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Engineering Design File

Evaporation Pond Lining System Equivalency Analysis (60% Design Component)

INEEL
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5. Summary:

A lining system designed to the requirements of Resource Conservation and Recovery Act Subtitle C (40 CFR 264.221) was developed for the evaporation pond. In addition to the Subtitle C design requirements, a 3-ft-thick soil operations layer was provided to allow the standard design to meet the performance specifications for the operation environment (temperature extremes) of the evaporation pond lining system. The operations layer added a design element (i.e., waste generation) not desirable to the operation of the evaporation pond. In order to accommodate these operational conditions, while minimizing waste generation due to periodic replacement of the operations layer, an alternative design is proposed for approval by the regulatory agencies.

The evaporation pond lining system equivalency analysis provides a demonstration that the proposed alternative evaporation pond lining system will function at least as effectively as the standard Subtitle C lining system. Criteria to demonstrate equivalency is two-fold: 1) prevent migration of any hazardous constituents into the groundwater or surface water at least as effectively as the standard lining system; and 2) allow leak detection through the top liner at least as effectively as the standard lining system. In addition to the broad criteria cited in the regulations, additional relevant technical equivalency criteria developed from project experience and the literature are presented and discussed.

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(See instructions for definitions of terms and significance of signatures.)

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ABSTRACT

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CONTENTS

ACRONYMS

CCL	compacted clay liner
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CDN	composite drainage net
CFR	Code of Federal Regulations
CQA	construction quality assurance
CQC	construction quality control
DOE-ID	Department of Energy, Idaho Operations Office
EPA	Environmental Protection Agency
gpad	gallons per acre per day
GCL	geosynthetic clay liner
HDPE	high-density polyethylene
ICDF	INEEL CERCLA Disposal Facility
IDEQ	Idaho department of Environmental Quality
INEEL	Idaho National Engineering and Environmental Laboratory
LDS	leak detection system
RCRA	Resource Conservation and Recovery Act

Evaporation Pond Lining System Equivalency Analysis

1. INTRODUCTION

1.1 Purpose and Scope

The purpose of this Engineering Design File (EDF) is to request Environmental Protection Agency (EPA) and Idaho Department of Environmental Quality (IDEQ) approval of an alternative design for the INEEL CERCLA Disposal Facility (ICDF) Evaporation Pond liner. The EDF demonstrates the necessary equivalency requirements to allow for an approval of the proposed design. Subtitle C (40 Code of Federal Regulations [CFR] Part 264 Subpart K) establishes regulatory requirements for design of lining systems for Resource Conservation and Recovery Act (RCRA) Subtitle C—Surface Impoundments.

A lining system designed to the requirements of RCRA Subtitle C (40 CFR 264.221) was developed for the evaporation pond.

The standard design for the evaporation pond lining system is presented in Figure 1-1 and consists of (top to bottom):

- Primary Liner: 60-mil high-density polyethylene (HDPE) geomembrane (textured)
- Leak Detection System: composite drainage net (CDN) with a transmissivity of 3×10^{-4} m^2/sec or greater
- Secondary Liner (Upper Composite): 60-mil HDPE geomembrane (smooth)
- Secondary Liner (Lower Composite): 3-ft compacted clay liner (CCL) with a hydraulic conductivity of no greater than 1×10^{-7} cm/sec.

In addition to the Subtitle C design requirements, the standard design was developed to meet the performance specifications (DOE-ID 2000) for the evaporation pond lining system, including the ability to withstand an extreme temperature range of –50 to +120 degrees Fahrenheit. These temperatures are considered extreme but do occur on the desert and therefore must be considered design criteria. A 3-ft thick soil operations layer is necessary to allow the standard design to meet the performance specifications for the expected operational environment (temperature extremes) of the evaporation pond lining system. The operations layer is provided mainly to provide thermal protection against freeze-thaw for the CCL component of the standard lining system design. CCLs are known to be vulnerable to large increases in hydraulic conductivity from freeze-thaw cycling (see detailed discussion in Section 2.3.2.1).

The operations layer added a design element (i.e., waste generation) not desirable to the operation of the evaporation pond. In order to accommodate these temperature extremes, while minimizing waste generation due to periodic replacement of the operations layer, an alternative design is proposed for approval by the regulatory agencies.

Figure 1-1 presents the alternative lining system design proposed for the evaporation pond lining system. The alternative design consists of (top to bottom):

- Operations Layer (sacrificial): 60-mil HDPE geomembrane (textured)

- Primary Liner (Upper Composite): 60-mil HDPE geomembrane (smooth)
- Primary Liner (Lower Composite): geosynthetic clay liner (GCL); needle-punched, reinforced with a woven geotextile as the upper backing and a non-woven geotextile as the lower backing.
- Leak Detection System (LDS): CDN with a transmissivity of 3×10^{-4} m^2/sec or greater
- Secondary Liner (Upper Composite): 60-mil HDPE geomembrane (smooth)
- Secondary Liner (Lower Composite): GCL (same as primary liner GCL)
- 1-ft Structural Fill: comprised of 12 in. of alluvium from the landfill excavation.

The alternative primary lining system is clearly superior to the standard design as it provides two geomembranes (the upper one is a sacrificial working surface for operations) and a GCL, compared to only the single geomembrane for the standard design. Thus, the alternative design meets the RCRA Subtitle C regulations for the primary lining system and the focus of the equivalency analysis and demonstration is on the secondary composite lining system. The principal difference between the standard and alternative designs is in the soil components of the secondary composite lining system. The standard design requires a 3-ft-thick CCL with a hydraulic conductivity of no greater than 10^{-7} cm/sec, while the alternative design proposes a GCL underlain by a 12-in.-thick, stable structural fill layer.

1.2 Regulations for Equivalency

The regulations exempt the owner or operator from the requirements of 40 CFR 264.221 (a) if the Regional Administrator finds, based on demonstration by the owner or operator, that alternate design and operating practices together with location characteristics, will prevent the migration of any hazardous constituents into the groundwater at any future time. In deciding to grant an exemption, the Regional Administrator will consider:

1. The nature and quantity of the wastes
2. The proposed alternate design and operation
3. The hydrogeologic setting
4. All other factors that would influence the quality and mobility of the leachate and the potential to migrate to groundwater or surface water.

The owner or operator is <u>not</u> requesting an exemption from the design and operating requirements stated in 40 CFR 264.221, but rather for approval of an alternative design to the requirements specified in 40 CFR 264.221 (c). Thus the focus will be on item 2 above, and the regulations governing approval of alternative design. It should be noted that the conditions for items 1, 3, and 4 would be equivalent for either the standard or alternative lining system design.

From Subtitle C (40 CFR Part 264.221 [d]) the criteria for demonstrating equivalency for approval of alternative designs is two-fold:

1. Prevent migration of hazardous constituents into the groundwater or surface water at least as effectively as the standard liner system.

2. Allow leak detection through the top liner at least as effectively as the standard liner system.

The purpose of the evaporation pond lining system equivalency analysis is to demonstrate that the proposed alternative lining system design will function as effectively as a Subtitle C liner system for the evaporation pond.

In addition to the broad criteria cited in the regulations, additional relevant technical equivalency criteria developed from project experience and the literature are presented and discussed. Koerner and Daniel (1993) developed a comprehensive list of technical issues to be considered for an equivalency assessment of GCLs to CCLs (which is the focus of this equivalency analysis). The approach suggested by Koerner and Daniel has become the widely accepted industry standard for comparison of GCLs and CCLs.

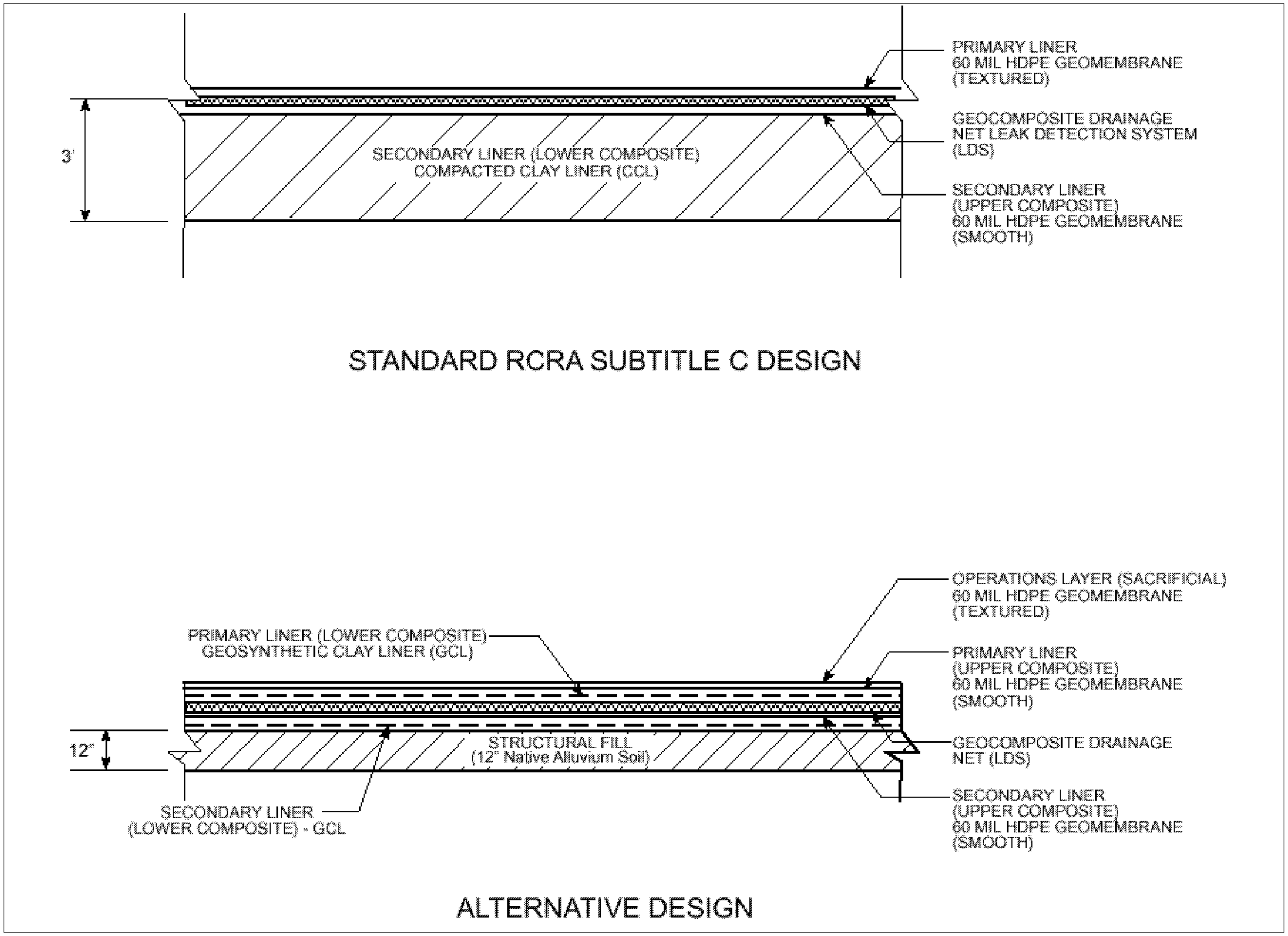

Figure 1-1. Evaporation Pond Lining System Sections.

2. EQUIVALENCY ANALYSIS APPROACH

Both the standard and alternative lining systems are composed of both a primary and secondary lining system as described in Section 1.1.

For the evaporation pond lining system equivalency analysis, the primary and secondary lining systems will be evaluated independently. As discussed in Section 1.1, it is clear that the alternative primary lining system design is more effective than the standard primary lining system design. An equivalency for the primary lining system is not being requested and the focus of the equivalency analysis is on the secondary lining system. However, it should be noted that when the lining system is evaluated as a whole, the effectiveness of the primary lining system must be considered. Thus, for the purpose of later evaluating the lining system as a whole, several key criteria that demonstrate the superiority of the primary lining system are discussed.

The approach for the secondary lining system will be to compare the composite liners in which the principal difference is the soil component. The standard secondary lining system utilizes a compacted clay liner (CCL) for the soil component, while the alternative uses a geosynthetic clay liner (GCL). The focus of comparison for the secondary lining system will be the soil component.

For the secondary lining systems, three broad categories of technical issues are considered for the assessment of equivalency between the standard and the alternative design:

- Hydraulic issues (i.e., leakage rate, steady flux [hydraulic conductivity], horizontal flow, attenuative capacity)
- Physical and mechanical issues (i.e., freeze-thaw, wet-dry, erosion vulnerability)
- Construction and operation issues (i.e., ease of construction, puncture resistance, weather constraints, water requirements, construction quality assurance/construction quality control [CQA/CQC], access for maintenance and repair).

Specific criteria for evaluating the primary and secondary lining systems is presented in Sections 2.2 (primary) and 2.3 (secondary). The equivalency analysis consists of reviewing these technical criteria to demonstrate that the alternative will be equivalent or superior to the standard design in terms of performance objectives. If the alternative liner meets the performance objectives, then equivalency has been established and the alternative liner should be used.

Following the analysis of the primary and secondary lining systems independently, the evaporation pond lining systems will be evaluated as a whole, taking into consideration the pertinent equivalency issues considered when evaluating the primary and secondary lining systems.

2.1 Overview of Geosynthetic Clay Liners

The key component of the alternative lining system design is the use of a GCL as the lower composite in the primary and secondary lining systems (see Figure 1-1). Because of the critical nature of the GCL in the alternative design, an overview of this manufactured product is provided.

GCLs are thin blankets of bentonite clay attached to one or more geosynthetic materials. Bentonite is a chemically stable clay mineral with very high swelling potential and water absorption capacity. When wetted, bentonite is the least permeable of all naturally occurring soil-like minerals.

GCLs are manufactured by placing and attaching a layer of dry bentonite, approximately 1/4-in. thick, on a geosynthetic material and attaching the bentonite to the geosynthetic material. There are two general configurations of GCLs: 1) bentonite sandwiched between two geotextiles, and 2) bentonite glued to a geomembrane. Currently, there are four commercially available GCL products: Bentomat, Bentofix, Claymax, and Gundseal.

The standard Bentomat and Bentofix are reinforced GCL products that consist of bentonite sandwiched between a woven and nonwoven geotextile that are then needle-punched together. Other combinations of upper and lower, woven and nonwoven geotextiles can also be manufactured.

The two Claymax, which are non-reinforced GCL products, include: 1) Claymax 200R, which consists of bentonite mixed with glue and sandwiched between two woven geotextiles; and 2) Claymax 600CL, which consists of bentonite mixed with glue and sandwiched between two woven geotextiles with a composite laminate applied to one of the geotextiles. As with Bentomat and Bentofix GCL products, the Claymax product can be manufactured with project-specific geotextiles.

The Gundseal GCL product is manufactured by mixing bentonite with an adhesive and attaching the bentonite to an HDPE geomembrane (either smooth or textured).

For the landfill lining system, the needle-punched, reinforced GCL with non-woven geotextiles on both sides (either Bentomat or Bentofix) were selected. This GCL product was selected primarily because of the tensile strength requirements required for stability on the landfill slopes (DOE-ID 2001a). The tighter weave non-woven geotextile minimizes the amount of bentonite that migrates to the interface with the geomembrane, thus minimizing the potential to create a slip surface.

These same stability concerns are not an issue for the evaporation pond lining system, especially the alternative design with no operations layer above the geomembrane. Thus, the standard needle-punched, reinforced GCL product (with a woven geotextile for upper backing material and the non-woven-geotextile for lower backing) was selected for the evaporation pond lining system.

2.2 Primary Lining System

The principal difference between the standard and alternative lining systems is that the standard design consists of a single geomembrane and the alternative design is a composite liner consisting of two geomembranes underlain by a GCL. As discussed earlier, equivalency for the primary lining system is not being requested as the alternative exceeds the requirements of the Subtitle C standard design. However, several criteria that demonstrate the superiority of the alternative design are discussed. The superiority of composite liner systems over single geomembrane liners is well documented (Bonaparte and Gross 1990), especially with respect to hydraulic criteria. The critical advantage for the composite liner is its ability to overcome occasional defects with a single geomembrane liner.

2.2.1 Hydraulic Criteria

The primary purpose of any barrier material is to contain liquids. The liquid depth considered for the primary lining system is the average maximum pond depth over the lining system. Figure 2-1 presents a north-south cross section of the evaporation pond water depth. A plan view from which the cross-section was taken can be found on Drawing H-202 in the "ICDF - Drawings (Title I)," 30% design submittal (DOE-ID 2001b). The pond is designed with a 2-ft freeboard (distance between the maximum water surface elevation and the berm crest elevation), resulting in a maximum water depth of 4.5 ft at the south end of the pond and 7 ft at the north end. A maximum average depth of 6 ft (1.83 m), at the center of the pond, was used for hydraulic head on the primary lining system.

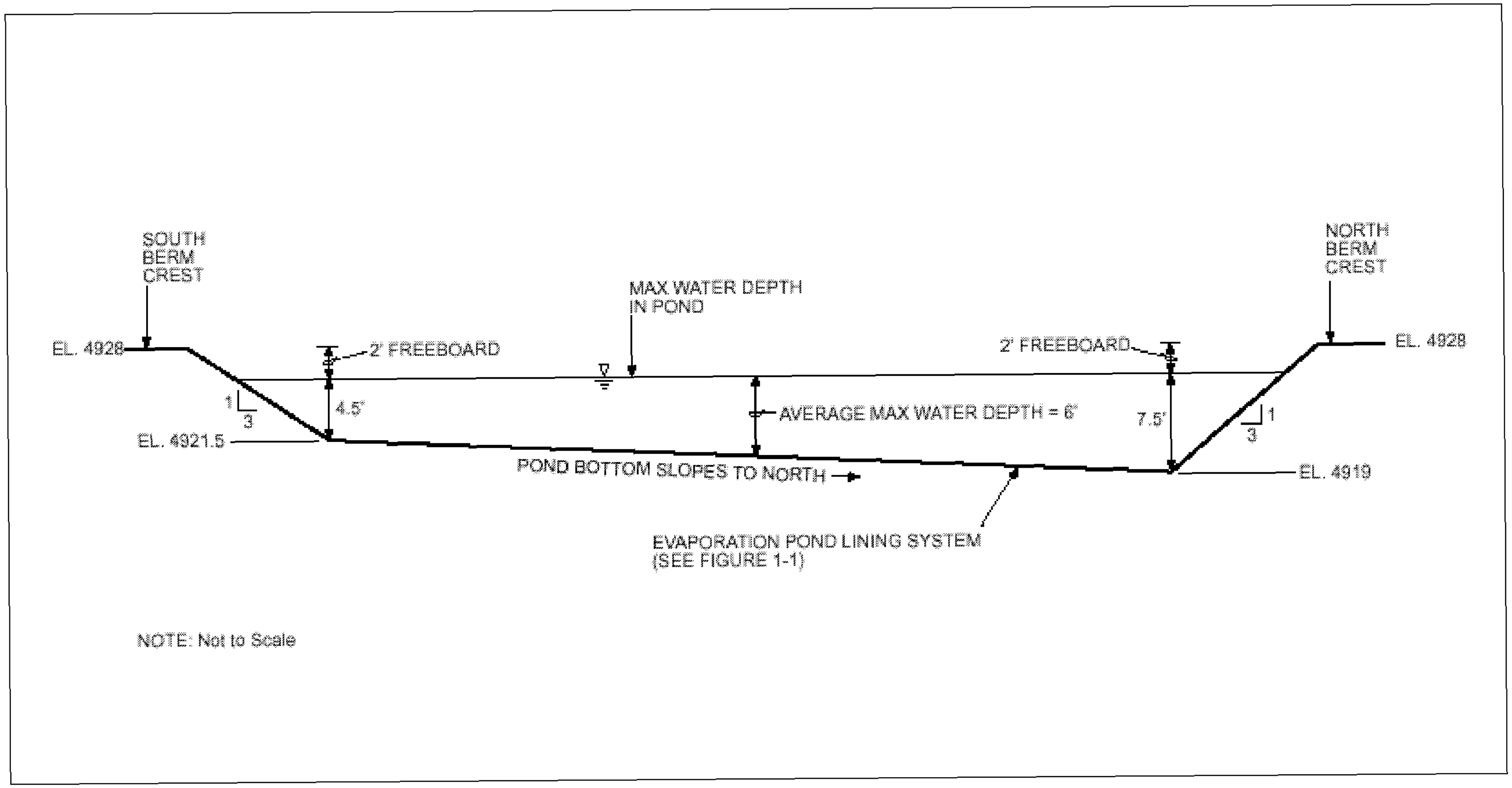

Figure 2-1. Evaporation Pond Lining System Water Depth (N-S Cross-Section).

The hydraulic evaluation of the primary lining system will focus on the calculation of leakage rate, which can be directly linked to the ability of the lining system to prevent migration of hazardous constituents into the groundwater or surface water.

2.2.1.1 Leakage Rate. The rate of leakage through lining systems with geomembranes due to permeation is negligible compared to the rate of leakage through geomembrane defects (Giroud and Bonaparte 1989a). Thus, for the purpose of this equivalency analysis, only the latter was considered.

Using equations either developed or refined by Giroud and Bonaparte (1989a) (Appendix B) and Giroud and Bonaparte (1989b) (Appendix C), the leakage rate calculations for both standard and alternative primary lining systems were derived. The Giroud and Bonaparte references are provided in Appendices B and C. For the single geomembrane liner, the leakage rate is determined from Bernoull's equation for free flow through an orifice:

$$Q = C_B a \sqrt{2gh}$$

where

Q = leakage rate

C_B = dimensionless coefficient (0.6 for aperture with sharp edge)

a = area of single defect

g = acceleration due to gravity

h = liquid depth over liner.

For the leakage rate calculations from the primary standard lining system, the head of the liner is as discussed in Section 2.2.1. Giroud and Bonaparte (1989a) concluded that for geomembrane liners installed with good construction CQA/CQC a defect frequency of one hole per acre is appropriate. They also recommended that a large hole size of 1 cm^2 (11.3 mm diameter) be used for calculations to size the LDS and that a small hole size of 3.1 mm^2 (2 mm diameter) be used to evaluate the performance of a lining system. Using these input parameters results in a leakage rate for the standard primary lining system of 8,325 gallons per acre per day (gpad) for a large geomembrane defect and 261 gpad for a small geomembrane defect. Detailed calculations are presented in Appendix A.

For the composite liner, the leakage rate is determined by the equation developed by Giroud (1997) (reference provided in Appendix D) for flow through a circular defect in the geomembrane and through the underlying soil component:

$$Q = 0.976 n C_q [1 + 0.1 (h/t_s)^{0.95}] d^{0.2} h^{0.9} k_s^{0.74}$$

where

Q = leakage rate

n = number of defects per considered area

C_q = liner contact quality (0.21 for good and 1.15 for poor contact between geomembrane and soil components)

d = diameter of circular defect

h = liquid depth over liner

t_s = thickness of soil component

k_s = hydraulic conductivity of the soil component.

The soil component of the alternative primary lining system is a 1/4-in.-thick GCL with a hydraulic conductivity of between 1×10^{-11} centimeters per second (cm/sec) and 1×10^{-8} cm/sec, depending on the confining stress (Daniel 1993). Estornell and Daniel (1992) reported an average permeability for the various GCL products of 4.6×10^{-9} cm/sec at confining stresses ranging from 200 to 400 pounds per square foot (psf), which is representative of the confining stress the primary lining system will be subjected to under the average water depth in the pond. For this equivalency assessment, a hydraulic conductivity value of 5×10^{-9} cm/sec was used.

For the leakage rate calculations from the primary alternative lining system, the input parameters for liquid depth and defect frequency and size are the same as used for calculating the standard design leakage rate. Using these input parameters results in a leakage rate for the alternative primary lining system of 1.3 (small defect) to 1.8 (larger defect) gpad for a composite liner with good intimate contact and 6.9 (small) to 9.8 (large) gpad for poor contact. The composite lining system has a much lower leakage rate than the single geomembrane liner. An additional benefit of the composite lining system is that the leakage rate is much less sensitive to the size of the geomembrane defect. Detailed calculations are presented in Appendix A.

The results of leakage rate calculations for the primary lining system support the findings of Bonaparte and Gross (1990), on data collected from LDS of constructed double-lined systems. In terms of leakage rate through geomembrane defects, a composite lining system, as shown in the alternative design, is vastly superior to a single geomembrane liner, as shown in the standard design, and will prevent migration of hazardous constituents into the groundwater or surface water at least as effectively as the standard lining system design.

2.2.2 Construction and Operation Criteria

The standard design for the primary lining system does not require an operations layer. The operations layer was added to allow the standard design to function effectively in the INEEL environment. Without the operations layer, the standard primary lining system is equivalent to the alternative design with respect to ability to detect leaks through the top (primary) liner and access for maintenance and repair. However, if one considers the operations layer as an integral component to the function of the standard design for the primary lining system, including the operations layer, a comparison with the alternative primary lining system is appropriate. In addition, the periodic requirement to sacrifice the 3-ft operations layer is not consistent with waste minimization policies.

2.2.2.1 Ability to Monitor Leakage. Both the standard and alternative lining system provide an LDS beneath the primary liner. Therefore, from the perspective of leak detection from below the primary lining system, they are considered equivalent.

In addition to the LDS layer, electronic leak detection methods are available to locate leaks in the primary lining system geomembrane from the surface. This method can be implemented for exposed or covered geomembranes; however, the testing is easier and more reliable for exposed geomembranes (Rollin et al. 1999).

The alternative primary lining system is not covered by the 3-ft operations layer. The ability to directly and reliably monitor leakage through the exposed primary lining system during operation of the evaporation pond is a critical advantage of the alternative primary lining system.

2.2.2.2 Access for Maintenance and Repair. The operations layer over the standard primary lining system presents difficulty for access to the lining system. The alternative primary lining system consists of an exposed geomembrane that provides direct and easy access for any required maintenance and repair. Repairs to the standard lining system would first require removal of the operations layer and later replacement of these layers after the repair. It is conceivable that the primary lining system could be further damaged during removal and/or replacement of the operations layer.

The exposed operations layer (sacrificial) geomembrane in the alternative primary lining system provides a convenient surface for occasional cleaning of sediments in the evaporation pond. The sediments on the exposed surface of the alternative design can be more readily accessed and removed than from the surface of the operations layer in the standard design.

One additional maintenance/operation advantage of the alternative design is that when it is time for periodic replacement and evaporation pond closure, the 3-ft operations layer would be contaminated with leachate. This material would have to be disposed in a facility such as the ICDF, or the evaporation pond would have to be closed in-place. There would be no contaminated soils requiring disposal at the time of closure for the evaporation pond with the alternative lining system design, other than remaining sediments in the pond.

The ease of access for maintenance and repair during operation and minimization for generation of contaminated soil during periodic replacement of the operations layer and at evaporation pond closure is a critical advantage of the alternative primary lining system.

2.3 Secondary Lining System

Both the standard and alternative secondary lining systems use a composite liner. The principal difference between the alternative secondary lining system and standard lining system design is in the soil components used for the lower composite of the lining system. For the purpose of the equivalency analysis, the GCL overlaying a 1-ft-thick structural fill layer in the alternative lining system is compared to CCL used for the standard secondary lining system.

2.3.1 Hydraulic Criteria

The primary purpose of any barrier material is to contain liquids. The liquid depth considered for the secondary lining system is very small and is essentially equivalent to the thickness of the LDS layer (Giroud and Bonaparte 1989a). A liquid depth of 200 mils (0.2 in.) (0.005 m) was used in hydraulic evaluation of the secondary lining system. A higher head condition is not anticipated for the secondary liner system, as it would require a continuous, steady-state hydraulic connection between the LDS and the liquid depth in the pond. This type of condition would result from a large tear or substantial puncture in the primary liner system (which is unlikely) and would trigger immediate remedial activities through exceedence of the action leakage rate for the ponds.

Mass flux of leachate through soil lining systems consists of water and solute components. Water flux is analyzed on the basis of advection, while solute flux of leachate is analyzed on the basis of advection plus diffusion. However, since the advective mass flux is the dominant component of mass flux, demonstration of equivalency in terms of water flux will be used to demonstrate equivalency in terms of total mass flux (Koerner and Daniel 1993).

2.3.1.1 *Steady Flux of Water.* Water flux is defined as the volume of flow across a unit area in a unit time. For a barrier in a lining system, water flux is equal to the rate of percolation of water through the barrier layer.

Water flux is usually analyzed based on the long-term, steady-state water flux. The flux of water (ν) through an individual layer of porous material is defined from Darcy's law as:

$$\nu = k\,[H + T]/T$$

Where k is the hydraulic conductivity, H is the head of liquid on the liner, and T is the thickness of the liner. The fractional coefficient by which k is multiplied represents the hydraulic gradient. The water pressure on the base of the liner is assumed to be atmospheric pressure in this equation. This equation applies to a CCL or GCL liner alone and not to composite liners involving one or more separate geomembrane components or additional soil layer below the GCL.

One can assume that water flux through the GCL is equal to water flux through a CCL, and calculate the required hydraulic conductivity of the GCL in the alternative lining system. The equation for calculating the required GCL hydraulic conductivity for equivalency is presented in Appendix E.

Input parameters for the calculations include the hydraulic conductivity of the CCL, thickness of the CCL and GCL and head on the liner. The CCL in the standard composite liner is 3 ft (1.83 m) thick and is required to have a hydraulic conductivity of no more than 1×10^{-7} cm/sec. The GCL component of the alternative liner is 1/4-in. (0.0064 m) thick. As discussed in Section 2.3.1, the thickness of the LDS (200 mils) was used for depth of liquid (head) ponded on the CCL or GCL in the secondary lining system.

Calculations for determining the required GCL hydraulic conductivity for equivalency are presented in Appendix E. For the low head conditions on the secondary lining system, a GCL hydraulic conductivity of 5×10^{-8} cm/sec is required to achieve equivalency to a CCL.

The GCL component of the alternative liner has a hydraulic conductivity of between 1×10^{-11} cm/sec and 1×10^{-8} cm/sec, depending on the confining stress (Daniel 1993). Estornell and Daniel (1992) reported an average permeability for the various GCL products of 4.6×10^{-9} cm/sec at confining stresses ranging from 200 to 400 psf, which is representative of the confining stress the secondary lining system will be subjected to under the maximum average water depth in the pond. Using the hydraulic conductivity value of 5×10^{-9} cm/sec reported by Estornell and Daniel results in a one order of magnitude margin of safety over the required hydraulic conductivity value of 5×10^{-8} cm/sec to establish equivalency for the GCL. This indicates that the GCL allows less water to flow through than a CCL for the secondary lining system. Therefore, the GCL is equivalent to, or better than, a CCL with respect to steady water flux through the liner as demonstrated by Darcy's law.

2.3.1.2 *Leakage Rate.* The rate of leakage through lining systems with geomembranes due to permeation is negligible compared to the rate of leakage through geomembrane defects (Giroud and Bonaparte 1989a). Thus, for the purpose of this equivalency analysis, only the latter was considered.

For the leakage rate calculations from the secondary standard lining system, the head of the liner is as discussed in Section 2.3.1. Giroud and Bonaparte (1989a) concluded that for geomembrane liners installed with good CQA/CQC, a defect frequency of one hole per acre is appropriate. They also recommended that a large hole size of 1 cm^2 (11.3-mm diameter) be used for calculations to size the LDS and that a small hole size of 3.1 mm^2 (2-mm diameter) be used to evaluate the performance of a lining system.

For a composite liner, the leakage rate is determined by the equation developed by Giroud (1997) for flow through a circular defect in the geomembrane and through the underlying soil component. The leakage rate equation for composite liners is the same as presented in Section 2.2.1.1.

The soil component of the standard secondary lining system is a 3-ft-thick CCL with a hydraulic conductivity of 1×10^{-7} cm/sec. The hydraulic conductivity for the CCL is a regulatory requirement stated in 40 CFR 264.221(c).

Using these input parameters results in a leakage rate for the standard secondary lining system of 2.5×10^{-3} (small defect) to 3.6×10^{-3} (larger defect) gpad for composite liner with good intimate contact and 0.014 (small) to 0.02 (large) gpad for poor contact. Detailed calculations are presented in Appendix A. Leakage rates are very low through defects in the secondary lining system geomembrane because of the very low head conditions over the secondary liner.

The soil component of the alternative secondary lining system is a 1/4-in.-thick GCL with a hydraulic conductivity of 5×10^{-9} cm/sec used for the leakage rate calculation (see Section 2.2.1.1).

Using these input parameters results in a leakage rate for the alternative secondary lining system of 3.0×10^{-4} (small defect) to 4.2×10^{-4} (larger defect) gpad for composite liner with good intimate contact and 1.6×10^{-3} (small) to 2.3×10^{-3} (large) gpad for poor contact. Although the leakage rates are very small for both the standard and alternative secondary lining systems, alternative design has a lower leakage rate than the standard design. Thus, in terms of leakage rate, the alternative design with GCL is at least equivalent and likely superior to the standard design with CCL.

2.3.1.3 Horizontal Flow Considerations

Flow in Seams or Lifts: Both steady flux and leakage rate compared the vertical flow through the CCL matrix to the vertical flow through a GCL. However, a potential exists for horizontal flow at GCL overlap seams, which may be more rapid and tend to increase the water flux over a large area.

For GCLs, the concern is primarily with the overlap seam area. Large-scale experiments support manufacturers' recommendations that the overlap areas (typically 6 to 12 in.) either self-heal by the swelling of the bentonite or, by adding powdered bentonite commingled with geotextile backing to form an adequate seal (LaGatta et al. 1997). In addition, horizontal seams across the slope are shingled downslope to promote sheet flow and prevent infiltration at these seams. For CCLs, the concern is with the area between individual lifts with inadequate bonding from one surface to the underlying lift. For both GCLs and CCLs, this issue is clearly related to CQA/CQC procedures. When properly constructed, horizontal flow in seams or lifts should not be a significant concern for either material.

Flow Beneath Geomembranes: When installed beneath a geomembrane component of a composite liner, both GCLs and CCLs must achieve intimate contact with the overlying geomembrane. Liquid passing through a hole in the geomembrane should not be able to spread horizontally, thus subjecting the underlying CCL or GCL to increased hydraulic head over an enlarged area.

Harpur et al. (1993) measured the apparent transmissivities of five different GCLs placed beneath a geomembrane with a small, centrally located hole (0.3-in. diameter). Transmissivity is defined as the volumetric flow rate per unit thickness, within the in-plane direction of the material. Transmissivity tests were performed using a radial transmissivity device. Test results at two different normal stresses were evaluated. Transmissivity values for the geomembrane-GCL combination were compared to the theoretical geomembrane-CCL value. The theoretical value for the geomembrane-CCL was obtained from Giroud and Bonaparte (1989b), who estimated the transmissivity by assuming a spacing of 0.02 mm between the geomembrane and the CCL and applying Newton's viscosity law for flow between parallel plates. The comparison indicates that all measured geomembrane-GCL combinations evaluated were significantly lower in transmissivity than the estimated geomembrane-CCL transmissivity. As refuse thickness increases, the normal stress on the GCL will increase, resulting in bentonite extruding through geotextile backing. This leads to even lower geomembrane-GCL transmissivity values. While actual geomembrane-CCL data needs to be developed, it appears as though GCLs are superior or at least equivalent to CCLs with respect to potential horizontal transmissivity.

It should be noted that for both GCLs and CCLs, the intimate contact issue can be compromised when the overlying geomembrane has wrinkles because of thermal expansion. This is an equal concern for both GCLs and CCLs with no preference for one material over the other. During construction, placement of overlying drainage and leachate collection materials must be controlled. The temperature of the geomembrane should be monitored and corrections applied to the panel layouts to accommodate thermal expansion and contraction of the geomembrane. During placement of overlying granular leachate collection materials, folds or wrinkles must not be covered, but controlled by allowing air to vent from the open panel end, placement of overlying materials at night with cooler temperatures, or removed if too extensive. These measures will be specifically covered in the construction specifications and the CQA plan.

2.3.1.4 Attenuative Capacity. Attenuative capacity is the ability of the liner to slow or stop leachate contaminants from passing into the native material below the lining system. A key component of attenuative capacity is the adsorptive capacity of the lining system.

Adsorptive capacity is the ability of the liner to absorb contaminants by providing attachment sites to chemicals passing through the liner. It depends on whether the contaminants are organic or inorganic, the ionic strength and charge of the contaminants, the density and thickness of the liner, cation exchange capacity of the liner materials, and site-specific factors such as the pH of the chemical environment and the composition of the leachate. Kd values for GCLs are reported to be similar to that of CCLs for COC at the ICDF (DOE-ID 2001c).

However, the mass of soil to provide adsorption capacity is very different for CCLs and GCLs. The CCL proposed for the compacted soil component of the standard secondary liner system is a bentonite-amended native soil liner. This CCL will contain approximately 5% by dry weight of bentonite (DOE-ID, 2001d). GCLs contain 100% by weight of bentonite (excluding the geotextile backing material which is not relevant to attenuative capacity discussion). Bentonite provides the adsorptive capacity of GCLs and CCLs (assuming the native soil has a much lower attenuative capacity compared to bentonite). Therefore, a simple way to compare adsorptive capacity between the standard liner and the alternative liner is to compare the dry weight of bentonite per unit area of liner. This comparison shows that a 1/4-in.-thick GCL has only approximately 15% of the weight of bentonite that would be in the 3-ft-thick soil/bentonite CCL of the standard composite lining system and therefore, has potentially less adsorptive capacity.

However, adsorptive capacity of the secondary lining system soil components is important only if the primary lining system and the secondary lining system geomembrane is compromised. If the HDPE geomembrane of either system were to be compromised, the adsorptive capacity of either the GCL or the CCL would be exhausted quickly compared to the design life of the evaporation pond. Therefore, variation in adsorptive capacities does not indicate a significant difference between the standard alternative lining systems.

In the long term, the mass flux through the barrier layer is critical. Mass flux is the volume of contaminants that pass through the liner per unit time. This factor is a valid point of comparison after adsorptive capacity has been exhausted. Mass flux is the same as steady flux of water discussed earlier in this report. The results of that analysis show that a GCL passes a lower volume of water through the liner per unit time as compared to a CCL. Hence, for long-term, steady flow through the lining system, the leakage of contaminants would be less through a GCL than through a CCL.

In summary, the short-term attenuative capacity of a GCL is likely to be inferior to a CCL for certain leachate constituents and until the adsorptive capacity of the soils in the lining systems is reached. At that time (and for those constituents not affected by adsorption), mass flux dominates the attenuative capacity of the lining system, and the GCL is equivalent or superior to the CCL.

2.3.2 Physical/Mechanical Issues

2.3.2.1 Freeze-Thaw Behavior. CCLs are known to be vulnerable to large increases in hydraulic conductivity from freeze-thaw cycling; although the data suggest that compacted soil bentonite admixtures may not be as vulnerable to damage as true clay liners (Kim and Daniel 1992; Benson and Othman 1993; Kraus et al. 1997). Existing laboratory and field test data indicate that GCLs do not undergo increases in hydraulic conductivity as a result of freeze-thaw conditions (Hewitt and Daniel 1997; Kraus et al. 1997). It should be noted that these lab and field tests were conducted with a limited number of freeze-thaw cycles. Based on these data, GCLs are superior to CCLs in terms of freeze-thaw resistance.

2.3.2.2 Wet-Dry Cycle Behavior. Wetting and drying cycles of CCLs and GCLs can cause either type of material to swell, and/or shrink. The resistance of CCLs to wet/dry cycles is known to be poor. Desiccation cracking during placement of the CCL will occur, which can lead to increases in the coefficient of permeability of a CCL depending on the number, width, and depth of cracks.

Tests by Shan and Daniel (1991) and Boardman and Daniel (1996) indicate that desiccation of wet GCLs does cause cracking, but rehydration of the GCL causes the bentonite to swell and the material to "self-heal." Thus, GCLs are superior to CCLs in terms of ability to self-heal if the material is wetted, dried, and rewetted.

2.3.2.3 Vulnerability to Erosion. Erosion resistance is a concern for the lining system during the construction phase, prior to placement of the geomembrane cover. With a well-designed and properly maintained geomembrane and adequate erosion controls, the GCL or CCL should not be subjected to erosion forces after the construction phase is over.

However, if the liner is exposed to erosive forces (rainfall or runoff) during construction, the presence of erosion-resistant geosynthetic materials in GCLs (top and bottom) make them more resistant to erosion than CCLs. If soil liners are exposed to rain, they are subject to direct erosion. For both the CCL and the GCL, the construction specifications will require that they be covered by geomembrane each day, to protect against rain, or desiccation in the case of the CCL. As will be discussed in the construction issues section, the greater speed of placement for GCLs will narrow the window for potential exposure to erosive forces.

2.3.3 Construction and Operation Issues

2.3.3.1 Speed/Ease of Construction. Although not regulatory requirements, these construction issues are relevant to ensure the quality of the liner placement. A GCL can be placed much easier and quicker than a CCL, unless weather conditions are adverse (i.e., constant rain) in which case a GCL will also be difficult to construct. In addition, the alternative lining system (with GCL) can be built with less potential for variation during construction, since the GCL is a manufactured product. GCLs are generally regarded as superior to CCLs in terms of speed of construction and ease of placement.

A typical GCL placement rate is 1 acre per day and so the time to install a GCL layer over the 3-acre pond is estimated at three days. A typical placement rate for a 3-ft-thick CCL is estimated at approximately 1/3-acre per day. The time to construct a CCL over the evaporation pond lining system area is estimated at two weeks, or two to three times the time it takes for installation of the GCL.

2.3.3.2 Puncture Resistance. GCLs are thin and, like all thin geosynthetic materials, are vulnerable to damage from accidental puncture during or after construction. In contrast, thick CCLs are less likely to be damaged from accidental punctures. GCLs have the capability to self-heal around punctures caused by sharp objects (such as a nail). The swelling property of bentonite gives GCLs this self-healing capability. In the case of the proposed alternative lining system for the evaporation pond, the 12-in.-thick underlying structural fill layer (as shown in Figure 1-1) will contribute to the overall puncture resistance of the system from sharp objects (e.g., rocks, sticks) below the liner system.

Of perhaps greater concern than penetration of the GCL by an object after construction is accidental puncture during construction. In this case, GCLs would not have equivalent puncture resistance to CCLs. However, this does not mean that a GCL cannot meet or exceed the performance objectives of a CCL. Proper QA/QC procedures will be established and implemented to protect both the geomembrane and GCL and make the probability of puncture occurring during construction extremely low.

2.3.3.3 Weather Constraints. Both CCL and GCL construction can be constrained by weather conditions that can reduce the quality of the final product or cause construction delays, both of which adversely impact the installation quality.

CCLs are difficult to construct when soils are wet, heavy precipitation is occurring, the weather is extremely dry (soil desiccates), the soil is frozen, or the temperature is below freezing. Because CCLs can desiccate in dry weather, the geomembrane liner placement must follow immediately after construction of the CCL to protect the CCL. The compaction and permeability requirements for CCLs make them especially sensitive to changes in moisture. These constraints narrow the window of weather conditions favorable to CCL construction. In addition, if CCL construction is attempted under adverse conditions, the quality of the final liner is compromised.

In contrast, a GCL can be placed under most weather conditions, except during precipitation and when the underlying foundation layer is too wet. GCLs are unaffected by freezing temperatures. While GCLs can desiccate in hot, dry weather, the geomembrane liner will protect the material. In some cases, hydration of the GCL from contact with the foundation soil is a concern, and an overburden pressure must be applied (such as a drain sand layer over the geomembrane) to confine the swelling of the GCL. However, this limitation can be accommodated through proper construction sequencing.

Because the weather constraints on placement of a CCL are more restrictive than for a GCL, CCL installation is more likely to face delays, potential for erosion, and especially desiccation problems. In conclusion, GCLs are superior to CCLs in terms of weather constraints creating construction delays, erosion potential, and quality limitations. GCLs are also superior to CCLs in terms of construction speed and ease of placement. Again, although not required as approval considerations, these issues do ensure the placement of a quality liner.

2.3.3.4 Water Requirements. Construction water is necessary for many soils in order to make a CCL. The soil material is usually placed at a moisture content wet of optimum to achieve the desired low hydraulic conductivity. The total amount of water required to moisten a CCL can be very large. The natural water content of the CCL base soil from Rye Grass Flats is approximately 9% and, based on results of the soil amendment study (DOE-ID 20001d), has to be increased by 7 to 10% to achieve the required moisture conditions. For a 3-ft-thick CCL constructed evaporation pond secondary lining system (approximately 3 acres), the total amount of water necessary would be approximately 200,000 to 300,000 gallons.

GCLs do not require water for construction and are superior to CCLs in this regard. The 12-in.-thick structural fill layer underlying the GCL (comprised of native alluvium) would require significantly less water than the CCL. The alluvium water content requires an increase of approximately 3%, resulting in the need for approximately 20,000 gallons of water.

2.3.3.5 CQA/CQC Considerations. The proper construction of a low-permeability CCL is a challenging task. Careful control must be exercised over materials, moisture conditions, clod size, maximum particle size, surface preparation for a lift of soil, lift thickness, compaction coverage and energy, and protection of each completed lift. Comparatively, because GCLs are manufactured under extensive QC protocols, construction QA/QC requirements are much less rigorous for GCLs than with CCLs, although they are no less critical. In general, while QA/QC for a CCL requires a number of relatively sophisticated tests and points of control by experienced and capable personnel, QA/QC for GCLs primarily involves diligent observation and the application of common sense. Far fewer things can go wrong with the installation of a GCL than with placement and compaction of a CCL.

2.3.3.6 Access for Maintenance and Repair. The operations layer over the standard primary lining system also presents difficulty for access to the secondary lining system. The alternative primary lining system consists of an exposed geomembrane, which provides direct and easy access for any required maintenance and repair. Repairs to the standard lining system would first require removal of the operations layer and later replacement of these layers after the repair. It is conceivable that the primary lining system could be further damaged during removal and/or replacement of the operations layer.

The ease of access for maintenance and repair during operation is a critical advantage of the alternative secondary lining system.

3. SUMMARY OF EQUIVALENCY ASSESSMENT

This section presents a summary of the technical equivalency assessment of the standard and alternative evaporation pond lining systems discussed in Section 2.

For the primary lining system discussed in Section 2.2, the alternative design is clearly more effective than the standard design. The composite lining system provided by the GCL provides superior performance with respect to protection against leakage through the top liner as required by 40 CFR 264.221 (d)(1).

With respect to ability to monitor leaks through the top liner and access for repair, the alternative design is equivalent to the standard design as required by 40 CFR 264.221 (d)(2). However, if one considers the operations layer an integral part of the standard design, the elimination of the soil operations layer provides more effective access for maintenance and repair and the ability to monitor leakage from the surface of the primary lining system as discussed in Section 2.2.2.

The equivalency analysis of the secondary lining system focused on the soil component of the standard (CCL) and alternative (GCL) designs, which is the principal difference between the two designs. The secondary lining systems are very closely related in comparison. A summary of the equivalency issues for the secondary lining system discussed in Section 2.3 is shown in Table 3-1. Table 3-1 is arranged for each of the equivalency criteria according to the following classifications:

- The Alternative is more effective (Category 1)
- The Alternative is equivalent (Category 2)
- The Alternative is not equivalent (Category 3)
- Site-specific design, operation, or QA/QC conditions to make each alternative equivalent or superior (Category 4).

Table 3-1. Summary of technical equivalency assessment for secondary evaporation pond lining system.

Issue	Criteria for Evaluation	Category 1	Category 2	Category 3	Category 4
Hydraulic	Steady flux of water	X			
	Leakage rate	X			
	Horizontal flow	X			
	Attenuative capacity		X		
Physical/Mechanical	Freeze-thaw	X			
	Wet/dry	X			
	Erosion vulnerability	X			
Construction/Operations	Speed of construction	X			
	Puncture resistance			X	X
	Weather constraints	X			
	Water requirements	X			
	Access for maintenance and repair	X			

Table 3-1 clearly illustrates that the alternative secondary lining system, with GCL as a soil component, is equivalent or more effective for nearly all criteria, except for puncture resistance. This criteria is discussed in greater detail below.

As discussed in Section 2.3.3.2, thin GCLs do not have the same puncture resistance as much thicker CCLs. Although the GCLs can be punctured during construction, careful QA/QC during construction should be capable of addressing this potential problem. GCLs will "self-heal" punctures up to 1 in. in diameter when hydrated (Shan and Daniel 1991; Estornell and Daniel 1992; Daniel 1997) because of the expansive characteristics of bentonite.

Table 3-2 summarizes the leakage rate calculations for both the primary and secondary liner systems.

Table 3-2. Leakage rate calculations for liner systems.

Liner system	Standard/Alternate	Leakage Rate (gpad)	Design Condition
Primary	Standard	8,325	Large defect
	Standard	261	Small defect
	Alternate	1.8 to 9.8	Large defect; good to poor contact
	Alternate	1.3 to 6.9	Small defect; good to poor contact
Secondary	Standard	3.6×10^{-3} to 2.0×10^{-2}	Large defect; good to poor contact
	Standard	2.5×10^{-3} to 1.4×10^{-2}	Small defect; good to poor contact
	Alternate	4.2×10^{-4} to 2.3×10^{-3}	Large defect; good to poor contact
	Alternate	3.0×10^{-4} to 1.6×10^{-3}	Small defect; good to poor contact

The hydraulic criteria, especially leakage rate and steady flux of water, demonstrate quantitatively the hydraulic superiority of the alternative lining system design. For the primary lining system, the standard design has a leakage rate of 261 to 8,325 gpad, depending on the size of the geomembrane defect. For the alternative primary liner design the leakage rate is 1.3 to 6.9 gpad depending on the size of the geomembrane defect and the contact quality between the geomembrane and the GCL.

In the hydraulic evaluation of the secondary lining system, the leakage rate is very small for the both the standard and alternative lining systems, however the alternative design has a lower leakage rate. In addition, with respect to steady flux of water through the secondary lining system, it was determined that a maximum hydraulic conductivity of 5×10^{-8} cm/sec was required for the alternative to be equivalent to the standard design. The hydraulic conductivity of the GCL is reported at 5×10^{-9} for the confining stress expected on the evaporation pond lining system.

In summary, the clear effectiveness of the alternative primary lining system, combined with the overall superiority of the alternative secondary lining system, demonstrate that the alternative evaporation pond lining design as presented in Figure 1-1 is at least equivalent to the standard design in its ability to 1) prevent migration of hazardous constituents into the groundwater or surface water at least as effectively as the standard liner system; and 2) allow leak detection through the top liner at least as effectively as the standard liner system. In addition, the alternative design is at least equivalent to the standard design for the majority of the other widely accepted technical criteria (Koerner and Daniel, 1993) presented in this analysis.

4. CONCLUSIONS

This analysis was performed to assess the equivalency of an alternative lining system as compared to the Subtitle C (40 CFR Part 264.221(c)) standard lining system for the evaporation pond. Equivalency was demonstrated by comparing design, construction, and operation criteria related to standard and alternative lining systems for the conditions and planned configuration of the evaporation pond. A summary of the analysis was presented in Section 3.

It has been shown that GCLs have many advantages over CCLs. These include better resistance to freeze-thaw cycles, better self-healing characteristics in wet/dry conditions, lower vulnerability to damage from differential settlement, easier and faster placement, no need for local soil materials, less need for construction water, and greater ease of quality assurance.

Furthermore, the alternative design will cost less than the standard design and provide a superior lining system, as has been demonstrated. Preliminary cost estimates (including elimination of the operations layer) indicates savings of $80,000 by implementing the alternative evaporation pond lining system design.

Although the alternative design incorporating the use of GCLs is not without limitations, the favorable properties of GCLs are sufficiently advantageous that the alternative lining system as presented herein has been demonstrated to be equivalent to the standard lining system for use in the evaporation pond lining system. Of particular importance are the operation and maintenance advantages of the alternative lining system. Key advantages of the alternative design include:

- A redundant composite primary liner system, which is more protective against leakage.
- The CCL component of the standard design cannot provide resistance to freeze/thaw cycles without potential compromise of performance and integrity, or without protective layers over the liners that would impair functionality or serviceability, or increase waste generation.
- The primary liner system can be readily accessed for maintenance and repair.
- There will be no contaminated soil requiring disposal either during periodic replacement of the operations layer or at the time of evaporation pond closure.
- Leakage from the primary lining system surface can be easily monitored and repaired as needed.

The alternative liner system, as a whole, is more protective and effective than the Standard Subtitle C liner. Therefore, the DOE-ID requests approval of the alternative design outlined in this EDF for use at the ICDF evaporation pond.

5. REFERENCES

40 CFR 264, 1999, "Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities," Subpart K, "Surface impoundments," *Code of Federal Regulations*, Office of the Federal Register, July 1999.

Boardman, B.T. and D.E. Daniel, 1996, "Hydraulic Conductivity of Desiccated Geosynthetic Clay Liners Subjected to Differential Settlement," *Journal of Geotechnical Engineering*, Vol. 122, No. 3, p. 204.

Bonaparte, R. and Gross, B.A., 1990, "Field Behavior of Double-Liner Systems," *Waste Containment Systems: Construction Regulation and Performance*, American Society of Civil Engineers, Geotechnical Special Publication No. 26, pp. 52-83.

Benson, C.H. and M.A. Othman, 1993, "Hydraulic Conductivity of Compacted Clay Frozen and Thawed In Situ. Journal of Geotechnical Engineering" Vol. 119, No. 2, p. 276.

Daniel, D. E. 1997, "Short Course Notes for Geosynthetic Clay Liners for Waste Containment," University of Illinois at Urbana-Champaign, February 17-18.

Daniel, D.E, 1993, "Geosynthetic Clay Liners in Landfill Covers," *31st Annual Solid Waste Solid Waste Exposition*, The Solid Waste Association of North America, San Jose, California.

Daniel, D.E. and R.B. Gilbert, 1993, "Short Course Notes for Geosynthetic Clay Liners for Waste Containment and Pollution Prevention," University of Texas at Austin, October 7-8.

Daniel, D.E., H.Y. Shan, and J. Anderson, 1993, "Effects of Partial Wetting on the Performance of the Bentonite Component of a GCL," *Proceedings of Geosynthetics*, Vancouver, British Columbia, Canada.

DOE-ID, 2000, "Performance Specifications for the ICDF and Evaporation Pond," SPC-332, Revision 0, November. U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.

DOE-ID, 2001a, "Slope Stability Assessments (Title I)," EDF-ER-268, Revision 0, July, U.S. Department of Energy Idaho Operations Office, Idaho Falls, Idaho.

DOE-ID, 2001b, "INEEL CERCLA Disposal Facility – Drawings (Draft Title I)," DOE-ID-10878, Revision 0, July, U.S. Department of Energy Idaho Operations Office, Idaho Falls, Idaho.

DOE-ID, 2001c, "Selection of K_d Values for INTEC Groundwater Modeling," EM-ER-010115, July, U.S. Department of Energy Idaho Operations Office, Idaho Falls, Idaho.

DOE-ID, 2001d, "Soil Amendment Study," EDF-ER-272, Revision 0, July, U.S. Department of Energy Idaho Operations Office, Idaho Falls, Idaho.

Estornell, P. and D.E. Daniel, 1992, "Hydraulic Conductivity of Three Geosynthetic Clay Liners," *Journal of Geotechnical Engineering*, Vol. 118, No. 10, p. 1,592.

Giroud, J.P. 1997, "Equations for Calculating the Rate of Liquid Migration Through Composite Liners Due to Geomembrane Defects," *Geosynthetics International*, Vol. 4, No. 3-4, pp. 335-348.

Giroud, J.P., and R. Bonaparte, 1989a, "Leakage through Liners Constructed with Geomembranes – Part I. Geomembrane Liners," *Geotextiles and Geomembranes,* Vol. 8, No. 1, pp. 27-67.

Giroud, J.P., and R. Bonaparte, 1989b, "Leakage through Liners Constructed with Geomembranes – Part II. Composite Liners," *Geotextiles and Geomembranes,* Vol. 8, No. 2, pp. 71-111.

Harpur, A., R. Wilson-Fahmy, and R.M. Koerner, 1993, "Evaluation of the Contact Between Geosynthetic Clay Liners and Geomembranes in Terms of Transmissivity," *Proceedings of the 7th GRI Seminar*, December 1993, Drexel University, Philadelphia, Pennsylvania.

Hewitt, R.D. and D.E. Daniel, 1997, "Hydraulic Conductivity of Geosynthetic Clay Liners After Freeze-Thaw," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 4, p. 305.

Kim, W.H. and D.E. Daniel, 1992, "Effects of Freezing on the Hydraulic Conductivity of a Compacted Clay" J*ournal of Geotechnical Engineering*, Vol. 118, No. 7, p. 1083.

Koerner, R.M. and D.E. Daniel, 1993, "Technical Equivalency Assessment of GCLs to Clay Liners," *Proceedings of the 7th GRI Seminar,* December 1993*,* Drexel University, Philadelphia, Pennsylvania.

Kraus, J.F., C.H. Benson, A.E. Erickson, and E.J. Chamberlain, 1997, "Freeze-Thaw and Hydraulic Conductivity of Bentonitic Barriers," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 3, p. 229.

LaGatta, M.D., B.T. Boardman, B.H. Cooley, and D.E. Daniel, 1997, "Geosynthetic Clay Liners Subjected to Differential Settlement," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 5, p. 402.

Rollin, A., M. Marcotte, T. Jacquelin, and L. Chaput. 1999, "Leak Location in Exposed Geomembrane Liners Using an Electrical Leak Detection Technique," *Geosynthetics'909 Conference Proceedings*, Vol. 2, IFAI, Boston, MA, pp 615-626.

Shan, H.Y. and D.E. Daniel, 1991, "Results of Laboratory Test on a Geotextile/Bentonite Liner Material," *Proceedings of Geosynthetics,* February 1991, Atlanta, Georgia.

Appendix A

Leakage Rate Calculations

ICDF Evap. Pond Lining System Equivalency Analysis
Leakage Rate Calculations
Geomembrane Liner - Primary Standard

Bernoulli's Equation for free flow through an orifice: $Q = C_B a\sqrt{2gh}$

Q =	Leakage Rate (m^3/s)
C_B =	dimensionless coeff; 0.6 for aperture with sharp edge
a =	area of single defect (m^2)
g =	acceleration due to gravity (m/s^2)
h =	liquid depth over geomembrane (m)

Per Giroud (1989)[a] - recommended hole size and frequency for design/performance evaluation:

Frequency: Assuming good CQA/CQC one hole per 4000 m^2 (acre)

Size:

For LCRS/Leak Detection Design (large hole):	1 cm^2 or	11.3 mm dia.
For Performance Evaluation (small hole):	3.1 mm^2 or	2 mm dia.

Liquid depth on Liner: 1.83 m Reference Dwg H-202; Avg.Max Depth
Considered Geomembrane Surface Area: 4000 m^2

Hole Descrip	Hole Area (m2)	Q (m3/s)	Q/A (m3/s/m2)	Q/A (gal/ac/day)
Large	1.0E-04	3.6E-04	9.0E-08	8325
Small	3.1E-06	1.1E-05	2.8E-09	261

Reference:
[a] J.P. Giroud and R. Bonaparte, "Leakage Through Liners Constructed with Geomembranes, Part I: Geomembrane Liners". *Geotextiles and Geomembranes,* Vol.8, No. 1, pp. 27-67. 1989.

ICDF Evap. Pond Lining System Equivalency Analysis
Leakage Rate Calculations
Composite Liner - Primary Alternative

Giroud (1997) Equation for flow through circular defect:

$$Q = n \times 0.976 \times C_q \times [1 + 0.1(h/t_s)^{0.95}] \times d^{0.2} \times h^{0.9} \times k_s^{0.74}$$

Q =	Leakage Rate (m^3/s)
n =	Number of defects per considered area
C_q =	contact quality factor
d =	diameter of circular defect (m)
t_s =	thickness of low-perm soil component (m)
h =	liquid depth over geomembrane (m)
k_s =	hydraulic conductivity of low-perm soil component (m/s)

Per Giroud (1989)a - recommended hole size and frequency for design/performance evaluation:

Frequency: Assuming good CQA/CQC one hole per 4000 m^2 (acre)

Size:

For LCRS/Leak Detection Design (large hole):	1 cm^2 or	11.3 mm dia.	0.0113 m
For Performance Evaluation (small hole):	3.1 mm^2 or	2 mm dia.	0.002 m

Liquid depth on Liner (h):	1.83 m	Reference Dwg H-202; Avg. Max Depth with 2 ft. freeboard
Considered Geomembrane Surface Area (A):	4000	m^2
Number of defects per area (n):	1	
Thickness of low-perm soil (t_s):	0.0064	m (= 0.25 in.)
Hydr. Cond. of low-perm soil (k_s):	5.00E-11	m/s
Contact Quality Factor (Cq) - Good:	0.21	
Contact Quality Factor (Cq) - Poor:	1.15	

Hole Descrip	Contact Quality	Q (m3/s)	Q/A (m3/s/m2)	Q/A (gal/ac/day)
Large	Good	7.7E-08	1.9E-11	1.8
Small	Good	5.5E-08	1.4E-11	1.3
Large	Poor	4.2E-07	1.1E-10	9.8
Small	Poor	3.0E-07	7.5E-11	6.9

Reference:

[a] J.P. Giroud, "Equations for Calculating the Rate of Liquid Migration Through Composite Liners Due to Geomembrane Defects". *Geosynthetics International,* Vol. 4, No. 3-4, pp.335-348. 1997.

[b] J.P. Giroud and R. Bonaparte, "Leakage Through Liners Constructed with Geomembranes, Part I: Geomembrane Liners". *Geotextiles and Geomembranes,* Vol.8, No. 1, pp. 27-67. 1989.

ICDF Evap. Pond Lining System Equivalency Analysis
Leakage Rate Calculations
Composite Liner - Secondary Standard

Giroud (1997) Equation for flow through circular defect:

$$Q = n \times 0.976 \times C_q \times [1 + 0.1(h/t_s)^{0.95}] \times d^{0.2} \times h^{0.9} \times k_s^{0.74}$$

Q =	Leakage Rate (m^3/s)
n =	Number of defects per considered area
C_q =	contact quality factor
d =	diameter of circular defect (m)
t_s =	thickness of low-perm soil component (m)
h =	liquid depth over geomembrane (m)
k_s =	hydraulic conductivity of low-perm soil component (m/s)

Per Giroud (1989)a - recommended hole size and frequency for design/performance evaluation:

Frequency: Assuming good CQA/CQC one hole per 4000 m^2 (acre)

Size:

For LCRS/Leak Detection Design (large hole):	1 cm^2 or	11.3 mm dia.	0.0113 m
For Performance Evaluation (small hole):	3.1 mm^2 or	2 mm dia.	0.002 m

Liquid depth on Liner (h):	0.005 m	Reference Giroud (1989) - liquid depth on secondary liner = LDS thickness (200 mils)
Considered Geomembrane Surface Area (A):	4000	m^2
Number of defects per area (n):	1	
Thickness of low-perm soil (t_s):	0.914	m (= 3 ft.)
Hydr. Cond. of low-perm soil (k_s):	1.00E-09	m/s
Contact Quality Factor (Cq) - Good:	0.21	
Contact Quality Factor (Cq) - Poor:	1.15	

Hole Descrip	Contact Quality	Q (m3/s)	Q/A (m3/s/m2)	Q/A (gal/ac/day)
Large	Good	1.6E-10	3.9E-14	3.6E-03
Small	Good	1.1E-10	2.7E-14	2.5E-03
Large	Poor	8.5E-10	2.1E-13	2.0E-02
Small	Poor	6.0E-10	1.5E-13	1.4E-02

Reference:

[a] J.P. Giroud, "Equations for Calculating the Rate of Liquid Migration Through Composite Liners Due to Geomembrane Defects". *Geosynthetics International,* Vol. 4, No. 3-4, pp.335-348. 1997.

[b] J.P. Giroud and R. Bonaparte, "Leakage Through Liners Constructed with Geomembranes, Part I: Geomembrane Liners". *Geotextiles and Geomembranes,* Vol.8, No. 1, pp. 27-67. 1989.

ICDF Evap. Pond Lining System Equivalency Analysis
Leakage Rate Calculations
Composite Liner - Secondary Alternative

Giroud (1997) Equation for flow through circular defect: $Q = n \times 0.976 \times C_q \times [1 + 0.1(h/t_s)^{0.95}] \times d^{0.2} \times h^{0.9} \times k_s^{0.74}$

Q =	Leakage Rate (m^3/s)
n =	Number of defects per considered area
C_q =	contact quality factor
d =	diameter of circular defect (m)
t_s =	thickness of low-perm soil component (m)
h =	liquid depth over geomembrane (m)
k_s =	hydraulic conductivity of low-perm soil component (m/s)

Per Giroud (1989)a - recommended hole size and frequency for design/performance evaluation:

Frequency: Assuming good CQA/CQC one hole per 4000 m^2 (acre)

Size:

For LCRS/Leak Detection Design (large hole):	1 cm^2 or	11.3 mm dia.	0.0113 m
For Performance Evaluation (small hole):	3.1 mm^2 or	2 mm dia.	0.002 m

Liquid depth on Liner (h): 0.005 m — Reference Giroud (1989) - liquid depth on secondary liner = LDS thickenss (200 mils)

Considered Geomembrane Surface Area (A):	4000	m^2
Number of defects per area (n):	1	
Thickness of low-perm soil (t_s):	0.0064	m (= 0.25 in.)
Hydr. Cond. of low-perm soil (k_s):	5.00E-11	m/s
Contact Quality Factor (Cq) - Good:	0.21	
Contact Quality Factor (Cq) - Poor:	1.15	

Hole Descrip	Contact Quality	Q (m3/s)	Q/A (m3/s/m2)	Q/A (gal/ac/day)
Large	Good	1.8E-11	4.6E-15	4.2E-04
Small	Good	1.3E-11	3.2E-15	3.0E-04
Large	Poor	1.0E-10	2.5E-14	2.3E-03
Small	Poor	7.1E-11	1.8E-14	1.6E-03

Reference:

[a] J.P. Giroud, "Equations for Calculating the Rate of Liquid Migration Through Composite Liners Due to Geomembrane Defects". *Geosynthetics International,* Vol. 4, No. 3-4, pp.335-348. 1997.

[b] J.P. Giroud and R. Bonaparte, "Leakage Through Liners Constructed with Geomembranes, Part I: Geomembrane Liners". *Geotextiles and Geomembranes,* Vol.8, No. 1, pp. 27-67. 1989.