

## **An Evaluation of Long-Term Performance of Liner Systems for Low-Level Waste Disposal Facilities – 11455**

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### **ABSTRACT**

Facility performance for a hypothetical disposal facility has been compared for different liner alternatives. Results were compared in terms of meeting the DOE Order 435.1 low-level waste performance objective of 0.25 mSv/yr (25 mrem/yr) all-pathways dose during the 1) institutional control period (0-100 years), compliance period (0-1000 years) and post-compliance period (>1000 years). Liner alternatives considered include traditional hydraulic containment systems (geosynthetic membrane and leachate collection), waste isolation systems (steel containers), and geochemical liners. Evaluation of the all pathways dose included the dose from ingestion and irrigation of contaminated groundwater extracted from a well 100 meters downgradient, in addition to the dose received from direct contact of radionuclides deposited near the surface resulting from facility overflow.

Depending on the disposal facility radionuclide inventory, facility design, cover performance, and the location and environment where the facility is situated, the dose from exposure via direct contact of near surface deposited radionuclides was found to be much greater than the dose received via transport to the groundwater and subsequent ingestion. This situation can occur when a hydraulic containment liner outlasts the leachate collection system and outperforms an engineered cover system. In contrast, the waste isolation liners and geochemical under-layers promote drainage while reducing either the release rate or migration rates of contaminants from the disposal facility.

The analysis provided indicates that facility performance is sensitive to the failure rate of engineered cover materials, assumptions of hydraulic liner longevity, the longevity of waste isolation liners, and degradation of geochemical barrier materials.

### **INTRODUCTION**

Traditional hydraulic isolation liner systems have been proposed to contain releases of low-level radioactive waste within the confines of low-level waste disposal facilities, thereby eliminating migration of radionuclides into the vadose zone and groundwater. Traditional hydraulic isolation liner systems have been applied to sanitary landfills and RCRA disposal facilities with the objective of reducing or eliminating movement of contaminants from the facility into the vadose zone and aquifer over time-periods spanning decades. They are typically composed of a geosynthetic liner coupled with a leachate collection system to collect and remove contaminated water that accumulates in the bottom of the lined disposal facility.

Hydraulic isolation liner systems obviously fail if the liner is breached. They can also fail if the liner remains intact, the leachate collection system is not maintained, and the overlying cover allows more total infiltration than the volumetric disposal system can accommodate. If either condition occurs during the low-level waste disposal facility lifetime, water will accumulate in the lined disposal facility. If the height of the hydraulic isolation liner extends above the waste, the waste will become submerged, and contaminated water will eventually overflow the liner. This condition is referred to as the “bathtub effect”. Waste saturation can potentially increase the waste form degradation and radionuclide releases into solution.

Transport from the disposal facility under this scenario will occur under saturated conditions in the waste. Contaminated water releases can migrate laterally in anisotropic sediments under saturated conditions. If the hydraulic isolation liner extends near land surface, contamination could reach land surface creating a direct exposure pathway. In isotropic sediments, water flux is likely to be more focused (i.e., little lateral spreading), resulting in shorter unsaturated transit times and higher radionuclide fluxes to the aquifer.

Alternative protective liner systems can be engineered that eliminate radionuclide releases to the vadose zone during operations and that minimize long-term migration of radionuclides from the disposal facility into the vadose zone and aquifer. Non-traditional systems include waste isolation liners that are assumed in this paper to be containers of steel or composite material that waste is placed in prior to disposal in the facility. The facility design for this system would promote drainage of clean infiltrating water through the facility without contacting the waste. As containers corrode, infiltrating water can contact the waste, allowing it to be transported downward. Release rates from the containers can be engineered by varying the steel composition (carbon steel vs stainless steel), and container thickness. These design features could be optimized to allow facilities to meet regulatory limits.

Other alternatives include geochemical barriers beneath the facility designed to transmit water while adsorbing radionuclides. Potential barrier materials include phosphate minerals, ion exchange resins, and clays. Man-made materials, engineered to reduce migration of specific radionuclides would subject to long-term degradation, as would natural materials. As a result, there is the potential for time-dependent performance of these materials, again allowing for engineered facility release rates.

In this paper, we examine the long-term performance of the traditional hydraulic isolation lined system, and several alternatives in terms of meeting the DOE Order 435.1 performance objective of 0.25 mSv/yr (25 mrem/yr) all pathways effective dose equivalent. Alternatives evaluated include waste isolation liners and geochemical sorption barriers.

## **CONCEPTUAL MODEL OF HYPOTHETICAL FACILITY**

For this evaluation, a hypothetical facility is evaluated having several different liner systems (Figure 1). The facility is assumed to be situated in a semi-arid environment with an annual precipitation of 35 cm/yr, and a natural recharge (infiltration) rate in undisturbed soil of 5 cm/yr. Water flow is generally assumed downward, however, anisotropy is also considered for one of the cases analyzed. The facility is assumed to have horizontal dimensions of 100 m × 100 m and a waste thickness of 6 m. An aquifer lies 30 m below the base of the facility and has a Darcy velocity of 20 m/yr and porosity of 10%. The vadose zone below the base of the facility is composed of 25 m of sand and 5 m of clay. The aquifer is also assumed to be sand and the waste backfill and surface soil are assumed to be loamy sand.

### Hypothetical Disposal Facility System with Liner and Leachate Collection System

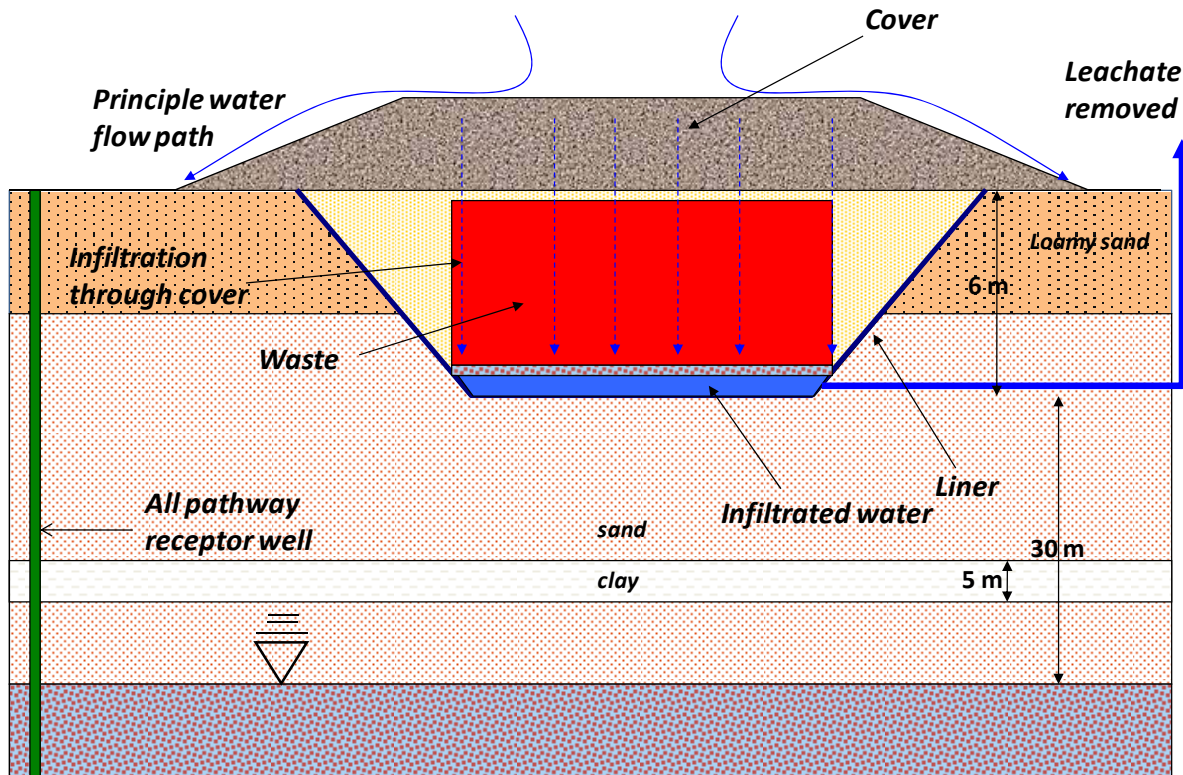


Fig. 1. Hypothetical low-level waste disposal facility showing key design features including a hydraulic isolation liner with a leachate collection system. Vadose zone lithology is also shown.

Several different liner systems are evaluated in this assessment. The conventional hydraulic isolation liner is assumed to be composed of a geosynthetic material coupled with a leachate collection system that removes water as it accumulates in the bottom of the facility. There is no leakage assumed while the hydraulic isolation liner is intact. If the hydraulic isolation liner fails, it is assumed it occurs over a relatively short period of time resulting in drainage of any water that has accumulated in the facility.

The waste isolation liner alternative considers radionuclide wastes are encapsulated in carbon steel containers. The steel containers are separated by a sand infill material. The sand infill allows infiltrating water to pass through the facility between the steel containers. Eventually, corrosion will breach the steel containers, allowing water to come in contact with the waste. In practice, the breaching time will be a function of the corrosion rate and the thickness of the steel. For the purposes of this assessment, the breaching time is described by a normal distribution of container failure times.

The geochemical barrier alternative assumes an anion exchange resin has been placed in the bottom of the disposal facility. This geochemical barrier is designed to retard the movement of key anions such as iodine and technetium. In this assessment, it is assumed that the material does not degrade over time as might occur if the material were to be coated geochemically or if the material were subject to biodegradation, for example.

In all of the cases considered, the waste form is assumed to be contaminated soil and miscellaneous waste where the release mechanism is surface wash with soil-water partitioning. Activated metal waste forms and contaminated ion exchange resins were not considered in this assessment.

## NUMERICAL MODELS

For evaluation of radionuclide transport, the Mixing Cell Model (MCM) [1] and GWSCREEN [2] were used to compute radionuclide transport in the vadose zone and aquifer, respectively. The MCM code is a 1-dimensional transient flow and transport model for assessment of water flow and radionuclide or chemical transport in a heterogeneous vadose zone environment. Output from the MCM code consisted of radionuclide fluxes at the vadose zone-aquifer interface. GWSCREEN is a semi-analytical model for assessment of the contaminant migration from surface or buried sources. The model includes a source, vadose zone, and aquifer model. In this application, only the aquifer model was used to assess downgradient concentrations given the radionuclide fluxes predicted by MCM.

All pathway doses were calculated using the methodology presented in NRC [3] and Peterson [4] and implemented in DOE-ID [5]. The all-pathways scenario assumes a receptor consumes (1) contaminated groundwater, (2) leafy vegetables and produce that were irrigated with contaminated groundwater, and (3) milk and meat from animals that consume contaminated water and pasture grass irrigated with contaminated groundwater derived from the well.

For the case involving the failure of the leachate collection system where the liner fills with water and saturates the waste zone (i.e. the “bathtub effect”), separate hand calculations were performed which are described in the Case Descriptions section that follows. The RESRAD computer code [6] was also used to evaluate doses from near-surface migration of radionuclides for the case where the hydraulic isolation liner does not fail resulting in the bathtub effect.

## MODEL PARAMETERS

Hydrologic parameters for the vadose zone (i.e. van Genuchten parameters and porosity, Table I) were obtained from Carsel and Parrish [7]. The engineered cover was assumed to reduce infiltration an order of magnitude from the natural infiltration rate (0.5 cm/yr) and to remain intact for 500 years following closure of the facility. After 500 years, the cover was assumed to degrade such that the net infiltration linearly increased to 5 cm/yr at 1000 years following closure of the facility. During disposal operations, infiltration through the facility was assumed to be enhanced to 20 cm/yr and disposal operations were assumed to continue for 20 years. Waste was assumed to be linearly emplaced over the 20-year period.

Table I. Saturated hydraulic conductivity ( $K_{sat}$ ), residual moisture content ( $\theta_r$ ), saturated moisture content ( $\theta_s$ ), and the van Genuchten fitting parameters  $\alpha$  and  $n$  for lithologies of the hypothetical LLW disposal facility (from Carsel and Parrish [7]).

Soil Type	Percent Sand	Percent Clay	$n$	$\alpha$ (cm <sup>-1</sup> )	$\theta_r$	$\theta_s$	$K_{sat}$ (cm yr <sup>-1</sup> )
Clay	14.9	55.2	1.09	0.008	0.068	0.38	1,752
Loamy Sand	80.9	6.4	2.28	0.124	0.057	0.41	127,808
Sand	92.7	2.9	2.68	0.145	0.045	0.43	260,172

Radionuclide inventories consisted of key radionuclides typically seen as dose drivers in low-level waste performance assessments. These radionuclides included <sup>14</sup>C, <sup>3</sup>H, <sup>129</sup>I, <sup>94</sup>Nb, <sup>99</sup>Tc, and <sup>238</sup>U (Table II). Soil-

water partitioning coefficients ( $K_d$ s) were obtained from Sheppard and Thibault [8] for sand, loam and clay lithology.

All-pathway doses were calculated for a receptor that drills a water well 100-m downgradient from the edge of the facility and sets up a subsistence farm at that location. The receptor was assumed to be at this location for all times following facility closure. Parameter values are provided in DOE-ID [5]. Dose coefficients for calculation of the Effective Dose Equivalent (EDE) were obtained from EPA Federal Guidance Report 13 [9] and the supplemental CD [10] containing dose conversion factors. Doses were calculated for a unit activity concentration in groundwater and divided by the concentration to yield the all-pathway dose conversion factor.

$$DCF_{AP} = \frac{D_{AP}}{C_U} \quad (1)$$

where  $DCF_{AP}$  = the all-pathways dose conversion factor ( $Sv \cdot m^3/Bq \cdot yr$ ),  $D_{AP}$  = the all pathways effective dose equivalent for a unit concentration in groundwater ( $Sv/yr$ ), and  $C_U$  = unit concentration in groundwater ( $Bq/m^3$ ). All-pathways dose conversion factors are listed in Table II.

Table II. Radionuclide inventories and soil-water partitioning coefficients ( $K_d$ ) for the long-term assessment of hydraulic isolation liners.

Radionuclide	Inventory (GBq [Ci])	Sand $K_d$ (mL/g)	Loamy Sand $K_d$ (mL/g)	Clay $K_d$ (mL/g)	Geochemical Barrier $K_d$ (mL/g)	All-Pathway Dose Conversion Factor ( $Sv \cdot m^3/Bq \cdot year$ ) <sup>b</sup>
C-14	3,700 [100]	5	20	1	20	$1.50 \times 10^{-9}$
H-3	$6.66 \times 10^6$ [1800]	0	0	0	0	$3.14 \times 10^{-11}$
I-129	3.7 [0.1]	1	5	1	20	$1.23 \times 10^{-8}$
Nb-94	1,850 [50]	160	550	900	550	$2.21 \times 10^{-8}$
Tc-99	555 [15]	0.1	0.1	1	20	$9.11 \times 10^{-10}$
U-238	185 [5]	35	15	1600	15	$3.92 \times 10^{-8}$
U-234 <sup>a</sup>	0	35	15	1600	15	$3.95 \times 10^{-8}$
Th-230 <sup>a</sup>	0	320	330	580	330	$1.64 \times 10^{-7}$
Ra-226 <sup>a</sup>	0	50	600	910	600	$2.23 \times 10^{-7}$
Pb-210 <sup>a</sup>	0	27	600	55	600	$1.99 \times 10^{-5}$
a. Radionuclide progeny of U-238.						

b. All pathway dose conversion factors described in DOE-ID [5].

The default RESRAD parameters were used to evaluate doses from radionuclides brought to the surface via the bathtub effect. Radionuclides were assumed to be present 0.5 m below the land surface. Exposure pathways included plant, milk, and meat ingestion, external exposure, and inhalation.

## CASE DESCRIPTIONS

Six cases were evaluated (Table III) for the all-pathways dose over time. These are:

1. Disposal facility without hydraulic isolation or waste isolation liners. This corresponds to the base case for comparison to the liner alternatives. The facility configuration is illustrated in Figure 1 except it does not contain the liner or leachate collection system. Waste is assumed to be placed in the facility during the 20-year operational period. After the operational period, the facility is covered with an infiltration reducing cover. The cover performs as designed during the first 500 years. During the subsequent 500 years, the cover performance degrades linearly to allow background infiltration of 20 cm/yr.
2. Disposal facility underlain with a geochemical barrier. This is an extension of Case 1 with an anion sorption barrier installed under the facility to remove  $^{99}\text{Tc}$  and  $^{129}\text{I}$  from the leachate. Waste emplacement and engineered cover performance are unchanged from Case 1. Although extended time-periods are required for the sorbing radionuclides to migrate through the vadose zone, it is assumed that the sorbing media remains unaltered over time.
3. Disposal facility with a conventional hydraulic isolation liner and leachate collection system. The engineered cover is assumed to function as described for Case 1. The hydraulic isolation liner is assumed to extend up to the top of the waste, and thereby eliminate any possibility of leachate escaping the leachate collection system during the 20-year operational period and during the 100-year institutional control period. After institutional control, it is assumed that maintenance of the leachate collection system stops and the facility accumulates water.

It is then assumed that the hydraulic isolation liner fails instantaneously uniformly across the area of the facility at 500 years. During the period prior to the hydraulic isolation liner failing, no radionuclides are released from the facility. Thus, with the exception of radioactive decay, the inventory in the facility has not been reduced from the initial value. Assuming an infiltration rate through the engineered cover of 0.005 m/yr, and saturated moisture content of 0.41, the time required to fill the liner system with water,  $t_{fill}$ , can be computed from:

$$t_{fill} = \frac{T \times \theta}{q_{cap}} = \frac{6 \text{ m} \times 0.41}{0.005 \text{ m/yr}} = 492 \text{ yrs} \approx 500 \text{ yrs} \quad (2)$$

Where  $T$  is the facility thickness,  $\theta$  = the saturated moisture content in the soils containing the waste (0.41); and  $q_{cap}$  = the infiltration rate through the engineered cover (m/yr). Thus, in this case, the hydraulic isolation liner fails just after the facility becomes saturated with water. The water in the waste is then allowed to freely drain from the facility

4. Disposal facility with a non-failing conventional hydraulic isolation liner. This is an extension of Case 3, but assumes that the hydraulic isolation liner does not fail (i.e. leak). In this scenario, it is assumed that the hydraulic properties in the vadose zone near the surface are anisotropic, layered, or low permeability, allowing the overflowing contaminated water to migrate laterally from the

facility. Because the hydraulic isolation liner is assumed to extend to near land-surface, the lateral migration brings contaminated radioactive leachate to the near surface where they can contribute to a direct exposure pathway in addition to contributing to the all-pathways groundwater dose. The spillover was assumed to spread 50 meters laterally before infiltrating.

5. Disposal facility with waste placed in waste isolation liners. This is an extension of Case 1, but assumes the waste is isolated from infiltrating water by steel liners in addition to engineered facility features allowing clean water to pass through the facility without water accumulation. Because all waste is initially encapsulated in the steel liners, releases into the disposal facility soils are only possible once the steel liner has failed. Waste isolation liner failure is assumed to occur through corrosion, with a corrosion rate described by a normal distribution. The assumed failure rate distribution determines the release rate from the waste isolation liners into the disposal facility soils. The steel liners have a mean lifetime of 1000 years with a standard deviation of 500 years. Once released into the soils, infiltrating water can carry the radionuclides downward through the vadose zone.
6. Disposal facility with waste placed in different types of waste isolation liners. Half the waste is placed in a container having a mean lifetime of 500 years (250 year standard deviation) and the other half in containers having a mean lifetime of 1500 years (500 year standard deviation). This case is similar to Case 5, but assumes that a range of waste isolation liners have been used. Use of different waste isolation liners results in a broader distribution of container lifetimes. This case is representative of either using steel liners of different compositions (e.g. carbon steel vs stainless steel) or using containers of various thicknesses.

Table III. Description of cases considered for the evaluation of hydraulic isolation and waste isolation liners.

Case Number	Isolation Liner?	Leachate Collection	Description
1	No	No	No hydraulic or waste isolation liner or leachate collection system.
2	Yes – geochemical	No	Anion geochemical barrier installed below facility
3	Yes – hydraulic	Yes	Hydraulic isolation liner fails after the facility fills with water 492 years after closure
4	Yes – hydraulic	Yes	Hydraulic isolation liner does not fail and the facility overflows after 492 years (bathtub effect)
5	Yes – waste	No	Waste is placed in containers that have a mean lifetime of 1000 years with a standard deviation of 500 years.
6	Yes – waste	No	Half the waste is placed in containers having a mean lifetime of 500 years (250 year standard deviation) and the other half in containers having a mean lifetime of 1500 years (500 year standard deviation).

## SOURCE RELEASE MODELS

In Cases 1– 3, the waste is assumed to reside in the disposal facility sorbed onto soils. The corresponding release model is simply desorption into the infiltrating water.

For Case 4 (bathtub effect), a separate source term model was used to account for facility overflow while using the 1-dimensional MCM model. For this case, the facility fills with water and is assumed to overflow along one of the edges. Water draining over the edge of the facility is assumed to spread laterally 50 m before infiltrating into the vadose zone. As the facility is being filled, no radionuclide releases are assumed to occur. The mass balance equation for radionuclides in the disposal facility is

$$\frac{dM}{dt} = - \left( \frac{Q(t)}{L W T R d \theta} + \lambda \right) M_{over} \quad (3)$$

where  $M$  = the mass of radionuclides in the facility at  $t = t + t_{over}$ ,  $t_{over}$  = the time the facility overflows,  $M_{over}$  = the mass of radionuclide in the facility at the time of overflow,  $Q(t)$  = the water flux overflowing the facility after facility overflow ( $m^3/yr$ );  $L$ ,  $W$ , and  $T$  are the facility length, width, and thickness respectively (m);  $Rd$  = the retardation coefficient ( $1 + K_d \rho/\theta$ ); and  $\lambda$  = the radioactive decay constant ( $1/yr$ ). The time when the facility overflows is the same as computed for Case 3 (492 years).

The amount of water that overflows the facility is approximately:

$$Q(t) = q_{cap}(t) \times L \times W \quad (4)$$

where  $q_{cap}(t)$  = the net infiltration through the cap ( $m/yr$ ). The net infiltration through the cap is a stepwise function. From 0 to 500 years,  $q_{cap}(t)$  is a constant 0.005  $m/yr$ . From 500 to 1000 years,  $q_{cap}(t)$  is a linear function described by

$$q_{cap}(t) = 0.005 + m(t - 500) \quad (5)$$

$m$  = the slope of the linear cap failure rate ( $m/yr^2$ ). After 1000 years,  $q_{cap}(t)$  is a constant 0.05  $m/yr$ . The net infiltration from water flowing over the waste isolation liner is  $Q(t)/(50 \text{ m} \times 100 \text{ m})$ . To determine the mass flux of radionuclides transported from the facility as a function of time, Equation (3), was solved numerically.

For Cases 5 and 6, determining the radionuclide release rate into the disposal facility was done assuming that the net water flux that comes in contact waste is proportional to the fraction of containers that have failed via corrosion. Under this assumption, the net water flux that comes in contact with waste is given by:

$$q(t) = CDF(t) q_{inf}(t) \quad (5)$$

where  $CDF$  = the cumulative probability density function of container failure times, and  $q_{inf}$  = net infiltration rate through cap and reaching the waste ( $m/yr$ ).

The  $CDF$  function for a normal distribution is given by



$$CDF(t) = \frac{1}{2} \left[ 1 + \operatorname{erf} \left( \frac{t-u}{\sigma\sqrt{2}} \right) \right] \quad (6)$$

where  $t$  is time from waste emplacement and  $u$  is the mean container lifetime (years). It is assumed that corrosion is the only waste isolation liner failure mode and the physical integrity of the waste isolation liner (i.e., subsidence followed by crushing of the container) does not occur.

## RESULTS

All-pathways effective dose equivalents ( $\mu\text{Sv}/\text{yr}$ ) for the six cases are shown in Figure 2 through 4 and summarized in Table IV. In the base-case containing no liners, tritium migrates from the disposal facility during the 100 year institutional control period resulting in a peak dose of  $187 \mu\text{Sv}/\text{yr}$  (Figure 2). The second peak occurs at the compliance period with the arrival of  $^{99}\text{Tc}$ . The remainder of the radionuclides peak during the post-compliance period.

In Case 2, adding an anion exchange resin as a geochemical barrier under the facility had no effect on the overall peak dose during the institutional control period because the geochemical barrier has no effect on the transport of tritium (Figure 2). The anion  $K_d$  barrier resulted in the lowest doses during the post compliance period, because the primary dose contributor was  $^{99}\text{Tc}$  which has  $K_d$  values of 0.1 to 1 in the subsurface but a  $K_d$  value of 20 in the geochemical barrier. The  $^{99}\text{Tc}$  peak dose for Case 2 was about a factor 2 less than in Case 1.

In Case 3, adding a hydraulic isolation liner and leachate collection system prevented the migration of all radionuclides from the disposal facility, allowing tritium to decay while still in the disposal facility (Figure 3). The hydraulic isolation liner has the effect of reducing or eliminating dose potential during the early period of performance for short-lived mobile radionuclides. In Case 3, releases from the facility were delayed by 500 years. Failure of the hydraulic isolation liner at 500 years resulted in initially higher vadose zone water fluxes and faster radionuclide travel times. The faster radionuclide travel times after 500 years were sufficient to offset the 500-year delay time as shown by the  $^{99}\text{Tc}$  peak dose occurring at about the same time and magnitude as in Case 1. Retention of the radionuclides in the facility for 500-years followed by instantaneous failure of the liner resulted in higher dose contributions of both  $^{129}\text{I}$  and  $^{14}\text{C}$  during the post compliance time compared to Case 1. The hydraulic liner has little effect on the peak  $^{238}\text{U}$  dose compared to Case 1 and 2, but for the highly sorbed  $^{94}\text{Nb}$ , the dose drops below  $1 \times 10^{-4} \mu\text{Sv}$  during the post compliance period.

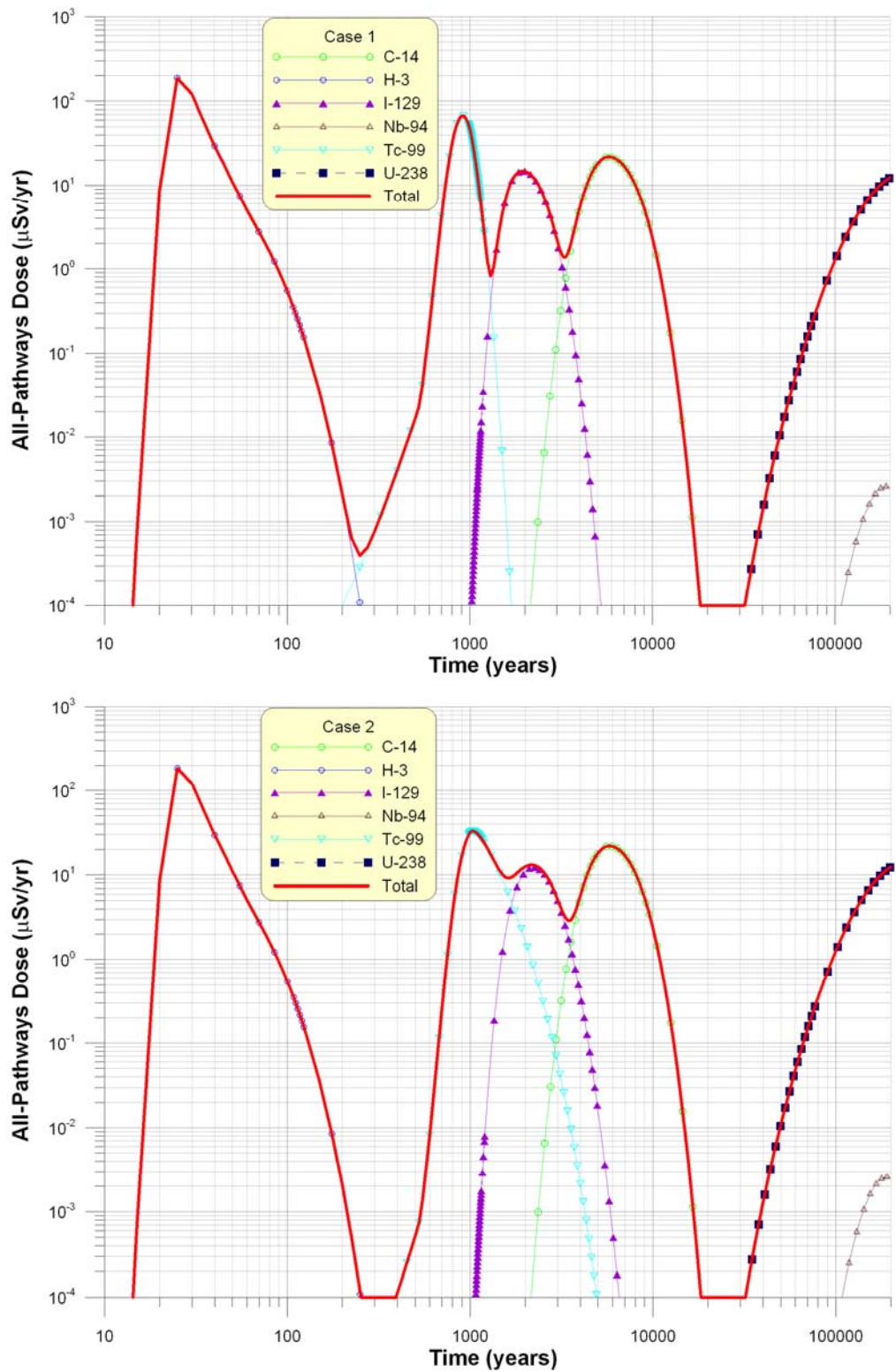


Fig. 2. All-pathways dose as a function of time for Case 1 (no liners) and Case 2 (geochemical barrier).

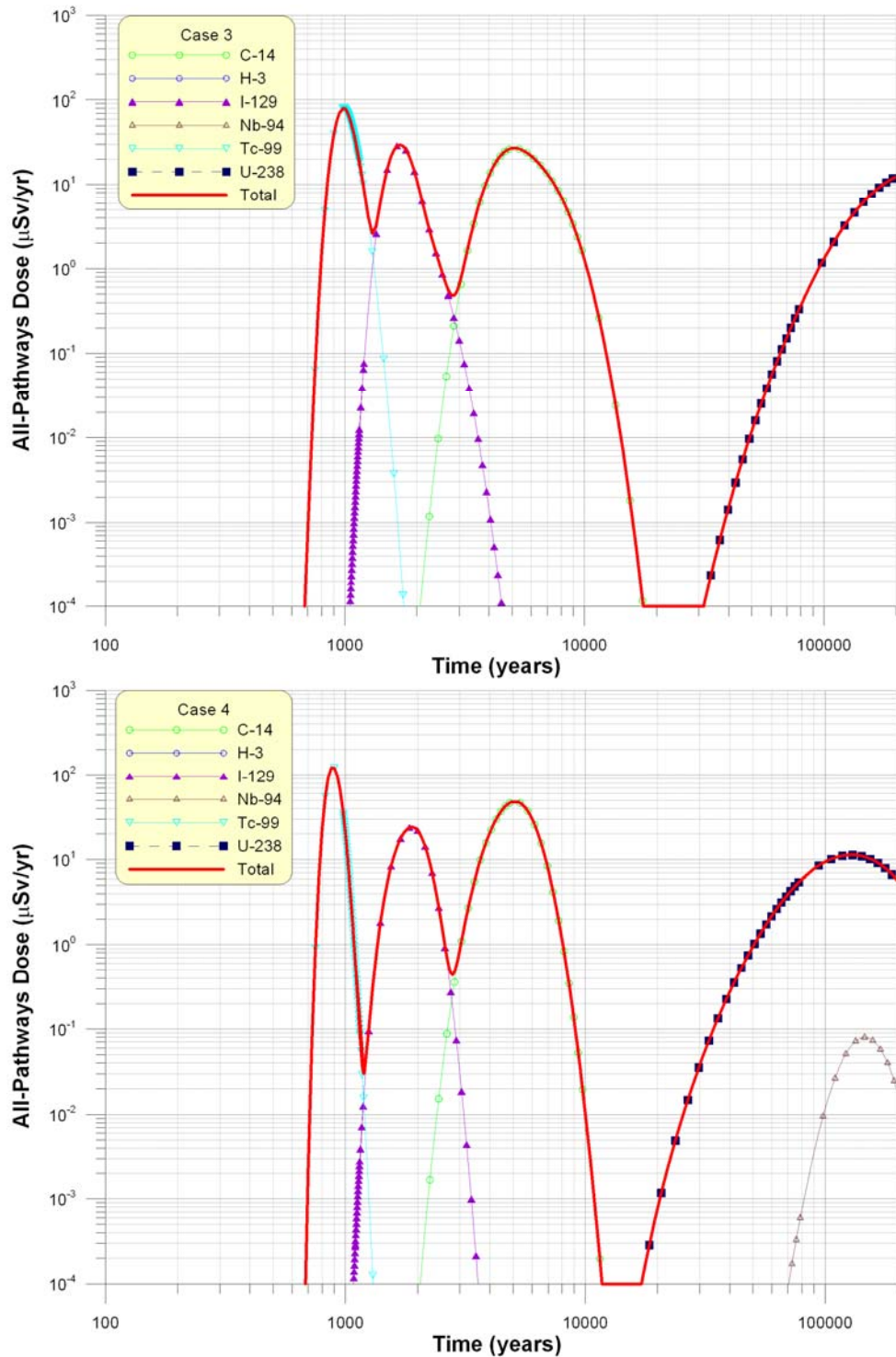


Fig. 3. All-pathways dose as a function of time for Cases 3 (hydraulic isolation liner fails after 500 years) and 4 (hydrologic isolation liner never fails resulting in bathtub effect). Case 4 doses are only for the groundwater pathway and do not show the doses from radionuclides brought to the surface from the bathtub effect.

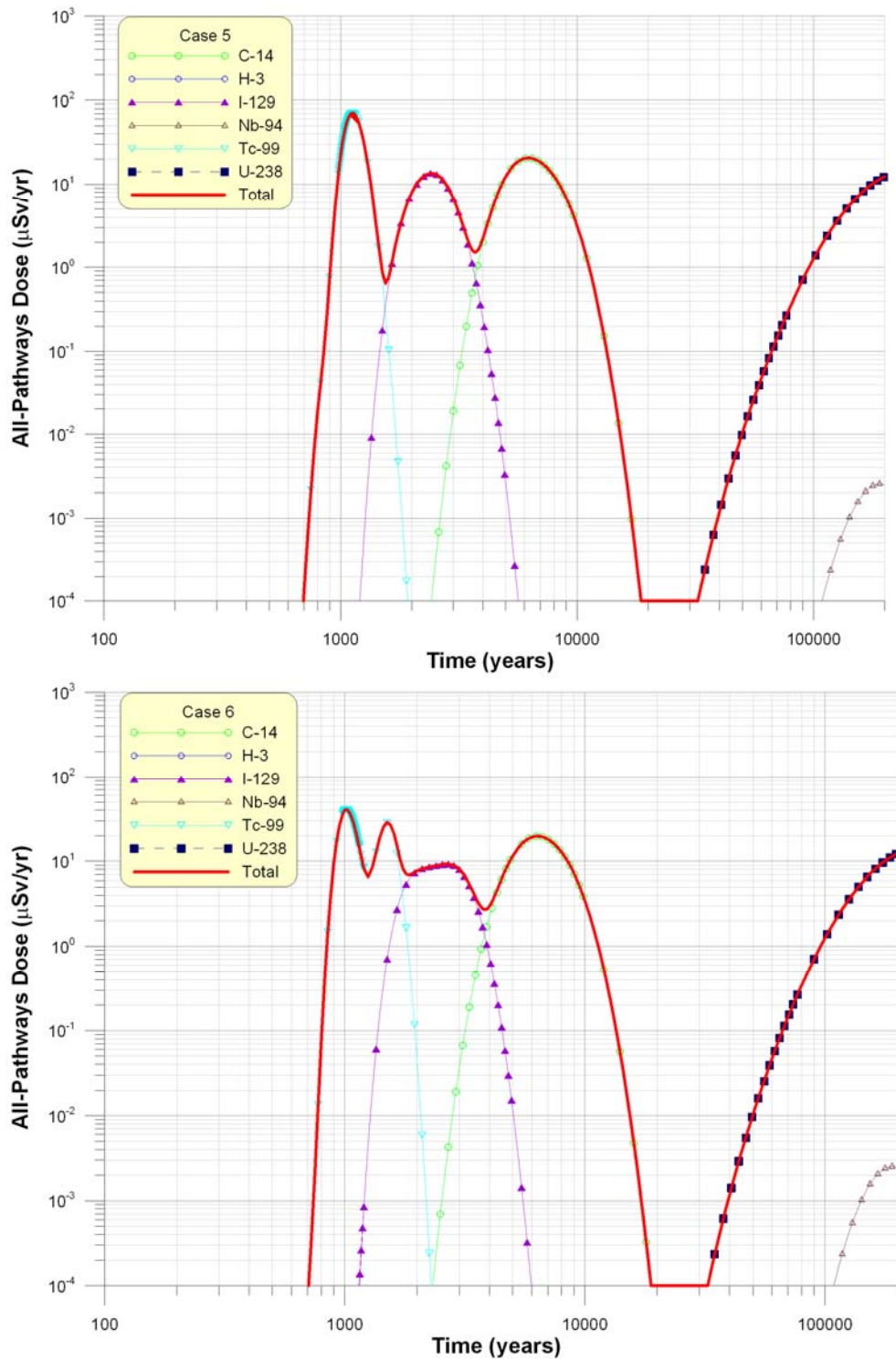


Fig. 4. All-pathways dose as a function of time for Cases 5 (waste isolation liner, mean container lifetime of 1000 years) and 6 (waste isolation liner, mean container lifetimes of 500 and 1500 years).

In Case 4, the intact hydraulic isolation liner allows the facility to overflow resulting in focused recharge, high vadose zone pore water velocities, and rapid radionuclide transport. Higher doses for Case 4 occur earlier in time for <sup>99</sup>Tc, <sup>129</sup>I, and <sup>14</sup>C. In the base-case, the cross-sectional area is equal to 100 m × 100 m. In the overflow scenario, the infiltration area is 50 m × 100 m. Therefore, the net infiltration rate is a factor of two greater than for Case 1 or Case 2. As shown in Figure 3 and Table IV, the predicted peak dose during the compliance period (from <sup>99</sup>Tc) is about a factor of two greater than the Case 1 dose. During the post compliance period, the predicted peak doses are almost equal. As shown in Figure 3 and Table IV, when compared with Case 3 (hydraulic isolation liner failing at 500 years), this facility overflow scenario predicts higher peak doses during the compliance period (122 versus ~80 μSv/y) and lower peak doses during the post compliance period (48 versus ~80 μSv/y). In addition to the dose from radionuclide migration to groundwater, if the facility fills with water and overflows, addition doses are received from radionuclides brought to the surface from the spillover. These doses are much greater than the all-pathways dose from the groundwater pathway alone. Carbon-14 accounts for most of the dose (370 μSv/yr) followed by <sup>129</sup>I (16 μSv/yr), and <sup>94</sup>Nb (11 μSv/yr). These doses exceed the 250 μSv/yr all-pathways dose criteria.

Table IV. Results of the all-pathways effective dose equivalent (μSv/yr) for the six cases considered. Compare with the DOE all-pathways dose limit of 250 μSv/yr.

	No Physical Liner		Hydraulic Isolation Liner		Waste Isolation liners	
Time Period	Case 1: No Hydraulic Isolation Liner (μSv/yr)	Case 2: No liner, anion K <sub>d</sub> barrier (μSv/yr)	Case 3: Fails at 500 years (μSv/yr)	Case 4: Bathtub Effect (μSv/yr)	Case 5: 1000-yr mean lifetime (μSv/yr)	Case 6: 500 yr and 1500 yr mean lifetime (μSv/yr)
Institutional Control Period (0-100 years)	187	187	0.00	0.00	0.00	0.00
Compliance Period (100-1000 years)	67.4	32.0	80.5	122	22.0	40.3
Compliance Period, dose from radionuclides brought to surface	---	---	---	406	---	---
Post-Compliance Period (>1000 years)	47.2	32.9	79.8	47.9	70.9	40.9

In Case 5, all the waste was assumed to be isolated in one type steel liner. The mean container lifetime was assumed to be 1000 years and the standard deviation for failure of the waste isolation container was 500 years. Using steel liners to encase the waste allowed the tritium to decay while still in the disposal facility. As shown in Figure 4 and Table IV, the predicted peak dose during the compliance period was three times smaller than the Case 1 predicted peak dose. During the post compliance period, the predicted peak dose was 1.5 times the predicted peak dose for Case 1. As shown in Figure 4, this waste isolation liner system delayed the time of the peak dose from  $^{99}\text{Tc}$ ,  $^{129}\text{I}$ , and  $^{14}\text{C}$  relative to the Case 1. The mean container failure time was short enough not to effect the transport of  $^{238}\text{U}$  and  $^{94}\text{Nb}$ . Because of the longer half-lives of these radionuclides, their peak dose contributions were not significantly decreased.

In Case 6, two different steel liners were assumed to contain the waste with half of the waste contained in each type. Mean container lifetime for the first container was 500 years and 1500 years for the second container type. Including half of the inventory in containers with a mean failure time of 500 years increased the predicted dose (Figure 4 and Table IV) during the compliance time period by almost a factor of two over the predicted dose in Case 5 (all the waste in one container with a mean failure time of 1000 years). It also results in a lower predicted peak dose in the post compliance time period. Splitting the initial inventory into the two container types effectively distributes the release rate over time. This is illustrated by the bimodal dose exhibited by  $^{99}\text{Tc}$  in the Case 6 plot in Figure 4. Sorption in the vadose zone however tends to reduce this effect as seen in the broader  $^{129}\text{I}$  dose curve, and in the case of  $^{14}\text{C}$ , the effect has completely dissipated.

## DISCUSSION

In general, the performance of all liner systems is superior to unlined systems during the institutional control period. Doses during the institutional control period for all cases were dominated by the ability to contain tritium. The most effective means of containment for radionuclide migration during this time-period corresponded to hydraulic isolation and waste isolation options. The hydraulic isolation options evaluated here assumed maintenance of the leachate collection system throughout the 100 year institutional control period and that the hydraulic isolation liner would remain intact through the first 500 years after installation. If the hydraulic isolation liner were to fail prematurely, leachate collection stopped earlier, or the engineered cover failed prematurely, the performance of the hydraulic isolation liner system would be adversely impacted. Similarly, steel liners were considered for waste isolation in this assessment, and corrosion rates were based on literature data in semi-arid environments. Material selection in terms of chemical composition and physical configuration could affect the performance of waste isolation liners.

Doses during the compliance period for all cases were dominated by  $^{99}\text{Tc}$ . The cases corresponding to the lowest doses were based on the use of waste isolation liners and geochemical barriers. The geochemical barrier considered was based on assumed sorption of anions, specifically targeting  $^{99}\text{Tc}$  and  $^{129}\text{I}$ , and therefore, the migration of cations and metals would not be affected. The highest dose during the compliance period was produced by Case 4 where a lined facility overflowed at around 500 years. This result is highly dependent upon the assumed cover lifetime, facility dimensions, and infiltration rate through the cover.

Doses during the post-compliance period predicted peak doses that were reduced through the use of geochemical barriers and combinations of waste isolation liners. None of the alternatives evaluated here significantly affected transport of  $^{238}\text{U}$ , predicted to arrive in the 100,000 year time period. The inability to reduce  $^{238}\text{U}$  dose using the alternative cases evaluated is in part due to the short-lived effectiveness of

the alternatives evaluated, and in part due to using an anion exchange resin as a geochemical barrier as opposed to using a mineral specifically targeting <sup>238</sup>U.

Implementation of the various options considered could have implications on the results. For example, alternative designs for conventional hydraulic isolation liners might consider not extending the liners toward land surface. Keeping the sides low would prevent water from ponding in the waste after the leachate collection system is turned off, preventing saturated flow conditions from developing, and preventing the potential for radionuclides to be released at land surface. While this design may seem attractive at first, there is a potential for leachate generated during the disposal operations to move laterally around the hydraulic isolation liner, thereby short-circuiting the leachate collection system resulting in tritium-derived doses earlier in the assessment period. The leachate collection system would have to be operated until the tritium concentrations have decayed to levels that are not a dose issue.

Geochemical amendments, layers, or barriers are subject to performance degradation through encapsulation, biodegradation, and could be adversely impacted by solution chemistry. For example, the performance of anion exchange resins is adversely impacted in high pH, high ionic strength environments that might exist in cement vault systems, and natural clays are subject to long-term mineralogical changes. In general, the long-term performance of geochemical barriers systems is an area of high uncertainty. However, the development of geochemical barriers to help decrease future doses from the groundwater pathway could be very valuable.

Waste isolation liner options require a lower operational and maintenance investment, but are subject to degradation. While steel liners were considered in this assessment, and corrosion rates were based on literature data in semi-arid environments, other materials could be used. Steel liners provide good protection during the institutional control, compliance, and post-compliance period. However, a significant portion of the waste needs to be containerized in the steel liner and the facility may need extra engineering structure to ensure physical integrity of the waste isolation liner is not compromised. Depending on the volume and type of waste, this practice may be prohibitively expensive.

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