--Continued

ITEM	NUMBER	MATERIAL	COMMENTS
12. Check valve O-ring retainer •	4	Brass	Brass Tubing .3125 OD x .45 with .031 wall (5/16 in OD x .45 in long, 1/64 in wall thickness). Local Hardware Store.
13. Button bleed valve	2	SS Poppet Dielrin Seat	Machined See Plate No. 3
14. Button bleed valve springs	2	SS	Light springs (See note, Plate No. 3)
15. Check valve insert	4	SS	Machined See Plate No. 1
16. O-rings			
A Cylinder ends	4	Buna-N	National ARP-568NS-120
B Switching valve spindle	5	Buna-N	National ARP-568NS-006
C Switching valve assembly-bottom	2	Buna-N	National ARP-568NS-006
D Switching valve assembly-ends	2	Buna-N	National ARP-568NS-010
E Pilot valve spindle	3	Buna-N	National ARP-568NS-010
F Piston rod seal	2	Buna-N	National ARP-568NS-010
G Check valve seats	4	Buna-N	National ARP-568NS-009
H Button bleed valves	2	Buna-N	National ARP-568NS-008
			Available Local Industrial Supply
17. Piston seals	4		Utex (Poly-Pak) 3/4x1x1/8 hydraulic seals. Available Local Industrial Supply.

Table 1.--Continued

ITEM	NUMBER	MATERIAL	COMMENTS
18. *Universal elbow fittings	2	Brass	Humphrey, UEF (see item 9 for address), 1 suction, 1 discharge. Custom fitting required.2/
19. *Universal tee fitting	1	Brass	Humphrey, UTF (see item 9 for address), discharge. Cutsom fitting required.3/
20. *¼ Hose (OD) barbed fitting	5	Brass	Humphrey, BFI (see item 9 for address). Custom fitting required of 1.4/
21. *Extension fitting	5	Brass	Humphrey, ExF (see item 9 for address). Modifications required of 4.5/
22. *Tubing connector 10-32 to 1/8"	4	Brass	Catalog No. 11923 Clippard Instrument Lab. Inc., 7390 Colerain Rd., Cincinnati, Ohio 45239. Modifications required of 3.5/
23. *Short coupling 10-32 x 10-32	2	Brass	Catalog No. 11999 (see item 22 for address). Modification required 6/
24. *Copper tubing 1/8"			x 4 ft. Catalog No. 3811-1 (see item 22 for address).
25. *Brass tubing ¼"			x 2.5 ft. (Local Hardware Store)
26. *Check valves	2	Brass	Model MCV-1 (see item 22 for address).

Table 1.--Continued

ITEM	NUMBER	MATERIAL	COMMENTS
27. *Tube connection	1	Brass	No. 262-P ¼" union Imperial Eastman Corp., 6300 W. Howard St., Chicago, Ill. 60648
28. *Tube connection	1	Brass	No. 268-P ¼"x1/8" NPT, Male connector (see item 27 for address). Modification required. 7/
29. *Tube connection	1	Brass	No. 268-P ½"x3/8" NPT, Male connector (see item 27 for address). Modification required. 8/
30. *Bulged stainless steel tubulation 1/16" x 1"	5	SS	Catalog No. TUBN-063-1 Scanivalve, Inc., P.O. Box 20005, San Diego, Calif. 92120
31. *Tube connector	1	SS & Al.	Catalog No. TC-063-T-RED (see item 30 for address).
32. *Tube clamps	6	SS	Catalog No. Clmp-063 (see item 30 for address).
33. Piston retainer nut	2	SS	¼-28NF, obtained locally
34. *Clear vinyl tubing			.063" x 3 ft. Catalog No. VINL-063 (see item 30 for address).
35. Needle valve needles	2	SS or Brass	Machined See Plate No. 2
36. Allen head cap screw	4	SS	#4-40x½", obtained locally

Table 1.--Continued

ITEM	NUMBER	MATERIAL	COMMENTS
37. Tube bundle		Polyethylene	Length, size & number as desired. The Okonite Co., subs. of Ling-Temco-Vought, Passaic, N.J. 07055
38. Pressure regulators SR 400 D	1	Brass	Victor Controls 2336 Auburn Blvd. Sacramento, Calif. 95821
39. Pump sheath PR-160 PVC 1120 Nominal 1½" 1.900" OD, .073 min. wall	1	Polyvinyl Chloride (PVC)	Obtained local Plastic Pipe Distributor
40. Support pulley	1	Steel	Fabricated by local shop. Support of tube bundle in well (see figure 5).
41. Miscellaneous tubing, tube fittings, quick disconnects, shut off valves, etc.		Brass & Nylon	(see item 27 for address).
42. Transport reel	1	Wood	Support frame constructed for tube bundle shipping reel.

1/ The pilot-valve operator used in the prototypes (see figure 2, part no. 9) is no longer manufactured. The pilot-valve operator, catalog no. 341A, is a substitute.

2/ Grind the suction fitting to fit the curvature of the pump for a lower profile and a sealing surface. Grind the discharge fitting flat for a lower profile and counter-drill its threaded port one-fourth-inch. Silver solder a one-fourth-inch brass tube in the counter-drilled port. Grind both retaining screw heads of the fittings to lower the profile.

Table 1.--Continued

3/ Counter-drill both threaded ports one-fourth-inch and silver solder one-fourth-inch brass tubing in the ports. (See the tubing at the top of figure 2). Grind the fitting bottom flat and grind the retaining screw head to lower the fitting profile.

4/ Drill the barbed end of one fitting one-eighth-inch and silver solder a one-eighth-inch copper tube in the drill hole. The copper tube connects to the gas supply operating the pump.

5/ Remove the male thread and counter-drill the fittings one-eighth-inch to receive one-eighth-inch copper tubing for silver soldering.

6/ Remove the male thread on one end and counter-drill to seat a one-sixteenth-inch stainless steel tube for silver soldering.

7/ Remove the one-eighth-inch NPT and silver solder a one-eighth-inch copper tube in place.

8/ Remove the three-eighths-inch NPT. Silver solder a coupler made of a one-half-inch long by one-half-inch diameter brass rod with three one-eighth-inch copper tubes through and soldered in the coupler onto the fitting.

Operation

Operating the pump requires pressurizing the gas-supply line at ground surface (figure 4). A pressure regulator is set to provide the necessary pressure and the shutoff valve opened in the gas-supply line. Compressed gas feeds through the pilot valve (figure 1) and the switching unit to the inner end of one piston. For the stroke with piston movement up and switching unit position shown by solid O-rings in figure 1, this pressure causes the pistons to travel upward, forcing a cylinder volume of water out through the discharge line to the surface while drawing the same volume of water into the lower cylinder. The gas above the piston in the lower cylinder is exhausted to the surface through the switching unit. At the end of the stroke, the lower piston actuates a button bleed valve. The pressure in the chamber at the end of the switching-unit spindle is exhausted through the button bleed valve to the space above the lower piston, which is at exhaust pressure. The needle-valve restrictions, shown in the pressure paths to the ends of the spindle, limit repressuring of the exhausted chamber at the end of the spindle. This permits sufficient pressure differential at the spindle ends to be developed to overcome the friction and force the spindle to move. The switching-unit spindle is thus shifted down to the position shown by the dashed O-rings in figure 1 by the high pressure at the top of the spindle. The spindle shift redirects the pump operating pressure to the exhausted lower cylinder while simultaneously exhausting the previously pressurized upper cylinder. This causes the pistons to move down, forcing water out of the lower cylinder and drawing water into the upper cylinder. The cycle is repeated and the pump, therefore, operates continuously, the flow stopping or hesitating as the direction of the piston travel reverses. Depressurizing occurs only in the cylinders, not in the pressure lines, thus providing economical utilization of compressed gas.

The pump may be stopped by two procedures that allow for immediate restart. The first procedure is to listen for the exhaust to occur and to immediately disconnect and depressurize the pump pressure line at the surface at that time. The pump will then stop in mid-stroke, and repressurizing will continue the stroke and pump operation. Quick-disconnect fittings facilitate this procedure. The second procedure for stopping the pump is by actuating the pilot-valve operator, either by shutting off or pressurizing the exhaust line, which is also used as the pilot-valve operator line. When the pump exhaust is shut off at the surface, pressure will build to the point of actuating the pilot operator after a short period of time. Once the pilot-operator valve is pressurized, the pilot-valve spindle will move down so that the O-ring seals are in the positions shown by the dashed lines in figure 1. Under this condition, the input pressure will be directed to the top of the switching spindle, causing it to move to its bottom position. Both lines can then be depressurized, and the pump will be ready to resume operation when the pressure line is again pressurized. If the exhaust line is pressurized by a second compressed gas source, the pump will stop immediately. This second procedure assures that the switching spindle is not stopped in a centered position.

The pump will stop operating if the pumping pressure decreases to the extent that the switching spindle does not completely shift and the spindle centers. This can occur when a gas supply bottle is exhausted or when the gas supply line to the pump is shut off without depressurizing and the pump "runs down". Also, the switching spindle will center if the pump breaks suction and cycles too fast for the switching spindle to reset, or if it is pumping too slow (.25 ft^3/hr, .12 L/m) for the piston movement to adequately actuate the button bleed valve. The switching spindle may be reset by simultaneously pressurizing both the pressure and exhaust lines. Pressurizing the exhaust line actuates the pilot operator, thus operating the pilot valve, to the positions shown by dashed O-rings in those components shown in figure 1. This causes the input pressure to be directed to the top of the switching spindle, simultaneously permitting gas from the pump gas inlet and the chamber at the bottom of the switching spindle to exhaust. The switching spindle is forced down and decentered. Hence, the pressure in the exhaust line must be at the lowest value at which the pilot operator will actuate in order to ensure sufficient pressure differential to decenter the switching spindle. When the exhaust line is subsequently depressurized, the pump will operate.

Gas Usage

The pump-operation time on a bottle of gas is dependent on the pumping head, rate and efficiency. Two pumps at Stanton, Texas, and Aurora, Nebraska, operated continuously over periods ranging from 21.5 hours to 47.3 hours with pumping efficiencies ranging from 17.7 to 24.3 percent (Table 2). The pumping efficiency is defined as the relationship:

$$\text{Pumping Efficiency (PE)} = \frac{\text{Pump Work Output}}{\text{Gas Expansion Work Input}}$$

Pump Work Output is the mechanical work of raising a given volume of water to land surface. Gas Expansion Work Input is the work or mechanical effect of expanding the gas from the pump-operating pressure to atmospheric or exhaust pressure. The work input value is computed, using the pressure change in the compressed-gas bottle and the thermodynamic laws for perfect gasses (see Table 2).

The pumping efficiency and perfect-gas laws can be utilized to estimate the length of time a gas supply will provide pumping operation. The pressure required to operate the pump alone is about 30 psi (2.11 kg/cm^2). Adding static pumping heads to the pump requirement and assuming an efficiency of 18 percent, the times of operation per unit weight of nitrogen for different heads and pumping rates were computed and are shown in figure 6. The data of figure 6 may be combined with a computation of the amount of nitrogen contained in any size of compressed gas bottle in order to obtain an estimate of pump-operating time.

Table 2. Pump-operating data from tests at Stanton, Texas and Aurora, Nebraska.

Location	Pump Unit	Operating Pressure, psi P_o	Head, ft	Pumping Rate, ft^3/hr	Time, hrs	Volume Pumped, ft^3	Tank Pressure Decline From, psi P_1	To, psi P_2	Work In,[1] ft-Lbs	Work Out,[2] ft-Lbs	Efficiency, percent
Stanton,[3] Texas (6/30-7/1/77)	1	70.4	106	.37	21.5	7.9	1390	690	263,302	52,116	19.8
	2	72.4	106	.74	21.5	15.9	2000	870	432,243	105,316	24.4
Aurora,[4] Nebraska (11/7-11/77)	1	89.1	90	.68	47.3	32.1	2450	400	1,012,064	179,998	17.8
	2	79.2	90	.71	36.4	25.8	2150	600	725,978	144,748	19.9

1/ Work In = mechanical effects x pounds mass of gas used, computed from perfect-gas laws (Eshbach and Souders, 1975).

Mechanical Effects = RT ln P_o/P_a ft-Lb_f/Lb_m

where: R = gas constant (54.9 ft-Lb_f/Lb_m °R)

T = temperature, °R (Stanton 520°R, Aurora 518°R)

P_o, P_a = pressures Lb/ft^2 abs. of operating and standard atmospheric pressure (14.7 psia), respectively.

Lb_f = pound force

Lb_m = pound mass

°R = degrees rankine (thermodynamic fahrenheit scale where absolute zero, 0°R is equivalent to -459.69°F)

Pounds mass of gas used = $(P_1-P_2)V_t/RT$

where: P_1, P_2 = pressures of the tank at start and finish of period, Lb/ft^2

V_t = tank volume, ft^3 (Stanton 1.493 ft^3, Aurora 1.754 ft^3)

T = 520°R

2/ Work Out = volume pumped x density of water x head, ft-Lbs.

3/ Wells were 10 ft apart.

4/ Both pumps were in the same well.

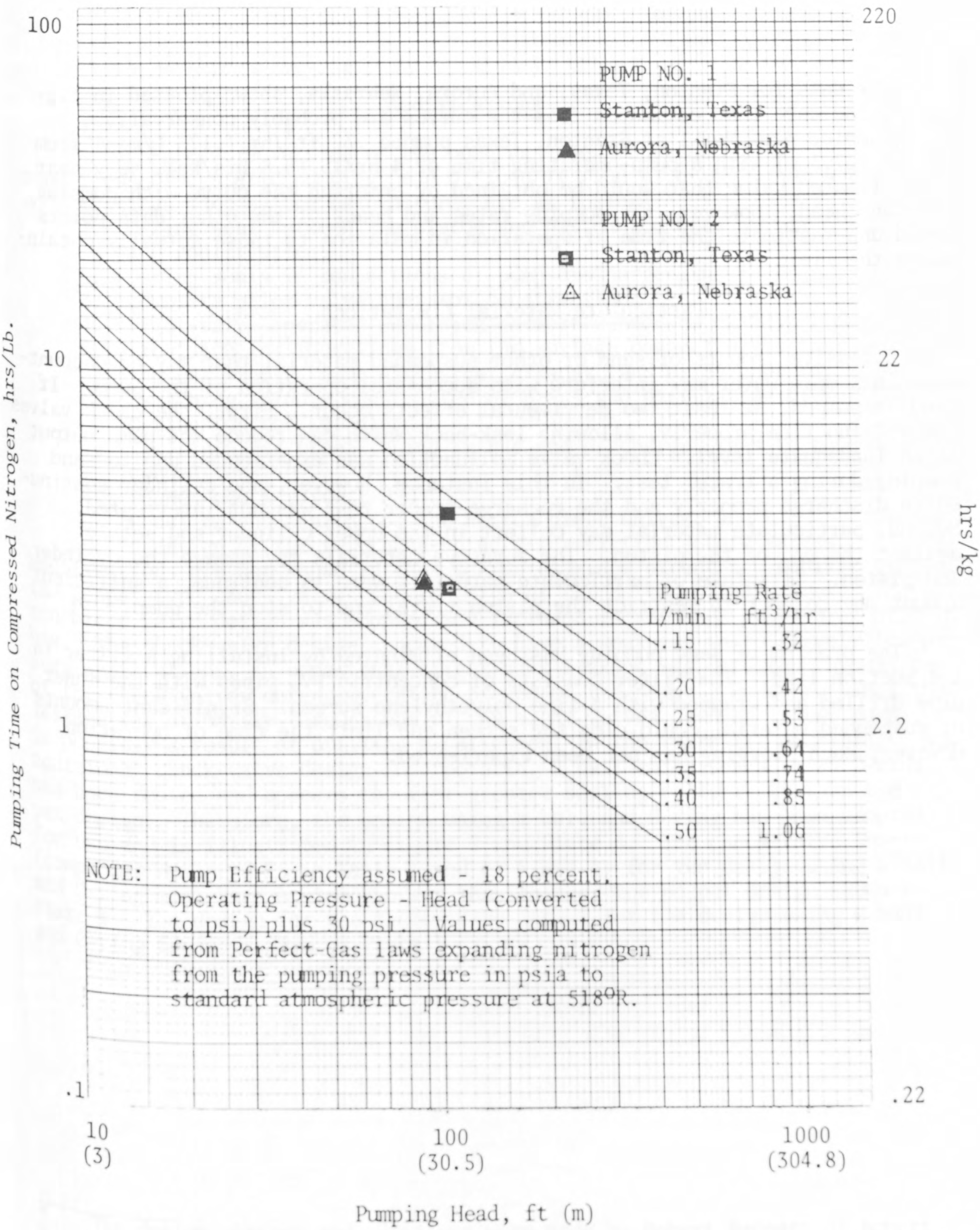

Figure 6.--Curves for estimating pump-operating time on compressed nitrogen.

The data for Stanton, Texas, and Aurora, Nebraska, shown plotted in figure 6, indicate that estimates from the curves are probably conservative. For example, pump No. 1 at Stanton, Texas pumped .37 ft^3/hr (.173 L/min) from 106 ft (37.3 m) with a pump-operating time of 4 hr/lb (8.8 hrs/kg), very near the estimated value that would be obtained by entering the curve with pumping rate and head. However, the pumping rates and heads of the other data points would underestimate the time of operation in relation to those actually obtained in the field.

Particulate Material Limitations

Excessive amounts of sand or other suspended material that may be encountered in sample water may interfere with successful operation of the pump. If sand is pumped, at least two detrimental effects occur. First, the check valves may not function properly, allowing leak-back which can reduce the pump output to an inadequate level. Check-valve malfunction was experienced due to sand pumping during a tracer test. In this instance, however, one cylinder continued to discharge properly and the recharge-tracer test was not interrupted. Second, particulate material may collect in the upper cylinder and settle against the end of the piston. The abrasive materials may damage the cylinder and piston. If intake of particulate materials were to continue, a sufficient amount may collect to restrict the piston travel and to stop the pump.

The problem of sand pumping has been eliminated by installing a filter in the suction line. The filter consists of concentric PVC pipes with the inner pipe drilled and wrapped with a fine polyethylene screen. Significant amounts of suspended material could clog the screen and limit the time of operation. However, such clogging has not been experienced.

Modifications

A high-pressure version of the pump has been constructed* for use under conditions of a static pumping head of 1640 ft (500 m) or of submergence. The modifications made by the manufacturer are as follows:

1. O-ring seal between the piston and piston rod with piston rod-threading modification;
2. O-ring seals in connections of pump-discharge lines;
3. Complete pilot-valve-operator construction;
4. Pilot-valve-operator expulsion chamber vented to exhaust line;
5. Provision for four lines from the surface connecting to the: operating gas supply, pump discharge, exhaust, and pilot operator pressure;
6. Switching spindle constructed of brass and utilization of teflon O-rings on the spindle;
7. All stainless steel tubing in gas and discharge lines to tube bundle connections;
8. Poppet check valves;
9. Redesign and sealing of the button bleed valves; and
10. Redesign of the switching-spindle-restriction needle valves.

Modifications are not shown in the machine drawings except the modification of the poppet-type check valves and redesign of the button bleed valves. The button bleed valve design was adopted and included in the USGS pumps presently in use. The check-valve design appeared to have a weakness in relatively low-pressure applications, as occasional slight back-leakage was detected through one of the check valves during operation of one of the pumps. However, since the leakage was primarily through one of the eight valves changed in two pumps, it is possibly a result of drilling misalignment in the retro-fit machining. An additional check-valve design incorporating a ball which seats in an O-ring has been tested and appears to offer greater sealing reliability than the poppet design. Therefore, the design using a ball and O-ring has been adopted for use and is illustrated in figure 2 and Plate 4. The check-valve insert (component numbered 15 in Table 1 and on Plate 4) for the design using a ball and O-ring must have a stem shorter than that of the poppet design shown on Plate 1. The design for the check-valve insert for the design using a ball and O-ring is also shown on Plate 1.

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* The design changes and additions were made by Robert Bennett of Robert Bennett Company, Machine Shop, P.O. Box 7644, Amarillo, Texas for the Lawrence Berkeley Laboratory, Oakland, California, and Weir-Jones Consulting Engineers, Vancouver, B. C., Canada. Additional information concerning high-pressure pump construction and operation may be obtained directly from these sources.

A modification or alternative design of the cylinder connector is included on the shop drawings, Plate 3. The alternative design does not contain an automatic switching unit, thus eliminating all other components shown on Plates 2 and 3. The pump would be operated by manual or timed switching. The mechanism for the switching would most reasonably be the pilot control valve of the top cylinder-end fitting of the pump, Plate 1, part 6. It would be necessary to add an exhaust port to the pilot control valve at the point shown on that drawing and designated "optional port 5 location". Connections to the pilot control valve for the alternative design of the cylinder-connector would be: 1 and 2 - cylinder connector; 4 - pump pressure; 3 and 5 - exhaust. A pilot operator, part 9, Table 1, could operate the pilot control valve at relatively low pressure, on the order of 20 psi (1.41 kg/cm^2), as a switch, alternately pressurizing and exhausting pump cylinders. The gas used by a pump with the alternative design of the cylinder connector operated by manual or timed switching would consume compressed gas at a rate approximately three times that used by the pump designed for continuous operation.

The first pump designed and constructed for use in the artificial recharge research program was of the manual type. A pump of this type was also built from this design by the U.S. Department of Agriculture at Bushland, Texas. This pump was still in use in 1978. The design for the continuously operating pump evolved from the design for the manually operated one primarily because of a need for continuous operation and conservation of gas. Trade-offs between complexity, gas usage and the purpose for which the pump is to be used are required when selecting a design.

Cost

A major consideration of the gas-operated pump is its cost. The machining is extensive and intricate and a recent (1978) price of the pump alone was $1750.00. The cost of the tube bundle is approximately $ .40 per foot, and the surface equipment, that is, the reel support, gear motor, pressure regulators and fittings, can be obtained for approximately $300.00. Pumps constructed in 1977 with the modifications described above for high-pressure applications cost approximately $3500.00. The pumps were complete however, excepting the tube bundle, surface valves and controls. Also, almost all pump components of the high-pressure pumps are stainless steel. No recent (1978) cost figures are available for the manually operated pump but it is believed to be significantly less expensive than the continuously operating pump.

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