

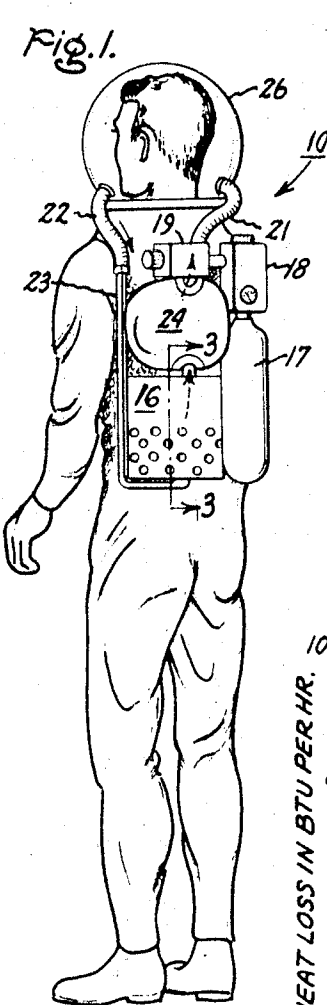
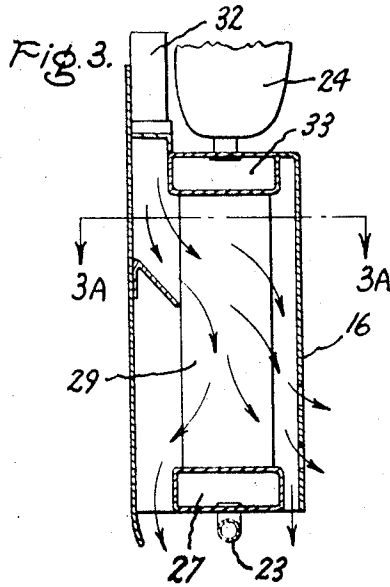
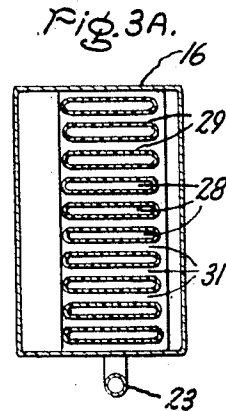
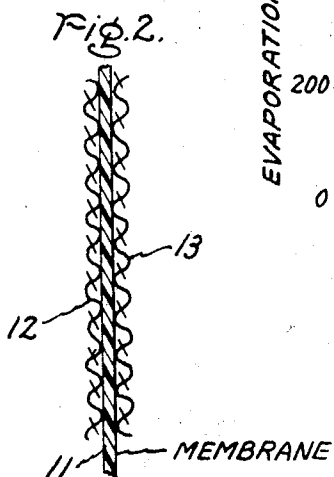
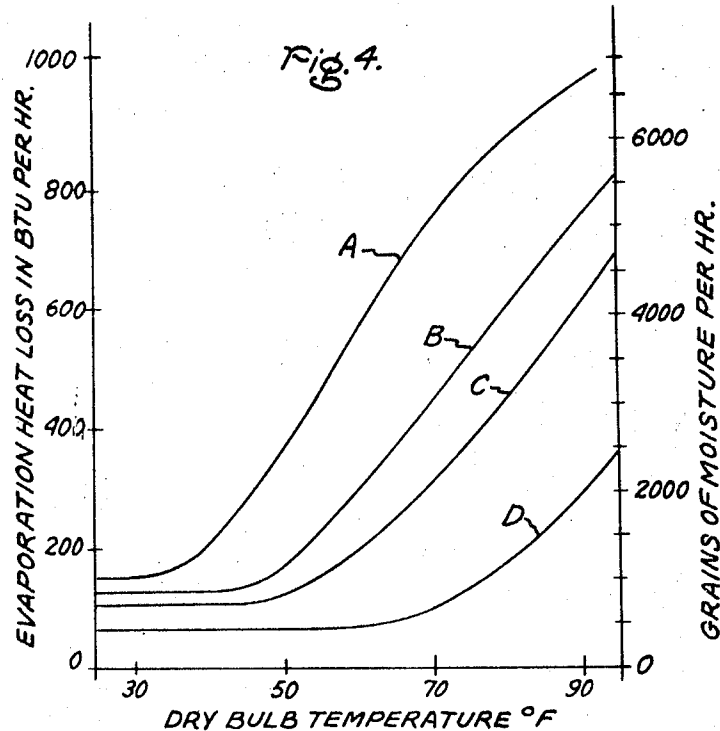
July 29, 1969

N. R. DIBELIUS ET AL
PERMEABLE PROTECTIVE SUIT IN COMBINATION WITH MEANS
FOR MAINTAINING A VIABLE ATMOSPHERE

3,457,918

Filed Feb. 13, 1967

2 Sheets-Sheet 1



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2 Sheets-Sheet 2

Fig. 6.

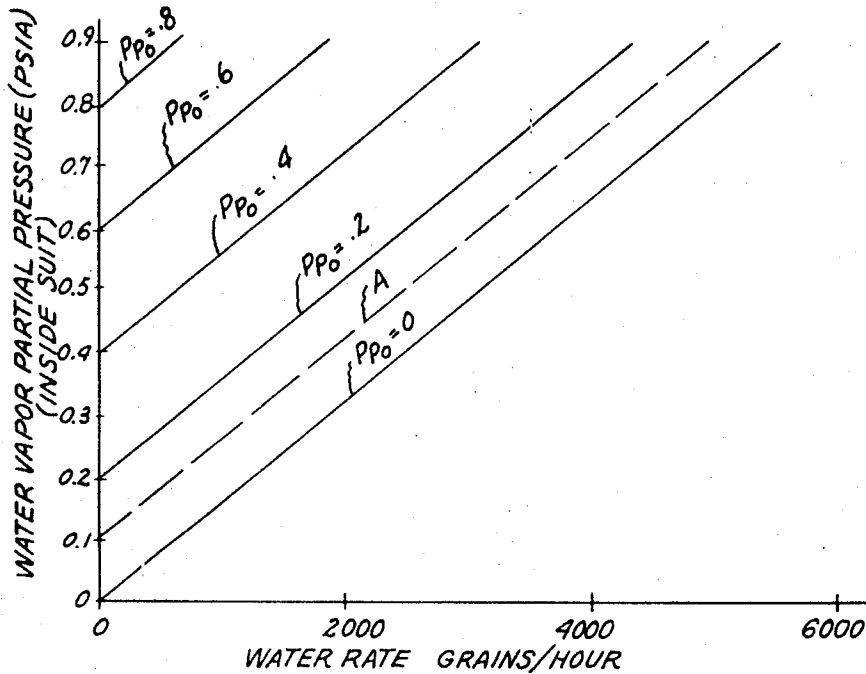
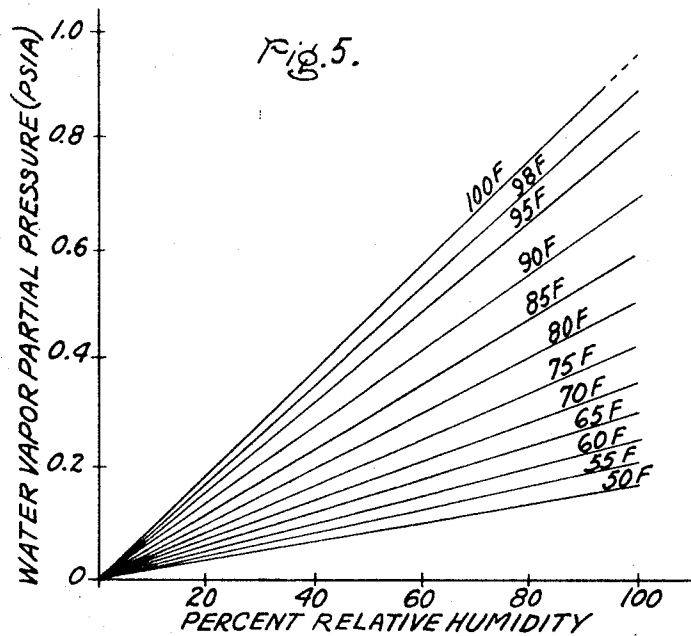


Fig. 5.



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PERMEABLE PROTECTIVE SUIT IN COMBINATION WITH MEANS FOR MAINTAINING A VIABLE ATMOSPHERE

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5 Claims

ABSTRACT OF THE DISCLOSURE

A protective system against bacteria and aerosols is provided wherein a suit made of permselective membrane materials is combined with a device having permeable non-porous wall area for the effective reduction of the water vapor and carbon dioxide content of exhaled gases admitted thereto at the same time as water vapor and noxious and toxic body-generated gases controllably leak through the suit material.

The human body, through metabolism generates heat and produces water vapor by perspiration and respiration. The body also consumes oxygen and eliminates carbon dioxide through breathing. The quantity of carbon dioxide and water eliminated varies from person to person and depends largely on the exercise and type of work being performed. For these reasons, a person working a totally sealed protective suit acting as a barrier to the entry of bacteria or aerosols, which may be present in the surrounding atmosphere, presents certain problems. Thus, the carbon dioxide content inside the protective garment must be controlled; air or oxygen must be supplied, and moisture and heat produced must be eliminated from the atmosphere within the protective garment.

Significant improvement in comfort for the wearer of a protective suit totally sealed against invasion by bacteria or aerosols in the surrounding atmosphere is attained by providing for the removal of water vapor through substantially all areas of the protective suit. Constant removal of moisture through the protective garment induces evaporation cooling of the occupant of the garment sufficient to eliminate excess heat produced by the body. At the same time a viable atmosphere is maintained for breathing by the occupant, this viable atmosphere being supplied by a source of oxygen in combination with a device having permeable, non-porous wall area. Exhaled breath of the occupant is conducted to the aforementioned device for the effective reduction therein of carbon dioxide and water vapor from the exhaled gases, which gases are then re-cycled and combined with fresh oxygen for readmission to maintain the viable atmosphere within the protective suit and/or helmet. The aforementioned device extends the capabilities of the given oxygen supply by at least an order of magnitude by refurbishing the exhaled gases rather than simply expelling these gases to the ambient atmosphere. Also, in spite of the capacity of the protective suit material to pass water vapor, liquid water will not pass therethrough for the suit material is fully waterproof.

It is, therefore, a prime object of this invention to overcome a serious problem encountered in protective clothing, which fully encloses the wearer, by insuring the effective removal therethrough of water vapor emitted by the body without permitting the passage of liquid water to the interior of the clothing from without the clothing.

It is an additional object to provide in combination with a suit for individual use of a system comprising a rebreather unit for extending the capability of the usual

oxygen supply to support respiration for the occupant of the protective garment.

It is still another object of this invention to provide the above mentioned objects with substantial weight reduction and increased comfort for the occupant.

In the usual protective suits designed to be impermeable to bacteria, a layer of latex rubber sheeting is disposed inside a layer of nylon cloth to form the basic structure. Because such a suit wall is relatively impermeable to water vapor, air must be circulated within the suit to remove the water vapor emitted by the body and keep the wearer reasonably cool and dry by evaporation. However, the difficulty of causing the air to be circulated effectively to the extremities (fingers and feet) often results in the gradual collection of liquid water in the suit and consequent discomfort for the wearer.

The exact nature of this invention as well as other objects and advantages thereof will be readily apparent from consideration of the following specification relating to the annexed drawing in which:

FIG. 1 is a three-dimensional view illustrating an embodiment of this invention;

FIG. 2 is an enlarged view showing in cross section the composite of suit fabric and permeable membrane material;

FIG. 3 is a sectional view of the rebreather unit taken on line 3—3 of FIG. 1;

FIG. 3A is a sectional view of the rebreather unit taken on line 3A—3A of FIG. 3;

FIG. 4 graphically shows the heat and moisture lost due to evaporation under different conditions of exertion by the wearer;

FIG. 5 graphically displays the relationship between partial pressure, humidity and temperature, and

FIG. 6 displays the equilibrium water vapor partial pressure within the suit as a function of the water permeation rate with partial pressure of water vapor outside the suit as a parameter.

The integrated protective suit-rebreather package 10 is fabricated of a composite material shown in detail in FIG. 2. The permeable membrane 11, as for example dimethylsilicone rubber is protected by the backing materials 12 and 13 to provide a composite rugged, wear-resistant suit fabric. In contrast to latex rubber (or neoprene or butyl, for example) the dimethylsilicone rubber is at least thirty times more permeable to water vapor. The backing materials 12 and 13 must be selected from materials easily bonded to the silicone rubber permselective membrane and yet of an appropriate weave such as not to impede the dispersion of water vapor after it permeates from permeable membrane 11. Fabrics or mats of cotton or synthetic fibers in a relatively open weave may be employed. As an example, open-mesh cloth having a thickness of from about 2—10 mils will suffice.

The composite fabric must be evaluated to insure compatibility between the component materials and establish a satisfactory overall permeation rate. The suits must be leak tight and, therefore, in the event that the fabric is assembled by sewing, care must be taken to seal the needle holes. This problem may be solved by the use of a liquid sealant to impregnate and seal the seam and holes or by sewing a thermoplastic strip within a lap seam, after which heat can be applied thereto to melt the tape and fill the holes as well as to impregnate the backing material in the seam. This large amount of care taken in assembling the suit to prevent the presence of pin holes is of particular importance to insure the effective performance of the permeable membrane material.

The term "permselective membrane" is used herein as an expression of the unique property (selective permeability) of certain organic film materials. This term does not imply the passage of one gas through the membrane to

the complete exclusion of others, but does indicate that a difference exists in the flow rate of two molecular species through a permeable membrane as contrasted to a porous material, such as paper. The mechanism by which gas or vapor permeates the membrane is not a simple diffusion process as may be effected with a porous material, but rather one in which the gas dissolves in the membrane, diffuses therethrough, and then leaves the membrane in the gaseous form on the other side.

The membrane area, thickness, and composite permeability are fixed in the particular suit design in order to function properly under specified conditions. The water vapor partial pressure inside the suit will depend on the level of exertion of the wearer and this parameter together with the outside temperature will control how much body water is emitted by the wearer. A guide is provided for design purposes in FIG. 4 wherein the relationship is established between outside temperature (dry bulb), the total evaporation heat loss in B.t.u./hour for an average man and the moisture loss/hour due to evaporation under different conditions of exertion for an average man. The several curves are explained as follows: curve A is for a man working at the rate of 66,150 foot pounds/hour; curve B is for a man working at the rate of 33,075 foot pounds/hour; curve C is for a man working at the rate of 16,538 foot pounds/hour, and curve D is for a man seated and at rest.

The outside water vapor partial pressure is controlled by the temperature, the relative humidity, and the air currents which sweep away the water vapor as it permeates the suit material, thus preventing a local increase in water vapor partial pressure. The relationship between temperature, relative humidity and the water vapor partial pressure applicable either inside or outside the suit is displayed in FIG. 5 for still air conditions.

Assuming that the protective suit would present a surface area of about 2 square meters (2.4 square yards) of permeable membrane 0.001 inch thick, the water permeation rate of such a suit is shown in FIG. 6 as a function of equilibrium internal water vapor partial pressure and outside water vapor partial pressure (P_{po}). This design data provide means for evaluating the effectiveness of a given permselective membrane protective garment with respect to its capacity to prevent the build-up of water vapor therewithin under varying conditions of ambient temperature, humidity and exertion level. By way of example, if conditions inside the suit are 75° F. at 90% relative humidity, the partial pressure of water vapor inside the suit is 0.39 p.s.i.a. (FIG. 5). Assuming that the occupant is seated and engaged in substantial arm and leg movement as would be the case with an airplane pilot, for example, an average man would produce approximately 1700 grains of moisture per hour (midway between curves C and D at 75° F. in FIG. 4). As long as the partial pressure of water vapor outside the suit is below 0.11 p.s.i.a. (line A in FIG. 6), the suit will permeate 1700 grains of moisture per hour with the partial pressure of water vapor inside the suit at 0.39 p.s.i.a. The ambient conditions under which 0.11 p.s.i.a. water partial pressure exists outside the suit can then be determined from FIG. 5. Thus, for example, at 100° F. there would be a comparable value of relative humidity of about 11% at which the 0.11 p.s.i.a. water partial pressure would not be exceeded, at 75° F. the comparable relative humidity would be 25%, at 50° F. the comparable relative humidity would be 62%. If the conditions outside the suit were to remain constant at a water partial pressure of 0.11 p.s.i.a. or below and the temperature inside the suit were to increase to 90° F., the water rate from the wearer would be increased to approximately 3000 grains per hour for the same level of activity and in order for the suit to permeate 3000 grains of water vapor per hour, the steady-state relative humidity inside the suit would have to be at least about 86%. This work rate could be carried on indefinitely in the suit of this invention, however, any

time limit being dictated by the capacity of the oxygen supply.

In addition to the aforementioned severe problem of the elimination of water vapor, which has been alleviated in the manner described, the problems of controlling carbon dioxide content within the protective garment and the conservation of oxygen supplied to the protective garment must be provided for.

Ordinarily, pure oxygen supplies are quantitatively evaluated for particular lengths of usage on the assumption that each breath of pure oxygen taken by the wearer is exhausted to the ambient upon exhalation. Such usage is manifestly wasteful of oxygen, because the average breathing rate for a man with moderate activity is about 10 liters per minute, while the actual oxygen used biologically is only about 0.5 liter per minute of oxygen (normal temperature and pressure, 25° C. and 760 mm. of mercury). In this invention as well as in the improved respirator system disclosed and claimed in U.S. application Ser. No. 615,582—Dibelius et al., filed concurrently herewith and assigned to the assignee of this invention, an effective and efficient device has been employed to solve this problem with a considerable resultant saving in oxygen. This saving in oxygen is effected by processing the exhaled mixture through permselective membrane rebreather device 16 shown in combination with the oxygen supply tank 17, demand regulator 18, mixer 19, inhalation duct 21, exhalation duct 22, inlet pipe 23 and breathing bag 24.

In much the same manner as is described in U.S. application Ser. No. 615,582 and incorporated herein by reference, exhaled gas (15.8% O₂, 79% N₂, 5.2% CO₂ plus water vapor in variable amounts) leaves helmet 26 via exhalation conduit 22 and is introduced to manifold 27 of rebreather 16 via conduit 23. Manifold 27 is in communication with many closely spaced permeation channels 28 in which the walls 29 thereof of dimethylsilicone film are closely spaced to insure maximum contact between gas passing therethrough and the walls 29. Ambient air is freely circulated through open lanes 31 as shown by the arrows by blower 32 powered by batteries (not shown).

In passage of the exhaled gas along permeation channels 28, the carbon dioxide level is reduced from 0.052 atmosphere partial pressure to about 0.01 atmosphere partial pressure, because of gas transfer through permeable walls 29. The driving force for such gas transfer through the membrane walls 29 is the difference in partial pressure of the component in question (CO₂ and/or water vapor). Thus, no large amount of reliance need be placed upon the lung power of the person wearing the protective suit to create a gross pressure differential across the film walls 29, although any such gross pressure differential would also serve to provide additional driving force. Thus, the significantly larger concentration of carbon dioxide (and water vapor) that exists in the exhaled gases as compared to the partial pressure thereof on the atmospheric side of membrane walls 29, is responsible for the conduct of the transfer of mechanisms of solution and diffusion whereby both carbon dioxide and water vapor leave permeation channels 28 through membrane walls 29 and move to open lanes 31 where they become part of the ambient atmosphere. The purged exhaled gases then continue into upper manifold 33 and thence into breathing bag 24 and into mixing valve 19. In the mixing valve 19 these purged gases are refurbished by the addition thereto of oxygen from oxygen bottle 17 via demand regulator 18 to compensate for oxygen depletion by biological consumption. The refurbished breathing gas is then ready for return to helmet 26 via tube 21. If desired, for aesthetic reasons, a separating diaphragm (not shown) may be used to isolate the volume of helmet 26 from communication with the open volume in the balance of the suit.

The criteria for selecting useful membrane materials are the following:

- (a) a CO₂/O₂ permeability ratio (permeability to CO₂ divided by the permeability to O₂) greater than 5:1;
- (b) absolute permeability to CO₂ in excess of about

$$200 \times 10^{-9} \frac{\text{cc. NTP-cm.}}{\text{sec.-cm.}^2\text{-cm. Hg } \Delta P}$$

(NTP being the abbreviation for "normal temperature and pressure"); and

- (c) the absolute permeability to water being greater than

$$3000 \times 10^{-9} \frac{\text{cc. NTP-cm.}}{\text{sec.-cm.}^2\text{-cm. Hg } \Delta P}$$

if humidity control is desired.

Further, the membrane material selected should be one that can be manufactured in pin-hole free uniform thickness of less than 2 mils in order to reduce the requisite area of membrane and permit construction of a compact rebreather package.

Silicone rubber is uniquely suited to this purpose and a method for the preparation of thin, substantially defect-free organopolysiloxane films is disclosed in U.S. application Ser. No. 466,698—Robb, filed June 24, 1965 and now U.S. Patent No. 3,325,330. The portions of said application describing methods for the preparation of such films in substantially uniform thicknesses of less than about 2 mils are incorporated herein by reference.

Since the membrane walls 29 are preferably of a thickness in the order of about 1 mil or less the permeable film should be supported against rupture during assembly and use. The general durability of such thin film material is increased by the application thereto of an open-mesh backup material such as a cloth or mat (not shown) having a thickness from 2–10 mils on one or both sides of the film and, where necessary, the added support of a screen (not shown) having a mesh size (U.S. Sieve) ranging from about 10–50.

Considerable care must be taken in sealing the membrane walls 29 to the walls of manifolds 17, 33 as only a very small leakage rate can be tolerated.

Circulating means, such as battery-powered blower 32 must have capacity for discharging approximately 84 liters per minute of purging air over the outside of membrane walls 29 in order to scrub away surface concentration of gas highly concentrated in carbon dioxide and/or water vapor. A rechargeable battery (not shown) having an 800 watt-hour capacity should provide sufficient energy for reliable operation of blower 32.

Assuming that an average carbon dioxide partial pressure differential across membrane walls 29 of about 0.031 atmosphere and a residence time for the gases in channels 28 of at least about 30 seconds, the area of dimethylsilicone rubber required would be approximately 7.5 square yards. Such an area of membrane can be packaged into a volume of approximately 0.375 cubic foot.

Since no nitrogen is consumed in the breathing process, the nitrogen partial pressure on the inside of the membrane is in equilibrium with that outside the membrane (both gaseous atmospheres containing about 79% nitrogen) and there will be no significant nitrogen permeation in either direction through walls 29. However, since the oxygen partial pressure in the ambient air is approximately 0.20 atmosphere while the oxygen partial pressure of the exhaled breath entering the rebreather package 16 is approximately 0.15 atmosphere and the oxygen partial pressure of the gas mixture leaving the rebreather 16 is about 0.17 atmosphere, there is an average partial pressure driving force from the ambient for oxygen of 0.04 atmosphere producing permeation through walls 29 into channels 28 at the rate of about 0.20 liter per minute. As a result of this inward permeation of oxygen, therefore, only 0.30 liter per minute of oxygen must be replaced from the oxygen cylinder, if a biological oxygen usage

of about 0.5 liter per minute by the wearer of the protective suit is assumed.

One of the prime advantages of this solution to the problem of removal of carbon dioxide to refurbish exhaled air is the fact that the permselective membrane walls 29 have an essentially indefinite life in contrast to various solutions that have been proposed for absorbing carbon dioxide gas. Also, assuming a makeup usage of about 0.30 liter per minute of oxygen effective conservation (by a factor of about 30) of oxygen over oxygen use in an open system wherein the exhalant is vented to the atmosphere is obtained.

Thus, with respect to the complete rebreather system the gases leaving upper manifold 33 have the approximate composition of 17.5% oxygen, 81.5% nitrogen and 1.0% CO₂ (dry volume). This mixture passes from breathing bag 24 to mixer 19 wherein makeup oxygen is received from oxygen supply 17 to provide an output from mixer 19 having a composition of approximately 20% oxygen, 79% nitrogen and 1.0% carbon dioxide. This mixture passes to helmet 26 through inhalation conduit 21. Both inhalation conduit 21 and exhalation conduit 22 require check valves (not shown) to insure movement of the gas mixture in the selected paths. Pressure control and demand regulator 18 sets the amount of oxygen passing from oxygen source 17 to mixer 19.

In addition to reducing the amount of oxygen required to support the viable atmosphere within the protective suit, the logistics problem of supplying oxygen to remote geographic locations wherein such suits may be employed is significantly reduced in severity.

Since the preferred material for the membrane walls 29 and as the permselective membrane 11 for the suit fabric is dimethylsilicone rubber, the values of permeabilities for this material have been set forth in Table I.

TABLE I

		Pr. cc. NTP-cm. sec.-cm. ² -cm. Hg ΔP
Gas:		
Nitrogen	-----	28 × 10 ⁻⁹
Helium	-----	35 × 10 ⁻⁹
Oxygen	-----	60 × 10 ⁻⁹
Hydrogen	-----	66 × 10 ⁻⁹
Carbon dioxide	-----	320 × 10 ⁻⁹
Freon 11	-----	1500 × 10 ⁻⁹
Freon 12	-----	138 × 10 ⁻⁹
Methane	-----	94 × 10 ⁻⁹
Ethane	-----	250 × 10 ⁻⁹
Propane	-----	410 × 10 ⁻⁹
n-Butane	-----	900 × 10 ⁻⁹
n-Propane	-----	2000 × 10 ⁻⁹
n-Hexane	-----	940 × 10 ⁻⁹
n-Octane	-----	860 × 10 ⁻⁹
n-Decane	-----	430 × 10 ⁻⁹
Ethylene	-----	135 × 10 ⁻⁹
Benzene	-----	1910 × 10 ⁻⁹
Phenol	-----	1080 × 10 ⁻⁹
Toluene	-----	913 × 10 ⁻⁹
Pyridene	-----	2100 × 10 ⁻⁹
Acetone	-----	1980 × 10 ⁻⁹
Ammonia	-----	586 × 10 ⁻⁹
Water	-----	3800 × 10 ⁻⁹
Hydrogen sulfide	-----	650 × 10 ⁻⁹

Although the use of this invention has been described in connection with respiration by humans, it is apparent that any vertebrate can be supplied oxygen in the same manner and such a device may find application in veterinary medicine as well as in the exemplary application described.

What we claim as new and desire to secure by Letters Patent of the United States is:

1. In a protective garment made in large part of waterproof flexible material for isolating the occupant from

direct contact with the gaseous ambient during the conduct of various degrees of physical activity by said occupant the improvement comprising, the waterproof flexible material having as part thereof a layer of non-porous permeable membrane having an absolute permeability to water vapor of greater than

$$3000 \times 10^{-9} \frac{\text{cc. (NTP) cm.}}{\text{sec.-cm.}^2\text{-cm. Hg } \Delta P}$$

2. The improved protective garment substantially as recited in claim 1 wherein the permeable membrane is dimethylsilicone rubber protected with porous backing material.

3. In protective equipment for isolating an occupant thereof from direct physical contact with the atmosphere comprising in general a protective garment made in large part of flexible waterproof material, means for supplying oxygen from an oxygen source to the occupant of said garment and means for reducing the carbon dioxide gas content of the gases exhaled by said occupant, the improvement comprising:

(a) the waterproof flexible material having as part thereof a layer of non-porous permeable membrane, and

(b) the means for reducing carbon dioxide gas content comprising a high surface area volume in communication with the interior of the protective garment to receive exhaled gases therefrom and return refurbished gases thereto, said volume being defined in large part by a non-porous permeable membrane having a CO₂/O₂ permeability ratio greater than

5:1 and having an absolute permeability to CO₂ in excess of about

$$200 \times 10^{-9} \frac{\text{cc. NTP-cm.}}{\text{sec.-cm.}^2\text{-cm. Hg } \Delta P}$$

4. The improved protective equipment substantially as recited in claim 3 wherein the layer of non-porous permeable membrane of the waterproof flexible material is dimethylsilicone rubber.

5. The improved protective equipment substantially as recited in claim 3 wherein the non-porous permeable membrane in the means for reducing carbon dioxide gas content is dimethylsilicone rubber.

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CHARLES F. ROSENBAUM, Primary Examiner

U.S. Cl. X.R.