

[54] **MICROPUMP**

[72] Inventor: Edward W. Merrill, Cambridge, Mass.

[73] Assignee: Hans H. Estlin, Leonard W. Cronkrite, Jr.
& William W. Wolbach, Trustees of the
Charles River Foundation, Boston, Mass.

[22] Filed: March 6, 1970

[21] Appl. No.: 17,169

[52] U.S. Cl. 222/135, 141/61, 222/215,
222/386.5, 222/541

[51] Int. Cl. B67d 5/40

[58] Field of Search 222/479, 207, 205, 386.5, 541,
222/209, 353, 437, 457, 206, 215, 135, 1; 128/DIG.
5, 2, 276, 214 F; 141/8, 59, 61, 215; 417/148, 437

[56] References Cited

UNITED STATES PATENTS

3,468,308 9/1969 Bierman 128/214 F

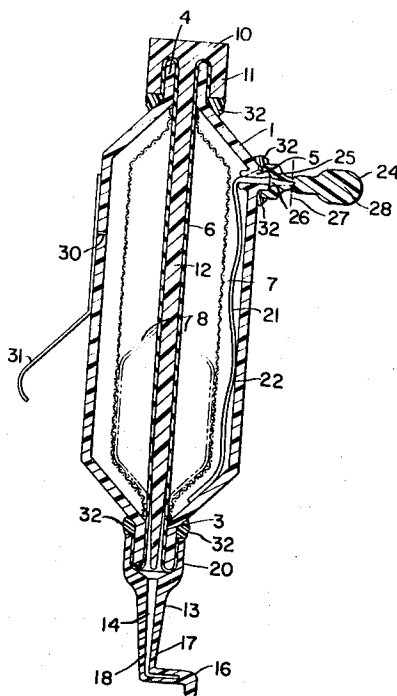
3,319,837 5/1967 Mueller 222/386.5 X
3,106,206 10/1963 Barr, Sr. et al. 128/276

Primary Examiner—Robert B. Reeves
Assistant Examiner—Francis J. Bartuska
Attorney—Kenway, Jenney & Hildreth

[57] **ABSTRACT**

A pump for delivering liquid at a relatively constant rate from a chamber having a compliant membrane wall which exerts a substantially constant resistive force when expanded under a pressure within the range of between zero and atmospheric and within the mechanical limits imposed on it. The outside surface of the membrane is located in a second chamber wherein the pressure is increased to atmospheric by diffusing gas through an elastomeric diffusion membrane. The pump is especially adapted for delivering microquantities of liquid at a constant rate for long periods.

3 Claims, 5 Drawing Figures



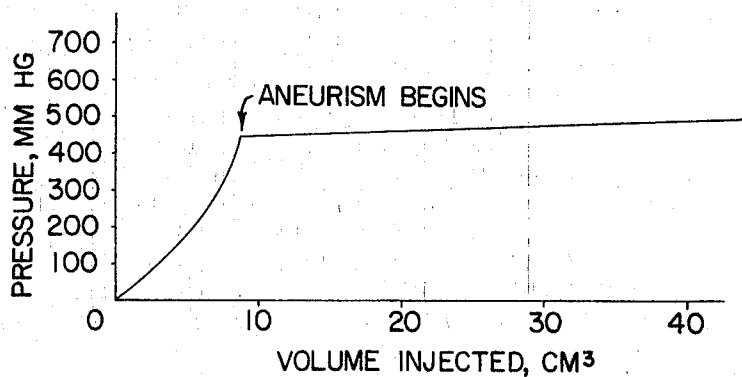


FIG. 1

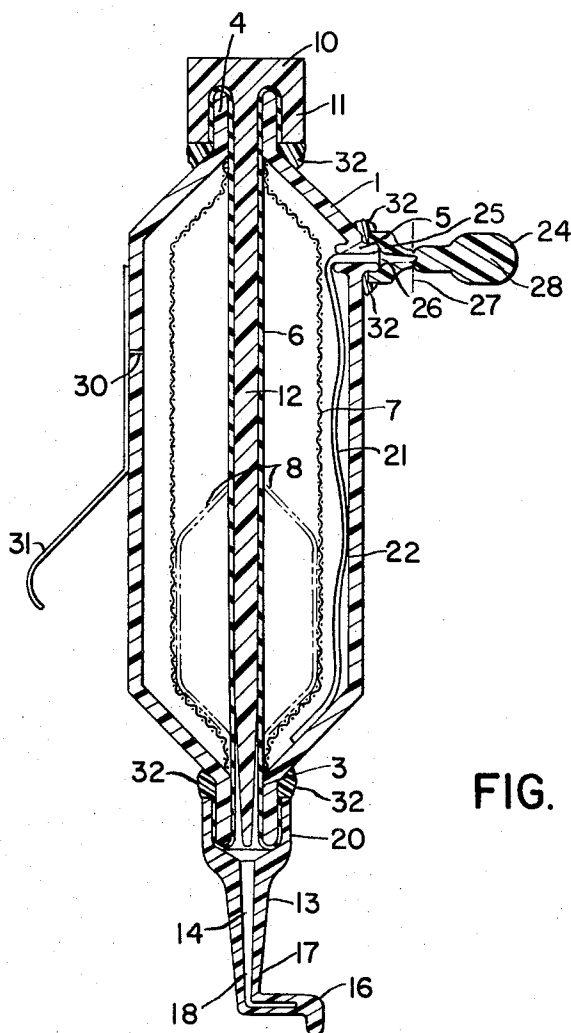


FIG. 2

INVENTOR
EDWARD W. MERRILL

BY

Kennedy, Jernsey & Hildreth
ATTORNEYS

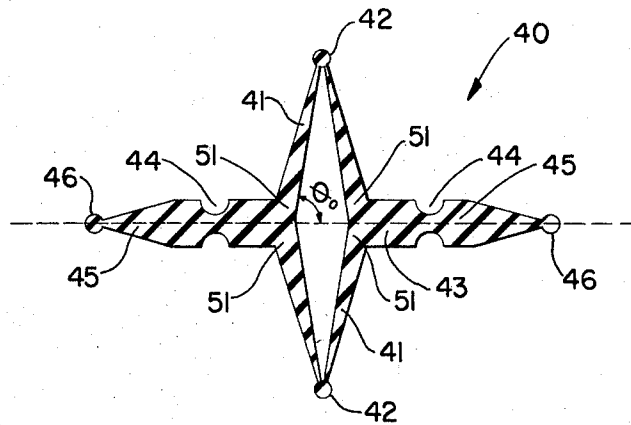


FIG. 3

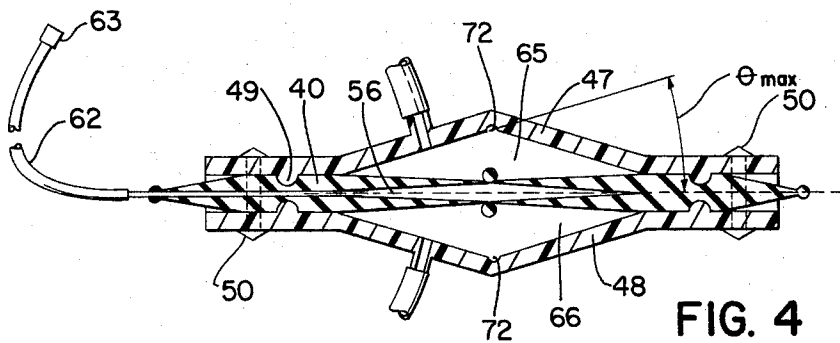


FIG. 4

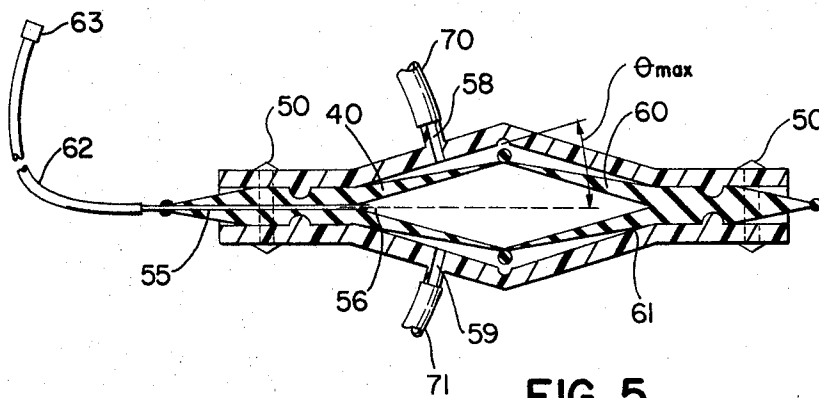


FIG. 5

INVENTOR
EDWARD W. MERRILL

BY

Kennedy, Jernsey & Nilsen
ATTORNEYS

MICROPUMP

This invention relates to a method and apparatus for delivering liquids at a relatively constant rate, particularly at a very low rate.

Presently, there exists a wide variety of systems requiring the delivery of minute quantities of liquid at a relatively constant rate and over relatively long periods such as in the administration of pharmacological drugs to humans and to experimental animals. Other exemplary systems involve delivering lubricants to machines, or delivering bactericidal agents to running water supplies for purification. Liquid delivery to these systems is effected at a rate of the order of a few cubic millimeters over a period ranging between an hour and several days or more.

Presently available pumps for delivering microquantities of liquids involve cumbersome expensive machinery combining complicated electromechanical devices to assure delivery of fluid with specified accuracy and rate over a long period. A typical device utilizes an infusion pump having as its principle of operation the progressive mechanical insertion of a hypodermic syringe barrel into a syringe. This device, as well as others now available, is impractical for use in remote places, or on moving systems such as moving experimental animals due to the cumbersome auxiliary control apparatus.

It has been proposed to pump liquids from a chamber by permitting expansion therein of a compressed hollow circular tube made from an elastomeric material. Expansion is effected by diffusion of air through the portion of the tube wall, which is pervious, extending from the chamber into the atmosphere. The expanded tube displaced liquid in the chamber which then is delivered to any desired location. Although tube expansion is slow and extends over relatively long periods, this device is unsatisfactory. The rate of tube expansion varies substantially from linearity thereby making the rate of liquid delivery non-linear. This is undesirable especially when the liquid delivered is a drug. Furthermore, the total amount of liquid delivered and the variance from linearity is dependent upon the degree of original tube compression, thereby rendering it difficult to control delivery of the liquid. This is especially undesirable when a drug is the liquid being delivered since it is desirable and sometimes essential that drugs be delivered to animals in precise amounts and at a substantially constant rate.

In accordance with this invention, liquid is delivered at a predetermined and essentially constant rate from a chamber defined by walls including an elastically compliant wall, by application of gas pressure increasing from zero to about atmospheric to the outside surface of the elastically compliant wall. The chamber is filled by replacing the gas therein with the liquid so that the compliant wall is expanded. The gas pressure is then applied to the outside surface of the expanded wall by diffusing gas through an elastomeric wall into a chamber originally under vacuum and surrounding the expanded wall to cause it to contract at a substantially constant rate. The compliant wall is formed so that it exerts a substantially constant resistive force over a relatively wide sub-atmospheric pressure range.

By employing a compliant wall which exerts a substantially constant resistive force when expanded, a slight pressure change on its outside surface effects a large change in the chamber volume defined by the wall. In addition, the rate of volume change as a function of change in outside pressure is substantially constant. By regulating the outside gas pressure to increase at very slow rates, liquid delivery can be effected for long periods at a substantially constant rate. Any structure and composition for the compliant wall can be employed so long as it exerts a substantially constant resistive force when expanded within a wide pressure range between zero and atmospheric pressure. The rate of gas pressure increase on the expanded wall is regulated by diffusing gas through a porous barrier open to the atmosphere and to a chamber under vacuum adjacent the compliant wall. The diffusion rate and consequent rate of pressure increase is regulated by the structure and composition of the diffusion barrier.

The pump provided by this invention is portable, does not require additional apparatus to regulate liquid delivery and can deliver liquid at a relatively constant rate even at low flow rates for a long period.

Reference is made to the attached drawings for further understanding of this invention.

FIG. 1 illustrates the relationship between internal pressure and volume in an elastomeric tube stretched and filled to form an aneurism.

FIG. 2 is a cross-sectional view of an embodiment wherein the inflated tube filled with a liquid is retained within a semi-rigid container.

FIG. 3 is a cross-sectional view of an elastomeric bladder used to force liquid through a delivery system.

FIG. 4 is a cross-sectional view of a pump employing the bladder of FIG. 3 with its interior being under partial vacuum.

FIG. 5 is a cross-sectional view of the pump of FIG. 3 with the interior of the bladder at atmospheric pressure.

Referring to FIG. 1, a tubular elastomeric material having the desired properties suitable for the device is stretched and then filled with varying amounts of gas and the pressure measured. The tube is made from cross-linked poly dimethylsiloxane and is available under the trademark "Silastic." It is 10cm $\times$ 0.183 inch $\times$ 0.132 inch and is then stretched and held to a length of 20cm. The stretched tube is filled with gas under pressure to determine the pressure-volume relationship in the tube. As shown by FIG. 1 after aneurism is initiated, the pressure in the tube is relatively constant over a wide gas volume range. Over a four fold range of volume the absolute pressure difference changed by about 10 percent, from 550 to 450 millimeters of mercury. Consequently, as the aneurism collapses, the absolute pressure in the gas space inside the tube gradually but slightly increases toward atmospheric by a rather small percentage. Thus, the driving potential for gas diffusion through the elastomeric wall namely, the difference between exterior pressure and internal pressure remains nearly constant. These data show that the delivery rate of fluid from the aneurism under the force exerted by the expanded elastomer is insensitive to pressure on the delivered fluid different from atmospheric by at least $\pm$ 20mm Hg. Beyond an aneurism volume of 50cm³ the entire tube had become converted into a single aneurism extending over the entire length, and further injection of gas caused rapid increase in pressure.

As shown in FIG. 2, rigid housing 1, made of glass, hard plastic, metal or the like having axial symmetry is provided with necks 3, 4 and 5 at both ends and on one side, these necks not necessarily having the same inside and outside diameters. A rubber tubing 6, made for example, from natural gum rubber, silicone rubber, or other highly elastic polymer suitably vulcanized is extended to approximately twice its length at rest, drawn through housing 1 and then everted over the opposite ends of necks 3 and 4 thereby being held in extension. An internal mesh-like retainer 7 fabricated from plastic screening or other suitable porous material, previously inserted into or built into housing 1, circumferentially surrounds the thus extended tubing 6 supporting it over its extension between the opposing necks 3 and 4.

When the aneurism as represented by dotted lines 8 is later formed, by means described below, it is contained by and prevented from indefinite expansion by the inner surface of retainer 7. Following the everting of the extended rubber tubing over the necks 3 and 4 a piece 10 is inserted into the lumen of the tubing 6 to its limit so that the cap portion 11 compresses the tubing 6 around the neck 4 thereby locking it while the extension 12 occupies volume inside the tubing 6 that would otherwise later be occupied by the liquid to be dispensed.

A dispensing nozzle 13 is fitted onto the neck 3 of the housing thereby locking the extended tube 6 onto the neck 3 and at the same time forming a needle-like passage 14 for the subsequent dispensing of the liquid. It is convenient to make the dispensing nozzle with a tip 16 attached to the main body 13 with a circumferential notch 17 so that when subsequently a vertical thrust is exerted on tip 16 it breaks off at the notch 17

thereby opening the dispensing orifice 18. The internal geometrical configuration of the collar 20 is similar to that of the cap 11.

A piece of thin-walled silicone rubber or other tubing 21, which serves as a diffusion membrane, is conveniently carried inside the housing 1 between the inner surface 22 and the exterior surface of the retaining cage 7. The diffusion tubing 21 sealed at one end is connected via its other end to the side neck 5 of the housing 1 by everting the tubing 21 around the neck 5. A covering piece 24 made of plastic or metal has a collar 25 designed to compress snugly the everted neck 26 of diffusive tubing 21 after its positioning on neck 5. Covering piece 24 has an orifice 27 terminating at a blind end. At a subsequent time the tab 28 is snapped off by the user thereby opening orifice 27 into the diffusion tube 21 to admit atmospheric air. At any convenient location on the body of housing 1 a small orifice 30 is covered by seal 31 carrying a thin layer of contact sensitive adhesive whereby the seal 31 is maintained over the orifice 30 until intentionally removed. Cement layers 32 around the everted tubings 6 and 21 and the respective caps 10, 25 and 20 serve to prevent significant leakage of atmospheric air into the device during storage. Preferably cement 32 is chosen from the well-known high vacuum sealants or cements. Liberal quantities may be used as necessary.

To prepare the pump for service it is convenient to start with the assembly shown except that orifice 30 is open and dispensing nozzle 13 has not yet been applied. The rest of the assembly is placed in a vacuum chamber and fully evacuated down to a few millimeters mercury of absolute pressure. It is often desirable to flush the whole device with nitrogen, carbon dioxide, or some other inert gas in order that after vacuumization there will be little or no oxygen left in the device capable of causing chemical deterioration of the rubber tubing 6 or the diffusion tubing 21. After evacuation, foil 31 is applied over orifice 30 and dispensing nozzle 13, intact with the attachment 16, is applied over the everted end of the interior tubing 6. The interior of housing 1 is now under vacuum and remains so.

When the micropump consisting of the elements recited above is to be placed in service to dispense a particular liquid, it is convenient to place this liquid in a beaker the floor of which may serve as a means to accomplish fracture of the piece 16. The micropump is filled by thrusting the entire assembly down against the floor of the beaker thereby detaching the tip 16 at the notch 17 whereupon the internal vacuum allows the liquid under atmospheric pressure to enter through the dispensing orifice 18 into the tubing 6 between its inner wall and extension 12. The tubing 6 is selected so that it will undergo aneurism formation at the pressure difference corresponding to unit atmosphere of vacuum of about 700 to 760 millimeters mercury. An aneurism progressively forms in the tubing 6 taking the shape progressively of 8 and this aneurism eventually fills the entire retaining cage 7. It will be understood that since the tip 16 is always immersed under liquid during filling, only liquid enters to take up the volume formed by the aneurism. When it is desired to dispense the liquid, usually within a short period after filling the micropump, first the tab 28 is broken off allowing atmospheric air to enter to interior of diffusion tube 21. Air will diffuse through it into the space between housing 1 and retaining cage 7 at a rate proportional to its area, which is constant and the pressure difference between ambient air and the instantaneous value inside the housing 1. To start the pump, tab 31 is pulled clear of orifice 30 to allow sufficient atmospheric air to enter via that port so that the aneurism 8 can begin to collapse in response to the elastic strain of the extended rubber tube 6. When the first drop of liquid appears at the end of dispensing nozzle 5, the tab 31 is quickly resealed over orifice 30. From that point, air can enter the interior of the housing 1 only via diffusion tube 21. As it does so, the aneurism 8 will gradually collapse expressing liquid from the orifice 18.

The pressure-volume data shown in FIG. 1 is typical of how the aneurism can collapse (decrease volume) under a nearly constant pressure. When nearly a total vacuum is required to render the tubing 6 in the aneurism form, as it collapses, it can pump against significant external pressures of the order of at least 50 millimeters of mercury. By the same token it can deliver liquid into systems substantially below atmospheric pressure, without affecting the nearly linear operation of the pump. It also will be understood from this design that as there is no absolute limit on the total volume of liquid that may be dispensed by this means. However, it is particularly suitable for dispensing quantities ranging from a few cubic millimeters to a few cubic centimeters, and it will further be understood that once the dispensing has been set in motion by opening the diffusion tube 21 to the atmosphere it may be stopped by resealing the tube 21.

Another embodiment of this invention is illustrated in FIGS. 3, 4 and 5. The bladder 40 can be formed from vulcanized silicone rubber stock or any other appropriate elastomeric stock as long as it is not significantly swollen by the liquid to be dispensed. When the bladder 40 is formed by compression molding, two identical pieces are assembled back to back, one piece being the mirror image the other piece. Alternatively, either half of the composite assembly taken along the horizontal axis as shown in FIG. 3 may be fabricated by compression molding and used by itself in a suitable housing. The bladder 40 comprises conical element 41 with tapering walls terminating in a bead 42 and defining an angle θ_0 with respect to the midplane of at least 60° and preferably 75°. The conical element 41 terminates in a base 43 having circumferential grooves 44 and extensions 45 terminating in a bead 46 that may be mechanically grasped. It will be observed that below the dashed line representing the midplane, an identical molding is placed back to back with the above-described molded piece.

When the vulcanizable elastomeric stock has been pressure molded, the molecules of the molded element constituting the cross linked elastomeric network are in their relaxed configuration when the piece as a whole has the shape shown in FIG. 3. When both halves of the rubber are to be used back to back in the micropump, they are assembled and clamped between rigid sections 47 and 48 fashioned out of a suitable non corrosive metal or a hard plastic like polycarbonate, either by injection molding, machining, or any other technique leading to reasonable precision of dimensions. The sections 47 and 48 have a circumferential bead 49 which engages in the circumferential channel 44 of the bladder 40. The bladder 40 is stretched radially by the equivalent of a tenter frame that grasps the bead 46 and extends the pieces until their channel 44 is enlarged to such a circumference that it will mate with the bead 49 of the outer housing pieces 47 and 48. Permanent clamping is accomplished by means of several circumferential equally spaced rivets 50. As a consequence of this radial stretching, the conical sections 41 become stretched into a very flat cone of shallow angle and the sections 51 go under very high tension tending to restore the cone to its unstressed configuration as shown in FIG. 3.

As the bladder is loaded between the frame plates 47 and 48 and clamped between them, the angle of the conical section with respect to the plane of symmetry, θ , is close to θ_{max} as shown in FIGS. 4 and 5 an angle of approximately 12° to 15°, thereby making a very flat conical section 41.

A hollow needle 55 clamped between the identical members of the bladder 40 at any position around the circumference of the assembly provides means whereby the space between surfaces 56 of opposing bladder pieces may be evacuated. When this evacuation occurs, the angle θ defined by the conical piece 41 and the plane of symmetry goes nearly to 0°. The rigid sections 47 and 48 are provided with ports 58 and 59 through which liquid subsequently to be dispensed may be drawn into the chamber as the bladder is being collapsed to the configuration shown in FIG. 4 by application of a vacuum on needle 55. When the chamber defined between the bladder

surfaces 60 and the housing surfaces 61 is filled with liquid, a predetermined length of diffusion tubing 62 is attached at the terminus of hollow needle 55. Diffusion tubing 62 terminates at its other end by a suitable plug 63. This tubing may be coiled or wound in any convenient configuration. It serves the same function as the tube 21 in FIG. 2, namely to permit the gradual ingress of air by molecular diffusion through its wall to permit relaxation of the bladder elements. Relaxation occurs by the progressive lifting of the conical surfaces owing to the tension in the areas 51 in the rubber molecules. The elastically deformed rubber structure owing to the limited angle of operation, that is, between zero and θ max of about 15 percent, provides nearly linear operation for precisely the same reasons as do the aneurism collapse in the device of FIG. 2. That is to say, as θ increases slowly from zero to about 15°, the tension in the rubber is relaxed by about 10 to 12 percent and thus the pressure difference between the space 56 inside the bladder and the liquid space 65 decreases only by that value. Therefore, the net diffusion driving force to cause diffusion of air through tube 62, namely the external atmospheric pressure less the inside pressure between the bladder surfaces, remains almost constant. In consequence, the rate of deflection of the bladder elements with increasing angle θ is nearly constant as gas progressively fills the space 56. Since the thickness and modulus of elasticity of the rubber stock as compression molded according to FIG. 3 is chosen such as to require nearly one full unit atmosphere of vacuum to elongate the conical section 41, this device, like the device of FIG. 1, operates successfully against variable output pressures within plus or minus 15 millimeters of mercury of the ambient atmospheric pressure.

The particular embodiment shown in FIGS. 3, 4 and 5 can be achieved by using precisely half of the assembly on either side of the plane of symmetry. For example, with reference to FIG. 3 the section lying above the midplane of symmetry may be the sole bladder element. This is drawn out by the tenter frame referred to above with a flat plate replacing the other half of the gasket. The principles of operation are exactly the same as explained above except that for a given device the total liquid output is approximately half of what it could be.

While employing the designs shown by FIGS. 4 and 5, it is possible to have different liquids in spaces 65 and 66 or they be the same liquids and the delivery may be joined by connecting delivery tubes 70 and 71 to a common connection. It will

be understood equally either section 70 or 71 shown in FIGS. 4 and 5 may be filled with liquid exclusively of the other and the other section may be left open to the atmosphere, without affecting the operation of this device. The beads 42 are intended only for reinforcement and may be omitted entirely. When present, the beads ultimately rest in hole 72.

Furthermore, the break-off tabs may be supplied as in the other embodiment of this invention described in reference to FIG. 2 and that the whole assembly may be prepackaged in a variety of forms. It will also be understood that whereas the invention has been described with reference to elastomeric vulcanized materials it is equally possible to use metal or other bellows to achieve the same objective, the common requirement being that over the range of their expected deflection their resistive force remains constant within plus or minus about 10 percent.

I claim:

1. A pump for delivering a liquid at a relatively constant rate comprising a first chamber and a second chamber for retaining liquid each defined by a separate rigid wall and a separate elastomeric membrane, means for filling the first chamber and second chamber with liquid, an orifice in each of said first chamber and said second chamber for removing liquid from said first chamber and second chamber, each of said elastomeric membranes exerting a substantially constant resistive force when expanded under a pressure within the range of between zero and atmospheric and within the mechanical limits imposed upon said elastomeric membranes, and a diffusion membrane located in a third chamber defined by said elastomeric membranes to permit gas diffusion from the atmosphere into the third chamber.

2. A pump for delivering a liquid at a relatively constant rate comprising an elastomeric tube, said tube exerting a substantially constant resistive force when expanded under a pressure within the range of between zero and atmospheric and within the mechanical limits imposed upon it, means for filling the tube with a liquid, an orifice for removing liquid from said tube, said tube located in a second chamber and a diffusion membrane located in said second chamber to permit gas diffusion from the atmosphere into the second chamber.

3. The pump of claim 2 wherein the tube is surrounded by a porous retaining means to impose the maximum limit of expansion.

* * * * *

45

50

55

60

65

70

75

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,677,444 Dated July 18, 1972

Inventor(s) Edward W. Merrill

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

On the Abstract page please delete "August 18, 1972" and insert -July 18, 1972- as the issuing date of the patent

Signed and sealed this 2nd day of January 1973.

(SEAL)

Attest:

EDWARD M. FLETCHER, JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents