COVERS

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APPENDIX A . Surface Barrier Degradation

GW Gee and AL Ward — 2004

Abstract

Surface barriers, consisting of vegetated soils and assorted sublayers, may be constructed and placed over as many as 200 waste sites at Hanford. These surface barriers, if effective, will isolate the general public from buried waste and limit surface erosion and minimize water and biotic intrusion into the waste. Over time, it is assumed that numerous forces, including wind, water, fire, drought, and seismic activity will act to degrade the barrier surface. This document describes key potential failure mechanisms and outlines several scenarios that could be used to simulate barrier degradation in long term assessments. The most probable failure mechanism is wind erosion resulting in sand dune formation, which can change surface texture and vegetation and result in increased recharge rates. In terms of recharge control, a surface barrier at Hanford may change from a very low recharge rate (< 0.1 mm/yr) to something more representative of a stabilized sand dune at the Hanford Site (e.g., 4 mm/yr or greater).

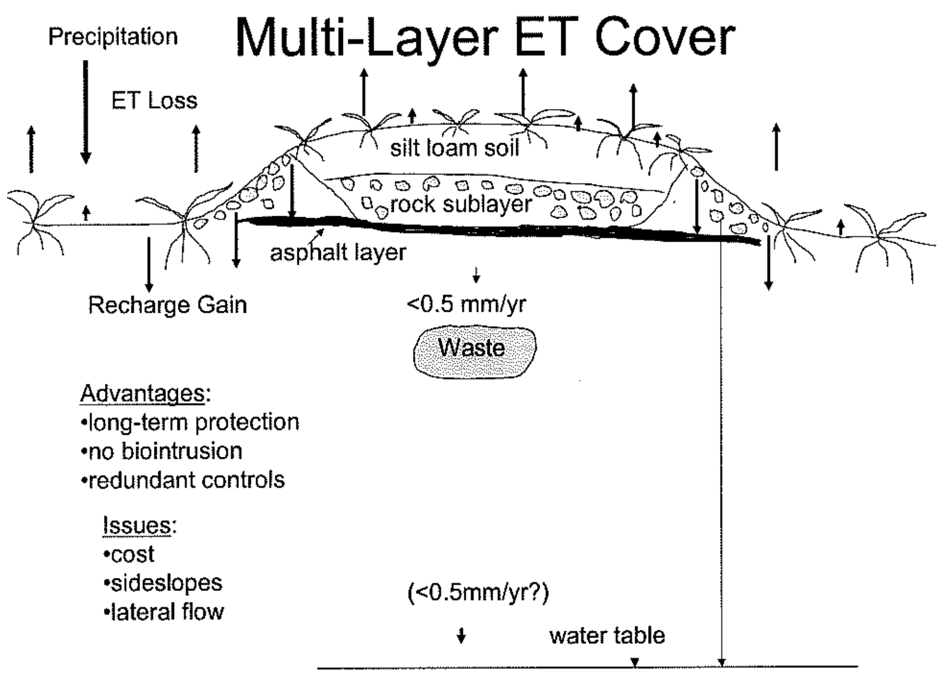
1.0 Introduction

In the mid 1980s the U. S. Department of Energy initiated a Barrier Development Program at the Hanford Site (see Appendix A). The purpose of the program was to develop a long-term barrier, capable of isolating waste for more than 1000 years. The barrier development program included 12 elements designed to address all aspects of barrier design and construction. These elements were:

- biointrusion
- water intrusion
- wind and water erosion
- physical stability
- material quality and quantity
- monitoring
- modeling
- prototype design and construction
- natural analogs
- climate change
- regulatory issues
- technical exchange

Field tests were initiated to test selected aspects of the long-term barrier and culminated in the design and construction of a prototype surface barrier (PSB), placed over the B-57 crib in the 200 BP-1 Operable Unit, adjacent to the BY tank farm in the 200 E Area at the Hanford Site. Over 130 reports and papers have been published to date, documenting various aspects of long-term barrier design, construction, and performance (see Appendix A). Figure 1 shows the general features of the Hanford prototype barrier designed for long-term (1000 year) protection.

Figure 1. Hanford Barrier designed for long-term (1000 year) protection of Hanford wastes.



Testing of the Hanford prototype barrier has successfully demonstrated that above-grade vegetated covers at Hanford act as a sponge, storing incident precipitation during wet (winter) periods and subsequently losing water by evapotranspiration (ET) during dry (summer) periods, thus minimizing water intrusion into underlying waste. In contrast, the sideslopes, built to engineering specifications (USDOE 1994), are designed to stabilize the barrier against wind and water erosion. Because they are coarse and mostly barren they allow significant water to infiltrate into subsurface sediments surrounding the waste (Ward and Gee 1997, Gee et al. 2002, Wittreich et al. 2003). The results from the Hanford barrier studies indicate that the complete barrier system, soil cover and sideslopes, must be understood to evaluate total barrier performance. In the final design of long-term barriers there may be tradeoffs between erosion control and water intrusion protection, as illustrated by the sideslope drainage measurements which have shown that

coarse sideslopes, used for erosion protection, can drain up to 20% or more of the annual precipitation (Wittreich et al. 2003).

Alternative Designs: In addition to the Hanford prototype barrier (Figure 1), other barrier designs have been proposed for Hanford (DOE 1997). Only the Hanford Barrier has been tested in full-scale prototype. However, some alternative covers have been tested in small lysimeters (Fayer et al. 1999). These include the so-called modified RCRA C cover. The modified RCRA C cover incorporates the low permeability (asphalt layer) layer of the Hanford Barrier but does not use the biointrusion layer, thus the total thickness is less than the Hanford Barrier and construction costs are correspondingly reduced. Monofill ET covers have also been proposed for use at Hanford. Figure 2 shows the general features of a monofill ET cover, which consists simply of a soil layer placed above the waste and vegetated with native plants. Sideslope issues that exist for all above-grade surface barriers will affect both the Modified RCRA C and the monofill ET cover. An alternative cover that has not been considered yet but has great potential for Hanford is what can be called the Shallow Liner ET Cover (Figure 3). This design eliminates sideslopes and biointrusion. and because these are two mechanisms that can aid to the degradation of surface covers, such design features should be seriously considered for placement at Hanford waste sites.

Figure 2. Simple ET cover, with silt loam soil (for optimal water storage) and native vegetation (shrub steppe) to enhance surface water loss.

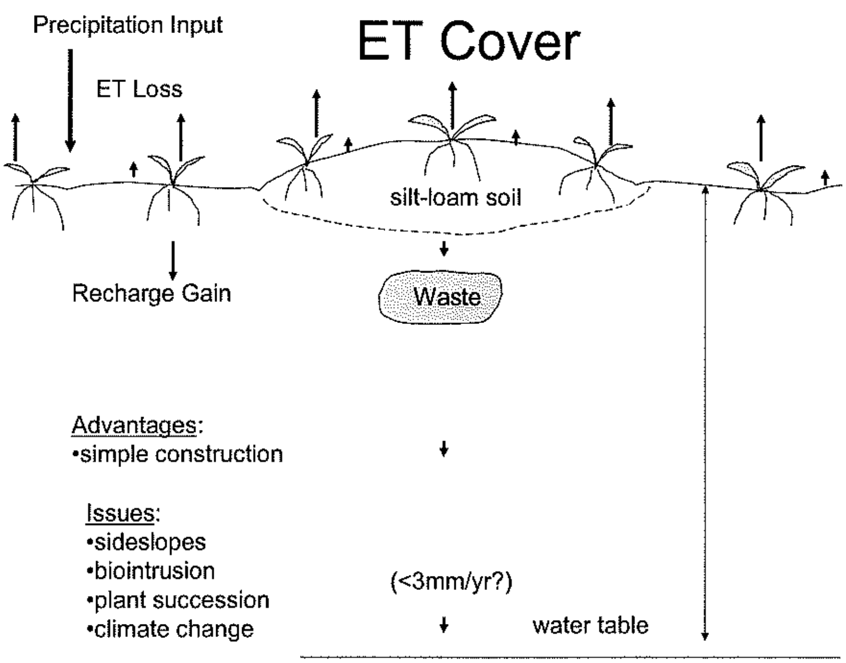
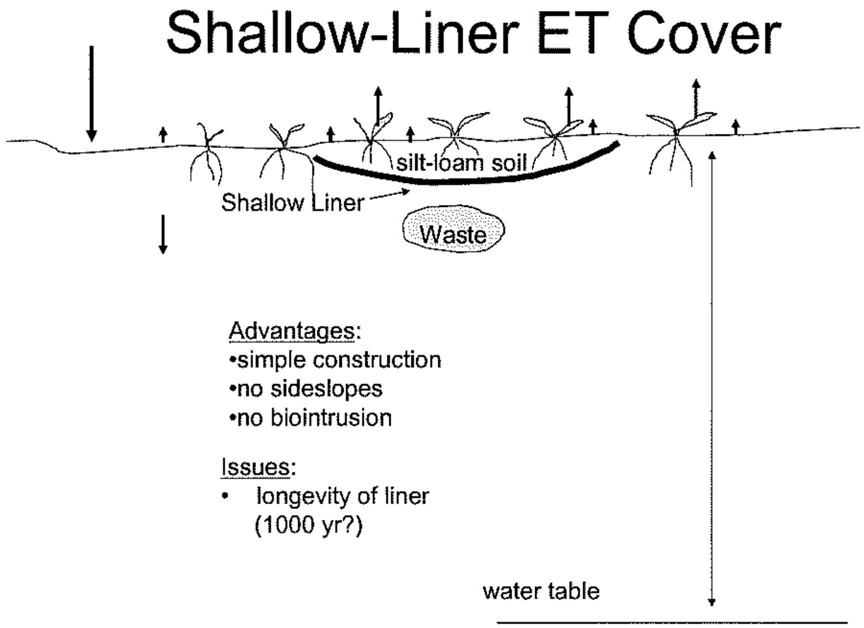


Figure 3. Shallow Liner ET Cover. Includes a low permeability (Geomembrane) below a silt loam surface to provide redundant drainage control, mimize biointrusion and eliminate sideslopes.



No systematic study of all surface barrier degradation mechanisms has been made to date. For example, the impact of sideslopes on net water infiltration into the waste has not been addressed in current designs of above grade surface barriers, nor previously factored into discussions of barrier degradation. The interaction of sideslope recharge, erosion control, depositional processes and impacts from fire, disease, etc. have not been systematically incorporated into a final design. In the following sections we attempt to describe the most reasonable and expected degradation (or failure) mechanisms for surface barriers at Hanford, including effect of wind erosion, biointrusion protection, and the impact of sideslopes on degradation on final barrier performance. We offer some alternative designs for improved sideslope performance, and provide several timelines for expected barrier degradation including estimates of overall net infiltration or recharge associated with final barrier performance, as a consequence of a specific design.

2.0 Barrier Degradation Assumptions. In recent numerical assessments, (such as the initial assessment performed with the System Assessment Capability (SAC) (Bryce, et. al. 2002) it was assumed that there were two kinds of barriers; 1) A long-term (1000 year) barrier used primarily for tank farms and transuranic (TRU) waste sites and 2) A 500 year barrier, used for solid waste landfills and other low-level waste sites at Hanford. There have been no specific degradation mechanisms specified but for the initial assessment performed with SAC, the following assumptions were made about performance and recharge rates.

2.1 Long-term,1000-year barrier. This barrier was assumed to perform optimally (0.1 mm/yr) for 1000 years. After 1000 years, the barrier was assumed to degrade (by a combination of unspecified failure mechanisms) to a pre-operations recharge level specified by the soil type that existed prior to the waste-site construction. The degradation was assumed to take place in 5 equal steps of 200 years over the next 1000 years. For example, if the pre-operations recharge level was 2 mm/year, the following scenario was assumed:

1) Year 0 to 1000 – recharge rate = 0.1 mm/yr
2) Year 1001 to 1200-recharge = 0.4 mm/yr
3) Year 1201 to 1400-recharge = 0.8 mm/yr
4) Year 1401 to 1600- recharge = 1.2 mm/yr
5) Year 1601 to 1800- recharge = 1.6 mm/yr
6) Year 1801 to 2000- recharge = 2.0 mm/yr

2.2 The 500-year barrier. This barrier was assumed to perform optimally (0.1 mm/yr) for 500 years. After 500 years, the barrier was assumed to degrade (by a combination of unspecified failure mechanisms) to a pre-operations recharge level specified by the soil type that existed prior to the waste-site construction. The degradation was assumed to take place in 5 equal steps of 100 years over the next 500 years. For example, if the pre-operations recharge level was 2 mm/year, the following scenario was assumed:

1) Year 0 to 500 -recharge = 0.1 mm/yr
2) Year 501 to 600 -recharge = 0.4 mm/yr
3) Year 601 to 700 -recharge = 0.8 mm/yr
4) Year 701 to 800 -recharge = 1.2 mm/yr
5) Year 801 to 900 -recharge = 1.6 mm/yr
6) Year 901 to 1000-recharge = 2.0 mm/yr

These stepwise degradation assumptions were made purely to simplify the modeling and do not represent any actual degradation responses. They are considered conservative assumptions, in that degradation processes are generally slow, though some catastrophic events such as floods, drought and related climate change events can cause rapid alteration of the landscape and in fact extreme dynamics are responsible for much of the geologic setting for Hanford (Baker et al. 1991, Bjornstad and Teel 1993, Gaylord and Stetler 1994, Peterson et al. 1993). Prediction of the exact timing of degradation is

virtually impossible, so the stepwise degradation assumptions are as reasonable as any other alternatives.

Other recent assessments (such as the ILAW performance assessment [reference]) have assumed that the barrier disappears at the end of its design life.

3.0 Potential Degradation Mechanisms. This section describes degradation mechanisms that could affect surface barriers placed over Hanford waste sites.

3.1. Wind deposition The most likely mechanism for long-term degradation of a barrier at Hanford is wind induced sand-dune formation (sand deposition). Studies by Gaylord et al. (1993); Gaylord and Stetler (1994) demonstrate that most of the surficial soils at Hanford are eolian (wind blown) in nature, with about half of the Hanford Site exposed to or covered by stabilized or active dunes. Active and stabilized dunes have their highest densities in areas to the south and east of the 200 Areas, while some stabilized dunes are located in the 200 E area. All soils in the 200 Areas are covered with a mantle of windblown sand material (Gaylord and Stetler 1994). For long-term considerations, all surface covers are assumed to be affected in some way by wind action. When vegetated, the soil surface is generally stabilized against wind erosion. However, there are local changes to microrelief because of wind action that can affect water storage and other surface properties. Coppice dunes are found extensively at the Hanford Site. These miniature dunes consist of fine sands deposited around shrubs, creating small mounds (hummocks) elevated 0.5 m or more above surroundings. The intermound (or swale) is a depression that is often sparsely vegetated and has different water-storage capacity than that found on the hummock. At one coppice dune site near the Yakima Barricade, west of the 200 Areas at Hanford, Link et al. (1994) found that water storage was strongly associated with vegetation patterns and that actual water storage was inversely correlated with vegetation, suggesting the greater the plant density the lower the available water in the soil profile, consistent with our ET cover concepts. An irrigation treatment demonstrated that all of the rainfall and irrigation water was consumed (transpired) by plants at this coppice dune site. Soil texture was coarser in the top 0.5 m of the hummock than in the swale but vegetation density was greatest on the hummock. It is entirely possible that as coarser soils accumulate, that water storage capacities will actually decrease, with corresponding decreases in vegetation density and conversion from deep-rooted vegetation to shallow rooted vegetation. Coppice dunes are complex systems and illustrate the dynamic nature of the soil surface in the Hanford environment. It is most likely that changes similar to coppice dune features will develop on even the most stable cover under the present Hanford climatic regime. Initially, this change may not directly impact barrier drainage rates, but features like coppice dunes are a precursor to larger accumulation of sands over time and the subsequent change from shrub vegetation to sparse grasses as observed on a significant portion of the Hanford Site (Gaylord and Stetler 1994). Based on these observations, it is likely that engineered surface barriers will change from well-contoured surfaces to surfaces with significant microrelief (hummocks and swales) and finally to more extensive stabilized dunes in the next 1000 years or more.

A possible scenario for wind action on the surface barrier is as follows:
1) Year 1 (barrier placement) to year 500. Barrier performance as specified (<0.1 mm/yr)
2) Year 501 to year 1000. Development of stabilized dunes – linearly degrades to 4 mm/yr of average recharge. This rate is based on recharge estimates of stabilized dunes obtained from chloride mass balance data of Murphy et al (1996).
3) Year 1001 and beyond. Surface barrier is assumed to behave like a stabilized sand dune. (Recharge assumed to be 4 mm/yr). It should be noted that the chloride mass balance method apparently predicts recharge reliably in the very low (< 1 mm/yr) range but there is less certainty when the recharge is above a few mm/yr (Prych 1995, Tyler et al. 1999), so a sand-dune recharge rate of 4 mm/yr may not be conservative and likely will have to be updated in the future, as more reliable results are obtained.

3.2. Water erosion. Studies conducted at the Hanford prototype surface barrier (PSB) have demonstrated that little if any runoff or surface erosion has occurred over the 9 years of monitoring of the surface barrier (Gee et al. 2002, Wittreich et al. 2003). The low grade on slopes for the soil cover plus the well-established vegetation has minimized any water erosion on the PSB. There is no evidence that water erosion would cause any significant barrier degradation at the Hanford site. Runoff occurs primarily in winter or early spring when soils are frozen and when snowmelt occurs rapidly due to warm (e.g., chinook) winds (Skaggs and Walters, 1981; Gee and Hillel 1988). For soils on gentle slopes with well-established vegetation, runoff is accompanied by little or no sediment loss. The lack of evidence for water erosion allows us to assume that there will be no changes in recharge rate due to any plausible water erosion scenario.

3.3. Biotic intrusion. There is ample evidence that biotic (plant and animal) intrusion has occurred at waste sites at Hanford in the past (Dabrowski 1973; O'Farrell and Gilbert 1975, Landeen and Mitchell 1982; Marshall 1987). Deep-rooted tumbleweed (*Salsoa kali)* has a tap root that can penetrate to depths of 5 meters or more in the sandy soils and backfill sediments at Hanford. Dabrowski (1973) describes waste sites near the Columbia River in the 100 Areas where tumbleweeds intruded in to wastes containing Cs-137 and Sr-90. Uptake of Sr-90 caused the plants to become radioactive. The radioactive tumbleweeds created problems, because as they aged, some were blown off the waste site, thus becoming an undesirable biotic vector. Ants and burrowing insects, small (pocket mice and gophers) and large mammals (badgers) also have been observed to intrude into wastes and bring contaminants to the surface where they have been scattered to locations some distance from the waste sites (O'Farrell and Gilbert 1975; Cline et al. 1980; Landeen and Mitchell 1982, Kennedy et al. 1985). A waste site, called the BC Cribs, located to the south of the 200E Area, has documented widespread surface contamination, attributed to biotic intrusion. In the 1950s, a badger hole was found at one of the BC cribs, which contained near-surface contamination (Sr-90 and Cs-137). The badger likely foraged for mice in contaminated soil. Jackrabbits then used the burrow and became contaminated (O'Farrell and Gilbert 1975). Coyotes and raptors subsequently ate the jackrabbits and spread the contamination over a wide area (more than several hundred hectares). Similar situations have been observed at the Idaho National Laboratory, near Arco, Idaho (Arthur and Markum 1983; Arthur et al. 1987). While such intrusion is possible, particularly at waste sites with surface spills or with

otherwise near-surface contamination, a properly designed surface cover will limit biotic intrusion. Features to prevent biotic intrusion were incorporated into the design of the Hanford surface barrier. These features included a sublayer of coarse rock designed to discourage digging (see Cline and Rogers 1982) and an asphalt layer that is impervious to water, small mammals and burrowing insects (Myers and Duranceau 1993, Wing and Gee 1994). An asphalt layer is placed below the rock layer, providing a redundancy that limits not only biotic intrusion (including both plant root and animal intrusion into underlying wastes) but prevents water intrusion as well. For ET cover systems with no rock or asphalt sublayers, the possibility of biointrusion remains. However, in the final barrier design for all waste sites at Hanford, we assume that some kind of biotic intrusion protection will exist and that borrowing animals will be confined to the near surface (top meter of soil) and their presence does not create pathways for water intrusion. This assumption is supported by the work of Landeen (1994) who demonstrated that pocket mice burrows acted much like vent tubes, allowing for advective drying of the near surface soils thus reducing the actual water content in the profile during the summer months and subsequently increasing the actual storage capacity of the soil. Based on past biointrusion studies we conclude that biotic transport can be minimized with a properly designed surface barrier and that water intrusion will not be enhanced. The most probable scenario for biotic intrusion then is to assume that it is minimal and that water intrusion is not affected by biotic vectors, so the recharge impact is zero from biotic intrusion.

3.4. <u>Fire, plant succession and associated wind erosion</u>. A concern about relying on evapotranspiration (ET) for water removal is the dynamic nature of the vegetation. At Hanford, a key component of any reliable surface barrier will be a vegetated surface. Periodic fires can remove the vegetation in dramatic and often catastrophic fashion. Wildfires have occurred periodically at Hanford. Two of them, one in 1984 and one in 2000, each burned over 160,000 acres leaving large portions of the landscape temporarily barren (Link et al 1990, Gee et al. 1992a). The 2000 fire occurred in late June, when understory vegetation (primarily cheatgrass) had senesced (died) and was tinder dry. The fire, started by an auto accident on Highway 24, quickly spread to the Hanford Site, jumping Highways 24 and 240 and burning most of Rattlesnake Mountain and part of Benton City, in addition to spreading onto and around the 200 Areas. The removal of almost all vegetation from the western perimeter of the 200 W Area on to the top of Rattlesnake Mountain left the land surface in that area vulnerable to wind erosion, which did occur. The surface soil in this area has a fine sand texture, which is highly susceptible to wind erosion. It was enough of a problem that tank farm operations were periodically curtailed because of blowing sand and dust. Subsequently, a windbreak, consisting of a double row of 1500-trees (Australian willow), was emplaced along the western boarder of the West Area to protect buildings, vehicles and personnel from sand blasting and dust inhalation. Irrigation of the windbreak was initiated in the summer of 2001 and is continuing because trees do not survive in the Hanford environment without supplemental irrigation (Gee et al. 2002). In addition to the tree placement and irrigation, other measures, including straw mulching were implemented to lessen the impact of bare surface exposures or wind erosion. By the spring of 2003, the surface has stabilized by natural revegetation, so that little erosion, if any, has occurred for the past two years. This

is consistent with the observations made by Link et al. (1990), who demonstrated that after the 1984 fire that plants on the Arid Land Ecology (ALE) Reserve recovered sufficiently to actively remove stored water from the soil profile in a fashion similar to pre-fire conditions. The effectiveness of the plant water uptake was such that after two years there were no marked differences between unburned and burned sites. The data of Link et al. (1990) clearly demonstrate that for silt loam soils, the effect of fire is temporary and recovery is rapid. For most, if not all of the Hanford Site, it would be expected that the no significant impact should occur, particularly when the soils are fine-textured with significantly large storage capacities. It should also be noted that wind erosion occurs from silt loam soils, only if they are very dry and highly disturbed. Vegetation tends to anchor the finer (silt loams) soils so that they are far less susceptible to wind erosion than coarse soil (e.g., fine sands). Based on these observations, we conclude that fire may have a temporary impact on surface barriers, but with fine soil (silt loam) dominating the surfaces, that recovery of vegetation is rapid and the impacts from fire can be considered negligible.

3.5. Drought and plant succession. Another concern with surface barriers is the potential for extended drought followed by elevated precipitation (wet climate) conditions. In such a scenario, the excess (or elevated) precipitation would either be incident on the soil surface and runoff or be infiltrated into the soil. For coarse soils the lack of vegetation would allow drainage while for fine soil drainage would be contained in the soil for subsequent use by plants (ET). Drought in the current shrub-steppe environment often leads to fire, so much of the discussion on fire and plant succession hold for this case of drought. There are no data to show performance of a cover under an extreme drought or extended period (multiple years) of dryness. Clearly vegetation would be affected. While much of the shrub-steppe has been altered by fire, the most dramatic thing is the potential conversion of the shrub-steppe vegetation, where deep-rooted shrubs dominate the vegetation type, to cool-season, shallow-rooted grasses (e.g., *bromus tectorum* or cheatgrass) thus reducing the water storage capacity of the soil by virtue of the change in both rooting depth and plant phenology (life cycle), such that less water can be lost from the soil by transpiration over time. The famous ecologist, Leopold (1966), described the process of converting the western U. S. native shrub-steppe vegetation to cheatgrass prairie through a succession of fires. Invasion of cheatgrass perpetuates itself. After senescence, cheatgrass stalks and heads acts like dry tinder. When a fire starts (via lightning strike or man) the fuel is the dead cheatgrass, which burns rapidly, destroying the shrubs. Regeneration of the shrubs requires a seed source and the seeds in turn must compete with cheatgrass for a limited water supply in fall and winter. The cheatgrass acts much like winter wheat, germinating in the fall, going dormant in winter, then sprouting in full vigor in early spring. It generally out-competes its rivals for water so that many shrub seedlings do not survive and the cheatgrass becomes the dominant plant species in a fire-swept steppe country. The process repeats itself until the cheatgrass dominates the entire landscape. It is entirely possible that over time much of the Hanford Site landscape could become cheatgrass dominated. The impact on coarse soil sites would be dramatic since water storage will change and more drainage and recharge will result. Increased recharge has been observed at Hanford where the coarse soil shrub-steppe landscape has been converted from shrub-steppe to grassland (Prych 1995, Fayer

and Walter 1995). A fire-affected site near the 300 Area, with a fine sand over coarse (Burbank loamy sand) soil, transitioned from shrub-steppe to grassland (bluegrass and cheatgrass). The estimated recharge rate was 25 mm/yr, as obtained from neutron-probe monitoring (Fayer and Walter 1995) while at this same site Prych (1995) used chlorine-36 analysis to estimate a recharge rate of about 5 mm/yr. This compares to shrub-steppe recharge rate estimates that are generally much less than 1 mm/yr (Prych 1995 and Murphy et al. 1996).

In contrast, where soils are fine textured (e.g., silt loams), there appears to be little impact on the recharge with this vegetation change, since the soil water storage is sufficient to contain the water, hold it near the surface long enough that both soil evaporation and plant transpiration act to remove it. Studies at the Field Lysimeter Test Facility near the Hanford Meteorological Station (HMS) have demonstrated that 1-m thick silt loam soils, void of any vegetation, are entirely capable of losing all of the annual precipitation via evaporation. Data collected for over a period of 12 years (Fayer et al. 1999) indicated that there has been no drainage from bare, silt loam soil data, suggesting that fire and subsequent vegetation changes, will have little or no effect on the drainage from a silt-loam surface-barrier. Based on these observations we assume that fire will not adversely impact the barrier performance but may impact the surroundings by increasing the recharge in surrounding areas where there are coarse soils dominated by cheatgrass or similar shallow-rooted plants.

3.6. Other Mechanisms. Other mechanisms for barrier degradation include subsidence, human intrusion and climate change. These mechanisms were considered in the Hanford barrier development program.

Subsidence or surface collapse is associated with consolidation of wastes (e.g., collapse of waste containers, etc., general settlement of surficial materials after backfilling operations or response to seismic events). While subsidence can affect the integrity of a capillary barrier and the impermeable asphalt by differential settlement, the assumption was made that stabilization of the wastes with grout injection, dynamic compaction or other means could minimize effects of consolidation at most waste sites. The Hanford prototype barrier has been studied for nearly 10 years and tested for consolidation and surface stability. Civil surveys indicate that the surfaces have remained stable for the first decade after construction (Wittreich et al. 2003) with little indication of settlement even on the 2:1 rock sideslopes. Based on these findings it is assumed that stable surfaces can be achieved and that subsidence will not be a major degradation mechanism for most of the Hanford waste sites. Where there are buried objects such as empty metal tanks, wooden boxes and building with large void spaces, special consideration will have to be given to address consolidation effects on barrier performance. In principle, technologies such as dynamic compaction and grout injection can be used to minimize subsidence effects.

Inadvertent human intrusion is a possible scenario but warning markers identifying no-dig zones at the wastes sites have been proposed for the Hanford waste sites (Adams and Wing 1986) and if such markers were used it would lessen the chance for inadvertent

intrusion. It could be envisioned that after loss of institutional control, that deliberate removal of an entire surface barrier is possible since the surface cover is always exposed and vulnerable. However, the likelihood of such a scenario of cover removal appears remote, particularly if the warning and marker systems are used.

Climate change on the other hand is entirely possible and was considered in the barrier development program. One scenario would be for Hanford to experience a wetter, cooler climate, which could increase the chance for water storage to be exceeded. Paleoclimate studies suggest that if the past were a indicator of the future that change to a wetter and cooler environment would produce at most a 30% increase in the precipitation over the long-term (Wing et al. 1995). In the design of the Hanford barrier, a doubling of precipitation was assumed to be the upper limit of precipitation for 1000-year performance (Myers and Duranceau 1994). Studies at the Hanford Prototype surface barrier indicated that applications of 1000-year-storm events and precipitation elevated to 3 times the annual average value caused less than 0.2 mm of drainage in 3 years of testing at rates of 480 mm/yr or three times the annual average rate (Gee et al. 2002a, Wittreich et al. 2003). Based on these observations, we assume that the human intrusion and climate change scenarios will not significantly impact the recharge rates for surface barriers at Hanford.

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4.0. Sideslope Impacts on Degradation. Sideslopes can have a huge impact on surface barrier performance. As demonstrated by the Hanford surface barrier tests, sparsely covered gravel and rock sideslopes, while effective in eliminating wind and water erosion, add drainage water to the areas surrounding the soil cover. Sideslope drainage can be as much as 20% or more of the annual precipitation (Gee et al. 2002a; Wittreich et al. 2003). While advective drying reduces the drainage rates, particularly on steep rock sideslopes, they still contribute a large portion of the total recharge, particularly when the waste areas are small and the ratio of the sideslope area to the total area is large. For sites with dimensions less than 100 m on a side the sideslope area can be 40% or more of the total area when the sideslopes have 5:1 (horizontal: vertical) dimensions or less. The contribution of the total recharge then becomes dramatically weighed toward the recharge rate of the sideslopes. For many of the proposed waste sites in the 200 Areas at Hanford, which have deep underlying water tables, the added water from the sideslopes can percolate into the subsurface and carry contaminants to groundwater. Degradation of stabilized, armored sideslopes is not expected under any of the probable scenarios, except in the case of sand-dune formation. Under such a scenario, the sideslope drainage would be reduced to the drainage rate of the sand dune material and attendant vegetative cover. Improvements over present sideslope design might include terracing and additions of fine materials trenched into the sideslopes to improve water holding capacity and provide adequate rooting media for native plants. If such schemes were employed it is possible that recharge rates could be reduced to values comparable to the soil cover but such schemes have not yet been demonstrated.

6.0. Timelines for Barrier Degradation. Timelines for drainage from 500 year and 1000 year barriers are listed in Table 1. The tables assume that sand dune formation is responsible for barrier degradation and increases the recharge over time. It is assumed

that the dune develops sooner on the 500-year-barrier but ends up at the final recharge rate at the same time as the 1000 year barrier. This assumption is tied solely to differences in climate effects that cause the sand dune formation (for the 500 year barrier scenario the sand dune forms sooner and expresses its full impact sooner than on the 1000 year barrier). The final rate for both barriers in 2000 years is assumed to be 4 mm/yr, a rate observed by Murphy et al. (1996) on a stabilized sand dune at Hanford. It should be noted that this rate may not be conservative, because it was estimated from chloride mass balance techniques, which become insensitive at rates much above a few mm/yr (Tyler et al. 1999). Also, higher recharge rates have been observed on stabilized soils that are vegetated (Fayer and Walters 1995). Selected barrier performance is illustrated in Table 2, where the final drainage rates for various covers are listed along with the probabilities of a number of degradation factors.

Table 1. Drainage rates (in mm/yr) for 500-year and 1000-year surface barriers, assuming an initial recharge rate of 0.1 mm/yr and a final recharge rate of 4 mm/yr after 2000 years.

Time (yrs)	**500 year barrier**	**1000 year barrier**
Present	0.1	0.1
+500	0.1	0.1
+600	0.4	0.1
+700	0.8	0.1
+800	1.2	0.1
+900	1.6	0.1
+1000	2.0	0.1
+1200	2.4	1.5
+1400	2.8	2.5
+1600	3.2	3.0
+1800	3.6	3.5
+2000	4.0	4.0

Table 2. Degradation Factor Probabilities (High, H; Medium, M; Low, L) for selected landfill covers at the Hanford Site.

Factors	**Multilayer Hanford**	**Modified RCRA C**	**Monofill ET**	**Shallow Liner ET**
Wind deposition	H	H	H	H
Water erosion	L	L	M	L
Biointrusion	L	L	H	L
Human intrusion	L	M	H	L
Subsidence	L	L	M	L
Fire	L	L	M	L
Drought	L	L	M	L
Sideslope impacts	H	H	H	L
Climate change	M	M	H	M

Final Recharge (mm/yr)	4	4	>4	<4

7.0 Summary and Conclusions. Wind and water erosion, biointrusion, fire, drought, subsidence, human intrusion and climate change were considered as possible barrier degradation mechanisms. In addition, sideslope water-intrusion was considered in light of its potential effects on overall barrier performance. The most plausible degradation mechanism for the Hanford Site is wind erosion, causing sand dune formation. Timelines of degradation were developed which assumed that the final barrier will be covered with a dune that drains at the rate of ~4 mm/yr. It is possible that higher rates may develop on barriers covered with sand dunes but such rates have yet to be documented.

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