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INDEXING OF LONG-TERM EFFECTIVENESS OF WASTE CONTAINMENT SYSTEMS FOR A REGULATORY IMPACT ANALYSIS

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A Technical Guidance Document

Office of Solid Waste
U.S. Environmental Protection Agency
Washington, DC 20460

INDEXING OF LONG-TERM EFFECTIVENESS OF WASTE CONTAINMENT SYSTEMS FOR A REGULATORY IMPACT ANALYSIS

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DISCLAIMER

This document is intended to assist U.S. EPA personnel in the assessment of long-term effectiveness of some containment systems for waste disposal. It is not advocated that the content of this document be used as the sole basis for decision making. However, this document sheds some light on the problems associated with the prediction of long-term effectiveness and presents one approach to relevant assessments.

This guidance is not a regulation (i.e., it does not establish a standard or conduct that can be enforced by law) and should not be used as such. The contents of this document do not necessarily reflect the views and policies of the U.S. EPA. Also, mention of trade names, commercial products, or publications do not constitute an unqualified endorsement of their use.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 PURPOSE

This document is intended to support a Regulatory Impact Analysis (RIA) required for a major Corrective Action regulation proposed by the U.S. Environmental Protection Agency. The objective of the RIA is to evaluate the impact of the proposed regulations on the regulated community, and determine whether the regulations will be protective of human health and the environment. The effectiveness indexing scheme described in this paper was developed to provide input data to a multi-media contaminant fate and transport model used in the RIA to assess the pollution potential of ground water, surface water and soil. In view of the fact that in certain situations, the proposed regulations may allow on-site containment of hazardous wastes (e.g., capping) as opposed to treatment/destruction (e.g., incineration), an assessment of the long-term effectiveness of containment systems is necessary. In such assessments, there exists the difficulty of predicting and verifying long-term effectiveness. This problem exists because engineered waste containment systems have existed for a relatively short time in comparison with other engineering structures. Numerical estimates of design lives and effectiveness of containment systems have been made without the benefit of field data on the past performance of similar systems over a reasonably long time interval.

Notwithstanding the paucity of long-term performance data on waste containment systems, numerical assessments are necessary for regulatory purposes. Available predictive tools exemplified by models, mostly deal with initial conditions under the tacit assumption that constructed systems will exist at the same degree of structural integrity over an extended period of time. Also, such models often treat a few elements of the overall issue of effectiveness. Effectiveness is herein defined as the ability of the waste containment system to prevent the mobilization and transport of contained waste outside the system in any phase and direction.

A rating (indexing) scheme has been proposed for assessing the long-term effectiveness of clay caps, synthetic caps, composite clay and synthetic caps, clayliners, synthetic liners, the Resource Conservation and Recovery Act (RCRA) Subtitle C liner systems, and vertical barrier walls. The indexing system is based on a review of literature on initial and potential performance indices of the structures mentioned above. Due to the existence of gaps in available information, technical judgment has been introduced into the selection process of specific rating numbers for long-term effectiveness. One of the most widely used models—the Hydrologic Evaluation of Landfill Performance (HELP) model allows the input of a "failure rate," which the user specifies on the basis of his/her judgment. This allowance is an acknowledgment of the uncertainties associated with predicting the field scale performance of facilities over time frames as long as one hundred years. The rating scheme proposed is based partly on subjectivity. It should be recognized as a rating scheme as opposed to a numerical model. Refinements may be necessary on a site-specific basis, especially, when conditions are such that specific parameters of long-term effectiveness of the entire containment system can be reasonably analyzed in greater detail.

2.0 INTRODUCTION

It is generally known that the structural integrity of waste containment systems usually degrades as time progresses. This situation stems from environmental conditions which induce stresses on various components of the system. The root causes of these stresses include thermal processes, biologic processes, geostatic and geodynamic loads, physico-chemical interactions between waste constituents and containment system materials, sunlight, and hydraulic processes. The rate at which the effectiveness of a containment system is affected over a given time period depends on the conservatism of the initial design, quality control during implementation activities, and the frequency of facility maintenance.

Ideally, it would be desirable to develop a "macro-model" that comprises sub-models, each of which treats the decay of the effectiveness of specific components of containment systems with time. Unfortunately, containment systems comprise many components in too many configurations in numerous hydrological settings. The relatively short experience with modern waste containment systems is such that there are too many unknowns. Each component of a containment system is susceptible to a different degree, to the stresses mentioned above. For example, polymeric materials of a geomembrane are more susceptible to ultraviolet radiation than clay liner materials. Furthermore, the burrowing activities of rodents may introduce defects into the system in the long term. The uncertainties associated with the physical response of the entire containment system to the synergistic stresses from various physical, chemical and biological processes plague the development of a useful "macro-model" for precise prediction of the loss of effectiveness of containment systems with time. In essence, such models might not attain a level of accuracy that supersedes that of a numerical indexing (or rating) scheme that is based on a non-quantitative analysis of available prediction schemes, test results and configuration of containment systems. The latter approach is adopted in this work. Similar approaches have also been adopted by others, e.g., Koerner and Daniel (1992).

3.0 APPROACH TO INDEXING

It is desirable that waste containment systems remain effective for a long time, reasonably, beyond the closure period. The design life of a facility should be as long as necessary to effectively restrict hazardous constituents from becoming a threat to human health and the environment. The durability of various components of containment systems in the laboratory have been investigated vigorously only in the past fifteen years. Experimental and modeling approaches to assessing long-term effectiveness have been adopted in such studies. Although these investigations have shed light on the significant processes and potential responses of individual components over extended periods, the overall long-term effectiveness of composite systems still remains a gray area. It may not be feasible to develop and verify a complete and precise numerical relationship between the effectiveness of composite systems and time-since-construction. Considering the diversity of possible configurations, hydrogeological conditions, and waste types, coupled with various maintenance frequencies, such an approach would require an extensive factorial experiment. It should also be noted that some of the relevant factors cannot be fully controlled. For example, the hydrogeology of a site is not normally controllable.

The approach adopted herein is to use available information on modeling approaches, laboratory experiments and field studies to develop a reasonable indexing system for evaluating the long-term effectiveness of waste containment systems for RIA purposes. In this approach, the entire system is considered rather than a single component. However, the entire system can comprise only one component in some cases. For multi-component systems, the degradation or failure of a single component does not necessarily mean that the entire system is completely ineffective.

In this approach, the effectiveness of a containment system is assumed to vary with time as illustrated in Figure 1. The figure also illustrates the potential gain in effectiveness that occurs with the implementation of an adequate maintenance scheme. A similar concept has been applied in the development of serviceability index for highway pavement structures, most of which comprise many components. When built initially, the containment system has an effectiveness, E_{t0}, which depends on the conservatism of the design and the adequacy of the construction quality control. Over time, the effectiveness decreases along curve A. For example, at time t_2, the corresponding effectiveness is E_{t2}. However, if maintenance activities are implemented at time t_1, the effectiveness improves to the level E_{t1} and system degradation follows curve B. The time horizon, t_d, may be taken as the design life of the containment system. For hazardous waste containment systems, t_d should be well beyond the 30-year post-closure period to which reference is often made in regulations. Obviously, the exact geometries of curves A and B are different for various configurations of waste containment systems. A cap consisting of a flexible membrane directly overlying a clay liner is potentially more effective than a system that comprises only one of these components. Nevertheless, the degradation-time pattern for the entire system should be similar. Furthermore, the addition of a new cap at a certain time can result in an effectiveness greater than existed at t_0 because of the residual effectiveness of the original cap.

The reader should note that the proposed indexing system is very general in nature. It is recognized that the degradation pattern for a particular facility depends on its design and on site-specific factors. For the purposes of a fairly general indexing system, numerous significant factors have not been directly integrated quantitatively into this proposed indexing system. Nevertheless, such information has been reviewed and taken into consideration in the selection of degradation rates proposed herein.

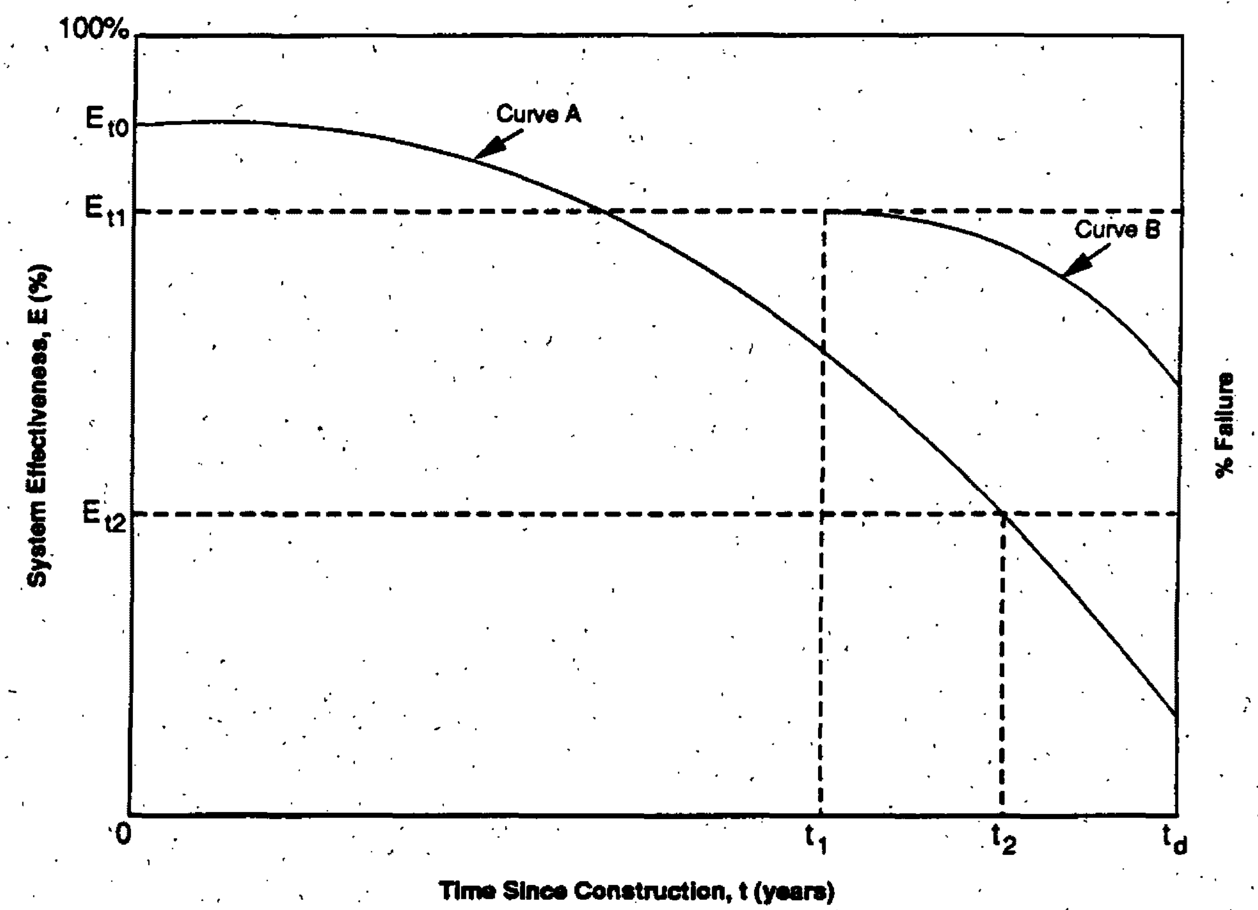

Figure 1. **An illustration of long range degradation tracks of waste containment systems**

4.0 INDEXING SYSTEM

The proposed effectiveness-time relationships are summarized in Table 1 for various configurations of waste containment systems. The time periods selected are 0 years, 10 years, 30 years and 100 years. The technical issues discussed above have been considered. Pertinent technical literature has also been reviewed. Existing models, experimental data and verbal propositions have been considered. In most cases, judgment is used in the analysis and adoption of information reviewed by the authors of this proposition. It should be emphasized that although the degradation-time relationship is influenced by the initial design of a waste containment system, design approaches are not the direct focus of this discussion. For more information on that aspect, the reader is referred to relevant documents such as Richardson and Koerner (1989), and U.S. EPA (1984a, 1985a, 1989a and 1989b) for covers and lining systems; Millet and Perez (1981), Barvenik et al (1985), Morgenstern and Amir-Tahmasseb (1965), Mott and Weber, Jr. (1992), D'Appolonia (1980) and U.S. EPA (1984b) for slurry walls; and May et al. (1985), Camberfort (1977), Weaver et al. (1992), Ran and Daemen (1992), USACE (1973 and 1984), Van Impe (1989), Hausmann (1990) and U.S. EPA (1985b) for grout curtains.

4.1 CAPS

Low permeability caps are used to cover waste materials to minimize contaminant migration on the land surface, through the air, and into the ground water. Caps protect ground water by minimizing the infiltration of precipitation into the waste which can mobilize contaminants through leachate generation. There are a variety of cap designs and capping materials available. Typically, a design will include a single or multiple layers of low-permeability natural clay or made-made materials (geosynthetic membrane). Generally, all designs include a high permeability drainage layer above the low-permeability layer(s) to promote precipitation runoff. All designs also include a vegetative layer or some other material placed above the drainage layer to minimize erosion. The discussion of effectiveness presented below focuses on the low permeability layers and refers to the ability of the cap to restrict infiltration of water into the underlying waste.

4.1.1 Clay Caps

The factors which may reduce the effectiveness of clay caps include subsidence, slope instabilities, desiccation cracking, burrowing activities of rodents, and vehicle loads. For the clay cap, effectiveness is herein defined as its ability to prevent the intrusion of moisture into the contained waste. For a given set of hydrological conditions, the quantity of leachate generated is directly proportional to the effectiveness of the clay cap. The latter depends on both intergranular flow (pore flow) and flow through flaws which may result from any combinations of the phenomena stated earlier. Due to the uncertainties associated with the occurrence of degradation events with time, an exact predictive relationship is difficult to develop and verify. Models exemplified by the Hydrologic Evaluation of Landfill Performance (HELP) computer model predict pore flow only. In Figure 2, increases in the permeability of a compacted clay soil layer due to several cycles of freezing and thawing are illustrated.

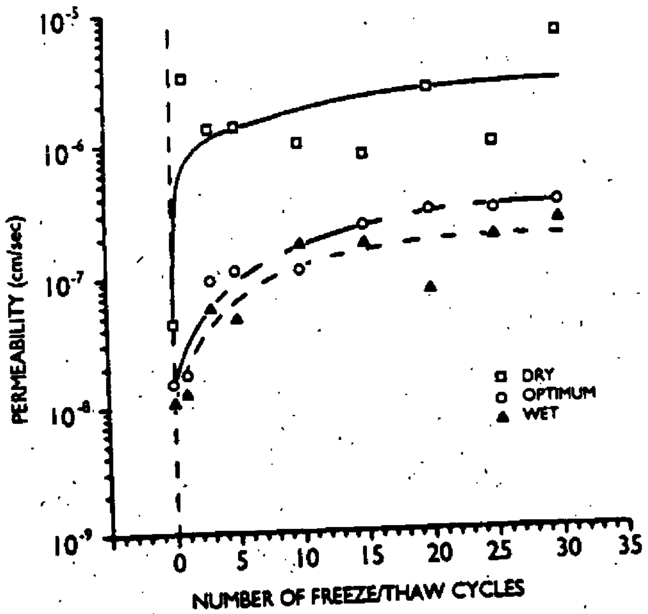

Figure 2. Summary of the one-dimensional freeze/thaw cycle effects on the Niagara Clay (Zimmie et al. 1992)

Such changes in permeability may be attributable to the generation of fissures, etc. When macro-flaws develop in a clay cover over an extended time period, Darcy flow relationships become inadequate for predicting moisture percolation. Using the approach proposed by Anderson et al. (1991), the macrofissures increase the hydraulic conductivity of the soil layer by the amount given in equation (1).

$$K = R^4 pg/8uD^2 \qquad (1)$$

K = hydraulic conductivity
R = radius of the channels
g = acceleration due to gravity
u = viscosity of ordinary water
D = spacing of the channels
p = density

In Table 1, a clay cap that meets minimum standards with respect to hydraulic conductivity, thickness and construction quality control is assigned an initial effectiveness of 80%. It is assumed that significant flaws exist even in the initial post-construction period of such cover materials. Consistent with the degradation-time pattern often observed in most engineering structures, it is assumed that the effectiveness will decrease exponentially with time.

It is estimated that over a service life of ten years immediately following their implementation, the effectiveness of the clay cap will drop to 75%. The probability of occurrence of phenomena that cause flaws increases as the duration of service increases. At 30 years, the effectiveness of the clay cap is estimated to be 60%. It is roughly estimated that after 100 years of service, settlement, rodent activity, etc., would reduce the effectiveness of single clay covers to 20%.

Note, however, if an additional clay cap is added to the system at 100 years, the effectiveness goes up to 85%. Replacing the cap at such a time when the original cap is no longer effective is consistent with the understanding that engineered structures will not last in perpetuity. Furthermore, adding a new cap also reflects the premise that, unlike a liner system, a cap can be easily maintained and, if necessary, replaced, without actually removing the waste. Adding a new cap also reflects the need to provide long-term reduction of leachate generation.

4.1.2 Synthetic Caps

Holes can be introduced into synthetic caps of waste containment systems during installation. Geomembrane caps may also be degraded by subsidence, ultraviolet radiation, thermal stresses and the burrowing activities of animals. Temperature effects on the

Table 1: Effectiveness of Selected Waste Containment Measures

	Effectiveness, Et (%)							
Indexing Time Increments (t years)	Clay Cap	Synthetic Cap	Clay Plus Synthetic Cap	RCRA C Composite Liner System	Clay Liner	Synthetic Liner	HDPE Wall	Slurry Wall
t_0	80	90	95	98	70	85	65	70
t_{10}	75	85	92	95	60	75	60	60
t_{30}	60	75	80	85	40	35	50	20 (70)[5]
t_{100}	20 (85)[1]	15 (90)[2]	35 (98)[3]	60	5	0	25 (65)[4]	0

Notes:

1. Assumes addition of new clay cap at 100 years.
2. Assumes addition of new synthetic cap at 100 years.
3. Assumes addition of new composite clay and synthetic cap at 100 years.
4. Assumes addition of new HDPE wall at 100 years.
5. Assumes addition of new slurry wall at 30 years.

durability of polymeric materials have been described using methods based on the Rate Process Analysis (Koerner et al., 1990; and Kanninen, 1992). However, the effectiveness of a synthetic cap material in the field is a function of temperature as well as radiation and other unpredictable events. Nevertheless, Koerner and Daniel (1992) rate a single geosynthetic cap above a single clay cap in terms of overall effectiveness. Relevant information is provided in Tables 2 and 3. Considering the factors rated in Tables 2 and 3 and those discussed above, a single synthetic cap is assigned an initial effectiveness of 90%. This rating takes into account the possible existence of imperfect seams through which water can pass.

Unavoidably, the volume of holes increases in synthetic layers over time. Increases in the hydraulic conductivity of such layers should be expected. The increase in the discharge (flow rate of such covers due to the presence of large holes) can be estimated using Bernouilli's equation as follows.

$$Q = Ca(2gz)^{0.5} \qquad (2)$$

- Q = discharge (m^3/s)
- C = dimensionless coefficient that pertains to the shape of the edges of the opening (approximately 0.6 for sharp edges)
- a = hole surface area (m^2)
- g = acceleration due to gravity (9.8 m/s^2)
- z = depth below water level; may be approximated by the design head of infiltrating water (m).

In the indexing system proposed in Table 1, the effectiveness of a single synthetic cap is assumed to be 15% after 100 years. This assumed effectiveness is greater than the assumption made in U.S. EPA (1982) that after 100 years, a synthetic cap will be completely ineffective. The 15% effectiveness is based on the assumption that synthetic caps will

Table 2. Performance of barrier layer materials (Adapted with modifications from Koerner and Daniel 1992)

Alternate	Liner Component	Climate			Settlement			Cover Erosion/Puncture Vulnerability			Allowable Percolation			Gas Collection		Slope Inclination		
		Arid	Cyclic	Humid	Major	Moderate	Nominal	Major	Moderate	Low	Essentially None	Very Little	Moderate	Gas	No Gas	Less than °	9-18°	Greater than 18°
A	CCL	1	1	3	1	1	3	1	2	3	1	2	3	1	1	5	4	3
B	GM	5	4	4	4	5	5	1	1	3	1	3	5	5	5	5	5	3
C	GCL	3	3	4	2	3	4	1	1	3	1	2	3	1	5	4	3	3
D	GM/CCL	2	3	4	2	3	4	3	4	4	3	4	4	3	5	5	3	2
E	GM/GCL	5	4	5	3	4	5	2	3	4	3	4	5	4	5	5	3	2
F	GM/CCL/GM	4	4	5	3	4	5	4	5	5	5	5	5	4	5	5	2	1
G	GM/GCL/GM	5	5	5	4	5	5	4	5	5	5	5	5	4	5	5	3	2

Note: 1 = Not recommended; 2 = Marginal; 3 = Possibly acceptable (depends on specific conditions); 4 = Acceptable; and 5 = Recommended.

CCL = Single compacted clay liner.
GM = Single geomembrane.
GCL = Single geosynthetic clay liner.
GM/CCL = Two-component composite.
GM/GCL = Two-component composite.
GM/CCL/GM = Three-component composite liner.
GM/GCL/GM = Three-component composite liner.

Table 3. **Overall benefit of each barrier configuration of cover/liner materials determined by summing the horizontal rows in Table 2 (adapted with modifications from Koerner and Daniel 1992)**

Design Alternate	Description	Overall Benefit	Estimated Cost (dollars/sq. ft.)	Benefit/Cost Ratio	Ranking in Group
One Barrier Layer					
A	CCL	36	0.70	51	3
B	GM	64	0.70	91	1
C	GCL	46	0.70	66	2
Two Barrier Layers					
D	GM/CCL	58	1.40	41	2
E	GM/GCL	66	1.40	47	1
Three Barrier Layers					
F	GM/CCL/GM	71	2.10	34	2
G	GM/GCL/GM	77	2.10	37	1

CCL = Single compacted clay liner.
GM = Single geomembrane.
GCL = Single goesynthetic clay liner.
GM/CCL = Two-component composite.
GM/GCL = Two-component composite.
GM/CCL/GM = Three-component composite liner.
GM/GCL/GM = Three-component composite liner.

degrade over time, but due to improvements in polymeric material technology, degradation will not occur quite as fast as originally predicted by EPA. If a new synthetic cap is installed at 100 years, the effectiveness of the synthetic cap is assumed to return to the original 90% estimate.

4.1.3 Composite Clay and Synthetic Caps

The processes and assumptions described above for clay caps and synthetic caps apply to the composite clay and synthetic cap; however, the composite cap yields a greater effectiveness than the additive effectiveness of the two individual layers. The clay layer underlying the geosynthetic cap acts as a low premeable barrier for leakage through holes in the geosynthetic layer. Furthermore, the effectiveness of the clay layer improves in this composite system because the synthetic affords some protection against the processes (discussed in section 4.1.1) which degrade clay caps. As indicated in Table 1, the initial effectiveness of the composite cap is assumed to be 95%. At 100 years, the effectiveness of the composite system is reduced to 35%. At 100 years, it is assumed that an entirely new composite cap will be installed resulting in an effectiveness of 98%. The increase from 95% to 98% is assumed to be due to the residual effectiveness of the original clay layer.

4.2 LINERS

Liners for waste containment systems are generally intended to prevent the migration of hazardous constituents into the underlying subsurface. Liners are generally constructed of low premeability soils (clay), geosynthetics, or a composite system consisting of both clay and geosynthetic membranes.

4.2.1 RCRA Subtitle C Composite Liner Systems

The RCRA Subtitle C liner system consists of both clay and polymeric layers. The minimum requirements for this liner system includes from top to bottom, a leachate collection system, a primary (upper) geomembrane, a leachate detection system, and a secondary composite liner consisting of an upper geomembrane directly overlying a clay layer. In contrast to the situation with caps, leachate compatibility becomes more significant but settlement (or subsidence) effects become less significant. In developing the effectiveness-time estimates contained in Table 1, it is assumed that there is no cover over the buried waste or contaminated materials. Since the RCRA Subtitle C liner is a multi-component system, the failure of one component does not necessarily imply that the whole system has become entirely ineffective. Some failures of single and multi-component lining systems have been reported in literature. Unfortunately, information is scanty or non-existent on the time

Table 4. Case histories of compacted clay liners (Daniel 1987)

Location of Site	Nature of Liner	Actual Field k (cm/sec)	Reference and Comments
Central Texas	2-acre (0.8 ha) Liner for Impoundment; 1-ft-(30-cm) Thick Liner Built of Local Clay Soil	4×10^{-5} (originally) 5×10^{-6} (Reconstructed)	Daniel (1984). Original liner may have desiccated somewhat. Reconstructed liner not subjected to desiccation. Poor CQA. Liner retained fresh water.
Northern Texas	25-acre (10 ha) Liner for Impoundment; 8-in-(20-cm) Thick Liner Built from Sand/Bentonite Mixture	3×10^{-6}	Daniel (1984). Virtually no CQA. Liner retained slightly saline water.
Southern Texas	1-acre (0.4 ha) Liner for Impoundment; Liner was 2-ft-(30-cm) Thick and Built with Local Clay Soil	1×10^{-5}	Daniel (1984). Liner retained brine solution. Little CQA.
Northern Mexico	Test Liner 50 x 50 x 0.5 m and Built with Local Clay Soil	1×10^{-6}	Auvinet and Espinosa (1981) and Daniel (1984). Good CQA. Liner tested with fresh water.
Texas A&M University	Prototype Liners; Each Prototype Measured 1.5 x 1.5 x 0.15 m; Soils Consisted of Kaolinite, Mica, and Bentonite Blended with Sand	1×10^{-6} to 1×10^{-5}	Brown, Green, and Thomas (1983). Good CQA. Soil compacted with hand-operated equipment. Liquids were xylene and acetone wastes.
University of Texas at Austin	Two Prototype Liners; Each Liner Measured 20 x 20 x 0.5 ft (6 x 6 x 0.15 m) and Was Built of Local Clay Soil	4×10^{-6} and 9×10^{-6}	Day and Daniel (1985a). Good CQA, although moisture content varied more than desired. Soil compacted with hand-operated equipment.
Confidential	100-acre (40 ha) Pond for Wastewater; 1-ft- (30-cm) Thick Liner Built of Local Sandy Clay	2×10^{-6}	Unpublished case history from author's files. Extensive CQA.
Midwestern U.S.	5-acre (2 ha) Pond for Wastewater; 5-ft- (1.5-m) Thick Liner Built of Local Clayey Soil	2×10^{-7}	Unpublished case history from author's files. Extensive CQA. Possible effects from organic solvents.
Western U.S.	3 Impoundments; 5-ft- (1.5-m) Thick Liners Built of Local Clayey Soil	Not Documented	RTI (1986). Good CQA. After 4 yrs of service, no waste in leak detection zone beneath 2 liners. Waste appeared in leak detection zone beneath one of the liners after 3 mos of service, but this liner had been left exposed and unprotected for 6 mos.
Western U.S.	6 Impoundments, 3-ft- (90-cm) Thick Liners Built from Local Clay Stone	1×10^{-7} to 4×10^{-7}	RTI (1986). Field performance determined from volume of liquid collected in leak collection zones beneath the liners.
Northeastern U.S.	2 Landfills, 1.5- to 2-ft (46 to 60 cm) Thick Liners	Not Documented	RTI (1986). Within one year of operation, leachate was detected in leak detection zone beneath the liner.
Toronto, Ontario, Canada	16-acre (4 ha) Municipal Waste Landfill; 1.2-m Thick Liner Built of Local Clayey Soil	2×10^{-8}	Reades et al. (1986). Keele Valley Landfill. Performance determined by underdrains, each 15 x 15 m. Excellent CQA. Test pads used to establish construction criteria.

Table 5. Summary of experience with liner performance in the field (Bass et al. 1985)

Site ID	Single (S) or Double (D) Liner	Primary Liner Material	Primary Liner (mil)	Total Surface Area (ac)	Exposed (E) or Buried (B)	Monitoring System	Layers in Liner System* (bottom to top)	Air Vents	Problems with Liner
V1-1	S	OR-CPE (R)	36	10	B	No	Gr/GeoTex/S&G/GeoTex/FML/Soil cement	Yes	—
V1-2	S	CSPE (R)	36	22	E	Yes	Comp Clay/S/FML	Yes	Yes
V1-3	S	PVC (U)	30	2	B	No	Lime Rk/S/FML/S/Lime Rk	No	—
V1-4	S	PVC (U)	30	10	B	No	Comp Soil/FML/Soil	No	—
V1-5	D	PVC (U), CSPE (?)	20, 36	1	E	Yes	Comp clay/S/FML/S/FML	Yes	—
V1-6	S	PVC (U)	30	2	B	No	Old fill/Clean fill/FML/clay	Yes	—
V2-1	S	CSPE (R)	30	120	E	No	Comp clay and limestone/FML	Yes	Yes
V2-2	S	CSPE (R)	30	8	E	No	Comp soil/S&G/FML	No	Yes
V2-3	S	CSPE (U)	30	2.3	E	No	Comp Sub-base/FML	No	Yes
V2-4	S	CSPE (R)	30	4.3	B	Yes	Comp Fill/FML/S/G	No	—
V3-1	S	PO (R)	30	42	B	Yes	Prepared limestone/FML/Stone	No	Yes
V3-2	S	PVC (U)	20	75	B	Yes	Comp Clay/FML/S	No	Yes
V3-3	S	PVC (U)	20	8	B	No	Comp Soil/FML/S	No	—
V3-4	S	Soil Sealant	4 in	25	B	Yes	Comp Sand/Liner/S	No	Yes
V3-5	S	Asphalt-concrete	5 in	2	E	Yes	Comp Soil/Asphalt (2 lifts)	No	—
V4-1	S	HDPE (U)	100	18	E	Yes	Comp Sand/FML	No	—
V4-2	D	HDPE (U)	100	18.5	E	Yes	Comp Clay/S/FML	Yes	—
V4-3	S	HDPE (U)	80	88	E	No	Comp Subgrade/FML	Yes	—
V4-4	D	HDPE (U)	80	6	E (sides)	Yes	Clay/S/Comp Soil/FML/Comp Soil	Yes	—
V4-5	D	HDPE (U)	80	3.2	B	Yes	Comp clay/FML/Comp clay	No	—
V4-6	S	HDPE (U)	100	0.3	E	Yes	Comp Soil/FML	No	—
V4-7	S	HDPE (U)	80	66	E (sides)	No	Subgrade/FML/S (bottom only)	No	—
V5-1	3D, 1S	CPE (U), CPE (U)	20, 30	1.5	E (CIM only)	Yes	Subgrade/CPE/Soil/Concrete/CIM	No (?)	Yes
V5-2	S	CPE (U)/PVC (U)	20, 10	13	B	Yes	Nat Soil/FML/Nat Soil	No	Yes
V5-3	S	CPU (U)	30	0.7	B	Yes	Nat Soil/FML/Nat soil/soil cement	No	—
V5-4	D	PVC (U)	20	1.4	B	Yes	Comp Soil/Clay/S/FML/Nat Soil	No (?)	Yes
V5-5	Triple	2xCPE (R), PVC (U)	30, 20	0.75	E	Yes	Comp fill/CPE/G/PVC/CPE/?	No (?)	—

* Comp = compacted; FML = flexible membrane liner; G = gravel; GeoTex = geotextile; Gr - ground; Nat = natural; Rk = rock; S = sand

at which the reported failures occurred. Daniel (1987) reported case histories of clay liner performance in the field. Pertinent information is provided in Table 4. Bass et al. (1985) provide the data shown in Table 5 on the failures and successes experienced with various configurations of lining systems. Some of the configurations described in Table 5 are similar to RCRA Subtitle C liners. Although the data presented in Table 5 have not been incorporated in any direct numerical manner into the indexing scheme of Table 1, they do illustrate the fact that some lining systems do fail unpredictably with time. Information provided by Daniel (1984) indicates that the actual hydraulic conductivities of four clay liners in Texas are generally ten to a thousand times higher than those measured on samples in the laboratory. Bonaparte and Gross (1990) have presented data on the field performance of double-liner systems within four to five years of their construction. Some of the measured leakage rates are attributed to the consolidation of the clay layer component of the lining systems investigated. For geomembrane layers of liner systems, Giroud and Bonaparte (1989a and b) suggest the use of a hole frequency of 2 to 5 holes per hectare and a hole size of 3 x $10^{-6}m^2$ to compute flow rates.

Using the electrical leak detection technique illustrated in Figure 3, Laine and Miklas (1989) surveyed 61 new or operating waste storage facilities in which geomembrane liners are used. An average of 3.2 leaks per 10,000 ft^2 within a range of 0.3 to 5.0 leaks per 10,000 ft^2 of liner was detected. Relevant data for bottom floor areas of impoundments surveyed are presented in Table 6. Of all leaks, 87% occurred through seams while the remainder occurred through internal areas of the geomembranes. Observed flaws ranged from circular holes of up to 1 inch in diameter to slits from 0.25 to 12 inches in length. Sometimes, flaws as large as 48 square inches were observed.

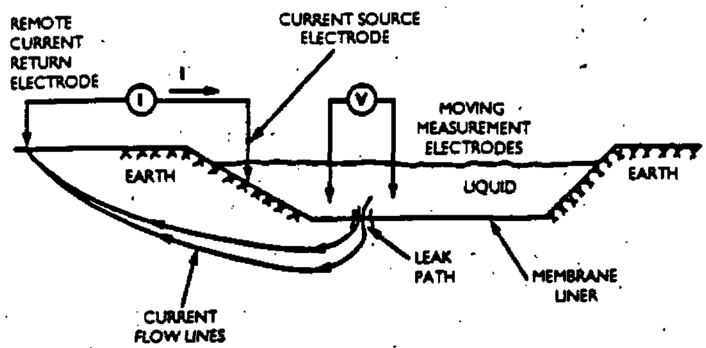

Figure 3. The setup of the Electrical Leak Location Method (Laine and Miklas 1989)

Considering all the factors and data discussed above, the RCRA Subtitle C liner system (multi-layered) is assigned an initial effectiveness of 98% as indicated in Table 1. In U.S. EPA (1983), 1% of the area of the synthetic layer component of the lining system is assumed to have the same vertical permeability as the underlying soil. This corresponds roughly to 99% effectiveness. However, considering the uncertainties in the distribution of holes at geomembrane seams, spatial variabilities in the hydraulic conductivity of the clay layer component of the system, an initial effectiveness of 98% is assigned in Table 1. By the end of the tenth year of operation, significant leakage would occur through the upper geomembrane barrier of the lining system. Assuming that some flaws would have developed in the secondary geomembrane and the underlying clay layer in ten years, there would be the possibility of seepage of fluids through the system. Considering this situation, the effectiveness of the system after 10 years is rated at 95%. Within the first 30 years, leachate that passes through degraded membranes and the drainage layer could also travel through relatively intact portions of the clay layer component of the system by intergranular (pore) flow and/or diffusion. For a clay layer thickness of up to 35 cm (about 13.8 in.), analyses of fluid transit time predictions by U.S. EPA (1984c) using various percolation equations indicate that transit times would generally be under one year. These predictions are presented in Figure 4. It should be noted that only the times of first arrival of retained substances are predicted. Similar analyses by Shackelford (1992) for a 91 cm (35.83 in.) thick clay layer indicate breakthrough times ranging from 2.6 to 9.8 years for various

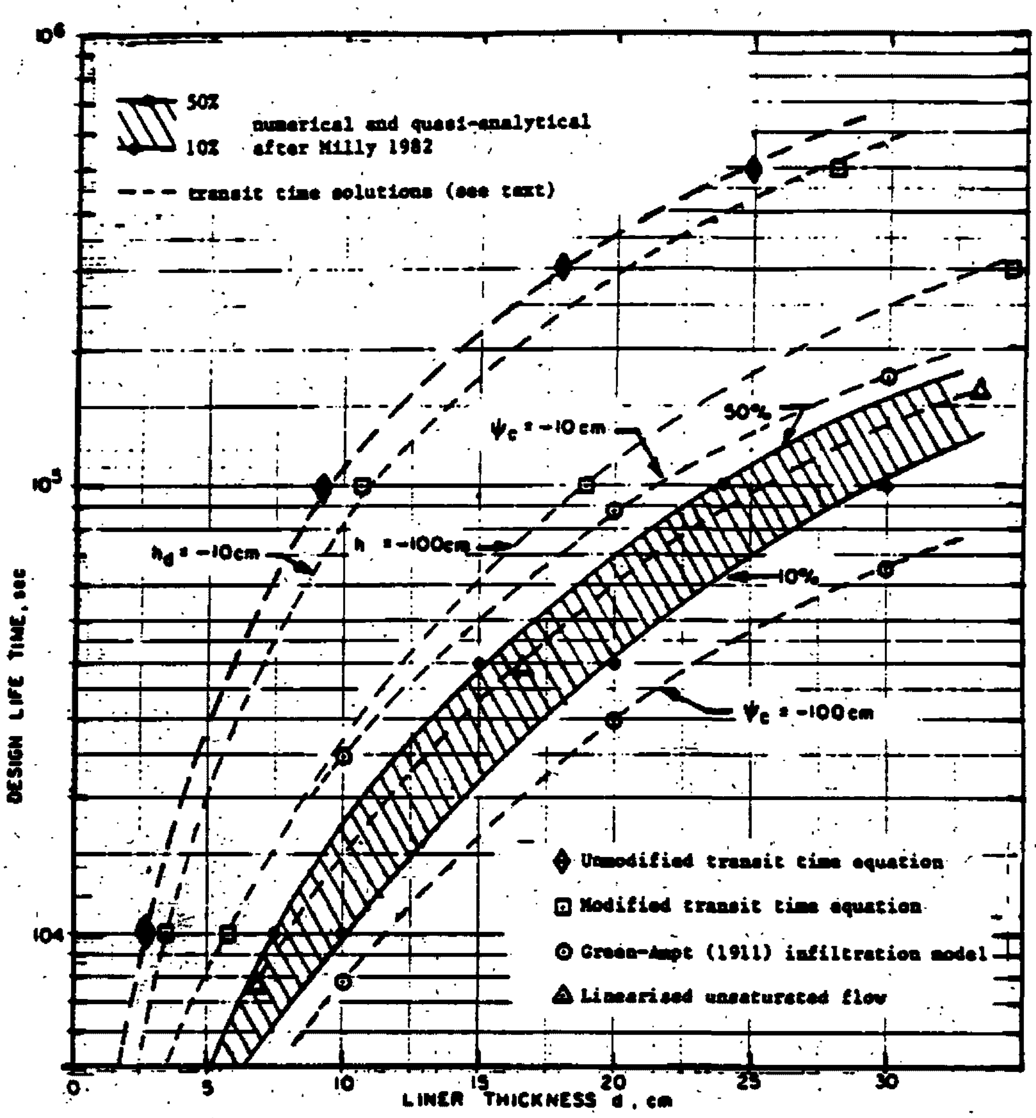

Figure 4. A comparison of liner thickness equations (U.S. EPA 1984c)

Table 6. Leak detection and location survey data for impoundments where the bottom floor areas were surveyed (Laine and Miklas 1989)

Survey No.	Size Sq. Feet	Total Leaks	Leaks Located in Bottom	Seam	Sheet	Leaks Per 10,000 Sq. Feet
1	958	2	2	2	0	20.9
2	958	3	3	3	0	31.3
3	958	3	3	3	0	31.3
4	1,000	4	4	3	1	40.0
5	1,798	0	0	0	0	0.0
6	2,625	6	6	6	0	22.9
7	3,000	21	21	21	0	70.0
8	3,000	4	4	4	0	13.3
9	3,200	0	0	0	0	0.0
10	4,951	0	0	0	0	0.0
11	4,951	17	17	17	0	34.3
12	4,951	2	2	2	0	4.0
13	5,175	2	2	1	1	3.9
14	7,007	4	4	4	0	5.7
15	12,600	7	7	7	0	5.6
16	18,346	50	50	35	15	27.3
17	26,016	7	7	7	0	2.7
18	26,016	4	4	4	0	1.5
19	27,297	8	8	6	2	2.9
20	32,292	25	25	25	0	7.7
21	43,560	2	2	2	0	0.5
22	45,345	4	4	4	0	0.9
23	50,000	6	6	6	0	1.2
24	50,400	193	193	188	5	38.3
25	54,500	29	29	18	11	5.3
26	55,025	12	12	12	0	2.2
27	58,900	8	8	6	2	1.4
28	62,500	21	21	19	2	3.4
29	64,583	29	29	21	8	4.5
30	65,340	56	56	55	1	8.6
31	65,369	6	6	6	0	0.9
32	65,369	7	7	5	2	1.1
33	65,369	5	5	3	2	0.8
34	65,500	7	7	5	2	1.1
35	65,500	5	5	3	2	0.8
36	74,088	20	20	19	1	2.7
37	82,500	18	18	15	3	2.2
38	87,120	8	8	7	1	0.9
39	87,120	17	17	17	0	2.0
40	99,050	18	18	14	4	1.8
41	135,036	17	17	16	1	1.3
42	150,781	64	64	46	18	4.2
43	152,460	2	2	2	0	0.1
44	152,460	7	7	7	0	0.5
45	157,584	12	12	10	2	0.8
46	164,085	18	18	16	2	1.1
47	362,690	51	51	37	14	1.4
TOTALS	2,769,336	811	811	709	102	2.9

assumptions of concentration ratios and relative fluxes of solutes at the bottom end of the clay liner. The latter analyses also indicate that maximum solute flux through the same clay liner would be attained in 83 years.

It should be noted that the data and predictions obtained for the cases discussed above do not necessarily apply to all cases. However, information on the range of breakthrough times exemplified by the preceding discussions has been considered in developing the effectiveness index for RCRA Subtitle C liners shown in Table 1. In the indexing scheme presented in Table 1, the RCRA C liner system is rated at 85% and 60% effectiveness at 30 and 100 years of operation, respectively.

4.2.2 Clay Liners

The processes and findings described in section 4.2.1, pertaining to clay liners, result in an assumed initial effectiveness for a single clay liner of 70% (see Table 1). After 100 years, the effectiveness of this liner is reduced to 5%.

4.2.3 Synthetic Liners

The processes and findings described in section 4.2.1, pertaining to synthetic liners, result in an assumed initial effectiveness for a single synthetic liner of 85 percent (see Table 1). Contrary to the single clay liner which retains some level of effectiveness at 100 years, it is assumed that a single synthetic liner will be completely ineffective (0%) at this time. This assumption is based on the fact that once the number and size of holes in the synthetic liner reaches a certain level, all infiltrating liquids will likely move along the liner to low points in the system. If these low points conincide with holes, then the liner will provide no barrier to leakage.

4.3 SUBSURFACE BARRIERS

The term subsurface barriers refers to a variety of low permeability cut-off walls or diversions installed below ground to contain, capture, or redirect ground- water flow. Subsurface barriers are commonly used at hazardous waste sites to constrain or restrict the migration of contaminants from a designated area. To date, the most commonly used subsurface barriers at hazardous waste sites are slurry walls. Barriers used in the RIA, however, also include high density polyethelene (HDPE) interlocking sheets. Although relatively new in the market place, these HDPE walls appear to be a viable and effective alternative to slurry walls for certain applications; therefore, they have been included in the proposed indexing system.

The effectiveness-time relationships shown in Table 1 for HDPE walls and slurry walls are proposed assuming no intervening barriers like liners and covers. This implies that these walls would be the first barrier layers against the migration of contaminants. The effectiveness of a particular barrier wall depends on site conditions, mix design of wall materials (for slurry walls), joint integrity (for HDPE walls), wall thickness, durability of wall materials to chemical attack, and the quality of construction. The effectiveness indices proposed for barrier walls in Table 1 are very general. Owing to the novelty of this containment technology, most of the available data are predictive in nature. Sufficient time has not elapsed for their verification in the field. The examples illustrated herein are also provided to indicate the numerical regime of the decay of effectiveness with time. Conditions vary widely; hence, the examples provided may not apply to some specific cases.

4.3.1 Slurry Walls

In Table 1, the initial effectiveness of slurry walls is rated at 70%. This rating roughly reflects the difficulties associated with controlling the in-situ permeability of the slurry during construction. Owing to the segregation of materials, zones of excessive permeability often develop. Over a period of 10 years, the quantity of materials that diffuse across the barrier would perhaps be significant. A pollutant detention time of 30 years would be sufficient to allow the physico-chemical interactions between contaminants and slurry material to cause increases in wall permeability. At 30 years, the assumed effectiveness of slurry walls is reduced to 20%. With the addition of a new wall, however, the effectiveness could be brought back to the original 70% effectiveness. Figure 5 is an example of the projections of solute transport across soil-bentonite barriers made by Mott and Weber, Jr. (1991). By the authors' estimation, slurry walls may not be effective after a hundred years of service, (0% effective). Pertinent failure mechanisms are discussed by U.S. EPA (1984d).

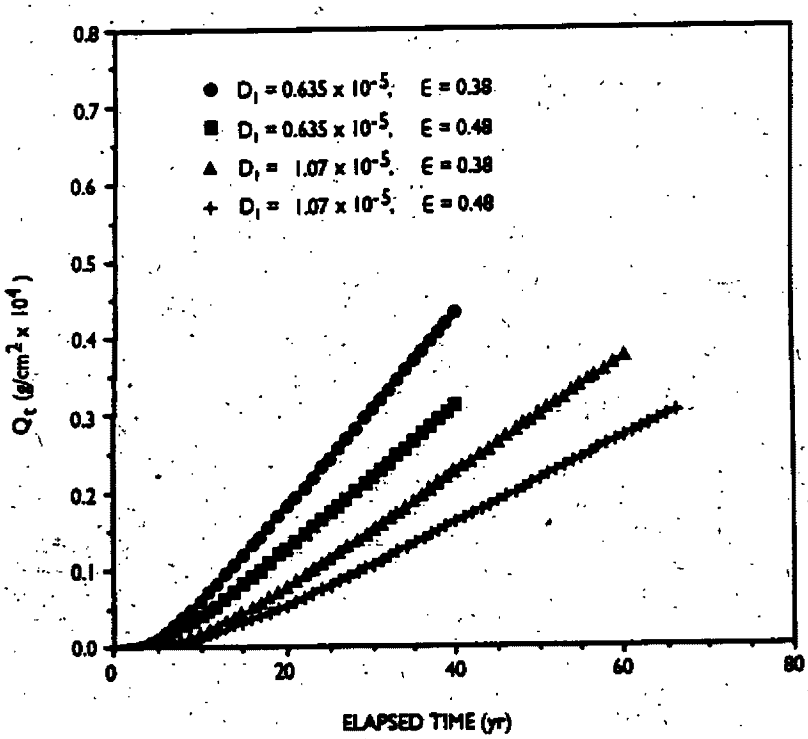

Figure 5. Simulations of cumulative diffusive solute transport through a hypothetical soil-bentonite barrier (Mott and Weber, Jr. 1991)

4.3.2 HDPE Walls

The effectiveness of HDPE barriers should depend largely on the tightness of the bonds between adjacent sheets. Manassero and Pasqualini have furnished illustrations of various bond configurations as shown in Figure 6. HDPE walls are perhaps the newest vertical barrier technology. Hence, long-term performance data are not available on them. The proposed numerical indices which are tabulated in Table 1 are for single vertical sheets without complementing slurry walls. The initial rating is 65% (lower than that of slurry walls) but the effectiveness decays at a much slower rate with increase in time. This pattern is chosen to be consistent with the fact that HDPE walls are not susceptible to most of the failure mechanisms that plague slurry walls. At 100 years, the effectiveness of HDPE walls is assumed to be reduced to the extent (25%) that the installation of a new wall would likely be warranted. This installation should increase the effectiveness back to the original 65% level.

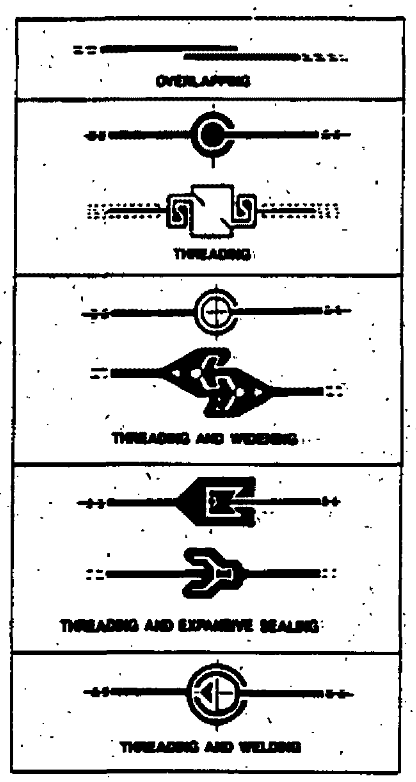

Figure 6. Types of locks for HDPE walls (Manassero and Pasqualini 1992)

5.0 SUMMARY

In this document, some of the technical issues that pertain to the long-term effectiveness of waste containment systems have been discussed. A conceptual model of effectiveness decay with service life has been described and illustrated. Based on that model, a numerical rating scheme which can be used in a Regulatory Impact Analysis (RIA) as well as other projects has been developed. The reader is reminded that the scheme is a rating system developed on the basis of a review of available literature and the technical judgment of the authors. It is general in nature, and a particular facility can exhibit a degradation pattern that reflects the curve configuration pattern of Figure 1 but defies the rating scheme. In essence, the proposed scheme will be refined as more field data become available for use with models to fill the information gaps that currently exist.

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