Performance of a Surface Barrier for Waste Isolation and Flux Reduction at the Hanford Site - 16099

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ABSTRACT

Based on the knowledge gained from a decade of laboratory, field, and numerical studies, the Prototype Hanford Barrier (PHB) was designed and constructed between late 1993 and late 1994 over the 216-B-57 Crib in the 200-BP-1 Operable Unit at the Hanford Site. The PHB has been monitored since 1994 to evaluate the physical, hydrologic, and ecological performance. Two stress tests were carried out in the past: 1) an enhanced (about 3 times the multi-year average of 160 mm/year) precipitation test from water year (WY) 1995 to WY1997, which included simulated 1000-year return, 24-hour rainstorms in March of each year, and 2) a controlled fire test in 2008. The purpose of this article is to present the main findings of the PHB demonstration since 1994. From 1994 to 2013—during which time the barrier experienced 3 years of enhanced precipitation, three 1000-year return, 24-hour simulated rainstorms, and a controlled fire—the PHB limited drainage to well below the 0.5 mm yr-1 design criterion and had minimal erosion. Although the test period represents only 2% of the design life, the observations suggest the PHB is robust enough to control drainage and isolate subsurface contaminants. Future barrier performance will depend on barrier stability and hydrology. Given the 19-year record of successful performance and considering all processes and mechanisms that could degrade barrier stability and hydrology in the future, the results suggest that the PHB is very likely to perform for at least the remainder of its 1000-year design life. This conclusion is based on two assumptions: 1) the exposed subgrade receives protection against erosion and 2) institutional controls prevent inadvertent human activity on the barrier. The findings at the PHB are useful for the design and monitoring of future surface barriers at Hanford and elsewhere.

INTRODUCTION

The Hanford Site is located in a semi-arid region of southeastern Washington State along the Columbia River and is approximately 1517 square kilometers (586 square miles) in size. From the early 1940s to approximately 1989, the site's mission included defense-related nuclear research, development, and weapons production activities. The mission of the Hanford Site since 1989 has been environmental remediation, focused on cleaning up waste sites and remediating contaminated soils and groundwater.

Potential remedial technologies were screened based on their effectiveness, implementability, and cost. Engineered surface covers (termed surface barriers in this paper) were identified and considered applicable to sites with radionuclides, heavy metals, inorganic compounds, and/or organic compounds. Surface barriers can be effective in minimizing 1) infiltration of precipitation into contaminated soil, thereby minimizing the driving force for downward migration of contaminants; 2) migration of windblown dust that originates from contaminated surface soils; 3) penetration of biota into the waste zone; 4) potential for direct exposure to contamination; and 5) the migration of volatile organic compounds and tritium to the atmosphere.

Conventional surface barriers or covers are often constructed of compacted clay, geomembranes, geosynthetic clay liners, or combinations of these materials. Multiple lines of evidence (including field studies, laboratory studies, and monitoring data) show that many existing conventional covers fall short of the low-conductivity targets. The conventional compacted barrier may suffer problems such as increasing permeability with time [1, 2], preferential flow path development within the barrier [3], and cracking because of desiccation [4]. Secondary permeability may develop in unprotected clay liners and covers as a result of wetting and drying, freezing and thawing, and deformation processes [5].

An alternative is the evapotranspiration (ET) barrier, which utilizes two natural processes, a different mechanism from that of the conventional barrier, to control infiltration into the underlying waste zone: the soil provides a natural water reservoir for precipitation and natural evapotranspiration empties the soil water reservoir. According to U.S. Environmental Protection Agency (EPA) [6], ET barriers are increasingly being considered for use at waste disposal sites.

For long-term performance of barriers, additional features are often added to a barrier. The storage capacity of an ET barrier can be enhanced by including a capillary break (CB) beneath the storage layer [7-9]. An ET barrier with a CB is referred to as an evapotranspiration-capillary (ETC) barrier hereafter. Additionally, including a proper amount of gravel in the storage layer can significantly reduce the erodibility of an ET or ETC barrier, but has little impact on the storage capacity and plant growth. A rock layer or pit-run gravel layer can be used to protect the side slope and for structural stability. The alternative ET or ETC barriers generally can perform very well in arid and semiarid regions [3, 7-10].

Surface cover designs have been tested at many locations, but the test durations have typically been limited to a few years. In 1998, the EPA initiated the Alternative Cover Assessment Program (ACAP) to develop field-scale performance data for multiple cover systems located at 12 sites around the country [3], but the intent of ACAP was to monitor the sites for only 5 years.

The multi-year barrier development program was conducted to develop, test, and evaluate the effectiveness of various barrier designs. The Prototype Hanford Barrier (PHB) was constructed between late 1993 and 1994 over the 216-B-57 Crib in the 200-BP-1 Operable Unit and included multiple instruments to facilitate rigorous testing. The purpose of the PHB demonstration was to evaluate surface barrier constructability, construction costs, and physical and hydrologic performance at field scale. The key performance objectives for the PHB [11] were as follows:

- Function in a semiarid to sub-humid climate
- Have a design life of 1000 years
- Limit drainage through the silt loam barrier to less than 0.5 mm yr^{-1}
- Limit runoff
- Be maintenance free
- Minimize erosion
- Meet or exceed Research Conservation and Recovery Act (RCRA) performance criteria

Monitoring and data collection at the PHB began in October 1994 and continues today. The purpose of this paper is to summarize the performance of PHB from 1994 to 2013. PHB performance is evaluated in three aspects: 1) hydrological performance based on data within, below, and around the barrier; 2) mechanical stability based the settlement of the barrier subgrade, elevation change of the barrier surface, and displacement of the riprap slope; and 3) the vegetation community and animal activities.

METHODS AND MATERIALS

This section briefly summarizes the study approaches and methods used to test the performance of the PHB.

Climate

The Hanford Site has a steppe (semi-arid) climate with typical dry, hot summers and cool, wet winters [12]. Under the Hanford climate, most of the precipitation (P) available for recharge comes between November and March (termed the winter season), when ET is low [13, 14]. In addition to winter rains, snowmelt can be an important contributor to recharge. Vegetation consists of shrub-steppe plant communities composed of annual grasses and perennial grasses and shrubs [15]. This shrub-steppe vegetation, a mixture of shallow- and deep-rooted plants, generally uses soil water very efficiently from roughly April to October (termed the summer season). To be consistent with the precipitation pattern, a water year (WY) is defined as the 12-month period from November to October. As such, a WY consists of a 5-month winter season and a 7-month summer season. A specific WY is denoted by “WYyy,” in which “yy” is the last two digits of a year. For example, WY1999 is denoted by WY99 and WY2000 by WY00. Subscripts “a,” “w,” and “s” denote a WY, winter season, and summer season, respectively, while a superscript “avg” denotes the average of a variable. The WY meteoric precipitation at the Hanford Site has an average, P^{avg}, of 171.3 mm and varies from 101.4 mm ($0.59P^{avg}$) to 293.6 mm ($1.71P^{avg}$). On average, 58.7% (100.6 mm, P_w^{avg}) of the precipitation falls in the winter season and 41.3% (70.7 mm, P_s^{avg}) falls in the summer season. During the barrier test period of WY95 to WY13, the average precipitation was 185.1 mm yr^{-1}, slightly higher than the long-term average.

The average recharge rate to the subsurface beneath undisturbed natural vegetation at Hanford is usually no more than 5.0 mm yr^{-1} [16]. However, when there is no vegetation, the recharge can be as high as 50 to 100 mm yr^{-1}, depending on the texture of the surface soil. A coarser surface soil tends to produce higher recharge.

Barrier Design

The PHB consists of four main components (Fig. 1): 1) a silt loam ET layer with an underlying CB and an intrusion prevention layer, termed the evapotranspiration-capillary, or ETC, barrier, in the middle; 2) a 10:1 gentle pit-run gravel side slope to the west; 3) a 2:1 steep basalt riprap side slope to the east; and 4) an asphalt concrete (AC) layer with a polymer-modified fluid applied asphalt (FAA) coating and a compacted soil layer at the bottom. The ETC barrier is the centerpiece of the PHB and sits directly above the waste zone (Fig. 1). It is designed to store precipitation and release the stored water into the atmosphere and to deter intrusion by plants, animals, or humans from barrier surface. The two side slopes protect the ETC barrier from damage or intrusion. The AC layer is the redundant barrier to divert drainage and to hinder intrusion from the sides.

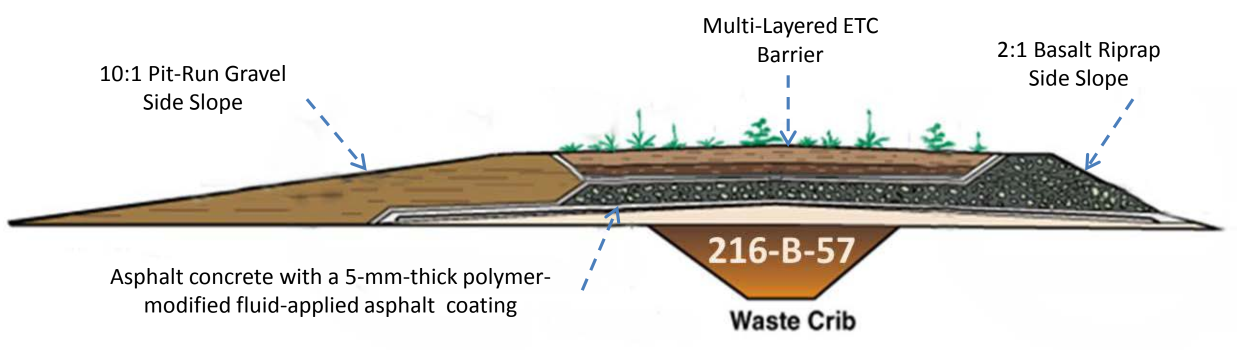

Fig. 1. Prototype Hanford Barrier Cross-Section.

Barrier Tests Conducted during the Demonstration Period

To test natural stresses on the performance of the surface barrier, the PHB was divided into the north and south sections separated by a 10-m-wide buffer zone. Two specific tests were carried out at north section of the PHB during the demonstration period: 1) an enhanced precipitation test from WY95 to WY97 and 2) a controlled fire test in 2008. In most of the years, when no tests were conducted, the performance of the PHB was monitored.

An enhanced precipitation test was used to test the barrier under both ambient (natural precipitation, south section) and extreme climate (enhanced precipitation, north section) conditions for a period of 3 water years (WY95 to WY97, within a time frame of 4 calendar years). The total meteoric precipitation and irrigation received by the north section was 493.3, 493.1, and 499.7 mm for WY95 through WY97, respectively. In late March of each year from 1995 to 1997, a 1000-year return, 24-hour rainstorm test was simulated on the north section. The barrier was exposed to the natural precipitation conditions in WY99 and after.

A controlled burn was conducted on the formerly irrigated north section of the PHB in September 2008 to understand the response of the engineered ecosystems to wildfire and to quantify the effects of wildfire on the function of the ETC barrier. The test area encompassed the silt loam ETC barrier and the gravel side slope.

Barrier Monitoring

A comprehensive system was used to monitor the hydrology, mechanical stability, and ecology at the PHB. The primary water-balance components monitored for hydrologic performance evaluation of the PHB included precipitation and irrigation, surface runoff, water content (θ) and water storage within the ETC barrier, drainage through the ETC barrier and side slopes, and deep percolation through the AC. Secondary confirmative components monitored include θ at the bottom of the silt loam and beneath the AC, soil water pressure head (h) within the silt loam barrier, and h below the AC.

Movement of the AC surface was quantified by measuring the change in the elevation of settlement markers, DSG1 and DSG2, attached to the AC layer. Elevation changes of a barrier surface indicate the inflation/deflation of the barrier or soil gain/loss at the barrier surface. Elevation surveys were taken at 338 (13 × 26) locations marked by wood stakes, 3 m apart. Because of the steepness of the riprap side slope (2:1), this slope was considered to have the potential for movement. A total of 15 creep gauges (CGs) were installed at 13 locations in the riprap slope during or after barrier construction to monitor slope displacement. The ecology monitoring included the characteristics of vegetation and animal activities.

RESULTS AND DISCUSSION

Vegetation

The plant community on the PHB was robust. Forty-nine species were observed between 1995 and 2011, with the highest number of species (35) observed 2 years after construction and the fewest (11) observed in 2008, just prior to the controlled fire. In 2009, 1 year after the fire, there were 12 plant species on the unburned side, but many more species (24) on the burned side. *Artemisia tridentata* (big sagebrush) was the dominant plant when there was no fire. The results indicate a normal vegetation community for the Hanford climate.

The vegetation community recovered after the fire. Burned and unburned plant communities were more similar to each other than to their counterparts at the McGee Ranch analog site, meaning that the vegetation community gradually recovered after the fire.

Hydrology of the ETC Barrier

The ETC barrier was able to store all winter precipitation, including that received during the precipitation stress tests. As expected, water storage peaked in the winter months, when ET is low. Peak total water storage during the enhanced precipitation treatment was 517.5±85.8 mm in the 2-m-thick silt loam, which is 98% higher than the field capacity because of the underlying capillary break. The average is less than the 600-mm design storage, suggesting that the ETC barrier could have stored even more water. From WY99 to WY13, total water storage was 194.2±20.2 mm for the north section and 189.4±23.5 mm for the south section, meaning that no more than one third of the pores were filled, even during the wettest time of the year.

The ETC barrier was able to recycle to the atmosphere, via ET, nearly all precipitation stored during the winter and received during the summer. Water stored near the soil surface was released the quickest, whereas water stored at the largest depths was released the slowest. The rate of water removal by ET was constant from April to June and decreased thereafter. The results indicate that ET was sufficiently strong to reduce soil water storage to minimum values even before the end of the summer season.

The maximum drainage below the barrier components was well below the intended design. The average drainage rate was 0.005 mm yr^{-1}, which is a factor of 100 less than the design criterion of 0.5 mm yr^{-1}. The maximum annual drainage observed during the monitoring period was 0.18 mm, and occurred during the enhanced precipitation test.

Snowmelt events on frozen ground such as the one in January 1997 pose a higher risk for generating runoff than rainstorms. During the monitoring period, three events contributed a total runoff of 38.1 mm, of which 36.3 mm (95%) was due to a snowmelt event.

The 2% slope successfully diverted water during the enhanced precipitation test. After the enhanced precipitation test and during the ambient precipitation test, there was no detectable water diversion, suggesting that ET kept water content small enough to preclude noticeable lateral movement.

The barrier demonstrated resilience to fire. After the controlled fire in September 2008, the burned section revegetated naturally, predominantly by shallow-rooted grasses with some annuals, bi-annuals, and shrubs. From WY09 to WY13, precipitation was near normal and the plant community on the burned section was able to remove all the stored water, albeit at a slower rate than the mature plant community (with shrubs) in the unburned section. Despite the significant change in plant community in the burned section, there was no discernible increase in drainage rates.

Hydrology of the Transition Zones, Side Slopes, and Asphaltic Concrete

Water in the silt loam of the transition zones migrated both vertically and laterally. The accumulation of soil moisture along the silt loam boundaries was noticeable only under the enhanced precipitation conditions and was minimal under natural precipitation conditions. The measured maximum drainage rate through the transition zones was much higher than the rate through the silt loam layer, but much lower than the rate through the side slopes.

Drainage through the side slopes was high. Drainage through the two side slopes was highest in winter and lowest in summer. The annual drainage rate from both side slopes was very high (135.3 mm yr^{-1} on average) during the enhanced precipitation treatment. After the enhanced precipitation test, the rate decreased to an average of 12.8 mm yr^{-1}. Although these rates are much lower than they were during the enhanced precipitation test, they are still far in excess of the barrier design rate of 0.5 mm yr^{-1}, suggesting that side slopes, if included in the design, need to be evaluated for their impact on overall performance. No obvious difference in seasonal pattern of drainage or rate of drainage was observed between the two types of side slopes.

The AC barrier minimized water percolation to rates below detection. The level of soil water pressure below the AC was comparable to the permanent wilting point, meaning the soil water was tightly bound to soil particles and thus fairly immobile. The stable or decreasing water content, stable soil water pressure, and very low percolation rate all indicate that the amount of water that percolated through the AC was negligible.

Structural Stability

The PHB surface resisted erosion by wind. The vegetation increased the height of zero wind velocity above the barrier surface and suggested reduced possibility of wind erosion. A small amount (72 kg ha^{-1}) of water erosion was observed during the first simulated 1000-year return rainstorm in March 1995, about 6 months after construction when the vegetation was at the seedling stage. No soil erosion was observed during the rest of the monitoring period, which included the simulated 1000-year rainstorms in 1996 and 1997, the snowmelt event in the January 1997, and the controlled fire in 2008.

The PHB did not subside or compact. From 1994 to 2012, the spatially averaged elevation of the barrier surface decreased by only 0.003 ± 0.018 m, meaning undetectable soil loss or gain because of wind or water erosion or barrier settlement. The elevation of the asphalt layer varied between -0.03 and 0.02 m, indicating near-zero settlement and a very stable asphalt surface and subgrade.

PHB side slopes were stable. During the 18-year monitoring period, the CGs at the riprap slope moved an average of 0.023 ± 0.032 m outward to the east, 0.020 ± 0.012 m to the north, and 0.007 ± 0.006 m lower in elevation. These small changes demonstrate that the riprap side slope was very stable during the monitoring period.

Animal activity did not affect barrier performance. The number and sizes of animal holes or mounds on the barrier surface were generally small (no more than 0.09 m in diameter and 0.3 m deep). One large hole about 0.6 m deep with a 0.3-m diameter was observed and filled. These holes presented little risk to barrier function.

Exterior processes affected the periphery of the PHB. The rainstorm event in May 2004 led to runoff from nearby facilities that eroded a small section of the toe of the steep riprap side slope. The barrier design did not consider an event of this nature. The erosion did not affect the stability of the side slope and was repaired.

Fire Impact to Soil Properties

The impact of the controlled fire on soil properties diminished gradually over several years. The controlled fire in 2008 caused decreases in wettability, hydraulic conductivity, air-entry pressure, organic matter, and porosity relative to pre-fire conditions, whereas dry bulk density increased. One year after the fire, hydrophobicity had returned to pre-burn levels, with only 16% of the samples still showing signs of decreased wettability. Hydraulic conductivity and air-entry pressure returned to pre-burn levels at one third of the locations, but remained similar to values recorded immediately after the fire at the other two thirds. Soil nutrients, pH, and electrical conductivity remain elevated.

CONCLUSIONS

The PHB functioned as designed from the completion of construction in 1994 to 2013. Monitoring activities included hydrological stress tests that far exceeded stresses expected over the next 1000 years. Most importantly, PHB performance demonstrated that the barrier satisfied nearly all key objectives. The PHB functioned in Hanford’s semi-arid climate, limited drainage to well below the 0.5 mm yr-1 performance criterion, limited runoff, minimized erosion, and far exceeded RCRA criteria. Although the test period represented only 2% of the design life, the observed surface and side slope stability suggests the PHB is robust enough to endure for at least 1000 years under similar stress conditions.

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