Action leakage rate for reservoir geomembrane liners

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ABSTRACT: Evaluating the performance of a reservoir liner is a challenge. While zero leakage into the ground is a legitimate goal if the leaking liquid may pollute the ground and the ground water, or the soil integrity can be impaired, zero is unrealistic and impossible to measure. In this paper, it is shown that the concept of action leakage rate, developed for landfills in the United States, can be adapted to reservoir liners. The action leakage rate provides a criterion that makes it possible to evaluate the performance of a reservoir liner and that triggers monitoring and remedial actions to be taken if the performance goal is not met. This paper presents a discussion of the parameters that have an influence on the selection of the action leakage rate for a given reservoir and suggests values of action leakage rates for reservoirs depending on the relevant parameters. It is concluded that it is possible to rationally select action leakage rates for reservoirs. This should contribute to the safety of geomembrane-lined reservoirs.

Keywords: geomembrane, liner, reservoir, leakage rate, action leakage rate, performance.

1 INTRODUCTION

1.1 *Leakage happens and must be addressed*

“All liners leak”: this was stated by Giroud & Bonaparte (1989a) at the beginning of their paper. This should not be construed as meaning that there is no way to safely store liquids. In fact, recognizing that all liners may leak is the first step to the safe design of liquid containment systems. The second step is to evaluate whether leakage into the ground is acceptable or not. If leakage into the ground is not acceptable, it is possible to design a containment system to manage and control leakage. The safe design of a containment system would not be possible if the likelihood of leakage through an individual liner had not been recognized in a first step. Depending on the desired degree of leakage control, there is a choice of adequate containment systems, including single geomembrane liner, composite liner (i.e. geomembrane underlain by clay or a bentonite geocomposite, also called geosynthetic clay liner, i.e. GCL), bentonite layer encapsulated between two geomembranes, double liner system, etc.

1.2 *Terminology related to leaks, leakage and leakage rate*

Adapting from several dictionaries, and restricting the discussion to liquids, it can be said that the word “leak” has two meanings: (i) a passageway through which liquid can unintentionally escape; and (ii) the liquid that escapes through a passageway, such as liquid flowing unintentionally out of a reservoir. To avoid possible confusion due to this dual meaning of the word “leak”, the word “hole” is used herein to mean a passageway through the liner such as a puncture, tear or crack, or a passageway at the periphery of the liner such as a gap between the liner and appurtenances.

The word “defect” should not be used to designate a hole, because many defects do not constitute a passageway for liquid. All holes associated with a liner are defects (either defects in the liner or inadequate connections between the liner and adjacent structures), but not all defects are holes.

The word “leakage” designates the amount of liquid that flows through one or several holes. The term “leakage rate” designates the amount of leakage per unit of time. The term “leak flow rate” is sometimes used for leakage rate, but it will not be used in this paper because the simple term “leakage rate” is used.

The term “leakage rate” is also used to designate what is more accurately called “leakage rate per unit area”. The distinction between “leakage rate” and “leakage rate per unit area” appears in the units.

1.3 *Units*

The following units are used for leakage rate:

1 m^3/s = 1000 liters per second = 15,852 gallons per minute (gpm) = 2.28×10^7 gallons/day

The following units are used for leakage rate per unit area:

1 liter per hectare per day (lphd) = 1.157×10^{-12} m/s = 1.157×10^{-10} cm/s = 0.107 gpad

1 gallon per acre per day (gpad) = 9.35 lphd = 1.08×10^{-11} m/s = 1.08×10^{-9} cm/s

Approximate conversions:

1 gpad ≈ 10 lphd 1 inch/day ≈ 3×10^{-7} m/s

1.4 *Action leakage rate*

The fact that leakage, or at least potential leakage, is an essential consideration in the design of a lined facility (landfill or reservoir) implies that leakage can be quantified and controlled. Accordingly, there are specified allowable leakage rates in the United States for landfill primary liners in the case of double-lined landfills, and for liners in municipal waste water treatment ponds. These allowable leakage rates are usually called “action leakage rates” because some action is required if the measured leakage rate is above the action leakage rate. (See Section 2.1.)

However, at the present time in the United States, there is no well-established action leakage rate for liners in deep reservoirs such as tailings, evaporation, and brine ponds used in the mining industry. The need for action leakage rates for reservoirs is being increasingly recognized. Among the issues being considered are the following: should the action leakage rate depend on the reservoir depth, the reservoir size, the type of liner, etc.?

1.5 *Zero leakage, a desirable goal but an inappropriate specification*

While zero leakage is certainly a desirable target, “zero leakage” is impossible to measure: is it one drip per minute, per hour, or per day? Or is it something else? In fact, “zero leakage” is impossible to measure, because “zero” is impossible to measure in engineering. Since zero cannot be measured, it is inappropriate to specify zero action leakage rate.

It should be understood that the only way to find zero leakage is through incorrect or inaccurate measurement. Potential errors in leakage rate measurement will be discussed in Section 1.9.

Another reason for selecting a reasonable value of the action leakage rate is the following: when zero or very small values of action leakage rates are specified, extensive investigations to find holes in the geomembrane and extensive liner repairs may be required to try to meet the action leakage rate. The investigation and repair activities may cause collateral damage to the liner, which has resulted in higher leakage rates in several instances.

1.6 *Acceptable and unacceptable leakage*

As discussed above, zero leakage is an inappropriate requirement. Therefore, the only relevant approach is, for each specific case, to determine the limit between acceptable and unacceptable leakage based on a rational analysis. As indicated by Giroud (1984a), and adding a fourth item, leakage from a reservoir can be acceptable if the following four requirements are met: (i) the loss of liquid remains small enough to be economically acceptable; (ii) the leaking liquid does not cause unacceptable pollution of the ground or the ground water; (iii) the leaking 1iquid does not cause a degradation of the soil supporting the geomembrane; and (iv) the leaking liquid does not uplift the geomembrane liner. In other words, the four types of detrimental effects of leakage are: (i) economic loss: (ii) environmental damage; (iii) geotechnical damage, and (iv) liner disturbance or damage. In all of these situations, a double liner system is a viable solution and is generally the best,

1.7 *Double liner system*

Recognizing that individual liners may leak has led to the development of the concept of the double liner system, which is a very safe way to contain liquids with negligible leakage into the ground, even though individual liners may leak. The concept was presented by Giroud (1973) and used for the first time with two geomembranes in 1974, as described by Giroud & Gourc (2014).

A double liner system consists of two liners and a leakage collection, detection and removal layer between the two liners. The leakage collection, detection and removal layer is generally referred to as the leakage detection layer, the upper liner is called the primary liner and the lower liner is called the secondary liner.

The leakage detection layer has two functions: (i) it makes it possible to measure the rate of leakage through the primary liner; and (ii) by evacuating the collected leakage as quickly as possible, it maintains a very low head of liquid on top of the secondary liner, thereby minimizing significantly the rate of leakage into the ground. It should be noted that the leakage detection layer is not a leak detection layer: it detects leakage, it does not find the leaks. The leakage detection layer material should be highly permeable to ensure rapid leakage detection and prompt evacuation of the collected leakage. Adequate leakage detection layer materials are gravel, geonets, and geocomposites with a geonet core. Sand is not adequate because it is not sufficiently permeable and it exhibits capillarity.

The secondary liner is not simply a back-up to the primary liner. It has an essential role for proper leakage collection and measurement. A typical leakage rate per unit area through a geomembrane-only primary liner is of the order of 10^{-10} m/s in a landfill and 10^{-9} m/s in a reservoir. These leakage rates per unit area are of the same order as the vertical flow rate through compacted clay with a hydraulic gradient of 1. Clearly, if the secondary liner is made of clay only (rather than geomembrane or clay overlain by a geomembrane), at least a large fraction of the collected leakage will infiltrate into the clay and, therefore, will not be detected. If the secondary liner is made of a bentonite geocomposite (GCL) only, most of the leaking liquid will be used to hydrate the bentonite. In other words, if the leakage detection layer does not rest on a geomembrane, the rate of leakage through the primary liner will not be measured.

It is important to note that the measured leakage rate in the case of a double liner system is not the rate of leakage into the ground. The measured leakage is the leakage collected by the leakage detection layer. In other words, it is the rate of leakage rate through the primary liner (assuming that the leakage detection layer functions properly and conveys all the collected leakage to an outlet where it is measured; which implies that leakage through the secondary liner is negligible.).

In the case of a double liner, the determination of the rate of leakage into the ground requires three steps: (i) determination of the rate of leakage through the primary liner; (ii) analysis of the flow in the leakage detection layer and determination of the hydraulic head on the secondary liner; and (iii) determination of the rate of leakage through the secondary liner, which is the rate of leakage into the ground.

1.8 *Composite liner*

A composite liner is a liner that includes two components: a synthetic component and a mineral component. Typically, a composite liner is a geomembrane underlined by a layer of compacted clay or a bentonite geocomposite (GCL). Composite liners are very effective in reducing leakage. As shown by Giroud & Bonaparte (1989b), the rate of leakage through a composite liner is two to four orders of magnitude less than the rate of leakage through a geomembrane alone with the same hole size and frequency.

Composite liners are used extensively in landfills. However, composite liners should be used with caution in reservoirs. A composite liner should not be directly exposed to the impounded liquid. As pointed out by Giroud & Bonaparte (1989a p. 37): “Composite liners must be used with caution in liquid containment facilities. If the geomembrane component of the composite liner is directly in contact with the contained liquid (in other words, if the geomembrane is not covered with a heavy material such as a layer of earth or concrete slabs), and if there is leakage through the geomembrane, liquids will tend to accumulate between the low-permeability soil (which is the lower component of the composite liner) and the geomembrane, since the submerged portion of the geomembrane is easily uplifted. Then, if the impoundment is rapidly emptied, the geomembrane will be subjected to severe tensile stresses because the pressure of the entrapped liquids is no longer balanced by the pressure of the impounded liquid. Therefore, a composite liner should always be loaded, which is automatically the case in a landfill or in a waste pile, and which must be taken into account in the design of a liquid containment facility.”

Clearly, un-ballasted composite liners should not be used as primary liners in reservoirs. In this paper, only double liners with the primary liner being a geomembrane-only liner will be discussed. And only leakage through the primary liner is discussed.

1.9 *Measurement of the rate of leakage from reservoirs*

To measure the leakage rate, it is necessary to fill the reservoir to the normal service level. If there are leaks, two cases can be considered for the measurement of the resulting leakage: double liner system (which makes it possible to directly measure the rate of leakage through the primary liner) and single liner (which requires an indirect evaluation of the leakage rate).

If there is a double liner system, the leakage rate is obtained by monitoring the outlet of the leakage detection layer. Caution is required in the first days following the filling of the reservoir because, if the water impounded in the reservoir is relatively cold, condensation of water vapor entrapped in the leakage detection layer will result in liquid flow at the outlet and should not be interpreted as leakage (a case history is presented by Giroud & Gourc 2014). Also, if the primary liner is a composite liner that consists of geomembrane on clay, water expelled from the clay under stress may be falsely interpreted as leakage. (However, as indicated in Section 1.8, the case of a composite primary liner is not considered herein.) In exceptional cases, there may be false leakage detection if high ground water percolates into the leakage detection layer through the secondary liner. On the other hand, a fraction, or all, of the leakage through the primary liner may not be detected for the following reasons: (i) capillarity in the leakage detection layer (for this reason sand should not be used as the leakage detection layer material); and (ii) leakage (by advection or diffusion) through the secondary liner. Leakage rate measurement using a double liner is not perfect, but it is much more accurate than leakage rate measurement using a water balance test.

If there is a single liner, the only way to measure leakage rate is a water balance test. The water balance test consists in filling a reservoir with water to the normal service level and measuring the water level drop during a certain period of time (e.g. 14 days). Corrections for evaporation, rainfall and runoff must be done, but it is difficult to make accurate corrections and errors are frequent. Water level measurements are not accurate. According to Darilek & Laine (2013), an error of 2 mm on water level is possible. Over 14 days, this amounts to an error of about 1400 lphd. If the action leakage rate is 2000 lphd, the error is 70%, and more if there are errors on evaporation and rainfall corrections.

1.10 *Detectable holes*

The modern technology for finding holes in geomembrane liners is designated by “electric leak location” or “electric liner integrity survey” or similar terms. This technology is essential in all geomembrane liner installations to ensure liner quality. This technology can be used with a geomembrane exposed, under water or under a layer of soil.

According to ASTM D 6747, an electric liner integrity survey should be able to find holes as small as 1.4 mm under water and 6.4 mm if the geomembrane is covered with up to 600 mm of soil. The diameter of 1.4 mm corresponds to a hole area of approximately 1.5 mm^2, and 6.4 mm to a hole area of approximately 30 mm^2. In fact, smaller holes can be found by experienced operators using modern equipment.

In the case of a geomembrane-only primary liner, the same leakage rate may result from one hole (easy to find by electric survey) or several small holes that are difficult to find. Darilek & Laine (2013) have expressed a concern that, if the specified action leakage rate can be generated by small holes, much time and cost could be wasted trying to find holes that the electric liner integrity survey cannot find. This situation shows the limit of the electric survey technology and is a reminder that electric survey does not replace geomembrane installation by a skilled crew with strict construction quality assurance, which is the best way to minimize the risk of holes before performing an electric liner integrity survey.

1.11 *Purpose and scope of this paper*

The purpose of this paper is to propose general guidance on action leakage rates for reservoirs with a double liner, where the primary liner consists of a geomembrane alone. To that end, this paper will present a thorough analysis of various items pertaining to leakage such as terminology, specification, detection, measurement, influence of parameters on leakage, acceptability of leakage.

The scope of this paper is limited to reservoirs (i.e. ponds, lagoons), and landfills will be mentioned only for comparisons and relevant experience. Also, dams are not considered because the situation is different in dams since there is a highly engineered structure downstream of the liner and the consequences of leakage are not the same as the consequences of leakage into the ground under a reservoir.

2 CONCEPT AND CURRENT VALUES OF ACTION LEAKAGE RATE

2.1 *The concept of action leakage rate*

Action leakage rate is a terminology originated in the practice of landfill operation in the United States. An action leakage rate is a preset leakage rate that triggers a preset action. Thus, when the measured leakage rate reaches or exceeds the action leakage rate, a series of predetermined actions must be undertaken. These actions are part of a response action plan. For example, in a landfill where the action leakage rate is 200 lphd, the following actions are typical:

- If the measured leakage rate is below 200 lphd, the primary liner performance is satisfactory and the landfill can be operated normally.
- If the measured leakage rate is above 200 lphd, the landfill operator should measure leakage rate every day and should prepare a response action plan (unless such plan has been prepared at the design stage).
- If the measured leakage rate is above 500 lphd (for example), the landfill operator should try to locate the holes that caused the leakage, and review the response action plan with the regulatory agency.
- If the measured leakage rate is above 2000 lphd (for example), the landfill operator should remove the waste and repair the holes that caused the leakage.

Essentially, the action leakage rate provides a criterion for evaluating the performance of a liner and triggers a plan of action to be implemented when the criterion is not met.

2.2 *Terminology related to action leakage rate*

The terminology used about action leakage rate in some documents is confusing. For example, some documents state that "the action leakage rate should be monitored". In fact, they mean that "the leakage rate should be monitored and compared to the action leakage rate". The action leakage rate cannot be monitored (or measured), since it is a pre-determined value. In this paper, the terminology "measured leakage rate" will be used for leakage rate that is actually measured.

2.3 *Action leakage rate values for landfills in the United States*

The typical action leakage rate for landfills in the United States is 20 gpad (≈200 lphd). This value results from studies sponsored by the United States Environmental Protection Agency in 1992 (USEPA 1992). Using the conversion indicated in Section 1.3, it appears that 20 gpad is about 2×10^{-10} m/s: this is a small leakage rate per unit area. It is sometimes considered difficult to achieve such a small leakage rate with a geomembrane alone. However, it is possible to construct a geomembrane-only primary liner that exhibits a measured leakage rate less than 200 lphd, as indicated in the citation provided below (where the rate of leakage though the primary liner is referred to as "leakage detection layer flow rate").

A comparison of 16 landfill cells with geomembrane-only top liners from data published by Bonaparte & Gross (1990) is presented in USEPA (1992 p. 4) as follows: "All eleven units constructed using construction quality assurance procedures had leakage detection layer flow rates of less than 50 gpad (500 lphd), and eight of the eleven facilities had flow rates of less than 20 gpad (≈200 lphd). In contrast, four of the five units that were constructed with less rigorous construction quality assurance procedures or with no construction quality assurance at all had leakage detection layer flow rates in excess of 50 gpad (≈500 lphd), and two units had leakage detection layer flow rates in excess of 100 gpad (≈1,000 lphd). At these two units leakage detection layer flow rates were on the order of 300 gpad (≈3,000 lphd). In summary, the leakage detection layer flow rates from waste management units with rigorous construction quality assurance programs are significantly lower than the flow rates from units without rigorous programs." [The citation is verbatim, with the exception of the acronyms which are spelled out for clarity.]

From the above citation, it is clear that, with adequate construction quality assurance, the measured leakage rate through a geomembrane-only primary liner can be less than 200 lphd in a landfill. Today, thanks to electric leak location surveys performed immediately after geomembrane installation, the rate of leakage through a geomembrane-only primary liner can be even lower. Therefore, in Section 3.5, it will be legitimate to consider that an action leakage rate of 200 lphd for geomembrane-only primary liner is consistent with the hydraulic heads that typically exist in landfills.

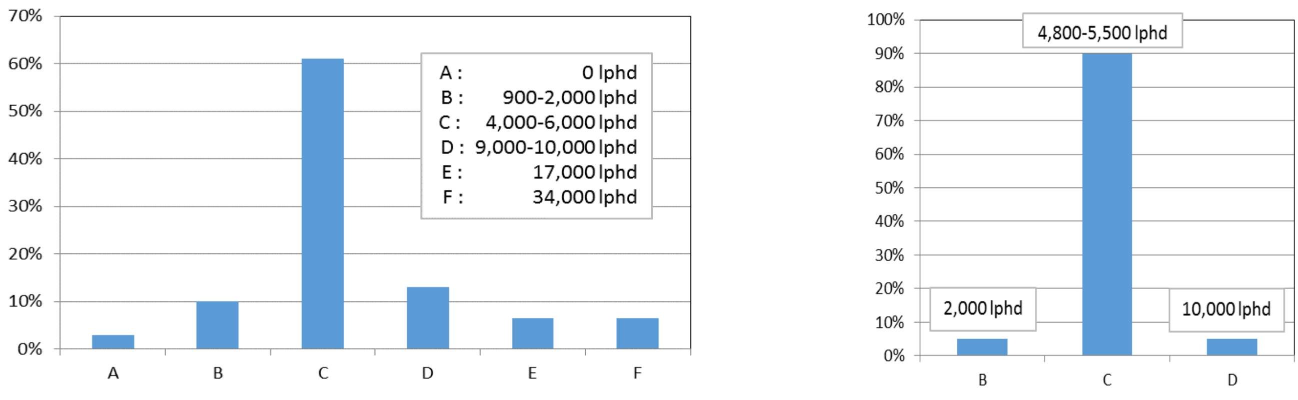
As discussed in Section 3.5, a leakage rate less than 200 lphd can only be achieved if a geomembrane liner has a small number of small holes. In the case of landfills, the use of a relatively low action leakage rate (such as 200 lphd) often leads to the use of a composite primary liner (since the rate of leakage through a composite liner is significantly less than the rate of leakage through a geomembrane-only liner). In the case of reservoirs, a composite primary liner is possible only if the geomembrane is entirely ballasted by a layer of soil sufficient to prevent geomembrane uplift (as indicated in Section 1.8).

2.4 *Action leakage rate values for reservoirs in the United States*

The Geosynthetic Institute (GI) published in White Paper 15 the results of a survey ("GI Survey") of action leakage rates required in US states for reservoirs (Koerner & Koerner 2009). All 50 states in the United States were contacted, but the action leakage rates for only 37 states were collected and are reported. The data provided in the GI survey are useful, but errors in unit conversions have led to incorrect conclusions. Furthermore, the GI survey does not distinguish between two types of action leakage rates: action leakage rates expressed in terms of water level drop (e.g. inch per day, or cm/s), which are mostly intended for water balance tests, and action leakage rates expressed in terms of leakage rates per unit area (e.g. gpad), which are mostly intended for double liners.

For these reasons, a new interpretation of the data presented in the GI survey is presented herein. Figure 1a presents a summary of all of the action leakage rates for reservoirs reported in the GI survey. It appears that the vast majority of states have adopted an action leakage rate between 4000 and 6000 lphd. It also appears in Figure 1a that one state has adopted a zero action leakage rate. It was mentioned in Section 1.5 that a zero leakage rate specification is inappropriate.

Figure 1b was derived from Figure 1a by eliminating all the action leakage rates expressed in units of water level drop. It appears that 90% of the action leakage rates for reservoirs expressed in units of leakage rates are approximately 5000 lphd. This is in part because the action leakage rate of 500 gpad recommended by the Great Lakes Managers (2004) is reported in the GI survey as being used by eight states in the United States (in fact it is used by ten US states plus a Canadian province).



(a) (b)

Figure 1. Action leakage rates for reservoirs in various states in the United States (based on a survey published by Koerner & Koerner 2009, referred to as "GI survey" in this paper): (a) statistics based on all action leakage rates; (b) statistics based on only action leakage rates apparently proposed for double liners (i.e. obtained from Figure 1a, after eliminating the action leakage rates expressed in terms of water level drop, i.e. action leakage rates intended for single liners).

The action leakage rate recommended by Great Lakes Managers (2004), which is reported as 500 gpad in the GI survey, is more precisely 500 gpad for a liquid depth of 6 ft (i.e. approximately, 5000 lphd for a liquid depth of 1.8 m). In Section 93.422, of the Great Lakes Managers' report, it seems to be implied that this action leakage rate could be extrapolated using Darcy's equation based on a clay liner that would be equivalent to a geomembrane liner. This strange extrapolation leads to an action leakage rate that is a linear (albeit non-proportional) function of the depth of liquid. The values of action leakage rates thus obtained for deep reservoirs are very high: approximately 12,000 lphd (for 5 m deep), 23,000 lphd (for 10 m), 45,000 (for 20 m), 67,000 lphd (for 30 m). Discussions presented later in this paper will show that these values are much too high. High action leakage rate values allow the use of geomembrane liners with a high leakage rate.

In addition to the data provided in the GI survey, an action leakage rate of 200 gpad (≈2000 lphd) is being used in the State of New York regardless of liquid depth, but typically for reservoirs 10 ft (≈3 m) deep and deeper (Phaneuf 2014). Also, the State of South Dakota, for one large mine evaporation pond (with a liquid depth unknown to the authors of this paper), proposed an action leakage rate of 20 gpad (≈200 lphd) followed by a response action plan as follows:

– < 20 gpad (≈200 lphd): No action required
– 20 to 200 gpad (≈200 to 2000 lphd): Monitor leakage rate closely, search for area of leak(s), prepare action plan
– 200 to 500 gpad (≈2000 to 5000 lphd): Locate leak(s), lower liquid level below leak(s), submit action plan
– > 500 gpad (≈5000 lphd): Repair leak(s).

This approach is similar to that of the response action plan described in Section 2.1. However, the low action leakage rate of 20 gpad (200 lphd) proposed by the State of South Dakota would be more appropriate for a landfill (see Section 2.3) than for a reservoir (see Section 4.4).

As leakage rates increase with increasing liquid depths (as shown in the following sections), it is clear that the action leakage rate for a reservoir should be a function of liquid depth. However, this does not appear to have been done to date (with the possible exception of the inappropriate extrapolation apparently suggested in the Great Lakes Managers' report). An important part of this paper will be devoted to the establishment of an action leakage rate for reservoirs that is a function of the depth of liquid.

3 ANALYSIS OF PARAMETERS GOVERNING LEAKAGE

3.1 *Review of parameters.*

The value proposed for the action leakage rate for reservoir liners must be realistic. Therefore, it is appropriate to study the influence of parameters on leakage rate. The parameters are: number of holes (expressed as a frequency, i.e. number of holes per unit area); size of holes; maximum depth of liquid; size of reservoir. These parameters are of two different natures. On one hand, the maximum depth of liquid and the size of the reservoir are fixed parameters for a given reservoir; on the other hand, the frequency and size of holes depend on the type of liner and construction quality.

3.2 *Data on frequency of holes in geomembranes*

The frequency of holes is the number of holes per unit area (e.g. per hectare or per acre). Since the first publication proposing a frequency and size of holes in geomembrane liners (Giroud & Bonaparte 1989a), a number a studies have been published. It would be beyond the scope of this paper to review these studies. A summary was published by Giroud and Touze-Foltz (2003) who stated "(i) The number of holes at the end of geomembrane installation with construction quality assurance is typically believed to be from 1 to 5 holes per hectare; these holes are generally small, and their number is smaller for large liners (e.g. greater than 2 ha) than for small liners. (ii) The number of holes caused by the placement of soil on top of the geomembrane varies in a wide range, from very few to 20 per hectare, depending on the amount of care taken during placement of soil on top of the geomembrane and the type of geomembrane protection used; these holes can be large (and often are)." It is important to note that that the number of holes of 1 to 5 per hectare at the end of geomembrane installation is representative of installation with construction quality assurance. In the case where there is no construction quality assurance, "A frequency of 25 holes per hectare (10 holes per acre) or more is possible when quality assurance is limited to an engineer spot-checking the work done by the geomembrane installer" (Giroud & Bonaparte 1989a p. 65).

3.3 *Data on size of holes in geomembranes*

Geomembrane hole sizes typically considered are between one and a few mm^2. These are assumed to be typical holes at end of geomembrane installation. Minimum hole sizes that can be detected by electric leak location survey are of the order of 1 mm^2 under the low depth of water required to perform the electric leak location survey and 10 mm^2 under a soil layer up to 0.6 m thick.

A crack due to stress cracking may have an area of the order of 10 mm^2. However, it may increase to 100 mm^2 or more if the geomembrane remains under tension after the opening of the crack.

The size of holes due to puncture by stones may be of the order of 10 mm^2 or more. Holes in the geomembrane due to tears by construction equipment during placement of a layer of soil on top of the geomembrane are generally large, e.g. 100 cm^2 or even 1000 cm^2 (i.e. 10,000 or even 100,000 mm^2).

3.4 *Influence of reservoir size on leakage*

As shown by Rollin et al. (1999), and confirmed by other data reviewed by the authors of this paper, the frequency of leaks is often greater in geomembrane liners having a surface area less than 2.5 ha than in larger geomembrane liners. Furthermore, for geomembrane liners larger than 2.5 ha, the frequency of leaks does not significantly depend on the liner surface area. The following reasons may explain the large amount of leaks in small liners: (i) there are relatively more penetrations in small liners; (ii) the geometry being more complex in the case of small lined facilities, geomembrane installation and seaming is more complex (unless the geomembrane liner is so small, e.g. 1000-1500 m^2, that it can be entirely prefabricated in factory); (iii) the geometry being more complex in the case of small lined facilities, stress concentrations may be higher, in particular in the case of reservoirs, where the geomembrane liner is displaced at every filling-emptying cycle; and (iv) in some small lined facilities, design and construction quality assurance may tend to be less thorough than in large facilities.

The above considerations, at least some of them, might suggest that higher action leakage rates should be used for smaller reservoirs. However, this is not recommended by the authors of this paper who consider that modern electric liner integrity survey technologies make it possible to achieve good liner quality even in small reservoirs. Furthermore, there are small reservoirs with no appurtenant structures to which the geomembrane is connected and no pipe penetration through the geomembrane. These reservoirs should be expected to have the same level of performance as large reservoirs.

3.5 *Influence of parameters on leakage rate through geomembrane liners*

In the case of a geomembrane liner resting on a permeable medium, such as a leakage detection layer, the leakage rate can be calculated using Bernoulli's equation as suggested by Giroud (1984b):

$$Q = 0.6 a \sqrt{2 g h} \qquad (1)$$

where Q = leakage rate, a = hole area, g = acceleration due to gravity, and h = hydraulic head. Equation 1 can be used with any set of coherent units. The basic SI units are: Q (m^3/s), a (m^2), g (9.81 m/s^2), and h (m).

The leakage rate per unit area is given by the following equation derived from Equation 1:

$$q = 51.84 a N \sqrt{2 g h} = 229.6225 a N \sqrt{h} \qquad (2)$$

with the leakage per unit area in lphd, the hole size in mm^2, the frequency of holes given as a number of holes per hectare, the hydraulic head in meters, and g = 9.81 m/s^2.

In the case of landfills, the above equations should be used with an average hydraulic head. Integral calculations (not presented herein) show that the average hydraulic head is the maximum hydraulic head divided by a factor 2.25 if the hydraulic head is distributed linearly over a year. The factor is 4 if the hydraulic head distribution is parabolic and 9 if the distribution is a fourth power parabola ($h = \lambda t^4$).

Calculations performed with Equation 2 show that the leakage rate through a geomembrane with holes larger than a few mm^2 is significantly higher than 200 lphd even under the small hydraulic head that exists in properly designed landfills. For example, in the case of 2.5 holes per hectare (1 hole per acre) with an area of 10 mm^2 (0.1 cm^2), the leakage rate is 200 lphd if the average head is 1.2 mm, which is unrealistic. If the hole size is 1 mm^2, a leakage rate of 200 lphd is obtained in the following two cases:

- 2.5 holes per hectare (1 hole per acre) with an average head of 120 mm, which corresponds to heads fluctuating between 0 and 270 mm (linear hydraulic head distribution) or between 0 and 1080 mm (fourth power parabolic distribution).
- 5 holes per hectare (2 holes per acre) with an average head of 30 mm, which corresponds to heads fluctuating between 0 and 70 mm (linear hydraulic head distribution) or between 0 and 270 mm (fourth power parabolic distribution).

The last case is the most realistic because the average head of 30 mm corresponds to typical average head in well-designed landfill leachate collection layers during the period of active leachate production. Also, the average head of 30 mm corresponds to a head fluctuating between 0 and 70 to 270 mm, which appears to be realistic. It should be noted that the leakage rate through a geomembrane liner is the same for 5 holes per hectare with a 1 mm^2 size and 2.5 holes per hectare with a 2 mm^2 size.

The above hole sizes (1 and 2 mm^2) show that a maximum leakage rate of 200 lphd for a typical landfill hydraulic head can be achieved only by a high-quality geomembrane liner installed with strict construction quality assurance and, preferably, subjected to an electric liner integrity survey (see Sections 1.10 and 3.3). This supports the comment made in Section 2.3 about the difficulty for a geomembrane-only primary liner to meet the 200 lphd action leakage rate. This is why, in landfills, a composite primary liner is generally used to meet the 200 lphd action leakage rate

4 RECOMMENDATIONS FOR ACTION LEAKAGE RATE

4.1 *Scope of the proposed action leakage rates*

The action leakage rates proposed herein are only for the primary liner of reservoirs with double liners and only for the cases where the primary liner is a geomembrane-only liner. In other words, the primary liner is not a composite liner, i.e. the primary liner geomembrane is not placed on a low-permeability material such as a bentonite geocomposite (i.e. GCL) or a layer of clay. However, the primary liner geomembrane may be separated from the leakage detection layer by a permeable material used for protection, such as a geotextile. The geotextile may be conductive to facilitate an electric liner integrity survey. Alternatively, a geomembrane with a conductive lower layer can be used.

4.2 *General considerations for selecting an action leakage rate value*

The following considerations are relevant to the selection of an action leakage rate value:

- An action leakage rate must not be zero (see Section 1.4).
- An action leakage rate must not be so low that experienced liner installers cannot meet it, nor must it be so high that inexperienced installers can meet it.
- The action leakage rate must be such that the holes responsible for leakage must be detectable and locatable (see Section 1.10).
- The action leakage rate must be established using a rational methodology.

4.3 *Methodology for developing action leakage rate for reservoirs*

The action leakage rate selected for a given reservoir may combine site-specific considerations and general guidance. This paper proposes general guidance in Section 4.4.

Site specific considerations may lead the owner or the designer of a reservoir to select an action leakage rate higher than the value proposed in Section 4.4 for the considered liquid depth. This may lead to the acceptance of a geomembrane primary liner of a lesser quality than the level of quality that can be obtained with construction quality assurance and electric liner integrity survey. On the other hand, selecting an action leakage rate lower than the value recommended in this paper would likely be counterproductive, because it may lead to extensive geomembrane inspection and repair, which may lead to more damage and more leakage, as has been seen in several instances. Also, as discussed in Section 3.4, the authors of this paper do not recommend that a higher action leakage rate be used for smaller reservoirs.

General guidance for action leakage rate selection was developed by calculating (as a function of liquid depth) the rate of leakage that: (i) corresponds to a realistic frequency of holes of a realistic size; and (ii) is consistent with the classical action leakage rate of 200 lphd for primary liners of landfills. The results are presented below.

4.4 *General guidance for action leakage rate for reservoirs lined with a geomembrane primary liner*

As indicated in Section 3.5, the 200 lphd action leakage rate for landfills is consistent with 5 holes per hectare (2 holes per acre) with a size of 1 mm^2 (or 2.5 holes per hectare (1 hole per acre) with a size of 2 mm^2) under liquid depth of 30 mm. Using Equation 2 with these data gives 200 lphd for a liquid depth of 30 mm (a typical average hydraulic head in landfills) and gives the values presented in Table 1 and Figure 2 for hydraulic heads (i.e. liquid depths) of 1 to 30 m, which are typical for reservoirs.

Table 1. Proposed values of action leakage rate for reservoirs. (The same values are shown in Figure 2.)

ALR unit	Liquid depth, m (ft)									
	1 (3.3)	2 (6.6)	3 (10)	4 (13)	5 (16)	10 (33)	15 (50)	20 (66)	25 (80)	30 (100)
lphd	1200	1600	2000	2300	2600	3600	4500	5200	5800	6300
gpad	120	170	210	250	270	380	480	550	600	670

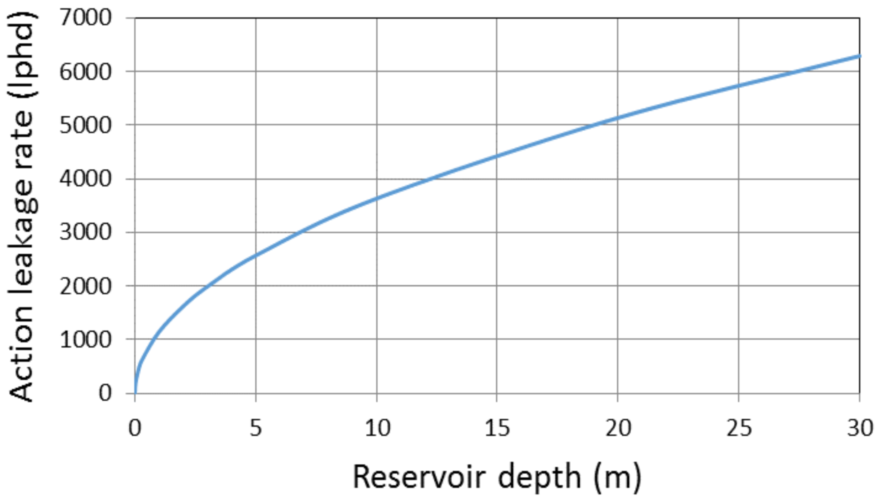


Figure 2. Proposed values of action leakage rate for reservoirs. (The same values are shown in Table 1.)

An action leakage rate value of 2000 lphd (≈200 gpad) is proposed for a liquid depth of 3 m (≈10 ft), and 3000 lphd (≈300 gpad) for a depth of 6 m (≈20 ft). This is less than the value of 5000 lphd (≈500 gpad), which is the most frequently specified in various states in the United States (see Section 2.4) for an unspecified head, presumably of the order of 3 to 6 m (10 to 20 ft). The authors of this paper consider that the action leakage rate values proposed in Table 1 and Figure 2 are consistent with the performance of non-ballasted geomembrane-only primary liners that can be achieved with strict construction quality assurance and an electric liner integrity survey performed at the end of geomembrane installation.

4.5 *Discussion of leakage detection system performance*

Accurate measurement of the leakage rate is necessary to ensure that compliance with the action leakage rate can be checked. To that end, the leakage detection system of the double liner system must be properly designed and constructed. It is suggested that the leakage detection system be designed for a flow capacity at least ten times the action leakage rate, e.g. for a flow capacity of 20,000 lphd if, for example, the action leakage rate is 2,000 lphd.

Some regulations define the action leakage rate as the maximum flow rate that the leak detection system can remove with a hydraulic head on the secondary liner less than 1 foot (300 mm). This definition is incorrect because it is too late to take action when the leakage detection system ceases to function.

5 CONCLUSIONS

The proposed values of action leakage rates for reservoirs vary significantly with the depth of liquid in the reservoir. This is different from the current situation in the United States where action leakage rates for reservoirs are usually specified as a fixed value regardless of the depth of liquid in the reservoir.

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