GIROUD, J. P.
GeoServices, Inc., Boca Raton, Florida, USA

Impermeability: The Myth and a Rational Approach

Impermeability is a legitimate goal at a time when conservation of resources and prevention of pollution are a priority. This goal is difficult to achieve because all liner materials are permeable. The first part of the paper provides practical information on geomembrane permeability and leakage evaluation. The second part of the paper shows how appropriate design can lead to almost zero leakage through the use of double or triple liners.

"Dear Henry: Thank you for your very pertinent letter on the use of the adjective impermeable... I agree...that the adjective "impermeable" should be given a relative value, not an absolute one... I am well aware of the damages caused by misunderstanding of the word impermeable. I am presently involved in the repair of a reservoir, "guaranteed impermeable" by the installer, where leakage triggered approximately one million dollars in damage." This excerpt of a letter by this paper's author responded to a letter from H. Haxo, Jr., of which excerpts follow.

"Dear Jean-Pierre: I have received a copy of Bulletin No. 1 announcing the International Conference on Geomembranes... I feel that the use...of the word "impermeable" in describing polymeric membranes is perpetuating a basic and serious misconception regarding these lining materials. No membrane, polymeric or otherwise, is completely impermeable or impervious to all gases, vapors, and liquids. All polymeric compositions are permeable in different degrees to different fluids - to gases, vapors, or liquids. The question is how much of a given waste constituent is transmitted through a specific membrane under the conditions of test or service exposure and in which direction. Even though membranes are not impermeable, because of their low permeability to many permeants they can be used effectively to control pollutant migration... The concept that membranes are impermeable is already causing considerable misunderstanding in the liner industry and among regulatory personnel, engineers, designers, users, and owners of waste impoundments... I also suggest that the International Conference on Geomembranes would be an appropriate forum at which to clarify this misconception and place this property of membranes and other liners in its proper perspective."

This exchange of correspondence, in May of 1983, inspired the following paper which is intended to illustrate a key sentence written by H. Haxo, Jr.: "Even though membranes are not impermeable,...they can be used effectively to control pollutant migration." Accordingly, the paper has two parts: in the first part it is shown that all materials are permeable, and in the second part it is shown that appropriate design using geomembranes can ensure a certain level of "impermeability".

1 PERMEABILITY OF MATERIALS

All materials used as liners are permeable to fluids (liquids and gases) and a certain amount of leakage should be expected through liners. Additional leakage results from defects such as cracks, holes and faulty seams.

The first part of this paper is intended to provide designers with practical information regarding evaluation of permeability and leakage.

1.1 Darcy's Equation

The permeability of soils is evaluated using Darcy's equation:

$$v = ki \qquad (1)$$

where: v = fluid velocity (m/s); k = conductivity (also called coefficient of permeability) (m/s); and $i = h/T$ = hydraulic gradient (dimensionless); h = hydraulic head (m); and T = geomembrane thickness (m).

The conductivity k depends on the fluid (and its temperature) and on the soil. When the fluid is water, k is the hydraulic transmissivity. The following relationship exists between conductivities related to two different fluids at different temperatures flowing in a same soil:

$$k_1/k_2 = (\rho_1/\rho_2)\ (\eta_2/\eta_1) \qquad (2)$$

where: ρ_1 and η_1 = density (kg/m^3) and dynamic viscosity (kg/(ms)) of fluid 1 at temperature 1; ρ_2 and η_2 = density (kg/m^3) and dynamic viscosity (kg/(ms)) of fluid 2 at temperature 2.

Darcy's equation is often called Darcy's law, which is improper. In mechanics of continuous media, a law is a relationship between stresses and strains, derived from tests. Examples of laws are: (i) Hooke's law which is a linear relationship between stresses and strains, describing the linear elastic behavior of a solid; (ii) Newton's law which is a linear relationship between shear stress and rate of strain, describing the linear viscous behavior of a liquid.

Integration of a law for given boundary conditions leads to an equation. Examples are: (i) integration of Hooke's law in a loaded semi-infinite soil mass leads to Boussinesq's equation giving a relationship between load and settlement of the soil, depending on the elastic modulus of the soil; (ii) integration of Newton's law in a pipe leads to Poiseuille's equation giving a relationship between discharge of liquid and geometry of the pipe, depending on viscosity of the liquid.

Darcy's equation is a special case of Poiseuille's equation for a porous medium which is a special case of a tortuous pipe. As Poiseuille's equation, Darcy's equation (as well as Eq. 2 above) is valid only for laminar flow.

The mechanisms by which fluids flow through geomembranes and soils are different. Darcy's equation can be used for geomembranes only if it is made clear that the coefficient of permeability used for the geomembrane depends on the flow conditions, hydraulic gradient or hydraulic head. Similarly, the relationships presented hereafter are applicable only within the regime of laminar flow as well as other limits of validity of Darcy's equation.

1.2 Evaluation of Permeability

Users of geomembranes are confused by the variety of terms used to evaluate permeability. A review of these terms is presented below.

Conductivity (or Coefficient of Permeability), k. Volume, V, of fluid passing per unit area, A, of geomembrane, per unit hydraulic gradient, i, per unit period of time, t.

$$k = V/(Ait) \qquad (3)$$

Dimension: LT^{-1}. Units: m/s; cm/s; perm-inch; perm-mil; "metric" perm-cm. Relationships between units:

$$1 \text{ cm/s} = 0.01 \text{ m/s}$$
$$1 \text{ perm-inch} = 1.67 \text{ "metric" perm-cm} = 1.42 \times 10^{-11} \text{ m/s}$$
$$1 \text{ perm-mil} = 10^{-3} \text{ perm-inch} = 1.42 \times 10^{-14} \text{ m/s}$$
$$1 \text{ "metric" perm-cm} = 0.598 \text{ perm-inch} = 598 \text{ perm-mil} = 8.51 \times 10^{-12} \text{ m/s}$$

Permittivity, Ψ. Volume, V, of fluid passing per unit area, A, of geomembrane, per unit hydraulic head, h, per unit period of time, t.

$$\Psi = V/(Aht) \qquad (4)$$

Dimension: T^{-1}. Unit: s^{-1}.

Impedance, I. Time t necessary for a unit volume, V, of fluid to pass through a unit area, A, of geomembrane, per unit hydraulic head, h.

$$I = Aht/V \qquad (5)$$

Dimension: T. Unit: s. While other terms presented in this section are proportional to the quantity of flow, impedance is inversely proportional to the quantity of flow and can be used as a measure of the relative "impermeability".

Permeance, ω. Mass, M, of fluid passing per unit area, A, of geomembrane, per unit pressure, p, per unit period of time, t.

$$\omega = M/(Apt) \qquad (6)$$

Dimension: TL^{-1}. Units: $kg/(m^2.Pa.s)$; perm = grain/(ft^2. inch Hg. hour); "metric" perm = g/(m^2.mmHg. 24 hours). Relationships between units:

$$1 \text{ perm} = 5.72 \times 10^{-11} \text{ kg/(m}^2\text{. Pa. s)}$$
$$1 \text{ perm} = 0.659 \text{ "metric" perm}$$
$$1 \text{ "metric" perm} = 1.517 \text{ perm}$$

Water Vapor Transmission Rate, WVT. Mass, M of water vapor passing per unit area, A, of geomembrane, per unit period of time (under a specified pressure which may vary from one test to another).

$$WVT = M/(At) \qquad (7)$$

Dimemsion: $ML^{-2}\ T^{-1}$. Units: $kg/(m^2.s)$; g/(m^2. 24 hours); grain/(ft^2. hour). Relationships between units:

$$1 \text{kg/(m}^2\text{.s)} = 8.64 \times 10^7 \text{g/(m}^2\text{.24h)}$$
$$1 \text{g/(m}^2\text{.24h)} = 0.0598 \text{ grain/(ft}^2\text{.hour)}$$
$$1 \text{kg/(m}^2\text{.s)} = 5.17 \times 10^6 \text{grain/(ft}^2\text{.hour)}$$

Relationships Between Various Terms. When Darcy's equation is applicable, the following relationships exist between the terms defined above:

$$k = \Psi T \qquad (8)$$
$$I = 1/\Psi = T/k \qquad (9)$$
$$\omega = \Psi/g \qquad (10)$$
$$WVT = p\,\omega = p\Psi/g \qquad (11)$$

where : T = geomembrane thickness; g = gravity (9.81 m/s^2); p = vapor pressure in the vapor transmissivity test.

The relationship between conductivity on one hand, and permittivity and impedance on the other hand, depends on the thickness of the geomembrane. If two geomembranes are made from the same polymeric compound, they have the same conductivity, k . Their impedances are proportional to their thickness; and their permittivities are inversely proportional to their thickness (provided Darcy's equation is applicable).

Since gravity has a fixed value, relationships can be established between the units of permeance and permittivity, using Eq. 10:

$$1 \text{ kg/(m}^2\text{.Pa.s)} = g\ s^{-1} = 9.81\ s^{-1}$$
$$1 \text{ perm} = 9.81 \times 5.72 \times 10^{-11} s^{-1} = 5.61 \times 10^{-10} s^{-1}$$
$$1 \text{ "metric perm"} = 8.51 \times 10^{-10} s^{-1}$$

Eq. 11 depends on the pressure which may vary from one test to another. Therefore it is impossible to establish a relationship between units of WVT, on one hand, and permittivity and permeance, on the other hand.

To deduce the permittivity or the permeance of a sample from a WVT measurement, it is necessary to know the vapor pressure in the WVT test. Sometimes, only the temperature and the relative humidity of the vapor are given. The vapor pressure can then be deduced using the following formula:

$$p = H \times p_s \qquad (12)$$

where: p_s = pressure of saturated vapor at a given temperature (which can be found in physics tables); and H = relative humidity.

Example. A WVT of 15.6 g/(m^2.24h) has been measured at a temperature of 24 °C and a relative humidity of 55%. According to physics tables:

$$p_s = 22.377 \text{ mmHg} = 22.377 \times 133.3 = 2983 \text{ Pa}$$

The vapor pressure is:

$$p = 2983 \times 0.55 = 1641 \text{ Pa}$$

The permeance of the sample is:

$$\omega = (15.6/8.64 \times 10^7)/1641 = 1.1 \times 10^{-10} \text{ kg/(m}^2\text{.Pa.s)}$$

1.3 Permeability of Geomembranes

Tests were conducted 1973 to 1977 under the responsibility of the author at the University of Grenoble, France, to evaluate the permeability of geomembranes.

Influence of Pressure. The tests were conducted with deaired water subjected to pressures ranging from 50 to 1000 kPa. Results are presented in Fig. 1. Also presented in Fig. 1 are values of conductivity of geomembranes derived using Eqs. 8 and 11 from values of water vapor transmission found in various chemistry manuals and manufacturer's brochures. These values were usually measured according to ASTM E-96, i.e. with pressures typically less than 10 kPa. Values obtained with water and values obtained with vapor are of the same order of magnitude, and the ranking of Hypalon, PVC and Butyl rubber is the same.

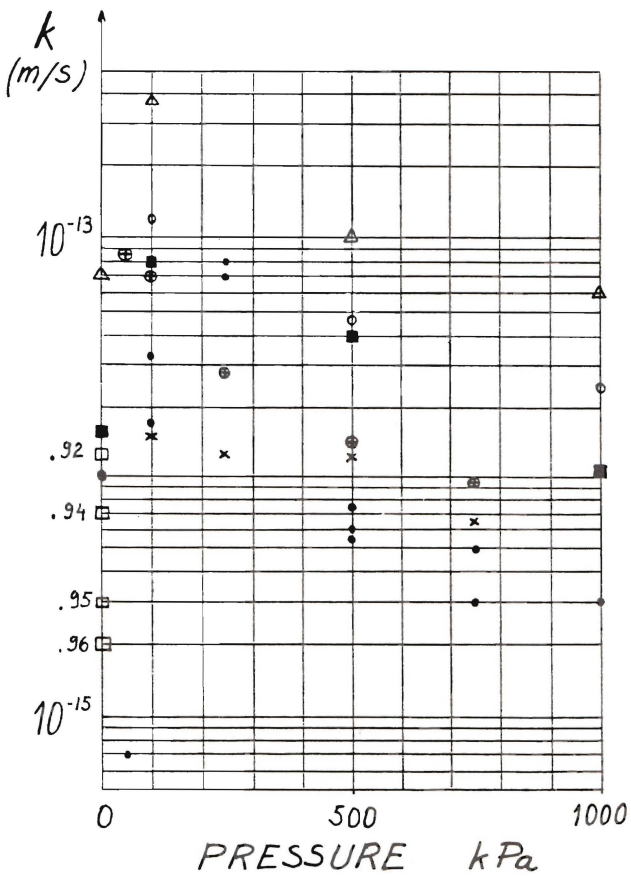

Fig. 1 Coefficient of permeability to water (hydraulic conductivity) of various geomembranes. Values shown on the vertical axis have been deduced from water vapor transmission tests. Other values were obtained with deaired water. Legend: ● Butyl rubber; ○ EPDM; △ CSPE (Hypalon); □ Polyethylene (value of density is indicated); ■ PVC; ⊕ and × asphaltic geomembranes.

Results of tests obtained with water show that the coefficient of permeability of Butyl rubber exhibits a peak for a pressure of 250 kPa and then decreases with increasing pressures. All other geomembranes tested, polymeric and asphaltic, have a coefficient of permeability decreasing with increasing pressure. If Darcy's equation were applicable to geomembranes, coefficients of permeability would be independent of pressure. Nonetheless, Darcy's equation can be used with certain precautions as explained in section 1.4.

Influence of Geomembrane Elongation. Tests were conducted with deaired water on Butyl rubber samples subjected to the following elongations in both directions: 0%, 4.9%, 9.5% and 22.5% resulting in area increase of 0%, 10%, 20% and 50%, respectively. Test results are presented in Fig. 2. It appears that the elongation, although it affects the shape of the curves, does not significantly affect the order of magnitude of the coefficient of permeability. Additionally, a few tests were conducted with an 80% area increase. Results of these tests were not significantly different from the 50% area increase results.

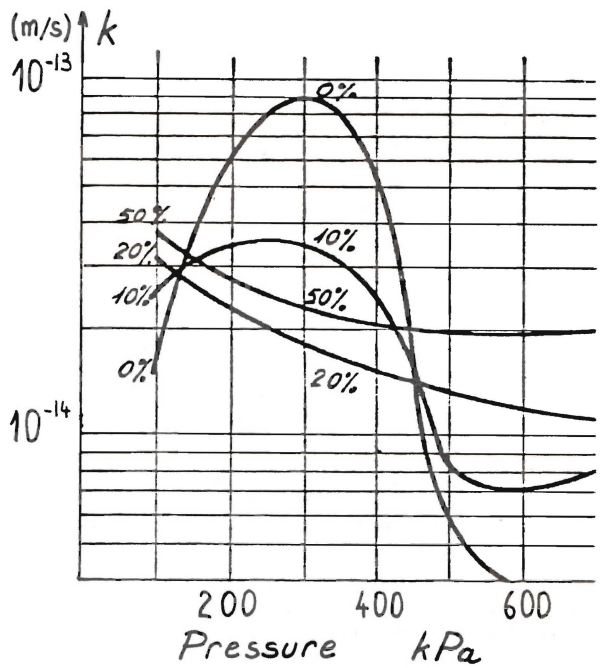

Fig. 2 Coefficient of permeability of a Butyl rubber geomembrane subjected to elongation. (Percentages are increases in area of the Butyl rubber geomembrane)

1.4 Leakage Evaluation

Leakage is due to permeability of the geomembrane and holes through the geomembrane.

Leakage due to permeability can be evaluated approximately using Darcy's equation (see section 1.1) if the coefficient of permeability has been measured on a geomembrane sample of the same thickness which has been subjected to the same fluid pressure as the considered geomembrane.

To evaluate leakage due to holes, two cases should be considered: pinholes and large holes. Pinholes can be defined as holes having a dimension (e.g., diameter if circular) significantly smaller than geomembrane thickness. For leakage calculation purpose, such a hole can be considered as a pipe and Poiseuille's equation can be used. Large holes are holes having a dimension (e.g., diameter if circular) significantly larger than geomembrane thickness. The classical Bernouilli's equation for flow through an aperture can therefore be used. In conclusion, the following three equations are useful for leakage evaluation:

. Darcy's equation (geomembrane permeability):

$$Q/A = k\ (z/T) \qquad (13)$$

. Poiseuille's equation (pinholes):

$$Q = \pi \rho g\ z\ d^4/(128\ \eta\ T) \qquad (14)$$

. Bernouilli's equation (large holes):

$$Q = Ca\sqrt{2gz} \qquad (15)$$

where: Q = discharge (m^3/s); Q/A = discharge per unit area (m/s); z = depth below water level (m); k and T = coefficient of permeability (m/s) and thickness (m) of the geomembrane; d = pinhole diameter (m); a = hole surface area (m^2); ρ and η = density (kg/m^3) and dynamic viscosity (kg/m.s) of water; and g = gravity (9.81 m/s^2). C is a dimensionless coefficient, valid for any Newtonian fluid, related to the shape of the edges of the aperture; for sharp edges, C = 0.6.

By integration along bottom and slope of a geomembrane-lined reservoir, Eqs. 13, 14 and 15 lead to the following equation giving leakage from the entire reservoir:

$$Q = (H/T)\ [k + \pi\rho\ gd^4 n\ (128\eta)]\ (S + S'/2) + 0.85\ a\ N\sqrt{gH}\ (S + 2S'/3) \qquad (16)$$

where: H = height of liquid in reservoir (m); n = number of pinholes per unit area (m^{-2}); N = number of holes per unit area (m^{-2}); S = reservoir bottom surface area; and S' = reservoir slope surface area.

Integrations leading to Eq. 16 have been made with the assumption that slopes are rectangles which is true only for reservoirs with vertical slopes and for canals. However, Eq. 16 is an excellent approximation when bottom area is equal to or larger than slope areas.

An example of the use of Eq. 16 is presented in (4). This example shows that leakage due to geomembrane permeability is negligible compared to leakage through holes. Leakage due to pinholes is also negligible, unless there is an unusually large number of pinholes.

The last term of Eq. 16, which is related to leakage through holes, is valid only if the medium located underneath the geomembrane is free draining. The discharge through holes would be much smaller if the medium located under the geomembrane became saturated with the leaking liquid. This case is discussed in (1, 2, 3).

Leakage through a geomembrane with a hole is drastically reduced if the geomembrane is placed on a low permeability soil such as clay. Composite liners made of a geomembrane placed on a layer of compacted clay are sometimes used to decrease the risk of leakage. Such composite liners are effective only if geomembrane and clay are in close contact over their entire surface. This requirement is difficult to fulfill due to geomembrane wrinkles and clay surface irregularities and cracks. As a result, a leak in the geomembrane, instead of being stopped by the clay, may travel a long way between the two liners, toward the lowest spot of the lined facility, usually the sump area, where a water content increase softening the clay is less than desirable. In conclusion, the use of composite liners can be detrimental as well as beneficial.

Also, a typical mistake with composite geomembrane - clay liners consists of placing a geotextile under the geomembrane as a protection against puncturing by stones. Such a geotextile would facilitate flow of liquid between the two liners.

A composite geomembrane-clay liner is by no means a double liner. As discussed in the next section, a double liner includes a drainage layer.

2 IMPERMEABILITY THROUGH DESIGN

2.1 Parameters Governing Leakage

The test results presented in section 1.3 show that all geomembranes are permeable. In addition, experience shows that there are always holes in geomembranes caused by accidents or improper installation. However, leakage must be prevented in all cases where leaking liquids would pollute ground water, deteriorate the ground supporting the liner (thus provoking a major failure of the liner), or cause unacceptable economic loss (5).

As shown in the previous section, leakage potential is mostly through holes in the geomembrane. Eqs. 15 and 16 show that the two parameters governing leakage through holes are number and size of holes, and head of liquid over the geomembrane. Therefore, to minimize leakage, the number and the size of holes should be minimized and the head of liquid on the geomembrane should be as small as possible.

The number and size of holes can be minimized by appropriate quality control of geomembrane installation and by minimizing stresses likely to damage the geomembrane through careful design. The head of liquid on the geomembrane can be kept small as a result of adequate conceptual design as discussed in the following two sections, i.e., the head can be minimized through the use of double or triple liners.

2.2 Double Liner

Description. The double liner concept has been presented in an earlier paper (6). A double liner consists of two liners with an intermediate drainage layer connected to a sump from where the collected leakage is eliminated by gravity or, more generally, by pumping. If the drainage system is properly designed for the amount of liquid seeping through the upper liner, the head of liquid on the lower liner should be small at any time and leakage through the secondary liner should be small, unless the lower liner has many holes. In addition to leakage prevention, another function performed by a double liner is leakage detection.

No portion of the lower liner of a double liner system should be horizontal. A slope is necessary to prevent accumulation on the lower liner of liquid leaking through the upper liner. Theoretically, the lower liner of a double liner does not need to be waterproof. Elements of geomembranes overlapped as shingles on a roof should be sufficient. In fact, it is recommended to seam the lower liner as carefully as the upper liner: (i) to prevent or, at least, minimize leakage through the lower liner if the drainage layer becomes saturated; and (ii)

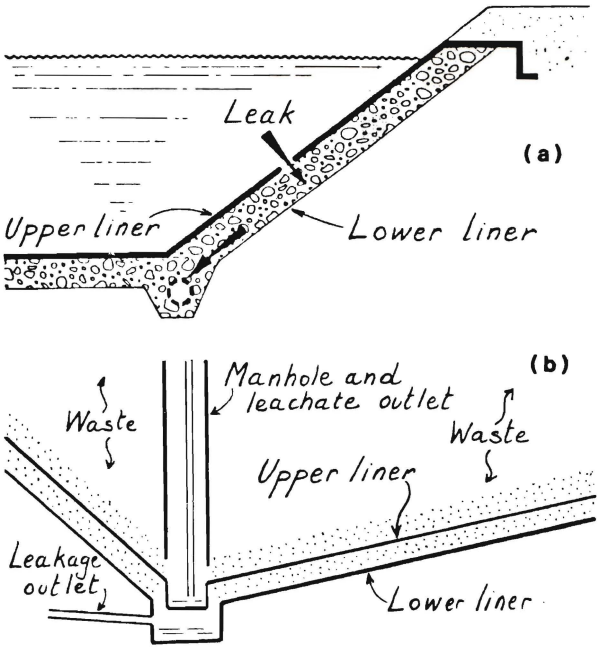

Fig. 3 Examples of double liners: (a) reservoir - original drawing published in 1973 (6); (b) solid waste disposal facility

also because even in the case of free flow, the head is never zero.

It should be emphasized that "double liner" does not mean merely putting two liners together. Leakage control through the use of double liners results from the combination of waterproofing and drainage.

Examples of Double Liners. Double liners are used in all types of liquid containments (reservoirs also called "liquid impoundments", dams and canals) and in solid waste disposal facilities (also called landfills) (Fig. 3). A double liner case history is presented in (4).

The upper liner in a solid waste disposal facility functions like the lower liner in a double liner system. If the drainage layer placed on the liner to collect leachate is properly designed and if the sump and the pump are properly operated, leachate should not accumulate on the liner and leakage should be small. Maximum head in drainage layers mentioned in USEPA (U.S. Environmental Protection Agency) recommendations is 0.3 m (1 ft.). However, cases where large quantities of leachate have accumulated in the bottom of landfills are not rare. Therefore, the upper liner of a landfill's double liner should be designed as if it were the upper liner of a liquid impoundment.

Problems with Double Liners. Ideally, a slope of the order of 5% should be selected at the bottom of a reservoir to ensure effectiveness of drainage between the two liners. Such a slope would significantly decrease the capacity of a reservoir or a landfill, and slopes of the order of 2% are usually selected. Such slopes require a large amount of care during earthwork. Often the slope is significantly less than 2% and ponding of liquid may occur in the drainage layer.

Geomembrane wrinkles, especially in the case of stiff geomembranes, may constitute a significant obstacle to drainage (7). The use of stiff wrinkle-prone geomembranes should be avoided for liners located under drainage layers. If for some reason a stiff wrinkle-prone geomembrane is used, precautions should be taken to minimize the development of wrinkles during and after installation.

A delicate part of the lower liners is their connection with sumps or other outlet structures. An example of the complexity of such structures is given in (4).

Conclusions on Double Liners. The principle of a double liner is to place a drainage layer on the geomembrane through which leakage is to be prevented. Drainage design should be such that the head on the liner is as small as possible. However, the head is never zero in a drain, so therefore a double liner minimizes but does not prevent leakage.

2.3 Triple Liner

As discussed above, a double liner does not offer a total guarantee of leakage prevention. When a higher level of impermeability is required, a triple liner can be used. Two cases can be considered.

Liquid Impoundment. A triple liner designed to prevent loss of liquid is shown in Fig. 4a. Such a triple liner was contemplated for the Proton Decay Experiment (4) once it was realized that a double liner did not offer a total guarantee. The triple liner solution was not selected when it was determined that liquid loss was not absolutely critical.

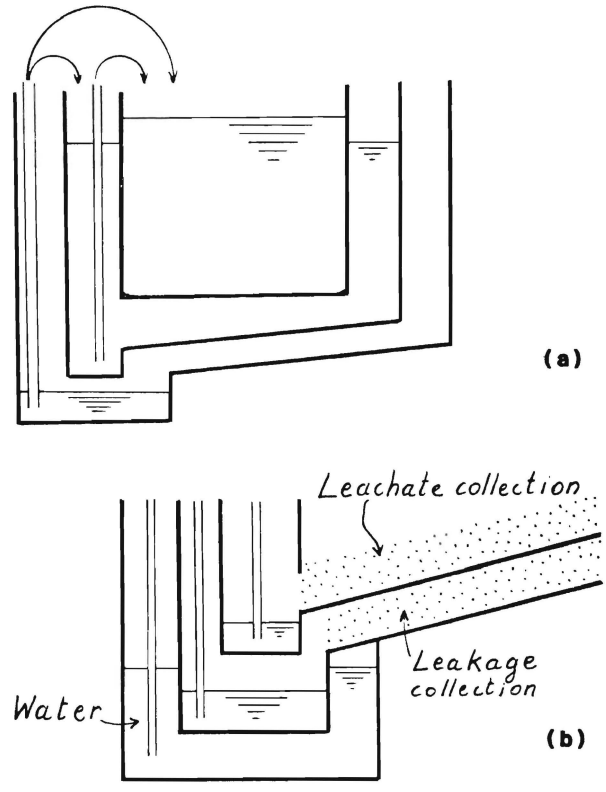

Fig. 4 Triple liner: (a) for liquid impoundment; (b) for solid waste landfill.

The principle is as follows. The space between the upper liner and the intermediate liner is filled with a porous medium containing the same liquid as in the upper liner, or a liquid having the same density. Leakage through the upper liner is almost zero because the pressure difference between both sides of this liner is kept very small. Leakage is expected to occur through the intermediary liner and then be collected by the drainage layer placed over the lower liner. Collected liquids can be recycled as shown in Fig. 4a. A refinement would consist of adjusting the compressibility of the porous medium located between the upper liner and the intermediary liner so that if the liquid level tends to move down in this medium, the effective stress increase compresses this medium which raises the liquid level.

A secondary feature of this type of triple liner is that the upper geomembrane is subjected to very small stresses which minimizes the risk of damage to the geomembrane but facilitates movements of the geomembrane. Therefore ballasting is necessary at the bottom, and some device to restrain movements may be useful on the sides.

Solid Waste Disposal Facility. A triple liner designed to prevent leakage of a hazardous liquid from a landfill sump is presented in Fig. 4b. The same systems could be used for the whole landfill.

The principle is as follows. Water is maintained around the sump at a higher pressure than the hazardous liquid. If leakage is governed only by pressure difference the hazardous liquid cannot leak out of the sump. In addition, in most circumstances, osmotic gradient should be from the water to the hazardous liquid. However, further studies should be done to evaluate if osmotic pressure may cause some components of the hazardous liquid to permeate through the geomembrane. Such a phenomenon would be detected by chemical analysis of the water, and if necessary, the water could be pumped out and replaced before significant leakage occurs through the lower liner.

The sump must be filled with heavy porous material such as gravel or must have structural resistance not to be uplifted by water pressure.

Conclusion on Triple Liners. Triple liners have not been used in actual projects to the author's knowledge. It is suggested that research be undertaken to assess the applicability of this concept. The feasibility of prefabricated triple liner sumps should also be investigated.

CONCLUSION

Impermeability is both a myth and a legitimate goal.

Impermeability is a myth because all liner materials are permeable. This myth is propagated by those who take advantage of the lack of information of many users and designers. This myth is also propagated by official bodies using the term impermeable to designate committees and conferences.

Impermeability is a legitimate goal at a time when conservation of resources and prevention of pollution are a priority. Although liner materials are not absolutely impermeable, impermeable containment or, more accurately "zero leakage" containment can be achieved with appropriate design. In fact, design of liquid or solid containments should always be done with the assumption that some leakage will occur through liner materials, because even if a liner is impermeable at the completion of installation, it may leak after some time.

The combination of adequate design and proper selection of materials is the only way to ensure impermeability. In fact, everyday life teaches us not to rely solely on material properties. Flying is a convenient way to travel. If we relied only on material properties to fly, we would be inclined to use balloons because their flying capability is based essentially on material property, (that is, their density is less than that of air). The fact is, however, that we use airplanes which fly primarily as a result of design. Of course, material selection is important in airplane construction. The materials used should have appropriate mechanical properties and be as light as possible, just as geomembranes should have appropriate mechanical properties and be as impermeable as possible.

It is tempting to pursue the comparison between geomembranes and airplanes. The remarkable reliability of the airline industry results essentially from the amount of care involved in the detailed design of airplanes, and the quality control of construction, maintenance and operation of airplanes. The liner industry faces today a challenge similar to the challenge faced years ago by the airline industry when it was plagued by an unacceptable number of accidents.

Adequate conceptual design, proper selection of materials, careful detailed design and quality control during construction, maintenance and operation of geomembrane-lined facilities: these are the necessary steps towards impermeability.

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